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Simplified Aircraft-Based Paired Approach: Concept Definition and Initial Analysis

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Contents

Table of Acronyms and Abbreviations

ADS-B	Automatic Dependent Surveillance – Broadcast
AGL	Above Ground Level
APA	AVOSS Prediction Algorithm
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
AVOSS	Aircraft VOrtex Spacing System
CAS	Calibrated Air Speed
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FTE	Flight Technical Error
GBAS	Ground-Based Augmentation System
GLS	GNSS Landing System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
IGE	In Ground Effect
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
KIAS	Knots Indicated Airspeed
LAAS	Local-Area Augmentation System
LPV	Localizer Approach Vertical Guidance
MASPS	Minimum Aviation System Performance Standards
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NGE	Near Ground Effect
NSE	Navigation System Error
NTZ	No Transgression Zone
OGE	Out of Ground Effect
PDE	Path Definition Error
PFAS	Planned Final Approach Speed
RNAV	aRea NAVigation
SAP	Stabilized Approach Point
SAPA	Simplified Aircraft-based Paired Approach
SAPA-CZ	SAPA Conformance Zone
SBAS	Satellite-Based Augmentation System
SOCMAP	SAPA Out of Conformance Missed Approach Point
SFO	San Francisco International Airport
TRACON	Terminal Radar Approach CONtrol
TSE	Total System Error
WAAS	Wide-Area Augmentation System
WVSAT™	Wake Vortex Simulation and Analysis Tool

Abstract

Simplified Aircraft-based Parallel Approach (SAPA) is an advanced concept proposed by the Federal Aviation Administration (FAA) to support dependent parallel approach operations to runways with lateral spacing closer than 2500 ft. At the request of the FAA, NASA performed an initial assessment of the potential performance and feasibility of the SAPA concept, including developing and assessing an operational implementation of the concept and conducting a Monte Carlo wake simulation study to examine the longitudinal spacing requirements. The SAPA concept was shown to have significant operational advantages in supporting the pairing of aircraft with dissimilar final approach speeds. The wake simulation study showed that support for dissimilar final approach speeds could be significantly enhanced through the use of a two-phased altitude-based longitudinal positioning requirement, with larger longitudinal positioning allowed for higher altitudes out of ground effect and tighter longitudinal positioning defined for altitudes near and in ground effect. While this assessment is preliminary and there are a number of operational issues still to be examined, it has shown the basic SAPA concept to be technically and operationally feasible.

Introduction

Capacity reduction from restricted operation in Instrument Meteorological Conditions (IMC) of Closely Spaced Parallel Runways, defined as runways laterally spaced closer than 4300 ft apart, is a major limiting factor in supporting future air traffic demand. There are a number of current and proposed future solutions for conducting efficient, simultaneous independent, parallel operations in Instrument Meteorological Conditions (IMC) for runways spaced between 4300 and 2500 feet (ft), such as high-update radar and path offset [CSPOWG2009]. For runways with centerline spacing closer than 2500 ft, wake turbulence encounters between aircraft on parallel paths become problematic, and dependent operations are required. Simplified Aircraft-based Parallel Approach (SAPA) [DeCleene2008] is an advanced concept being considered for dependent, low-visibility operations for dual and triple runways spaced closer than 2500 ft.

At the request of the Federal Aviation Administration (FAA), an initial assessment of the potential performance and feasibility of the SAPA concept was performed. This initial assessment included an initial system study of the SAPA concept to assess operational benefits and constraints to inform SAPA standards development plus a preliminary technical feasibility analysis to aid the FAA in the development and refinement of the SAPA concept. This effort was jointly funded by the FAA and the National Aeronautics and Space Administration (NASA) under its Airspace Systems Program.

Overview of FAA SAPA Concept

The ability to conduct dependent parallel approaches to closely spaced runways under IMC offers an important opportunity for a significant increase in the rate of flight operations and the potential to foster growth of operations at airports. The Simplified Aircraft-based Paired Approach (SAPA) concept is a proposed mid-term (2013-2018) concept for operation of closely spaced parallel runways in IMC. SAPA is designed to increase capacity at airports in the United States where lateral runway spacing for parallel runway operations under IMC currently require aircraft-to-aircraft longitudinal separation equivalent to single runway operations. The target application is simultaneous, dependent operations to two or three parallel runways spaced closer than 2500 feet (ft), possibly as close as 700 ft. In the current analysis, SAPA operations to runways with lateral spacing as close as 750 ft were examined.

The SAPA concept leverages advanced navigation and flight-guidance technology along with dependent surveillance to minimize parallel-approach spacing requirements. With the use of an augmented Global Navigation Satellite System (GNSS) navigation source for precise, reliable guidance, plus a modern autopilot to provide very reliable and accurate path tracking throughout the approach, safe IMC operations are possible at very close lateral runway spacing. The aircraft use Automatic Dependent Surveillance – Broadcast (ADS-B) to share precise position and velocity data, as well as other application-specific data that is not currently available in commercial systems such as autopilot status. The pair of aircraft must remain in approximately abeam positioning to avoid any wake vortex encounters. The approach path is based on constant-width navigation performance.

Aircraft are initially established on final approach with a minimum of 1000 ft of vertical separation, and Air Traffic Control (ATC) is responsible for initially pairing the aircraft with appropriate relative longitudinal positioning. During the SAPA operation, the aircraft employ onboard flight-guidance speed cues to maintain longitudinal alignment within the required tolerance.

During the SAPA procedure, a breakout maneuver must be initiated in the following situations:

- lateral position error beyond tolerance,
- longitudinal position error beyond tolerance, and
- ADS-B status indication of loss of autopilot coupling or augmented GNSS navigation accuracy.

The breakout maneuver is a climbing turn that is executed via actuation of a preprogrammed path.

Lateral Navigation Requirements

Similar to the Airborne Information for Lateral Spacing (AILS) concept [Abbott2001], the primary means for conducting safe SAPA operations is that the possibility of interference between the two aircraft on approach must be remote. In SAPA, this requirement is met by defining a high Required Navigational Performance standard for the performing aircraft, which could be achieved by flying coupled autopilot with high precision navigation. The SAPA pairing only occurs once the aircraft are established on the final approach course, conducting a straight-in approach guided by highly accurate navigation and flight guidance. There are two key components that affect the go-around rate: the likelihood that an aircraft blunders (i.e., crosses unacceptably close to the paired aircraft's approach path), and the likelihood that an aircraft's alerting will falsely perceive a blunder when none has occurred.

The current study does not include any assessment of the feasibility of designing alerting algorithms that are sensitive enough to detect blunders quickly yet yield acceptably low false alarm rates. This may be quite difficult to achieve because the available time to avoid a collision or strong wake encounter will be quite small given the target lateral runway spacing of 750 ft or lower. The current study also does not address the likelihood that a minor deviation from the center of the flight path might trigger a false alarm. Future studies aimed at designing the alerting algorithms will need to address issues such as whether deviations within these lateral bounds would trigger false alarms, necessitating even tighter lateral navigation requirements. Based on the results of several studies currently underway, standards for implementing parallel runway operations are likely to change before SAPA could be operational. For example, based on an assessment of historical operational data, the assumed likelihood used in safety case calculations of a 30^{o} blunder along the final approach course may change significantly.

What is presented in this section is essentially a discussion of the feasibility of a single aircraft conducting an approach to one of a pair of runways spaced as close as 750 ft laterally without crossing the mid-line between the two runways. This is a first cut at examining the navigation systems on the existing fleet, because there is a significant question whether existing navigation systems have sufficient precision to support the targeted 750 ft lateral runway spacing. The purpose of this section is not to offer recommended SAPA lateral navigation standards, but rather to examine key issues in order to make an initial assessment of the feasibility of operational implementation of SAPA based on the likely equipage of the relevant aircraft fleet.

Navigation Accuracy of Existing Systems

In order to characterize the navigation precision required for SAPA operations to a specific lateral runway spacing, a number of assumptions must be made. The SAPA approach path is based on constant-width navigation performance.

Current and near-term future procedures for runways spaced closer than 2400 feet, such as Simultaneous Offset Instrument Approach (SOIA), RNP Parallel Approach Transition (RPAT), and RNP Parallel Approach (RPA) can and do require the use of a No Transgression Zone (NTZ) of up to 2000 feet during an IMC segment, followed by a visual segment supporting closer lateral runway spacings. Clearly, the requirement of a 2000 ft NTZ would preclude the use of SAPA for runways spaced closer than 2000 ft. In the current analysis, no additional safety buffer is assumed, and the maximum allowable Total System Error (TSE) is defined by the point at which the wingtip crosses the midline between the two runways, as shown in Figure 1. Clearly, this does not make any accommodation for blunder reaction time.

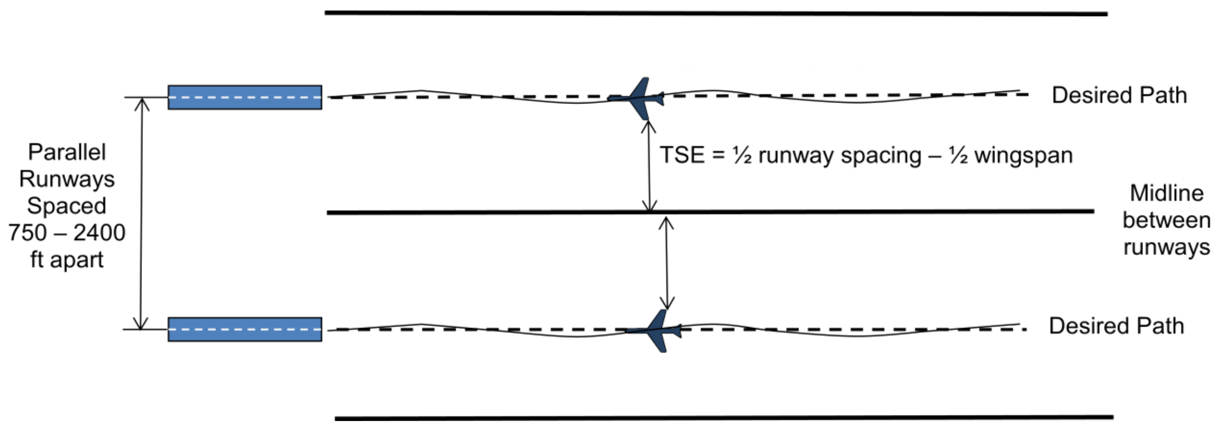

Figure 1. Maximum allowable TSE

The components of TSE are Path Definition Error (PDE), Navigation System Error (NSE) and Flight Technical Error (FTE). Because the SAPA operation occurs on the straight final approach course to a heavily used runway, the contribution of PDE is assumed to be negligible compared to the other components.

The NSE is a function of the navigation system in use at the given airport. In this study, the NSE for Ground-Based Augmentation System (GBAS) and a Localizer Approach Vertical Guidance (LPV) approach are examined. Many high density airports with very closely spaced parallel runways will have implemented GBAS ground stations in the timeframe that SAPA will be operationally deployed. However, it is envisioned that SAPA operations could also be implemented at airports without GBAS that have runways with larger spacings.

The lateral accuracy of GBAS, as specified by the DO-245A Minimum Aviation System Performance Standards (MASPS), is specified as a function of distance from the touchdown point, and can vary from 5 meters (m) to 27.7 m. The aircraft systems using GBAS information for navigation, including displays and autopilot, are designed to mimic the angular accuracy of Instrument Landing System (ILS) equipment, with more sensitivity closer to the runway. Thus, direct comparison to NSE required for the constant-width SAPA approach is problematic. However, the FAA has performed flight tests to determine the accuracy of GBAS systems and verified a 95% lateral accuracy of 2 m for GBAS-equipped aircraft.[1] It is assumed that this

[1] Information obtained from Jason Burns, Engineer, FAA Navigation Services, GBAS Program Office, valid as of 12/08/2009.

accuracy can be provided with a lateral integrity limit (99.999%) of 40 m, which is consistent with Satellite-Based Augmentation System (SBAS) requirements for LPV approaches. This lateral accuracy and integrity limit is independent of the FTE component of TSE (described below).

GBAS operations are valid within a specified range of the ground station, as represented by the broadcast parameter D_{max}. The currently deployed Honeywell ground stations have this parameter set to 23 nautical miles (nm). For SAPA operations, the aircraft will initially be established on the final approach course with 1000 ft altitude separation. It is assumed that the aircraft would need to be cleared to begin the SAPA procedure before the higher altitude aircraft intercepts the 3^{o} glide slope, which would be more than 5 nm from the runway threshold, but well within the 23 nm limit.

For airports without GBAS ground stations, the lateral accuracy (95%) of SBAS is characterized by the FAA to be on the order of 2-3 m. LPV approaches are designed to look like ILS approaches from an overlay standpoint, but the lateral accuracy of the approach is not angular (like ILS) and does not vary as a function of the distance from the runway. Thus, for all practical purposes, the use of SBAS for a SAPA procedure should give roughly the same NSE as GBAS. So, the NSE requirement for SAPA operations should not be difficult to obtain. The FTE requirement is the toughest component of TSE to obtain.

The FAA SAPA concept paper [DeCleene2008] quotes an FTE range of 40 m for newer aircraft to 80 m for existing older aircraft. This seems reasonable and is confirmed by some public domain information from Boeing, which measured TSE from 695 GPS (not GBAS) coupled approaches. The 95% TSE figure was 59 m. In the current study, there were no statistically significant sources found for GBAS- or SBAS-coupled FTE data, and FTE data is closely held proprietary information. Additionally, the FTE allocation must support the worst case weather condition for which the SAPA operation is expected to be approved. The FTE requirement will be examined further in the following subsection.

Applicability of Required Navigation Performance Standards

The SAPA concept is a potential mid-term solution under the NextGen (Next Generation Air Transportation System) concept of operations. Since one of the key transformations of NextGen is the principle of performance-based operations, it is appropriate to attempt to define the lateral navigation requirements in terms of Required Navigation Performance (RNP)[2].

Lateral navigation accuracy in RNP RNAV (aRea NAVigation) is defined by a normal performance and a containment limit. For RNP-1, the aircraft is guaranteed to stay within the

[2] The ICAO (International Civil Aviation Organization) definition of RNP does not quantify the containment of navigation accuracy, leaving this to the "appropriate technical bodies." The containment values for RNP used in this paper are from the RNP MASPS (Minimum Aviation System Performance Standards). Throughout this paper, the term RNP will be used to denote RNP RNAV, as defined in the RNP MASPS.

RNP value, or 1 nm, of the desired path with 95% probability. The aircraft is guaranteed to stay within 2 x the RNP value, or 2 nm, of the desired path with 99.999% probability. To be operationally acceptable, a parallel operations concept must ensure that the go-around rate due to real or perceived blunders is acceptably low. For this study, a go-around rate on the order of 10^{-4} per landing was used. To achieve a 10^{-4} rate for unacceptable navigation blunders, the containment limit is the relevant value. RNP containment is defined based on the desired path of the center of mass of the aircraft and does not consider the wingspan, so half the wingspan must be added for each aircraft. Thus, assuming there is no additional buffer to be added, the runway lateral spacing supported can be calculated for a given RNP value by:

Runway lateral spacing = left aircraft RNP x 2 + ½ wingspan
+ right aircraft RNP x 2 + ½ wingspan

For example, if we assume a worst case of two Airbus A380 aircraft paired on approach, with a wingspan of approximately 260 ft, then for RNP = 0.1, the minimum lateral runway spacing would be 2660 ft (4 x 600 + 260). Table 1 shows the RNP levels required for various runway lateral spacings.

Table 1: Selected Minimum Lateral Runway Spacings Using
RNP Containment Plus Wingspan Buffer of 260 ft

RNP Level	Lateral Runway Spacing (ft)
RNP-0.088	2400
RNP-0.047	1400
RNP-0.03	1000
RNP-0.02	750

It should be noted that all of the RNP values in Table 1 are below the minimum RNP RNAV applicability range of RNP-0.1 RNAV specified in the current MASPS for RNP. The MASPS state that future revisions of the MASPS may consider RNP values below this range to accommodate future potential applications. Despite this limitation, the following analysis is performed to determine the FTE requirement to satisfy SAPA operations at various lateral runway spacings.

The TSE is computed statistically by adding the PDE, NSE and FTE in the following equation:

$$\sigma_{TSE} = \sqrt{\sigma^2_{PDE} + \sigma^2_{NSE} + \sigma^2_{FTE}}$$

As discussed above, the PDE should be negligible compared to the NSE and FTE, and can be assumed to be zero for the purposes of this calculation. Using the formula shown above to derive the 95% requirement for TSE, substituting the RNP numbers derived above in place of TSE, and backing out expected NSE of 2m, yields the FTE requirement for various runway lateral spacings shown in Table 2.

Table 2. FTE for Various Runway Lateral Spacings

Runway Lateral Spacing	RNP Value	FTE
2400ft	RNP-0.088	163 m (535 ft)
1400 ft	RNP-0.047	102 m (334 ft)
1100 ft	RNP-0.03	64 m (210 ft)
750 ft	RNP-0.02	37 m (122 ft)

While these FTE levels are aggressive, there are certainly demonstrated auto-pilot applications that are well within these requirements, such as auto-land systems. For operations with RNP values below 0.1, a much higher integrity requirement may be considered appropriate. This could also significantly affect the system hardware fault detection/monitor design and software level. Additionally, it is not clear how SAPA operations would be impacted by weather conditions, such as crosswinds, atmospheric turbulence, wind gusts, and wind shear, and there would be limits on the weather conditions in which SAPA operations would be conducted.

There are no operational systems currently certified to the RNP levels that would be required for SAPA operations to 750 ft lateral runway spacing, and the required navigation and FTE accuracy are aggressive; however, this navigation performance is probably within the realm of existing state of the art avionics. Again, these assessments were conducted assuming that the limitation on lateral deviations allowed the wingtip to graze the midline between the two runways, which may not be realistic. Additionally, there was no consideration of the lateral deviations triggering false alarms for the blunder alerting algorithms.

Operational Assumptions

In order to assess the technical and operational feasibility of the SAPA concept, a detailed description of how the concept might be implemented was developed and assessed. The SAPA concept uses procedures, precise navigation, ADS-B in and cockpit-based guidance to conduct simultaneous dependent instrument approaches to two or even three runways spaced from 2500 down to 750 ft centerline spacing. The feasibility of applying the SAPA concept for runway lateral spacings less than 750 ft was not analyzed in this study.

Abeam Positioning

In a dependent operation, the pair of aircraft must maintain longitudinal spacing within a specified window for safe operation. Many of the proposed solutions for dependent parallel operations use an echelon pairing position, where one aircraft (the trailer) maintains a fixed, relative position slightly behind the other aircraft (the leader) for the entire final approach segment from before the Final Approach Fix (FAF) to landing [Stone1996, Hammer1999]. As shown on the left in Figure 2, the trailer maintains an echelon position behind the leader aircraft within a safe zone window defined by a rear boundary to keep the trailer ahead of any possible encounters with a wake generated by the leader and a front boundary defined such that if the leader blunders, it will pass ahead of the trailer with a low probability of a collision occurring [Landry2000].

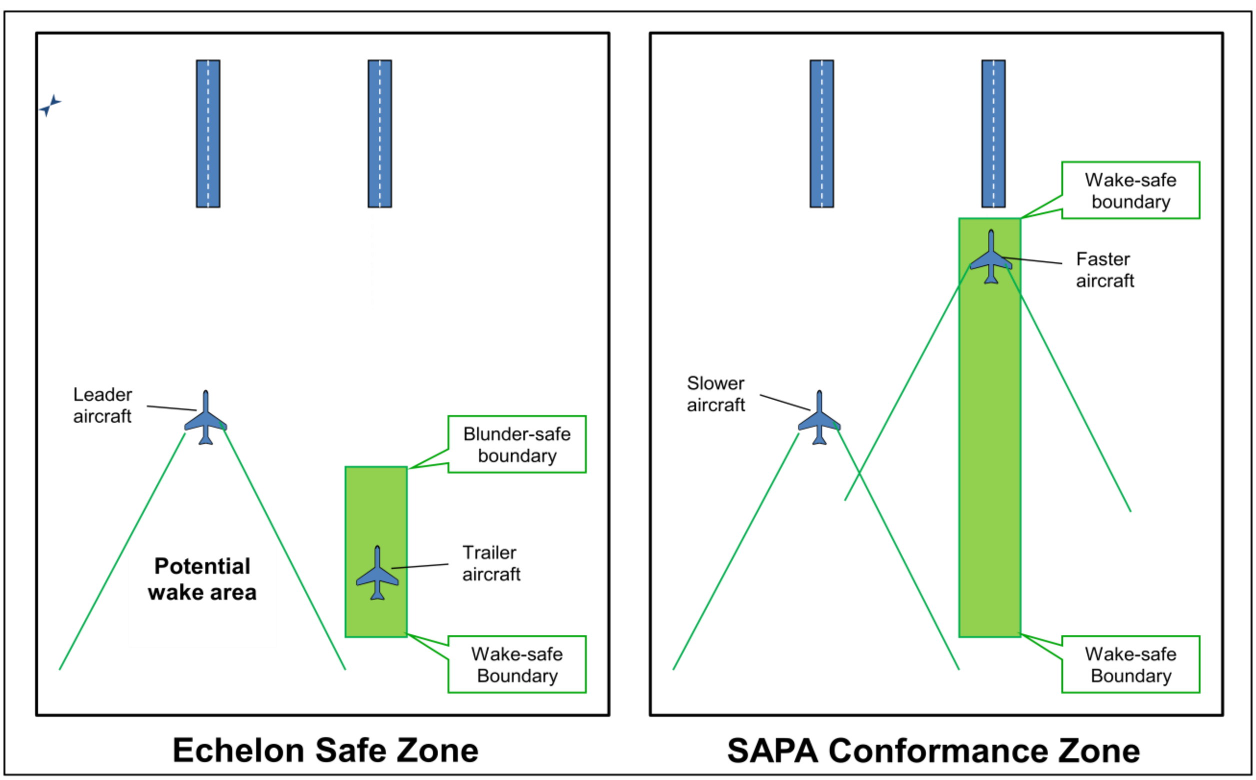

Figure 2. Depiction of echelon safe zone versus SAPA conformance zone

Unlike the echelon positioning, the SAPA concept allows one aircraft to pass the other aircraft during the approach segment. While the echelon longitudinal spacing window is often referred to as a safe zone, in this paper the term SAPA Conformance Zone (SAPA-CZ) will be used because the longitudinal maneuvering must conform to this zone, but staying within the zone does not provide blunder protection. As shown on the right in Figure 2, the faster aircraft maintains a position relative to the slower aircraft within a SAPA-CZ defined by a rear boundary to keep the faster aircraft ahead of any possible encounters with a wake generated by the slower aircraft and a front boundary defined to keep the faster aircraft from moving so far ahead that the slower aircraft will encounter a wake generated by the faster aircraft. Since SAPA allows one aircraft to pass the other and the SAPA-CZ allows for maneuvering an equal distance ahead of or behind the paired aircraft, this longitudinal positioning is referred to herein as abeam positioning. However, it should be noted that the two aircraft will only be abeam as one passes the other, and for most of the operation the two aircraft will be separated by a significant longitudinal distance.

Because the echelon safe zone window between blunder collision risk in front and wake encounter risk behind is fairly limited in size, echelon positioning requires that aircraft pairs are flying nearly identical approach speeds. For a given landing situation of aircraft landing weight, atmospheric conditions, headwind, etc., a typical civil air transport aircraft should land within approximately 5 knots of its nominal final approach speed. Any slower speed increases risk of a stall, while any higher speed may lead to potential runway overrun problems. In a realistic operational environment, there are significant inefficiencies associated with attempting to arrange for pairs of aircraft with similar approach speeds to arrive with appropriate timing for pairing. The SAPA concept allows for pairing of aircraft with more dissimilar approach speeds, but sacrifices the blunder collision protection. To mitigate the need for blunder collision protection, SAPA relies heavily on advanced navigation to reduce the probability of an aircraft blundering.

Speed and Altitude Profiles

This subsection describes the speed and altitude profiles assumed in this paper for the approach. As shown in Figure 3, the approach follows a 3^{o} glide slope, which terminates 1000 ft beyond the runway threshold. The FAF is assumed to be 5 nm from the runway threshold, and the Stabilized Approach Point (SAP) is at 1000 ft Above Ground Level (AGL), which is slightly more than 3 nm from the runway threshold.

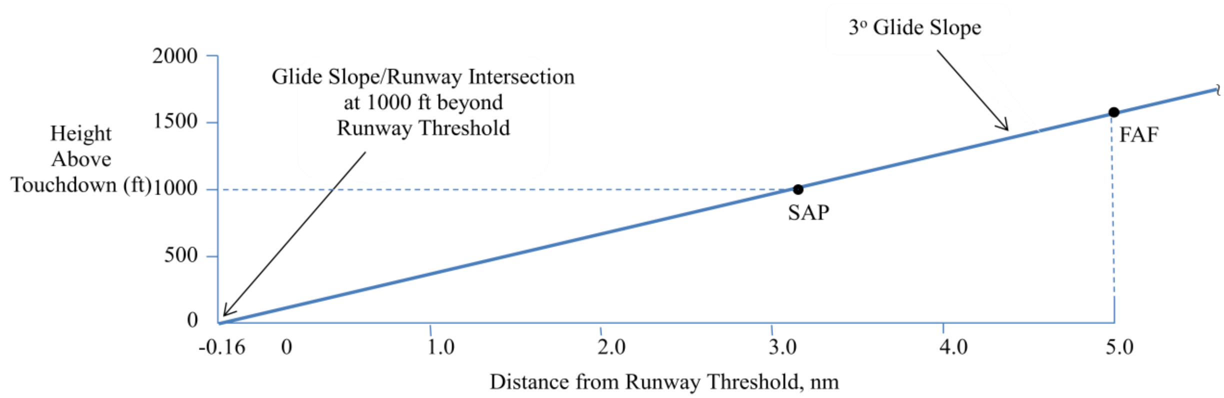

Figure 3. Approach altitude profile

Figure 4 shows the speed profile for the approach. The approach begins with a constant speed segment prior to the FAF, which could be different for a given airport or runway pair. From the FAF, the two aircraft slow to their respective final approach speeds and proceed to land open loop.

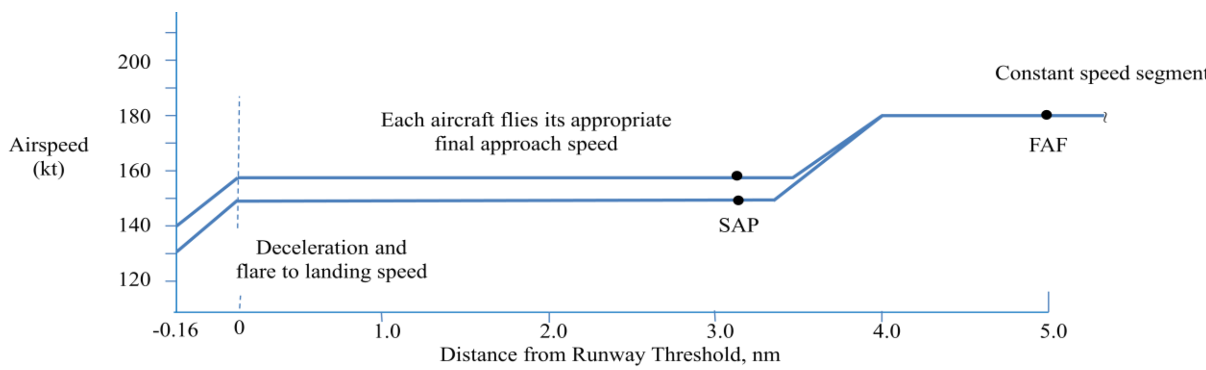

Figure 4. Approach speed profile

Characterization of SAPA Pair Positioning

A Monte Carlo wake encounter experiment was conducted to characterize the front and rear "wake-safe" boundaries for a SAPA-CZ. Prior to the current study, McKissick et al conducted a Monte Carlo experiment to examine wake encounters between pairs of aircraft conducting dependent approaches to closely spaced parallel runways, which provided some initial results applicable to the SAPA concept [McKissick2009]. The prior experiment examined within-pair wake encounters for runway centerline spacing ranging from 500 ft to 1500 ft. The experiment showed that, for each lateral runway spacing, the vast majority of the wake encounters occurred at low altitudes, less than 225 ft AGL, and that these low-altitude encounters occurred at much closer longitudinal distances between the aircraft than the encounters seen at higher altitudes. For example, for the 500 ft runway centerline spacing case with 15 kt crosswinds, below 225 AGL there were 32,611 encounters (relative frequency of encounters 36%) with the closest encounter occurring 1382 ft behind the leader. Above 225 AGL there were 1984 encounters (relative frequency of encounters 2%) with the closest encounter occurring 3159 ft behind the leader. This result seems logical from an analytical viewpoint, since it is known that wakes that are in ground effect move laterally much faster than they do out of ground effect, and wakes descend more slowly and/or experience a bouncing behavior in ground effect.

Based on the results from this previous experiment, the study team developed the idea of using more than one conformance zone for SAPA operations. Initial longitudinal positioning between a pair of aircraft would be governed by an Out-of-Ground-Effect (OGE) conformance zone. A second In-Ground-Effect (IGE) conformance zone might govern the longitudinal positioning for all altitudes in which the wake behavior might be subject to ground effects, from a conservatively defined ceiling for Near-Ground-Effect (NGE) down to landing. Alternatively, if the impact on performance was quite significant, having separate conformance zones for Near-Ground-Effect and In-Ground-Effect altitudes might be desirable. The boundary altitudes for Near-Ground-Effect and In-Ground-Effect wake behavior are a function of the wingspan of the aircraft generating the wake. To implement SAPA operations at a given airport, the boundary altitude between the two conformance zones could be conservatively defined based on the largest wingspan of aircraft expected to be operating at that airport.

Wake Encounter Experiment Scenarios and Conditions

A Monte Carlo simulation experiment to investigate wake encounters at various altitudes was conducted using the Wake Vortex Simulation and Analysis Tool (WVSAT^{TM}). WVSAT^{TM}, developed by Air Traffic Simulation, Inc. [ATSI2010], uses the FAA's Aviation System Standard database and procedure templates to simulate aircraft performance with a high level of accuracy and incorporates the Aircraft Vortex Spacing System (AVOSS) Prediction Algorithm (APA) version 3.2 wake model developed by NASA Langley [Proctor2009b, Proctor1998, Sarpkaya2000]. The purpose of the experiment was to provide an initial estimate of the extent of OGE and IGE conformance zones for SAPA operations. The process of establishing appropriate conformance zones for operational implementation of SAPA is beyond the scope of this study.

The size and initial position of the wake that is generated depends on the weight, wingspan, speed, power and control surface configurations of the generating aircraft. If there is a significant crosswind, the wake may move laterally into the path of the aircraft on the parallel approach, but this lateral movement is heavily influenced by crosswind strength and direction and other atmospheric conditions. For a given runway lateral separation and crosswind, the safe distance for the trailing aircraft to stay ahead of the wake of the lead aircraft depends on the relative speed of the trailing aircraft. The relative distances between the two aircraft varies as they slow from the nominal terminal area maneuvering speed to the final approach speed.

Simulation Profile and Conditions

The simulation flight profile was designed to accurately reflect SAPA operations, but the conditions were chosen to reflect a near-worst case environment for generation and lateral transport of wakes. The simulation profile parameters are shown in Table 3. To maximize the size and strength of the generated wakes, the two simulated aircraft are comparable to the characteristics of Boeing 747-8F size aircraft. A low eddy dissipation rate for ambient turbulence in the atmosphere was chosen to reduce the rate of decay of the wakes. To achieve the desired speed differential, the fast aircraft simulates a heavily loaded aircraft with a nominal approach speed of 159 kt Indicated Air Speed (KIAS), while the slow aircraft is at the empty aircraft weight with a nominal approach speed of 149 KIAS. The simulated aircraft flew an approach with a 3^{o} constant glide slope with high navigation precision. At the request of the FAA, the aircraft flight-path accuracy for the study was chosen based on standards for Wide-Area Augmentation System (WAAS) approaches supplied by the FAA[3]. The aircraft flew a nominal constant speed of 180 kt starting at the FAF, and each aircraft slowed to its nominal approach speed before reaching the SAP. In all cases, the crosswinds were constant at 15 kt, and crosswinds were always coming from an adverse direction; i.e., moving from the direction of the currently leading aircraft towards the currently trailing aircraft.

[3] Information obtained from Martin Heller, FAA Aeronautical Information Systems (AJR-321), from 2009 Sun N Fun presentation.

Table 3. Simulation Parameters[4]

Simulated aircraft:	Wingspan 224.5 ft; Tail height 64.2 ft
Fast aircraft: heavily loaded	Landing weight: 749,000 lb Nominal approach speed: 159 KIAS Nominal landing speed: Normal (140 kt, 1.2 kt)
Slow aircraft: empty	Landing weight 425,000 lbs Nominal approach speed: 149 KIAS Nominal landing speed: Normal (130 kt, 1.2 kt)
Lateral navigation deviation	Uniform (15 m, -15 m)
Vertical navigation deviation	Uniform (4 m, -4 m)
Crosswinds	Constant 15 kt; always adverse direction
Air temperature	15^{o} C 0 ft AGL, 5^{o} C 3000 ft AGL
Eddy dissipation rate	0.0001 m^2/s^3; Constant 0-3000 ft AGL

Principal Scenario Parameters

There were three scenario parameters, shown in Table 4, in addition to the ones listed in Table 3, that were used in the experiment to examine various aspects of SAPA operations. The aim was to understand the basic SAPA dynamics as they relate to the safe following distance as several important parameters were varied. The parameters in Table 4 were expected to be the dominant parameters affecting the safe following distance.

Table 4. Scenario Parameters

Runway Lateral Spacing	750 ft 1000 ft 1400 ft
Wake Detection Surface	Circle (673.5 ft diameter); Rectangle (673.5 ft lateral, 2000 ft vertical)
Runway Threshold Offset	0 ft 1500 ft

Runway Lateral Spacing

The first scenario parameter was lateral spacing between runway centerlines. SAPA operations at parallel runways with lateral spacings of 750 ft, 1000 ft, and 1400 ft were examined. Although the use of SAPA operations at runways spaced as close as 700 ft has been suggested, a minimum spacing of 750 ft was deemed to be more likely. Wake experts suggest that for the size of aircraft used for this study at 700 ft lateral spacing, the wakes of abeam aircraft could

[4] Throughout the paper, probability distributions will be formatted as: Name of distribution (Parameter1, Parameter2, …)

interact with each other in ways that are not yet well understood [Proctor2009a]. The WVSAT™ tool does not attempt to model such wake interaction between such closely spaced abeam aircraft. Lateral spacings greater than 1400 ft were not modeled and would need to be validated in future studies.

Wake Detection Surface

The second scenario parameter in the study was wake detection surface. The WVSAT™ tool models the wake generated behind each aircraft wing as a single point representing the center of the vortex and predicts the movement in space and decay over time. Detection of a potential wake encounter by another aircraft is accomplished by defining a wake detection surface surrounding the trailing aircraft. During a simulation run, a wake encounter is logged if the center of the wake vortex touches the detection surface.

A heavy aircraft can generate a vortex as large as half a wingspan in diameter. Also, a vortex tends to bobble and bounce as it moves, which is not captured in an engineering model of wake behavior, such as APA. Thus, there is uncertainty in the position of the vortex. Observations of wake vortices generated by a B747 aircraft in flight show that the full position uncertainty plus vortex size are bounded within one wingspan. To be conservative for this study, a wake detection surface in the shape of a circle with a diameter three times the wingspan (673.5 ft) was used. The flight profile used in the experiment, which maintains a constant 3^o slope, always has the trailing aircraft approximately co-altitude or above the altitude of the leading aircraft when both aircraft are approaching the same longitudinal runway threshold position. The detection circle was sized to detect wake encounters assuming both aircraft are approximately following the glide slope.

However, the initial longitudinal pairing of the aircraft occurs before the FAF with the aircraft separated vertically by 1000 ft, and then the higher aircraft descends until it is approximately co-altitude with the other aircraft. During this transition maneuver, if the higher aircraft is the leading aircraft, then wakes generated from the higher aircraft could descend and encounter the lower aircraft. To explore design alternatives for implementing the initial transition into the SAPA operational procedure, it was desired to also investigate a wake-safe boundary without this relative-altitude restriction for OGE altitudes. To accomplish this, a tall rectangular wake detection surface was also used in a second set of simulations for the OGE scenario cases. The rectangle was the same size laterally as the detection circle, but extended 1000 ft above and below the trailing aircraft. Thus, any wake that passed within 1000 ft above or below the trailing aircraft would be detected as an encounter.

Runway Threshold Offset

The third scenario parameter in the study, runway threshold offset, was *not* used to assess the benefits of runway threshold offsets, but rather was used to examine the worst case scenario of a runway threshold offset in the presence of adverse crosswinds. Runway threshold offsets of 0 ft and 1500 ft were simulated.

When two aircraft are in abeam positioning approaching a pair of parallel runways where one runway has a threshold that is longitudinally offset relative to the other runway threshold, the aircraft that is approaching the nearer runway will be at a slightly lower altitude than the other aircraft. After a wake is generated by an aircraft, it will slowly descend or perhaps persist at a constant altitude, and unless unusual atmospheric conditions are present, it can generally be assumed that a wake will not rise significantly. It is probable that in some cases this altitude difference could result favorably in relaxed longitudinal wake spacing requirements for a dependent paired operation, as long as the operational restriction is in place that the leading aircraft is always at a lower altitude than the trailing aircraft. However, in SAPA operations, this operational restriction is not feasible, because SAPA allows the fast aircraft to overtake and pass the slow aircraft.

Experiment Scenarios

In order to investigate wake encounters at various altitudes, Monte Carlo simulations were conducted using a sequence of three scenarios, as shown in Figure 5. These scenarios were used to characterize wake behavior in OGE, NGE, and IGE, respectively. As shown in Figure 5, the ground effect boundaries for wakes generated by the simulated aircraft are as follows [Proctor1999]:

IGE lower boundary = 0 ft AGL
IGE upper boundary = $b_0 = \pi \frac{\text{wingspan}}{4}$ = 176 ft AGL
NGE upper boundary = 3 x b_o = 530 ft AGL

where b_0 is the initial vortex span.

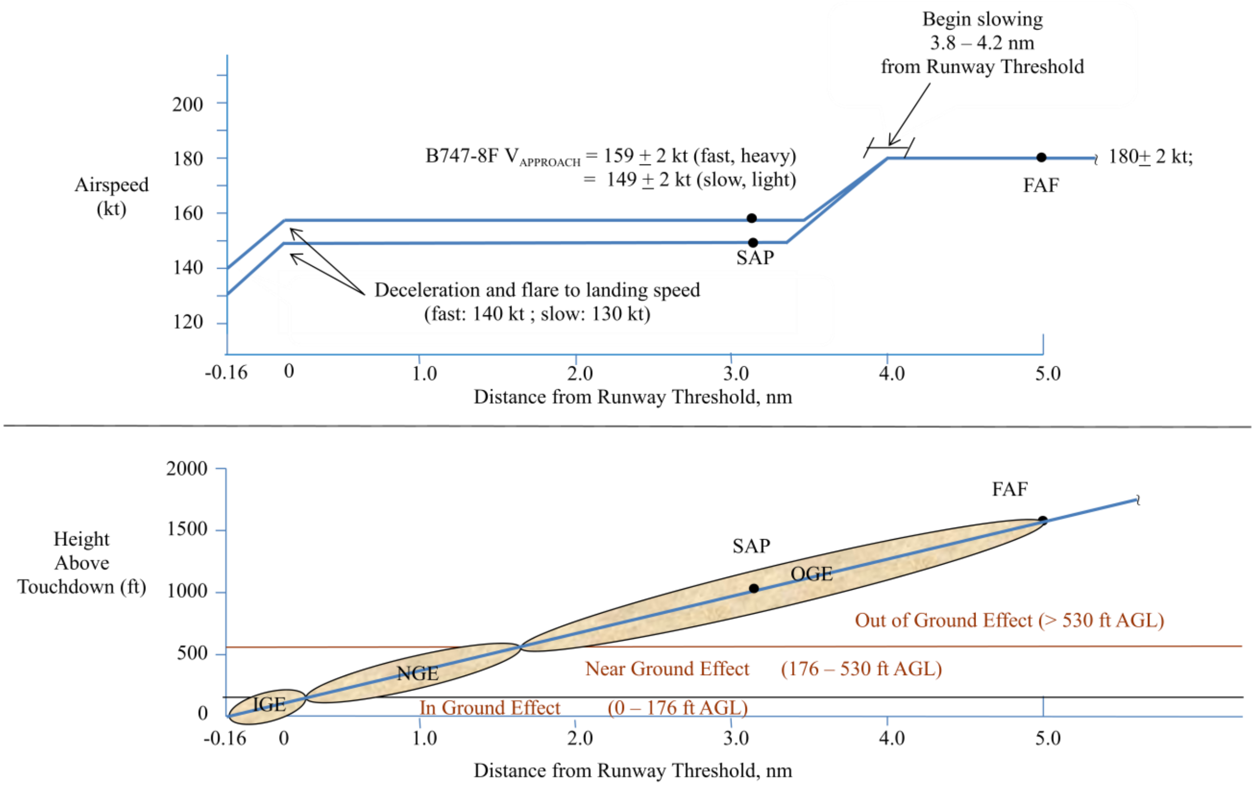

Figure 5. Altitude and speed profiles for three experiment scenarios: OGE, NGE, and IGE

OGE Scenario: Out of Ground Effect

The OGE Scenario was designed to explore encounters of wakes out of ground effect (above 530 ft AGL). The altitude and speed profiles for this scenario are shown in Figure 6.

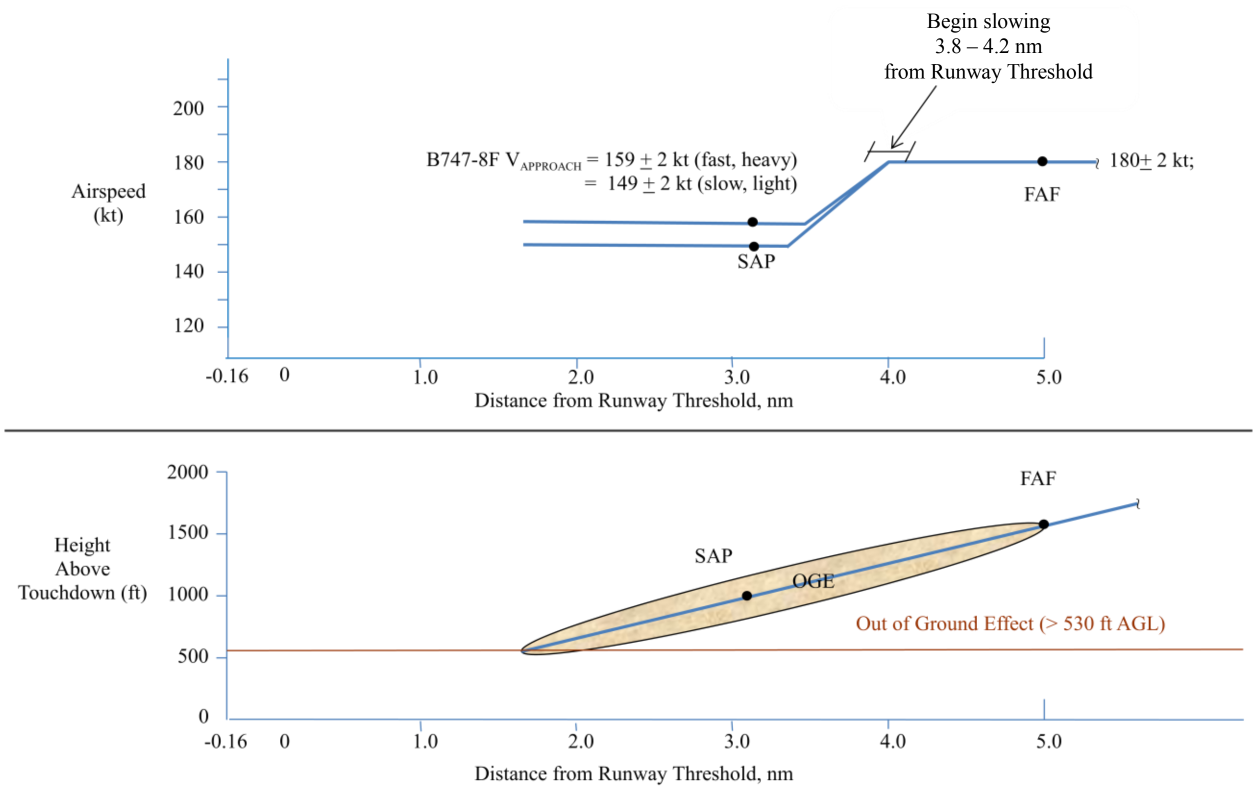

Figure 6. Altitude and speed profiles for OGE scenario

This scenario begins with the slow aircraft at the FAF and the fast aircraft on the 3^{o} glide slope some longitudinal distance behind. Each aircraft is assigned an initial speed based on the distribution Uniform (178 kt, 182 kt), and in the first nautical mile the relative longitudinal spacing between the aircraft may be slightly increasing or decreasing because they are both traveling at the same speed ± 2 kt. At a distance Uniform (3.8 nm, 4.2 nm) before the runway threshold, the slow leading aircraft begins to decelerate to reach Uniform (147 kt, 151 kt) at some point just prior to the SAP. Once the slow aircraft begins the deceleration, the fast aircraft will be moving closer to the slow aircraft. The slow aircraft continues at this speed until it reaches 250 ft AGL, at which point it finishes its simulation run and ceases to generate a wake. The fast aircraft also begins to slow when it reaches a distance Uniform (3.8 nm, 4.2 nm) before the runway threshold, decelerating to reach Uniform (157 kt, 161 kt) before the SAP. The simulation of the fast aircraft was continued below the lower boundary to ensure continuity between scenarios, but only wakes encountered by the fast aircraft at or above 530 ft AGL were recorded for this scenario.

For the OGE scenario, 2500 runs were executed for each of the three runway lateral spacings using the wake detection circle. An additional 2500 runs were executed for each of the runway lateral spacings in the OGE scenario using the tall detection rectangle. The in-trail distance between the slow and fast aircraft at the beginning of each run was varied uniformly within the windows shown in Table 5.

Table 5. Initial In-Trail Distance Windows for OGE Scenario

Runway Lateral Spacing	Initial In-Trail Distance Window
750 ft	0.3 nm – 1.3 nm
1000 ft	0.8 nm – 1.8 nm
1400 ft	1.6 nm – 2.6 nm

During each run, the two aircraft were released at a given in-trail distance and the run was monitored to determine whether or not a wake encounter occurred. The initial in-trail distance windows were chosen for each lateral spacing to ensure that the boundary of the conformance zone would be exercised, i.e., so some runs would result in encounters and other runs would be clear of encounters.

NGE Scenario: Near Ground Effect

The NGE scenario was designed to explore encounters of wakes at altitudes that transition from OGE into IGE (i.e., from 530 ft AGL to 176 ft AGL). This scenario, shown in Figure 7, begins

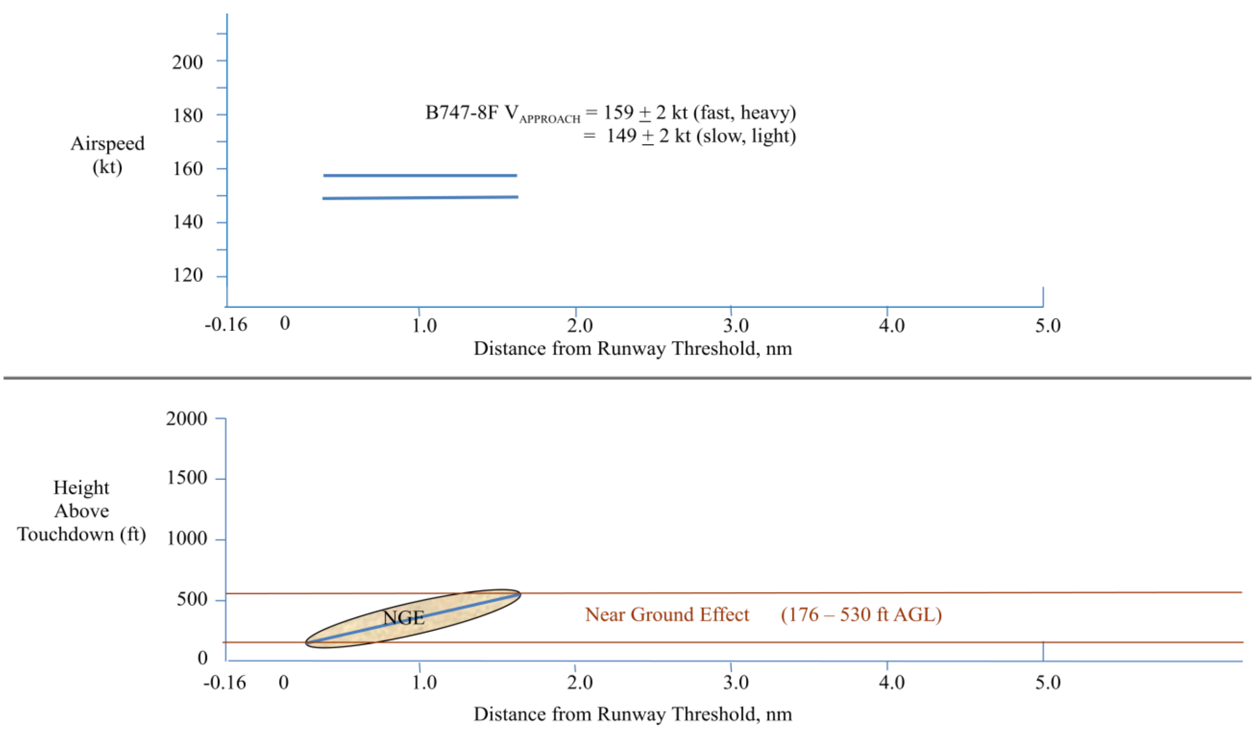

Figure 7. Altitude and speed profiles for NGE scenario

with the slow aircraft on the 3° glide slope at 530 ft AGL, at approximately 1.5 nm from the runway threshold. The fast aircraft is initiated on the glide slope some longitudinal distance behind.

Both aircraft maintain their constant approach speeds during this scenario, with the slow aircraft traveling at Uniform (147 kt, 151 kt), and the fast aircraft closing from behind at Uniform (157 kt, 161 kt). The slow aircraft continues until it reaches 150 ft AGL, at which point it finishes its simulation run and ceases to generate a wake. Only wake encounters occurring at or above 176 ft AGL, however, were recorded for this scenario.

There were 2500 runs executed for each of the three runway lateral spacings using the wake detection circle. The in-trail distance between the slow and fast aircraft at the beginning of each run was varied uniformly within the windows shown in Table 6.

Table 6. Target Initial In-Trail Distance Windows for NGE Scenario

Runway Lateral Spacing	Initial In-Trail Distance Window
750 ft	608 ft – 6684 ft
1000 ft	3646 ft – 9722 ft
1400 ft	8507 ft – 14,583 ft

These in-trail distances, however, are positions relative to a fixed location on the approach path in both NGE and IGE scenarios. Because the starting altitude of the leading aircraft is specified, and because each aircraft has some level of vertical navigational error, the leading aircraft will not always start at the same position on the approach path for every simulation run. Because the in-trail distance is in the earth reference system and not along the glide slope, this navigational error introduces more randomness to the in-trail distribution. This also changes the actual in-trail windows simulated by increasing their size by approximately 500 ft, and thus the effective in-trail windows simulated in the NGE scenario are as shown in Table 7.

Table 7. Actual Initial In-Trail Distance Windows for NGE Scenario

Runway Lateral Spacing	Initial In-Trail Distance Window
750 ft	350 ft – 6934 ft
1000 ft	3396 ft – 9972 ft
1400 ft	8256 ft – 14,833 ft

With respect to these simulated in-trail distances, the OGE scenarios do not need these corrections. In the OGE scenarios, the initial positions of each aircraft were referenced to the runway thresholds (and not specific altitudes) and thus, for each simulation run, the exact initial in-trail distance was specified from the uniform distributions tested.

IGE Scenario: In Ground Effect

The IGE scenario was designed to explore encounters of wakes at altitudes considered to be in ground effect (from 176 ft AGL to landing). The altitude and speed profiles for this scenario are shown in Figure 8. This scenario examined the front wake-safe boundary of the SAPA-CZ under worst case conditions where the fast aircraft has passed the slow aircraft and moved out in front. The scenario begins with the fast aircraft ahead on the 3^{o} glide slope at 176 ft AGL, which is approximately 0.396 nm from the runway threshold. The slow aircraft is initiated on the glide slope some longitudinal distance behind.

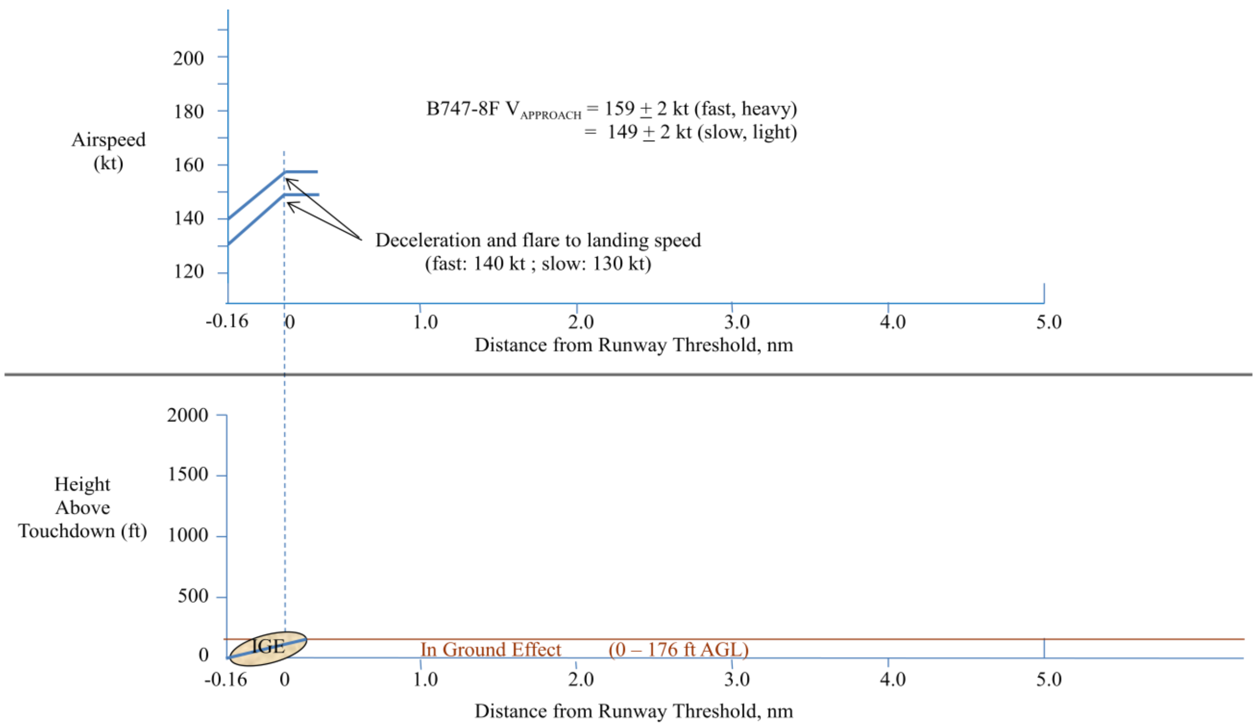

Figure 8. Altitude and speed profiles for IGE scenario

The aircraft begin the scenario at their respective approach speeds, with the fast aircraft moving out ahead at Uniform (157 kt, 161 kt) and the slow aircraft lagging behind at Uniform (147 kt, 151 kt). Upon crossing the runway threshold, each aircraft decelerates and flares at AGL altitude Normal (45 ft, 2 ft, with bounds 40-50 ft), with the fast aircraft landing at Normal (140 kt, 1.2 kt) and the slow aircraft landing at Normal (130 kt, 1.2 kt). The 3^{o} glide slope intercepts the runway 1000 ft beyond the threshold, but after flaring, the aircraft touchdown is at a constant distance of 1800 ft beyond the threshold.

There were 2500 runs executed for each of the three runway lateral spacings using the wake detection circle. The in-trail distance between the slow and fast aircraft at the beginning of each run was varied uniformly within the windows shown in Table 8.

Table 8. Targeted Initial In-Trail Distance Windows for IGE Scenario

Runway Lateral Spacing	Initial In-Trail Distance Window
750 ft	800 ft - 2,800 ft
1000 ft	1,500 ft - 3,500 ft
1400 ft	3,500 ft - 5,500 ft

As in the NGE scenario, the simulated RNP navigational errors and the requirement for a specific leading-aircraft start altitude imply that the effective in-trail windows with respect to the actual leader's starting position on the approach path are as shown in Table 9.

Table 9. Actual Initial In-trail Distance Windows for IGE Scenario

Runway Lateral Spacing	Initial In-Trail Distance Window
750 ft	550 ft – 3050 ft
1000 ft	1250 ft – 3750 ft
1400 ft	3250 ft – 5750 ft

Experimental Results and Discussion

This subsection presents the results of the Monte Carlo simulation experiment.

Out-of-Ground-Effect Wake Encounters

The OGE scenario was designed to investigate encounters of wakes out of ground effect. There were 2500 runs conducted for the OGE scenario with 750 ft runway lateral spacing, with the slow aircraft starting at the FAF and the fast aircraft starting with a distance behind the FAF varied uniformly from 1800 ft to 7800 ft. During each run, the wake was monitored to determine whether at any time during the run the trailing aircraft encountered a vortex generated by the leading aircraft. The OGE scenario results for runway lateral spacing of 750 ft are shown in Figure 9.

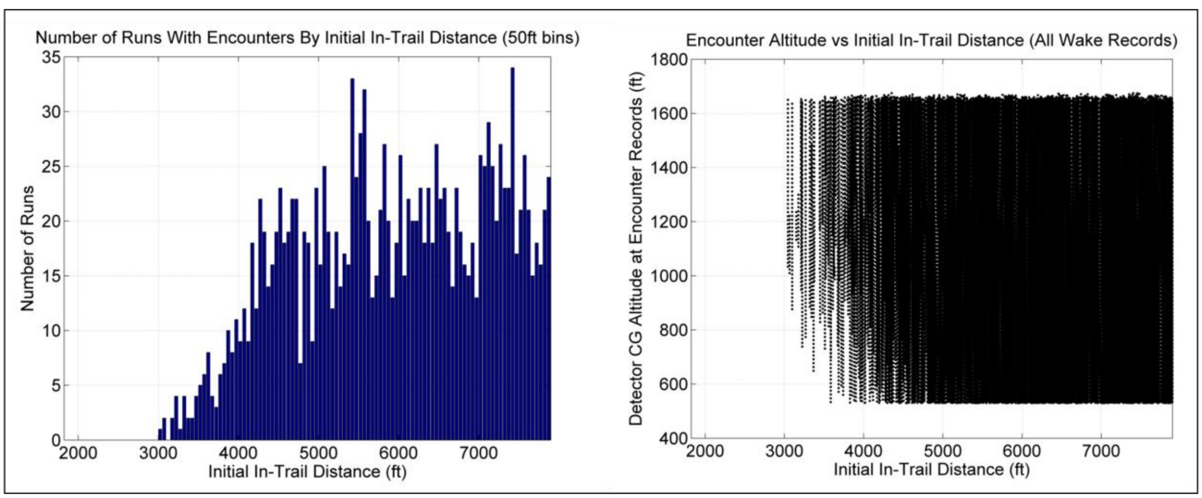

Figure 9. OGE scenario, 750 ft lateral runway spacing

The histogram on the left in Figure 9 shows the number of runs in which wake encounters occurred for a given initial in-trail distance, with each bar representing a span of in-trail distance of 50 ft. Out of 2500 runs, wake encounters occurred in 1627 runs. The smallest initial in-trail distance for which a wake was encountered was 3044 ft. The initial in-trail distances for the OGE runs had an average of approximately 20 runs per bin for the OGE case, so the bins above 5000-ft initial in-trail distance are saturated with 100% of runs generating an encounter.

The graph on the right in Figure 9 shows the wake encounters recorded for the entire scenario simulation. Each recorded wake encounter – from the 1Hz sampling – is shown at the altitude of encounter and versus the initial in-trail distance of the respective simulation run. Thus, each vertical strip of data represents the same simulation run and all recorded wake encounters each second for that run. Note that at the right side of the right graph, the trailing aircraft was in a continuous wake encounter from the FAF (approximately 1644 ft AGL) down to the OGE lower boundary (530 ft AGL). For the 3000 ft initial in-trail distance, the trailing aircraft started with a wake encounter at the FAF but pulled ahead of the leading aircraft's wake after it had descended below an altitude of 870 ft AGL.

As can be seen in the encounter altitude graph, when the two aircraft were released with an initial in-trail distance of approximately 4000 ft or more, the trailing aircraft was encountering the wake of the leading aircraft throughout the entire run. When the two aircraft were released with initial in-trail distance of approximately 3500 ft or less, the trailing aircraft moved ahead of the wake generated by the leading aircraft towards the end of the scenario. At the beginning of the OGE scenario, the two aircraft are traveling at approximately the same speed during the constant speed segment and thus maintaining a steady in-trail distance, but once the leading aircraft slows just before the SAP, the distance between the two aircraft decreases, and the trailing aircraft may move ahead of the wake generated by the leading aircraft.

There were a small number of runs in which wake encounters did not occur early in the scenario at higher altitudes but did occur at lower altitudes ranging from approximately 1000 to 1300 ft AGL. In these simulation runs, the speeds assigned to the two aircraft were such that the trailing "fast" aircraft was in fact slower than the leading "slow" aircraft during this constant-speed segment as a result of small speed variations. Thus, instead of maintaining a constant in-trail distance during this segment, the trailing aircraft lagged further behind the leading aircraft until it began to encounter the wake generated by the leading aircraft. These only occurred when the two aircraft were released within an initial in-trail distance range of approximately 3000 to 3300 ft, so the initial positioning was such that the trailing aircraft was initially just ahead of the wake generated by the leading aircraft. In operational practice, if the trailing aircraft was utilizing onboard speed guidance to stay within the SAPA-CZ, then these cases would presumably not have resulted in wake encounters.

For the case of 1000 ft lateral runway spacing, the results for the OGE scenario are shown in Figure 10. As expected, with the larger lateral runway spacing, the time required for the wake to move across to the other runway increased significantly. The smallest initial in-trail distance leading to wake encounters was 6026 ft.

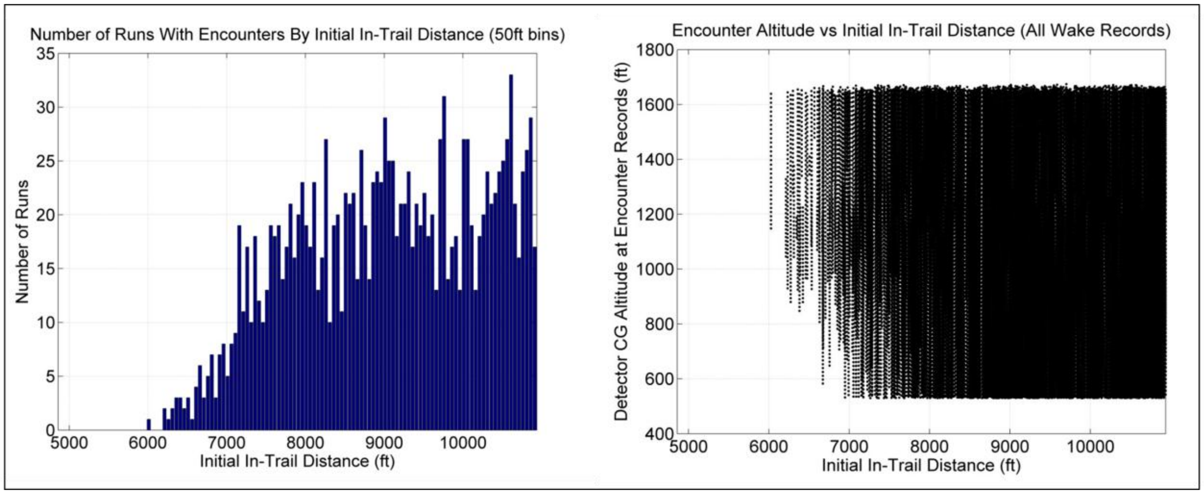

Figure 10. OGE scenario, 1000 ft lateral runway spacing

For the case of 1400 ft lateral runway spacing, the results for the OGE scenario are shown in Figure 11. Again, with the larger lateral runway spacing, the time required for the wake to move across to the other runway increases significantly. The smallest initial in-trail distance leading to wake encounters was 11,171 ft.

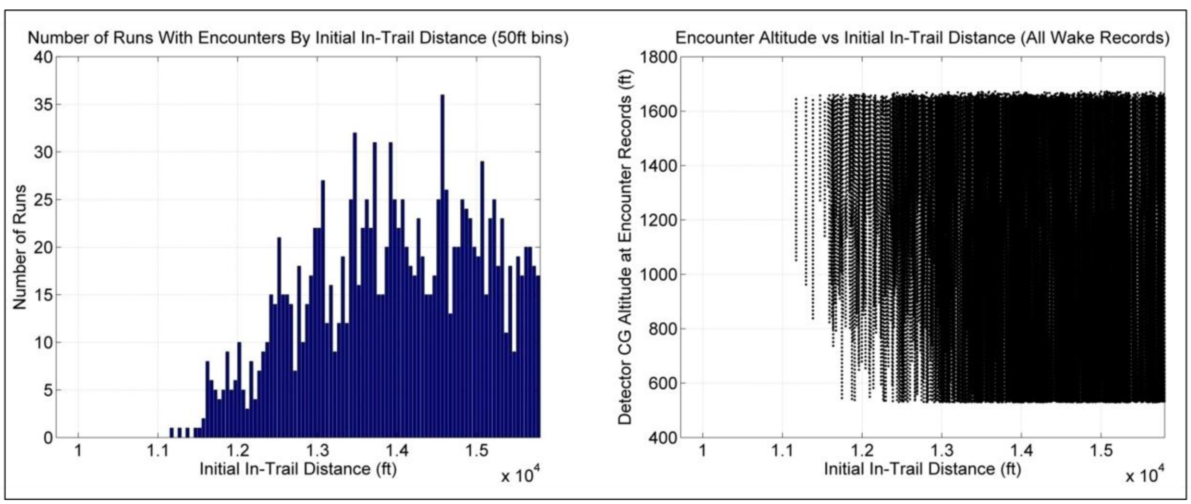

Figure 11. OGE scenario, 1400 ft lateral runway spacing

Near-Ground-Effect Wake Encounter

The NGE scenario was designed to investigate encounters of wakes near ground effect, at altitudes ranging from 176 ft to 530 ft. The scenario began with the fast aircraft at a given initial in-trail distance behind the slow aircraft, with the two aircraft traveling at their respective final approach speeds, so the fast aircraft was closing from behind on the slow leading aircraft.

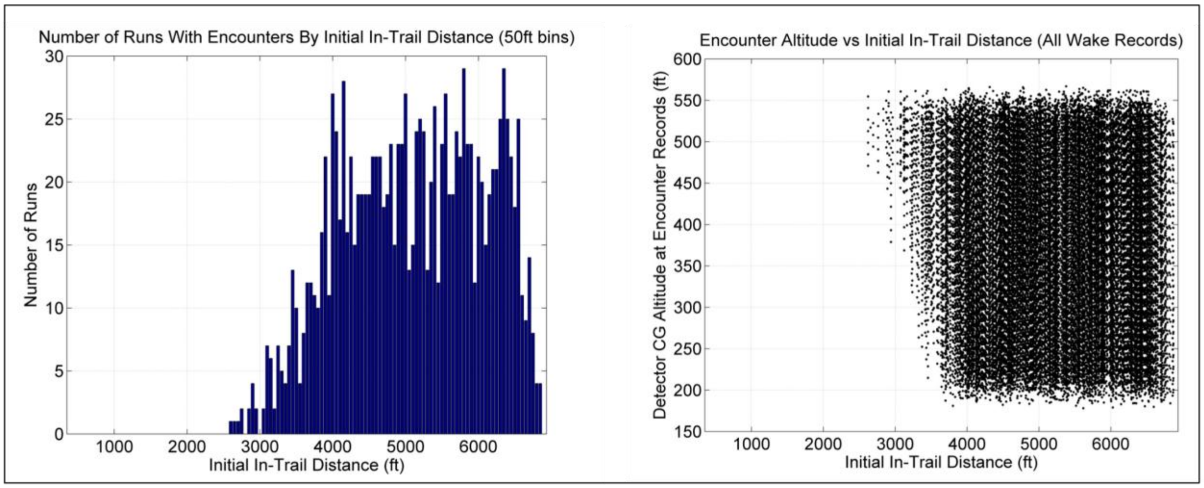

Figure 12. NGE scenario, 750 ft runway lateral spacing

For the NGE scenario case of 750 ft lateral runway spacing, the results are shown in Figure 12. As shown in the histogram on the left, the initial in-trail distances resulting in wake encounters were slightly smaller for the NGE scenario than for the OGE scenario. This was expected, because, as vortices begin to experience ground effect, they move laterally more quickly and thus arrive at the parallel runway faster than out of ground effect. Out of 2500 runs, wake encounters occurred in 1326 runs. The smallest initial in-trail distance for which a wake was encountered was 2621 ft.

The graph on the right in Figure 12 shows that all of the wake encounters occurred near the beginning of the scenario. This was as expected, since the in-trail distance between the two aircraft was decreasing throughout the scenario. This resulted in either a simulation run that started and stayed in a continuous encounter, or a simulation run that started in an encounter and exited the encounter before the end of the run. There were no runs that started free of encounters and then entered an encounter.

For the case of 1000 ft lateral runway spacing, the results for the NGE scenario are shown in Figure 13. As expected, with the larger lateral runway spacing, the NGE wake-encounter distances for 1000 ft lateral spacing were much larger than for 750 ft lateral spacing, and the smallest in-trail distance leading to a wake encounter was 5374 ft. Again, the NGE wake-encounter distances for the 1000 ft lateral case were slightly smaller than the OGE 1000 ft wake-encounter distances.

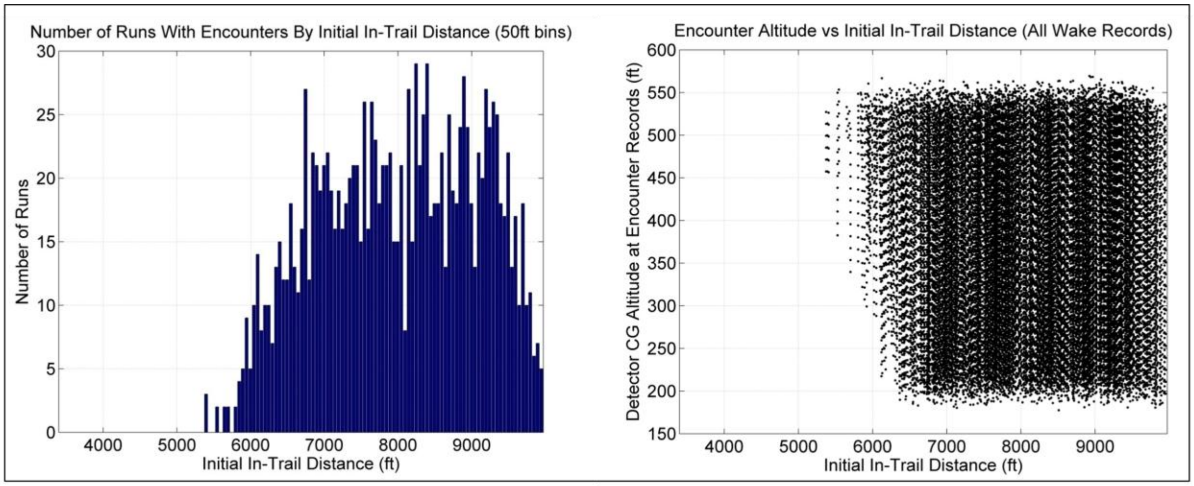

Figure 13. NGE scenario, 1000 ft lateral runway spacing

Results for the NGE scenario for the case of 1400 ft lateral runway spacing are shown in Figure 14. The NGE wake-encounter distances for 1400 ft lateral spacing were again much larger than for 1000 ft lateral spacing, and the smallest in-trail distance leading to a wake encounter was 9802 ft. Again, the NGE wake-encounter distances for the 1400 ft lateral case were slightly smaller than the OGE 1400 ft wake-encounter distances.

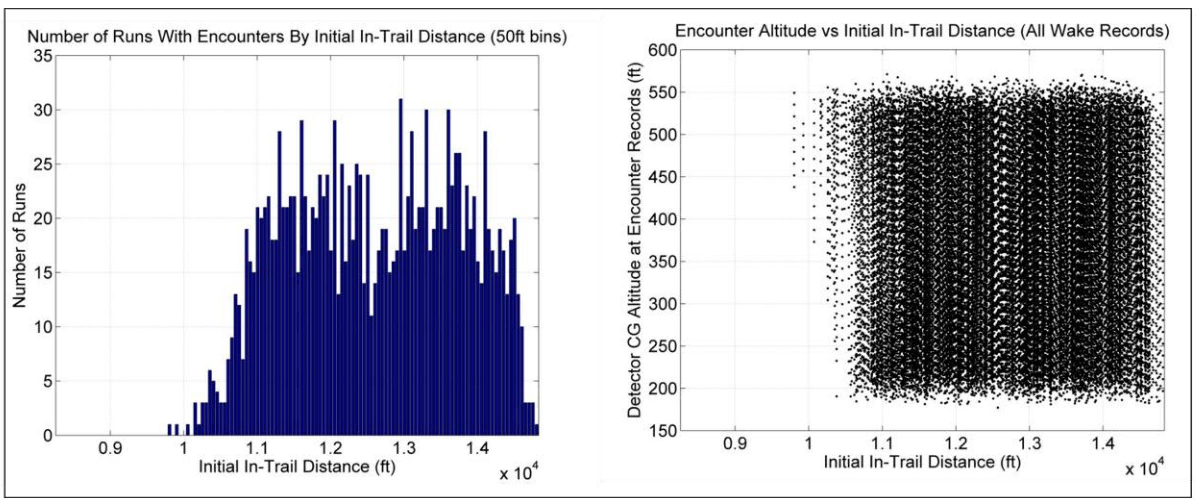

Figure 14. NGE scenario, 1400 ft lateral runway spacing

In-Ground-Effect Wake Encounters

The IGE scenario was designed to investigate encounters of wakes in ground effect, below 176 ft AGL. Unlike the two other scenarios, this scenario began with the fast aircraft ahead and the slow aircraft at a given initial in-trail distance behind. During the scenario, the distance between the two aircraft was continually increasing, with the fast aircraft moving farther ahead of the slow aircraft.

For the IGE scenario case of 750 ft lateral runway spacing, the results are shown in Figure 15. As shown in the histogram on the left, the initial in-trail distances resulting in wake encounters were significantly smaller for the IGE scenario than for the NGE and OGE scenarios. Out of 2500 runs, wake encounters occurred in 1886 runs. The smallest initial in-trail distance for which a wake was encountered was 1008 ft, which was less than half the 2621 ft encounter distance for the NGE 750 ft case. It was expected that shorter in-trail distances would be seen for the IGE case, and the influence of ground effect on vortex lateral movement would be very pronounced.

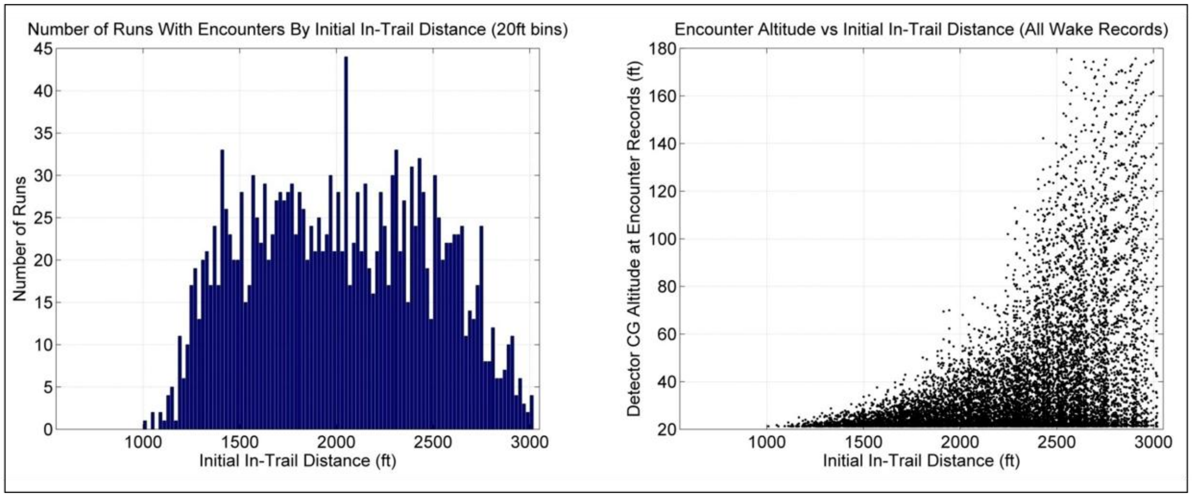

Figure 15. IGE scenario, 750 ft runway lateral spacing

The graph on the right in Figure 15 shows the wake-encounter altitudes. The encounter patterns in this graph are quite different from the previous two scenarios. Since the faster aircraft is now leading, once it has pulled far enough ahead to cause a wake encounter for the slow trailing aircraft, the trailing aircraft was in a continuous wake encounter for the remainder of the simulation. Note that the altitude of a wake encounter was measured at the center of gravity of the trailing aircraft, which is 21.2 ft when the simulated aircraft is on its landing gear on the ground; therefore, there were no encounters detected below 21.2 ft. The graph shows that the wake encounters occurred at all altitudes in the scenario, but the smallest encounter in-trail distances occurred at very low altitudes, with many occurring at less than 50 ft AGL. There appear to be three reasons for the prevalence of wake encounters just before touchdown. First, the in-trail distance between the two aircraft was increasing throughout the scenario, so the two aircraft were the farthest apart just before landing. Second, the influence of ground effect on vortex lateral movement became more pronounced with closer proximity to the ground. Third, just prior to landing, the aircraft flared and slowed considerably for touchdown. The flare-slowing maneuver created vortices with stronger circulation, which then translated into faster lateral movement when the vortices neared the ground. Examination of sample cases using the WVSAT™ wake-visualization feature showed a pronounced change in wake lateral movement at this point in the simulation.

For the case of 1000 ft lateral runway spacing, the results for the IGE scenario are shown in Figure 16. In this case, out of the 2500 runs, there were 1292 encounters. As expected, with the larger lateral runway spacing, the IGE wake-encounter distances for 1000 ft lateral spacing were much larger than for 750 ft lateral spacing, and the smallest in-trail distance leading to a wake encounter was 2141 ft. Again, the IGE wake-encounter distances for the 1000 ft lateral runway spacing case were significantly smaller than the 5374 ft minimum for the NGE 1000 ft lateral runway spacing case.

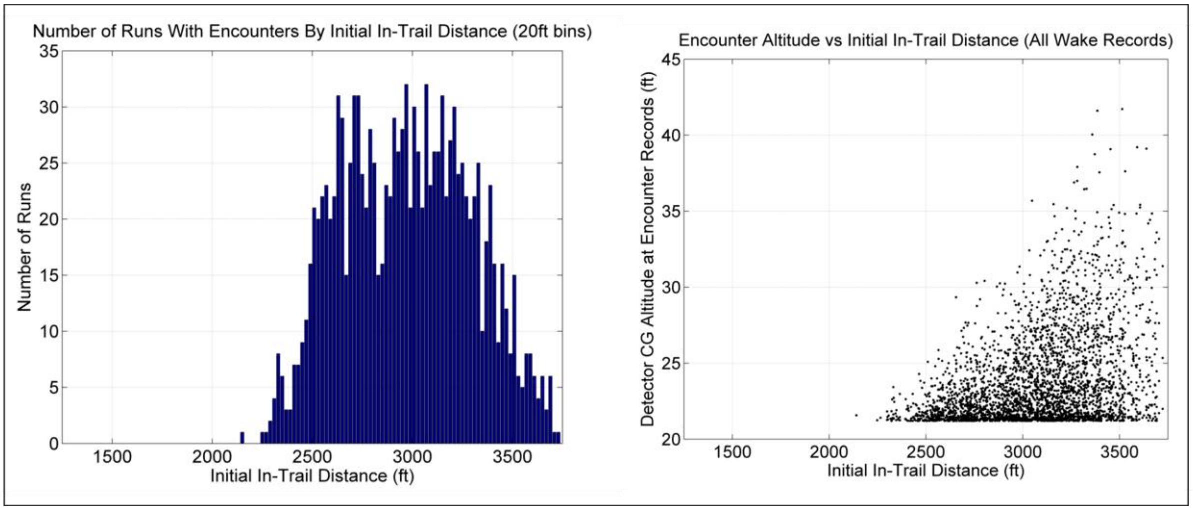

Figure 16. IGE scenario, 1000 ft lateral runway spacing

Results for the IGE scenario for the case of 1400 ft lateral runway spacing are shown in Figure 17. In this case, out of the 2500 runs, there were 1037 encounters. With the 1400 ft lateral runway spacing, the IGE wake-encounter distances were much larger than for the 750 ft or 1000 ft lateral runway spacing cases, and the smallest in-trail distance leading to a wake encounter was 4319 ft. Again, the IGE wake-encounter distances for the 1400 ft lateral spacing case were significantly smaller than the 9802 ft for the NGE 1400 ft case.

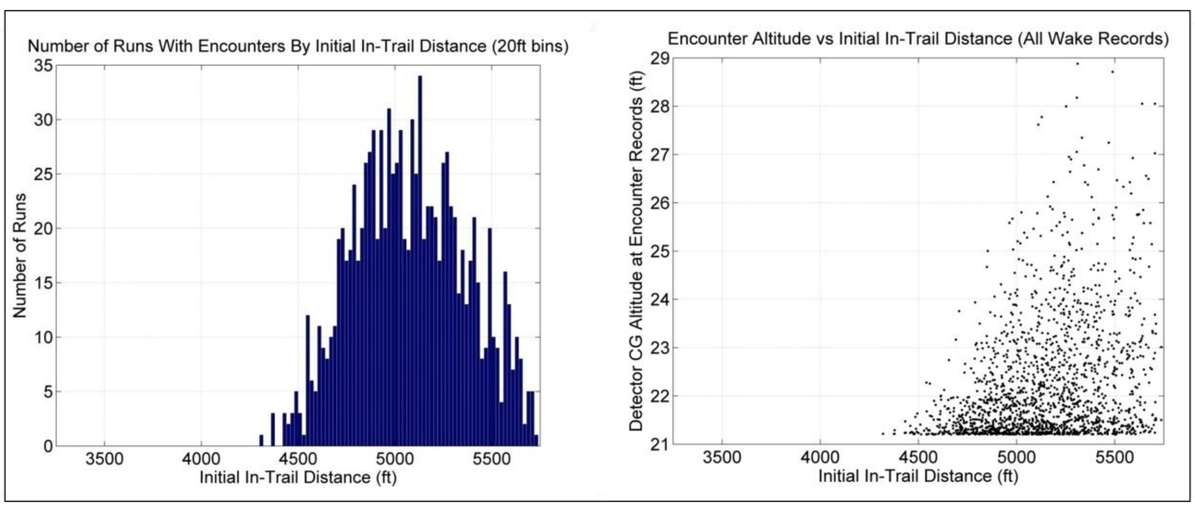

Figure 17. IGE scenario, 1400 ft lateral runway spacing

Out-of-Ground-Effect Wake Encounters with Tall Detection Rectangle

To investigate the effect of relative altitudes of the aircraft on wake-encounter distances, 2500 runs with a tall, rectangular wake-detection surface were conducted for each of the three lateral runway spacings for the OGE scenario. The detection rectangle was the same size laterally as the detection circle, but extended 1000 ft above and below the trailing aircraft center of gravity so that any wake that passed within 1000 ft above or below the trailing aircraft would be detected as an encounter. For the simulation scenarios, this was essentially positive and negative infinity in the vertical direction. The results for the OGE case of 750 ft lateral runway spacing for the rectangular wake detection surface are shown in Figure 18.

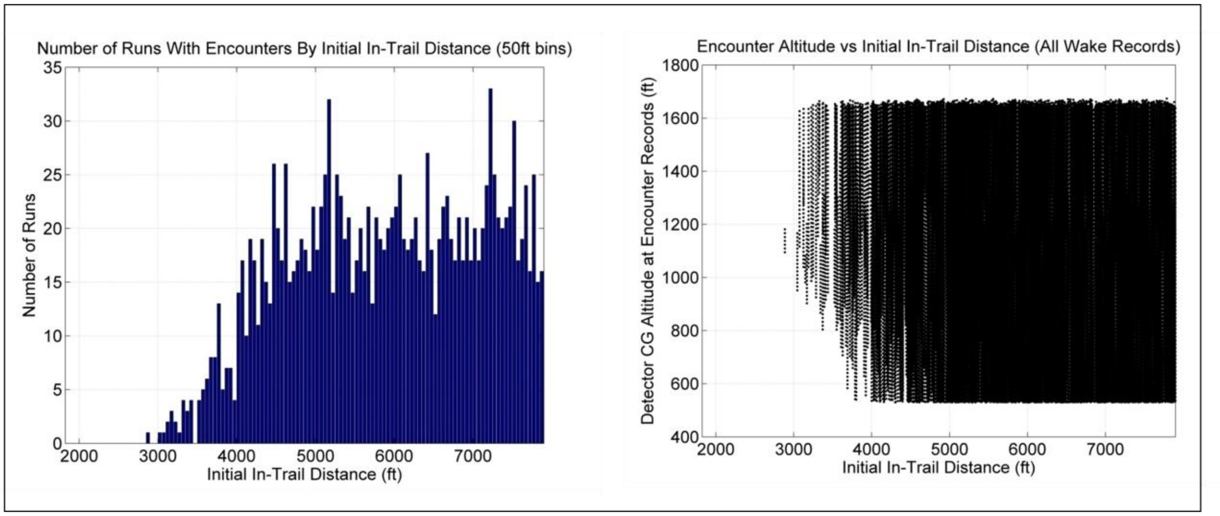

Figure 18. OGE scenario, 750 ft runway lateral spacing
with 2000 ft vertical detection rectangle

Compared to the detection circle, the use of the vertical detection rectangle resulted in slightly smaller initial in-trail distances leading to wake encounters. For the 750 ft case, the smallest observed in-trail distance leading to a wake encounter was 2886 ft, compared to 3044 ft with the detection circle. The histogram on the right in Figure 18 shows that, again, the smallest initial in-trail distance resulting in wake encounters occur in runs where the in-trail distance increased during the start of the scenario (i.e., the “fast” aircraft was traveling slower than the “slow” aircraft during the initial constant speed segment). Onboard speed management could perhaps preclude these cases.

Similarly, the results for 1000 ft and 1400 ft lateral runway spacing also showed only slight decreases for initial in-trail distance that led to a wake encounter. For the 1000 ft case, the closest initial in-trail distance that led to an encounter was 5800 ft, which is slightly smaller than the 6026 ft distance observed with the detection circle. For the 1400 ft case, the closest initial in-trail distance resulting in an encounter was 10,550 ft, which was slightly less than the 11,171 ft distance observed with the detection circle.

Runway Threshold Offset

To investigate the worst case effect of an offset runway threshold on wake-encounter distances, a set of 2500 runs was conducted for each of the three scenarios (OGE, NGE, and IGE) with each of the three lateral runway spacings. The circular detection surface was used for all of the runway threshold offset simulations. In each scenario, the initially trailing aircraft is approaching the nearer runway to maximize the likelihood of wake encounters. The results for the 1500 ft runway threshold offset for 750 ft lateral runway spacing for the OGE, NGE, and IGE scenarios are shown in Figures 19, 20, and 21, respectively.

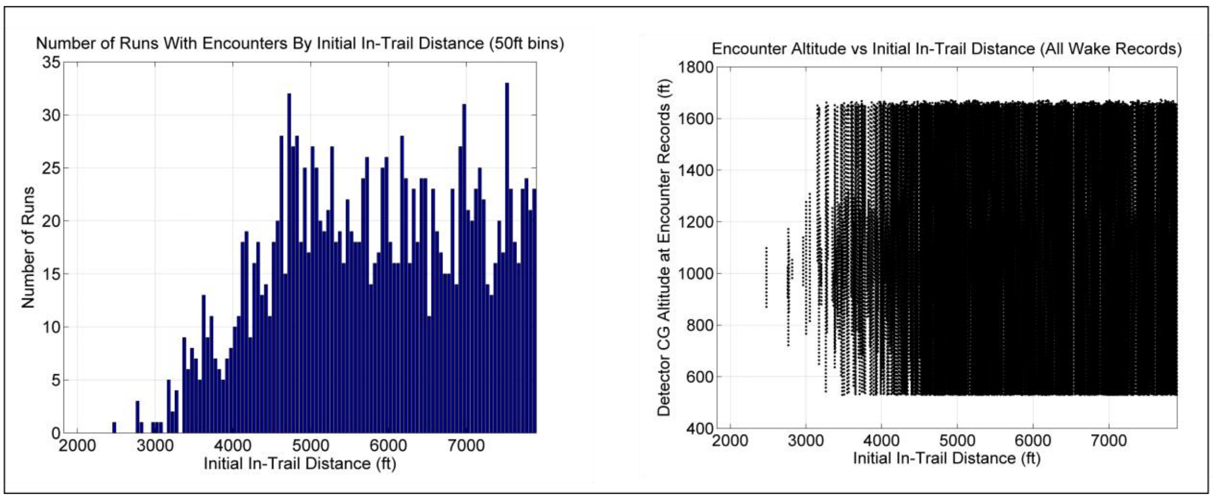

Figure 19. 1500 ft runway threshold offset, OGE scenario, 750 ft runway lateral spacing

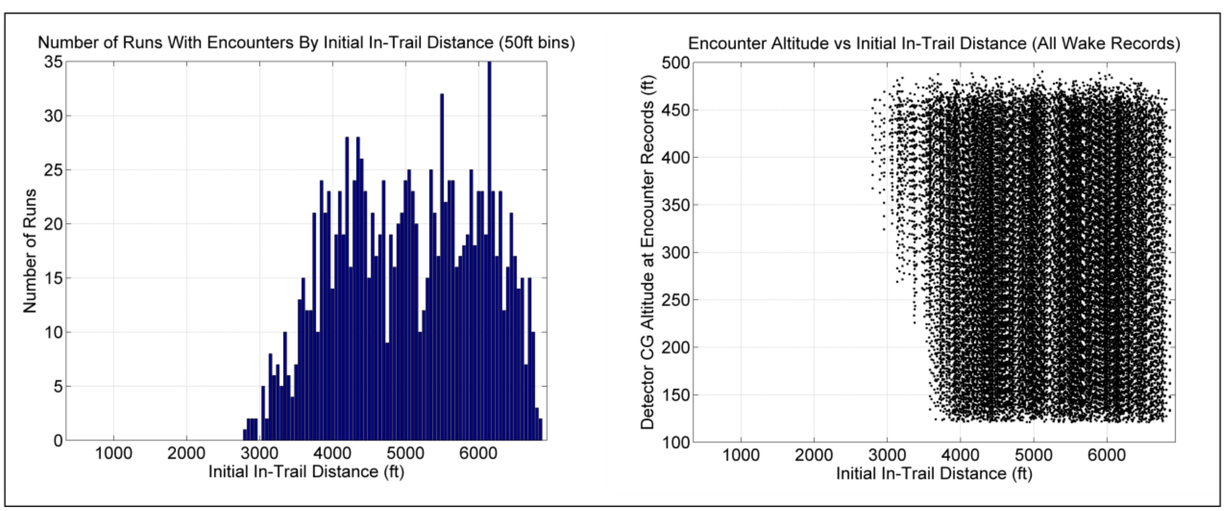

Figure 20. 1500 ft runway threshold offset, NGE scenario, 750 ft runway lateral spacing

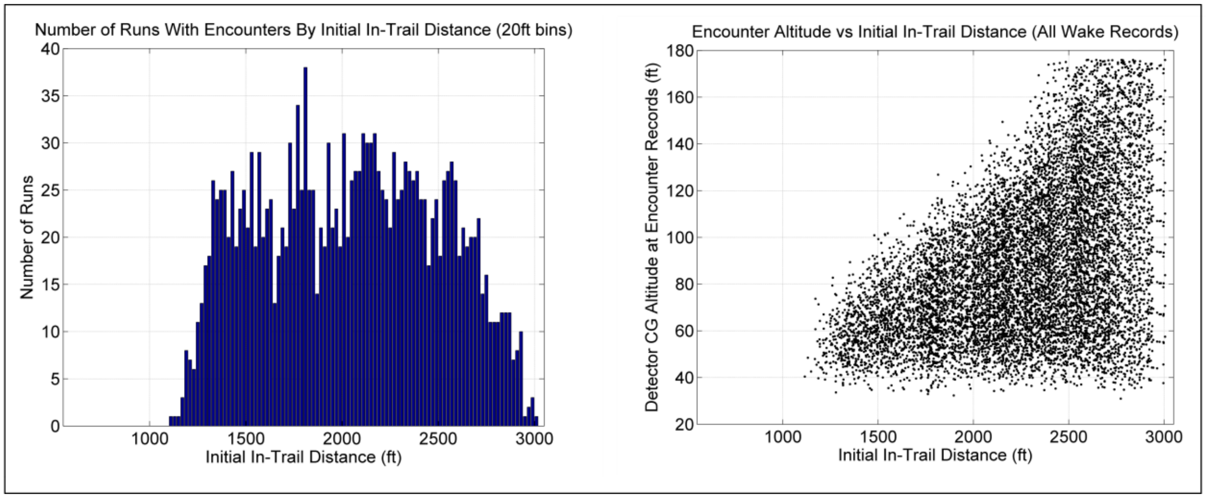

Figure 21. 1500 ft runway threshold offset, IGE scenario, 750 ft runway lateral spacing

Interestingly, the comparison of the 1500 ft runway threshold offset to the results with no offset yielded mixed results. For the OGE scenario, the smallest observed in-trail distance leading to a wake encounter was 2477 ft, which was less than the 3044 ft with no threshold offset. For the NGE scenario, the smallest observed in-trail distance leading to a wake encounter was 2799 ft, which was larger than the 2621 ft with no threshold offset. For the IGE scenario, the smallest observed in-trail distance leading to a wake encounter was 1115 ft, which was slightly larger than the 1008 ft with no threshold offset. The OGE scenario histogram on the right in Figure 19 shows that there were quite a number of cases where the smallest initial in-trail distances resulting in wake encounters occurred in runs where the in-trail distance increased during the scenario (i.e., the "fast" aircraft was traveling slower than the "slow" aircraft during the constant speed segment). Onboard speed management could perhaps preclude these cases.

The same mixed results were found for the 1000 ft and 1400 ft lateral runway spacing cases, as shown in Table 10.

Table 10. Smallest Observed Initial In-Trail Distance Leading to a Wake Encounter for 1500 Ft Runway Threshold Offset vs. No Offset for All Three Runway Lateral Spacings and All Three Scenarios

	750 ft Runway Spacing		1000 ft Runway Spacing		1400 ft Runway Spacing	
Scenario	No Offset	1500 ft Offset	No Offset	1500 ft Offset	No Offset	1500 ft Offset
OGE	3044	2477	6026	5824	11,171	10,718
NGE	2621	2799	5374	5385	9802	9383
IGE	1008	1115	2141	2257	4319	4360

For the OGE cases for 1000 ft and 1400 ft lateral runway spacings, as in the 750 ft case, the runway threshold offset resulted in smaller initial in-trail distances leading to wake encounters, and the smallest distances were in situations where the wake encounters did not occur near the beginning of the scenario. For the NGE and IGE cases for all of the three lateral runway spacings, the runway threshold offset counter-intuitively resulted in larger distances for the closest initial in-trail distances leading to wake encounters.

Limitations of Simulation Study

The Monte Carlo simulation study investigated the effects of parametric variations on wake encounter distances. The results are useful in furthering understanding of the basic SAPA dynamics as they relate to the safe following distance, examining implementation options as they relate to wake lateral movement, and investigating the overall feasibility of the SAPA concept. If a decision is made to implement SAPA in an operational environment, additional studies will be required to quantify the appropriate sizes of conformance zones for a given set of operational parameters and assumptions.

In this study, a limited investigation of the initial in-trail distance leading to a wake encounter was examined for a specific set of cases. The quantified results of the study are only directly applicable to the specified aircraft pair with the assumed speed profiles, atmospheric conditions, crosswinds, and other assumptions. However, the test scenarios were chosen to reflect near-worst case conditions, and some general characteristics of the SAPA-CZ can be inferred from the analysis of these cases. For a detailed performance analysis of SAPA, additional wake encounter studies will be required to quantify a SAPA-CZ for any given aircraft pair.

The fact that this is a simulation and not a real-world experiment, imposes some limitations on the results. A number of studies have been conducted to observe the behavior of wakes in a real-world environment out of ground effect. These studies typically entail ground-based sensors measuring wakes of over-flying aircraft or an instrumented aircraft flying through aircraft wakes. However, there is a significant lack of observational data on wake behavior in the presence of ground effect. Additionally, wake behavior in ground effect is more difficult to model accurately because the interaction with the ground is complex. Thus, state-of-the-art wake behavior models, including the APA algorithm implemented in WVSAT^{TM}, are more reliable predictors of wake transport and decay at higher altitudes than in ground effect [Proctor2000]. Our results have shown that wake behavior in ground effect is likely to be the main driver of pair positioning requirements, yet this IGE wake behavior is, in fact, the least understood.

With these limitations in mind, the next subsection presents a summary of the results of the simulation study.

Summary of Monte Carlo Simulation Results

The Monte Carlo simulation experiment confirmed that the initial in-trail distances that result in wake encounters vary significantly between the three lateral runway spacings and between the OGE, NGE, and IGE scenarios, as shown in Table 11.

Table 11. Comparison of Closest Initial In-Trail Distance Resulting in a Wake Encounter for Each Lateral Runway Spacing for Each Scenario with the Circular Detection Surface and No Runway Threshold Offset

Scenario	Lateral Runway Spacing		
	750 ft	1000 ft	1400 ft
OGE	3044 ft	6026 ft	11,171 ft
NGE	2621 ft	5374 ft	9802 ft
IGE	1008 ft	2141 ft	4319 ft

As stated in the limitations discussion above, these numerical results should not be interpreted as recommended final values for conformance zone boundaries, but are indicative of relative SAPA-CZ sizes. As expected, the requirements for pair positioning to avoid wake encounters are much tighter for very closely spaced parallel runways than for runways with larger lateral spacing. To support a more comprehensive comparison to minimum in-trail distances leading to wake encounters across all of the scenario parameters of the experiment (Table 4), see the box plot in Appendix B. Appendix C presents a statistical analysis of the data from the experiment, defining asymptotic confidence intervals for the minimum in-trail distances for each case. These statistical analyses are provided as an example of how extreme value theory might be used to define a SAPA-CZ, not as recommended values.

More significantly, this study confirmed that proximity to the ground has a significant effect on the requirements for pair positioning. This suggests that an altitude-based approach to defining pair positioning requirements is prudent for SAPA operations. It is clear from the results above that any future implementation of a SAPA operational procedure will be driven by the requirement to be within the SAPA-CZ in ground effect. For every combination of parameters in this study, the SAPA-CZ would be much smaller in IGE than in OGE. Since the SAPA-CZ in NGE would be only slightly smaller than in OGE, the NGE wake boundary will likely not be a factor due to the tight IGE window. This suggests that a two-phased conformance zone may be most appropriate for operational implementation of SAPA.

This altitude-based difference in wake behavior also means that in order to accommodate a maximum approach speed differential between the two aircraft, the optimal initial positioning is for the aircraft with the faster approach speed to be trailing the aircraft with the lower approach speed. The maximum distance between the two aircraft should occur while they are within larger OGE SAPA-CZ.

For the purposes of example, let's consider an aircraft pairing on a 750 ft runway centerline spacing and no runway threshold offset, where two aircraft are at the nominal experimental profile speeds and with zero navigational errors of the speed and altitude profiles used in this experiment. Further, assume that the trailing aircraft does not overtake the slower aircraft on the approach, and place this aircraft at the back of the IGE SAPA-CZ (1000 ft in-trail) at the point where the leader reaches 176 ft altitude. Performing a backwards integration of the speed profiles for the two aircraft, the in-trail distance between the two aircraft at the beginning of the NGE altitude boundary is approximately 1453 ft, which is much smaller than the experimentally observed smallest in-trail distance leading to a wake encounter of 2621 ft. This shows that the

NGE wake boundary is not a limiting factor due to the much smaller IGE wake boundary. Further, integrating the speed profiles of the two aircraft until the leader is at 5 nm from the runway threshold (the start of the OGE zone for this experiment) results in an in-trail distance between the two aircraft of 2765 ft, which is still well within the experimentally observed OGE smallest distance leading to a wake encounter of 3044 ft. Conversely, if a pair of aircraft are initially positioned such that the faster aircraft is at the rear of the OGE SAPA-CZ and the pair are to be positioned within the IGE conformance zone by the time they reach 176 ft altitude, then the speed differential between the two aircraft must be greater than the 10 kt used in this experiment.

This simple example serves to illustrate that aircraft pairing on a proposed SAPA procedure will have to consider the planned final approach speeds of both aircraft and the size of the IGE SAPA-CZ to determine the appropriate initial in-trail distance for any SAPA pairing. It is not as simple as placing each pair at the extreme boundaries of the OGE SAPA-CZ because the difference between the speed profiles of the two aircraft is what determines the in-trail separation at the runway.

It is well understood that, except for unusual atmospheric conditions, wakes typically descend rather than rise. In VMC in-trail approaches where wakes are a concern, pilots are cautioned to maintain a flight path that is at or above the path that was taken by the aircraft they are following. In very closely spaced parallel-runway operations, the two aircraft typically turn onto the final approach course with 1000 ft altitude separation. Once the aircraft are confirmed to be longitudinally spaced within the SAPA-CZ, the higher-altitude aircraft is cleared to descend until the two aircraft are approximately co-altitude. If the trailing aircraft is the higher altitude aircraft, then the trailing aircraft would potentially remain above any wakes generated by the lower-altitude leading aircraft during the descent. However, if the leading aircraft is the one that is initially at the higher altitude, then the leading aircraft's descending wake vortices are more likely to encounter the trailing aircraft as the two aircraft near co-altitude position.

This concern of higher likelihood of wake encounter could be mitigated by requiring that the initially trailing aircraft be assigned to the higher altitude. However, the trailing aircraft must be the faster of the pair. Requiring that the faster aircraft in each pair be routed to the parallel runway with the higher final approach altitude may be a significantly inconvenient operational restriction for the controller.

In order to investigate whether altitude variations significantly affect minimum wake-encounter distances, a tall rectangular wake detection surface was used in a second set of simulations for the cases of the OGE scenario to detect wakes at any possible vertical separation distance between the leading and trailing aircraft. The circular detection surface is only effective for simulating wake encounters when the two aircraft are approximately co-altitude. The results for the tall detection rectangle vs. the detection circle are summarized in Table 12. As shown in the table, the closest in-trail distances resulting in wake encounters were only slightly affected by changing the detection circle to a tall rectangle. Because such a large circular detection surface was used in the simulation, there were very few wakes that passed just below (or above) the detection surface. This indicates that accommodating either the trailing or the leading aircraft to be at the higher initial altitude would likely result in a performance penalty of only approximately 200 ft in the size of the OGE conformance zone.

Table 12. Comparison of Closest Initial In-Trail Distance Resulting in a Wake Encounter for Detection Circle vs. Tall Detection Rectangle, for Each Lateral Runway Spacing

Detection Surface	Lateral Runway Spacing		
	750 ft	1000 ft	1400 ft
Detection Circle	3044 ft	6026 ft	11,171 ft
Tall Detection Rectangle	2886 ft	5800 ft	10,550 ft

The results for the runway threshold offset cases show that runway threshold offset can have a significant impact on the wake interaction between a pair of aircraft conducting SAPA operations. The mixed nature of the results corroborate the need for additional simulation studies to understand the impact that various runway threshold offsets will have on wake-safe boundaries for SAPA operations, particularly as the pair of aircraft move longitudinally and hence vertically in relation to each other.

Conduct of SAPA Operations

The results of the Monte Carlo wake study yielded several key design parameters for SAPA operations. The pair of aircraft should initially be positioned such that the aircraft with the faster approach speed is trailing the aircraft with the slower approach speed. When the pair of aircraft are initially established by ATC on the final approach course separated vertically by 1000 ft, either the trailing or the leading aircraft can initially be placed at the higher altitude.

This section presents issues related to how SAPA operations would be conducted. The following section describes in more detail the controller and flight crew processes for initiating the SAPA procedure and attaining the initial pair positioning.

The primary means for safely conducting SAPA approaches to very closely spaced parallel runways are through approach procedure design, highly accurate navigation sources, and flight operations requirements to include the use of autopilot and SAPA-unique speed management, where the combination of these practices greatly reduces the probability of one aircraft intruding into the approach path of another or creating a wake vortex encounter. In support of these considerations, it is expected that the SAPA procedure will be conducted with the use of autopilot and auto-thrust for flight-path control for both aircraft in the SAPA pair. The characteristics of an effective speed management algorithm for SAPA operations are explored in the first sub-section. Issues related to initial vertical separation are presented in the second sub-section, followed by a discussion of missed approach procedures. SAPA relies on the participating aircraft pair broadcasting via ADS-B critical flight information, such as position, ground track, ground speed, the PFAS, and SAPA status information, and these requirements are discussed in the final subsection.

Speed Management

ATC will sequence the aircraft pair such that the leading aircraft will have a planned final approach speed (PFAS) that is equal to or slower than the trailing aircraft. These aircraft are designated as the "slow aircraft" and the "fast aircraft," respectively. Once the aircraft are established on the final approach course, the clearance to conduct a SAPA procedure may then be issued, with both aircraft requiring the SAPA clearance. Upon issuance of the SAPA clearance, the SAPA paired aircraft will fly the necessary speed profiles required to perform the SAPA operation.

To avoid a possible “race” condition where each paired aircraft keeps changing speed to catch up with the other, the aircraft with the slower PFAS will be assigned as the reference aircraft. After the SAPA clearance is issued, the slow aircraft will maintain the last ATC assigned speed until it reaches the FAF or the position designated in the procedure where the deceleration to the PFAS begins. This is consistent with single runway in-trail operations at high traffic volume airports. At this point, the slow aircraft will decelerate to its PFAS using a linear deceleration schedule such that it will just reach its PFAS at a distance from the runway touchdown point corresponding to 1000 ft AGL on the glide slope (Figure 22). It will then maintain that speed until landing. The fast aircraft in the SAPA pair is the active spacing aircraft. As stated previously, this is the aircraft that ATC initially places in the trailing position in the pair.

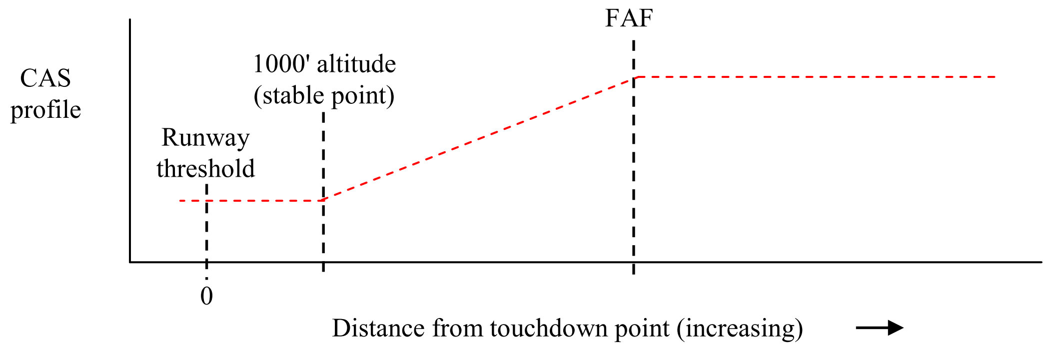

Figure 22. Generic Calibrated Air Speed (CAS) profile.

After the SAPA clearance is issued, the fast aircraft will adjust its speed to obtain the correct position within the SAPA-CZ. This correct position is dependent on the PFAS of both aircraft in the SAPA pair. The computation for this correct position is provided in Appendix A.

A speed management algorithm was developed to support SAPA operations. The basic operational requirements for the speed management algorithm are as follows:

- aircraft will be at their final approach speed at a position no closer to the runway touchdown point than a distance that corresponds to an altitude of 1000 ft AGL on the glide slope;
- aircraft will fly their aircraft / operator specified final approach speeds; and
- speed guidance will provide speeds that are operationally reasonable relative to current operations.

In exploring various speed management algorithms, it was determined that varying the speed schedules for when each aircraft slows to its respective PFAS can have a significant impact on what speed differences between the two aircraft can be allowed as well as on the operational acceptability of the speed management to pilots. Four different models or techniques for speed management were examined. From the four models that were considered, the one that had the greatest merit relative to simplicity and operational robustness was a station-keeping technique. In this technique, the fast aircraft, once properly positioned, would then remain in a fixed relative position by matching the ground speed of the leading aircraft. Once it reached a speed equal to its PFAS, which would naturally occur due to the leader decelerating, it would then maintain that speed until landing. This technique allows the spacing aircraft to make minor spacing adjustments to compensate for wind prediction or other similar errors until it reaches its PFAS while still achieving a smooth deceleration to that speed. After the fast aircraft reaches its PFAS, the relative aircraft positions will begin to change, with the fast aircraft beginning to overtake the slow aircraft. Assuming that the initial pair positioning criteria are met at the beginning of the procedure and that there are no large, unaccounted errors (e.g., large wind prediction errors), then the aircraft should remain within the SAPA-CZ until both aircraft land. An example of the generic ground speed profile for this station-keeping technique is provided in Figure 23.

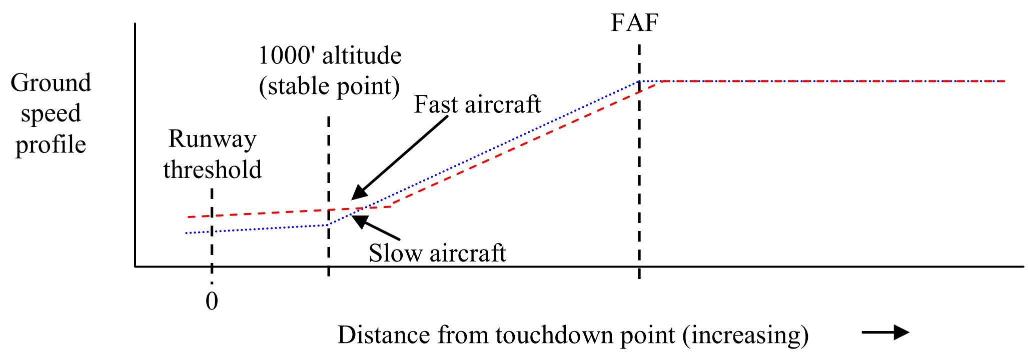

Figure 23. Generic ground speed profile for station-keeping.

Initial Vertical Separation

When ATC initially establishes the SAPA aircraft pair on the final approach course, the pair is initially separated vertically by 1000 ft, and ATC may place either the fast or the slow aircraft on the "high-side" approach. The aircraft are likely not yet longitudinally positioned within the SAPA-CZ early on the final approach course, but ATC will have positioned them such that the actively spacing trailing aircraft can catch up to the appropriate SAPA-CZ positioning. After the SAPA clearance is issued and prior to the paired aircraft losing vertical separation, the aircraft must be longitudinally positioned within the SAPA-CZ. This within-the-window requirement must occur prior to the high-side aircraft reaching its glide-slope-intercept point. The worst case situation for the two possible aircraft / altitude combinations is when the slow aircraft is the high-side aircraft. In this situation, the SAPA-CZ requirement must be met at a point where both aircraft are farther from the runway threshold, as compared to the situation where the fast aircraft is the high-side aircraft. If the slow aircraft is the high-side aircraft, and assuming a 4000 ft high-side intercept on a 3^{o} glide slope, the pair of aircraft must be within the SAPA-CZ window before the slow aircraft reaches 12.3 nm from the runway. If the SAPA-CZ requirement is not met at the point that the high-side aircraft intercepts its glide slope, then the SAPA operation cannot continue and the high-side aircraft will conduct a missed approach. In this instance, the high-side aircraft will maintain its altitude, tracking the final approach course, and notify ATC of the situation.

It is expected that ATC will issue a SAPA clearance to the relevant SAPA aircraft pair sufficiently early in the final approach such that they may maneuver in the manner described in the *Speed Management* subsection to obtain the appropriate relative position prior to the high-side aircraft reaching its glide-slope-intercept point.

Missed Approach

Once SAPA procedures are being used for separation, i.e., after the high-side aircraft begins its descent on the glide slope, several situations could lead to one or both of the SAPA paired aircraft needing to conduct a missed approach or "breakout" maneuver. The most obvious situation requiring a missed approach would be the physically trailing aircraft lagging outside of the SAPA-CZ. In this instance, a traditional missed-approach procedure would be adequate, i.e., a climb until passing the missed-approach point, located near the runway threshold, followed by any turn that is required by the procedure. The second situation that would require a missed approach or "breakout" maneuver would be if one aircraft inadvertently turned toward the other aircraft and created a collision risk. The development of an alerting algorithm and blunder avoidance maneuver will be the subject of a future study. The third situation, which eventually drove the missed-approach requirement in this concept analysis, is the case where the physically leading aircraft must conduct a go-around maneuver due to other non-SAPA operational problems; e.g., a blocked landing runway for the leading aircraft. This situation is likely to occur at a sufficiently high probability that it must be addressed by the SAPA procedure. Because the leading aircraft will be immediately climbing during this situation, the trailing aircraft cannot conduct a traditional missed approach and expect to avoid the wake vortex of the leading aircraft. This condition will require the trailing aircraft to both climb and turn to avoid the wake and to reduce the collision risk. Therefore, the recommended SAPA missed approach procedure is an immediate climbing turn in a direction away from the parallel approach path for the other runway. Previous research has shown that a 45^{o} climbing turn away from the opposite aircraft's approach path provides an operationally acceptable maneuver while producing a rapid separation in relative aircraft positions [Winder2001].

SAPA Data Requirements and SAPA Status Information

Due to the unique aircraft-to-aircraft cooperative characteristics of the SAPA concept, data that are not part of the current ADS-B message set will be required to support SAPA operations (noting that these data could potentially be provided by other means). These data would be used to derive the SAPA status information used by both the SAPA aircraft and ATC. These data would also be used for the SAPA-CZ and speed guidance calculations by the SAPA aircraft. Data in addition to ADS-B state data would include the PFAS for each aircraft and the last ATC assigned speed for the slow aircraft. Database information would also be required that could include runway locations and elevations. SAPA status information that would be derived within each aircraft and broadcast could include:

- SAPA failure: derived from navigation performance, auto-flight system status (to include engagement status), and SAPA equipment status;
- SAPA-CZ status: derived from the computed SAPA-CZ and the relative aircraft positions;
- SAPA speed conformance: derived from the SAPA speed guidance and the aircraft's actual CAS; and
- SAPA go-around status: derived from the go-around status of the auto-flight system.

The SAPA failure and SAPA go-around status would be used by the other aircraft in the SAPA pair as part of its go-around requirement derivation. The SAPA failure and SAPA go-around status could also be used by ATC as an alert to a SAPA go-around, prior to observing it on a radar display or before receiving a radio call from the aircraft. The SAPA-CZ status and SAPA speed conformance information could be used by ATC as a trigger for required ATC intervention.

To set up the aircraft to perform the SAPA approach, the controller must deliver the aircraft on approach with spacing such that the pilots can achieve the longitudinal spacing within the SAPA-CZ window before reaching the point where they must begin the SAPA procedure. The requirements for onboard guidance and the controller and pilot procedures for setting up, initiating, and conducting the SAPA procedure are examined in detail in the next section.

Set Up and Initialization of SAPA Procedure

This section focuses on procedures to support the SAPA operation from the groundside. For the SAPA concept to be operationally acceptable, several procedural issues require resolution. The SAPA concept will require procedures significantly different than those used today for the conduct of instrument approaches and approaches to closely spaced parallel runways. In response to these differences, new procedures are described in this section. While these new procedures demonstrate the operational feasibility of the SAPA concept, further investigation is needed to finalize procedures for SAPA operations.

The following description is provided as background information for discussions regarding the integration of SAPA procedures into air traffic operations. Note that airspace configurations, procedures, and techniques vary among facilities; this description is based on a "common denominator" of operations.

Current Operations

Airport acceptance rates are based on many factors, including the types of operations that are being performed on parallel runways. For instrument approaches to closely spaced parallel runways, the pair of runways are treated as a single runway when the distances between centerlines are less than 2500 ft. The airport acceptance rate translates into in-trail separations at "metering" fixes at the terminal boundary. Metering fixes are usually 30 - 40 miles from the airport. Aircraft are "handed-off" (transfer of control responsibility) from the Air Route Traffic Control Center (ARTCC) to the Terminal Radar Approach CONtrol (TRACON) prior to the TRACON boundary. In general, the initial controller in the TRACON responsible for arrival aircraft is the "feeder" controller (note that terminology with respect to positions in TRACONs may vary). Upon verifying that the flight crew has received the current Automatic Terminal Information Service (ATIS) broadcast, the feeder controller separates and sequences arrival traffic such that a manageable flow is provided to the "final" controller. The final controller accepts hand-offs from the feeder controller and is responsible for transitioning aircraft to the final approach course, sequencing of aircraft (usually to one runway), and providing the requisite separation[5]. Transfer of communications to the tower normally takes place at or outside the FAF. Specific procedural requirements for the aforementioned tasks are found in FAA Order 7110.65T [FAA7110.65].

[5] The distance between aircraft outside the final approach fix does not normally reflect the separation required between a specific aircraft pair. Additional spacing is normally applied to allow for "compression" which occurs when the lead aircraft decelerates to its final approach speed at which time separation would reduce. This is not necessarily the case when the final approach speed of the leading aircraft is higher than the following aircraft.

SAPA Procedures

The SAPA procedures impose additional requirements for aircraft entering the terminal area and landing. Critical to the procedure is knowledge by the flight crews and ATC of the planned final approach speeds of both aircraft and identities of both aircraft in the pair. Aircraft not participating in the SAPA procedure have to be identified early in the process of spacing and sequencing aircraft so that spacing adjustments can be made. Positioning of the SAPA pair has to be accomplished with reasonable precision such that both aircraft are established in the SAPA-CZ prior to loss of 1000 ft vertical separation at the SAPA Out of Conformance Missed Approach Point (SOCMAP). Upon acceptance of a clearance for the SAPA procedure, the flight crew assumes certain responsibilities for successful execution of the procedure.

The following subsection discusses an element to the conduct of SAPA operations–the positioning of aircraft such that they are within acceptable bounds to conduct the procedure. In considering the feasibility of controllers placing aircraft within acceptable bounds, an operation currently in practice with similarities is noted. At San Francisco International Airport (SFO), simultaneous visual approaches are routinely conducted to parallel runways separated by 750 ft (centerline-to-centerline). Due to aircraft departing between arrivals on a set of perpendicular parallel runways, arrivals need to be paired and the pairs separated by 4 1/2 to 5 miles. Although these arrival aircraft are conducting visual approaches, there are parallels to be drawn between these operations and those proposed for SAPA. The simultaneous visual approaches in use at SFO today were used as a starting point for developing an initial set of candidate SAPA procedures.

Positioning Task

The SAPA concept requires establishment of a geometrical relationship within a pair of participating aircraft; this relationship must be maintained within defined acceptable bounds. Separation of the pair of aircraft from the next pair of aircraft ahead and behind must also be maintained. In the case of separation from another pair of aircraft conducting the SAPA procedure, separation must be maintained from the aft-most permissible position of the lead set of aircraft.

In the conduct of approaches to two runways, there are normally two controllers each providing spacing and sequencing to their respective runways.

There are several basic assumptions upon which the procedures discussed in this document with respect to the pairing process are based. They are as follows:

- Aircraft with the faster final approach speed will be initially positioned as the trailing aircraft in the pair;
- Standard procedures for final approach course turn-ons used for simultaneous instrument approaches to parallel runways are employed; and

- Vertical separation requirements for turning aircraft onto parallel final approach courses will be observed; specifically, 1000 ft vertical separation will be maintained during turn-on.

The required actions for positioning the aircraft in the SAPA-CZ are described below. Initial positioning is accomplished by ATC; this positioning sets up the flight crew for the final positioning phase. The final phase is accomplished by the flight crew and positions the aircraft in the SAPA-CZ.

Initial Positioning of Aircraft

Both the feeder controller and the final controller are responsible for initial positioning of aircraft for the SAPA procedure. The process is as follows. The ATIS broadcast includes verbiage that SAPA is in use for a runway pair and that flight crews that will not be participating shall notify ATC upon initial contact with the TRACON[6]. A slot in the flow will be created to provide for aircraft that will not be paired with another aircraft. Upon entering the terminal area, the flight crew advises the feeder controller of their PFAS. PFASs are critical information for the final controllers; they can be transmitted to the final controller verbally or through alternative methods. One potential method is having the feeder controller enter the PFAS into the data block scratch pad (see Figure 24). Note that in the data block on the left, the airspeed field shows "24" for a current groundspeed of 240 kt. A scratch pad entry could permit display of the PFAS, in this case "S" indicating "speed" and "134" indicating a PFAS of 134 KIAS (example on right). The PFAS would "time share" with the current ground speed. This information display could serve as coordination of the PFASs, which in turn will indicate which aircraft will be vectored onto the final approach course in the lead position.

Figure 24. Depiction of PFAS (S134) input by controller in standard data block using time-sharing capability.

The feeder controller is responsible for positioning the aircraft, through issuance of headings and speeds, such that the final controller can achieve the objective of further positioning the aircraft for the SAPA procedure. A handoff to the final controller will be accomplished using standard handoff procedures.

[6] Note that as the Traffic Flow Management process is refined, knowledge of non-participating aircraft should be known much earlier than terminal area entry. This information could perhaps be part of the flight plan. If SAPA procedures are not in use upon arrival at the destination, it would not matter.

The leading and trailing aircraft are handled differently with respect to the SAPA procedure. Recall that the aircraft with the slower PFAS will always be positioned by the final controller as the leading aircraft in the SAPA pair. This aircraft with the slower PFAS will be vectored onto the final approach course and given a speed to maintain to the FAF that will provide adequate separation from the lead pair of aircraft ahead. This will be described in detail in the following Separation Requirements subsection.

The leading aircraft, once established on the final approach course at the assigned speed, basically serves as the "reference" aircraft. The trailing aircraft, which is the active-spacing aircraft, will be positioned such that the appropriate position in the SAPA-CZ can be achieved through speed management.

Ultimately, the objective of the final controller is to position the trailing aircraft such that the flight crew can achieve the appropriate position in the SAPA-CZ through application of speed management. There are several strategies for appropriate positioning of the trailing aircraft, and these will need to be investigated further in future studies. The feeder controller hands off the aircraft in a position that will permit the final controller to provide a transition to the final approach course within reasonable proximity to the leading aircraft. The final controller issues appropriate control instructions (discussed in the following paragraph) to establish the trailing aircraft on the final approach course followed by a speed command that permits positioning in the SAPA-CZ prior to the SOCMAP.

Conduct of the SAPA procedure requires authorization from ATC and this will be issued in the form of a clearance. This clearance could be incorporated in the approach clearance; however, current approach clearance phraseology is fairly long. For the current iteration of SAPA procedures development, clearance for the SAPA procedure will be a separate clearance. Recall that both aircraft in the pair will be issued the SAPA clearance.

Candidate phraseology for the SAPA procedure is:

"(A/C ID), PAIRED TRAFFIC (A/C ID of paired aircraft), CLEARED SAPA PROCEDURE"

For the leading (reference) aircraft, the clearance for, and acceptance of, the SAPA procedure implies the following:

- Flight crew will maintain the last speed assigned from ATC until reaching the FAF;
- Altitude shall be maintained as assigned by ATC until glide slope intercept; and
- Once the aircraft intercepts the glide slope and the 1000 ft vertical separation is no longer in effect, the flight crew assumes responsibility for monitoring parallel traffic for blunders using onboard alerting.

For the trailing (active-spacing) aircraft, the clearance for, and acceptance of, the SAPA procedure implies the following:

- Flight crew will maintain the last speed assigned from ATC until deceleration is required to assume the appropriate position in the SAPA-CZ;
- When the trailing aircraft is established in the SAPA window, speed may be adjusted as necessary; however, the aircraft must remain within the confines of the SAPA-CZ window;
- Altitude shall be maintained as assigned by ATC until glide slope intercept; and
- Once either aircraft intercepts the glide slope and the 1000 ft vertical separation is no longer in effect, the flight crew assumes responsibility for monitoring parallel traffic for blunders using onboard alerting.

Upon acceptance of the SAPA clearance, ATC shall assume a monitoring role with respect to the two aircraft. Figure 25 provides a plan view of the aircraft positioning scheme for the SAPA procedure.

Final Positioning of Aircraft

Final positioning refers to actions taken by the flight crew of the trailing aircraft to appropriately position their aircraft relative to the leading aircraft. At this point, both flight crews have accepted the SAPA clearance, and the final controller will have assigned speeds to each aircraft that will permit a closure rate allowing for final positioning to occur in advance of the aircraft reaching the SOCMAP. The flight crew of the leading aircraft will maintain the assigned speed until just prior to the Stabilized Approach Point, then decelerate to the final approach speed by the time the SAP is reached. The trailing aircraft will maintain the speed assigned by the controller until deceleration is necessary for maintaining appropriate position within the SAPA-CZ. It is assumed that there is automation onboard the aircraft to assist with the positioning task.

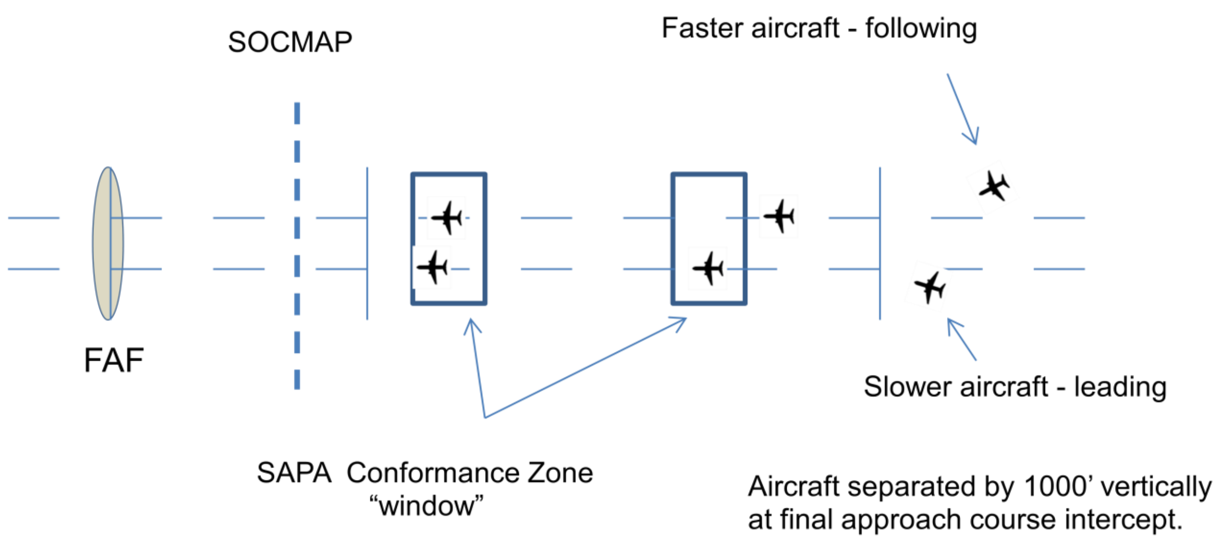

Figure 25. Positioning of SAPA aircraft on final approach course.

Separation Requirements

There are two considerations with respect to separation requirements for the SAPA procedure. First is the existing requirement to provide separation between all aircraft on the final approach courses.

Within a pair of aircraft conducting SAPA operations, vertical separation is applied until the higher-altitude aircraft intercepts the glide slope and begins its descent. So for the SAPA procedure, separation responsibility ends for ATC when the higher-altitude aircraft initiates the descent.

In the case of separation between two SAPA aircraft pairs, in-trail separation is applied between the SAPA-CZ boundaries. For the following discussion, refer to Figure 26. Separation is essentially being applied between the forward-most and aft-most positions in the SAPA-CZ; this is necessary because aircraft pairs are permitted to use the entire longitudinal bounds of the SAPA-CZ. Since the aircraft that is initially leading is the reference aircraft, the SAPA-CZ boundaries are defined with respect to the position of the leading aircraft. The candidate SAPA procedures enhance the controller's ability to effectively monitor and maintain appropriate separation between aircraft pairs by having the reference aircraft maintain the speed assigned by the controller until just prior to the SAP. Rather than trying to anticipate the movement of the active-spacing aircraft, the controller simply ensures that the entire SAPA-CZ defined around the reference aircraft is safely separated from the SAPA-CZ for the pair ahead and the SAPA-CZ for the pair behind.

To support the controller in separating SAPA-CZ boundaries, display of those boundaries is likely required. In the example below, 4 nm is required at the threshold between aircraft pair A and pair B and between pair B and pair C. Note that there is currently 5 nm between pair B and pair C to allow for compression as the lead pair decelerates. Absent presentation of the SAPA-CZs, an allowance is required to ensure appropriate separation is applied. One way this could be accomplished is through adding spacing to allow for what to the controller is an unknown. The determination of maximum bounds could provide for the establishment of appropriate additions to current standards. A reasonable analogy is the additional separation required for formation flights from other aircraft; an additional mile is required when a formation flight is involved [FAA7110.65].

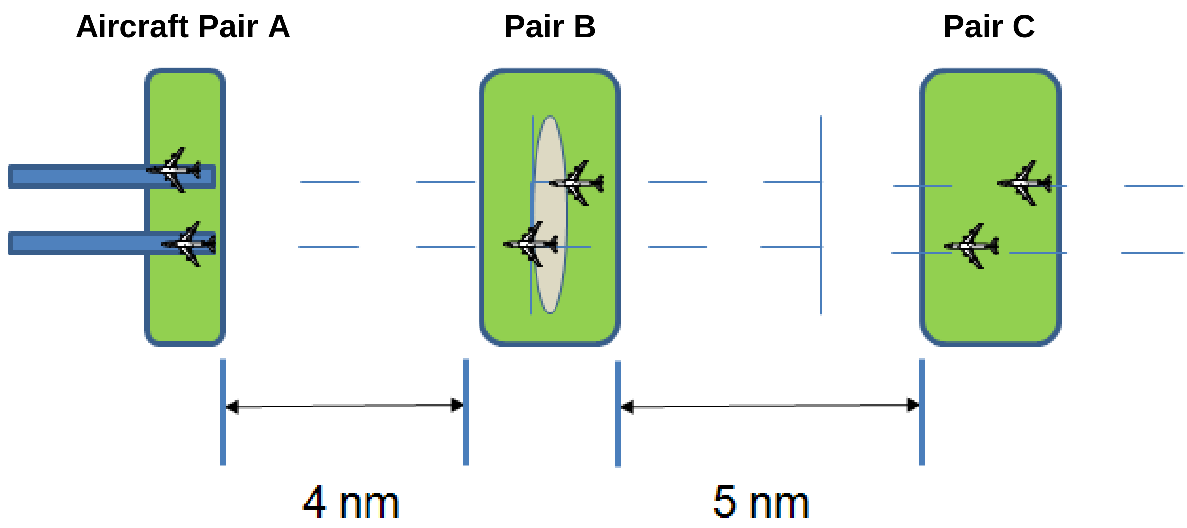

Figure 26. In-trail separation requirements between pairs of aircraft.

Roles and Responsibilities

Previous discussions have alluded to responsibilities through description of procedures. The following list summarizes responsibilities of ATC and the flight crews. Note that the procedures listed are limited to those unique to the SAPA procedure.

Responsibilities of ATC

- Advertise the following on an ATIS broadcast: use of SAPA procedures, runways, and advise ATC on initial contact of PFAS, or if unable to participate in SAPA procedure
- On initial contact verify PFAS; if advised by flight crew that they will not accept the SAPA procedure, initiate coordination for appropriate handling of aircraft
- Coordinate SAPA pairing of aircraft as appropriate
- Provide appropriate control instructions to position aircraft for the SAPA procedure
- Issue clearance for SAPA procedure (this includes a traffic call pointing out appropriate traffic)
- Monitor position of aircraft conducting the SAPA procedure[7]

[7] "Monitoring" in this case refers to the responsibility that rests with controllers for scanning their area for situations requiring corrective action. As mentioned, display of the SAPA window would be of benefit to the controller. Detecting deviations from acceptable bounds for aircraft pairs would not be feasible with traditional terminal displays. Further, the current concept does not require staffing of monitor positions as required for simultaneous independent instrument approaches or a Precision Runway Monitoring (PRM) position, or similar capability.

Responsibilities of the flight crew

- Flight crew obtains ATIS broadcast prior to contact with TRACON; advises TRACON on initial contact of: PFAS (indicates that will accept SAPA procedure) or non-participation in SAPA Procedure
- Acceptance of SAPA procedure; implies that flight crew will perform positioning task associated with the SAPA procedure
- In the event of deviation from SAPA-CZ, flight crew will initiate a missed approach using SAPA-specific missed approach procedure and advise ATC

Airspace Requirements

To facilitate the conduct of the SAPA procedure, adequate distance is required along the final approach course. The required distance would have to reside in the final controller's airspace. The final determination of the distance required is the subject of further investigation focused on techniques applied by ATC and the flight deck. In the previous section, *Conduct of SAPA Operations*, it was determined that the aircraft would have to be positioned within the SAPA-CZ as much as 12.3 nm from the runway threshold. A preliminary assessment of distances available for aircraft positioning in the final controller's airspace at four major air traffic facilities suggest that adequate airspace is available.

Traffic Flow Management Considerations

The SAPA procedure is designed to increase capacity at airports with closely spaced parallel runways during periods when instrument approach procedures are in use. The use of instrument approach procedures (as opposed to the use of visual approaches) requires the application of separation standards. The use of the SAPA procedure permits operations to two runways where current procedures would limit arrival operations to one of the parallel runways. The airport acceptance rate would reflect use of the procedure. Note that there may be limitations on use of the procedure for reasons such as maximum crosswind limitations. There will also have to be accommodations made for non-participating aircraft. Finally, airport capacity considerations based on availability of the procedure could influence selection of runway configurations.

Role of Automation

There are several areas where the SAPA procedure will require tools or displays aids. Those mentioned here support the role of ATC in the conduct of the procedure. To minimize workload and coordination, metering of the aircraft to fixes at the terminal boundary is useful; whether or not this is a requirement is the subject of future research. Current traffic management tools such as the Center-TRACON Automation System (CTAS) Traffic Management Advisor (TMA) could provide the needed functions, including identities of the paired aircraft. A depiction of the SAPA-CZ, although not currently considered a requirement, would be highly beneficial and would assist the controller in applying the appropriate in-trail separation between aircraft pairs and other aircraft pairs or single aircraft. If the SAPA-CZ is not displayed, additional separation would be required as the controller could not be certain where the bounds of acceptable longitudinal maneuvering could occur.

Concluding Remarks

At the request of the FAA, NASA has performed an initial assessment of the potential performance and feasibility of the SAPA concept. This initial assessment included an initial system study of the SAPA concept to assess operational benefits and constraints plus a preliminary technical feasibility analysis. While this assessment is preliminary, it has shown the basic SAPA concept to be technically and operationally feasible. An example implementation of the concept was developed in some detail, including identification of potential pilot/controller roles and responsibilities. Several design and implementation issues were explored, which should be useful to aid the FAA in the development and refinement of the SAPA concept.

The assessment has revealed that the SAPA concept has significant operational advantages in allowing the pairing of aircraft with dissimilar final approach speeds for dependent operations, if blunder safety, which was not addressed in the current study, can be shown to be acceptable. The use of abeam positioning rather than echelon positioning will require higher lateral navigation performance to reduce the likelihood of blunders, but this requirement appears achievable in the mid-term timeframe. A preliminary look at lateral navigation requirements revealed that the required navigation and FTE accuracy are aggressive, but seem to be within the realm of existing state-of-the-art avionics.

The requirements for longitudinal positioning were investigated through a Monte Carlo simulation. The use of a two-phased conformance zone, with a larger longitudinal conformance zone defined for higher altitudes out of ground effect and another conformance zone defined for altitudes near and in ground effect, has the potential to allow even larger speed differentials. On-board speed management, such as station-keeping, is probably required to achieve robust performance in a realistic operational environment.

The current study was only a preliminary assessment of the basic SAPA concept, and many more studies will be required before an implementation decision could be supported. There are a number of studies that need to be conducted related to the breakout maneuver, including identification of the appropriate triggering conditions and alerting mechanisms, the operational aspects of using coupled autopilot for the maneuver, and developing operational procedures for the breakout and missed-approach maneuvers.

There are a number of operational issues that need to be studied related to the SAPA procedure design. Onboard speed management requirements and algorithms must be developed. The design of SAPA operational procedures that are robust to off-nominal and non-normal situations must be investigated. Also, because the SAPA operation will be performed in conjunction with other current and future planned procedures, such as time-based metering and merging and spacing, the initial pairing of aircraft needs to be studied with consideration for other current and future planned ATC equipage and procedures.

A detailed examination of the feasibility, safety, and operational details of the blunder avoidance maneuver is needed. Blunder detection and reaction times are minimal at the targeted lateral runway spacings, and the feasibility of meeting the timing requirements should be explored, including the timing required to initiate a pre-programmed breakout maneuver. The SAPA concept includes the use of ADS-B to share position and status information between the aircraft, and the sharing of additional SAPA-specific information via ADS-B intent to aid in timely onboard blunder alerting should be explored.

Additional studies are required to define the requirements for the SAPA-CZ. The current study explored wake encounters only for a specific pair of aircraft, and wake studies need to be conducted to define safe zone parameters across the full range of possible SAPA use scenarios, including aircraft pairs, landing weights, approach speeds, runway lateral spacings, runway threshold offsets, crosswind velocities and directions, etc. The behavior of wakes at various altitudes on approach as they transition into ground effect also needs to be characterized in order to define effective altitude-based conformance zones. These studies are especially problematic because of the lack of observational data and understanding of wake movement and decay in and near ground effect. This will be a serious problem in defining a wake-safe conformance zone boundary for operational implementation of any dependent closely spaced parallel operation, not just for SAPA.

Acknowledgements

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Appendix A – Speed Management using a Station-Keeping Model

Definitions and Abbreviations

CAS	Calibrated airspeed.
CFAGS	Corrected final approach speed (CAS) converted to ground speed.
D	The desired distance the trailing aircraft is behind the leading aircraft as the leading aircraft crosses the FAF.
FAF	Final approach fix or the final glide slope intercept point from the lowest published altitude.
GAP	The glide slope abeam point. This is the point at the centerline of the runway that is abeam of the glide slope. This is also the approximate point where the aircraft lands.
GndSpd	Ground speed.
M	The point on the CAS speed profile of the aircraft with the slower PFAS where the CAS is equal to the PFAS of the faster aircraft.
PFAS	Planned final approach speed. The CAS the aircraft will fly along the stable approach segment.
SAP	Stabilized Approach Point. The distance from the runway where the aircraft must be configured for landing and be at its PFAS. This point is typically 3.14 nm from the GAP (distance = 1000 ft/ tan 3°), assuming a 3^{o} glide slope.
TTL	Time to land. The time to fly from a given point to the GAP.
SAPA-CZ	The "window" length, either forward or rearward from a nominal aircraft's center point to the SAPA wake vortex boundary limit. Note that because ground effect influences wake lateral movement, the length of this window will change depending on where it is on the approach, e.g., $\text{SAPA-CZ}_{FAF} \neq \text{SAPA-CZ}_{GAP}$. It is also assumed that above some altitude, and therefore beyond some point on the approach, that this value will not change, e.g., $\text{SAPA-CZ}_{FAF} = \text{SAPA-CZ}_{\text{Glide slope Intercept Point}}$.

Unique Subscripts

fast	aircraft with the faster PFAS.
slow	aircraft with the slower PFAS.

General

This appendix describes a station-keeping model designed to accommodate pairs of aircraft with dissimilar final approach speeds performing SAPA approaches. In this model, a station-keeping technique is used to control the speed of the fast aircraft, aircraft_{fast}, not only up to the FAF but until aircraft_{fast} reaches its PFAS. The final control point for this model is just prior to the SAP; after this point no relative positioning control occurs. No winds are assumed in the equations but may be used in the ground speed calculations if they are known. In this station-keeping technique the ADS-B state data for the slow aircraft, aircraft_{slow}, is used directly by aircraft_{fast} in computing its speed command. Aircraft_{fast} will match the current ground speed of aircraft_{slow} until the CAS speed command for aircraft_{fast} matches its PFAS. Unless the PFAS for both aircraft are the same, $aircraft_{fast}$ will reach its PFAS at a point farther from the runway than the 1000 ft SAP. An example of this concept is shown in Figure A1.

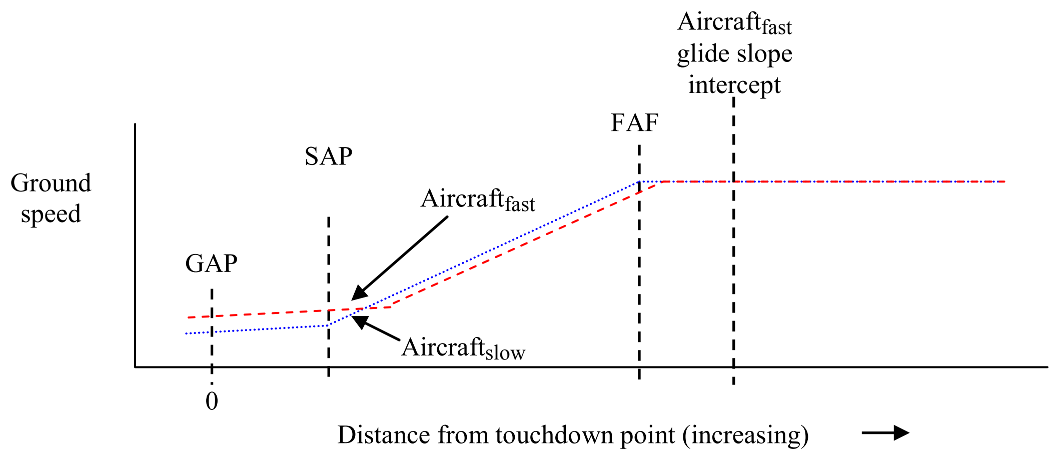


Figure A1. Station-keeping ground speed for $aircraft_{fast}$.

Maximum Time Criterion

In order to determine whether a given pair of dissimilar final approach speeds can be accommodated, the length of time that the aircraft are traveling at different speeds must be calculated. The time of interest in this calculation occurs at the point where $aircraft_{fast}$ reaches its PFAS along the CAS profile of $aircraft_{slow}$. To calculate the maximum time criterion for this model, the following equations are used:

Using the speed profile for $aircraft_{slow}$, the point M (Figure A2) is the distance along the CAS profile of $aircraft_{slow}$ where the CAS value is equal to $PFAS_{fast}$.

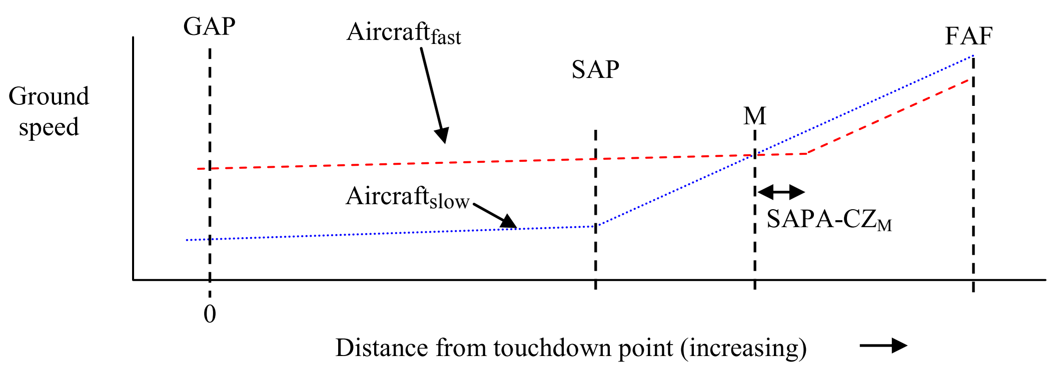


Figure A2. Station-keeping speeds after the FAF.

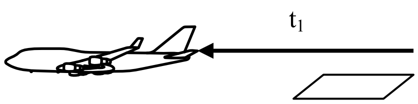
Then,

equation 1: $TTL_{fast} = (M + SAPA\text{-}CZ_M) / CFAGS_{fast}$, where $SAPA\text{-}CZ_M$ is the window length at position M and $CFAGS_{fast}$ is the average ground speed between point M + $SAPA\text{-}CZ_M$ and the GAP. Note that M is the point where $aircraft_{fast}$ reaches its PFAS, so $CFAGS_{fast}$ is the corrected $PFAS_{fast}$ (CAS) converted to ground speed.

The maximum time criterion to allow a SAPA operation is:

$$TTL_{slow} < TTL_{fast} + t_1,$$

where TTL_{slow} is the time for $aircraft_{slow}$ to fly from M to the SAP plus the time to fly from the SAP to the GAP, and t_1 is the delta time from $aircraft_{fast}$ reaching the GAP until $aircraft_{slow}$ reaches the GAP.



$$t_1 = s_1 / CFAGS$$
$$s_1 \leq SAPA\text{-}CZ_{GAP}.$$

where s_1 is the relative distance between the two aircraft when $aircraft_{fast}$ reaches the GAP. Then let

$$t_2 = (M - SAP) / ((GndSpd_M + CFAGS_{slow,SAP}) / 2)$$

where $GndSpd_M$ is the ground speed at a distance = M and $CFAGS_{slow,SAP}$ is the ground speed at the SAP, noting that for the general case, $CFAGS_{slow}$ is the corrected $PFAS_{slow}$ (CAS) converted to ground speed.

$$t_3 = SAP / ((CFAGS_{slow,SAP} + CFAGS_{slow,GAP})/2)$$

where $CFAGS_{slow,GAP}$ is the ground speed at the GAP.

$$TTL_{slow} = t_2 + t_3,$$

The maximum time criterion test is then:

$$TTL_{slow} < TTL_{fast} + t_1$$

Position Offset at the FAF

This section examines the desired initial longitudinal offset between the pair of aircraft. Because the aircraft will be station-keeping until $aircraft_{fast}$ reaches its PFAS, the position offset at the FAF is the same as the position offset at the point that $aircraft_{fast}$ reaches its PFAS. In this model,

$$SAPA\text{-}CZ_{FAF} = SAPA\text{-}CZ_M.$$

The calculation of the desired position offset between $aircraft_{slow}$ and $aircraft_{fast}$ at the point where $aircraft_{fast}$ reaches its PFAS along the speed profile of $aircraft_{slow}$ is as follows:

1. Case where $aircraft_{fast}$ does not pass $aircraft_{slow}$ after the FAF

In some situations where the PFAS differences are not large, $aircraft_{fast}$ may not need to pass $aircraft_{slow}$ after the FAF. This situation occurs when TTL_{slow} is less than TTL_{fast},

$$TTL_{slow} < TTL_{fast}$$

In this situation, assuming that abeam landing of the two aircraft is preferred, the desired distance, D, that $aircraft_{fast}$ should be behind $aircraft_{slow}$ as $aircraft_{fast}$ reaches its PFAS is based on determining a value of D such that

$$TTL_{slow} = TTL_{fast} = (M + D) / CFAGS_{fast},$$

where from equation 1, D is substituted for $SAPA\text{-}CZ_M$ and $CFAGS_{fast}$ is the average ground speed between point M + D and the GAP.

Then,

$$D = (TTL_{slow} \times CFAGS_{fast}) - M$$

2. Case where $aircraft_{fast}$ passes $aircraft_{slow}$ after the FAF

If the conditions of the previous case do not apply, i.e., if TTL_{slow} is greater than TTL_{fast}, then $aircraft_{fast}$ should initially be positioned at the rear of the SAPA-CZ; thus,

$$D = SAPA\text{-}CZ_M.$$

Advantages and Disadvantages

The major advantage for this model is that any ground speed or wind errors prior to $aircraft_{fast}$ reaching its PFAS are eliminated. The major problem with this model is that differences in the headwind speed due to wind forecast or wind prediction errors after this point may result in spacing errors during that portion of the approach. However, this distance is by far the smallest for any of the models studied. It should be noted that with this model, $aircraft_{fast}$ will begin to slow prior to the FAF since it is station-keeping on $aircraft_{slow}$.

Appendix B – Box Plot of Initial In-Trail Distance Data

A synopsis of all initial in-trail distance data with recorded wake encounters in the SAPA study is shown in Figure B1. This figure provides a quick visual comparison of the minimum in-trail distances resulting in wake encounters for all of the cases run in this experiment.

The notation used in the figure is as follows. The boxes represent the 25% and 75% containment limits for the data, the line denotes the median, and the whiskers represent the extreme boundaries of the data. The data is grouped by each simulation, with the following notation:

Scenario – Runway centerline spacing – Runway threshold offset

where

S1 refers to the OGE scenario with the wake detection circle,
S2 refers to the NGE scenario with the wake detection circle,
S3 refers to the IGE scenario with the wake detection circle, and
S4 refers to the OGE scenario with the vertical wake detection window.

For example, "S1-750-0" refers to the OGE scenario runs using the detection circle for a 750 ft runway centerline spacing with zero runway threshold offset.

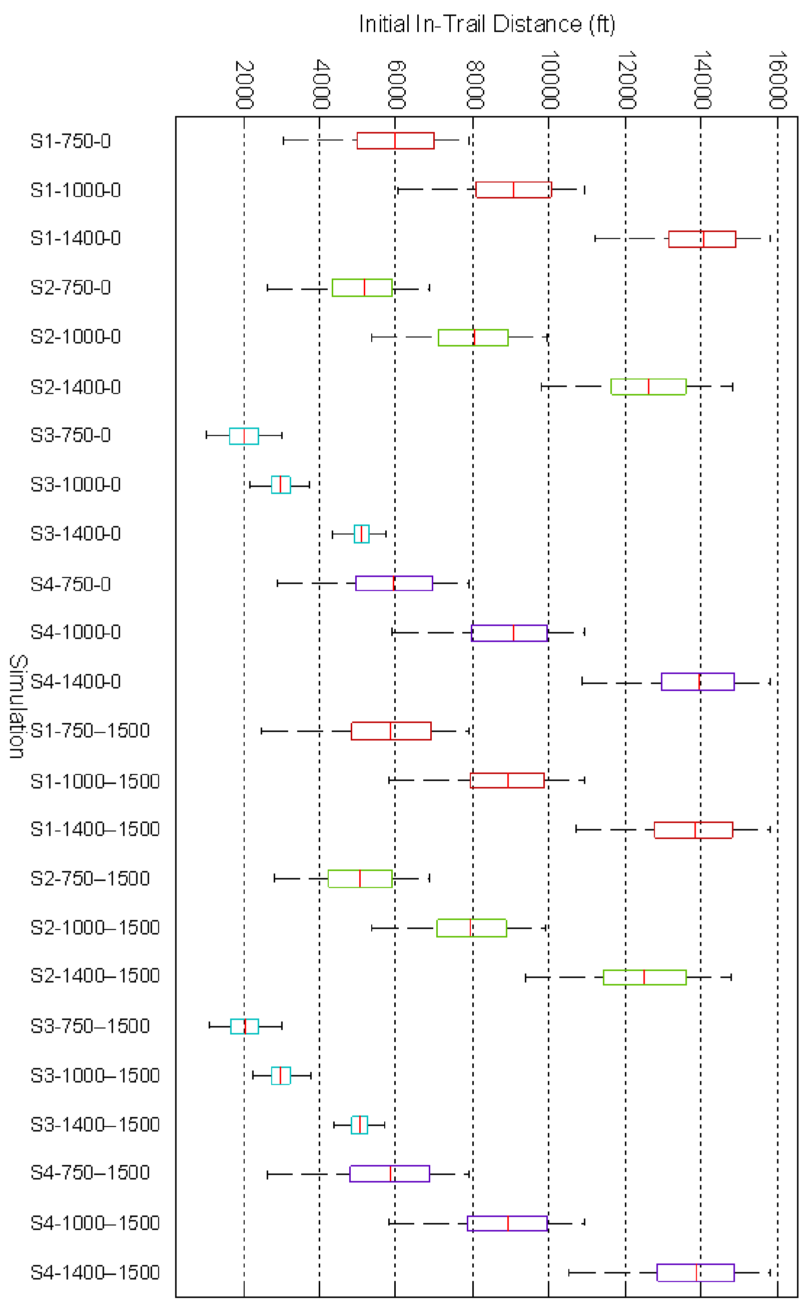


Figure B1. Box plot of results for all experiment cases.

Appendix C – Asymptotic Confidence Intervals for Minimum Initial In-Trail Distances

A necessary part of experiments is statistical inference. This inference extends the relevant results for the sample of data collected or produced by or during the experiment to the population from which the sample was taken. The Monte Carlo simulation study investigated the minimum initial in-trail distance given a vortex encounter for a scenario case. The current study only examined a specific set of cases, so the quantified results of the study are only applicable to the specified aircraft pair and for a minimal subset of scenario parameters. Before operational implementation of the SAPA concept, detailed analyses will be required to accurately quantify minimum in-trail distances and develop standards for the boundaries of the SAPA-CZ. This appendix presents a statistical analysis of the data from the experiment, defining asymptotic confidence intervals for the minimum in-trail distances for each case. These statistical analyses are provided as an example of how extreme value theory might be used to define a SAPA-CZ, not as recommended values.

In the Monte Carlo simulation, the range of initial in-trail distances for each case was defined to capture the tail of the distribution rather than the mean. While this decision limited the applicability of standard statistical techniques that might be used to characterize the overall distribution of the data, it enabled the capture of significantly more data points at the tail, which is the region of interest.

Statistical inference was applied to compute confidence intervals for the 18 combinations of scenarios (three) and cases (six). An application of extreme value theory and maximum likelihood estimation was used to compute the confidence intervals. But, before any computations are presented, it may be instructive to know what confidence intervals are and what they are not. In this experiment, the confidence intervals are used to evaluate and report on the precision of estimates. The meaning of a confidence interval is often misunderstood, as described in the textbook *Common Errors in Statistics (and How to Avoid Them)*:

> A common error is to misinterpret the confidence interval as a statement about the unknown parameter. It is not true that the probability that a parameter is included in a 95% confidence interval is 95%. What is true is that if we derive a large number of 95% confidence intervals, we can expect the true value of the parameter to be included in the computed intervals 95% of the time. (That is, the true values will be included *if* the assumptions on which the tests and confidence are based are satisfied 100% of the time.) Like the *p* value, the upper and lower confidence limits of a particular confidence interval are random variables because they depend upon the sample that is drawn [Good2003].

Thus, if we repeated our Monte Carlo experiment and analyses many times, we could expect the minimum initial in-trail distance leading to a wake vortex encounter to be within our confidence interval 95% of the time. But it is not accurate to say that we have 95% confidence that the minimum initial in-trail distance leading to a wake vortex encounter is within our defined interval. It is essential to realize that the confidence to be placed in the interval is no greater than the confidence we have in the experiment it is based upon.

Extreme Value Theory

Extreme value theory was used to select the family of distributions that approximated the true distributions of the in-trail distance data. Extreme value distributions are the limiting distributions for the minimum (or the maximum) from a large set of random observations from a distribution. Tables C1 through C11 contain descriptive statistics about the initial in-trail distance data collected in the Monte Carlo experiment runs. These statistics were computed using the software EasyFit (Standard) [EasyFit2011]. The Beta distribution was selected as appropriate due to two of its properties: (1) the distribution of the limit (as the number of random variables increase) of the minimum of a sample of properly normalized independent identically distributed random variables is the general extreme value distribution and (2) the Beta distribution is in the minimum domain of attraction. Property (1) does not hold for all probability distributions. But, property (2) means that property (1) does apply to the Beta distribution. The Beta distribution family is as follows:

Parameters

α_1 continuous shape parameter ($\alpha_1 > 0$)
α_2 continuous shape parameter ($\alpha_2 > 0$)
a, b continuous boundary parameters ($a < b$)

Domain

$a \leq x \leq b$

Probability Density Function

$$f(x) = \frac{1}{B(\alpha 1, \alpha 2)} \frac{(x-a)^{\alpha_1 - 1}(b-x)^{\alpha_2 - 1}}{(b-a)^{\alpha_1 + \alpha_2 - 1}}$$

Cumulative Distribution Function

$$F(x) = I_z(\alpha_1, \alpha_2)$$

where $\equiv \frac{x-a}{b-a}$, B is the Beta Function, and I_z is the Regularized Incomplete Beta Function.

The Generalized Extreme Value Distribution is as follows:

Parameters

k continuous shape parameter
σ continuous scale parameter ($\sigma > 0$)
μ continuous location parameter

Domain

$1 + k\frac{(x-\mu)}{\sigma} > 0$ for $k \neq 0$

$-\infty < x < +\infty$ for $k = 0$

Probability Density Function

$$f(x) = \begin{cases} \frac{1}{\sigma}\exp(-(1+kz)^{-\frac{1}{k}})(1+kz)^{-1-\frac{1}{k}} & k \neq 0 \\ \frac{1}{\sigma}\exp(-z - exp(-z)) & k = 0 \end{cases}$$

Cumulative Distribution Function

$$F(x) = \begin{cases} \exp(-(1+\mathrm{kz})^{-1/\mathrm{k}}) & k \neq 0 \\ \exp(-\exp(-\mathrm{z})) & k = 0 \end{cases}$$

where $\equiv \frac{x-\mu}{\sigma}$.

The General Extreme Value distributions have three subclasses: Frechet distributions, Gumbel distributions and Weibull distributions. Specifically, the Beta distribution is in the minimum domain of attraction of the Weibull distribution. More about extreme value theory can be found in [de Haan2006] and also in [Embrechts1997].

Maximum Likelihood Estimation

After selecting the Beta distribution, maximum likelihood estimation was applied to each of the 18 scenario case combinations. The appropriateness of the fit of the distribution to the data was judged visually and also by use of the Anderson-Darling goodness-of-fit test. An example of the visual judgment is shown in Figures C1 through C4 for the OGE scenario, 750 ft runway centerline spacing with zero runway threshold offset. Figures C2 and C3 contain examples of "probability plots." A probability plot is used to compare two distributions. If the distributions are the same then the points of the plot will lay on a straight line. Two types of probability plots are used. C2 is a probability-probability (p-p) plot, while C3 is a quantile-quantile (q-q) plot. A p-p plot is the plot of the percentages (probabilities) of one distribution on the percentages (probabilities) of a second. Similarly, a q-q plot is the plot of the percentiles (quantiles) of one distribution on the percentiles (quantiles) of a second. It is important to note that the points on the left end of the plots appear to almost lie on a straight line. This indicates that the beta distribution is a good choice for estimating the lower end point of this empirical distribution. The EasyFit (Standard) software was used to perform the maximum likelihood approximations and generate the plots for these figures. The Anderson-Darling test did not reject the hypothesis at the 99% level that the empirical distribution and a Beta distribution are the same for the above scenario case combination. The Anderson-Darling test was used because it is more sensitive to data at the ends of the distributions than other popular tests (for example the χ^2 test or the Kolmogorov-Smirnov test). These are typical results. A maximum likelihood estimate for the minimum initial in-trail distance is a=0.49774 for the above scenario case combination. More about maximum likelihood estimation can be found in [vanderWaerden1969] and also [Casella2002]. [D'Agostino1986] is a good source of information about the Anderson-Darling test and other goodness-of-fit tests.

Asymptotic Confidence Interval

According to van der Waerden, the maximum likelihood estimate for the minimum initial in-trail is asymptotically normally distributed. That is, as the number of samples increase, the distribution functions of the estimates minus the true value times $\sqrt{n}$ tends to a normal distribution with mean zero and standard deviation c

where n is the number of samples,
$\frac{1}{c^2} = E\left(\frac{\partial lnf}{\partial a}\right)^2$,
f is the Beta density, and
a is the left end point of the Beta density.

The expected value $E\left(\frac{\partial lnf}{\partial a}\right)^2$ was computed using the initial in-trail data and estimated value of a. In the literature this computation is known as the "observed" information number. By applying the above information, the asymptotic confidence interval can easily be generated.

Let $\hat{a}$ be the maximum likelihood estimate of the true value a and let x^* be the minimum of the sample of data of interest. Then the asymptotic confidence interval is written as

$$(\hat{a} - g_\alpha \frac{c}{\sqrt{n}}, \min[\hat{a} + g_\alpha \frac{c}{\sqrt{n}}, x^*])$$

where g_α is given by $\frac{1}{\sqrt{2\pi}}\int_{-g_\alpha}^{g_\alpha} e^{-\frac{x^2}{2}}\, dx = 1 - \alpha$.

This is the $(1-\alpha)\%$ asymptotic confidence interval. The R project statistical software version 2.7.2 [RFoundation2011] was used to compute the confidence intervals. Tables C12 and C13 list the 99% confidence intervals for this experiment.

Use of Confidence Intervals

The confidence intervals constructed are intervals containing the left end points of the distributions 99% of the time. Data less than the lower confidence intervals limits are points where there were no encounters 99% of the time. The initial in-trail distances less than the lower confidence limits are points where there are no encounters 99% of the time.

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Tables

Table C1. OGE Scenario, 750 ft Runway Centerline Spacing, No Runway Threshold Offset

Case: OGE, 750, 0	
Statistic	**Value**
Sample Size	1627
Range	0.79884
Mean	0.97469
Variance	0.03889
Std. Deviation	0.1972
Coef. of Variation	0.20231
Std. Error	0.00489
Skewness	-0.18746
Excess Kurtosis	-1.0055

Initial In-Trail Distance	
Percentile	**Value**
Min	0.50091
5%	0.65128
10%	0.7053
25% (Q1)	0.81696
50% (Median)	0.98253
75% (Q3)	1.1546
90%	1.2327
95%	1.2657
Max	1.2998

Table C2. OGE Scenario, 1000 ft Runway Centerline Spacing, No Runway Threshold Offset

Case: OGE, 1000, 0	
Statistic	**Value**
Sample Size	1589
Range	0.80819
Mean	1.4875
Variance	0.03738
Std. Deviation	0.19334
Coef. of Variation	0.12998
Std. Error	0.00485
Skewness	-0.20751
Excess Kurtosis	-0.97165

Initial In-Trail Distance	
Percentile	**Value**
Min	0.99173
5%	1.1709
10%	1.2166
25% (Q1)	1.3314
50% (Median)	1.494
75% (Q3)	1.6547
90%	1.7437
95%	1.772
Max	1.7999

Table C3. OGE Scenario, 1400 ft Runway Centerline Spacing, No Runway Threshold Offset

Case: OGE, 1400, 0	
Statistic	**Value**
Sample Size	1425
Range	0.76109
Mean	2.3012
Variance	0.03101
Std. Deviation	0.17609
Coef. of Variation	0.07652
Std. Error	0.00466
Skewness	-0.24852
Excess Kurtosis	-0.83158

Initial In-Trail Distance	
Percentile	**Value**
Min	1.8386
5%	1.9916
10%	2.0572
25% (Q1)	2.1646
50% (Median)	2.3079
75% (Q3)	2.4484
90%	2.5292
95%	2.5683
Max	2.5997

Table C4. NGE Scenario, 750 ft Runway Centerline Spacing, No Runway Threshold Offset

Case: NGE, 750, 0	
Statistic	**Value**
Sample Size	1326
Range	0.69915
Mean	0.84049
Variance	0.0256
Std. Deviation	0.16001
Coef. of Variation	0.19038
Std. Error	0.00439
Skewness	-0.18904
Excess Kurtosis	-0.91989

Initial In-Trail Distance	
Percentile	**Value**
Min	0.43138
5%	0.57233
10%	0.6291
25% (Q1)	0.71217
50% (Median)	0.84766
75% (Q3)	0.97215
90%	1.052
95%	1.0771
Max	1.1305

Table C5. NGE Scenario, 1000 ft Runway Centerline Spacing, No Runway Threshold Offset

Case: NGE, 1000, 0	
Statistic	**Value**
Sample Size	1445
Range	0.75355
Mean	1.3157
Variance	0.03127
Std. Deviation	0.17682
Coef. of Variation	0.1344
Std. Error	0.00465
Skewness	-0.14494
Excess Kurtosis	-1.0068

Initial In-Trail Distance	
Percentile	**Value**
Min	0.88439
5%	1.0206
10%	1.0725
25% (Q1)	1.1702
50% (Median)	1.3236
75% (Q3)	1.4664
90%	1.5478
95%	1.5808
Max	1.6379

Table C6. NGE Scenario, 1400 ft Runway Centerline Spacing, No Runway Threshold Offset

Case: NGE, 1000, 0	
Statistic	**Value**
Sample Size	1617
Range	0.82455
Mean	2.0741
Variance	0.03612
Std. Deviation	0.19004
Coef. of Variation	0.09163
Std. Error	0.00473
Skewness	-0.0487
Excess Kurtosis	-1.1008

Initial In-Trail Distance	
Percentile	**Value**
Min	1.6132
5%	1.7801
10%	1.8188
25% (Q1)	1.912
50% (Median)	2.0765
75% (Q3)	2.2373
90%	2.3306
95%	2.3689
Max	2.4378

Table C7. IGE Scenario, 750 ft Runway Centerline Spacing, No Runway Threshold Offset

Case: IGE, 750, 0	
Statistic	**Value**
Sample Size	1886
Range	0.33101
Mean	0.33214
Variance	0.00581
Std. Deviation	0.07622
Coef. of Variation	0.22948
Std. Error	0.00176
Skewness	0.05449
Excess Kurtosis	-1.0144

Initial In-Trail Distance	
Percentile	**Value**
Min	0.16587
5%	0.21427
10%	0.22987
25% (Q1)	0.26851
50% (Median)	0.33149
75% (Q3)	0.39502
90%	0.43456
95%	0.45315
Max	0.49688

Table C8. IGE Scenario, 1000 ft Runway Centerline Spacing, No Runway Threshold Offset

Case: IGE, 1400, 0	
Statistic	**Value**
Sample Size	1292
Range	0.26032
Mean	0.48925
Variance	0.00282
Std. Deviation	0.05307
Coef. of Variation	0.10847
Std. Error	0.00148
Skewness	0.06367
Excess Kurtosis	-0.81048

Initial In-Trail Distance	
Percentile	**Value**
Min	0.35233
5%	0.40823
10%	0.41974
25% (Q1)	0.44642
50% (Median)	0.48888
75% (Q3)	0.52975
90%	0.5596
95%	0.57689
Max	0.61265

Table C9. IGE Scenario, 1400 ft Runway Centerline Spacing, No Runway Threshold Offset

Case: IGE, 1400, 0	
Statistic	**Value**
Sample Size	1037
Range	0.23325
Mean	0.83591
Variance	0.00227
Std. Deviation	0.04769
Coef. of Variation	0.05705
Std. Error	0.00148
Skewness	0.06711
Excess Kurtosis	-0.64031

Initial In-Trail Distance	
Percentile	**Value**
Min	0.71091
5%	0.75898
10%	0.77585
25% (Q1)	0.80062
50% (Median)	0.8354
75% (Q3)	0.87079
90%	0.90433
95%	0.91827
Max	0.94416

Table C10. OGE Scenario, 750 ft Runway Centerline Spacing, 1500 ft Runway Threshold Offset

Case: OGE, 750, 1500	
Statistic	**Value**
Sample Size	1678
Range	0.8918
Mean	0.95937
Variance	0.04135
Std. Deviation	0.20336
Coef. of Variation	0.21197
Std. Error	0.00496
Skewness	-0.14095
Excess Kurtosis	-0.95818

Initial In-Trail Distance	
Percentile	**Value**
Min	0.40771
5%	0.61485
10%	0.68535
25% (Q1)	0.79594
50% (Median)	0.96516
75% (Q3)	1.1386
90%	1.2368
95%	1.2694
Max	1.2995

Table C11. OGE Scenario, 1400 ft Runway Centerline Spacing, 1500 ft Runway Threshold Offset

Case: OGE, 1400, 1500	
Statistic	**Value**
Sample Size	1681
Range	0.84143
Mean	1.4591
Variance	0.04096
Std. Deviation	0.20238
Coef. of Variation	0.1387
Std. Error	0.00494
Skewness	-0.203
Excess Kurtosis	-0.91215

Initial In-Trail Distance	
Percentile	**Value**
Min	0.9585
5%	1.1171
10%	1.1789
25% (Q1)	1.3033
50% (Median)	1.4683
75% (Q3)	1.6298
90%	1.7283
95%	1.7615
Max	1.7999

Table C12. 99% Confidence Intervals

99% Asymptotic Confidence Intervals for In Trail Distances (nm)				
Scenario	Runway Centerline Spacing (ft)	Runway Threshold Offset (ft)	Lower Limit	Upper Limit
OGE	750	0	0.48841	0.50091
OGE	1000	0	0.98398	0.99173
OGE	1400	0	1.82408	1.8386
NGE	750	0	0.40646	0.43138
NGE	1000	0	0.86645	0.88439
NGE	1400	0	1.60263	1.6132
IGE	750	0	0.16299	0.16587
IGE	1000	0	0.34541	0.35233
IGE	1400	0	0.69973	0.70995
OGE	750	1500	0.39643	0.40771
OGE	1000	1500	0.94053	0.9585
OGE	1400	1500	1.75331	1.7639
NGE	750	1500	0.44558	0.46071
NGE	1000	1500	1.08853	1.0938
NGE	1400	1500	1.53168	1.5442
IGE	750	1500	0.18144	0.18347
IGE	1000	1500	0.36478	0.3715
IGE	1400	1500	0.70988	0.71761

Figures

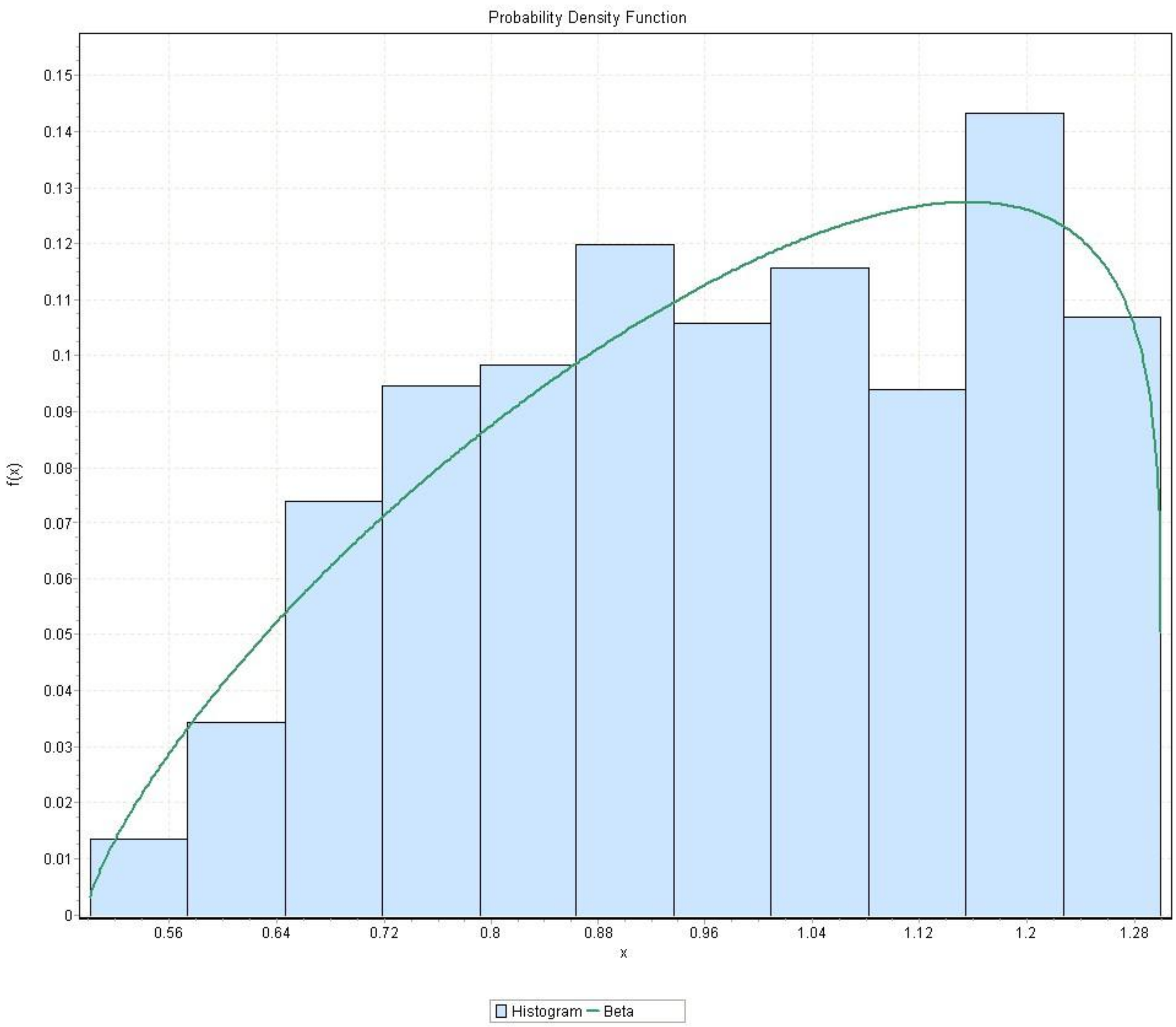

Figure C1. Probability Density Functions (α_1=1.7417, α_2=1.1613, a=0.49774, b=1.2999)

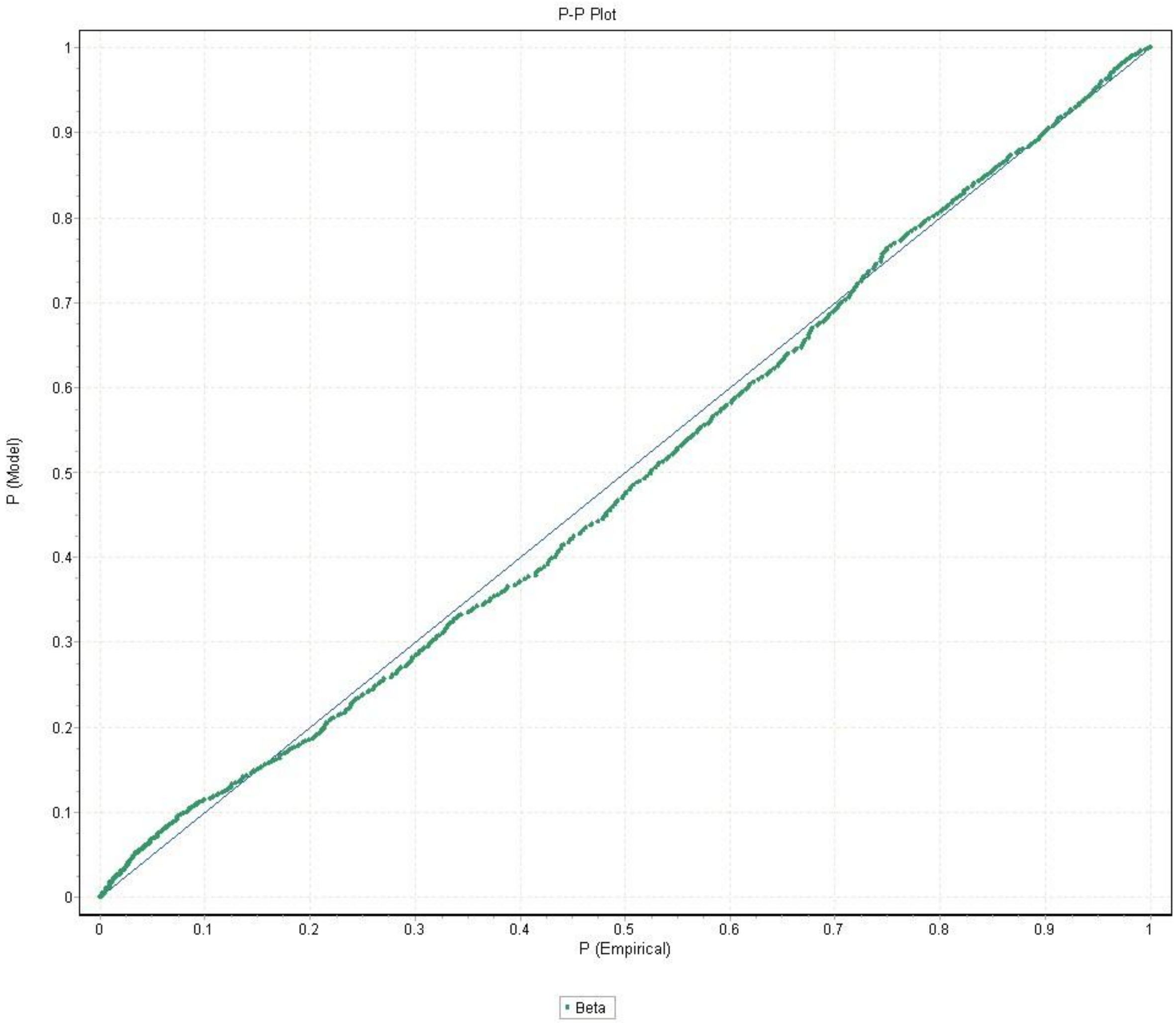

Figure C2. Probability-Probability Plot (α_1=1.7417, α_2=1.1613, a=0.49774, b=1.2999)

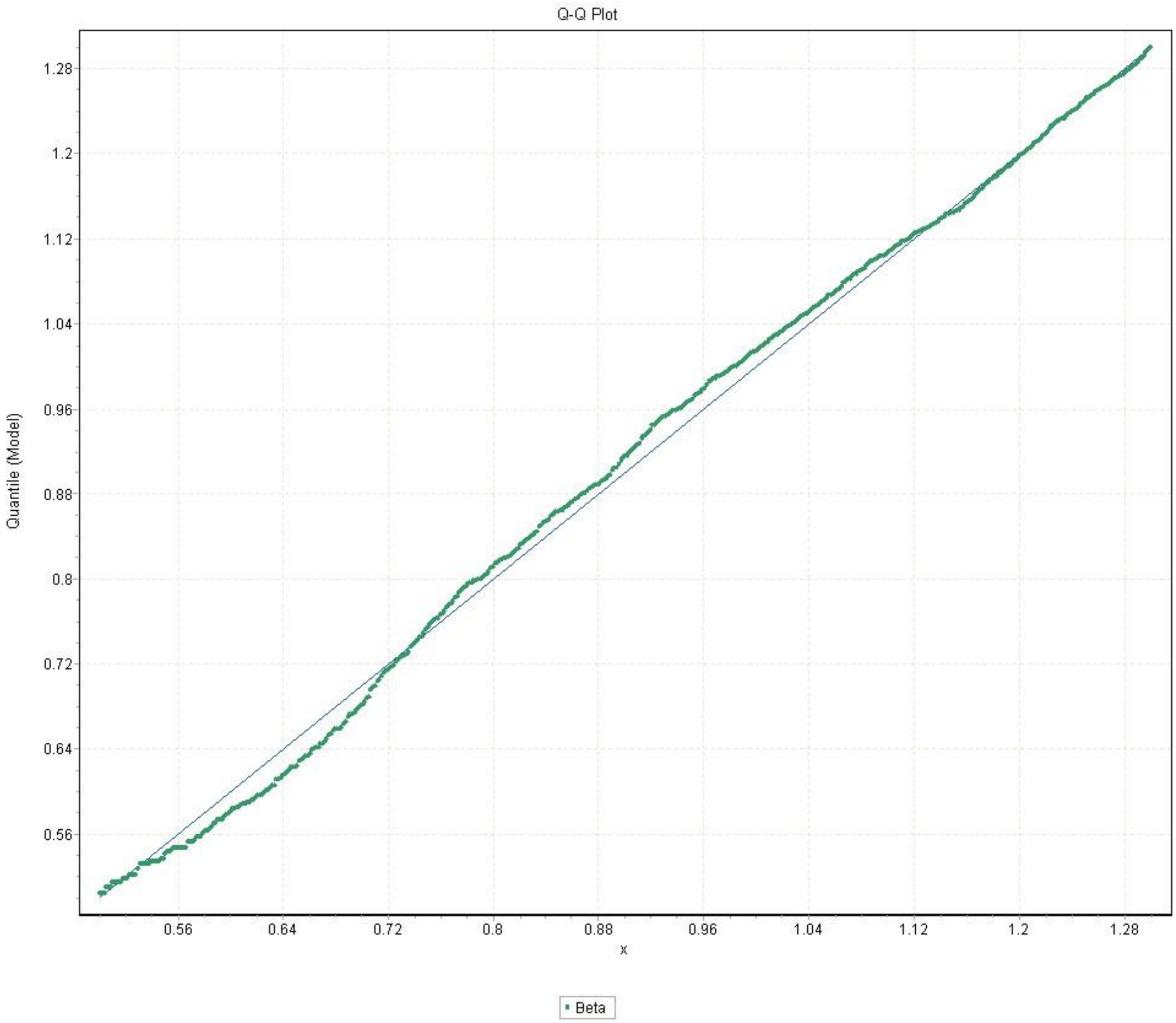

Figure C3. Quantile-Quantile Plot (α_1=1.7417, α_2=1.1613, a=0.49774, b=1.2999)

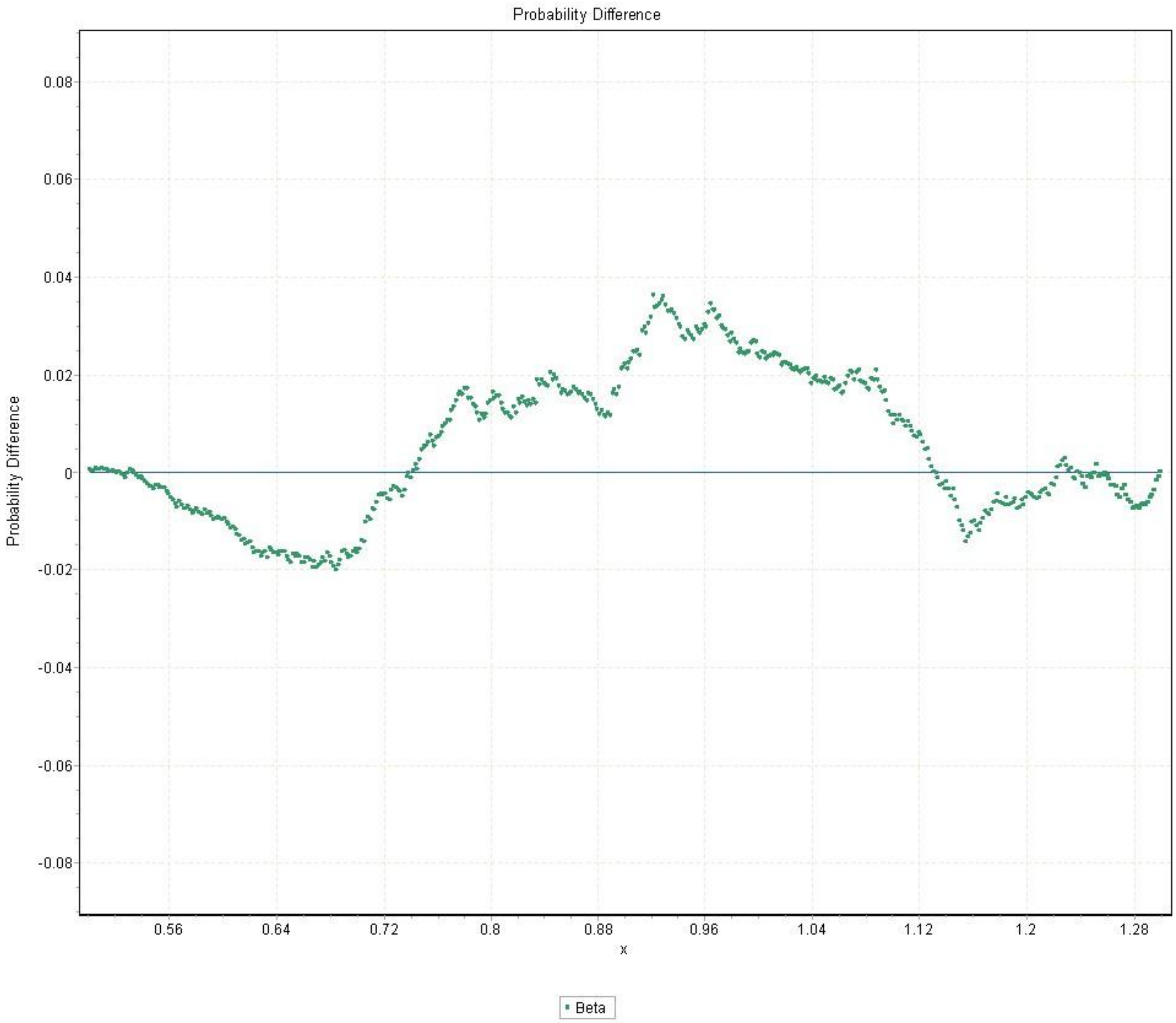

Figure C4. Probability Difference Plot (α_1=1.7417, α_2=1.1613, a=0.49774, b=1.2999)

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14. ABSTRACT
Simplified Aircraft-based Parallel Approach (SAPA) is an advanced concept proposed by the Federal Aviation Administration (FAA) to support dependent parallel approach operations to runways with lateral spacing closer than 2500 ft. At the request of the FAA, NASA performed an initial assessment of the potential performance and feasibility of the SAPA concept, including developing and assessing an operational implementation of the concept and conducting a Monte Carlo wake simulation study to examine the longitudinal spacing requirements. The SAPA concept was shown to have significant operational advantages in supporting the pairing of aircraft with dissimilar final approach speeds. The wake simulation study showed that support for dissimilar final approach speeds could be significantly enhanced through the use of a two-phased altitude-based longitudinal positioning requirement, with larger longitudinal positioning allowed for higher altitudes out of ground effect and tighter longitudinal positioning defined for altitudes near and in ground effect. While this assessment is preliminary and there are a number of operational issues still to be examined, it has shown the basic SAPA concept to be technically and operationally feasible.

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