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Advanced Interval Management (IM) Concepts of Operations

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Contents

List of Acronyms, Abbreviations, and Symbols

ADS-B	Automatic Dependent Surveillance – Broadcast
AGL	Above Ground Level
ALAS	Adjacent Landing Alerting System
ARC	Aviation Rulemaking Committee
ATC	Air Traffic Control
ATM	Air Traffic Management
ATO	Air Traffic Organization
b	Wingspan
CAS	Calibrated Air Speed
CSPO	Closely Spaced Parallel Operations
CSPR	Closely Spaced Parallel Runways
DI	Defined Interval
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FIM	Flight Interval Management
GNSS	Global Navigation Satellite System
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IM	Interval Management
IMC	Instrument Meteorological Conditions
MLS	Microwave Landing System
MRS	Minimum Radar Separation
MTOW	Maximum Takeoff Weight
NASA	National Aeronautics and Space Administration
NTZ	No Transgression Zone
OPD	Optimized Profile Descent
PFAS	Planned Final Approach Speed
PRM	Precision Runway Monitoring
RECAT	FAA’s Wake Turbulence Recategorization Program
RNP	Required Navigation Performance
SAPA	Simplified Aircraft-Based Paired Approach
SAPA-CZ	SAPA Conformance Zone
TPA	Terminal Proximity Alert
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
WTMD	Wake Turbulence Mitigation for Departures
Γ	vortex circulation
C_{l_v}	vortex-induced rolling moment coefficient
C_{L_α}	three-dimensional lift curve slope of the follower

Introduction

The ADS-B In Aviation Rulemaking Committee (ARC) has identified three Interval Management (IM)[1] applications that they feel will provide significant user benefit in the future. These applications include:

- IM for Closely Spaced Parallel Operations (CSPO);
- IM with Defined Interval (DI); and
- IM with Wake Mitigation.

The advanced IM capabilities should provide two related benefits:

- Increased capacity, and
- Increased throughput.

A runway's capacity is the upper limit on the number of operations (in this case, arrivals) that can occur in a period of time. Advanced IM will look to increase a runway's capacity by reducing the separation requirements for aircraft landing on that runway. A runway's throughput is the realized utilization and is less than the runway capacity. Advanced IM will increase a runway's throughput by precisely meeting the applicable separation standards and thereby reducing lost space due to delivery uncertainty. Both will be measured based on analysis and simulation of relevant environments.

This document provides a high-level description of several advanced IM operations that NASA is considering for future research and development. It covers two versions of IM-CSPO and IM with Wake Mitigation. These are preliminary descriptions to support an initial benefits analysis.

[1] The current FAA terminology is to call all of these operations Interval Management. NASA has continued to use the older terminology of Flight Deck Interval Management. The ADS-B In ARC used Interval Management, Flight Deck Interval Management and Ground-based Interval Management interchangeably. For consistency, this document will refer to all operations as Interval Management.

NEW IM Capabilities

Interval Management for Closely Spaced Parallel Operations

Current System

Parallel runways with centerline spacing of less than 2500 ft are defined as closely spaced parallel runways (CSPR). Simultaneous operations are authorized on these runways only under Visual Meteorological Conditions (VMC) which results in the loss of throughput when visual separations cannot be maintained (Eftekari *et al.* 2011). The Federal Aviation Administration has provided guidance on how to conduct CSPR operations (FAA Order JO 7110.308) in Instrument Meteorological Conditions (IMC). Under this order, select airports are authorized to conduct 1.5 nmi diagonally-spaced dependent ILS approaches to closely-spaced parallel runways (Figure 1). Prior to both aircraft being established on their final approach courses, standard radar separation, 1000 ft vertical or 3 nmi lateral, is required. This allows for partial recovery of VMC arrival rates in low-visibility conditions. However, for many airports with CSPR but not covered by 7110.308, the loss of visual separation results in a major reduction in capacity. To overcome the loss of throughput under IMC, several procedures have been proposed in the past. These procedures include the Unified Paired Approach (Mundra *et al.* 2008) and the Simplified Aircraft-based Paired Approach (Johnson *et al.* 2013). A modification of the Unified Paired Approach concept is being included in the Advanced Interval Management concept being developed by RTCA SC-186.

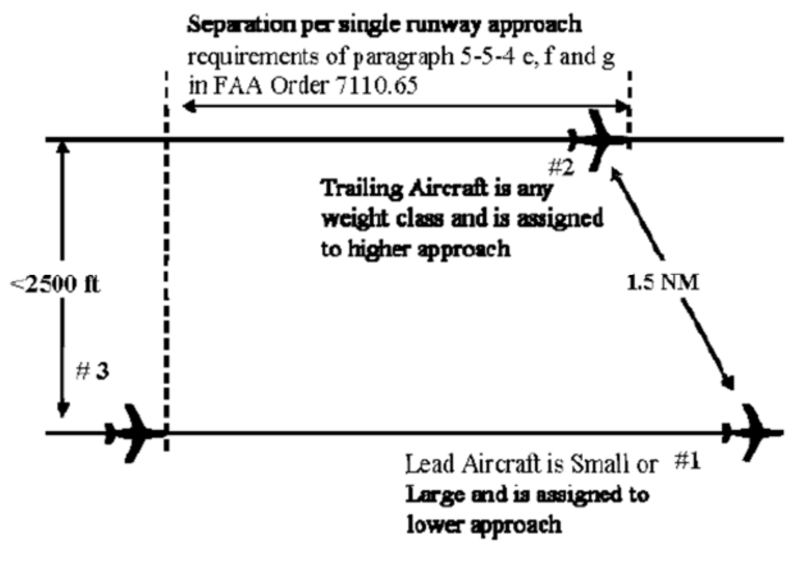

Figure 1: Top down view of parallel dependent ILS/MLS approaches (FAA Order JO 7110.308).

Simplified Aircraft-based Paired Approach (SAPA)

The Simplified Aircraft-based Paired Approach (SAPA) concept is a proposed mid-term concept for operation of closely spaced parallel runways in IMC. SAPA is designed to increase throughput 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 (e.g., San Francisco International Airport, where the lateral distance between runways is 750 ft). The target application is simultaneous, dependent operations to two or three parallel runways spaced closer than 2500 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 (Johnson *et al.* 2013).

The SAPA concept leverages advanced navigation and flight-guidance technology along with shared surveillance to minimize parallel-approach spacing requirements. By utilizing precise navigation, achieved through the use of augmented Global Navigation Satellite System (GNSS), and an advanced autopilot that can conform to RNP values of 0.02, safe IMC operations are possible at very close lateral runway spacing (Johnson *et al.* 2013; Torres-Pomales *et al.* 2014). 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 (Johnson *et al.* 2013).

During the SAPA operation, the aircraft employ onboard speed cues to maintain longitudinal alignment within the required tolerance (Johnson *et al.* 2013). Air Traffic Control (ATC) will sequence the aircraft pair in the arrival flow 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.

The SAPA concept allows one aircraft to pass the other aircraft during the approach segment. The term SAPA Conformance Zone (SAPA-CZ) will be used to describe the area where the faster aircraft may transgress. It should be noted, however, that staying within the zone does not provide blunder protection (Johnson *et al.* 2013). As shown 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 (Johnson *et al.* 2013).

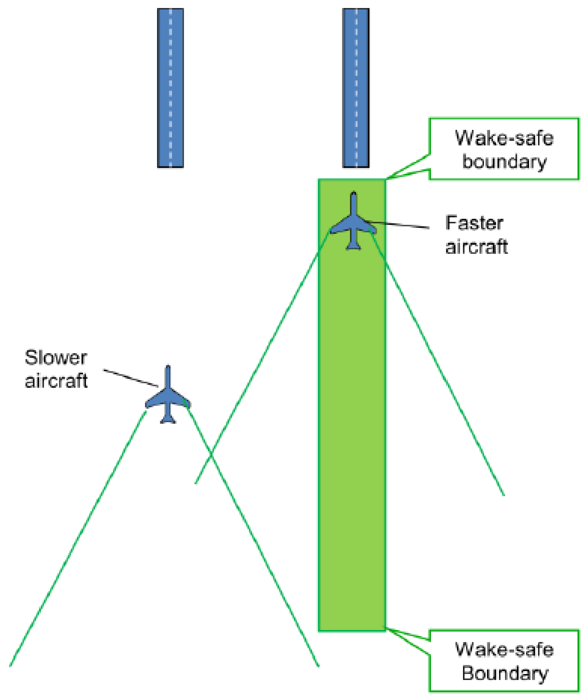

Figure 2: Simplified Aircraft-based Paired Approach (SAPA) Conformance Zone (Johnson *et al.* 2013).

Once it is known which two aircraft will be paired together and which will be the slow aircraft and the fast aircraft, the controller can issue the IM clearance. The IM Clearance is given to the fast aircraft to achieve a spacing prior to transitioning to SAPA operations. This operation makes use of the non-coincident route capability expected in the second generation FIM equipment (DO-328). For the SAPA operation, it does not matter if IM is initiated prior to top-of-descent or much closer to where the SAPA operation will begin. It is expected that the IM operation must start at least 10 nmi prior to transitioning to SAPA so that the IM aircraft can achieve the correct spacing.

The IM Achieve-by Point is on the final approach course. The aircraft should be separated by 1000 ft vertically and the assigned spacing goal within the SAPA window. The IM Operation terminates at the final approach fix; however, the SAPA guidance continues until both aircraft have touched down on the runway.

After the SAPA portion of the operation has started, the slow aircraft will maintain the last assigned speed until it reaches the FAF or the position designated in the procedure where the deceleration to the PFAS begins. At this point, the slow aircraft will decelerate to its PFAS with an assumed linear deceleration schedule such that it will reach its PFAS at a distance from the runway touchdown point corresponding to 1000 ft AGL on the glide slope (Figure 3). It will then maintain that speed until landing. If the slow aircraft is also conducting an IM Operation, it should be terminated prior to the start of this SAPA operation.

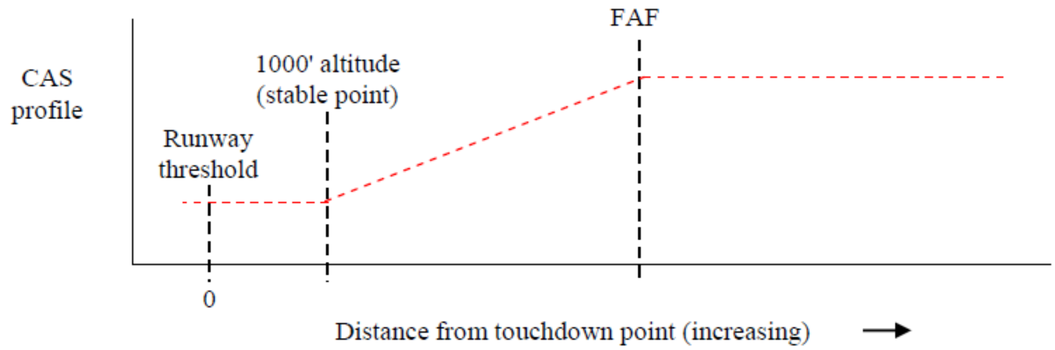

Figure 3: Generic Speed Profile for "Slow Aircraft" (Johnson *et al.* 2013).

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. After the SAPA clearance is issued, the fast aircraft will adjust its speed, which is given by the SAPA algorithm, to obtain the correct position within the SAPA-CZ. This correct position is dependent on the PFAS of both aircraft in the SAPA pair (Johnson *et al.* 2013).

Fast-time and high-fidelity simulations have shown that using the Adjacent Landing Alerting System (ALAS) algorithm, which is an alerting algorithm designed to detect intrusions on closely spaced parallel runways (Torres-Pomales *et al.* 2014), SAPA procedures may be carried out at 1050 ft separations with next-generation avionics and at 1400 ft separations with current ADS-B compliant avionics with an aggressive escape maneuver (Torres-Pomales *et al.* 2014).

This concept is closely related to the Paired Approach concept in the FAA's Advanced Interval Management Concept of Operations (FAA 2014). The main difference is that the SAPA capabilities allow for the initially trailing aircraft to pass the slow aircraft due to the advanced surveillance and navigation requirements. This increases the opportunity for a pair of aircraft to perform the operation as there are lesser requirements on the difference between the aircraft's respective PFAS.

Operational Scenario

Below is one example of how IM operations can be combined with SAPA operations.

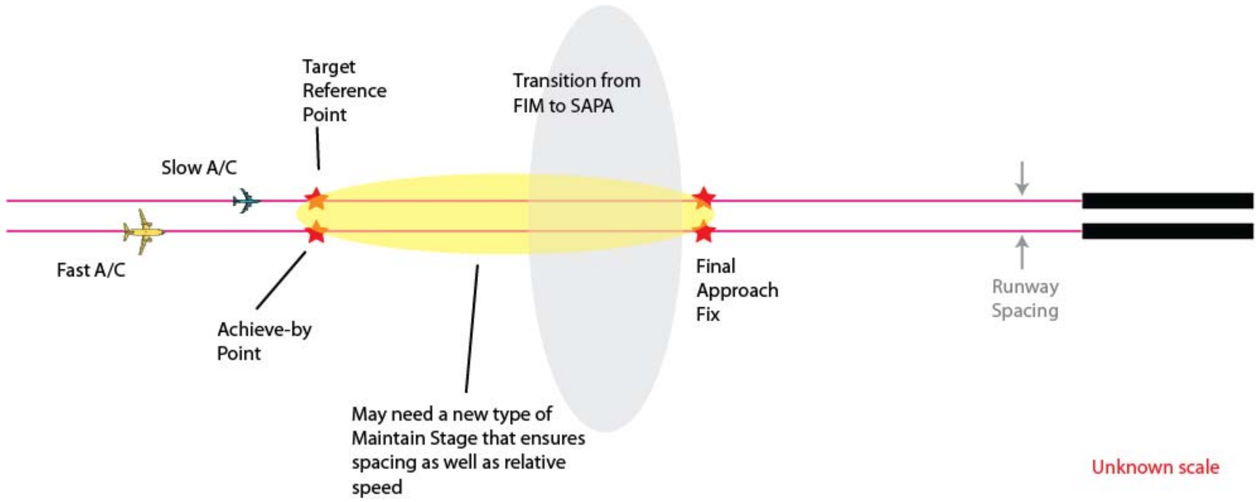

Figure 4: Schematic for FIM-SAPA Operation

When the two aircraft that will participate in the SAPA operation are about 25 nmi flight distance from the airport, the controllers are notified that they should be paired and are provided with the information to know which aircraft will be the fast aircraft. The controller for the fast aircraft issues that aircraft an IM Clearance to achieve a spacing interval relative to the slow, aka target, aircraft. The assigned spacing goal is 10 seconds (approximately 0.5 nmi). The IM Aircraft is attempting to cross the Achieve-by Point 10 seconds after the Target Aircraft crosses the Target Reference Point. The IM Aircraft then manages their speed to cross the Achieve-by Point at the proper spacing. At this point the controller is able to clear both aircraft for the SAPA procedure. Although the IM Operation is terminated at this point, the IM Aircraft continues to have speeds presented to them as part of the SAPA operation to ensure that they stay within the safe window.

Open Questions

1. Where should the Achieve-by Point be relative to initiating the SAPA operation? Does there need to be a maintain phase (on non-coincident routes) so that the two aircraft are at a common speed as well as properly spaced?
2. What is the relationship between the SAPA window and the assigned spacing goal for IM?
3. How much of the routing and special points can be inferred from the operation versus must be explicitly communicated? Does IM transitioning to SAPA require a new IM clearance type?

Interval Management for Dependent Parallel Approaches

Interval Management for Dependent Parallel Approaches enables an air traffic controller to instruct a properly equipped aircraft to achieve precise spacing relative to two other aircraft in order to increase both runway throughput and utilization of Optimized Profile Descents (OPD) when parallel dependent approaches are in use. The controller uses advanced scheduling and sequencing tools to determine the desired landing runway and sequence. This tool also provides the information that must be passed to the aircraft. The flight crew uses onboard automation that provides speed guidance to meet the controller's desired inter-aircraft spacing (Barmore *et al.*

2012). This section describes two closely related operations labeled Dependent Staggered Approaches with One Target (DSA1) and Dependent Staggered Approaches with Two Targets (DSA2) in the FAA's Advanced Interval Management Concept of Operations (FAA 2014).

For independent parallel operations to be conducted where the lateral separation between the runways is less than 9000 ft but greater than or equal to 4300 ft, a 4.8 second radar update rate is required, a designated ATC monitoring position must be in use, and a No Transgression Zone (NTZ) of 2000 ft must be displayed between the centerlines of the parallel runways on the controller radar display. For independent parallel operations occurring on runways with centerline separation between 4300 ft and 3400 ft, the aforementioned conditions must be met, with the addition that a precision runway monitoring (PRM) system must be in use. Finally, independent operations occurring on runways with down to 3000 ft centerline separation may be achieved with the aforementioned conditions, with the addition of PRM radar display with a 1 second update rate and localizers that are offset by at least 2.5 degrees (Barmore *et al.* 2012).

Independent operations on parallel approaches are often preferred as they provide generally greater throughput. Dependent operations, however, have fewer infrastructure requirements, but specific separation between the aircraft proceeding to different runways is now required. For dependent operations to runways with more than 4300 ft lateral runway separation, a minimum distance of 2 nmi must be maintained between aircraft established on parallel approaches. This is in addition to the in-trail wake separation requirements for common runway operations. For runways with lateral spacing between 2500 ft and 4300 ft, a distance of 1.5 nmi must be maintained. Again, the in-trail wake separation requirements may require greater separation (Barmore *et al.* 2012).

The upper diagram in Figure 5 shows the typical case of high-demand operations for dependent parallel runways. For a given aircraft, there is an aircraft at approximately the separation minimum directly in front of them going to the same runway and another aircraft on the parallel approach that is "in-between" the first two. In this case, the two-target operation should be used. The spacing aircraft will space to achieve the larger spacing between the two requirements (in-trail and stagger). If the same-runway leading aircraft is far enough in front of the aircraft of consideration that separation will be easily met, then a one-target stagger operation can be used (lower left diagram in Figure 5). If the aircraft on the parallel approach is further ahead than the same-runway leading aircraft (lower right diagram in Figure 5) so that the stagger separation requirement does not apply, then the typical in-trail spacing operation can be used.

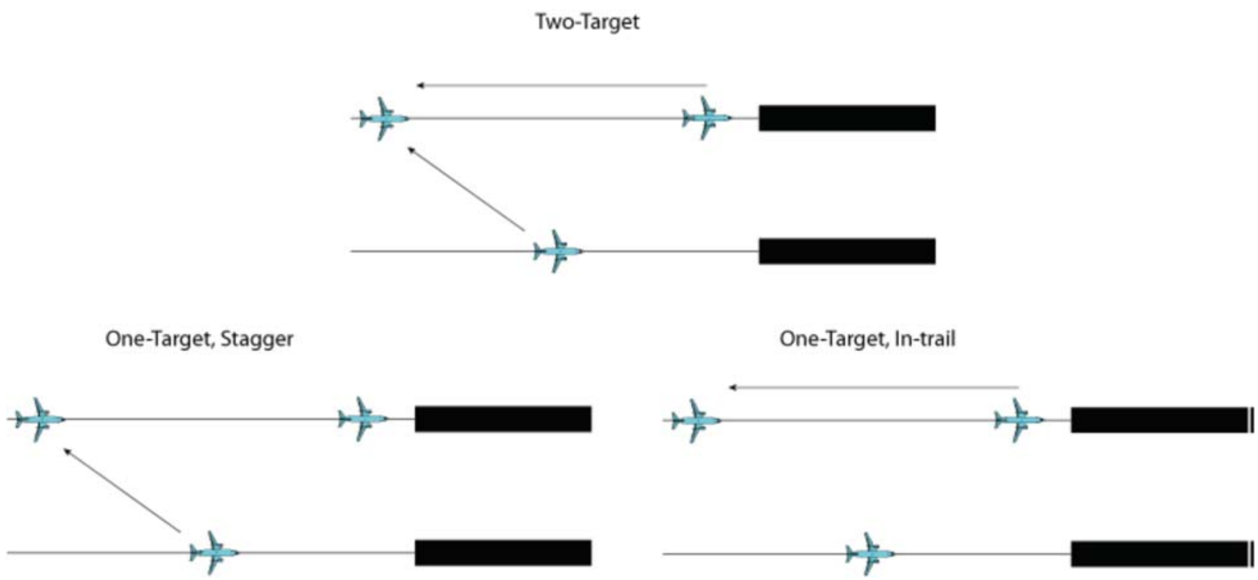

Figure 5: One-Target vs. Two-Target Dependent Parallel Airborne Spacing Operations (Smith 2012).

In two-target operations, a distinction is made between a primary target and a secondary target. When determining this, the spacing aircraft calculates a resultant spacing position for each spacing aircraft. The aircraft whose spacing interval results in a spacing position further back is defined as the primary target, while the secondary target's spacing interval results in a closer spacing position. The spacing aircraft precisely meets the spacing interval of the primary aircraft, while exceeding or meeting the spacing interval of the secondary aircraft. This is illustrated below in Figure 6 (Smith 2012).

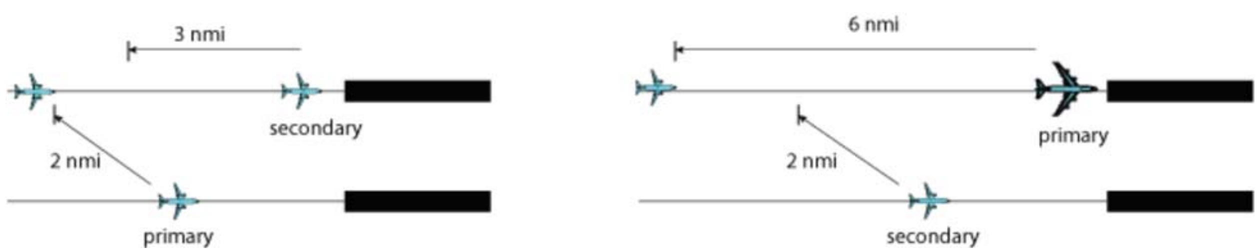

Figure 6: Primary vs. Secondary Targets while Conducting Dependent Parallel Airborne Spacing Operations (Smith 2012).

Smith 2012 found that a secondary target was a necessity in order to maintain safe separation between both the primary target aircraft and the secondary target aircraft. These violations occurred specifically because the spacing between an aircraft and its secondary target was not being monitored. As well, it was observed that the addition of a secondary target did not appear to change the stability of the operations.

Operational Scenario

As previously mentioned, Smith concludes that, for safety reasons, if dependent parallel operations are conducted while using Interval Management, the aircraft performing the spacing must monitor both a primary and secondary target. In the example scenario, see Figure 7, the

scheduling and sequencing automation tools determines that aircraft J must actively monitor and perform dependent spacing operations on aircraft I and aircraft H. In this scenario, the controller provides a clearance to aircraft J to achieve 130 second spacing behind aircraft H and to achieve 2.2 nmi spacing from aircraft I (Barmore e al. 2012). Although the clearance is given in terms of distance, this clearance could have also been given in terms of time.

The crew would acknowledge the receipt of the clearance and enter this information into the flight deck automation equipment. An IM speed is presented to the crew, who will follow the speed guidance. The speeds given to the crew will satisfy the greater separation distance between the two targets (i.e., the speeds given will satisfy achieving spacing behind the primary target). In this example, the primary target for aircraft J is aircraft H (Barmore *et al*. 2012).

If aircraft J only required spacing of 90 seconds behind aircraft H and 2.2 nmi behind aircraft I, then aircraft I would be the primary target, and speeds would be given to the flight crew that satisfy the 2.2 nmi spacing from aircraft I (Barmore *et a*l. 2012).

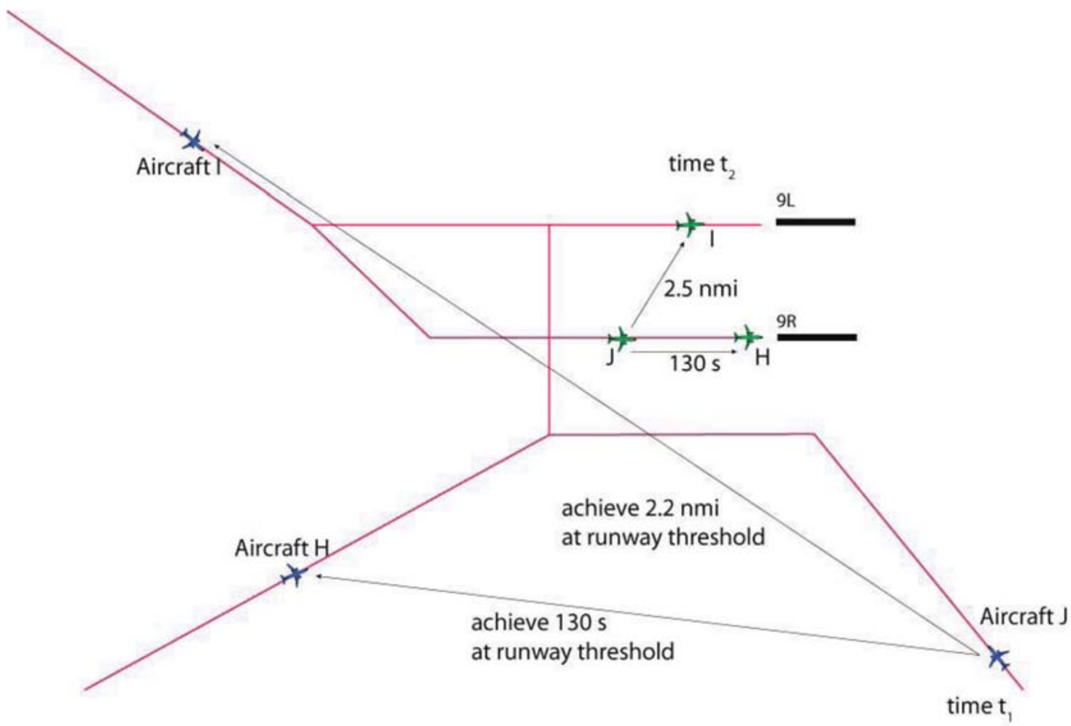

Figure 7: Schematic of two-target dependent parallel airborne spacing operation. The spacing clearance is issued at time t1 (blue aircraft). Time t2 (green aircraft) shows the relative positions when the first target (aircraft H) reaches the runway threshold (Barmore *et al.* 2012).

Interval Management with Wake Mitigation

Current System

A brief description of the current wake separation standards and newly introduced wake vortex separation rules is given in this section.

Under the current FAA regulations, the Air Traffic Control imposes wake spacing standards for IFR aircraft based on maximum certified takeoff weight (FAA AC 90-23G). The separation standards and weight categories are listed in Tables 1-2. Although B757 is in the large weight category, a special wake separation standard has been set for it.

Table 1: FAA Wake Separation Standards (At the Threshold)

		Follower (Nautical Miles)				
		Super	**Heavy**	**B757**	**Large**	**Small**
Leader	**Super**	MRS	**6**	**7**	**7**	**8**
	Heavy	MRS	**4**	**5**	**5**	**6**
	B757	MRS	**4**	**4**	**4**	**5**
	Large	MRS	MRS	MRS	MRS	**4**
	Small	MRS	MRS	MRS	MRS	MRS

MRS = Minimum Radar Separation

Table 2: Aircraft Weight Classes

Category	Weight
Heavy	MTOW ≥ 300,000lbs
Large	41,000lbs < MTOW < 300,000
Small	MRS ≤ 41,000lbs

The "super" category has been approved on an interim basis and at present consists of two aircraft – Airbus A380 and Antonov AN225.

To alleviate the capacity constraints imposed by the current wake separation standards, the FAA has suggested a phased approach to re-categorize the standards. FAA's Wake Recategorization Program consists of three implementation phases:

- RECAT-I Static Six Category Separation
- RECAT-II Static Pair-wise Separation
- RECAT-III Dynamic Pair-wise Separation

New wake separation standards under RECAT-I (Tables 3-4) were recently introduced and are described in FAA Order N JO 7110.608. These standards are based on aircraft dynamics parameters (wingspan, final approach speed, and roll moment capability) in addition to the maximum takeoff weight (MTOW). The effort also took into account the traffic mix at five US airports (Atlanta, Newark, John F. Kennedy, Chicago O'Hare, and San Francisco) and four European airports (Heathrow, Amsterdam, Frankfurt, and Charles de Gaulle) to further optimize the re-categorization. Enhancements to Terminal Proximity Alert (TPA) software are also underway to aid controllers.

RECAT-I has been implemented at four airports: Memphis International Airport and Louisville International Airport. Implementation at other airports (Cincinnati, Miami, and Charlotte) is planned and work is underway on RECAT-II which is expected to go into effect by 2016.

Table 3: RECAT-I Wake Separation Standards

Leader	Follower (Nautical Mile)					
	A	**B**	**C**	**D**	**E**	**F**
A	MRS	**5**	**6**	**7**	**7**	**8**
B	MRS	**3**	**4**	**5**	**5**	**7**
C	MRS	MRS	MRS	**3.5**	**3.5**	**6**
D	MRS	MRS	MRS	MRS	MRS	**5**
E	MRS	MRS	MRS	MRS	MRS	**4**
F	MRS	MRS	MRS	MRS	MRS	MRS

MRS = Minimum Radar Separation

Table 4: RECAT-I Weight Categories

Category	Weight	Wingspan
A	MTOW ≥ 300,000lbs	$b > 245$ft
B	MTOW ≥ 300,000lbs	175ft $< b \leq$ 245ft
C	MTOW ≥ 300,000lbs	125ft $< b \leq$ 175ft
D	MTOW < 300,000lbs	125ft $< b \leq$ 175ft
	or aircraft with: 90ft $< b \leq$ 125ft	

E	MTOW > 41,000lbs	65ft < $b \leq$ 90ft
F	MTOW < 41,000lbs	$b \leq$ 125ft
	or aircraft capable of a MTOW less than 15,500lbs regardless of wingspan, *or* a powered sailplane	

Wake Turbulence Mitigation for Departures (WTMD) is another recently introduced rule that allows reduced separation behind Heavy/B757 for CSPR operations (FAA Order JO 7110.316). WTMD depends on current and forecasted weather conditions and allows runways to operate as wake independent from Heavy/B757 under favorable crosswind conditions (Figures 8-9).

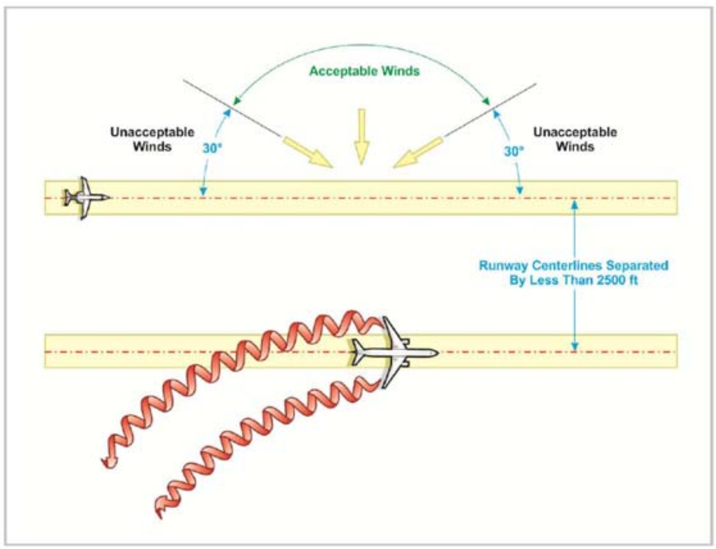

Figure 8: Transport of wake due to crosswinds (FAA AC 90-23G).

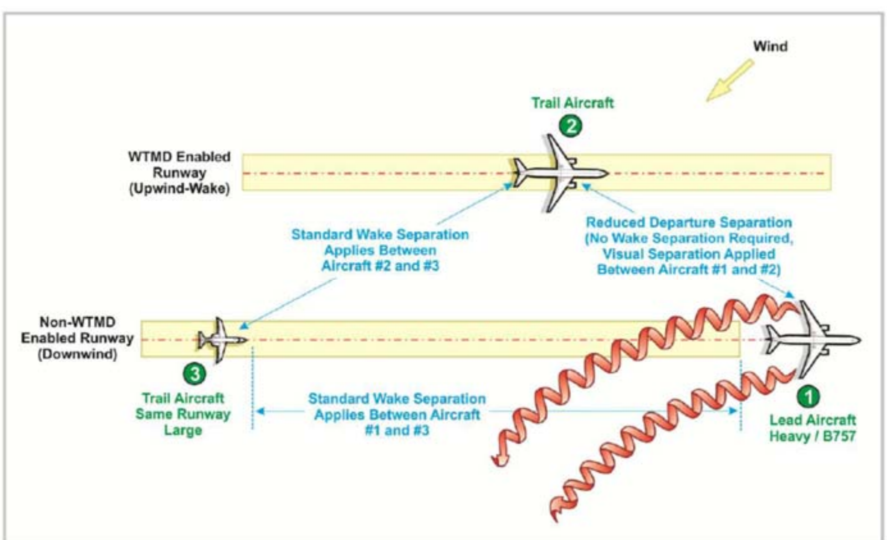

Figure 9: Reduced separations under WTMD (FAA AC 90-23G).

Justification for Change

Wake vortex based separation standards are a major constraint to the airspace capacity. A reduction in wake spacing standards while maintaining the current levels of operational safety will substantially improve the efficiency and capacity of the NAS. A wake-informed IM procedure can further increase the traffic throughput.

New Concept

As aircraft approach an airport, a scheduling tool in the ground automation predicts the expected wake separation distance needed and schedules the aircraft appropriately. Standard Interval Management operations are then used to allow the aircraft to space precisely at the predicted wake separation requirement. Supporting the ground scheduling tool is a real-time wake modeling tool. Dynamic wake separation standards can be set based on wake models (Proctor 2009; Robins *et al.* 2001; Ahmad *et al.* 2014). The following steps lead to the scheduling of the aircraft:

1. Weather forecast (approximately one hour in advance) for providing environmental initial conditions to the fast-time wake models. These initial conditions include crosswinds to predict the transport of the wakes and the level of ambient atmospheric turbulence and stratification to predict the decay of wake vortex circulation strength (Γ).

2. Calculation of an aircraft response metric (e.g., C_{l_v}, the vortex-induced rolling moment coefficient) based on wake circulation strength.

3. Estimation of time/distance separation between aircraft pairs based on the model output.

4. The scheduler uses the model-based time separation estimates to schedule aircraft in its queue.

Figure 10 shows the flow of information needed by the scheduler. The scheduler requires aircraft data (route, weight, aircraft type, and planned final approach speed), and surveillance data to set up the queue and issue the FIM clearance constrained by the airport acceptance/departure rate. In the new concept, an additional static aircraft database is required that includes estimates of characteristics such as wingspan, and the three-dimensional lift curve slope (C_{L_α}).

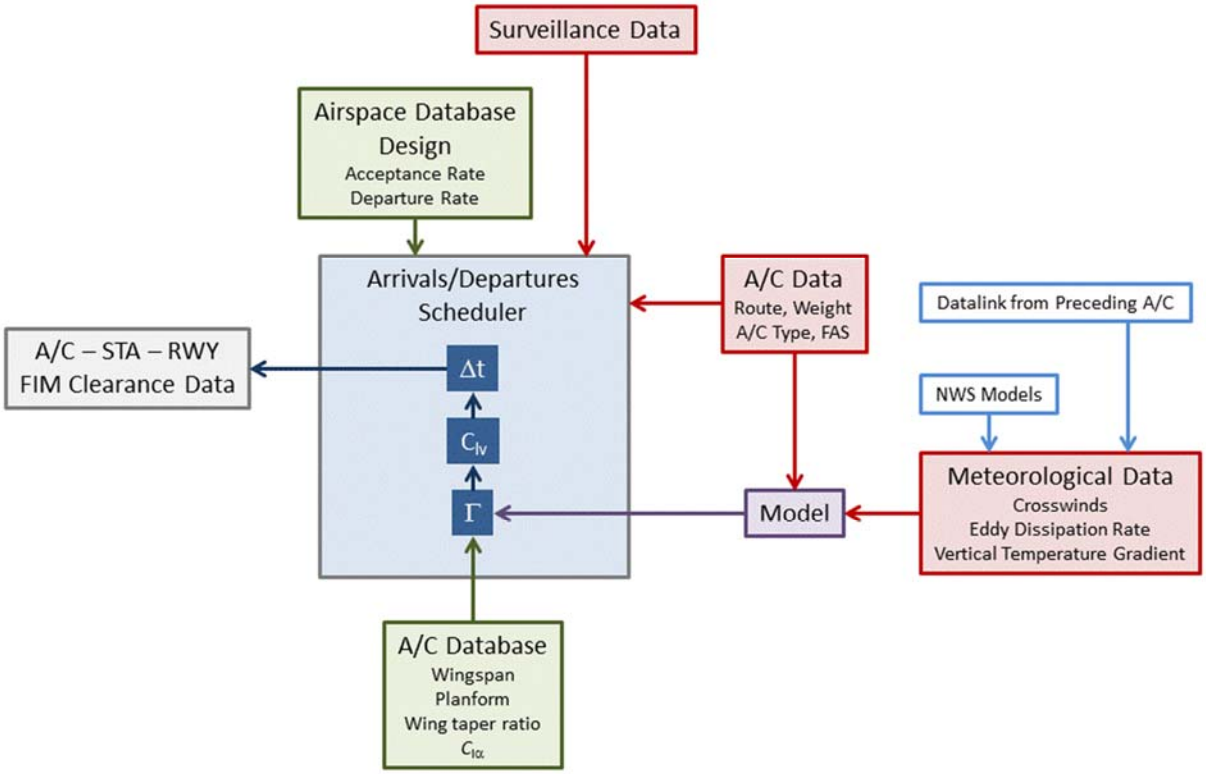

Figure 10: Modeling-based dynamic wake separation. The fast-time models prediction of wake transport and circulation decay based on weather forecast is used to set the wake separations.

Meteorological forecast data for the terminal area will be needed approximately one hour in advance to initialize the wake models. This data can be provided by the National Weather Service (NWS) model forecasts. Additional meteorological data can be obtained via datalink from preceding aircraft landing/departing from the airport. The wake models will take the aircraft information (route, weight, true airspeed) and the meteorological forecast to predict the circulation decay. The scheduler will estimate wake hazard based on an aircraft response model (e.g., vortex-induced rolling moment coefficient, C_{lv}) from the wake model prediction and update the queue which optimally should result in a time compression. The queue is updated at the freeze horizon (30-45 min in advance) based on the wake information. A real-time wake warning sensor can be deployed initially to build confidence in the system. For example, pulsed lidars can provide estimates of crosswind, turbulence and wake circulation strength.

Operational Scenario

Figure 11 shows an operational scenario. Aircraft B follows Aircraft A in the scheduler queue. The separation distance for Aircraft B is 5 nmi. Based on the wake model forecasts it is predicted that this distance can be reduced to 4.5 nmi. Similar updates are made for all aircraft pairs in the queue resulting in a time compression while maintaining the constraints imposed by the airport/airspace design such as the acceptance/departure rates. The scheduler update is done 30-45 min in advance at the freeze horizon. Information from the real-time wake warning system is used to update the queue again at 15 min to take into account observed differences from the forecast.

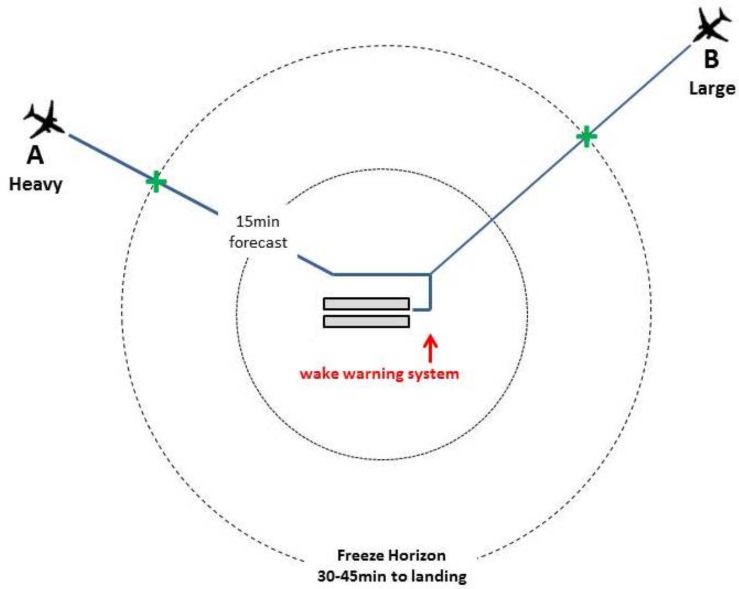

Figure 11: A weather forecast of 30-45min in advance will be required by the scheduler to queue aircraft based on dynamic wake separations.

Open Questions

Implementation would need to address the following questions:

- Given the current accuracy/reliability of weather forecasts (time window is approximately 1hr), what is the feasibility of the proposed method?
- What are the computational constraints, if any? A computationally feasible method might require building look-up tables based on models and measurements for characterizing wake decay and transport under varying atmospheric conditions instead of running the models.
- Availability of aircraft dependent parameters, e.g., C_{L_α} for the aircraft response module. Can these parameters be approximated with reasonable accuracy from data available in open literature?
- Current state-of-the-art in wake sensing technology for deploying a real-time wake warning system. Pulsed lidars can provide estimates of crosswinds, eddy dissipation rates and wake vortex circulation strength. The processing of raw lidar data for estimating wake circulation strength is computationally intensive.

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This document provides a high-level description of several advanced IM operations that NASA is considering for future research and development. It covers two versions of IM-CSPO and IM with Wake Mitigation. These are preliminary descriptions to support an initial benefits analysis.

15. SUBJECT TERMS

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