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A Concept for Airborne Precision Spacing for Dependent Parallel Approaches

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Abstract

The Airborne Precision Spacing concept of operations has been previously developed to support the precise delivery of aircraft landing successively on the same runway. The high-precision and consistent delivery of inter-aircraft spacing allows for increased runway throughput and the use of energy-efficient arrivals routes such as Continuous Descent Arrivals and Optimized Profile Descents. This paper describes an extension to the Airborne Precision Spacing concept to enable dependent parallel approach operations where the spacing aircraft must manage their in-trail spacing from a leading aircraft on approach to the same runway and spacing from an aircraft on approach to a parallel runway. Functionality for supporting automation is discussed as well as procedures for pilots and controllers. An analysis is performed to identify the required information and a new ADS-B report is proposed to support these information needs. Finally, several scenarios are described in detail.

Introduction

One of the major keys to airport landing rate efficiency is the ability to manage the longitudinal aircraft-to-aircraft spacing during the arrival and approach. While several new concepts and technologies are currently being developed and evaluated to further enhance Air Traffic Control's (ATC) ability to accurately deliver arriving aircraft to the runway threshold, including NASA's Airborne Precision Spacing (APS) concept (refs. 1-3), these concepts have primarily focused on aircraft landing on the same runway. There are numerous airports, however, that routinely conduct parallel approach operations. Depending upon the airport layout, surveillance infrastructure and controller staffing, different types of operations can be performed on the parallel approaches. Under some situations, described in more detail in the Concept Overview section, arrivals to one parallel runway are dependent upon arrivals to the other. The ability to support ATC in the precision spacing of aircraft that are performing dependent parallel operations is the focus of NASA's next generation adaptation of its APS concept.

Beyond the requirement to track two Target Aircraft instead of just one, there are several challenges in developing an airborne system that accommodates dependent parallel approach operations. First, the airborne spacing tool must be able to compensate for runway threshold offsets. If the runway thresholds are not aligned, then the desired spacing interval relative to the landing runway must be adjusted to obtain the correct aircraft-to-aircraft longitudinal spacing to account for the difference in the longitudinal runway threshold distances. Second, the standard ATC longitudinal separation minimums change for parallel approach aircraft once both aircraft are on their respective final approach paths. In the U.S., the 3 nmi separation between aircraft within terminal airspace is reduced to either 1.5 or 2 nmi separation between aircraft on dependent parallel approaches, with the specific diagonal distance dictated by the distance between the two parallel runways. Assuming that spacing is desired against both common-

runway and parallel-runway Target Aircraft, then the airborne spacing system must determine which aircraft it is actually spacing against. In all spacing conditions noted to date, this determination is based on which of the two spacing requirements results in the greater longitudinal distance since it is operationally better to be too far from than too close to another aircraft. Being too far behind results in reducing the actual throughput from the theoretical maximum while being too close could result in separation violations and a reduction in safety.

Airborne Precision Spacing is a specific operational application of the class of spacing applications called Interval Management (IM). In addition to the work on APS, there is much work being done to develop IM operational applications and define standards and requirements. Where appropriate, this document uses the language captured in the Safety, Performance and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management (ref. 4).

Definitions

Active Target Aircraft – the Target Aircraft that is driving the currently presented IM speed. When spacing guidance is being provided relative to two Target Aircraft, PDS will determine which Target Aircraft provides the most stringent requirements and use that for the IM speed command.

Airborne Precision Spacing (APS) – the operational concept where a properly equipped aircraft is instructed by the air traffic controller to achieve a spacing interval relative to one or two other aircraft at the runway threshold. There is no guarantee that the interval will be met prior to the threshold; however, the crew should conform to the spacing instruction or notify the controller of their inability to conform to the instruction.

Assigned Spacing Goal – the ATC-assigned interval between aircraft to be achieved at the runway threshold. Can be given in time or distance.

Automatic Dependent Surveillance – Broadcast (ADS-B) – a technology that automatically and periodically broadcasts the aircraft’s current position, velocity and other data to receivers on the ground or other aircraft.

IM Aircraft – an aircraft that is performing the airborne spacing (interval management) operation.

IM Speed – the speed presented by the PDS system to the flight crew.

Ownship – the aircraft being flown by the flight crew. In this document, it is the aircraft receiving the spacing clearance from ATC.

Pair Dependent Speed (PDS) – an onboard system, including automation and crew interfaces, that supports the crew in conforming to a spacing instruction. The PDS system calculates the airspeed required to achieve the assigned spacing goal using the required time of arrival, forecasted and sensed winds, and planned routing and final approach speed of the Target Aircraft and of the ownship.

Required Time of Arrival (RTA) – the time at which an aircraft is assigned to arrive at the

runway threshold. The RTA is used by PDS as an arrival goal time when there are no Target Aircraft within ADS-B range.

Target Aircraft – any aircraft that the spacing operation is performed against.

Concept Overview

Airborne Precision Spacing 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.

The main goal of APS is to enable high throughput operations when both single runway and dependent parallel runway operations are in use. The main benefits of APS are expected to be seen when there is high demand for the airport resources. By precisely controlling the spacing between landing aircraft, APS can be used to maximize runway utilization. The use of APS can also enable energy-efficient arrivals such as OPD, Continuous Descent Arrivals (CDA), and Green Arrivals by providing small speed changes that keep the aircraft close to the preferred descent profile (speed and vertical path) while actively managing the spacing between the aircraft. Another goal of APS for Dependent Parallel Approaches operations is to manage, prior to both aircraft being on final approach, the along track spacing so that vertical separation techniques between arriving aircraft are not needed as these tend to decrease the efficiency gains of the energy-efficient arrivals.

The focus of the current work is on dependent parallel runway operations. However, it is expected that this concept of operations could be expanded to work for other types of dependent runway operations.

Parallel runway approaches where the runway lateral separation is less than 9000 ft but greater than or equal to 4300 ft can be treated as independent if the following conditions are met:

- a 4.8 second radar update is available;
- a designated ATC monitoring position is in use; and
- a 2000 ft No Transgression Zone is displayed between the centerlines on the controller radar display.

Parallel runway approaches with lateral separation between 4300 ft and 3400 ft, may be treated as independent if the above conditions are met plus:

- a Precision Runway Monitor (PRM) system is in use.

Independent operations may be used down to 3000 ft runway lateral separation with the addition of:

- a 1 second update PRM radar with display; and
- localizers offset by at least 2.5°.

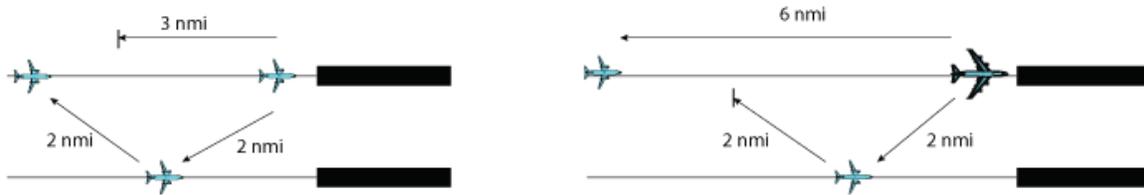


Figure 1: Placement of aircraft based on parallel approach and in-trail separation requirements.

Independent operations on parallel approaches are often preferred as they provide generally greater throughput. Dependent operations 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. The left side of Figure 1 shows the case where the in-trail wake separation requirement is less than consecutive separation distances for the parallel approaches. The right side shows the case where the in-trail wake separation is greater than the consecutive separation distances for the parallel approaches.

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.

Since APS is a spacing concept where the controller retains responsibility for detecting and correcting possible separation violations, a 0.2 nmi buffer was added to the separation requirement to allow the controller time to react. The exact value of this buffer has not been determined and would depend upon controller experience, the reliability of the APS equipment, and any monitoring and alerting system available to the controller. The value of this buffer has no material effect on the concept but would affect the available benefits of performing APS operations.

Although the goal of this concept is to allow simultaneous OPDs to dependent parallel approaches, the separation requirements on final approach are not the only constraint. Prior to both aircraft being established on their final approach courses, the normal 3 nmi lateral separation or 1000 ft vertical separation must be maintained. Requiring vertical separation at the turn onto final approach course would require one of the two aircraft to intercept the final approach course at least 1000 ft below the OPD altitude. This would require a low-altitude, level flight segment which is counter to the efficiency objectives of an OPD. Such level-flight segments use much more fuel and create more noise than the OPD segment. Therefore, vertically separating the aircraft is undesirable.

Figure 2 shows the expected lateral distance between aircraft, blue circles and green triangle, as the trailing aircraft turns onto the final approach course. The respective goal at the runway threshold is shown by the blue and green lines. The calculations are for the aircraft flying 200 kt at the turn onto final and a final approach speed of 135 kt. For runways separated by more than 3200 ft, the trailing aircraft would have to violate the 3 nmi separation standard prior to turning on to final in order to achieve the desired spacing of 1.7 nmi or 2.2 nmi. Figure 3 shows the achievable spacing relative to the aircraft on the parallel approach when the separation at the turn onto final approach course, 3.2 nmi, is used as the delivery constraint. For runways separated by between 2500 ft and 4300 ft, the achievable spacing is very close to what the expected spacing goal would be (2 nmi separation requirement plus a 0.2 nmi buffer). For runways separated by more than 4300 ft, the achievable spacing is at least 0.5 nmi greater than desired (1.5 nmi separation requirement plus the 0.2 nmi buffer). Therefore, for runways separated by greater than 4300 ft, either OPD benefit must be reduced to allow for vertical separation prior to both aircraft being established on their final approach courses, or potential throughput is lost to ensure lateral separation prior to both aircraft being established on their final approach courses. Which choice is more beneficial requires specific knowledge of the operating environment and the OPD design.

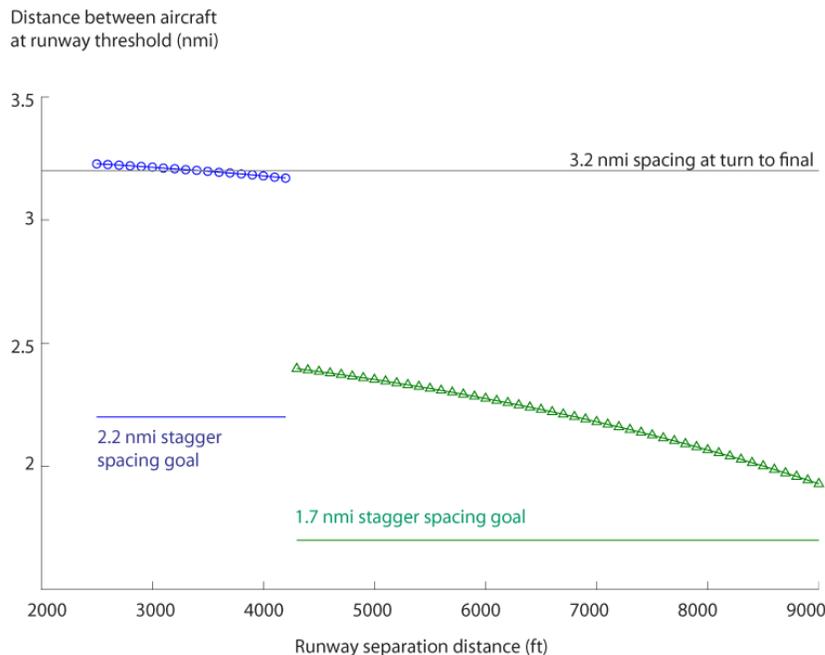


Figure 2: Distance between aircraft when the trailing aircraft turns onto its final approach course when achieving the minimum spacing for the parallel approach at the runway threshold.

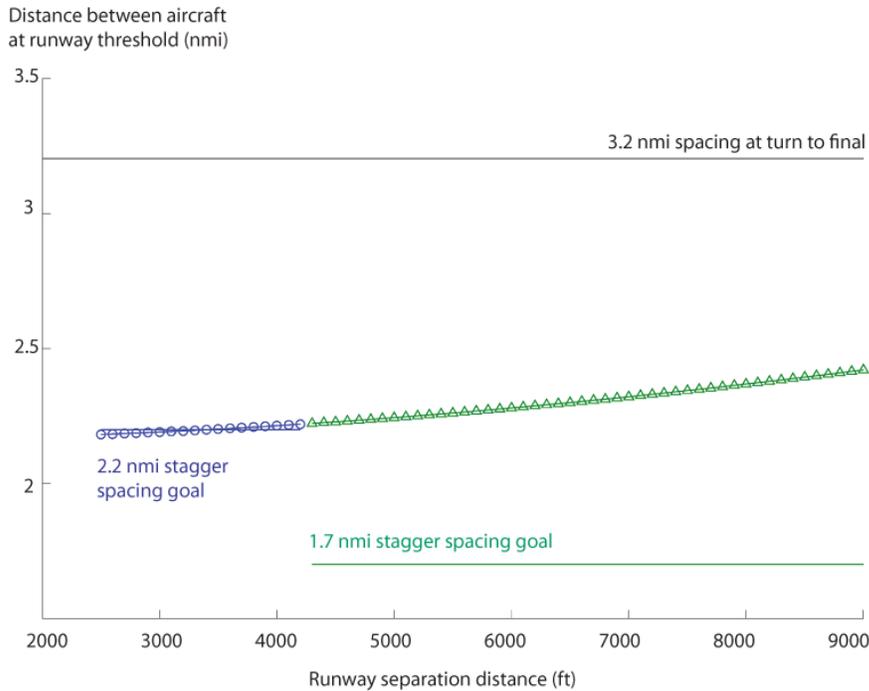


Figure 3: Achieved spacing at the runway threshold when lateral separation is applied when the trailing aircraft turns onto its final approach course.

To support the use of APS, a new onboard guidance system has been developed called Pair-Dependent Speed (PDS). PDS allows for the selection of two Target Aircraft and associated spacing goals and provides IM speeds to achieve the tightest spacing possible that is consistent with the spacing goals.

APS Assumptions and Expectations

This concept of operations is based upon the following fundamental assumptions and expected behavior. Changes to these assumptions and expectations would likely lead to changes to the human-machine interfaces, data exchange, or procedures. Assumptions capture the assumed infrastructure and capabilities available to support APS. The expected behaviors section captures the behaviors and actions of the controller and flight crew from which the procedures are developed.

Assumptions

- An IM Aircraft can have only one active spacing clearance. The identification of a second Target Aircraft is an amendment to the spacing clearance and not a separate clearance.
- The assigned spacing goal behind an aircraft proceeding to a parallel runway is given in distance, and is based upon the distance between runway centerlines.
- The assigned spacing goal behind an aircraft to the same runway is given in time, and is based upon the weight category of both aircraft and the forecasted winds.

- Information to build a four-dimensional (4D) trajectory for the Target Aircraft, including route and planned final approach speed, is available via ATC voice radio communication, an on-condition ADS-B report, or Controller Pilot Data Link Communications (CPDLC).
- APS status information is broadcast via a new on-condition ADS-B report and is available to the controller for monitoring. [Note: A proposal for this report is made in the section “New ADS-B Message.”]
- ATC uses a scheduling and sequencing tool to provide a feasible arrival sequence for the pair of runways, and sufficient spacing between aircraft to meet all separation requirements (wake vortex, dependent parallel operations, etc).
- At some point prior to starting spacing operations, the schedule and sequence are frozen. Once the spacing operations have started, further modifications to the sequence are considered undesirable.
- The scheduling and sequencing tool provides the controller with the information that must be passed to the flight crew as part of the spacing clearance including Target Aircraft identification, assigned spacing goals and a Required Time of Arrival (RTA) at the runway threshold.
- The PDS system will provide IM speeds to achieve the RTA until sufficient surveillance information is available for at least one Target Aircraft. At that point, the PDS system will provide IM speeds to achieve the assigned spacing goal.
- Information is made available to the flight crews through the Automatic Terminal Information Service (ATIS) or other methods that parallel approach operations and spacing operations are in effect at the airport.

Expected Behaviors

- The controller issues the initial spacing clearance prior to the aircraft’s top of descent. If needed, amendments may occur later in the operation.
- The controller includes at least the Target Aircraft identification, the assigned spacing goal, and an RTA.
- The controller includes a second Target Aircraft only if it is operationally relevant.
- The controller issues navigation clearances that are complete paths to their respective runway thresholds for all participating aircraft prior to initiating the spacing operations.
- The flight crew will follow the IM speed in a timely manner.

PDS Guidance Modes

The PDS system has five internal modes that determine how the IM speed is calculated. Depending on the circumstance, some modes may transition to others. A state diagram is included in Figure 4.

PROFILE

- is active only when explicitly selected
- provides IM speeds that exactly match the published speeds on the intended route
- does not deviate from the published speeds to achieve an RTA or spacing interval

RTA

- is active when RTA-only is selected
- is active at initiation of a spacing operation if the Target Aircraft data are not valid
- provides IM speeds to achieve the RTA at the runway threshold

PAIRED

- is active when a Target Aircraft is selected and that aircraft's surveillance data are received and are valid
- provides an IM speed to achieve the assigned spacing goal relative to the Target Aircraft at the runway threshold

FINAL

- is active when the aircraft must start its final deceleration to ensure a stabilized approach within the specified constraints
- provides IM speed that matches the planned final approach speed

SPEED REVERSION

- is a fail-safe mode if PDS is unable to provide a valid IM speed
- provides the lesser of the published speed and last IM speed if the target data become invalid
- provides the last IM speed if the ownship data becomes invalid.

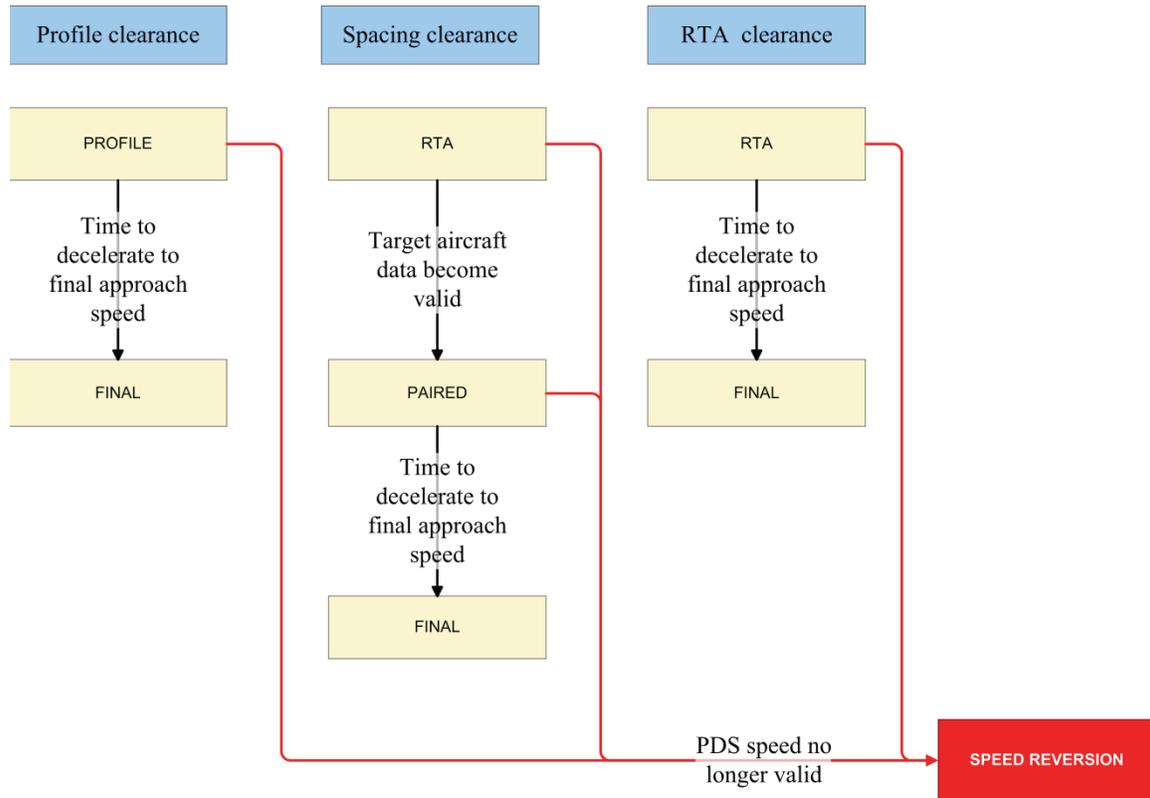


Figure 4: State logic diagram for PDS.

Operational Sequence of Events

A typical spacing operation consists of the following sequence of events:

1. As aircraft approach the destination airport, an arrival sequence of aircraft to the airport is generated by the controller's automation. This includes runway and arrival route assignments and scheduled times of arrival to the runways. An aircraft is added to the sequence approximately 60-90 minutes prior to landing.
2. The controller's automation fixes the arrival sequence and runway assignment of a particular aircraft approximately 20 minutes prior to the aircraft's top of descent.
3. ATC issues an arrival clearance.
4. ATC decides to use airborne spacing operations for an aircraft.
5. ATC issues clearance(s) for airborne spacing. There are three types of airborne spacing clearance that can be given:
 - Standard Profile – Aircraft uses PDS to fly the published profile. No additional

information is needed¹.

- Pair-wise Spacing – Aircraft uses PDS to achieve a pair-wise interval at the runway threshold. This is the expected operational mode of PDS. The controller must include the Target Aircraft identification (ID), the assigned spacing goal and type, and an RTA in the clearance.
 - Required Time of Arrival – Aircraft uses PDS to achieve a required time of arrival at the runway threshold². ATC includes an RTA in the clearance.
6. Crew enters the spacing clearance data into PDS.
 7. PDS calculates the IM speed.
 8. PDS provides feasibility feedback to the flight crew.
 9. Crew accepts or rejects the IM clearance from ATC.
 10. If accepted, the crew implements IM speed. If rejected, the crew continue flying the current speed.
 11. The crew actions for IM operations are:
 - fly the arrival procedure and monitor for conformance;
 - fly the IM speed;
 - notify ATC once PDS couples to each of the Target Aircraft; and
 - monitor PDS for notifications or alerts.
 12. ATC actions during IM operations are:
 - provide separation assurance from all traffic;
 - terminate IM if required; and
 - identify additional Target Aircraft, if needed (repeat steps 5-8, excluding the RTA).
 13. ATC issues descent clearances as able.
 14. When necessary, the controller hands off aircraft to the next sector controller along with information on the clearance and spacing status. This information could include the IM

¹ This would be very similar to the flight crew following published procedure as in current-day operations. The added benefit of using PDS is that the flight crew would receive guidance to achieve a stabilized approach.

² PDS uses the same trajectory calculation and speed logic to meet an RTA as to do pair-wise spacing. This capability allows RTAs to the runway threshold regardless of Flight Management System capability.

Aircraft ID, the Target Aircraft ID, the assigned spacing goal and type, and other operationally relevant information.

15. Crew and ATC manage off-nominal events.
16. Controller issues approach clearance.
17. Controller issues landing clearance.
18. PDS transitions to FINAL mode and ends active spacing guidance.
19. Procedure terminates at the runway threshold.

Spacing Initiation Criteria

In order to initiate APS, the criteria listed in Table 1 must be met. These criteria would be applied independently to both Target Aircraft if two Target Aircraft are to be used.

Table 1: APS Initiation Criteria.

Criteria	Justification
IM Aircraft and Target Aircraft runway assignments are fixed.	Needed to support assignment of arrival and approach procedures to the runway.
IM Aircraft and Target Aircraft are cleared for published arrivals that extend to the assigned runway.	Need to have aircraft on known arrival routes that extend to the runway so that reasonably accurate trajectory calculations can be done by both the ground scheduling tool and by PDS.
Predicted sequence is stable.	Need to know the expected arrival sequence for both runways to assign appropriate Target Aircraft and type of spacing. Changes to the sequence during spacing operations are possible, but could be disruptive and are, hence, discouraged.
Desired spacing between the IM Aircraft and Target Aircraft is known.	Need to consider all influences on the spacing goal such as wake turbulence, separation requirements, runway utilization, and arrival times.
RTA for the IM Aircraft is known.	Needed as part of the spacing clearance to enable stable operations when a Target Aircraft is beyond ADS-B range of the IM Aircraft.

Procedures

The following are proposed procedures to support APS. It should be noted that there may be

multiple ways to achieve the same goal, but only one method is described in these procedures.

Nominal Pair-Wise Spacing

1. The controller determines to issue a spacing clearance.
2. The controller ensures that the initiation criteria are met.
3. The controller issues a spacing clearance to the IM Aircraft. The clearance includes the Target Aircraft ID, the assigned spacing goal, and the RTA at the runway threshold.
4. The flight crew enters the information from the spacing clearance into the PDS.
5. The flight crew enters the ownship's planned final approach speed and verifies it in PDS.
6. The flight crew accepts or rejects clearance.
7. The flight crew follows the IM speed.
8. If the data for the Target Aircraft (e.g., ADS-B position and trajectory information) are valid, the procedure goes to step 11.
9. PDS presents IM speed to achieve the RTA.
10. The flight crew follows IM speed.
11. As PDS receives valid data for each Target Aircraft and couples to them, the crew notifies ATC that they have coupled to that target.
12. If the controller expects the crew to have begun spacing, based on observed range between aircraft and ADS-B performance, and the crew has not reported beginning spacing, the controller queries the crew regarding their spacing status. The controller may cancel the spacing clearance.
13. When the Target Aircraft data are valid, PDS presents IM speed. The RTA part of the clearance is no longer valid.
14. The flight crew follows IM speed based on paired aircraft.
15. The flight crew follows normal arrival procedures as cleared, with the exception of using IM speed instead of following the published arrival procedure speeds.
16. The flight crew follows IM speed and makes adjustments to speed and aircraft configuration.
17. The controller monitors the aircraft to ensure separation from all traffic and ensure efficient flow of traffic.
18. If needed, the controller issues a spacing clearance amendment. The amended clearance

includes the Target Aircraft ID and the spacing interval of the second aircraft. No RTA is given with an amended clearance.

19. The controller monitors the spacing data to ensure conformance and expected behavior.
20. PDS commands final approach speed to enable a stable approach by 1000 ft above ground level (AGL).

Sample phraseology:

ATC: NASA 557, Denver Center, spacing clearance, advise when ready to copy.

NASA557: Denver Center, NASA 557, ready to copy.

ATC: NASA 557, cross runway seventeen right at 10:10:43. When able, cleared IM Spacing 120 seconds with UAL122. Report commencing IM spacing.

NASA557: Cross runway seventeen right at 10:10:43, when able cleared for IM spacing 120 seconds with UAL122, NASA557.

.

---- later time ----

.

NASA557: Denver Center, NASA557 has begun IM spacing with UAL222.

ATC: NASA557, roger.

Nominal Profile or RTA Operations

1. The controller, using supporting automation, determines to issue a standard arrival profile or RTA clearance.
2. The controller ensures that initiation criteria are met noting that criteria related to Target Aircraft do not apply.
3. The controller clears the aircraft for a standard arrival profile or an RTA at the runway threshold. The message includes the RTA value, if applicable.
4. The flight crew enters or verifies information in PDS.
5. The flight crew enters or verifies their planned final approach speed in PDS.
6. PDS presents IM speeds to meet the RTA or matches the standard profile.

7. The flight crew accepts the clearance.
8. The flight crew follows normal arrival procedures with the exception of using the IM speed.
9. The flight crew follows speeds from the PDS system and makes adjustments to speed and aircraft configuration.
10. The controller monitors aircraft to ensure separation from all traffic and ensure efficient flow of traffic.
11. PDS commands final approach speed to enable a stable approach by 1000 ft AGL.

Off-Nominal Events/Procedures

Several situations could necessitate the use of off-nominal procedures. The expected resolutions are provided in the subsequent text with mitigation methods that are included in either PDS or the procedures.

No Valid IM Speed

The lack of speed guidance occurs when PDS is unable to produce a valid speed for the crew. This condition can occur due to the following situations:

- no ADS-B data is received from a Target Aircraft;
- received data is of insufficient quality;
- no intent information available for Target Aircraft or ownship;
- PDS is unable to construct a 4D trajectory from the intent data for either Target Aircraft or ownship;
- Target Aircraft or ownship is out of conformance with the intent information;
- no spacing goal has been entered;
- there is a hardware failure; or
- no RTA has been entered and there is no ADS-B data from the Target Aircraft.

In this case, the procedures are:

- PDS alerts the crew of loss of IM speeds. This alert would include the source of the problem, such as “ownship data invalid,” or target ID of invalid data.
- The flight crew flies current speed or published speed, whichever is less.
- The flight crew advises ATC of failure that includes the appropriate Target Aircraft ID if

provided by PDS.

- The controller determines if the canceled spacing clearance should be replaced by another. Particularly in the case of spacing relative to two Target Aircraft, it may still be useful to have the IM Aircraft space relative to the remaining Target Aircraft. However, the spacing clearance for two Target Aircraft is a single clearance, so a new clearance for the single Target Aircraft must be issued.
- The controller issues a new clearance to the crew or resumes non-spacing operations.

Spacing Goal No Longer Feasible

The predicted spacing at the runway is continually compared to the spacing goal. If the deviation is larger than the conformance bounds, PDS will alert the pilot that there is a high-probability of not being able to achieve the assigned goal. The conformance tolerance bounds decrease as the aircraft gets closer to the runway. A 30-second deviation might be acceptable at 70 nmi, it would not be acceptable at 20 nmi. The IM speed remains active.

If this occurs at initiation of paired spacing:

- the crew verifies that the Target Aircraft ID, the spacing interval and the RTA match the clearance.
- If the spacing information matches the clearance, the crew notifies ATC they are unable to accept the spacing clearance.
- If the spacing information differs from the clearance, the flight crew corrects the data in PDS and reevaluates the IM speed.

If crew has already started IM spacing:

- the crew continues following IM speed; and
- the crew advises ATC that they are outside of the PDS conformance range.
- The controller may cancel spacing on that Target Aircraft, cancel all spacing, or modify the spacing interval on the current Target Aircraft.

Unacceptable IM speeds

The crew may determine that the IM speed is unacceptable. This situation exists if the crew determines that the current IM speed is inconsistent with safety of flight. This may be due to changing atmospheric conditions, e.g., turbulence, aircraft configuration, or other concerns.

To limit the occurrence of unacceptable speeds, PDS applies the following speed limitations:

- not greater than the current maximum maneuver speed of the aircraft;
- not greater than 250 kt when below 10,000 ft;

- not greater than 110% of the published speed for the current route leg; and
- not less than 90% of the published speed for the current route leg.

If this occurs, the procedures are:

- The flight crew selects a safe speed.
- The flight crew notifies the controller that they are unable to continue the spacing clearance and provide the reason for this deviation.
- ATC determines whether to cancel spacing or to allow the crew to maintain their current speed and resume spacing when able.

PDS Failure

If the PDS system should fail for a reason not identified above, it will terminate all spacing and alert the crew.

- The flight crew flies current speed or published speed, whichever is less.
- The flight crew notifies ATC that they must terminate spacing.
- The controller issues a new clearance, or resumes non-spacing operations.

Information Requirements

Table 2 lists the data elements, users, source, and whether it is required ('R'), expected ('E') or desired ('D'). Required data are necessary for the operation to occur as described here, including safely reacting to non-normal events. Expected data are required to achieve the expected outcome; however, if these data are unavailable a small percentage of the time, the operation can continue with less than optimal results. Desired data are not required to achieve the desired results, but are useful to maintain operational efficiency during non-normal events.

Table 2: Data Elements

Data Element	Users			PDS	Source
	Ground Automation	Controller	Flight Crew		
Flight plan including runway assignment for all relevant traffic	E	R			Existing ground automation
Aircraft position for all relevant traffic	R	R	E		Radar or ADS-B

Forecast of winds and temperatures aloft	E		D	E	Ground-based system
Airport configuration	E	R			Existing ground automation
Runway allocation and other requirements (e.g., scheduled departures, configuration changes, closures)	E	E			Tower scheduler, if available
Inter-aircraft spacing requirements	E	R			Standard procedures or controller automation
Planned arrival sequence, and schedule	E	R			Ground automation, if available
Aircraft capabilities such as Required Navigation Performance level, ADS-B, APS, etc. (all traffic aircraft)	E	R			Part of filed flight plan or existing ground automation
For IM Aircraft, first Target Aircraft and spacing interval	E	R	R	R	Ground automation or controller
For IM Aircraft, RTA at runway	R	R	R	R	Ground automation or controller
For IM Aircraft, second Target Aircraft and spacing interval	E	E	E	E	Ground automation or controller
Ownship and Target Aircraft intent including planned final approach speed	D			R	ADS-B from Target Aircraft or data link from ground
List of eligible ADS-B aircraft			D	R	ADS-B
Real-time winds and outside temperature aloft				E	Ownship sensors

from ownship sensors				
Real-time winds and outside temperature aloft from ground source or other traffic			D	ADS-B (for other aircraft) or data link from the ground
Feasibility of spacing clearance			E	Calculated in PDS
Aircraft speed limits			E	Ownship
IM speed			R	PDS
PDS guidance mode			R	PDS
Spacing deviation trend			R	PDS
Spacing status including Target Aircraft, spacing interval, current interval, other flags	D	D	R	PDS

The ownship and target-aircraft intent constitute the information needed to reasonably calculate an estimated time of arrival at the runway. This information is expected to include route information, modifications for different cruise or descent speeds and the final approach speed. For this concept, route information on the ADS-B is a named arrival route, including the approach and its transition. This translates into a path using an onboard database.

Example Scenario Descriptions

This section includes several scenarios that explore the proposed procedures. All of these are based on the following conditions:

Airport KZYYX has two parallel runways, 9R and 9L, which are 3400 ft apart. The runways are currently handling both arrivals and departures. Dependent operations are in use and require a minimum of 1.5 nmi distance between aircraft on the parallel approaches. Normal wake and radar separation is required for aircraft that are in-trail. Three nautical mile radar separation is required prior to both aircraft being established on the final approach course during parallel operations. All arrival routes are OPD so lateral separation is being provided prior to the aircraft being established on their final approach courses. The controller managing the arrival stream has access to a scheduling and sequencing tool that provides suggestions for pairing aircraft for airborne spacing operations. This tool also provides the necessary information for the spacing clearances. The controller could be presented with a timeline that would also provide the necessary information for initiating an IM operation. That information includes which aircraft to pair together, whether they will be conducting single or dependent runway spacing, the appropriate assigned spacing goals, and the RTA at the runway threshold.

Each scenario description is accompanied by a schematic diagram showing the situation when the spacing clearance is issued and when the first Target Aircraft arrives at the runway threshold. The spacing clearance is issued at time t_1 ; the aircraft are shown in blue. The assigned spacing goal is given by the text accompanying the arrow pointing from the spacing aircraft to the Target Aircraft. The aircraft are repeated at time t_2 , this time colored green, when the Target Aircraft reaches the runway threshold. The schematic is not drawn to scale but is to illustrate the relative position and timing of the aircraft.

Scenario 1

Aircraft H and G are arriving along the same route to runway 9R (Figure 5). Aircraft H has reached the point prior to its top of descent where spacing clearances are normally issued. The controller checks their automation display and sees the suggestion to have aircraft H space 100 s relative to aircraft G. The 100 s spacing corresponds to at least 3.2 nmi at the closest point of approach. The controller clears aircraft H to space relative to aircraft G at 100 s along with an RTA of 12:05:50. The RTA of 12:05:50 correlates to the RTA of aircraft G plus 100 s. The crew acknowledges and enters the information into their PDS system. This entry includes verifying their planned final approach speed. PDS is able to calculate a spacing interval on aircraft G and determines that spacing is feasible. The crew accepts the clearance. The crew follows the IM speeds presented and implements new speeds as the IM speed changes. The crew configures the aircraft as necessary to maintain the IM speeds. Since the Target Aircraft was within ADS-B

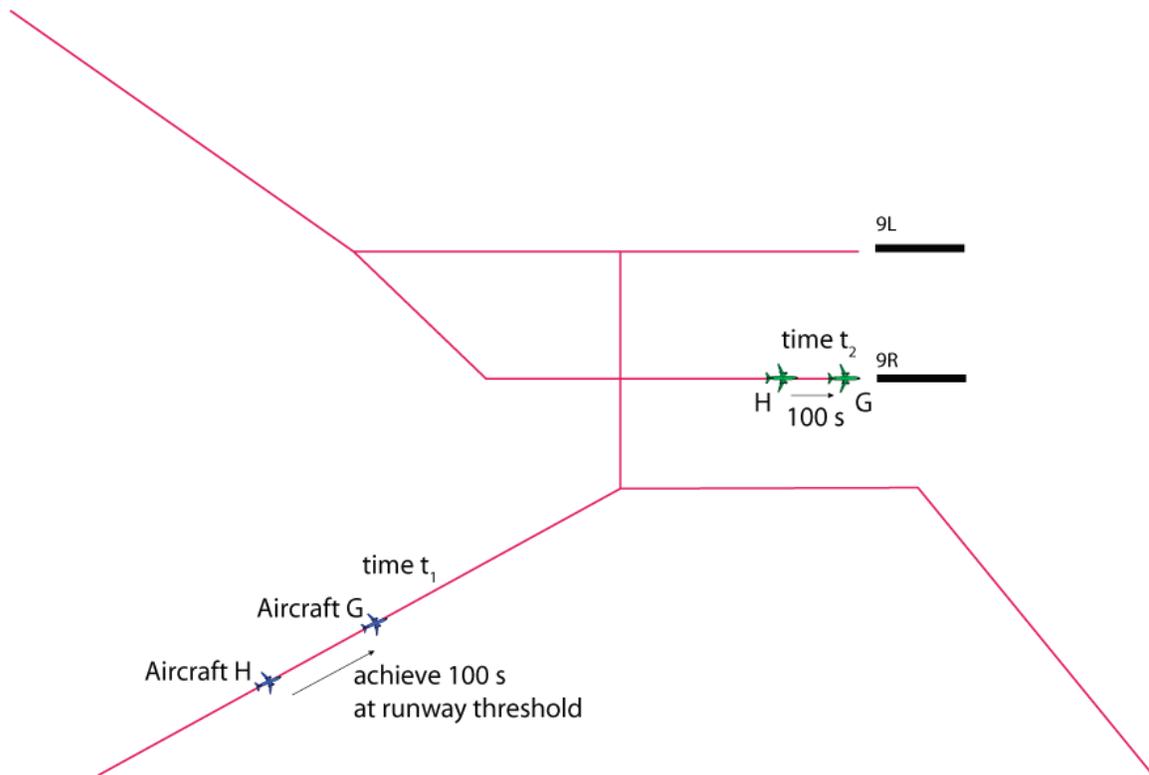


Figure 5: Schematic of in-trail spacing (scenario 1). The spacing clearance is issued at time t_1 (blue aircraft). Time t_2 (green) shows the relative positions when the Target Aircraft (G) reaches the runway threshold.

range at the time of the clearance, the RTA was never used by the PDS system. As the aircraft transition from sector to sector, each receiving controller is able to see that the IM and Target Aircraft are conducting spacing operations. The controllers can call up the active spacing

clearance and the status information from the aircraft for monitoring. Aircraft H eventually crosses the runway threshold at 12:06:03 which is 98 s after aircraft G crossed the threshold (12:04:25). This is 13 s after the scheduled time (RTA) but is within tolerances for the inter-aircraft spacing.

Scenario 2

As aircraft I approaches its top of descent point (Figure 6), the controller sees the recommendation for aircraft I, which is going to runway 9L, to space 2.2 nmi relative to aircraft H. A spacing of 2.2 nmi at the runway threshold will give at least 3.2 nmi prior to each aircraft being established on final. The 3.2 nmi spacing requirement prior to final approach is now the limiting factor on how close aircraft I can get to aircraft H. Note that there is no arrival immediately in front of aircraft I going to runway 9L. The controller instructs aircraft I to space 2.2 nmi relative to aircraft H with an RTA of 12:06:40. At the expected final approach speeds of aircraft H and I, the scheduling tool estimates the 2.2 nmi spacing will be equivalent to 50 s. Therefore, aircraft I's RTA is aircraft H's 12:05:50 plus 50 s. The crew acknowledges and enters the information into their PDS system. This entry includes verifying their planned final approach speed. Aircraft H is outside ADS-B range; therefore, the PDS system provides speeds to achieve the RTA and the crew notifies the controller they are managing to the RTA. A few minutes later aircraft H comes within ADS-B range and the PDS system on aircraft I is able to transition to paired spacing. PDS is now providing speeds to achieve the 2.2 nmi relative to aircraft H and is no longer providing guidance relative to the RTA. The crew is notified that PDS guidance is now based on aircraft H. The crew informs the controller that they have begun spacing relative to aircraft H. Aircraft I is 2.2 nmi from aircraft H as aircraft H reaches the runway threshold.

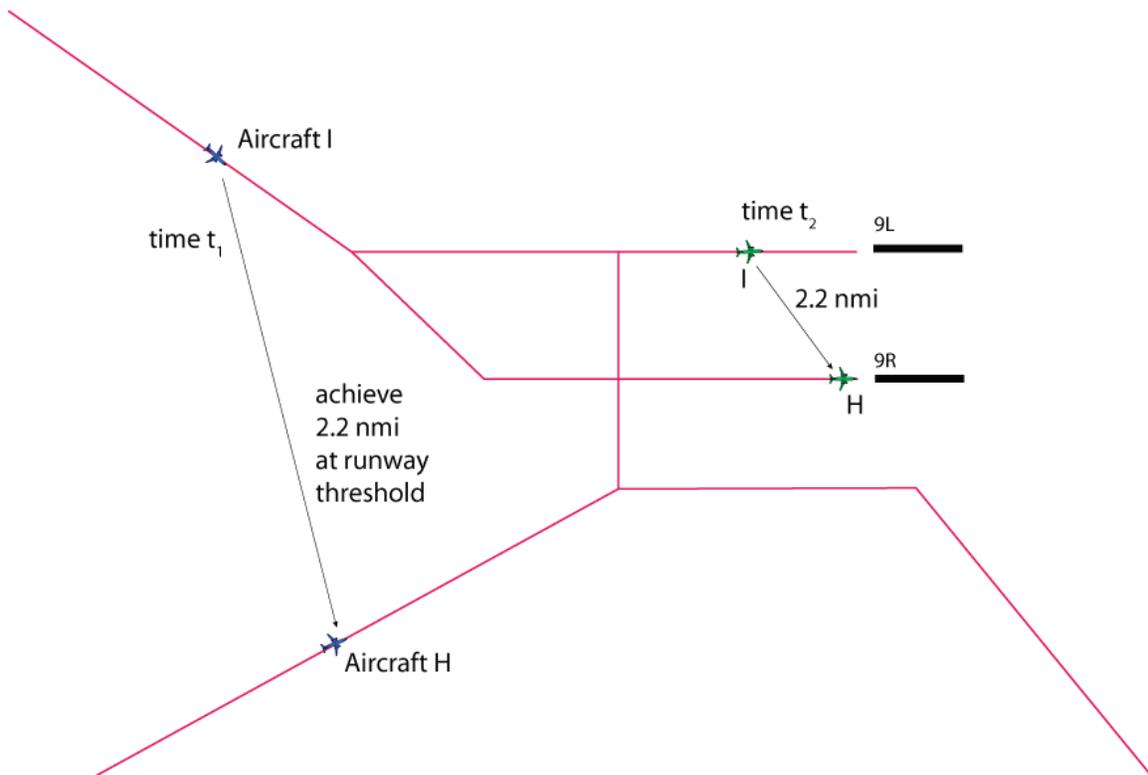


Figure 6: Schematic of spacing to a parallel approach (scenario 2). The spacing clearance is issued at time t_1 (blue aircraft). Time t_2 (green) shows the relative positions when the Target Aircraft (H) reaches the runway threshold.

Scenario 3

As Aircraft J approaches its top of descent (Figure 7), the controller's automation tool determines that aircraft J should perform dependent spacing operations relative to both aircraft H and I. The controller therefore clears aircraft J to space relative to aircraft H to achieve 130 s spacing and relative to aircraft I to achieve 2.2 nmi spacing with an RTA of 12:08:00. The RTA time is based on 130 s after the RTA for Aircraft H which is predicted to be a greater distance than the two distances for the parallel approaches: H to I and I to J. The crew acknowledges and enters the information into their PDS system. This entry includes verifying their planned final approach speed. Aircraft H is a valid Target Aircraft and PDS determines spacing is feasible. IM speed is presented to the crew who implements that speed and notifies ATC they have begun spacing relative to aircraft H. The crew follows the IM speed and configures the aircraft as necessary. PDS provides speeds to achieve the greater of the 130 s relative to aircraft H and the 2.2 nmi relative to aircraft I. In this example aircraft J is 2.5 nmi from aircraft I when aircraft I crosses the threshold of 9L and crosses the threshold of 9R 134 s after aircraft H.

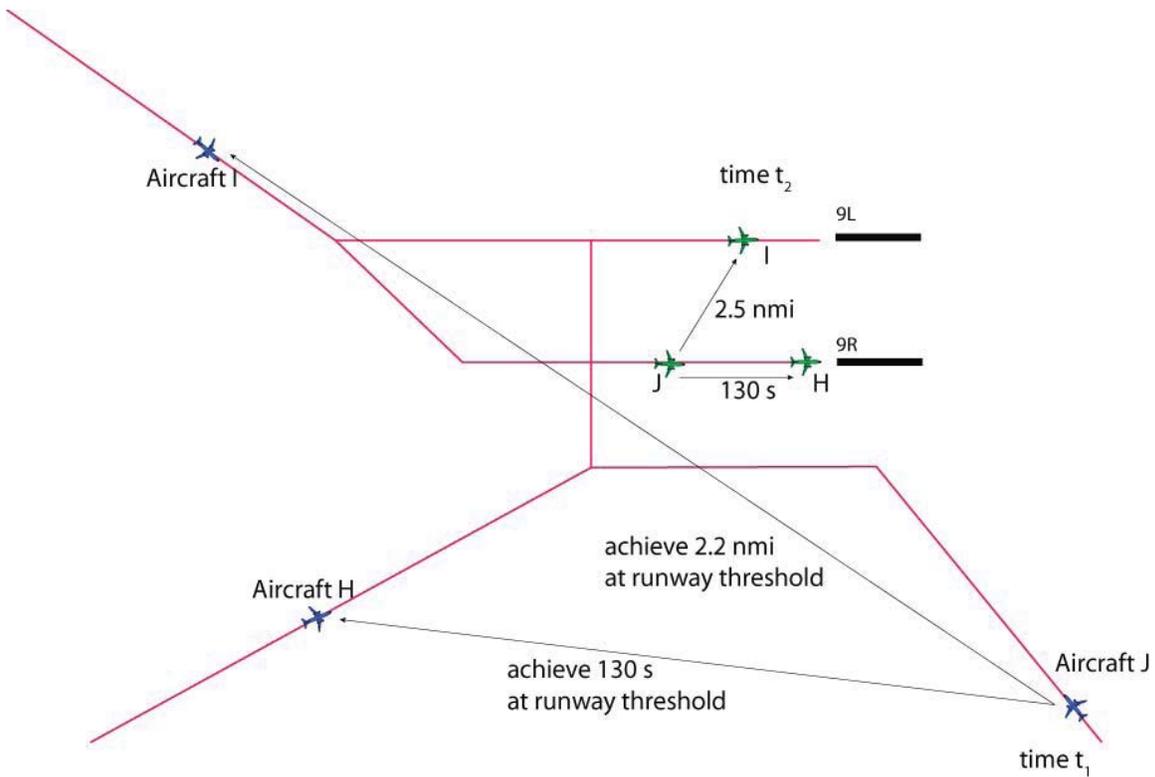


Figure 7: Schematic of combined in-trail and parallel approach spacing (scenario 3). The spacing clearance is issued at time t_1 (blue aircraft). Time t_2 (green) shows the relative positions when the first Target Aircraft (H) reaches the runway threshold.

Variations on Scenarios

In this section, variations on the above scenarios will be discussed.

Variation on Scenario 2

When aircraft I receives its spacing clearance, the crew reports that they are conforming to the RTA. Not reporting that they are spacing relative to aircraft H implicitly informs the controller of this situation via the procedural reporting requirement. The controller monitors the spacing data coming across ADS-B and notices that the crew has selected the wrong Target Aircraft. The controller contacts the crew and clarifies the spacing instruction. The crew then selects the proper aircraft and is able to begin spacing.

If the controller did not have the status information from the aircraft, the controller would need to wait until the spacing and Target Aircraft were within the expected ADS-B range and then query the crew. This additional monitoring would increase the controller's workload relative to having the status information available.

Variation on Scenario 3

Aircraft J needs only 90 s behind aircraft H on runway 9R (Figure 7). In this case, the two intervals of 2.2 nmi are greater than the 90 s in-trail spacing, so aircraft J eventually achieves 2.3 nmi spacing relative to aircraft I and 105 s relative to aircraft H.

Proposed ADS-B Message

Table 3 describes a new ADS-B message proposed to support APS operations. This message would include intent information needed by PDS and monitoring information for the controller. An update rate on the order of 30 s is sufficient for this application.

Table 3: Elements of On-condition ADS-B Message to Support APS Operations.

Parameter / Content	Container	Comments / Notes
Arrival route name	40 character array	A unique code that identifies the arrival routing.
Planned final approach speed	Unsigned integer	< 255; given in knots
Planned cruise speed	Unsigned integer	The planned cruise speed in Indicated Air Speed or Mach. If less than 100, interpret as hundredth of Mach. Can be taken from the Flight Management Computer or the current speed when spacing is engaged.

Parameter / Content	Container	Comments / Notes
Planned cruise altitude	Unsigned integer	The planned cruise altitude in flight levels if less than 100 and in feet if greater than 100. Can be taken from the Flight Management Computer or the current speed when spacing is engaged.
Wake vortex category	2 bit flag	00 = Small 01 = Large 10 = B-757 11 = Heavy
State of Target Aircraft #1	2 bit flag	00 = no target selected [default] 01 = target identified; not coupled 10 = target identified and coupled 11 = target not located (after 300 s)
Target Aircraft #1 ID	7 character array	Call sign of first Target Aircraft [ignored if Target Aircraft #1 state is 00]
Spacing goal for Target Aircraft #1	Unsigned integer	< 255; given in seconds [ignored if Target Aircraft #1 state is 00] [if assigned spacing goal is in distance this is the time conversion PDS is using.]
State of Target Aircraft #2	2 bit flag	00 = no target selected [default] 01 = target identified; not paired 10 = target identified and paired 11 = target not located (after 300 s)
Target Aircraft #2 ID	7 character array	Call sign of second Target Aircraft [ignored if Target Aircraft #2 state is 00]
Spacing goal for Target Aircraft #2	Unsigned integer	< 255; given in seconds [ignored if Target Aircraft #2 state is 00] [if assigned spacing goal is in distance this is the time conversion PDS is using.]

Parameter / Content	Container	Comments / Notes
Route Conformance Flag	1 bit flag	0 = aircraft has moved off path ³ 1 = aircraft is on-path

The two spacing goal elements may need to be enlarged to support intermixing arrival and departure operations on the same runway and to support distance-based spacing goals where values beyond 255 s are needed.

Summary

This document describes a new operational concept to enable high throughput operations when dependent runway operations are in use. This is an extension of a previous Airborne Precision Spacing concept [1]. Dependent runway operations are enabled by allowing for the selection of two Target Aircraft, one going to the same runway as the IM Aircraft and the other going to the dependent, parallel runway. The onboard spacing tool will ensure that the IM speed provided to the flight crew meets both spacing criteria.

Acronyms

4D:	Four dimensional
ADS-B:	Automatic Dependent Surveillance - Broadcast
AGL:	above ground level
APS:	Airborne Precision Spacing
ATC:	Air Traffic Control
ATIS:	Automatic Terminal Information Service
CDA:	Continuous Descent Arrival
CPDLC:	Controller Pilot Data Link Communications
ID:	identification
IM:	Interval Management
NASA:	National Aeronautics and Space Administration

³ The proposed criteria for route conformance are within 2.5 nmi laterally of the path, 6000 ft vertically of the expected path, and a track within 90° of current leg.

OPD:	Optimized Profile Descent
PDS:	Pair Dependent Speed
PRM:	Precision Runway Monitor
RTA:	Required Time of Arrival
t_1 :	first time in sequence
t_2 :	second time in sequence

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REPORT DOCUMENTATION PAGE

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14. ABSTRACT The Airborne Precision Spacing concept of operations has been previously developed to support the precise delivery of aircraft landing successively on the same runway. The high-precision and consistent delivery of inter-aircraft spacing allows for increased runway throughput and the use of energy-efficient arrivals routes such as Continuous Descent Arrivals and Optimized Profile Descents. This paper describes an extension to the Airborne Precision Spacing concept to enable dependent parallel approach operations where the spacing aircraft must manage their in-trail spacing from a leading aircraft on approach to the same runway and spacing from an aircraft on approach to a parallel runway. Functionality for supporting automation is discussed as well as procedures for pilots and controllers. An analysis is performed to identify the required information and a new ADS-B report is proposed to support these information needs. Finally, several scenarios are described in detail.					
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