ADS-B In Strategy Document

Closing the Loop on the Flight Deck

This document was produced by participants in ADS-B Equip 2020, Working Group 4. It is the product of the members of the group and does not constitute the opinions or policy of the FAA.

Executive Summary

ADS-B In applications have been developed for several decades but have gained little traction in air transport operations around the world. Air transport operators have invested in equipping their fleets with ADS-B Out equipment to meet the ADS-B Mandate in 2020. Operators are now looking forward to the benefits from ADS-B In applications to build on their ADS-B Out investments.

ADS-B In applications provide opportunities for significant gains in efficiency, capacity, and safety in the U.S. National Airspace System (NAS), especially when integrated with Trajectory-Based Operations (TBO), which promises benefits in high-density operations. While the fundamental capability for improved cockpit situational awareness of surrounding traffic has universal appeal to flight crews, applications such as Cockpit Display of Traffic Information (CDTI)-Assisted Visual Separation (CAVS) and Interval Management (IM) will yield significant efficiency and throughput benefits for the operators. The CAVS and IM applications build on the basic airborne and surface traffic display capabilities, which current pilots using ADS-B In testify provide significant safety benefits.

Successful deployment of ADS-B In applications depends on coordination and alignment between several stakeholders. With the need for coordination and alignment in mind, this document has incorporated inputs from the Federal Aviation Administration (FAA), as regulator and air navigation services provider; the operators; and, the avionics and aircraft manufacturers. In the past, this group of stakeholders encountered roadblocks to success resulting from limited budgets and lack of a clear understanding of the benefits provided by ADS-B In applications, and these roadblocks and uncertainties have limited development and deployment to date. With the advent of ubiquitous ADS-B Out equipage, the stage is set to access the operational benefits of ADS-B In.

This document provides a description of selected ADS-B In applications, benefits, and an evolutionary deployment strategy for key ADS-B In applications in the U.S. NAS. An update to the benefits and cost analyses, originally developed in 2012 for the ADS-B In Aviation Rulemaking Committee, shows overall benefits-to-cost ratios between 1.4 and 4.5 depending on equipage timelines, retrofit versus new production aircraft, and industry feedback on equipage cost estimates. An evolutionary operational deployment path has been defined, first leveraging TSO-defined applications, such as CAVS, that require no changes to Air Traffic Control (ATC) automation systems. As the ATC and pilot communities and airline operators gain confidence and see benefits in ADS-B In applications, more complex, higher-benefit applications requiring FAA investment in ATC automation systems, like additional operational uses of the CAVS application and IM, will be pursued. ADS-B In applications, and IM in particular, are key components of the FAA's future TBO vision.

Objectives of this Document

The primary objective of this document is to propose an operational deployment strategy, developed by key stakeholders, that motivates: 1) avionics and aircraft manufacturers to develop equipage; 2) airline operators to equip; and, 3) the FAA to make the necessary ATC automation changes enabling use of ADS-B In equipage to achieve the benefits.

To accomplish this objective, the document:

- provides an overview of selected ADS-B In applications and a brief history of ADS-B In applications development to date;
- describes the key ADS-B In operations driving benefits for airline operators and the work needed to deploy those operations in the U.S. NAS; and,
- outlines a stakeholder-defined roadmap to achieve ADS-B In operational deployment.

The document is organized as follows.

Section 1: Overviews of ADS-B Out and a selected set of ADS-B In applications.

Section 2: History of the ADS-B Out mandate, ADS-B In applications development, and FAA/Industry coordination to date.

Section 3: Airline interest in ADS-B In applications, including current roadblocks preventing airlines from investing fully in ADS-B In applications.

Section 4: ADS-B In benefits, including a description of benefits mechanisms, the operational benefits pool, and NAS-wide benefits.

Section 5: A vision of ADS-B In applications within the future Trajectory-Based Operations (TBO) environment.

Section 6: A proposed stakeholder-developed roadmap for ADS-B In applications development and deployment.

Section 7: Description of systems and operations that must be in place before the full benefits of ADS-B In applications can be achieved.

1 Introduction

1.1 Overview of ADS-B Out and In

Automatic Dependent Surveillance-Broadcast (ADS-B) is recognized by the FAA and industry as an important enabler for future trajectory-based air traffic management. ADS-B data (from ADS-B Out-equipped aircraft) is already used for separation in FAA Air Traffic Control (ATC) systems and is being received by ADS-B In systems onboard equipped aircraft today.

ADS-B is a surveillance technique that relies on an aircraft broadcasting its position (latitude and longitude), altitude, velocity, aircraft identification, and other information. ADS-B is dependent on a position source (e.g., global navigation satellite system [GNSS]) of required quality and requires additional information from other on-board systems. Every ADS-B message includes an indication of the quality of the position and velocity data. This allows ADS-B recipients to determine whether the data is adequate to support the intended use.

ADS-B supports both ATC and airborne surveillance. Because ADS-B Out information is broadcast, any suitable receiver can process the received messages. Aircraft surveillance applications (ASA)/airborne surveillance capabilities require aircraft to be equipped with ***ADS-B In*** receivers to process data from surrounding aircraft equipped with ADS-B Out. For most ADS-B-In capabilities and applications, a traffic display is used to present traffic information graphically.

Several initiatives are on-going worldwide to mandate equipage of ADS-B Out using 1090 MHz as the global link technology. However, the minimum acceptable link version is different between regions. To date, several ADS-B In applications have been designed to use ADS-B Out data from all ADS-B versions, allowing those applications to be used across regions. More detail on ADS-B Out link versions is provided in Appendix A.

1.2 Overview of ADS-B In Applications

The FAA, with European and industry partners, has developed concepts and avionics standards for several ADS-B In applications. Avionics suppliers and aircraft manufacturers (OEMs) have developed some of those applications, which are in varying states of deployment. Appendix B lists ADS-B In standards documents, and Appendix C describes some current ADS-B In industry offerings.

1.2.1 Basic Airborne Situation Awareness (AIRB)

AIRB was primarily developed to enhance traffic situational awareness for pilots, improving flight safety and flight operations through the provision of surrounding ADS-B Out traffic on an on-board traffic display. AIRB supplements the other available sources of information on traffic (e.g., visual scans and/or radio communications) and supports pilots having better awareness of the traffic in the vicinity. While pilots have used the Traffic Collision Avoidance System (TCAS) II display to improve their understanding of the surrounding traffic, its primary objective is to support visual acquisition when a Traffic Advisory is generated, and therefore, its use for understanding the surrounding traffic is limited.

AIRB provides the following information to the pilot:

- Relative horizontal position and ground track of surrounding traffic; and
- Altitude and vertical direction.

The following information can be provided to the pilot on demand:

- Aircraft identification; and
- Speed information (ground speed).

AIRB is defined for use by aircraft operating in any airspace, both controlled and uncontrolled (e.g., classes A to G), in which the traffic density can range from low to very high. AIRB is relevant to traffic operating under Instrument Flight Rules (IFR) or Visual Flight Rules (VFR). The application may be used any time during airborne operations, from the runway departure on take-off until touchdown on landing.

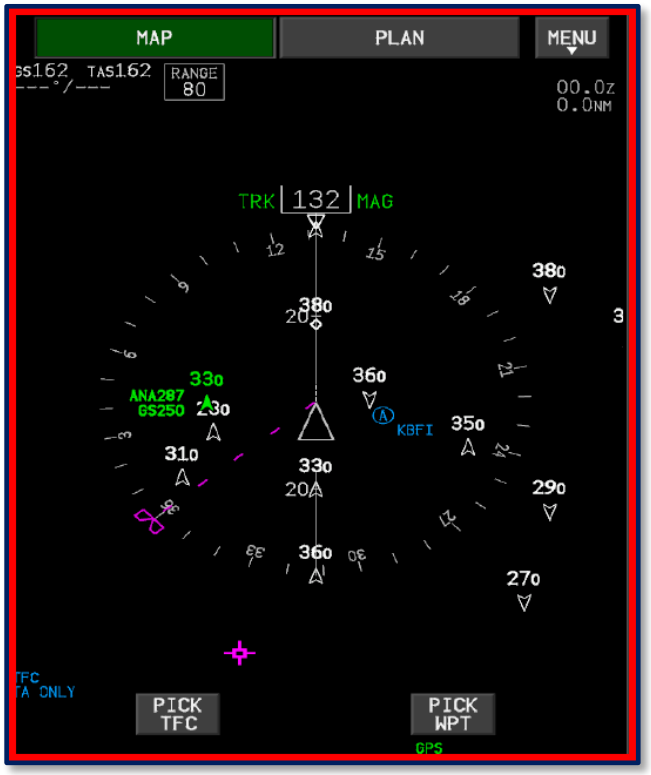


Figure 1. Example AIRB Cockpit Display of Traffic Information (CDTI) display [Richards 2017].

There are no specific requirements on ground ATC systems from communication, navigation and surveillance perspectives when AIRB is used. AIRB can be integrated into current operations without any changes to operations or pilot or ATC procedures.

For more information, refer to RTCA DO-319 / EUROCAE ED-164, the Safety, Performance and Interoperability Requirements document for AIRB. The latest version of FAA Advisory Circular 20-172 specifies how implementers must integrate AIRB and TCAS information on at least one display if there are two separate cockpit systems (i.e., an AIRB display and a TCAS display).

Benefits of AIRB

With an increase in traffic situational awareness, AIRB can improve the safety and efficiency of flight operations. Improved identification of surrounding traffic enables pilots to make more informed clearance requests to ATC (e.g., requesting a flight level change). Several operational trials conducted since 2010 have shown the following operational benefits of AIRB.

- Additional information available onboard the aircraft (e.g., call sign of nearby traffic) improves pilots' understanding of ATC clearances and turbulence reports.
- Information on traffic conditions helps pilots make more informed flight level change requests and tactical routing requests. In oceanic cruise environments, improved fuel efficiency can be attained by making more informed flight level change requests.

1.2.2 CDTI-Assisted Visual Separation (CAVS)

The objective of CAVS is to assist pilots in maintaining visual separation (called "own separation" by the International Civil Aviation Organization [ICAO]) from an aircraft equipped with ADS-B Out during successive visual approach procedures. CAVS can only be used under Visual Meteorological Conditions (VMC).

ATC provides traffic information to the pilot of the trailing aircraft as in current visual approach operations. On reception of this traffic information, the pilot of a CAVS-equipped aircraft can use the traffic display to support visual acquisition of the leading aircraft during the visual approach procedure. Once the leading aircraft is initially acquired out the window and identified on the CDTI, the pilot is allowed to use the traffic display to continue visual separation operations even if visual contact with the leading aircraft is temporarily lost (e.g., lost in city lights at night).

The CAVS avionics require two alerting features: an advisory level, pilot-selectable range indication and a caution level surveillance alert. The pilot-selectable range indication is set in accordance with individual company policy and is intended to assist the pilot in achieving an operationally desirable distance from the leading aircraft. The caution level surveillance alert cannot be modified by the pilot and activates when the range to the preceding aircraft is less than 1.4 nautical miles (NM) and surveillance quality does not support closer ranges. When the surveillance alert occurs, the pilot is no longer authorized to use the CDTI as a substitute for out-the-window visual observation of the preceding aircraft.

Relative to AIRB, the following additional information is provided to the pilot:

- Relative groundspeed information (between the leading aircraft and ownship), enabling the pilot to readily assess the closure rate with the preceding aircraft; and
- Alerting information as described in the previous paragraph.

There are no new requirements on ground systems from communication, navigation, and surveillance perspectives when CAVS is used. CAVS operations are transparent to ATC and to the leading aircraft and can be used in the same environments as current visual approaches.

FAA requires operational approval for use of the CAVS capability (see the latest version of FAA Advisory Circular 90-114, Appendix B). As of mid-2019, American Airlines has received this approval.

Benefits of CAVS

CAVS improves arrival throughput by allowing visual approach operations to continue when they would otherwise have been cancelled due to pilots losing the out-the-window visual. At least one airline believes that use of CAVS will reduce go-arounds due to traffic getting too close on final.

For more operational information on CAVS, see RTCA DO-354 / EUROCAE ED-233, the Safety, Performance and Interoperability Requirements document for CAVS.

1.2.3 Additional Operational Uses of the CAVS Application

American Airlines has expressed interest in extending the use of the CAVS avionics functions to other operations. Other operational uses of the CAVS application are currently being explored by the FAA in collaboration with American Airlines and would extend the use of the CAVS avionics to ceiling/visibility conditions that do not allow visual separation.

Unlike CAVS operations, ATC would provide the leading aircraft's traffic ID and issue an "own separation" clearance. The flight crew would identify the leading aircraft on the CDTI. The use of the CDTI allows the flight crew to manage "own separation" from the leading aircraft when out-the-window visual contact is not possible or is lost.

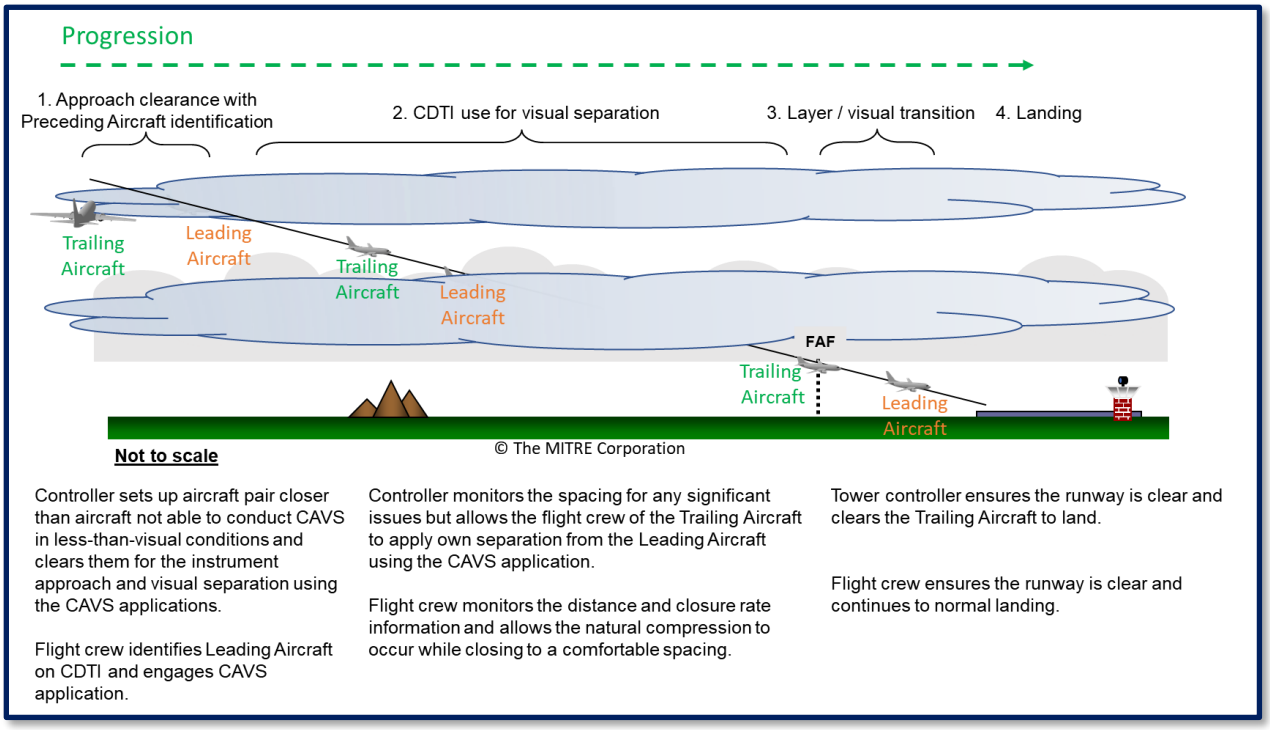


Figure 2. Use of the CAVS Application in Less-than-Visual Conditions, illustrating additional operational uses of the CAVS Application.

As described in Section 1.2.2, the CAVS application would provide caution-level and advisory-level alerting based on an operator-specified range and a minimum surveillance range, respectively, to the leading aircraft.

Benefits of Extending the Use of the CAVS Application

The NAS operates at its peak performance (i.e., throughput and efficiency) when air traffic controllers can apply visual separation standards and visual approach clearances to maintain maximum runway capacity at major airports. As weather conditions approach the minimum requirements for conducting visual operations at a given facility, or when pilots are unable to accept visual separation clearances, airport capacity is reduced. This occurs in conditions well above the 1000-feet/3-NM minimums required for

VMC. The notional diagram[1] below shows how visual approaches may be suspended as weather conditions and visibility degrade. The degradation of visual operations adds arrival delay and directly impacts airline schedule reliability and efficiency.

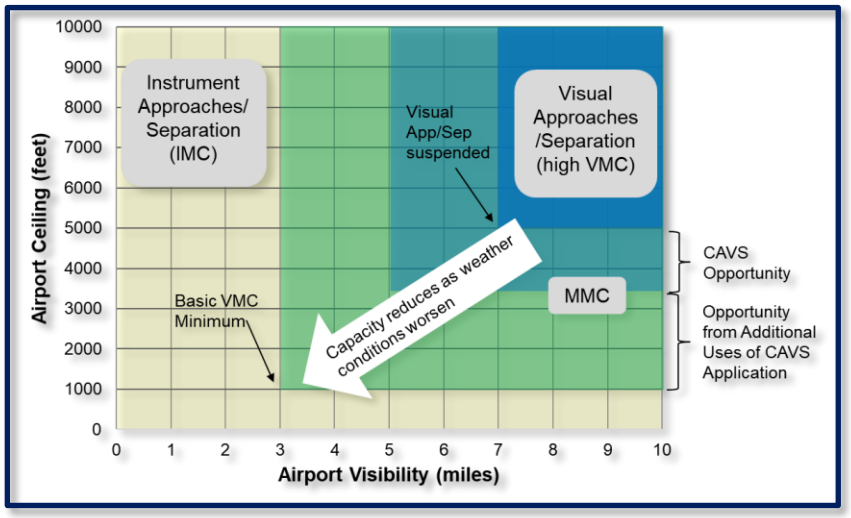


Figure 3. Marginal Meteorological Conditions provide opportunity for additional operations using the CAVS application.

Reduced arrival rates can mean more flight miles and less predictability in arrival times. New operational uses of the CAVS application will enable the controller to condition traffic for visual approach-like operations and conduct reduced separation operations in non-visual weather conditions to the runway threshold. The potential to increase runway capacity in more varied weather conditions is significant for airline operators. Table 1 compares the arrival throughput for different meteorological conditions for the top 35 airports in the NAS.[2] As expected, capabilities that achieve visual-like throughput in non-visual conditions can significantly increase the arrival throughput at an airport.

Table 1. Arrival Throughput in Different Meteorological Conditions (Top 35 Airports)

Airport	VMC Throughput (ac/hr)	MMC Throughput (ac/hr)	IMC Throughput (ac/hr)	VMC increase over MMC	VMC increase over IMC
ATL	117.9	117.5	104.4	0%	13%
BOS	70.6	41.7	35.1	69%	101%
BWI	52.7	42.1	33.2	25%	59%
CLT	106.3	105.1	93	1%	14%
DCA	47.1	43.9	37.4	7%	26%
DEN	140.7	138.8	114.5	1%	23%
DFW	177.3	151.3	110.2	17%	61%
DTW	132.3	97.4	90.9	36%	46%
EWR	49.5	43.6	37.5	14%	32%
FLL	54.7	54.3	54.3	1%	1%
HNL	61.3	34.5	30.2	78%	103%
HOU	41.4	38.9	31.5	6%	31%
IAD	93	78.7	67.7	18%	37%

[1] This diagram will differ by facility.
[2] The top 35 airports in the U.S. NAS are based on the number of annual operations.

IAH	113.4	84	79	35%	44%
JFK	84.8	63.9	62.6	33%	35%
LAS	89.9	77.5	37.3	16%	141%
LAX	81.4	76.1	64.2	7%	27%
LGA	47	45.4	40.3	4%	17%
MCO	85.6	86.1	69.4	-1%	23%
MDW	43.8	43.5	34.2	1%	28%
MIA	79.7	78.4	65.4	2%	22%
MSP	119.5	90.1	60.7	33%	97%
ORD	127.5	127.9	110.5	0%	15%
PHL	58.4	68.8	37.1	-15%	57%
PHX	88.6	46.7	44.7	90%	98%
SAN	44.4	40.2	32.8	10%	35%
SEA	59.1	51.7	48.3	14%	22%
SFO	73.6	50.5	36.8	46%	100%
SLC	94.2	75.8	65.6	24%	44%
STL	88.5	40.9	33.1	116%	167%

1.2.4 In-Trail Procedures (ITP)

Oceanic ITP enables a leading or following same-track aircraft to perform a climb or descent to a requested flight level through intermediate flight levels. ADS-B messages provide the aircraft identification, altitude, position, and ground speed of reference aircraft, and this information is assessed by the ITP-equipped aircraft's on-board equipment to determine whether an ITP climb or descent is possible. Based on the processed ADS-B data from one or two reference aircraft, a pilot can make an ITP climb or descent request to ATC. ATC performs other checks, and when acceptable, applies ITP separation minima to approve the climb/descent of the ITP aircraft relative to suitable reference aircraft. ITP requests and clearances are communicated via a Controller/Pilot Datalink Communication (CPDLC) message exchange.[3]

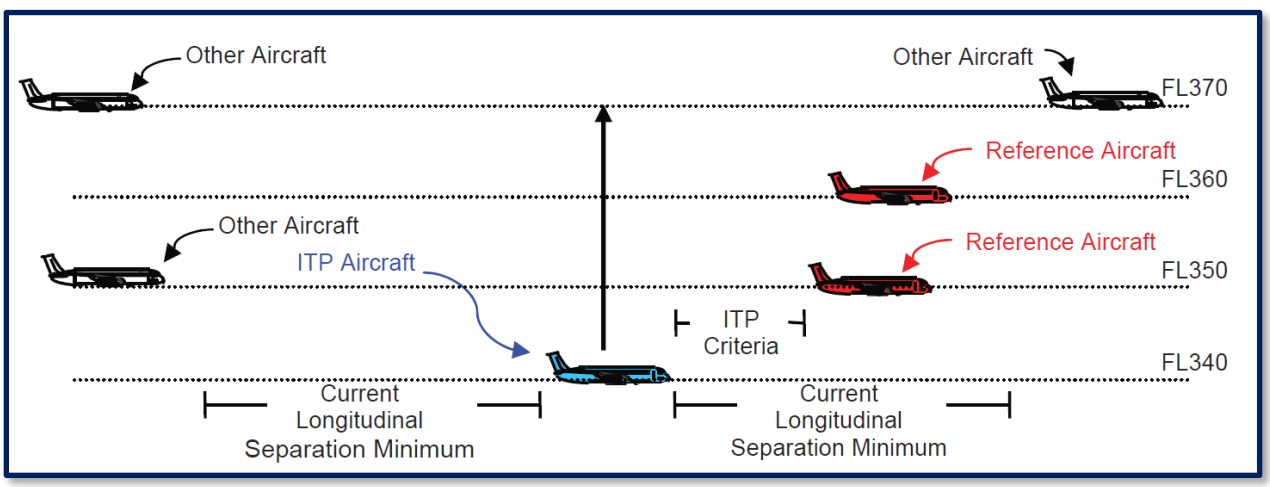


Figure 4. Notional example of an ITP procedure relative to two reference aircraft in Oceanic Airspace [ITP SPR DO-312].

[3] While Space-based ADS-B (SBA) will enable smaller oceanic separation, it requires all aircraft separated at the reduced separation standard to have CPDLC and RNP-4. In contrast, ITP only requires the reference traffic to have ADS-B.

Pilots are responsible for using the ITP equipment to evaluate the situation and provide the required information to the controller. The controller always maintains separation responsibility between aircraft as dictated by the airspace class in which the operations occur.

ITP is described in detail in the ICAO Procedures for Air Navigation Services – Air Traffic Management (PANS-ATM), Doc 4444, including the related CPDLC messages.

Additional information related to ITP may be found in ICAO Circular 325, In-Trail Procedure (ITP) Using Automatic Dependent Surveillance — Broadcast (ADS-B).

ITP is designed to be applied in the en-route remote airspace, where separation is provided according to ICAO PANS-ATM Chapter 5 provisions. FAA requires operational approval for use of the ITP capability (see FAA Advisory Circular 90-114A). United, American, Delta, and Hawaiian Airlines have received this approval.

The FAA and United Airlines conducted an operational evaluation of ADS-B ITP using twelve United B747-400 aircraft. In June 2011, a Supplemental Type Certificate was granted by the FAA for the ITP system installation on the B747-400 model operated by United Airlines. On the same day, the FAA Air Traffic Organization received approval from its safety regulator to offer ADS-B ITP services to properly equipped aircraft in the Oakland Oceanic Flight Information Region (FIR). FAA En Route and Oceanic Safety and Operations Support authorized Oakland Center to initiate the operational evaluation in August 2011; the FAA has put in place an Air Traffic Order under which Oakland Center continues to support ADS-B ITP operations. United Airlines received Operational Approval from FAA Flight Standards to commence ITP operations in August 2011. FAA modified the Advanced Technologies & Oceanic Procedures (ATOP) ATC automation system to provide direct controller support for ADS-B ITP, including conflict probe changes, making this capability operational at all US Oceanic Centers (Anchorage, New York, and Oakland).

Benefits of ITP

The use of ITP facilitates climb and descent of aircraft during the en-route phase to enable better use of optimal flight levels in environments where procedural airspace requires large separation standards. The benefits of ITP include the fuel savings and corresponding environmental benefits from operating more closely to the aircraft's optimal cruise altitude. Furthermore, ITP increases cabin comfort and safety, as ITP allows the pilot to more readily achieve an operationally desirable flight level to avoid extended turbulence during cruise.

The FAA and United Airlines collaborated to analyze and publish a summary of the operational economic benefits United Airlines experienced as a result of ADS-B ITP equipage [FAA ITP Benefits]. While there were few ITP requests to the Oakland Oceanic FIR in 2017 (30 requested, 4 accepted) and 2018 (108 requests, 36 accepted), there is evidence of increasing use of this application as more aircraft are equipped.[4]

[4] There are several factors contributing to low numbers of ITP requests and a low rate of accepted requests. Pilots do not know the separation standard that is currently being applied, which means ATC may not be able to accept the request in some cases. However, when a pilot makes the ITP request, it draws attention to the pilot's desire to climb. Therefore, success can be categorized as the pilot receiving a climb clearance even if it is not an ITP climb. Additionally, there have been issues with the formatting of the request, indicating issues with ITP equipment. Lastly, controllers may not be comfortable accepting the ITP request given the frequency of use.

As part of the ADS-B ITP Operational Benefits Evaluation conducted by the FAA in partnership with United Airlines, flight crews were interviewed about their use of the ITP system during oceanic operations. During post-flight interviews, flight crews stated they were able to use the display to continuously optimize their altitude with the knowledge of proximate traffic. A study was conducted to assess and quantify the economic benefits from the situational awareness (SA) aspect of the ITP display. The ITP display provides flight crews with the position, flight ID, distance, altitude, and closure rates of proximate traffic up to 250 NM away from the ITP aircraft position.

Analysis of the data demonstrated there was an SA benefit based on flight crew surveys and supported with situational awareness fuel benefit values when the data were analyzed at the aggregate level for all valid flights inbound and outbound in both the Trans-Atlantic and Trans-Pacific regions. The additional SA provided by the ITP display allowed pilots to make standard climb requests with a higher probability of success. Also, knowledge of the traffic competing for optimum altitudes at oceanic entry points, particularly on the North Atlantic, allows for an earlier request for the optimum altitude. The SA fuel savings benefit was 573 lbs for all valid flights in both the Trans-Atlantic and Trans-Pacific regions (670 lbs. per flight in the Trans-Atlantic region and 521 lbs per flight for the Trans-Pacific region) [FAA ITP Benefits].

1.2.5 Interval Management (IM)

IM combines ground-based and flight-deck systems to provide precise inter-aircraft spacing between aircraft, providing air traffic controllers with another tool to manage traffic flows.

- Ground capabilities assist the air traffic controller in issuing IM clearances to merge and space aircraft safely and efficiently and in monitoring the progress of those IM operations; and
- Airborne capabilities allow the pilot to conform to the IM clearance by providing speed guidance to achieve and maintain a precise spacing goal relative to another aircraft, like the adaptive cruise control feature in newer cars. These airborne capabilities are referred to as the flight-deck interval management (FIM) avionics.

The objective of the IM application is to achieve and/or maintain an assigned spacing goal (ASG) between the IM aircraft and the ATC-designated aircraft (referred to here as the Target Aircraft), by having the pilot follow speed commands generated by the FIM avionics. The ASG is provided by the controller and may be given in time or distance. The value of the ASG should align with the controller's goal of establishing an efficient and safe traffic flow.[5] In a TBO environment, the ASG will be based on the time-based schedule at a point in the airspace.

ATC and pilots will be provided with new procedures and phraseology for IM operations. During IM operations, ATC retains responsibility for separation. In a TBO environment, the IM clearance information for aircraft equipped with FIM avionics would be displayed to ATC. ATC communicates the IM clearance to the flight crew of the IM Aircraft via voice or using Data Communications (Data Comm), when available. The flight crew on the IM Aircraft enters the IM Clearance information into the FIM avionics or autoloads it from the Data Comm receiving system. If the FIM avionics determines the IM clearance is valid (for example, the data in the Target Aircraft's ADS-B Out message must be of sufficient quality), IM speed guidance is displayed to the flight crew. The flight crew begins implementing the IM speeds manually (or

[5] The ASG should not be set equal to the separation standard (or a time-based approximation of the separation standard). An additional buffer should be added to account for expected spacing variations during the operation. This is similar to ATC's separation management today.

the autoflight system could automatically implement the IM Speeds). The IM operation continues until reaching the Planned Termination Point (PTP) or until terminated by ATC.

Figure 5. CDTI for IM application (prototype used in MITRE HITL experiments).

Arrival and approach applications are expected to provide throughput and efficiency benefits, supporting spacing from a Target Aircraft going to the same runway, a parallel runway, and crossing or converging runways.[6] Detailed benefits for the IM applications are described in Section 4.

Same-runway operations, illustrated in the figure below, can begin when aircraft are on different arrival routes and as soon as the Target Aircraft is within ADS-B range of the IM Aircraft. The IM speed guidance is designed so that the IM Aircraft will cross the Achieve-by Point (ABP), specified as a part of the IM clearance, at a time interval equal to the ASG after the Target Aircraft crossed the ABP.[7] Because the IM and Target Aircraft may be on different routes prior to the ABP, the IM speed guidance is based on the *predicted* spacing at the ABP. Between the ABP and the PTP, the IM speed guidance is designed to precisely maintain the ASG.

[6] Currently, the FIM avionics standards do not include requirements to support IM operations when aircraft are climbing (i.e., no IM operations have been defined for departures).

[7] The FIM avionics also support distance-based ASGs. In the case of a distance-based ASG, the IM speed guidance is designed so that the IM Aircraft is an along-path distance equal to the ASG from the ABP when the Target Aircraft crosses the ABP (or the TRP, if the IM and Target Aircraft are on different routes).

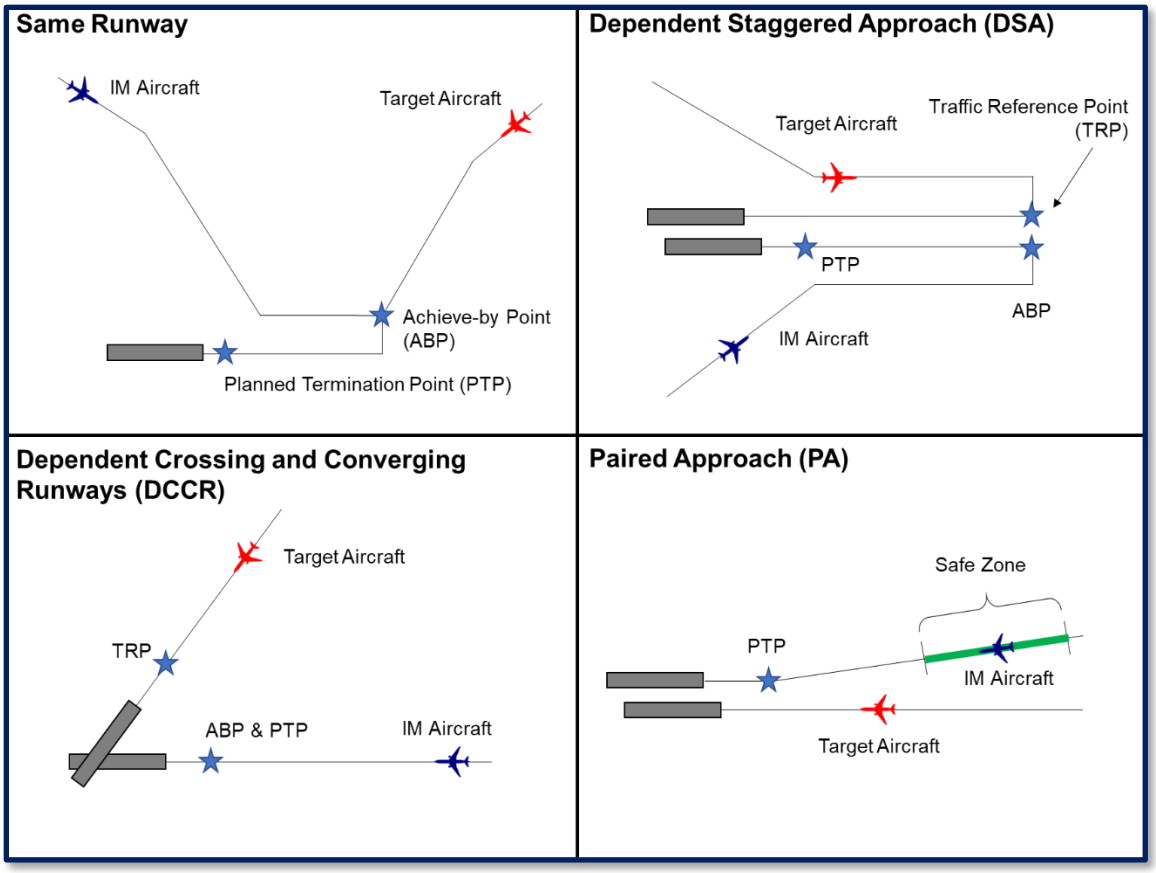


Figure 6. Illustration of the range of IM operations supported by the avionics standards.

The FIM avionics functions also support IM operations to dependent parallel and crossing and converging runway configurations, called Dependent Staggered Approaches (DSA) and Dependent Crossing and Converging Runways (DCCR), respectively. For dependent runway operations, the IM speed guidance drives the IM Aircraft to cross the ABP at an interval equal to the ASG after the Target Aircraft crosses the Traffic Reference Point (TRP).

IM operations for Closely Spaced Parallel Runways (CSPRs) are also supported through an IM application called Paired Approach (PA). In the PA application, a safe window is identified behind the Target Aircraft that protects the IM Aircraft from a collision with the Target Aircraft if the Target Aircraft deviates from its approach path and from the Target Aircraft's wake if it drifts across the IM Aircraft's approach path.

While many IM applications will be possible using clearances delivered using voice communications alone, IM-related Data Comm messages, including IM clearance and flight-crew response messages, have been defined in the RTCA/EUROCAE avionics standards for Aeronautical Telecommunications Network Baseline 2 (ATN B2). In addition to allowing communication of more complex clearances, ATN B2 messages enable IM to be used in environments with dynamic routing. The timeline for implementation of ATN B2 messages is uncertain at this time.

Additional descriptive information related to IM may be found in the Safety, Performance and Interoperability Requirements Document for Airborne Spacing – Flight-deck Interval Management (ASPA-FIM), DO-328A/ED-195A. Note that modifications to DO-328A/ED-195A are under development and are expected to be published by the end

of 2020. Data Comm messages for IM are defined in the Standard for Baseline 2 ATS Data Communications standards, DO-350A and DO-351A.

The FIM Minimum Operational Performance Standards, DO-361()/ED-236(), describe the minimum equipment requirements for the FIM application. The required functions that comprise the "FIM avionics" may reside in several flight-deck systems (e.g., surveillance computer, flight guidance system, the Flight Management System [FMS], and the CDTI).

Benefits of IM

Expected benefits of IM operations include:

- Increased capacity in high-density arrival and approach environments through reduced spacing buffers between aircraft pairs, leading to additional landing slots during busy periods;[8]
- Reduced vectoring in environments using defined Performance-based Navigation (PBN) procedures as a result of the improved precision made possible with the use of FIM avionics; and,
- More efficient aircraft operations for FIM-equipped aircraft, when aircraft are pre-sequenced using a ground-based arrival manager and IM operations are initiated to help manage spacing during arrival and approach.

The IM benefits are described in more detail in Section 4.

1.2.6 Other ADS-B-In applications

Other ADS-B In applications are defined in the latest version of DO-317/ED-194. These applications include Visual Separation on Approach (VSA), ADS-B Traffic Awareness System (ATAS), and Basic Surface Situational Awareness (SURF). Since VSA functionality does not offer the benefits of CAVS and ATAS is only applicable to aircraft without TCAS II, there has been less U.S. airline interest in these applications.

SURF is similar in functionality to AIRB, providing pilots with improved situation awareness on the airport surface. There has been some U.S. airline interest in SURF, but none of the airliner aircraft OEMs, such as Airbus, Boeing, Bombardier, and Embraer, currently offer the SURF application.[9] One expected benefit to the airlines is more efficient engine start times during taxi out. Anecdotal evidence from an early installation of similar Surface Area Movement Management (SAMM) functionality on several UPS aircraft appears to indicate that a safety benefit is also likely, providing improved situation awareness during poor visibility conditions.

While some operational, performance, and safety requirements were developed for a concept called Surface Situational Awareness with Indications and Alerts (SURF-IA) (see RTCA DO-323), no RTCA or EUROCAE avionics standards exist from which the SURF-IA application may be developed. FAA/RTCA development work on SURF-IA around 2010 indicated several technical challenges that would need to be overcome before standards could be developed. The alerting features of SURF-IA could provide a

[8] The additional arrival capacity is specific to the airport and operation but could range from 1-2 aircraft per hour to upwards of 5 or more aircraft per hour.

[9] Airbus provides an Onboard Airport Navigation System (OANS) and Boeing provides Airport Moving Map (AMM), which displays a moving map of the airport surface relative to ownship; however, these displays are not SURF-compliant as they do not display ADS-B-equipped traffic.

significant surface safety improvement by reducing runway incursions if these technical challenges can be addressed.

Figure 7. SURF-IA display showing a runway incursion [DO-323].

2 A Brief History of ADS-B In Research and Development

2.1 ADS-B In Applications Research and Development

The FAA and RTCA began developing the first Aircraft Surveillance Applications (ASAs) through the FAA's Safe Flight 21 Program in the late 1990s and early 2000s. While some of the ASAs were basic situation awareness applications, some are considered predecessors to the IM applications being developed today. The Requirements Focus Group (RFG), a partnership between the FAA and RTCA in the U.S. and EURCONTROL and EUROCAE in Europe, developed most of the avionics standards documents for the ADS-B In applications described in Section 1.

A series of four medium-fidelity flight deck simulations were conducted in 2002 and 2003 to examine several aspects of the CAVS application and its associated procedures. There were two primary goals of the research. The first was to objectively measure the pilot's ability to safely maintain visual-like separation from another aircraft using the CDTI in varying visibility conditions. The second goal was to measure the pilot's subjective comfort level and willingness to perform visual-like separation across varying visibility conditions. The simulations were based on an FAA and industry developed concept and through input from the FAA and industry on the simulation design and goals. After the initial research, additional HITL simulations were conducted in the early 2010s to determine how the concept of using a CDTI for visual-like separation could be expanded to achieve additional benefits. A review of the work is provided in [Bone, 2015].

NASA Langley Research Center led much of the early research into ADS-B In avionics to enable flight crews to manage in-trail spacing in the terminal environment. Other organizations, such as EUROCONTROL and MITRE, also studied ADS-B In avionics and ASAs in HITL experiments to help refine the concepts. A detailed history of ASA and IM development is provided in [Barmore, 2016].

Several flight tests have been conducted over the last two decades, demonstrating the feasibility of using ADS-B In and flight-deck avionics to support the flight crew in conducting a precision spacing task. A flight

test in Chicago in 2002 evaluated NASA's early in-trail spacing tool for maintaining a time-based spacing interval behind a lead aircraft.

In the mid-2000s, ADS-B In Merging and Spacing (M&S), a predecessor to IM, was evaluated by UPS for arrivals into Louisville, KY. The M&S operations into Louisville involved a limited number of UPS Boeing 767 aircraft equipped both with ADS-B Out and certified ADS-B In avionics. The UPS Airline Operations Center (AOC) provided the M&S information (e.g., lead aircraft identification) to flight crews via voice. Flight crews entered the information into the M&S application, which was hosted on an Electronic Flight Bag with an ADS-B Guidance Display (AGD) showing the speed guidance in the forward field of view, and manually implemented the speed guidance that was displayed. The results obtained in those conditions were compelling as the UPS aircraft were able to achieve and maintain a spacing interval within 8 seconds of the spacing goal, 95% of the time. Flight test details and results are covered in [Penhallegon, 2016].

NASA partnered with Boeing, Honeywell, and United Airlines on the Air Traffic Management Technology Demonstration-1 (ATD-1) flight test in 2017, which evaluated IM performance on merging routes, where the lead and trail aircraft were subject to different wind conditions. The flight test used prototype avionics based on a subset of requirements in the Flight-deck IM (FIM) Minimum Operational Performance Standards (MOPS). Results showed that IM operations are feasible and precise spacing within 10 seconds of the spacing goal can be achieved with real-world operational uncertainties [Swieringa, 2017].

Figure 8. The NASA ATD-1 Flight test team with the Honeywell and United test flight aircraft.

An IM Paired Approach (PA) Demo was sponsored by the FAA's NextGen organization to demonstrate the feasibility and performance of IM operations to closely spaced parallel runways at San Francisco International Airport (SFO) in 2019. The PA Demo included prototype avionics, developed by Honeywell, and aircraft were provided by Alaska Airlines and United Airlines to serve as lead aircraft. Results showed precise spacing within 5 seconds of the spacing goal is achievable when setting up operations on final approach at a busy airport.

More details on flight test and demo activities for IM and predecessors to the IM concept can be found in Appendix D.

Future operations, like PA, can help maintain arrival throughput in non-visual conditions. With high FIM-avionics equipage rates, arrival rates nearing those seen in VMC are possible. At airports like Newark International Airport (EWR) and SFO, this could result in no Ground Delay Program (GDP) for much of the day and dramatically decreases the frequency and duration of GDPs during peak periods.

2.2 ADS-B Out Mandate and the ADS-B In ARC

In response to a recommendation from the ADS-B Aviation Rulemaking Committee (which advised the FAA regarding comments on the proposed ADS-B Out mandate), the FAA chartered the ADS-B In Aviation Rulemaking Committee (ARC) on June 30, 2010, to provide a forum for the U.S. aviation community to define a strategy for incorporating ADS-B In technologies into the NAS. The ARC was tasked to provide recommendations that clearly defined how the community should proceed with ADS-B In while also ensuring compatibility with ADS-B Out avionics standards and the 2020 ADS-B Out equipage mandate.

The ADS-B In ARC submitted its findings and recommendations to the FAA on September 30, 2011. The ARC supported "ADS–B as the primary mechanism to provide future surveillance for ATC in the NAS" [ADS-B In ARC Report, 2011]. Additionally, the ARC made four recommendations in its 2011 report. Three of those four recommendations remain relevant today:

1. Based on the current maturity of ADS-B In applications and achievable benefits, the ARC did not recommend an equipage mandate.
2. The ARC recommended that the FAA use operational demonstrations of ADS-B In applications to mature equipment standards, certification guidance, and operational approval guidance to enable NAS-wide ADS-B In implementation.
3. The ARC also reviewed and ranked ADS-B In applications listed in the FAA's Application Integrated Work Plan in order of maturity, operational impact, and level of interest from operators.

In response to direction from Congress in the 2012 FAA Reauthorization Act, the FAA extended the ARC's charter to "submit additional recommendations on how to frame an ADS-B In equipage mandate such that the benefits exceed costs before 2035" [ADS-B In ARC Report, 2012]. The ARC's recommendations are quoted here:

> *The ARC finds a subset of airports with high air traffic density in their terminal airspace and surface domain will generate most of the economic benefits from ADS–B In applications.*
>
> *Because of funding uncertainty, the need for mature MOPS and TSOs for key applications, and the length of time needed to develop and deploy equipage for affected aircraft, the ARC finds that any ADS–B In required equipage is unachievable by 2020.*
>
> *The ARC recommends the FAA focus funding on accelerating the development of equipment standards, certification guidance, operational approval guidance, ground automation, and any necessary policy adjustments to enable operational implementation (NAS-enabled) of key ADS–B In applications and/or enabling capabilities. If ADS–B In technology reaches an acceptable level of maturity, the FAA conducts flight trials for a sufficient number of ADS–B In applications to validate the utility of operational concepts and validate the benefits case, and the FAA contemplates proposing an equipage rule for ADS–B In for those specific*

applications, then this ARC recommends the FAA establish a new ARC early enough in the process to leverage the industry's view of a proposed equipage rule for ADS–B In. At this time, the ARC recommends no ADS-B In equipage mandate be proposed by the FAA.

The ARC urges the FAA to seek, and Congress to provide, the funds needed to reduce these uncertainties and thus build confidence in the substantial related investments by the operator community if a future mandate is considered.

Reference: ADS-B In ARC Report, 2012

In summary, the ADS-B Out mandate was affirmed by the ADS-B In ARC under the premises that ADS-B Out, primarily benefitting the ATC infrastructure and general aviation community, was a prerequisite to ADS-B In applications that would bring benefits to airline/business operators. However, as summarized in the ARC Reports of 2011 and 2012, the avionics standards and ADS-B In application benefits needed to be further developed and demonstrated to motivate airlines to equip with ADS-B In. The 2012 ARC Report also included an ADS-B In business case (see Appendix J in the ARC report), which did not show a satisfactory return on investment within the period that operators require (i.e., the cost of equipage and installation used in the business case analysis in 2012 could not be amortized in a reasonable timeframe).

2.3 Ongoing FAA and Industry Coordination

Since the 2012 ARC report, the FAA and its partners have continued to research and develop ADS-B In applications.

- The FAA and industry partners have continued to evaluate benefits.
- Avionics and aircraft manufacturers and airline operators have continued their engagement with the FAA through avionics standards development, flight demonstration activities, and FAA/industry forums like the NextGen Advisory Committee (NAC) and various NextGen Implementation Working Groups (NIWGs).
- Boeing, Airbus, ACSS, Honeywell and Collins Aerospace have all developed certified ADS-B In equipment and applications (see Appendix C).

Through continued development and evolution, original equipment and retrofit costs have dropped significantly since estimates at the time of the ADS-B In ARC in 2012. New benefit-to-cost (B/C) ratios, relating the airline direct operating cost benefits to the cost to equip aircraft with ADS-B In avionics, have been estimated between 1.4 to 4.5 depending on equipage timelines, retrofit versus new production aircraft, and industry feedback on equipage costs. More detail on the cost/benefit analysis is in Section 4 and in [Howell, 2019].

3 Interest from Airlines and Aircraft and Avionics Manufacturers

Airline interest in ADS-B In applications is primarily driven by an interest in achieving VMC arrival rates in conditions that prevent visual separation today. With improved arrival rates in non-visual conditions, airlines will be able to maintain schedule integrity and reliability a higher percentage of the time.

Several ADS-B In applications offer the promise of improved arrival rates with varying levels of complexity. Because CAVS does not require changes to ATC automation, airlines may equip and accrue some benefits immediately. Additional operational uses of the CAVS avionics increase operational availability to more

weather conditions but will require ATC automation changes to inform the controller which aircraft are eligible to receive the “own separation" clearance. IM offers significant benefits in high-density operations and in IMC but requires more significant changes to ATC automation systems to achieve those benefits. Applications such as CAVS may offer interim benefits while the NAS evolves to TBO, which is a necessary step in achieving the ultimate benefits available with IM.

3.1 What have airlines and aircraft and avionics manufacturers done?

Some OEMs have already developed ADS-B In applications that are offered as priced options on new production aircraft, and avionics manufacturers have some retrofit options (see Appendix C). Airlines remain interested in the potential benefits of ADS-B In and are encouraging the FAA to continue its development and funding towards implementation and deployment. Over the past decade, airlines, aircraft manufacturers, and avionics manufacturers have partnered with the FAA and NASA to further understanding of ADS-B In operations through flight tests, field or operational trials, and demonstrations.

As noted in Section 1.2.4, the FAA and United Airlines conducted an operational evaluation of the ITP application in 2011. The UPS M&S field trial in 2010, the NASA ATD-1 flight test in 2017, and the PA Demo in 2019 (all described in Section 1.2.5) leveraged government/industry partnerships to move the IM concept forward.

The FAA also partnered with US Airways and ACSS around 2010 to demonstrate use and benefits of CAVS operations. While the activity provided some feedback on benefits and pilot and ATC operational acceptability, the limited number of ADS-B Out-equipped aircraft ultimately led to few opportunities to use the CAVS avionics capabilities. When US Airways merged with American Airlines, there was continued interest in the CAVS and IM applications. American Airlines renewed the collaboration with the FAA and ACSS under the ADS-B In Retrofit Spacing (AIRS) Evaluation and is planning to equip American Airlines’ entire fleet of Airbus A321s (over 300 aircraft) with CAVS and Initial-IM avionics. American Airlines will begin equipping their aircraft in late 2019/early 2020, and CAVS operations can begin wherever the equipped American A321s fly. Initial-IM operations will begin in the Albuquerque Air Route Traffic Control Center when a critical number of aircraft are equipped to enable regular use of the capability.

3.2 What are these stakeholders waiting for?

Despite the successful flight test and demonstration activities, questions still linger about the feasibility and achievability of IM in a real-world environment when subject to uncertainties due to weather and ATC procedures. To achieve the full benefits of IM in high-density operations, the TBO framework[10] must be in place and ATC automation must be updated to accommodate IM operations. The airlines recognize that TBO is a very different way of operating compared to the ATC system today, and therefore, poses risk to the foundation on which IM benefits have been quantified. If TBO capabilities do not perform as expected or are deployed to fewer sites in the U.S. NAS than planned, IM operations and/or benefits may be limited.

The numerous flight tests, demonstrations, and operational trials have demonstrated that flight-deck capabilities can achieve the desired spacing precision and objectives. However, there is skepticism as to whether the systemic changes that are necessary to implement IM in high-density operations at all

[10] TBO involves sequencing aircraft starting in en route airspace so that aircraft may remain on their PBN arrival procedures into the terminal area using speed alone to fine tune inter-aircraft spacing.

capacity-constrained airports in the NAS will be achieved. This skepticism makes airlines cautious about investing in the flight-deck equipage without seeing evidence that the FAA's TBO plans and timelines are realistic and being achieved.

From the OEM perspective, commitment to developing ADS-B In applications like CAVS is easier to justify than IM, since CAVS benefits do not rely on the air navigation service provider to update ATC automation systems. As soon as aircraft are equipped and flight crews are trained, operations may begin, and benefits are accrued. OEM investment in IM applications requires confidence and evidence that the TBO foundation and updated ATC automation will be deployed on the planned schedule.

From a technical development perspective, service bulletin retrofits of the existing fleet of a particular aircraft model (e.g., Boeing 737 MAX) are straight forward after the ADS-B In capability has been developed and certified in production. It is more difficult for an OEM to develop a service bulletin retrofit offering for an aircraft model which never had a certified ADS-B In capability in production, such as the Boeing 737NG.

From the aircraft integration perspective, some aircraft and avionics manufacturers have noted the ADS-B In development challenge is primarily in the area of display and control interfaces. Older aircraft tend to have displays and control systems which are more difficult (and costly) to modify for presenting ADS-B In applications in the forward field of view. In addition, the complexity and cost of aircraft integration may go up rapidly if new interfaces are required to the Flight Management System and/or Flight Control systems.

3.3 What needs to happen?

For the airlines to overcome their skepticism about ADS-B In benefits and the FAA's commitment to making the necessary ATC automation and operational changes, a large-scale demonstration of TBO and ADS-B In applications is needed.

American Airlines' recent decision to equip over 300 aircraft with ADS-B In avionics for the AIRS Evaluation provides a fleet of ADS-B In equipped aircraft that may be leveraged for a large-scale demonstration. A large-scale demonstration should go beyond what is already planned for the AIRS Evaluation by integrating the use of CAVS and IM with ATC automation systems. Other operators may also choose to equip a portion of their fleet if the FAA commits to conducting a large-scale demonstration. This integrated air/ground demonstration should take place over a long enough period to gather data showing system benefits and benefits to the operator.

For the aircraft manufacturers, a firm understanding of the real benefits of ADS-B In applications will support a business case assessment for each aircraft model to determine offerability and appropriate pricing of ADS-B In features.

Provided a positive outcome of this large-scale operational demonstration, the FAA should ensure support of ADS-B In applications and operations by developing a roadmap for updating ATC automation systems, training the operational workforce, and deploying new procedures to leverage ADS-B In applications.

4 ADS-B In Benefits

4.1 Benefits Mechanisms

ADS-B In benefits derive from the more-precise inter-aircraft spacing that is possible with a relative, flight-deck spacing application. Precise spacing at key points in the arrival flow allows aircraft to remain on their planned PBN procedures, reducing off-path, controller-directed deviations, leading to fuel savings. It is estimated that improved spacing at key points in the airspace will support PBN conformance when the airport is operating between 40 and 70% of its maximum arrival capacity. When demand exceeds 70%, flight-deck spacing tool are needed to provide the necessary precision for PBN conformance [FAA, 2012]. Arrival traffic that enters the terminal area with improved spacing will allow controllers to avoid issuing instructions to vector and/or maintain fuel-wasting level offs during airport approach operations [Shresta, 2009].

Relative Spacing, as enabled by CAVS and IM, provides benefit by reducing the number of errors that must be accounted for when spacing two aircraft. *Relative Spacing* is contrasted with *Absolute Spacing* in the figure to the right. In *Absolute Spacing*, each aircraft is aiming to cross a specified point at its Scheduled Time of Arrival (STA). The error in each aircraft meeting its STA, as shown by the red error distributions, must be considered when determining the STAs. Whereas when using *Relative Spacing*, the trailing aircraft's spacing is based on the lead aircraft's *Actual* Time of Arrival (ATA). Therefore, only the error in meeting the relative spacing interval, as shown by the blue error distribution, must be considered, allowing aircraft to be spaced closer together.

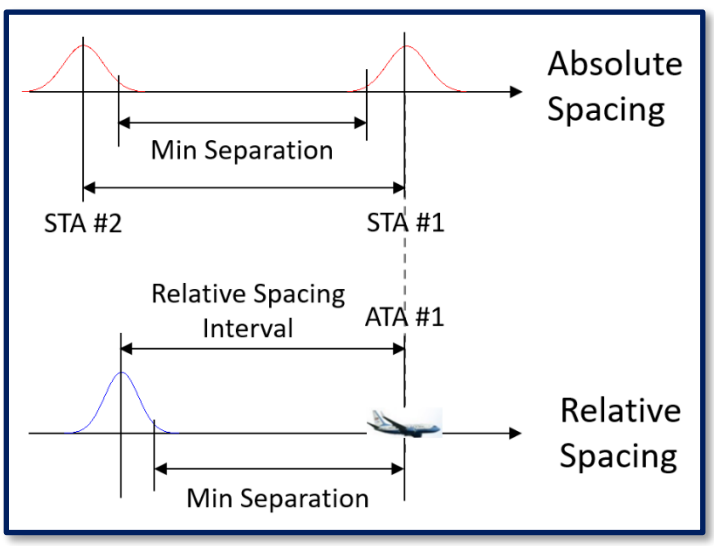


Figure 9. Comparing absolute and relative spacing and the impact errors have on the schedule.

Spacing management tools can reside "on the ground" in ATC automation or "on the flight deck" as an avionics capability. Spacing management is inherently a "closed-loop" capability, where guidance to meet a spacing objective is updated as the information used to compute the guidance evolves. For example, the Estimated Time of Arrival (ETA) at a downstream point is updated as the flight progresses, and guidance should be updated as the ETA deviates from the flight's STA. Flight-deck spacing management tools are expected to provide improved precision in meeting a spacing objective as guidance can be updated more frequently when provided directly to the flight crew. The Required Time of Arrival (RTA)

function in the Flight Management System (FMS) is an example of an absolute, flight-deck-based application, which determines speeds to cross a point at a specified time. Flight-deck tools are compared to an air traffic controller that may be managing several flights at the same time using ground-based tools. For a single aircraft, the air traffic controller would need to recognize the need to intervene in an aircraft's trajectory, interpret the information provided by the ATC automation, communicate a trajectory intervention (speed or path change) to the flight crew, and the flight crew would need to accept the trajectory intervention and implement it on their flight deck. When comparing the two spacing management approaches, it is easy to see how flight-deck capabilities can provide greater precision through more frequent updates with fewer delays.

Spacing Tool Domain	Type of Spacing: Absolute	Type of Spacing: Relative
Ground Based	**TBFM, TSAS**	**Radar-based Separation, CRDA, MIT**
Flight-deck Based	**RTA**	**Visual Separation, CAVS, IM**

TBFM and TSAS *– provide STAs and Decision Support Tools to manage flights to their STAs; TSAS is Terminal Sequencing and Spacing and refers to the tools in the terminal environment.*

CRDA *– Crossing Runway Display Aid provides a relative position behind another aircraft for crossing or converging runways.*

MIT *– Miles in Trail is a distance-based relative spacing.*

Figure 10. Spacing concepts and their mapping to the spacing tool domain (ground based or flight-deck based) and type of spacing (absolute or relative spacing).

4.2 Benefits Pool

With all the operational and technological changes planned as a part of TBO, airlines are asking whether any arrival and approach benefits will remain after TBO capabilities, such as en route and terminal metering, are deployed. Benefits research by the FAA and EUROCONTROL shows there is a unique benefits pool for ADS-B In applications.

Comparing "ideal" flight times in 2025 (assuming no delays between origin and destination) and current flight times (including airborne and ground-based delays), 17.4% of current flight times can be attributed to delays [FAA, 2016]. According to a 2015 study, the mean excess delay is 11.4 minutes per flight [FAA/EUROCONTROL, 2015]. It should be noted that this delay is averaged over all aircraft arriving to the top-30 airports in the U.S. NAS. While some aircraft have larger delays and some have smaller delays, considering only those aircraft arriving to top-30 airports is a way to identify those flights more likely to receive delays in high-density operations. Reference [FAA/EUROCONTROL, 2015] also suggests 38%, or 4.3 minutes per flight, of the total delay is attributed to airborne delays.

Delays are expected to increase to 15.5 minutes per flight by 2025 [FAA, 2016]. Assuming the proportion of airborne delay remains constant at 38% (as estimated in [FAA, 2016]), 5.85 minutes of *airborne* delay per flight is expected in 2025 (the remainder of the delay is on the ground due to inefficient taxi times,

for example). NextGen improvements, such as ATC automation improvements for en route and terminal metering and wake recategorization, are expected to reduce airborne delays by 1.75 minutes per flight [FAA, 2016]. This leaves 4.10 minutes of airborne delay per flight, which may be addressed by other applications, such as flight-deck ADS-B In applications. ADS-B In applications (CAVS, additional operational uses of the CAVS application, and IM) are estimated to further improve airborne delay by 1.15 minutes per flight [FAA, 2016]. Additional benefits resulting from incentives for equipped aircraft, such as exceptions from GDPs, have not been modeled. It is expected that these additional incentives would increase the ADS-B In applications delay savings to more than 1.15 minutes per flight.

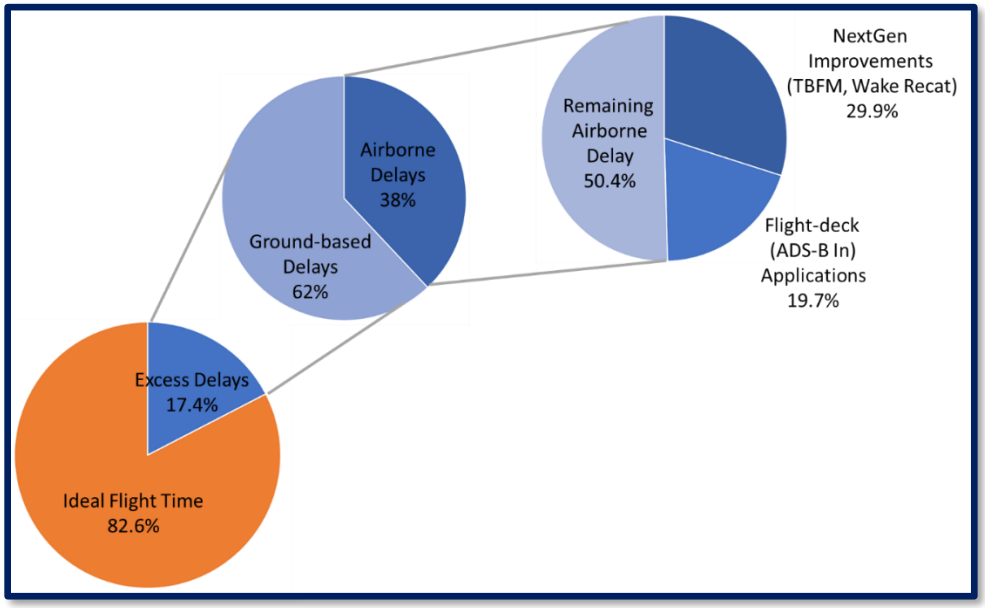


Figure 11. Remaining shortfall in airborne delays that may be addressed by ADS-B In applications.

The figure below [FAA, 2016] shows the estimated delay by year (brown line), assuming no changes to the current system, and the delay reduction when NextGen capabilities (without ADS-B In applications) (blue line) are deployed through 2030. The blue line includes changes to ATC automation enabling TBM and Data Comm. The green dot in 2025 shows the data point where the additional delay savings for ADS-B In applications was simulated. The green line assumes the incremental delay savings remains constant relative to the NextGen-enabled capabilities.

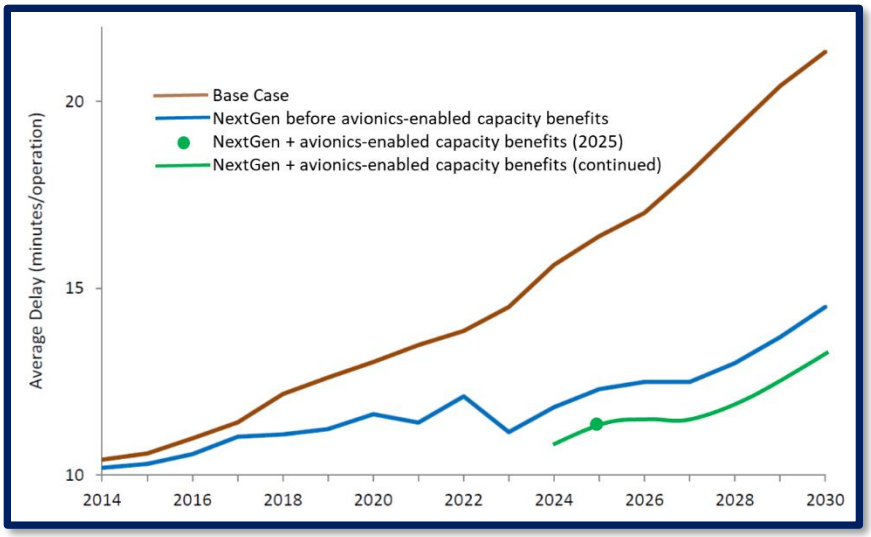


Figure 12. Average delay by flight when ADS-B In applications are implemented.

4.3 NAS-Wide Benefits

The FAA recently updated the ADS-B In benefits and cost analysis to align assumptions with new developments since the 2012 ADS-B In ARC report was published. The benefits case translates improved delivery at the runway into a throughput increase and resulting delay savings at the top-30 airports using Time-based Management (TBM). A full description of the benefits and cost analysis is provided in [Howell, 2019].

There were two key phases to the benefits analysis. First, arrival/departure curves were developed for IMC, VMC, and Marginal Meteorological Conditions (MMC) assuming smaller spacing "buffers" at the runway due to the improvements enabled by IM and using visual-like separation for CAVS and additional operational uses of the CAVS application in less-than-visual conditions.[11,12] In the second phase, those arrival/departure curves were input to a system-wide model of the NAS, called System-Wide Analysis Capability (SWAC), which models U.S. en route and terminal airspace, airports, weather conditions, air-carrier operating practices, and ATC procedures. The SWAC simulation produces the following outputs per flight:

- Delay at the gate
- Delay on the ground
- Delay in the air
- Cancellation (Yes/No)

The delays are calculated compared to an optimal flight flown on the flight plan as opposed to using scheduled times to manage progression along the flight plan.

[11] Because of the way the CAVS improvements were modeled, a significant portion of the resulting benefits are attributable to using the CAVS application in less-than-visual conditions (referred to as MMC here).

[12] More information on how improved spacing precision enables smaller spacing buffers and throughput improvements can be found in Appendix E.

Table 2 presents the estimated increase in maximum arrival throughput at the top-30 airports as compared to the baseline assumptions of a TBM environment using ground-based metering tools in en route and terminal airspace [Howell, 2019]. Same runway benefits were estimated for all airports. Benefits for the dependent runway applications (DSA, DCCR, and PA) were estimated if the airports are expected to use those IM applications based on possible runway geometries and current operations.

Table 2. Estimated Increase in Arrival Throughput as Compared to Baseline

Airport	SR (VMC, MMC, IMC)	SR+DCCR	SR+DCCR+DSA/PA
ATL	12%, 13%, 10%		
BOS	5%, 6%, 1%	MMC 12%, IMC 10%	IMC 15%
BWI	16%, 12%, 9%		
CLE	13%, 14%, 10%		
CLT	13%, 11%, 10%		
CVG	13%, 14%, 11%		
DCA	11%, 14%, 11%	VMC 14%, MMC14%	
DEN	14%, 14%, 11%		
DFW	14%, 14%, 11%		
DTW	14%, 6%, 5%		
EWR	9%, 4%, 1%	VMC 12%	MMC 35%, IMC 36%
FLL	0%, 2%, 2%		
HNL	19%, 19%, 15%	20%, 23%, 18%	
IAD	13%, 12%, 11%		
IAH	5%, 0%, 3%		
JFK	13%, 6%, 10%		
LAS	14%, 16%, 12%	MMC 17%	
LAX	12%, 12%, 10%		
LGA	14%, 14%, 12%		
MCO	13%, 14%, 11%		
MDW	26%, 26%, 24%		
MEM	12%, 10%, 10%	VMC 12%, MMC10%	
MIA	12%, 13%, 12%	12%, 13%, 12%	
MSP	6%, 11%, 10%	VMC 6%, MMC 11%	
ORD	13%, 13%, 10%		
PDX	13%, 13%, 10%		
PHL	21%, 10%, 4%	21%, 10%, 4%	
PHX	14%,0%,0%		
PIT	28%, 29%, 24%		
SAN	13%, 11%, 9%		
SEA	10%, 8%, 7%		MMC 9%, IMC 7%
SFO	11%,0%,0%		MMC 18%, IMC 31%
SLC	18%, 18%, 15%		
STL	9%, 0%, 6%		MMC 13%, IMC 7%
TPA	29%, 17%, 15%		

The monetized benefits were calculated for two equipage schedules [Howell, 2019]: (1) a baseline equipage projection based on American Airlines planned A321 equipage for the AIRS Evaluation and the

IM standards document timeline, and (2) an early-adoption schedule. Delays from the SWAC model are monetized using variable Aircraft Direct Operating Costs (ADOC) and Passenger Value of Time (PVT) [FAA Investment Planning]. Values for ADOC (fuel, crew, maintenance) per hour differ by aircraft type and phase of flight. The benefits in 2025 by ADS-B In application are linearly related to aircraft equipage (right).[13] CAVS benefits comprise about 1/8th of the CAVS plus IM Same Runway (SR) benefits. The addition of DCCR and PA/DSA provides an incremental benefit beyond the IM SR benefits. It should be noted these benefits do not include benefits due to equipage incentives like exceptions to GDPs.

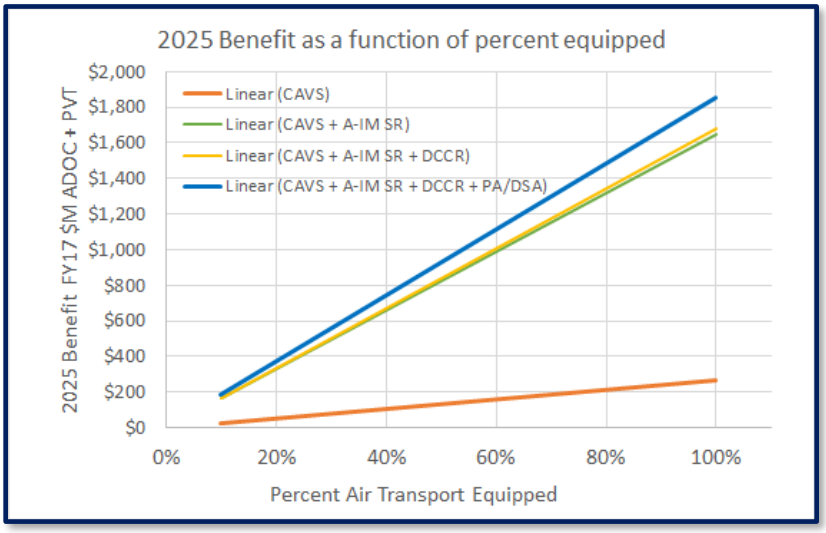


Figure 13. Benefits by equipage percentage assuming different ADS-B In applications are implemented.

The lifecycle costs based on the projected and early-adoption equipage assumptions are shown below. The benefits attributed to "Enhanced TBFM" describe the baseline environment with en-route and terminal TBM. The most significant portion of benefits comes from IM SR. While the DSA, DCCR, and PA benefits are smaller, fewer airports operate in these runway configurations today. IM may ease the use of these dependent runway configurations, resulting in greater utilization, which may provide an additional benefit not captured in this analysis.

[13] The linear relationship between monetized benefits and equipage rates was found by running the SWAC simulation with different equipage rates and evaluating the benefits.

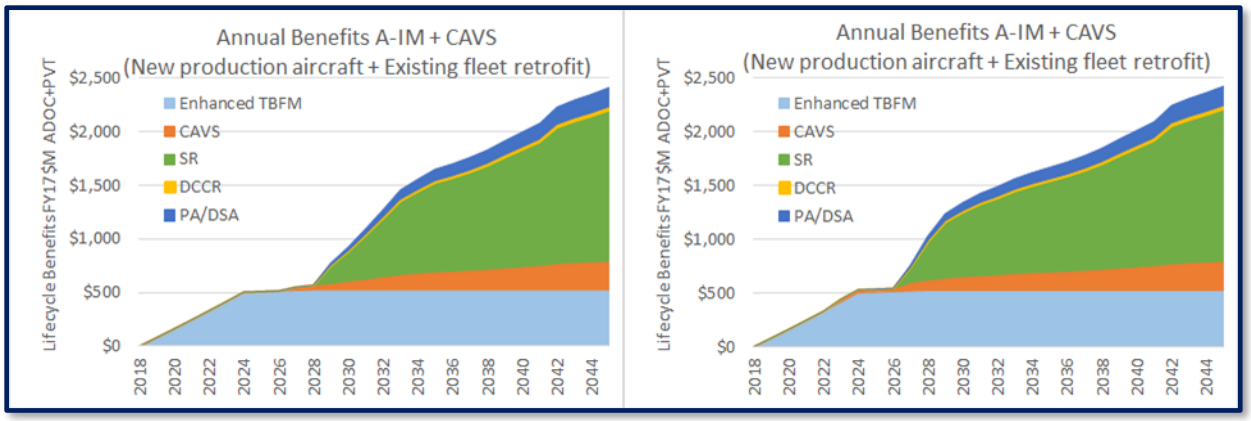


Figure 14. Baseline equipage assumptions (left) and Early-adoption equipage assumptions (right).

A survey of major avionics vendors and OEMs was conducted in 2018 to gather inputs on ADS-B In unit costs, including procurement and installation. The ADS-B In unit costs varied widely depending on application, airframe, and whether the aircraft receives the application during production or as a retrofit. In the 2018 survey, some manufacturers reported much lower retrofit costs as a result of continued research and development since the 2012 ARC ADS-B In ARC report was published.

Table 3 shows the B/C ratios for new production and retrofit installations for ADOC only, which is the airlines' primary benefits metric. Table 3 also compares the B/C ratios for average installation costs (second column) and for the most optimistic costs estimates received (third column), which reveals the variation in cost estimates. The optimistic cost assumes that low-cost, non-integrated avionics are used across the board for retrofit. Therefore, benefits can be reaped early for the fleet in operation while integrated avionics progressively become available on new delivery aircraft. The data in Table 3 is based on lifecycle costs through 2045; new production aircraft are assumed through 2045; and, the retrofit estimates were applied to those aircraft retrofitted from no ADS-B In applications to CAVS and IM over a seven-year period (2029-2035 for the baseline equipage assumptions and 2025-2031 for the early-adoption equipage assumptions)[14] [Howell, 2019]. B/C ratios vary from 1.4 to 4.5, suggesting ADS-B In application benefits outweigh the equipage costs for the airline operators.

Table 3. Benefits-to-Cost Ratios Based on Lifecycle Benefits and Estimated ADS-B In Costs

Fleet Type	B/C ADOC Only Using Average Costs	B/C ADOC Only Using Optimistic Costs
Baseline Equipage Projection		
New Production	2.1	4.1
Existing Fleet Retrofit	1.4	3.3
Early Adoption Equipage Projection		
New Production	2.4	4.5
Existing Fleet Retrofit	1.7	3.9

[14] Regional airlines are also assumed to equip according to the equipage projections. Business jet operators were not included.

5 Vision of ADS-B In within a TBO Framework

TBO is the FAA's future vision to integrate Time-Based Management (TBM) and Performance-based Navigation (PBN) to increase throughput, efficiency, flexibility, and incorporate user preferences in the U.S. NAS during high-density operations [FAA TBO Vision, TBO Storyboard].

TBM provides a fundamental change from traditional air traffic management approaches, where ATC uses distance and Miles-in-Trail (MIT) to manage inter-aircraft separation and flow rates into high-density airspace. With the deployment of TBM, ground-based automation will schedule flights to different points in the airspace, deconflicting schedules at merge points to support controllers in managing separation between flights. ATC will use information provided by Decision Support Tools (DSTs) on the ground to manage flights to their scheduled times.

PBN procedures define a three-dimensional path (i.e., a horizontal path over the ground and a constrained altitude profile). Aircraft that are appropriately equipped with a Global Positioning System (GPS) and surveillance-monitoring equipment can file to fly a PBN procedure. Required Navigation Performance (RNP)-equipped aircraft may be approved to fly procedures and approaches which reduce track miles flown and provide more direct paths to the runway. PBN procedures also include airspeed constraints that provide more consistent flight times between different aircraft types, which improves flow management during high-density arrival operations.

Initial TBO (iTBO) deployment in the 2020-2025 timeframe will focus on ATC automation systems that support the operational transition to TBM. Strategic traffic flow management will improve planning to address demand/capability imbalances, and air traffic controllers will leverage DSTs to manage flights to time-based schedules, aiming to minimize airborne delays and inefficient vectoring. Advanced flight-deck capabilities, such as ADS-B In avionics functions and RTA, will be integrated into the TBO concept in later (post-iTBO) phases.

ADS-B In applications, such as CAVS and IM, are in line with the objectives of TBO, providing greater inter-aircraft precision needed to maximize TBO benefits during high-density operations [FAA TBO Vision].

CAVS supports more consistent visual separation, allowing visual separation to continue even if the flight crew loses the out-the-window view of the preceding aircraft. Other operational uses of the CAVS application could extend the use of the CAVS application to lower weather minimums, increasing the opportunity to conduct visual separation and allowing aircraft to get closer than the separation standards employed in IMC. IM provides highly accurate and repeatable inter-arrival times on final approach during virtually all weather conditions. Additionally, IM operations can be used to more precisely space aircraft throughout the arrival and approach operation, helping ATC in meeting their operational objectives in other phases of flight. Past work to integrate IM with TBM and PBN concepts, such as the IM and Terminal Sequencing and Spacing (TSAS)[15] integration HITL, has demonstrated that IM can be used in concert with planned iTBO capabilities [Bone, 2018].

[15] TSAS refers to automation enhancements enabling terminal time-based metering operations.

To take advantage of the precision enabled by these ADS-B In applications, TBO systems must account for ADS-B In equipage and support ATC in leveraging the advanced flight-deck capabilities.

5.1 Incorporating Advanced Flight-deck Capabilities

Flight-deck capabilities, such as IM and RTA, will provide more precise spacing accuracy at points in the airspace as the speed guidance, provided directly to the flight crew, responds to errors resulting from wind forecast and other modeling uncertainties as they arise during an operation. It will be difficult for ATC to respond to these uncertainties with the same level of precision given the time needed for:

- ATC to recognize the need for a corrective action,
- ATC to determine the appropriate action,
- ATC to communicate the speed or path change to the flight crew,
- the flight crew to acknowledge and accept the ATC-issued clearance, and
- the flight crew to implement that clearance in the flight-deck automation.

Because IM is a relative spacing application, IM operations are responsive to how the Target Aircraft meets its STA at a downstream point. If the Target Aircraft is late when meeting its STA, the IM Aircraft will adjust its spacing accordingly, which helps prevent the IM and Target Aircraft from being too close.[16] This behavior may be particularly important in terminal metering operations when ATC does not necessarily drive aircraft to schedule times but may use DST display elements to manage relative spacing between aircraft [Bone, 2018].

IM operations may transition to CAVS on final approach in VMC, allowing the flight crew to manage separation relative to the preceding aircraft. Other operational uses of the CAVS application may allow visual-like separation in less-than-visual conditions, allowing throughput improvements in those conditions. In a TBO environment, the use of the flight-deck capabilities can help improve throughput and efficiency through increased opportunities to use visual-like separation, while also reducing the frequency of missed approaches due to the loss of visual contact with the preceding aircraft via the use of cockpit displays and alerting.

5.2 Phased Deployment of ADS-B In Operations

CAVS operations can be conducted today without any new ATC automation or procedures. Flight crews may use the CAVS avionics functions whenever they receive a visual separation instruction from ATC. Increased use of CAVS avionics, as operators equip and train their flight crews, should be evaluated to understand the impact on TBO benefits and resiliency.

TBO deployment of ATC automation systems supporting ADS-B In applications will take place over many years. A phased approach, with each phase increasing the complexity of operations, has been proposed by the FAA.

5.2.1 Tactical ADS-B In Applications (Estimated Start of Operations in 2025)

In the first phase (Phase A), operations will be more tactical in nature with ATC automation providing indications of ADS-B In equipage.

[16] ATC may clear a series of IM-equipped aircraft to conduct IM operations. The FIM avionics standards have taken special care to address "string behavior," preventing IM aircraft farther back in the string from continuously speeding up and slowing down (behavior we have all observed when driving on a busy highway).

ATC is expected to need only an indication that an aircraft is equipped with the CAVS avionics functions to provide the "own separation" clearance. Therefore, additional operational uses of the CAVS equipment would be enabled once the ADS-B-In equipage indication is available and ATC is trained. These operations will extend the use of visual-like approach operations in less-than-visual conditions, providing throughput improvements.

Relatively few ATC automation changes may enable near-term, tactical initiation of IM operations. An indication of those aircraft equipped with FIM avionics will allow ATC to initiate en route direct-to-merge operations or in-trail spacing on an arrival procedure. With information from the TBM schedule (i.e., sequence and difference in schedule times at a common point), ATC could issue simple IM clearances to achieve the spacing at a downstream meter point. However, fewer automation changes may limit the potential IM operations. For example, initiation of IM operations may be limited to aircraft pairs in the same sector.

An indication of IM equipage in the terminal ATC automation may enable ATC to tactically initiate operations to closely spaced parallel runways, like the arrival runways at SFO. In non-visual conditions, ATC may apply the JO7110.308C separation standard, which defines the stagger separation rules for dependent arrivals to runways spaced less than 2,500 feet. IM can help precisely manage the stagger relative to the leading aircraft on the parallel runway, alleviating ATC workload, reducing the current spacing buffers applied to the stagger, and improving throughput by increasing the use of dependent runway operations in non-visual conditions.

5.2.2 IM Operations in a TBM Environment (Estimated Start of Operations in 2028)

In the second phase (Phase B), IM operations will be more fully integrated with the TBM automation. The ATC scheduling functions could schedule aircraft closer together based on aircraft equipped with the CAVS and/or IM avionics functions, yielding greater throughput benefits through use of advanced flight-deck capabilities.

IM operations in a TBM environment, where operations are initiated in en route airspace and merging in the terminal, require ATC automation to determine viable IM clearances and provide them to the controller. The IM operational state (e.g., available, active, or terminated clearance) and an indication of those aircraft that are serving as Target Aircraft in IM operations must be clearly indicated to ATC. This environment will enable IM operations to begin as soon as aircraft are within ADS-B range, so aircraft may be spacing from opposite sides of the terminal area and may be in different sectors at the time of initiation.

A third phase (Phase C), is proposed for the IM PA application. Because this application requires changes to underlying separation standards and additional changes to ATC automation in the terminal, it has been included in a later phase following successful deployment of Phase B.

5.2.3 IM Operations in a Dynamic TBO and Data Comm Environment (Unknown Timeline)

More complex IM operations are possible when Data Communications are available to enable clearances which are too complex for the voice environment. For example, IM could be used on dynamic routes designed to avoid weather. As TBO operations become more complex, IM operations can also increase in complexity to provide precise spacing along defined routes, whether those routes are defined by published procedure or dynamically determined.

The use of Data Communications for IM clearance delivery and flight-crew responses is considered a future phase as the timeline for support of the IM messages defined in ATN B2 is unknown at this time.

6 Industry Roadmap for Future Development

Stakeholders in the development and deployment of ADS-B In applications include the aircraft operators, the air navigation service provider (FAA), the regulator (FAA), the aircraft manufacturers (OEMs), and the avionics suppliers. All stakeholders must be involved in the successful implementation of ADS-B In applications.

The following points summarize past challenges in deploying ADS-B In applications:

- The FAA has struggled with reliable and consistent funding for the development of the applications and the ATC automation systems to support ADS-B In applications.
- The operators have had difficulty in making the business case for investment in ADS-B In equipage and applications given the uncertainty in the FAA's commitment to invest in the necessary ATC automation systems.
- OEMs did not have a business case to invest in the implementation of ADS-B In equipage and applications on new (and retrofit) aircraft, and
- The avionics suppliers did not have their own business case to invest in the development of ADS-B In equipage and applications, which requires development of hardware, software, and human/machine interfaces.
- All four entities have had difficulty in making the commitment to invest in ADS-B In equipage and applications without an operational demonstration of the benefits.

All stakeholders must work together to develop a roadmap for deployment in the U.S. NAS that leads all sides to invest.

As noted, some OEMs and avionics manufacturers are already offering certified ADS-B In applications for some new production and retrofit aircraft. Some of those offerings improve flight-deck situation awareness through traffic displays made possible by ADS-B. The ITP and CAVS applications provide direct benefits to the operators as soon as the first aircraft is equipped. The necessary changes to the U.S. oceanic ATC automation systems and procedures have already been made for ITP, and no automation or procedures changes are needed to begin CAVS operations. Therefore, equipped aircraft may obtain those associated benefits today. If the ATC automation systems and procedures are in place, early CAVS (and additional operational uses of the CAVS application) and IM benefits could be accrued using non-integrated avionics architectures through retrofit installations on existing fleets. Retrofit aircraft would accelerate the overall equipage rate and would leverage the airlines' investments until integrated architecture / forward-fit solutions become available for new production aircraft.

As the CAVS application does not require changes to the FAA's ATC automation systems, the use of CAVS is a logical first step in introducing the use of the avionics to flight crews. With regular use, it is expected that operational benefits will be observed. Additional operational uses of the CAVS application will require ATC automation changes to indicate equipage to ATC, but those aircraft equipped with CAVS could conduct those additional operations once the ATC automation has been updated.

As the airlines see benefits from CAVS and additional operational uses cases of the CAVS application, they will consider software upgrades to include IM applications. The airlines have clearly stated that the FAA must commit to:

- investing in the ATC automation changes needed to support IM operations and
- following through with the operational changes that come with IM before further investment by the airlines.

These operational changes will require ongoing community engagement to develop safety risk management studies, phraseology, procedures, and pilot and controller training.

An evolutionary deployment strategy is needed to smartly introduce IM operations to the NAS. Initial operations (e.g., Initial-IM through the AIRS Evaluation and ADS-B In Phase A) should be simpler to allow ATC and flight crews to gain trust in the use of the avionics. Phase A, for example, involves initiating IM operations in the same en-route sector and continuing the spacing operation if the aircraft remain on the same route (including into other sectors). Tactical initiation in the terminal could enable high-benefit applications, such as the use of IM to closely spaced parallel runways at SFO. As trust is gained, more complex operations (e.g., ADS-B In Phase B and Phase C) may be introduced. More complex operations in Phase B allow IM initiation when the aircraft are in different sectors and would support lead/trail pairs going to different runways at the same airport. Phase C introduces Paired Approach operations, enabling the spacing precision needed for new separation standards to dependent runways spaced less than 2,500 feet apart. Later phases (beyond Phase C) would include the use of Data Communications to enable IM operations on dynamic routes around weather.

The figure below lays out a feasible timeline for developing and deploying ADS-B In applications in the U.S. NAS, aligning timelines for concept development (gray boxes), development of avionics standards (green boxes)[17], development of ATC automation enhancements (blue boxes), and deployment of new operations (purple boxes). Those activities with dashed outlines indicate potential phases with undefined timelines currently; their placement on the timeline is notional and is intended to show relative timelines between development and deployment phases. Three FAA/industry milestones, or decision points, are noted by the black diamonds and specify events when the FAA and industry stakeholders should decide on a forward path for development and deployment. For the FAA, that forward path involves investing in ATC automation system enhancements to enable ADS-B In applications and the resources necessary to deploy those operations. For the industry stakeholders, that forward path involves developing the avionics, equipping aircraft, and training flight crews to enable the ADS-B In applications.

[17]The avionics standards documents for the Airborne Surveillance Applications (ASA) (DO-317()/ED-194()), which includes the requirements for CAVS, and Interval Management (DO-361()/ED-236) are currently being updated and will be published in 2020.

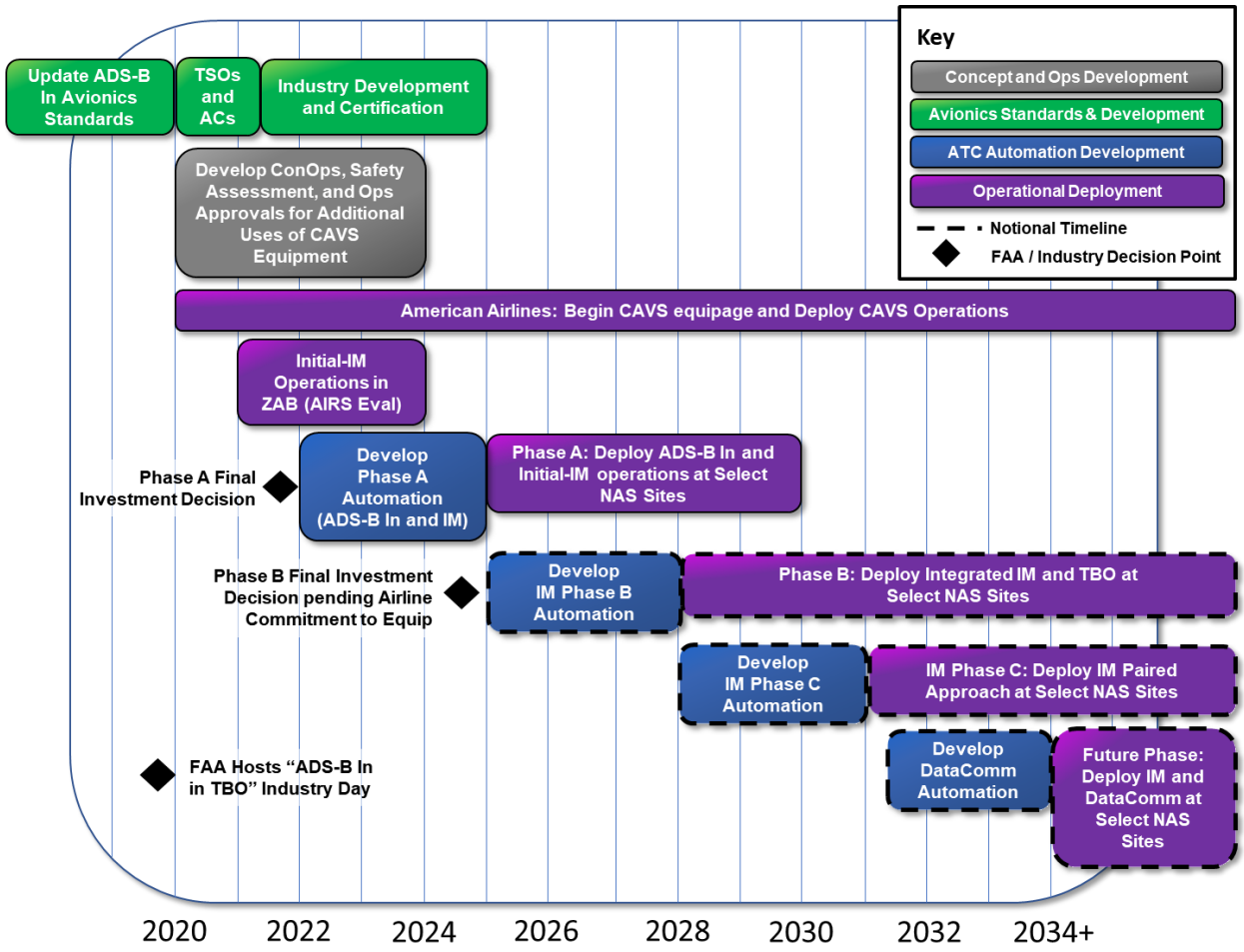


Figure 15. Notional roadmap for developing and deploying capabilities needed to enable ADS-B In applications.

All stakeholders must work together to develop a roadmap for equipage development and operational deployment in the U.S. NAS that leads all sides to invest.

A table summarizing the state of key ADS-B In applications, including the operators' required investments, FAA investments, the benefit mechanisms, and when those investments are expected making operations available, is provided in Appendix F.

The airlines would also like the FAA to consider incentives for equipage since IM operations also provide a system benefit through increased arrival throughput and reduced average delays. These equipage incentives could include exemptions from GDPs or additional arrival slots at busy airports where an equipped airline comprises a significant portion of arrivals.

7 The Necessary Foundation for ADS-B In Applications

For ADS-B In applications to achieve the expected benefits in high-density environments, TBO concepts must be successfully implemented and used in every-day operations. These include PBN arrival procedures that have defined paths through the descent and connect to the approach procedure for each arrival runway. Also, TBM systems must be deployed across the NAS, allowing ATC to begin pre-

conditioning flights such that speed adjustments alone can achieve the schedule and inter-aircraft spacing goals. Issues, such as how to handle close-in airport departures and procedures to accommodate go-arounds in a high-density TBM environment, need to be addressed and demonstrated in the TBO environment. Although these issues are not directly related to ADS-B In applications, such as IM, the integration of TBM and PBN forms the foundation of the TBO environment in which IM will be deployed. These challenges must be addressed for the operators to fully achieve ADS-B In equipage benefits.

References

[**ADS-B In ARC Report, 2011**] A Report from the ADS-B In Aviation Rulemaking Committee to the Federal Aviation Administration: Recommendations to Define a Strategy for Incorporating ADS-B In Technologies into the National Airspace System, Chairs: Steven J. Brown and Thomas L. Hendricks, September 30, 2011.

[**ADS-B In ARC Report, 2012**] A Report from the ADS-B In Aviation Rulemaking Committee to the Federal Aviation Administration: Recommendations in Response to the Federal Aviation Administration May 30, 2012 Tasking, Chairs: Steven J. Brown and Thomas L. Hendricks, October 31, 2012.

[**Barmore, 2016**] Bryan E. Barmore, William J. Penhallegon, Lesley A. Weitz, Randall S. Bone, Ian Levitt, Julie A. Flores Kriegsfeld, Doug Arbuckle, and William C. Johnson, "Interval Management: Development and Implementation of an Airborne Spacing Concept," in the proceedings of the AIAA Guidance, Navigation, and Control Conference, 2016.

[**Bone, 2015**] Randall S. Bone, Andrew S. Mendolia, and Eric Vallauri, "Air Traffic Controller and Flight Crew Conduct of a No-Closer-Than Spacing Task utilizing a Cockpit Display of Traffic Information", MITRE Technical Report, MTR150066, McLean, VA, 2015.

[**Bone, 2018**] Randall S. Bone and Andrew S. Mendolia, "Pilot and Air Traffic Controller use of Interval Management during Terminal Metering Operations," MITRE Technical Report, MTR170570, January 2018.

[**FAA, 2012**] Federal Aviation Administration, "Surveillance and Broadcast Services Benefits Basis of Estimate," May 2012.

[**FAA/EUROCONTROL, 2015**] Federal Aviation Administration and EUROCONTROL, "Comparison of Air Traffic Management-Related Operational Performance," August 2016.

[**FAA ITP Benefits**] Federal Aviation Administration-Surveillance and Broadcast Services (SBS) Program Office, "Automatic Dependent Surveillance-Broadcast In-Trail Procedures (ADS-B ITP) Operational Flight Evaluation: Economic Benefits Analysis Report," Washington, DC, December 2015; available online: https://www.faa.gov/nextgen/programs/adsb/media/ADS-BITPOpFlightEvalBenefitsReport.pdf.

[**FAA, 2016**] Federal Aviation Administration, "Update to the Business Case for the NextGen Air Transportation System based on the Future of the NAS Report," July 2016.

[**FAA Investment Planning**] Federal Aviation Administration-Investment Planning and Analysis, "Economic Information for Investment Analysis," June 2017.

[**FAA TBO Vision**] Federal Aviation Administration, "Vision for Trajectory-Based Operations," Version 2.0, September 2017.

[**FAA Storyboard**] https://www.faa.gov/about/office_org/headquarters_offices/ang/offices/tc/library/Storyboard/tbo.html

[**ITP SPR DO-312**] RTCA, "Safety, Performance, and Interoperability Requirements Document for the In-Trail Procedure in Oceanic Airspace (ATSA-ITP) Application," Washington, DC, June 2018.

[**Howell, 2019**] Dan Howell, Rob Dean, and Gary Paull, "Benefits and Costs of ADS-B In Efficiency Applications in US Airspace," submitted to the Air Traffic Management Research & Development Seminar, 2019.

[**Penhallegon, 2016**] William J. Penhallegon and Randall S. Bone, "Field Test of Interval Management-Spacing during an Optimized Profile Descent Arrival and Approach," MITRE Technical Report, MTR110426R1, McLean, VA, April 2016.

[**Richards, 2017]** William Richards, "ADS-B – A Boeing Perspective," ADS-B Implementation Meeting, November 2017.

[**Shresta, 2009**] Sanjiv Shresta and Ralf Mayer, "Benefits and Constraints of Time-based Metering Along RNAV STAR Routes," in the Proceedings of the 28th Digital Avionics Systems Conference, October 2009.

[**Swieringa, 2017**] Kurt A. Swieringa, Sara R. Wilson, Brian T. Baxley, Roy D. Roper, Terence S. Abbott, Ian Levitt, and Julien Scharl, "Flight Test Evaluation of the ATD-1 Interval Management Application," in the proceedings of the AIAA Aviation Forum, 2017.

Acronyms

ADS-B	Automatic Dependent Surveillance-Broadcast
AGD	ADS-B Guidance Display
AIRB	Airborne Situation Awareness Application
AIRS Eval	ADS-B In Retrofit Spacing Evaluation
ARC	Aviation Rulemaking Committee
ASG	Assigned Spacing Goal
ATA	Actual Time of Arrival
ATC	Air Traffic Control
ATD-1	Advanced Technology Demonstration-1
ATN B2	Aeronautical Telecommunications Network Baseline 2
B/C	Benefits-to-Cost
CAVS	CDTI-Assisted Visual Separation
CDTI	Cockpit Display of Traffic Information
CSPR	Closely Spaced Parallel Runways
DCCR	Dependent Crossing and Converging Runways
DSA	Dependent Staggered Approaches
FAA	Federal Aviation Administration
HITL	Human in the Loop
IM	Interval Management
IMC	Instrument Meteorological Conditions
ITP	In-Trail Procedures
MIT	Miles in Trail
MMC	Marginal Meteorological Conditions
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
PA	Paired Approach
PA Demo	Paired Approach Flight Demonstration
PBN	Performance Based Navigation
RNAV	Area Navigation
RNP (RF)	Required Navigation Procedure (Radius-to-Fix)
STA	Scheduled Time of Arrival
TSAS	Terminal Sequencing and Spacing
TBM	Time-Based Management
TBO	Trajectory-Based Operations
VMC	Visual Meteorological Conditions

Appendix A ADS-B Out Versions

As of mid-2019, there are three versions of ADS-B with different levels of performance:

> ***Version 0*** provides basic ADS-B capability with position integrity/accuracy provided by a parameter called navigation uncertainty category (NUC). This was the initial version of ADS-B, and there are a variety of Version 0 installations. Typically, only those ADS-B Version 0 installations complying with EASA AMC 20-24 are approved for use in air traffic control (ATC) separation applications.
>
> ***Version 1*** provides, among other things, separate accuracy and integrity parameters that replace the NUC, such as navigation integrity category (NIC), navigation accuracy category (NAC), and surveillance integrity level (SIL). The Version 1 message format also provides target state and status data.
>
> ***Version 2*** provides, among other things, a renaming and new definition for source integrity level (SIL); includes several new message fields, such as system design assurance (SDA) and geometric vertical accuracy; removes vertical information from the NIC, NAC, and SIL parameters; provides improved support of surface operations through changes to NIC encoding; supports non-diversity/single antenna options for smaller (general aviation) aircraft plus various other improvements. Version 2 equipment is required by United States and European mandates that go into effect in 2020.

Each ADS-B version maps to a different standard: *Version 0 refers to RTCA/DO-260 or EUROCAE/ED-102, Version 1 refers to RTCA/DO-260A or RTCA/DO-282A, and Version 2 refers to RTCA/DO-260B or EUROCAE/ED-102A or RTCA/DO-282B.*

ADS-B Version 3 (DO-260C/ED-102B) avionics standards are under development as of mid-2019 and are expected to be finalized by the end of 2020 and incorporated into future revisions of [E]TSO-C166 by 2022. This version of ADS-B will add more information from the aircraft, relative to ADS-B Version 2.

Appendix B ADS-B Standards and Certification Documents

The following FAA guidance material (e.g., avionics standards, Technical Standard Orders [TSOs], Advisory Circulars [ACs]) and RTCA standards have been developed to support ADS-B Out development and installation (the European Union, EASA and EUROCAE publish identical or equivalent documents):

- Regulation – 14 CFR (Code of Federal Regulation) Part 91, Section 225, Automatic Dependent Surveillance – Broadcast (ADS-B) Out equipment and use and Section 227, Automatic Dependent Surveillance – Broadcast (ADS-B) Out equipment performance requirements
- FAA Technical Standard Order (TSO) – TSO-C166b, Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information – Broadcast (TIS-B) Equipment Operating on the Radio Frequency of 1090 Megahertz (MHz)
- FAA Guidance material – Advisory Circular (AC) 20-165B, Airworthiness Approval of Automatic Dependent Surveillance – Broadcast (ADS-B) Out Systems
- RTCA Equipment Standards – DO-260B, Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Services – Broadcast (TIS-B)

The following FAA guidance material and RTCA standards have been developed to support ADS-B In applications (EASA and EUROCAE publish identical or equivalent documents):

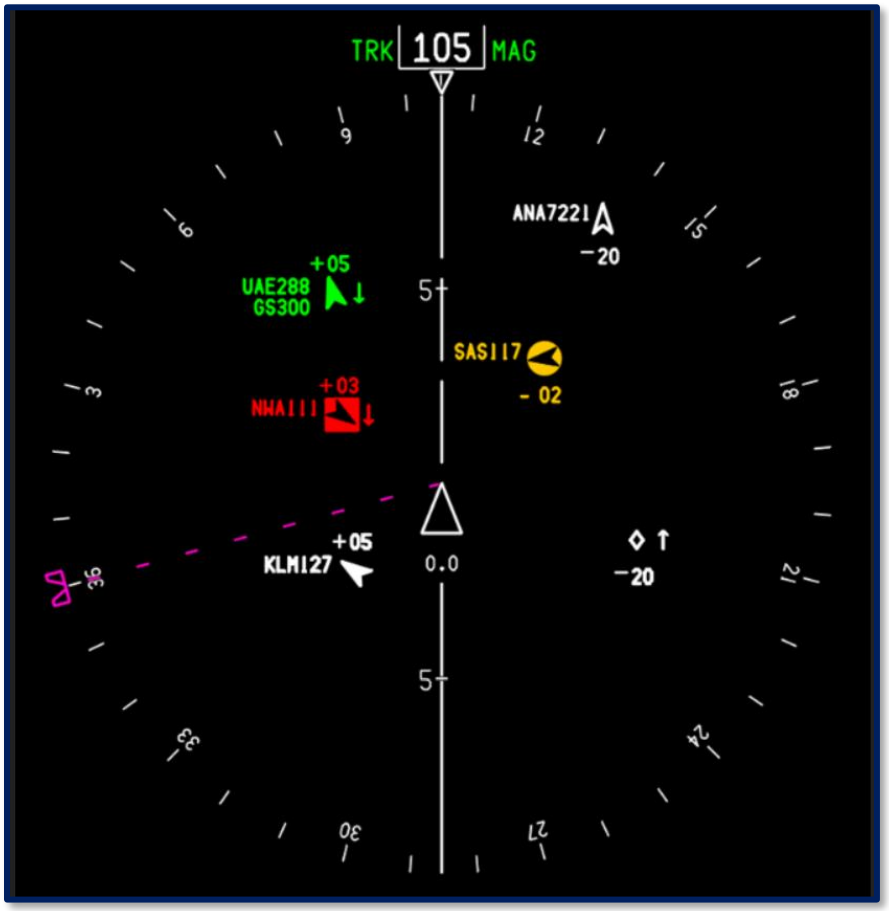
- FAA Technical Standard Order (TSO) – TSO-C195b, Avionics Supporting Automatic Dependent Surveillance – Broadcast (ADS-B) Aircraft Surveillance Applications (ASA)
- FAA Guidance material – Advisory Circular (AC) 20-172B, Airworthiness Approval for ADS-B In Systems and Applications
- FAA Guidance material – Flight Standard's Advisory Circular (AC) 90-114A Change 1, Automatic Dependent Surveillance – Broadcast Operations including ITP and CAVS
- RTCA Equipment Standards – DO-317B/ED-194B, Minimum Operational Performance Standards for Aircraft Surveillance Applications Systems
- RTCA Equipment Standards – DO-361A/ED-236A, Minimum Operational Performance Standards (MOPS) for Flight-deck Interval Management (FIM)

Appendix C Available ADS-B In Applications

FAA guidance materials for developing, testing, installing, and certifying ADS-B Out and ADS-B In systems have been published, and are detailed in Appendix B. Original Equipment Manufacturers (OEMs) and avionics manufacturers have several certified ADS-B In avionics offerings, described here.

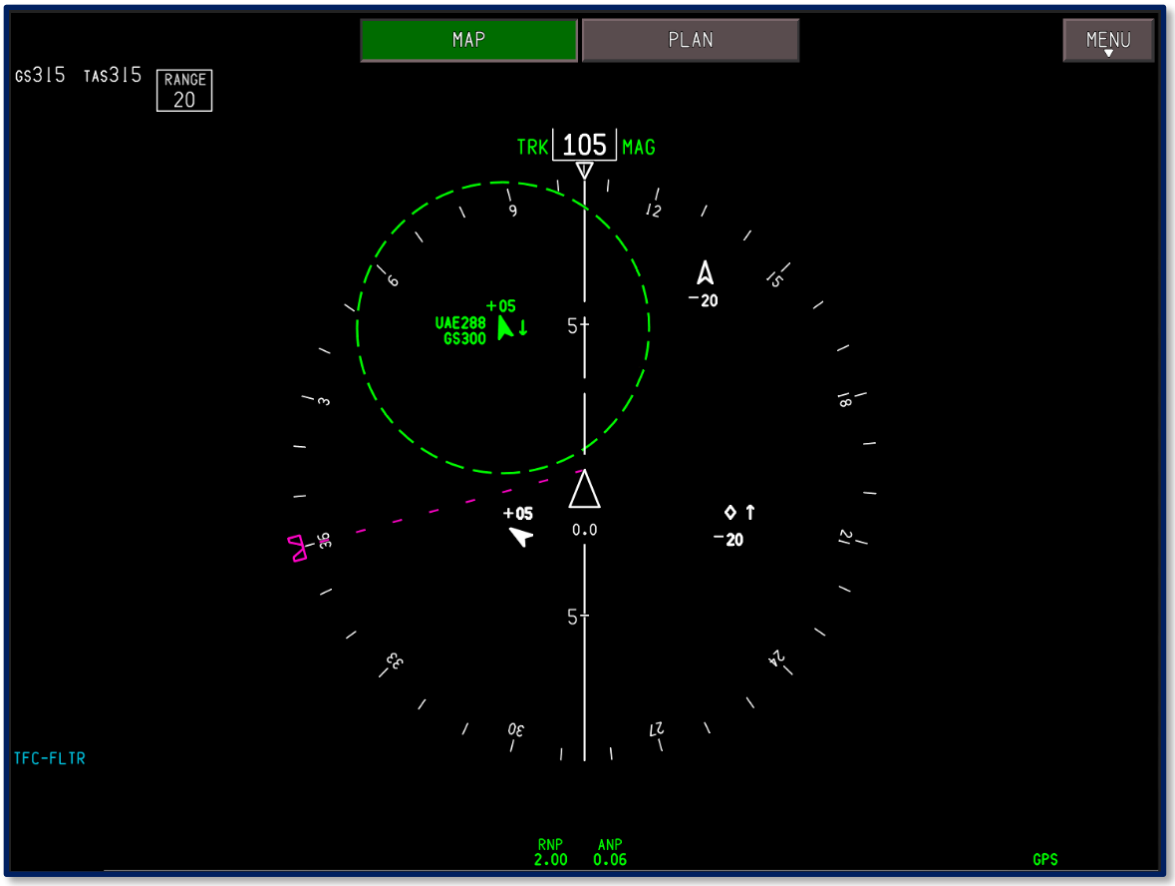
Boeing

In November 2015, Boeing began installing new production ADS-B-In capability on the B787 as a priced option. The specific capabilities offered are AIRB (**Error! Reference source not found.** and **Error! Reference source not found.**), VSA (**Error! Reference source not found.**), and ITP (**Error! Reference source not found.** and **Error! Reference source not found.**). A B787 Service Bulletin is also available to retrofit this capability into any B787. Boeing has stated this same capability will also be provided as a priced option on the B777X at Entry-Into-Service.

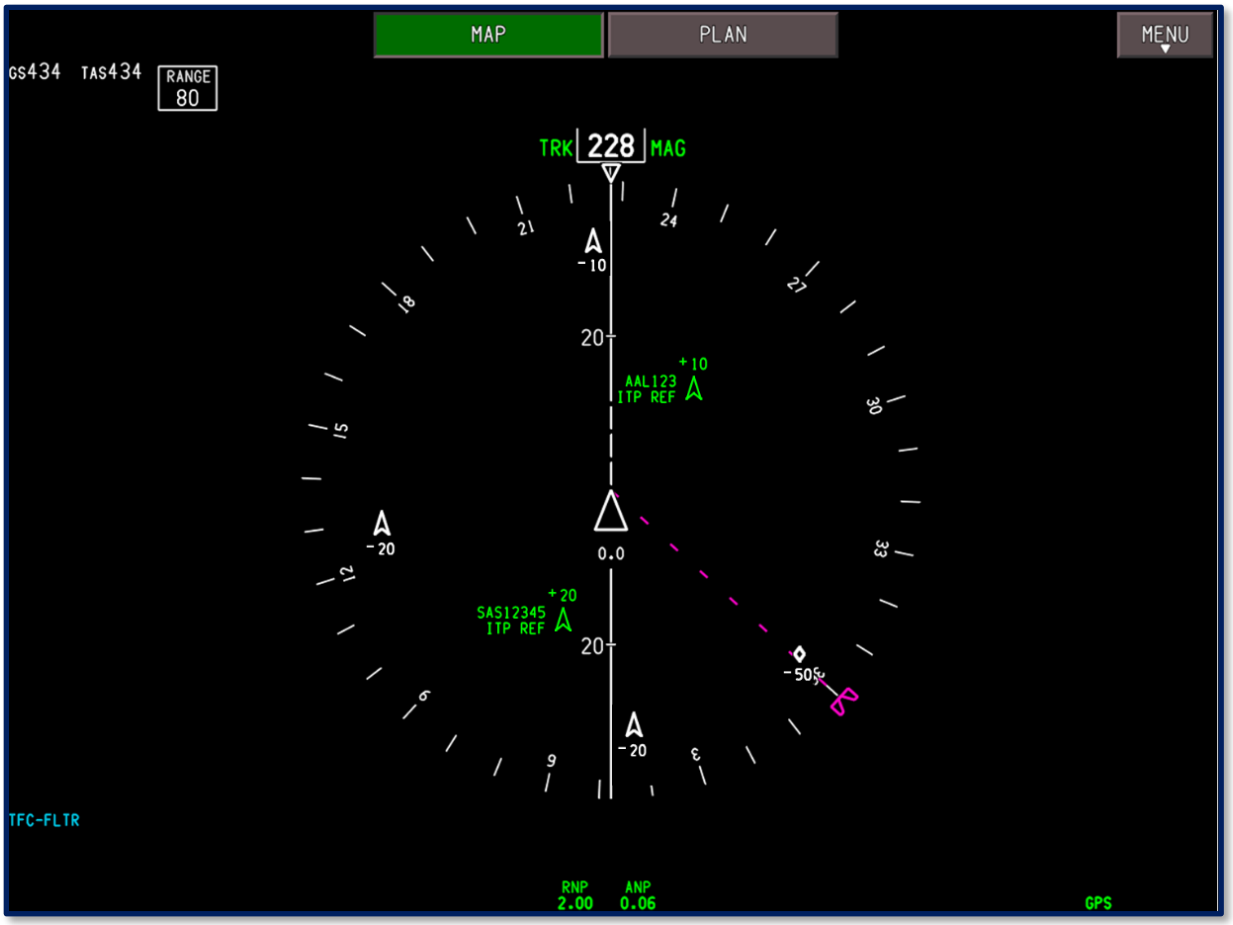


Traffic on the 787 Navigation Display (selected traffic in green).

787 Traffic List on the 787 Multi-Function Display (selected traffic in green).



Visual Separation on Approach (VSA) on the 787 Navigation Display (selected traffic and range ring in green).



In Trail Procedure (ITP) on the 787 Navigation Display (reference traffic in green).

In Trail Procedure (ITP) vertical display on the 787 Multi-Function Display (selected flight level and reference traffic in green).

Airbus

As of January 2018, Airbus offers new production ADS-B-In capability on all models except for the A380 (available for Single Aisle, A330/340, and A350), as a priced option. The specific capabilities offered are AIRB/VSA and ITP. A Service Bulletin is available to retrofit this capability into all A350 aircraft. A Service Bulletin is available to retrofit this capability into Single Aisle or A330/A340 aircraft produced since 2011.

ACSS

ACSS offers retrofit installations with AIRB, ITP, CAVS, Surface Area Movement Management (SAMM) and M&S. The initial ADS-B In flight-deck architecture implemented at UPS, US Airways, and Delta Airlines included use of Class 3 EFBs. ACSS's 2019 retrofit solution leverages existing flight-deck equipment and the use of a forward field of view graphical ADS-B Guidance Display (AGD) to provide a significantly lower cost ADS-B In solution than the EFB design.

Collins

Collins Aerospace has developed AIRB, VSA, and ITP for the Integrated Surveillance System (ISS-2100) currently delivered on the 787 and available on the 777X at entry into service. These traffic applications are available as an option for forward fit delivery and via service bulletin for retrofit. Additionally, Collins Aerospace has developed ACAS-X and CAVS in the ISS-2100 for demonstration on a future 787 Eco-Demonstrator. Current development activity includes AIRB, VSA, CAVS, and FIM in the federated TCAS (TTR-2100) that will be offered via supplemental type certification in the 2022 timeframe. Plans for this solution include display of situational awareness and HMI via personal electronic device (PED) and display of forward field of view parameters via stand-alone display and/or heads-up display.

Honeywell

Honeywell has a retrofit solution called “SmartTraffic” that is certified for installation on the B747-400, and which requires an auxiliary display which meets the requirements of a Class 3 EFB. This solution provides AIRB and ITP capability, and with additional installation/certification work, could be installed on any aircraft with an appropriate Honeywell TCAS computer (TPA-100B).

Appendix D Validation of the IM Concept

As described earlier, the UPS field trial in 2010 and the NASA ATD-1 flight test in 2017 validated that a flight-deck spacing tool can provide the precise inter-aircraft spacing assumed when estimating benefits.

The 2010 UPS field trial assumed en route merges with the IM and Target in-trail during the descent. The Area Navigation (RNAV) Standard Terminal Arrivals (STAR) used in the field trail was an early-generation Optimized Profile Descent (OPD), where procedural altitude and speed constraints were designed to reduce level segments during the descent, leading to a more fuel-efficient descent than conventional arrival procedures. The early-generation IM functions were hosted on an Electronic Flight Bag, and flight crews manually entered the IM Speeds into the Mode Control Panel on the flight deck. Throughout the descent to the Final Approach Fix, the IM aircraft maintained spacing intervals to within 10 seconds of the spacing goal (95% of the time), and spacing was within 8 seconds of the spacing goal at the Final Approach Fix where the IM operation were terminated. The outcomes of this field test showed that the flight crews were able to conduct the spacing operation even when manually entering the IM speeds. Additionally, results showed clear correlation between the spacing precision and pilot conformance to the displayed IM speeds.

NASA's ATD-1 Flight Test in 2017 evaluated IM operations on custom-designed RNAV arrival procedures into Moses Lake that connected to RNAV and RNP (RF) approach procedures. Boeing directed the flight test that involved three aircraft: a Honeywell Dassault Falcon-900 (acting as the lead aircraft), a Honeywell Boeing-757, and a United Airlines Boeing-737. Honeywell developed prototype IM avionics that were based on a subset of requirements in DO-361. A primary contribution of the ATD-1 Flight Test was the validation of spacing operations that begin when the IM and Target Aircraft are on different RNAV STARs, which requires the IM avionics to generate a predicted trajectory for each aircraft. The flight test results those cases that involved an Achieve Stage are summarized in the following table [Swieringa 2017]. While the standard deviation is slightly greater than the required performance (5.0-second standard deviation), some cases that exceeded the desired performance could be attributed to the RNAV procedure design.

ATD-1 Flight Test: Achieve Stage Results [Swieringa 2017].

ABP Location	N	Mean (seconds)	Standard Deviation (seconds)
Merge Point	25	-1.65	6.24
Final Approach Fix	41	6.24	8.28

The Maintain Stage results, which included IM clearances for in-trail spacing where the IM speeds are designed to quickly capture the ASG, maintain the current spacing, or for maintaining the ASG after crossing the ABP, are in Table 3. In these cases, the performance is well within the desired performance.

ATD-1 Flight Test: Maintain Stage Results [Swieringa 2017].

Clearance Type	N	Mean (seconds)	Standard Deviation (seconds)
Maintain Current Spacing	18	-1.13	2.99
Capture Then Maintain	32	0.55	2.63
Post Achieve Stage	27	-0.47	2.45

The Paired Approach Demonstration (PA Demo) was conducted at San Francisco International Airport (SFO) and Tucson International Airport (TUS) in 2019. Honeywell's flight test Boeing-757 was equipped with prototype avionics, building from the avionics used in the National Aeronautics and Space Administration (NASA) Advanced Technology Demonstration-1 (ATD-1) Flight Test with additional functions to support the PA application. Additionally, the avionics were developed in line with the Flight-Based Interval Management (FIM) Minimum Operational Performance Standards (MOPS), DO-361A. Before the PA Demonstration, fast-time simulation runs were evaluated, and engineering flight tests were conducted at TUS to verify the prototype avionics performed as expected.

To conduct the demonstration, the Target and IM PA aircraft were aligned on their respective final approaches to the CSPRs. After receiving the visual clearance from ATC, the trail aircraft received the PA clearance from the PA Demo flight test director. The flight crew entered in the PA clearance information into the prototype avionics and began receiving speed guidance. The flight crew in the trail aircraft implemented the IM speed guidance to capture and maintain the time-based spacing goal relative to the lead aircraft. Once the lead aircraft reached at altitude of 100 feet above the runway, both aircraft would perform a go around, completing a PA run. The first flight day was held at SFO with an Airbus A320 as the lead aircraft and a Boeing 757 as the trail aircraft. The second flight day was held at TUS with a Boeing 777 as the lead aircraft and a Boeing 757 as the trail aircraft. Seven PA runs were completed on each demonstration flight day. Results demonstrated that precise spacing was achievable with final spacing values consistently within 5 seconds of the spacing goal.

Appendix E Relationship Between Inter-Arrival Time and Throughput

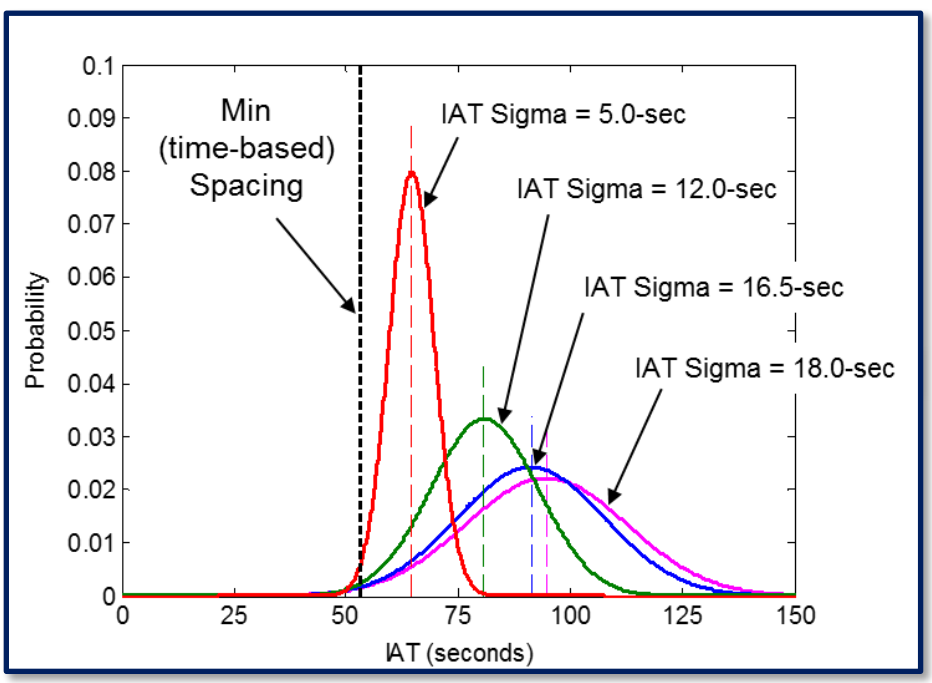
Spacing precision can be related to throughput using a few simple relationships. Inter-arrival Time (IAT) describes the time elapsed between two consecutive aircraft crossing a point in space like the Final Approach Fix or the runway threshold. IAT Sigma refers to the standard deviation in the IAT variability. Smaller IAT Sigma values mean less variability around a desired spacing interval.

For example, suppose an air traffic controller needed to ensure a minimum spacing interval between aircraft at the Final Approach Fix. If the spacing management tool provides an IAT Sigma of σ_{IAT} seconds, a buffer could be added to the minimum spacing to ensure that spacing would be less than the minimum in only 1% of operations.

$$Inter\text{-}aircraft\ Spacing\ Goal = Minimum\ Spacing + 2.33 \times \sigma_{IAT}$$

Note: the factor of 2.33 shifts the spacing error distribution so that only one percent of the operations will result in a spacing value less than the minimum spacing.

The figure below shows the spacing error distributions shifted from the minimum spacing based on the value of σ_{IAT}. In this case, the minimum (time-based) spacing was assumed to be 53 seconds, which is derived from a 2.5-NM spacing at the Final Approach Fix with a ground speed of 170 knots. The σ_{IAT} values were chosen to represent the variability expected in an environment with no metering (σ_{IAT} = 18 seconds), an environment with en-route metering only (σ_{IAT} = 16.5 seconds), a TBO environment with en-route and terminal metering (σ_{IAT} = 12 seconds), and lastly, a TBO environment with IM (σ_{IAT} = 5 seconds).



Shifting the spacing error distribution from the minimum spacing based on the value of IAT Sigma.

In the figure, the spacing goal is denoted by the dashed line showing the mean spacing from which the average throughput can be computed, assuming a uniform flow and no gaps in the arrival flow.

$$throughput\ \left[{}^{aircraft}/_{hour}\right] = \frac{3600\left[{}^{seconds}/_{hour}\right]}{mean\ spacing\ [seconds]}$$

Table 4 shows the IAT sigma value, spacing buffer to ensure fewer than 1% of operation fall below the minimum spacing, spacing goal, and throughput.

Table 4 Relationship Between IAT Sigma and Throughput

IAT Sigma [seconds]	Spacing Buffer [seconds]	Spacing Goal [seconds]	Throughput [ac/hr]
18.0	41.8	94.8	38.0
16.5	38.3	91.3	39.4
12.0	27.8	80.8	44.5
5.0	11.6	64.6	55.7

In addition to arrival throughput benefits, IM is expected to support increased adherence to PBN procedures and reduced block time variability. As described in Section 4.1, IM is a flight-deck tool that enables closed-loop response to uncertainties that arise throughout the operation. An IM-equipped aircraft will meet schedule times more accurately, while being responsive to the Target Aircraft it is following, using speed changes alone. ATC will be less likely to intervene as aircraft are delivered more precisely. Using IM operations consistently will lead to greater path conformance and less variability in operations, leading to reduced block time variability.

Appendix F State of ADS-B In Applications

ADS-B In Application	Operators' Required Technology Investment	FAA's Required Technology Investment	Benefit Mechanism	Availability	Notes
ITP	ITP application compliant with TSO-C195b (DO-317B) and display changes as required	No further investment required	Enables altitude changes at reduced separation (ITP separation) leading to fuel savings	Currently available	ATOP enhancements have been implemented. SBS Program completed an Operational Demonstration in 2013.
CAVS	CAVS application compliant with TSO-C195b (DO-317B) and display changes as required	No further investment required	Increased situational awareness, fewer "go-arounds"	Currently available	SBS Program is planning an Operational Demonstration in 2020 (AIRS project).
Additional Operational Uses of the CAVS Application	Expected to be the same as CAVS	Software enhancements to ERAM and STARS	Higher Airport Arrival Rates on days with lower weather minimums	2025	SBS Program pursuing an Operational Demonstration for additional operational uses of the CAVS application (AIRS Project). The earliest date that terminal automation enhancements could be implemented is 2025.
IM Phase A: Same Corner Post	FIM application compliant with DO-361A and display changes as required	Additional software enhancements to ERAM, STARS, and TBFM	Reduced variability in aircraft spacing leading to higher throughput and increased PBN conformance	2025	The avionics standards for FIM will be finalized in 2020. The SBS Program is currently planning an Operational Demonstration based on a limited set of capabilities in 2022 (AIRS project).
IM Phase B: DSA and DCCR	FIM application compliant with DO-361A and display changes as required	Additional software enhancements to ERAM, STARS, and TBFM	Reduced variability in aircraft spacing leading to higher throughput and increased PBN conformance	2028	IM with Dependent Staggered Approach (DSA) and Dependent Converging & Crossing Runways (DCCR).