Modeling ADS-B Position and Velocity Errors for Airborne Merging and Spacing in Interval Management Application

Satish C. Mohleji Ganghuai Wang Center for Advanced Aviation System Development (CAASD) The MITRE Corporation 7515 Colshire Drive McLean VA 22102 smohleji@mitre.org

Abstract

As a part of the Next Generation Air Transportation System (NextGen), the Federal Aviation Administration (FAA) is developing an advanced airborne Merging and Spacing (M&S) concept utilizing satellite-based surveillance information provided by Automatic Dependent Surveillance- Broadcast (ADS-B). The M&S concept is defined as Airborne Spacing- Flight deck Interval Management (ASPA-FIM), which includes both a ground component and an airborne component including a speed control algorithm as a part of the Interval Management (IM) capability. The ground based function establishes a sequence for an IM aircraft conducting ASPA-FIM procedure to merge behind another designated target aircraft at a waypoint with a desired spacing interval, and then maintain the desired spacing interval. The aircraft achieve the spacing requirement through speed commands generated by Interval Management (IM) equipment in the aircraft. The IM speed control algorithm relies upon ADS-B position and velocity measurements broadcasted by the target aircraft, where the position accuracy depends upon the Global Positioning System (GPS) measurement errors including a bias and an instantaneous jitter. Since most mathematical models for GPS position errors do not take into consideration the correlation between the successive position measurement errors, this paper presents a model for time correlation between position measurement errors using a Gauss-Markov process. In order to determine the minimum position and velocity accuracy required for successful implementation of ASPA-FIM procedure so that the number of speed commands to achieve the desired spacing is acceptable to flight crew and the errors in the achieved spacing is satisfactory, the paper presents results from a Monte Carlo simulation capability which includes ADS-B position/velocity error models, flight dynamics models, a wind model and an IM speed control algorithm. The paper also describes the determination of a desired spacing interval based on established aircraft separation minima during different phases of flight and estimation of the safety tolerance for operational uncertainties.

The simulation results provide a preliminary assessment of minimum position and velocity accuracies required to support this ADS-B application. There is a tradeoff between the number of speed adjustments and the accuracy of achieved spacing interval. Using operational scenarios for en route and descent flight paths into Louisville International airport, example results are presented showing the number of IM-equipment-derived speed commands needed and corresponding spacing interval achieved during merge and maintain phases of flight. A

qualitative discussion of expected benefits from the ASPA-FIM application is also included in the paper.

Introduction

The Next Generation Air Transportation System will transform current ground based Communication, Navigation and Surveillance (CNS) capabilities to satellite based systems, and ground centric Air Traffic Management (ATM) to an aircraft centric system [1]. The new CNS technologies include data link for air/ground information sharing, Area Navigation (RNAV) and Required Navigation Performance (RNP) for precise navigation using GPS, and ADS-B for aircraft surveillance providing highly accurate aircraft position and velocity information [2]. The integrated time based flow management forming the basis for future ATM automation will provide strategic flight planning for Four Dimensional (4D) Trajectory Based Operations (TBO) by accurately predicting flight times along the desired routes of flight. For transformation to NextGen, the FAA and the aviation community are developing concepts to permit sharing of tactical flight management and conformance monitoring responsibilities between the aircraft and ground control systems. One of such concepts is associated with an ADS-B application called Flight Deck Based Interval Management-Spacing [3] or ASPA-FIM [4]. In this concept an appropriately equipped aircraft is permitted to accurately achieve and maintain a desired spacing (time or distance) interval from a designated aircraft, while the controller remains responsible for assuring separation. The controller essentially needs information on aircraft capabilities so as to decide which aircraft could participate in self spacing [5].

During the past few years, the ASPA-FIM concept has been undergoing research, development, simulation evaluations and field trials by the FAA, the National Aeronautics and Space Administration (NASA), the MITRE Center for Advanced Aviation System Development (CAASD) and United Parcel Service (UPS). The FAA and MITRE/CAASD described an earlier concept of Flight Deck Based Merging and Spacing (FDMS) application for aircraft to maintain a desired spacing interval [6]. This work was followed by human in the loop simulations to validate the concept, and the development of an Airline Based En route Sequencing and Spacing (ABESS) capability, which allows the Airlines Operations Center (AOC) to sequence and space traffic arrival flows from en route airspace into the terminal area. The FAA, NASA, MITRE and UPS evaluated the concept at Louisville International Standiford (SDF) Airport [7, 8]. The AOC, after coordinating with ATC system, sends the desired spacing requirement to appropriate aircraft over the Aircraft Communications Addressing and Reporting System (ACARS), and the aircraft achieve and maintain the required spacing from the designated aircraft using airborne derived speed commands. The field trials showed promise and the work is continuing to develop specifications for this application. NASA also conducted human in the loop simulations to evaluate the use of the concept to support Continuous Descent Arrivals (CDA) [9]. The results show pilot acceptance of the application. The research and simulation studies at EUROCONTROL assessed the airborne merging and spacing concept in an extended terminal area environment using Time to Fly (TTF) calculations. The simulation results showed improved runway throughput with time based spacing targets and reduced air/ground communications [10].

The successful use of ASPA-FIM application depends on the position and velocity measurement accuracies offered by ADS-B, which is a satellite based surveillance system using input from

various navigation sources such as Global Navigation Satellite Systems (GNSS) (e.g., GPS) and Inertial Navigation Systems (INS). The ADS-B state vector report from a broadcasting aircraft includes horizontal position, horizontal velocity, altitude and altitude rate. The broadcast ADS-B state vector reports can be received by the ground stations as well as by other aircraft equipped with ADS-B capability. The ground stations direct the ADS-B broadcast state vector reports to Air Traffic control (ATC) automation systems. A receiving aircraft with ADS-B equipment can use the received ADS-B report for situational awareness or, in the future, for more advanced airborne applications. The ASPA-FIM application uses ADS-B state vector reports broadcast from a designated target aircraft to enable the crew of an IM capable aircraft to perform selfspacing operations. The IM speed control algorithm in the cockpit uses position and velocity information from the target aircraft and own aircraft to calculate speed adjustments needed to meet the spacing objective, and provides the speed change instruction to the crew to enable them to appropriately space their aircraft from the target aircraft [11].

According to RTCA Minimum Aviation System Performance Standards (MASPS) for Aircraft Surveillance Applications (ASA), the Navigation Accuracy Category for position (NACp) and velocity (NACv) are established so that each ASA needs to determine what level of these accuracy parameters can support the application [12]. In order for the ASPA-FIM application to operate properly, the accuracy of the position and velocity data from both the target and own aircraft should meet minimum standards. The objective of the work presented in this paper is to provide a preliminary assessment of such minimum airborne surveillance requirements using satellite navigation based position measurement error models in Monte Carlo simulations of ASPA-FIM application for its effective use during different phases of flight and acceptable to the flight crew.

Airborne Spacing- Flight deck Interval Management Concept

The ASPA-FIM concept is one of the applications enabled by ADS-B and includes a suite of functional capabilities which permit an IM equipped aircraft to achieve and maintain a desired spacing interval from a designated target aircraft [3, 4]. The objective of the ASPA-FIM capability is to attain precise and consistent inter-aircraft spacing intervals from other aircraft. This concept has two components: 1) a ground based component; and 2) a flight deck based component [5]. The ground based component relies on ATC automation to provide information on the IM capable aircraft, the desired spacing interval (time or distance) between the selected aircraft to perform IM functions and the designated target aircraft. The integrated time-based flow management function as a part of the ground automation determines aircraft arrival sequence at en route merge points and at the runway threshold. The flight deck-based component needs ADS-B information on current state vector data and some form of intent data (including arrival and approach information at trajectory change points and runway threshold) for target aircraft.

Two types of speed control algorithms for the ASPA-FIM application described in the literature have been used in operational performance requirement assessment simulations. The first type is based on time history of the target aircraft by projecting target aircraft's historical position onto the IM aircraft's intended flight path. The speed control algorithm adjusts the speed of the IM aircraft so that it arrives at any horizontal position on its path at a time that is desired spacing

interval later than the target aircraft. The second type of speed control approach is based on Estimated Time of Arrival (ETA) of both target and IM aircraft at a merge or an achieve-by point (for example, the final approach fix - FAF). The ETAs of both the IM aircraft and the target aircraft are used as input to the speed control algorithm to calculate the speed command for the IM aircraft [4]. The ETA of the IM aircraft can be calculated either by its Flight Management System (FMS) or by its ETA-based speed control algorithm. The ETA of the target aircraft could either be estimated by the speed control algorithm of the IM aircraft, or broadcasted by the target aircraft as its intent to the IM aircraft as a part of ADS-B report.

Modeling of Time Correlated Position Measurement Errors

The onboard navigation equipment supporting the airborne surveillance function requires conversion of navigation sensor measurement data into standard ADS-B data format. The following parameters specify navigation data quality requirement for determining position accuracy and velocity accuracy for ADS-B transmitting subsystem. The position accuracy parameters are usually called horizontal Estimated Position Uncertainty (EPU), NACp and Geometric Vertical Accuracy (GVA). The EPU is defined as the radius of a circle centered at the true horizontal position within which the measured horizontal position lies with 95% probability. A NACp is a 4-bit representation of a corresponding EPU in an ADS-B broadcast state vector report. For example a NACp with a decimal value 11 corresponds to an EPU of less than 3 meters. EPU is usually called Horizontal Figure of Merit (HFOM) if it is reported by GPS or other GNSS. A GVA is a 2-bit representation of geometric altitude accuracy. For example, a GVA with decimal value 2 corresponds to geometric vertical accuracy (95% accuracy bound) of 45 meters or less. The 95% accuracy bound is also called Vertical Figure of Merit (VFOM) if it is reported by a GNSS [12, 13, 14]. Similarly, the NACv parameter describes the accuracy region about the relative velocity vector within which the true velocity is assured to be with a 95 percent probability at the reported time of applicability [12].

Tables 1, 2 and 3 show the values of the NACp, NACv and GVA [14]. As shown, horizontal position accuracy is characterized with NACp and the corresponding horizontal EPU; horizontal velocity accuracy is characterized with the NACv; and GNSS vertical accuracy is characterized with the GVA.

NACp	95% Horizontal Accuracy	Comment		
	Bound (EPU)			
0	$EPU \ge 10 NM$	Unknown accuracy		
1	EPU < 10 NM	RNP-10 accuracy		
2	EPU < 4 NM	RNP-4 accuracy		
3	EPU < 2 NM	RNP-2 accuracy		
4	EPU < 1 NM	RNP-1 accuracy		
5	EPU < 0.5 NM	RNP-0.5 accuracy		
6	EPU < 0.3 NM	RNP-0.3 accuracy		
7	EPU < 0.1 NM	RNP-0.1 accuracy		
8	EPU < 0.05 NM	e.g., GPS (with SA)		
9	EPU < 30 m	e.g., GPS (SA off)		
10	EPU < 10 m	e.g., WAAS		
11	EPU < 3 m	e.g., LAAS		

Table 1. Navigation Accuracy Category for Position (NACp)

 Table 2. Navigation Accuracy Category for Velocity (NACv)

NACv	Horizontal Velocity Error
0	Unknown or ≥10 m/s
1	< 10 m/s
2	< 3 m/s
3	< 1 m/s
4	< 0.3 m/s

Table 3. Geometric Vertical Accuracy (GVA)

GVA Encoding	Meaning (meters)			
0	Unknown or > 150 meters			
1	\leq 150 meters			
2	\leq 45 meters			

The aircraft position measurement accuracy NACp ranges from 0 to 11. This definition does not specifically state whether the measurement errors in successive measurements over time are correlated or not [15]. Traditionally, the measurement errors are modeled as Gaussian distribution random numbers, where the time correlation among the measurement error time series is not modeled (Appendix AC [12]). The observation of GPS position measurement errors show that the position errors are time correlated over short time interval (4 to 8 minutes).

A first-order Gauss-Markov process is developed as follows to realistically model the time correlated GNSS position measurement errors for use in a Monte Carlo simulation described later in this paper to assess the position and velocity accuracy requirements for ASPA-FIM application.

Gauss-Markov Process

A first-order Gauss-Markov process is a random process that describes the behavior of a random variable as a function of time. Because the Monte Carlo simulation used in this work is a discrete time simulation, a discrete first-order Gauss-Markov process is used in which the time is modeled as discrete instead of continuous. The discrete first-order Gauss-Markov process is defined with the following equation:

$$y(n) = ay(n-1) + u(n)$$
 (1)

where *n* is the discrete time that takes values 1, 2, 3, ...; u(n) is a random variable that follows Gaussian distribution $N(0, \sigma_u^2)$; y(0) is a random variable that follows a Gaussian distribution $N(0, \sigma_{y0}^2)$; *a* is a coefficient greater than 0 and less than 1; and y(n) is the output of the random process.

We make y(0) = 0 here.

The mean, variance, and autocorrelation of y(n) are as follows:

$$E[y(n)] = 0$$

$$Variance(y(n)) = \sigma_u^2 (1 - a^{2n})/(1 - a^2)$$
(2)
$$Covariance(y(m), y(n)) = \sigma_u^2 a^{m-n} (1 - a^{2n})/(1 - a^2) \text{ when } m > n$$

$$Autocorrelation(y(m), y(n)) = a^{m-n} \text{ when } m > n$$

Or

Autocorrelation
$$(y(n), y(n+\tau)) = a^{\tau}$$
 for any $\tau = 1, 2, 3, ...$ (3)

In order to calculate the value of coefficient *a* from a given correlation time – the lag time *T* corresponding to the autocorrelation value being equal to 1/e [16], from Equation (3), we have $a^T = 1/e$. If we know the correlation time T, we can calculate the value of *a* as

$$a = e^{-1/T} \tag{4}$$

That is, if the correlation time of y(n) is T, then it can be shown that $a = e^{-1/T}$.

When *n* is large, from Equation (2), the variance of y(n) is:

$$Variance(y(n)) = \sigma_u^2 / (1 - a^2)$$
(5)

If the variance of y(n) is known, the variance of u can be calculated from Equation (5).

For ADS-B, the GPS horizontal radial position measurement error is generally modeled as a Rayleigh distribution random variable (Appendix AC in [12]), where the measurement errors in x and y components of the aircraft position (x, y) are modeled as Gaussian distributed random errors. The 95% accuracy bound of the horizontal radial position error can be used to map into the standard deviations of the measurement errors in the x and y components.

In the Monte Carlo simulation used to analyze the performance of ASPA-FIM application, instead of using Gaussian distributed random numbers to model the measurement errors in the x and y components, the above first-order Gauss-Markov process is used to model these errors. The coefficient *a* is determined by the correlation time of the position measurement errors using Equation (4); and the variance of u(n) is determined using Equation (5), given that the 95% accuracy bound of the x and y component position measurement errors y(n) is known. In turn, the 95% accuracy bound of the x and y component position measurement errors y(n) is calculated from the 95% accuracy bound of the horizontal radial position measurement as shown below.

Assuming the radial horizontal error $R = \sqrt{X^2 + Y^2}$, where X and Y are random variables from a Gaussian distribution $N(0, \sigma^2)$, then R is a random variable following a Rayleigh distribution, and the cumulative distribution function (CDF) for Rayleigh distribution is:

$$F(r) = 1 - exp(-r^2/(2\sigma^2))$$
(6)

From Equation (6), we have $\sigma = r/\sqrt{(-2ln(1-F(r)))}$

If F(r) = 0.95, then r is the 95 percentile of the Rayleigh distribution, and we have

$$\sigma = r/\sqrt{2ln(20))} = r/2.448 \tag{7}$$

Therefore, given the horizontal radial position 95 percent accuracy bound r, the standard deviation of the x component and y component of the horizontal position error can be calculated by using Equation (7).

Although not included in the paper, results indicate that position accuracy corresponding to NACp 6 or lower may not be adequate to support the ASPA-FIM application. Therefore NACp values of 7 and above were chosen for the performance assessment of the application. Figure 1 and Figure 2 show a comparison between the uncorrelated errors that were modeled with a Gaussian distribution and the correlated position measurement errors that were modeled with a Gauss-Markov process with the same position error accuracy – NACp 7 (0.1 NM 95 percentile). As shown, the time correlation of the position measurement errors are significantly reduced with the Gauss-Markov process compared with the Gauss probability distribution.



Figure 1. Comparison of Simulated Correlated Errors and Uncorrelated Horizontal Position Errors – X Axis (NACp 7)



Position Errors – Y Axis (NACp 7)

Figure 3 shows the impact of velocity measurement accuracy on aircraft true air speed during en route cruise phase of flight for an aircraft flying at a nominal true airspeed of 458 knots (kts). As shown in the figure, the velocity measurement accuracy defined as NACv 1 is not adequate to support the ASPA-FIM application.



Figure 3. Target aircraft Velocity Measurement Errors during En Route Cruise (0.8 Mach, 37,000 feet)

Desired Aircraft Spacing Interval Determination for ASPA-FIM Application

The FAA Order 7110. 65R establishes the horizontal separation requirements (Standards) between a pair of aircraft flying at the same altitude as 3.0 NM if the aircraft are within 40 NM of a radar site typically in the TRACON airspace, and 5 NM when the aircraft are more than 40 NM from the radar location in the en route and transition airspace. The horizontal separation requirement is uniformly enforced, regardless of whether the aircraft are on the same route when the above separations are applied longitudinally, or when the aircraft are on different routes these separations are applied laterally. On final approach for arrivals, the Order defines the separation standards as 2.5, 4.0, 5.0 and 6.0 NM depending upon the weight classes of the lead and following aircraft to avoid wake vortices in Instrument Meteorological Conditions (IMC). Air traffic controllers are responsible for maintaining these separations, the ATC system applies additional spacing (a spacing buffer) beyond the minimum desired separation to account for aircraft position variations. The spacing buffer varies with the phase of flight and the traffic conditions.

The operational data for flights using jet routes and RNAV Q-routes in Miami (ZMA) and Jacksonville (ZJX) Air Route Traffic Control Centers (ARTCC) were analyzed to determine achieved separations between aircraft in en route airspace. The analysis of operational data for flights operating in and out of Atlanta (ATL) and Denver (DEN) TRACONs provided separations achieved during arrival and final approach phases of flight. Table 4 shows the results of the operational data analysis for the observed inter-aircraft longitudinal spacing during various phases of flight and on the final approach between different classes of aircraft in the U.S. The Table highlights the mean achieved separations in distance and time, as well as provides the values of one Standard Deviation (S.D.). The difference between the observed and desired

minimum separation indicates the magnitude of the spacing buffer estimated in current operations [17].

Phase of Flight	Minimum Required Separation (NM)	Observed Distance Separation (NM)		Observed Time Separation (Seconds)		
		Mean	S. D.	Mean	S. D.	
En Route Arrivals	5.0	10.6	2.54	101	32	
TRACON	3.0	8.1	2.1	99	27	
Final Approach						
Large/Large Aircraft	2.5	3.4	0.78	85	17	
Heavy/Heavy Aircraft	4.0	5.5	1.13	118	24	
Large/Heavy Aircraft	5.0	6.2	1.16	133	25	
En Route Departures	5.0	12.3	3.57	122	41	

Table 4. Longitudinal Aircraft Separations

In order to account for aircraft performance variations, the desired separations between consecutive aircraft should be determined considering the required minimum separation plus a tolerance to account for aircraft performance variations in order to prevent violation of minimum separation standards. Operational data from current National Airspace System (NAS) was analyzed for en route, terminal and final approach phases of flight to determine the distribution (mean, standard deviation) of achieved separations between aircraft pairs in high density traffic conditions. Assuming that the aircraft performance variations are normally distributed, the desired separation tolerance between a pair of aircraft is 1.65 times the S.D. The desired spacing interval is determined by adding this tolerance to the minimum required separation for the time. The corresponding time separation intervals can be determined from the above distance based separations and the expected average ground speed over the desired segments of the flight. If the objective of the IM application is to assure minimum required separation between aircraft 99 percent of the time, then the desired minimum separation tolerance is 2.33 times S.D.

Monte Carlo Simulation Performance Assessment of Merging and Spacing Functions for IM Application

The Monte Carlo simulation layout used in this work is as shown in Figure 4. A flight dynamics model calculates the true position and true velocity of the aircraft in the simulation. Rapid update

(RUC) wind data and the corresponding analysis files were used to model the winds. Wind speed and direction data at different flight levels were part of the input to the flight dynamics model. The flight dynamics model also used as input the speed commands generated by the IM speed control algorithm. The true position and true velocity calculated in the flight dynamics model were input to the position and velocity measurement model which used position and velocity accuracy values (e.g., NACp and NACv) to calculate the measurement errors and add those errors to the true position and velocity to represent ADS-B position and velocity measurements. Then the position and velocity measurements were used as an input to the ADS-B transmitter model which models the ADS-B quantization, transmit latency, etc. The ADS-B receiver model takes the ADS-B state vector report broadcasted from the target aircraft considering the probability of receiving it. The received ADS-B state vector of the target aircraft and the own aircraft's navigation measurements were used by the IM speed control algorithm to derive the speed command. This simulation used the time-history-based speed control approach to provide speed adjustments to the IM aircraft so that it arrives at any horizontal position at a time that is "t" seconds later than the target aircraft, where "t" is the time corresponding to the desired spacing interval.



Figure 4. Monte Carlo Simulation Layout

To analyze performance for merging and spacing functions, the above Monte Carlo simulation model simulated the operational scenarios shown in Figure 5. The scenarios represent the IM and target aircraft operations during en route cruise, Continuous Descent Arrival (CDA) and final approach phases of flight. The figure also shows the simulation capability to model two types of situations where: 1) each scenario representing a segment of flight is assessed separately and independently of other phases of flight; and 2) the entire flight path is considered as one with performance for each scenario representing a phase is linked to the previous phase and the IM aircraft performance during phases are interdependent.

Sixteen flights were simulated: Merging in the en route phase of flight before the top of descent (TOD) point, during continuous descent arrival (CDA) and in the final phase of flight. Performance was measured in terms of the achieved separation intervals compared to the desired intervals discussed above at various waypoints to determine the achieved spacing tolerance variance, and the frequency of speed commands needed to achieve or maintain the desired interval as a function of position and velocity accuracies. These performance parameters were determined where the flights merged at a point, as well as during the in-trail mode when the IM aircraft was required to maintain the above desired interval from the target aircraft. The performance is determined as composite over the entire flight path shown in Figure 6 for arrival to Louisville International Airport. The spacing between each aircraft pair in the sequence was achieved or maintained with the speed changes provided by the speed control algorithm. Other parameters considered in the simulation included the initial spacing error when the IM aircraft starts using the ASPA-FIM application and the wind forecast uncertainty.



Figure 5. Phases of Simulated Flight



Figure 6. Nominal Horizontal Trajectory of Each Aircraft

Simulation Results

For the operational scenarios discussed above, the Monte Carlo simulation was run for ADS-B position accuracy varying from NACp 7 to NACp 10, and velocity accuracy of NACv 2 and NACv 3. The IM aircraft performance was assessed in terms of the achieved spacing variance at the merge point and the final approach fix and the corresponding speed commands needed to achieve or maintain spacing over the entire flight path from the start up to the performance measurement point. Figure 7 shows an example of the error in achieved spacing at FAF based on a horizontal position measurement accuracy of 30 meters (95% bound) which corresponds to NACp 9, a horizontal velocity measurement accuracy of 1 meter/second which corresponds to NACv 3, and an initial spacing error with standard deviation of 15 seconds. Figure 8 shows the corresponding total number of speed commands from the starting point in en route cruise to the FAF.



Figure 7. Example Achieved Spacing Errors at the FAF



Figure 8. Example Frequency of Speed Commands by FAF

Table 5 and Table 6 show some example of overall performance assessment results. The results show that the IM aircraft performance is less sensitive to the improvement in position measurement accuracy over the minimum value of NACp 7 (185.2 m to 10 m), however the number of speed commands are reduced as the velocity measurement accuracy improves from NACv 2 (3 m/sec) to NACv 3 (1 m/sec). The IM performance is either sustained or has small differences when the performance of first aircraft pair is compared to the performance of 15th aircraft pair in the chain.

Aircraft Pair 1 at the merge point and at the Final Approach Fix (FAF)						
	Spacing Erro	r (second)	Number of Speed Commands			
	At Merge Point	At FAF	Before Merge Point	Before FAF		

SD

3.0

3.0

3.1

2.9

3.5

3.6

3.5

3.5

Mean

0

0

0

0

0

0

0

0

Mean

-2.6

-2.5

-2.6

-2.7

-1.3

-1.2

-1.2

-1.1

Mean

3.2

2.4

3.0

1.5

2.5

2.5

2.3

1.4

NACp

7

8

9

10

7

8

9

10

NACv

3

3

3

3

2

2

2

2

SD

10.9

11.0

10.9

10.7

10.7

10.3

10.9

10.2

SD

1

1

1

1

1

1

1

1

Mean

7

7

7

7

8

8

8

7

SD

1

1

1

1

2

1

1

1

Table 5. Spacing Error and Number of Speed Commands for Desired Spacing = 120 sec,
Initial Spacing Mean = 120 sec, Initial Spacing Error Standard deviation (SD) = 15 sec,
Aircraft Pair 1 at the merge point and at the Final Approach Fix (FAF)

Table 6. Spacing Error and Number of Speed Commands for Desired Spacing = 120 sec,
Initial Spacing Mean = 120 sec, Initial Spacing Error SD = 15 sec, Aircraft Pair 15 at the
merge point and at the Final Approach Fix (FAF)

		Spacing Error (second)			Number of Speed Commands				
						Before Merge			
		At Merge	e Point	At FAF		Point		Before FAF	
NACp	NACv	Mean	SD	Mean	SD	Mean	SD	Mean	SD
7	3	0.1	9.8	1.5	5.8	1	1	7	2
8	3	-0.2	9.2	1.4	5.9	1	1	7	2
9	3	-0.1	9.8	1.2	5.9	1	1	7	2
10	3	0.8	9.9	1.3	5.7	1	1	7	2
7	2	-0.5	9.0	1.7	5.9	1	1	10	2
8	2	0.2	9.6	2.0	6.0	1	1	9	2
9	2	0.2	9.6	1.8	5.8	1	1	9	2
10	2	-0.1	9.1	1.8	5.8	1	1	9	2

ASPA-FIM Application Benefits

General

The IM equipment onboard the aircraft will permit flight crew (or FMS) take over the task of achieving and maintaining desired spacing in all phases of flight, viz, departure climbs, en route, descents and during final approaches. The ASPA-FIM application is expected to help achieve spacing intervals between aircraft pairs accurately with tighter tolerances. The reduction in spacing tolerances will improve aircraft times of arrival at waypoints along the flight paths, and potentially increase airport throughput. By redistributing some of the tasks from the ATC to the cockpit for achieving/maintaining spacing, air/ground communications will be reduced significantly depending upon the number of aircraft pairs using ASPA-FIM application in various phases of flight operations. Moreover, the pair-wise use of the ASPA-FIM application would minimize the need for mile-in-trail restrictions across the board, thereby reducing delays and improving flight efficiency. Lastly, by precisely merging and spacing of aircraft at selected waypoints, the ASPA-FIM application could provide metering of traffic at airports, which do not have a metering or traffic flow management capability e.g., Traffic Management Advisor (TMA).

Assessment of ASPA-FIM Application Benefits

The type and amount of ASPA-FIM application benefits depend upon the specific situations which warrant the use of the application, and the number of aircraft pairs simultaneously using the IM equipment. As discussed above, the overall benefits of using IM applications are to: 1) reduce airborne delays and improve flight efficiency thereby saving flight time and fuel yielding reduction in Direct Operating Costs (DOC); and 2) reduce air/ground communications by using air derived speed commands and sometimes turn to merge guidance thereby potentially reducing workload. Although a quantitative assessment of benefits requires radar data and voice communication analysis that is beyond the scope of this report, a qualitative assessment of the type, and size of benefits as well as the number of operations impacted during various operational situations is presented as follows. Six scenarios are defined where the use of ASPA-FIM application for IM aircraft could provide benefits in departure, en route, transition, terminal and approach phases of flight.

1. ASPA-FIM Application Benefits for IM Aircraft to Remain Behind in a Chain

Although the situation highlighted in this scenario could apply in any phase of flight (level en route or descent) this IM application will be most beneficial to the stream of aircraft converging onto their final approach path. The tighter tolerances for the final approach spacing achievable by the IM aircraft could increase runway throughput thereby reducing airborne delays during medium to heavy traffic periods. During en route phase of flight, these situations would enhance flight efficiency making the aircraft to stay close to their optimal trajectories. In both situations, the resulting benefits would be reduction in flight time and fuel consumption yielding Direct Operating Costs (DOC) savings. As a result of air derived commands requiring no ATC

instructions for achieving/maintaining required spacing, there will also be a reduction in air/ground communications and as such workload. Minimizing reliance on vectoring in the terminal maneuvering areas could yield on the average about three minutes reduction in flying time per aircraft, 362 lbs of fuel savings and 30 percent less air/ground communications [18]. Since these situations occur most of the time during busy traffic periods at medium to high density airports, a large number of operations could benefit from the ASPA-FIM application. The overall benefits however will depend upon the number of aircraft equipped with the IM equipment.

2. ASPA-FIM Application Benefits during a Turn Maneuver to Merge

In situations when the IM equipment derived speed commands are not adequate to meet the spacing interval requirement at a merge point, the IM equipment is also capable of determining when to efficiently turn the aircraft to accurately achieve the desired spacing. Since the ASPA-FIM application may be used infrequently, the only benefit for a limited number of aircraft will come from one less vectoring instruction from the ground system. However, Aircraft selecting the precise time to turn could provide small savings in flight time and fuel consumption.

3. ASPA-FIM Application Benefits during Optimized Profile Descents

Most of the time/fuel/cost saving benefits for aircraft conducting Optimized Profile Descents (OPD) will come from the aircraft descending from the top of descent point to the final approach efficiently and economically when compared to routine step down descents. The added benefits of aircraft using IM equipment will only come from maintaining tighter spacing tolerances for achieving/maintaining spacing intervals. Consequently there will be insignificant benefits during light traffic conditions. However the majority of benefits will accrue for a large number of aircraft pairs conducting OPDs during medium to heavy traffic conditions that could otherwise be reduced due to operational inefficiencies. Based on information from the pilots conducting OPDs, the composite benefits of using ASPA-FIM application during OPDs will be about 500 lbs savings in fuel per aircraft, two minutes of flying time and about an 80 percent reduction in air/ground communications when compared to step down descents. Moreover the use of OPDs will cut down on noise and emissions. Since the IM aircraft will be able to stay on the desired flight paths with few deviations, the use of ASPA-FIM application will help sustain the noise/emission reduction benefits for a large number of operations.

4. Benefits of using ASPA-FIM Application in Turn Maneuver for Crossing Runways Arrival Operations

With the use of ASPA-FIM application, the IM aircraft would achieve tighter arrival spacing tolerance and predictable turn to conduct final approaches to the desired runways. This will maximize airport arrival/departure capacity resulting in reduced delays and DOC savings. The IM aircraft will also require fewer air/ground communications for arrivals. There are 23 airports in the U.S. with intersecting runways, about half of them are medium traffic density airports and the other half airports are high density. A large number of operations at the medium density airports could benefit from this application in terms of fuel savings on the average of 300 lbs and reduction in air/ground communications of about 10 percent. Since the intersecting runways are

used less frequently at major airports, as other primary runways are mostly used, the benefits at such airports for IM aircraft using this application will be small.

5. ASPA-FIM Application Benefits from Accurately Maintaining Departure Spacing

By efficiently adhering to the most efficient climb profiles and accurately achieving and maintaining the desired spacing at the merge points, the IM aircraft could alleviate the need for ATC miles-in-trail restrictions. The resulting benefits will likely be reduction in time/fuel and DOC savings. Because there is less variability in climb profiles, such benefits are expected to be small, although a significantly large number of aircraft could realize the benefits. Most benefits will come from reduction in air/ground communications expected to be about 5 to 10 percent.

6. ASPA-FIM Benefits for Two Target Aircraft Arrival Operations

The IM aircraft will benefit from the ASPA-FIM application at airports with dependent parallel runway operations through an increase in airport throughput and reduction in delays. There are 19 airports in the U.S. with dependent parallel runway configurations. 12 of these airports have exclusively dependent parallel runway operations, while the other seven airports also have independent parallel runways. IM operations at these 12 airports will provide benefits through increased throughput during the medium to high density traffic conditions. Although the operations at other seven airports are conducted mostly on independent parallel runways, where an IM aircraft will follow an individual target aircraft arriving at a designated runway with reduced spacing thereby enhancing throughput at that runway, the above ASPA-FIM application will improve throughput during situations when operations at dependent runways are conducted.

Summary

The FAA and the aviation community are developing concepts to permit sharing of tactical flight management and conformance monitoring responsibilities between the aircraft and the ground control system. One of such concepts is associated with an ADS-B application called ASPA-FIM. In this concept an appropriately equipped aircraft with an IM capability is permitted to accurately achieve and maintain a ground-desired spacing (time or distance) interval from a designated target aircraft, while the controller remains responsible for assuring separation.

A model for time correlation between position measurement errors using a Gauss-Markov process was presented. In order to determine the minimum position and velocity accuracy required for successful implementation of ASPA-FIM procedure so that the number of speed commands to achieve the desired spacing is acceptable to flight crews, a Monte Carlo simulation capability was developed including the Gauss-Markov ADS-B position error model, flight dynamics models, and a wind model. Based on operational data analysis, the ground system desired spacing interval determination approach is presented based on established aircraft separation minima during different phases of flight and estimation of safety tolerances to compensate for operational uncertainties. The simulation assessment of IM aircraft performance under various operational scenarios showed at a preliminary first level that a minimum ADS-B position accuracy of NACp 7 (185.2 m) and velocity accuracy of NACv 2 (3 m/sec) will be needed to support the use of ASPA-FIM application. There is a tradeoff between achieving

smaller spacing tolerances and the number of speed adjustments needed to achieve them that are acceptable to the flight crew. The preliminary results presented here show some sensitivity to the velocity accuracy. However, additional rigorous analysis is needed to establish minimum ADS-B data requirements for successful implementation of the application.

The ASPA-FIM application is expected to help accurately achieve spacing intervals between aircraft pairs with tighter spacing tolerances. The reduction in spacing variances will improve aircraft times of arrival at waypoints along the flight paths, and potentially increase airport throughput. By redistributing some of the tasks from the ground to the cockpit for achieving/maintaining spacing intervals, air/ground communications will be reduced significantly depending upon the number of aircraft pairs using the IM application in various phases of flight operations. Moreover, the pair-wise use of IM applications would minimize the need for miles-in-trail restrictions across the board, thereby reducing delays and improving flight efficiency. Lastly, by precisely merging and spacing aircraft at selected waypoints, the IM application could provide metering of traffic at airports, which do not have a metering or traffic flow management capability (e.g., Traffic Management Advisor).

References

[1] Concept of Operations for the Next Generation Air Transportation System, V 2.0, Joint Planning and Development Office, 13 June, 2007.

[2] FAA's NextGen Implementation Plan, Federal Aviation Administration, March 2010.

[3] Application Integrated Work Plan, V 2.0, Federal Aviation Administration, June 2010.

[4] Safety, Performance and Interoperability Requirements Document for Airborne Spacing-Flight Deck Interval Management (ASPA-FIM), Interim Draft V 0.6, RTCA Inc, 16 July, 2010.

[5] Advanced Merging and Spacing Concepts of Operation for NextGen Mid-Term, V 1.4, Federal Aviation Administration, 18 September, 2009.

[6] Flight Deck- Based Merging and Spacing (FDMS) Application Description, R.S. Bone, J. Marksteiner, V 2.1, MITRE /Federal Aviation Administration, 19 February, 2008.

[7] Evaluation of Flight Deck-Based Merging and Spacing Concept on en route Air Traffic Control Operations, W.J. Penhallegon, R.S. bone, Seventh USA/Europe Air Traffic Management R&D Seminar, July, 2007.

[8] Field Test Results of an Airline Based En route Sequencing and Spacing Tool, P.M. Moertl, W.C. Arthur, M.E. Pollack, J.L. Stein, Laura Zheng, 28th Digital Avionics Systems Conference, October, 2009.

[9] Evaluation of an Airborne Spacing Concept to Support Continuous Descent Arrival Operations, J.L. Murdoch, B.E. Barmore, B.T. Baxley, T.S. Abbott, Eighth USA/Europe Air Traffic Management R&D Seminar, June, 2009.

[10] Delegating Upstream: Mapping Where It Happens, I. Grimaud, E. Hoffman, E.R. Rognin, K. Zeghal, Fourth USA/Europe Air Traffic Management R&D Seminar, December, 2001.

[11] Airborne Spacing-Interval Management (ASPA-IM) OSED Description, Package 1, Edition 1.4.0, 4 December, 2009.

[12] Minimum Aviation System Performance Standards for Aircraft Surveillance Applications (ASA), RTCA DO-289, Change1, Special Committee 186, RTCA Inc, December, 2003.

[13] Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Service – Broadcast (TIS-B), RTCA DO-260B, 2 December, 2009

[14] Minimum Operational Performance Standards for Universal Access Transceiver (UAT) Automatic Dependent Surveillance – Broadcast (ADS-B), RTCA DO-282B, 2 December, 2009

[15] Global Positioning System: Theory and Applications, Vol I, B.W. Parkinson, J.J. Spilker Jr., Volume 163 Progress in Astronautics and Aeronautics, American Institute of Aeronautics and Astronautics, Inc.

[16] Applied Optimal Control, Arthur Gelb, The MIT Press, 15 May, 1974.

[17] Analysis of Observed Aircraft-to-Aircraft Separation, S. Szurgyi, S. Shresta, D. Neskovic, J. DeArmon, S. Williams, 2008 ICNS Conference, May, 2008.

[18] A Route-Oriented Planning and Control concept for Efficient Flight Operations at Busy Airports, S. C. Mohleji, Control Engineering Practice Journal, Vol. 4, No. 8, pp 1143-1151, August, 1996.