

# Comparison of Trajectory Synthesis Algorithms for Monitoring Final Approach Compression

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This study analyzes the performance of aircraft in-trail separation monitoring algorithms using 480,000 flights on the final approach courses of 25 major airports in the National Airspace System. While compression monitoring is expected to help air traffic controllers achieve and maintain higher arrival rates, the trajectory prediction requirements for it are not well understood. To address this gap, analytical trajectories were constructed from flight plan and track data for flights arriving at the 14 major and 11 satellite airports of the 8 busiest terminal areas. Three types of analytical trajectory models were compared. These trajectory models were a constant speed model, and two heuristic deceleration models. The trajectory prediction accuracy and separation prediction accuracy of each of these models were calculated for all aircraft pairs along the final approach course. The results were used to rank the overall performance of the various trajectory models in terms of the true and false alerts by the compression monitoring algorithms. The best performing trajectory model enforced the landing speed constraint, used a landing speed based upon weight class, and did not adjust the landing speed by airport elevation. All of the trajectory models exhibited significantly more false alarms when excess in-trail separation was less than 0.5 nm.

## I. Introduction

THE Next Generation Air Transportation System (NextGen) plan mandates the development of advanced air traffic management technologies and procedures to accommodate a significant traffic demand increase in the already congested terminal environment.<sup>1</sup> A concept of operations for NextGen terminal airspace, referred to as Super-Density Operations, envisions the use of advanced ground and flight deck automation, efficient horizontal routes, optimized vertical profiles, and delegated interval management to maintain achieve high airspace and airport utilization in all weather conditions.<sup>2</sup> The development of advanced decision support tools for tactical separation assurance is also recognized as a critical component of the Super-Density Operations concept of operations. Recently, tactical separation assurance of aircraft on final approach, so-called compression monitoring, has become a stated goal of the FAA in order to reduce separation violations and increase arrival throughput “by helping controllers consistently maintain the precise minimum separation standards.”<sup>3</sup>

Compression refers to the natural reduction of in-trail separation between two successive aircraft as a result of the leading aircraft (“leader”) slowing ahead of the trailing aircraft (“trailer”). Compression can occur between any pair of aircraft anywhere in the terminal airspace. However, it is most pronounced on final approach for several reasons. First, the leader will be slowing to its landing speed, and thus, can be significantly slower than the trailer. The standard air traffic control technique of matching speeds is not likely to be available, because the slowest speeds that controllers are instructed to assign (170 KIAS for jets and 150 KIAS for turboprops) are higher than typical landing speeds. Furthermore, flight crews that have been cleared for landing are allowed to make their own speed adjustments to complete the approach. Second, the leader and trailer will be at different altitudes, and thus, subject to different atmospheric winds. If the headwind component of the atmospheric winds increases as the aircraft descends, the severity of compression will increase.

This paper uses a systematic approach for calculating aircraft separation errors to compare different trajectory prediction models for compression monitoring along the final approach course. Four trajectory prediction models are applied to aircraft established on final approach to predict their future in-trail separation for two prediction intervals

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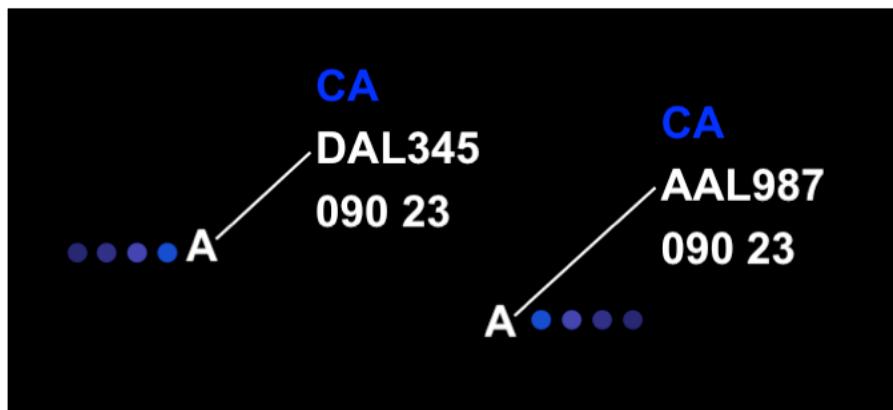
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into the future. The methods used for this comparison rank the relative accuracy of each trajectory prediction model, identify their particular strengths and weaknesses, and suggest areas of possible improvement. The nature of compression of aircraft along the final approach course and existing conflict alerting and compression monitoring tools are described in Sec. II. The motivation of the current study, influenced by an inherent desire to determine the trajectory prediction requirements for FAA compression monitoring tools, is explained in Sec. III. In Sec. IV, the analysis methodology is described in detail. Results are presented in Sec. V for 25 major airports of the 8 busiest terminal areas in the National Airspace System (NAS). Finally, Sec. VI discusses these results, and Sec. VII provides conclusions and recommendations regarding the implementation of compression monitoring capabilities.

## II. Background

Controllers account for compression along the final approach course by initially providing extra in-trail separation (i.e., more than the required separation) so that the required separation can be maintained downstream. Advanced time-based scheduling tools, such as the FAA's Traffic Management Advisor (TMA), attempt to precondition the traffic flows with the appropriate amount of extra separation as the aircraft enter terminal airspace.<sup>4</sup> Recent studies have shown that the optimal amount of extra separation is affected by the aircraft performance, desired speed profile, and atmospheric wind profile.<sup>5</sup> Unexpected compression creates a problem because controllers do not have much ability to use tactical control along the final approach course to avoid a loss of separation. When controllers recognize a loss of separation is about to occur along the final approach course, they often have no other recourse than to instruct the aircraft to abort the approach.

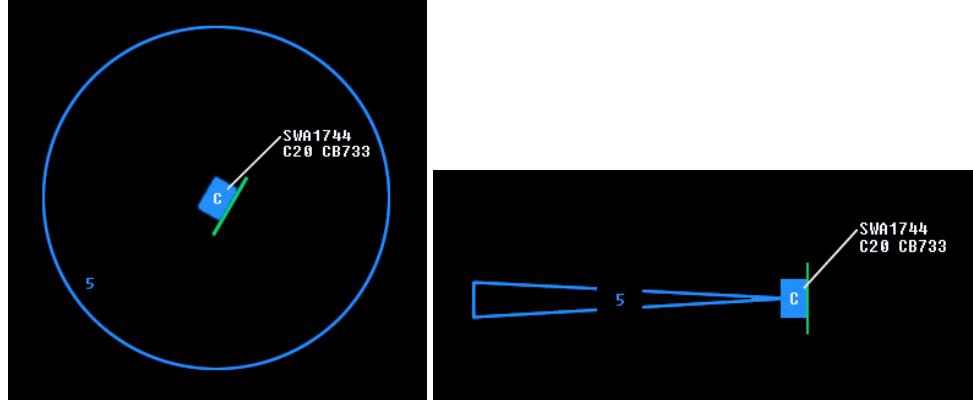
For this reason, compression monitoring is a special case of conflict detection. Controllers use their traditional conflict detection tools to monitor compression along the final approach course. However, the complexity of terminal operations, especially final approach operations, presents a difficult challenge for these systems. The contributing factors include the high traffic density, frequency of large turns, use of radar vectors, complex separation standards, aircraft-specific landing speed profiles, and purposeful operation near the required separation to maximize runway throughput. Presently, there is no single conflict detection tool for the terminal airspace. Instead, controllers have several systems that provide slightly different conflict prediction capabilities.



**Fig. 1 Example of conflict alert flight data block text**

First, Conflict Alert (CA) is the FAA's legacy system for conflict detection.<sup>6</sup> It is designed to determine if a collision of two aircraft is imminent rather than if a loss of separation is imminent. It relies mainly on dead reckoning to predict aircraft trajectories. Typically, CA projects the aircrafts' current positions 40 seconds into the future. It is often desensitized, or even inhibited, in areas where frequent false alerts would otherwise occur. It provides controller alerts in the form of flight data block text and aural chimes. Fig. 1 shows the flight data blocks of two aircraft that are displaying warning indicators (indicated by CA text). In this example, the two aircraft are approaching each other from opposite directions on collinear paths and are flying at the same altitude (9000 feet) and ground speed (230 knots).

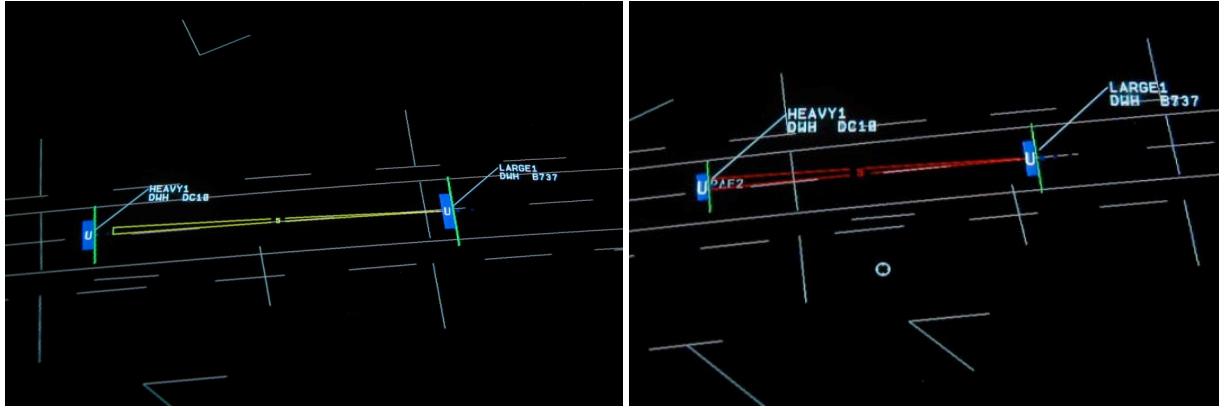
Another tool, the FAA's Terminal Proximity Alert (TPA), allows air traffic controllers to display directional cones in front of and halos (known as J-Rings) around individual aircraft.<sup>7</sup> The controller typically sets the lengths of these cones (and the radii of the halos) equal to the required radar separation. TPA displays simple fixed-distance cones or halos, and it does not perform any trajectory prediction. Instead, air traffic controllers make their own cognitive estimates of the aircraft's near-term trajectory, and use the cones and halos to identify imminent losses of separation. Unlike CA, TPA is intended to help identify a loss of separation before it happens. Fig. 2 shows



**Fig. 2 Examples of Terminal Proximity Alert J-rings (left) and cones (right)**

examples of the TPA symbology. In this example, the aircraft on the left has a halo with a 5 nmi radius; the aircraft on the right has a cone with a 5 nmi length.

Finally, the FAA's Automated Terminal Proximity Alert (ATPA) extends the TPA functionality by automatically sizing the directional cones by the required radar separation for leader/follower pairs along the final approach course.<sup>8</sup> ATPA predicts the near-term in-trail spacing to determine if a loss of separation is imminent. If a loss of separation is not predicted to occur within 45 seconds, its cone is drawn blue. This state is referred to as an "ATPA monitor". If a loss of separation is predicted to occur within 22 to 45 seconds, its cone is drawn yellow. This state is referred to as an "ATPA warning". If a loss of separation is predicted to occur within 22 seconds, its cone is drawn red. This state is referred to as an "ATPA alert". In addition, ATPA can be configured to display the current in-trail spacing in the follower's flight data block and the required in-trail spacing in the cone. Figures 2 and 3 show examples of the ATPA symbology for the monitor, warning and alert states. In Fig. 2, the aircraft on the right has a monitor cone with a 5 nmi length. In Fig. 3, the trailer on the left (LARGE1) has a yellow warning cone with a 5 nmi length, because a loss of separation is predicted to occur within 22 to 45 seconds. In Fig. 3, the trailer on the right (LARGE1) has a red alert cone with a 5 nmi length, because a loss of separation is predicted to occur within 22 seconds.



**Fig. 3 Examples of Automated Terminal Proximity Alert warning cones (left) and alert cones (right)**

### III. Motivation

The principal motivation of this study was to understand the impact of different trajectory prediction methods on the performance of compression monitoring algorithms. In particular, the goal was to determine the best trajectory prediction algorithm for the FAA's ATPA in terms of true and false alerts. This objective was pursued by:

- evaluating the accuracy of different final approach trajectory prediction methods;
- investigating the sensitivity of the estimated compression to trajectory prediction accuracy; and
- investigating the behavior of compression warnings and alerts for different traffic densities.

Few studies have systematically analyzed the value of incorporating additional data to improve the trajectory prediction accuracy. Recently, Gong and Sadovsky investigated the performance of compression monitoring along the final approach course using a simple constant ground speed profile (i.e., dead-reckoning) and an empirical ground speed profile mined from a database of historical operations.<sup>9</sup> Although empirical speed profiles of sufficiently small sub-populations of flights might lead to better trajectory predictions, such speed profiles are the least feasible given the capabilities of today's air traffic automation systems. This study complements Gong and Sadovsky's work by modeling several analytical speed profiles that are feasible in today's automation systems.

Motivated by the research questions stated above and the scope of the previous research, the analysis methodology was designed to explore the potential impact of different analytical trajectory models on compression monitoring for various aircraft types, airports, wind conditions, and traffic levels. The results of this study quantified the effectiveness of different trajectory prediction methods. In addition, the compression monitoring performance that would be expected for each of the trajectory prediction methods was estimated across a wide range of traffic scenarios.

#### IV. Analysis Methodology

Arrival flights to multiple airports in multiple terminal areas were analyzed in order to encompass congested metroplex environments, like New York, as well as super-hub environments, like Atlanta. This research examines the behavior of compression monitoring algorithms for more than 480,000 flights. The traffic analysis was performed using NASA's Center/TRACON Automation System (CTAS) infrastructure in conjunction with Air Route Traffic Control Center (ARTCC) and Terminal Radar Approach Control (TRACON) flight plan and track data.<sup>10</sup> The Aviation Systems Division at NASA Ames Research Center has 24 hour-a-day, 7 day-a-week access to the following data:

- FAA flight plan and track data for all 20 ARTCCs, as well as 27 TRACONS in the NAS;
- NOAA Rapid Update Cycle (RUC) weather forecasts; and
- NWS Meteorological Aviation Reports (METAR).

Compression monitoring algorithms were evaluated using recorded flight plan and radar track data. The results were imported into an SQL data warehouse in order to investigate the macroscopic factors that strongly affect the performance of the compression monitoring algorithms. Four trajectory models, three landing speed models, two airport elevation adjustments, and two required separation models at two prediction intervals were used for a total of 64 discrete model combinations.

##### A. Scope of Study

Compression along the final approach course was examined for arrival flights into the 14 OEP 35 (Operational Evolution Partnership<sup>11</sup>) and 11 major satellite airports of the eight busiest Terminal Radar Approach Control (TRACON) facilities in the National Airspace System (NAS). These TRACONS were Atlanta TRACON (A80), Chicago TRACON (C90), Dallas/Fort Worth TRACON (D10), Denver TRACON (D01), New York TRACON (N90), Northern California TRACON (NCT), Potomac TRACON (PCT), and Southern California TRACON (SCT). Table 1 lists these airports and summarizes their traffic statistics.

For each airport, arrival flights were analyzed for between thirty and sixty 24-hour traffic samples. These daily traffic samples were distributed between February 2010 and early May 2010. The traffic samples covered the entire day starting at 0800Z (between 0100 and 0400 local time) on the day of interest and ending at 0800Z on the next day. Table 2 summarizes the days and the number of operations captured by these traffic samples. The traffic samples chosen for analysis were required to have uninterrupted ARTCC and TRACON track data during the busiest period of the day, specifically between 0600 local time and 2200 local time. Uninterrupted data were available for all hours of most days.

The proportions of flights by weight-class<sup>12</sup> were 76% large, 7% heavy, 6% Boeing 757, and 10% small, plus 105 individual super-heavy flights. Regional, business and micro jets constituted more than 35% of the jet traffic. The proportions of flights by engine type were 93% jets, 6% turboprops, and 1% pistons. The traffic samples span approximately one-quarter of the 2010 calendar year and more than 12% of the expected 2010 arrival operations to the 25 airports listed in Table 1.

**Table 1 Summary of airports that were studied**

Facility Name	Facility ID	2009 Ops Count	2009 Ops Rank	OEP 35 Airports	Major Satellite Airports
Atlanta	A80	1,275,000	5	ATL	—
Chicago	C90	1,186,000	6	MDW ORD	—
Dallas/Fort Worth	D10	1,066,000	7	DFW	DAL
Denver	D01	853,000	10	DEN	—
New York	N90	1,831,000	2	EWR JFK LGA	HPN TEB
Northern California	NCT	1,446,000	4	SFO	OAK SJC SMF
Potomac	PCT	1,490,000	3	BWI DCA IAD	RIC
Southern California	SCT	1,972,000	1	LAX SAN	BUR LGB ONT SNA

Source: FAA Administrator's Fact Book, March 2010

**Table 2 Summary of 24-hour daily traffic samples that were studied**

Facility Name	Facility ID	February 2010		March 2010		April 2010		May 2010	
		Days	Arrival Ops	Days	Arrival Ops	Days	Arrival Ops	Days	Arrival Ops
Atlanta	A80	3	3,347	11	15,520	13	18,147	5	6,456
Chicago	C90	13	17,733	13	19,613	17	26,420	5	7,649
Dallas/Fort Worth	D10	19	19,467	16	19,449	21	23,328	4	4,522
Denver	D01	4	3,312	14	12,429	15	14,309	0	0
New York	N90	14	22,814	17	32,296	23	42,964	5	10,592
Northern California	NCT	16	15,498	21	21,351	8	7,251	4	3,997
Potomac	PCT	2	1,880	10	12,262	20	22,733	4	4,059
Southern California	SCT	10	14,951	19	27,913	17	25,409	6	8,985

Source: [www.airnav.com](http://www.airnav.com), June 2010

These traffic samples were not explicitly chosen to represent all possible airspace and airport configurations or weather conditions. A summary examination of the airport configurations in use during each traffic sample suggests that many of the most common airport configurations, if not all of them, are included in the analysis. A subsequent and more complete accounting of the weather conditions is desired, since rare weather conditions may exhibit more compression and, at the same time, worse performance of the trajectory prediction algorithms. These traffic samples were also used for analysis of the potential benefit pool associated with improved descent profiles throughout the entire arrival phase of flight.<sup>13</sup>

## B. Analysis Using Recorded Flight Plan and Tracks

Analysis of the compression monitoring algorithms follows these steps: characterize the operational scenario (i.e., landing runway, landing time, flight distance, etc.), determine eligible aircraft, generate time-synchronized track pairs, synthesize short-term trajectories, and compare the predicted separation with actual separation for various candidate trajectory prediction algorithms. The remainder of this section discusses these steps in detail.

### 1. Flight Plan and Track Information

The purpose of this study was to determine how well compression monitoring algorithms could perform with information available from today's air traffic automation systems. This design constraint, adopted in order to limit the cost and complexity of the changes needed to implement a compression monitoring tool for the final approach course, has two impacts.

First, the compression monitoring algorithms were limited to ordinary flight plan and radar track information in order to be consistent with today's terminal automation systems like the Automated Radar Terminal System (ARTS)

and the Standard Terminal Automation Replacement System (STARS). The specific information used by this study included the aircraft position, ground speed, altitude, and heading, as well as its destination, assigned runway, and aircraft type. Use of additional intent and state information, such as the aircraft's expected speed profile along the remainder of final approach course, would likely improve the system's predictive accuracy, but it was not considered.

Second, the compression monitoring algorithms did not incorporate wind models, and instead used ground speed as a surrogate for airspeed. While this simplifying assumption affects the trajectory prediction accuracy along the final approach course, it has less impact on the separation prediction accuracy. In general, in-trail pairs experience similar wind speed profiles and have spatially correlated trajectory errors since they descend along very similar vertical profiles. The performance of compression monitoring was evaluated across a broad range of traffic scenarios and wind conditions in order to capture the collective behavior of the compression monitoring algorithms. Results were compared for the different compression monitoring algorithms on an aircraft pairwise basis to eliminate the correlated effects of the winds.

## 2. Assumptions

The results presented in this study compare the relative, not explicit, behavior of the different algorithms. The explicit dynamic behavior of the different algorithms, and hence their controller acceptability, can only be ascertained using high-fidelity human-in-the-loop simulations or operational evaluations. Two explicit assumptions were made related to the use of recorded traffic scenarios by this study.

First, the study did not attempt to isolate aircraft that were unmanaged by controllers (so-called *open-loop* aircraft) from those that were actively controlled along the final approach course; the same trajectory prediction models were used in both situations. As previously described, this study was constrained by information available from today's air traffic automation systems. Identification of actively controlled aircraft would require additional information regarding the clearances issued by the controllers. It is assumed that the relative differences in the models' behavior are dominated by events that occur when aircraft are being actively controlled and unexpected compression would be a problem.

Second, the study did not try to identify aircraft pairs that had experienced a true loss of separation due to unexpected compression from those that did not. Inevitably, some of the aircraft pairs that are considered true alerts by this study will be non-alerts because their actual required in-trail separation was less than the amount assumed. For example, the aircraft might have been executing visual approaches and the controller no longer maintaining radar separation. Operationally, the actual required in-trail separation will be provided to the compression monitoring algorithm. It is assumed that the relative differences in the models' behavior are insensitive to these slight changes to the required in-trail separation.

## 3. Eligibility Criteria

Compression monitoring was limited to the final approach course and between aircraft landing on the same runway or a parallel dependent runway. For this study, an aircraft was eligible for compression monitoring if all of the following criteria were satisfied:

- The aircraft had an assigned arrival runway. All of the aircraft's tracks were pre-processed to identify its eventual arrival runway.
- The aircraft's current track was recent. The maximum acceptable age of the track was 10 seconds in order to maintain continuity despite an occasional missing track.
- The aircraft's current track was aligned with its assigned runway centerline. The maximum skew angle between the track's heading and the runway's compass direction was 20 degrees. Controllers are instructed to use a maximum final approach intercept angle of 30 degrees.
- The aircraft's last three tracks were each near the assigned runway's final approach course. The maximum lateral offset of the track from the final approach course was the smaller of 0.50 nmi and half of the distance between parallel runways (if applicable). The maximum lateral offset was different on either side of the final approach course in the instance of parallel runways.

When a track was received for an eligible aircraft, its future in-trail separation with the closest preceding eligible aircraft was determined. The leader associated with any particular trailer was allowed to change over time as other aircraft merged in front of the trailer along the final approach course.

These eligibility criteria are slightly different than those used by the FAA's ATPA tool. The FAA's ATPA tool specifies geographic regions that surround each runway's final approach course. Any tracks that lie inside one of

these regions are considered eligible for compression monitoring. For a particular aircraft, its leader is the closest preceding aircraft whose heading is within 90 degrees of its heading. The aircrafts' assigned runways are not used to identify in-trail or diagonal pairs. Instead, a runway is associated with the geographic region containing the aircraft's track, and it is used as a surrogate for the aircraft's assigned runway. This study used the actual landing runway in order to separate the effects of incorrect runway assignment and trajectory prediction error.

#### 4. Time-Synchronization of Tracks

Aircraft tracks are refreshed with a nominal update period of 4.8 seconds for terminal radars like the Airport Surveillance Radars (e.g., ASR-9 and ASR-11). The tracks of individual aircraft are updated independently due to their different relative positions with respect to the rotating radar antennas. Therefore, determining an aircraft pair's actual current separation and predicting their future separation required the selection of a common reference time. The trailer's track time was used as the common reference time for each aircraft pair. This approach ensures that the trailer's track position does not need to be projected to a different time. The current time could also be used as the common reference time; however, this approach would have required both the leader's and trailer's track to be projected. The trailer's trajectory was constructed by starting from its current track. The leader's track was first projected to the common reference time using its current ground speed. Then, the leader's trajectory was constructed from this estimated track at the common reference time. Except in the rare event of a missed radar track, the leader's track and trailer's track were within 4.8 seconds.

### C. Trajectory Models

Three analytical trajectory prediction algorithms, one constant speed model and two heuristic speed models, were used to construct trajectories for compression monitoring. The trajectories were one-dimensional models of an aircraft's position along the final approach course (i.e., its distance from the runway threshold).

#### 1. Constant Speed Model

The simplest trajectory model maintained the aircraft's current ground speed. This model is referred to as the *dead-reckoning* model. Fig. 4 illustrates the ground speed profile of this type of trajectory. The grey diamonds are example radar tracks used as the trajectory's time-varying initial condition. The blue line shows a trajectory extending through the prescribed prediction interval for one of these radar tracks; the dotted line shows that trajectory continuing to the runway threshold. The constant speed model often overestimates the aircraft's speed since the aircraft will naturally be decelerating to its landing speed along the final approach course. The magnitude of the error depends upon the duration and rate of deceleration. Decelerating at a typical rate of 1 knot per second for 45 seconds would result in an overestimate of the distance flown by approximately one-quarter of a nautical mile. As a result, it is expected to perform more poorly than models that enforce a landing speed constraint.

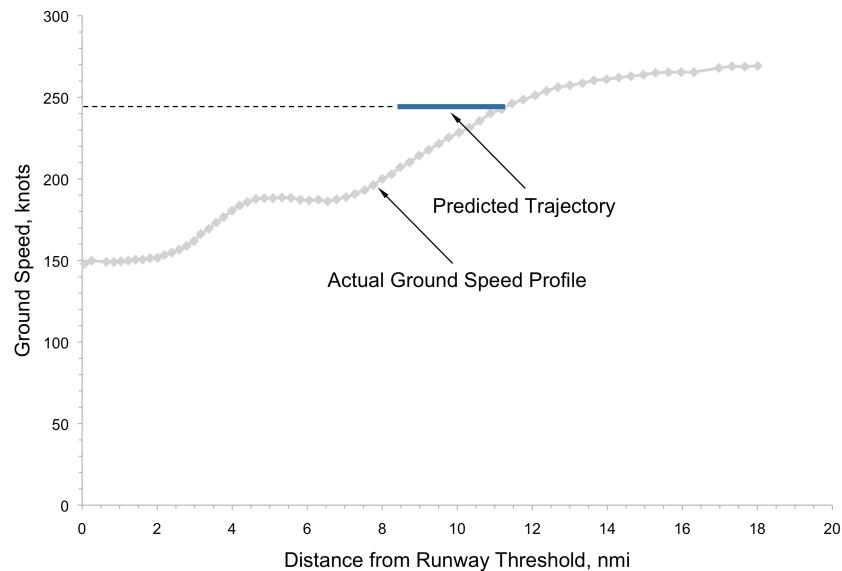
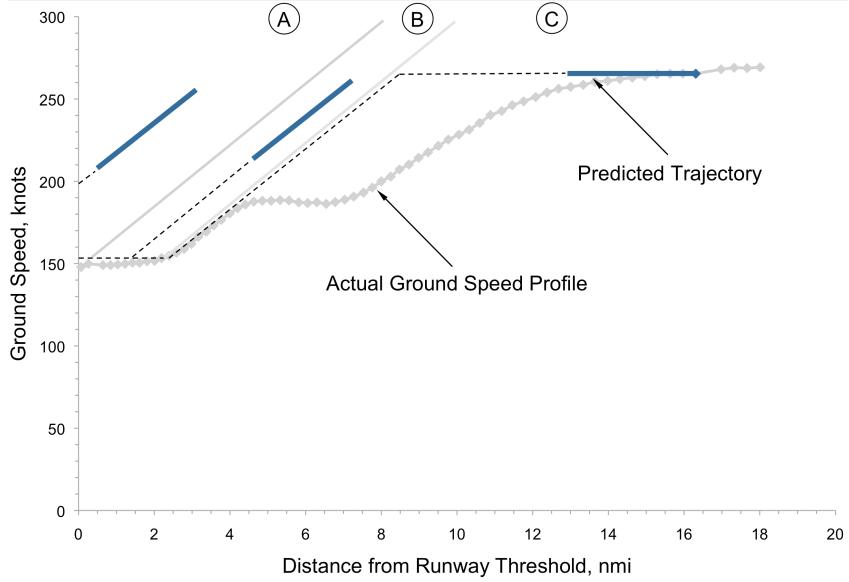


Fig. 4 Illustration of dead-reckoning trajectory model

## 2. Three-Segment Heuristic Deceleration Model

The second trajectory model used a three-segment speed profile (i.e., constant-deceleration-constant). This model is referred to as the *three-segment* model. It enforces a single speed constraint, slow to the landing speed, in order to overcome the limitations of the dead-reckoning model. The first segment maintains the aircraft's current ground speed. The second segment is a deceleration from the aircraft's current ground speed to its landing speed using a nominal deceleration rate. This nominal deceleration rate is fixed at 0.8 knots per second, and it is not allowed to change. The nominal deceleration rate was chosen to correspond to a typical slow down from 170 knots to 130 knots in preparation for landing once the aircraft passes the final approach fix. The end of the landing speed deceleration segment is nominally prescribed to be 2 nmi from the runway threshold. However, the location of the landing speed constraint can be relaxed in order to maintain the fixed nominal deceleration rate. The third segment maintains the aircraft's landing speed to the runway threshold. Fig. 5 illustrates the ground speed profile of this type of trajectory. The regions indicated by (A), (B), and (C), indicate different relaxations of the speed constraint's location. Aircraft in (A) will have the complete constant-deceleration-constant speed profile; aircraft in (B) will not have the segment that maintains their current ground speed and will achieve their modeled landing speed at less than 2 nmi from the runway threshold; aircraft in (C) will only have a deceleration segment and will not achieve their modeled landing speed before the runway threshold. The formatting is the same as the formatting used for Fig. 4. For completeness, trajectories are shown for each region. This method of relaxation was chosen to ensure the smoothest possible behavior despite of large variations in observed ground speed values relative to the nominal ground speed profile.

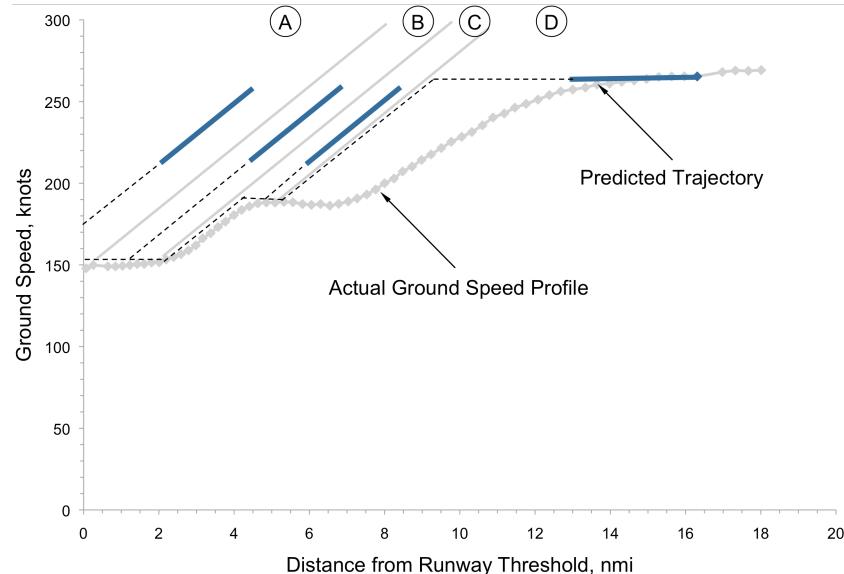


**Fig. 5 Illustration three-segment trajectory model**

## 3. Five-Segment Heuristic Deceleration Model

The third trajectory model used a five-segment speed profile (i.e., constant-deceleration-constant-deceleration-constant). This model is referred to as the *five-segment* model. It enforces the landing speed constraint, as well as an additional final approach course speed constraint, slow to 170 knots at the final approach fix, in order to account for typical procedures at high-density airports. The first segment maintains the aircraft's current ground speed. The second segment is a deceleration from the aircraft's current ground speed to the final approach course speed using the nominal deceleration rate described previously. The end of this deceleration is nominally prescribed to be the runway-specific final approach fix - generally 4 to 6 nmi from the runway threshold. The third segment maintains the final approach fix speed. The fourth segment is another deceleration from the final approach course speed to the aircraft's landing speed using the nominal deceleration rate. The end of the landing speed deceleration segment is nominally prescribed to be 2 nmi from the runway threshold. The fifth segment maintains the aircraft's landing speed. Fig. 6 illustrates the ground speed profile of this type of trajectory. The regions indicated by (A), (B), (C), and (D) again indicate different relaxations of the speed constraints' locations. Aircraft in (A), (B), and (C) behave as described for the three-segment model. Aircraft in (D) will have the complete constant-deceleration-constant-

deceleration-constant speed profile. Again, the formatting is the same as the formatting used for Fig. 4, and trajectories are shown for each region.



**Fig. 6 Illustration of five-segment trajectory model**

#### D. Landing Speed Models

Three models of an aircraft's landing speed were used to evaluate how improved landing speed information would affect the performance of the different trajectory prediction models. The landing speed is a speed constraint for the three-segment and five-segment trajectory models. The first landing speed model is based upon the aircraft's engine type – Jet, Turboprop or Piston. Table 3 shows the values associated with each engine type. The second landing speed model is based upon the aircraft's weight class category – Super Heavy, Heavy, Boeing 757, Large or Small. Table 4 shows the values associated with each weight class category. These speeds are based upon the observed average landing speeds of the most common commercial aircraft types. The FAA's ATPA tool uses this particular landing speed model. The third landing speed model used the ground speed of the aircraft's final radar track. This value was considered the aircraft's actual landing speed.

**Table 3 Landing speed based upon engine type**

Engine Type	Landing Speed, knots
Jet	135
Turboprop	118
Piston	94

**Table 4 Landing speed based upon weight class**

Weight Class	Landing Speed, knots
Super Heavy	140
Heavy	138
Boeing 757	135
Large	131
Small	124

For the basic landing speed models (engine type and weight class category), the computed landing ground speed can optionally be increased by the amount of 1.4 knots for each 1000 feet of field elevation. For example, the computed landing speed would be increased 7 knots for an airport whose field elevation was 5000 feet above sea level. This adjustment represents the nominal increase with altitude of the ground speed associated with a particular indicated airspeed.

## E. Required In-trail Separation Model

For this study, standard radar separation was defined as the required in-trail separation.<sup>8,14</sup> Table 5 shows the specific horizontal separation values for each combination of leader and trailer weight class categories. Operationally, the FAA's ATPA tool will require traffic managers to update the required in-trail separation values to reflect the current airport configuration and airspace procedures. For example, in-trail separation at the runway threshold can be reduced to 2.5 nmi under certain conditions.

**Table 5 Required in-trail separation based upon weight class category (in nmi)**

		Trailer				
		Super Heavy	Heavy	Boeing 757	Large	Small
Leader	Super Heavy	6	6	8	8	10
	Heavy	4	4	5	5	6
	Boeing 757	4	4	4	4	5
	Large	3 <sup>a</sup>	3 <sup>a</sup>	3 <sup>a</sup>	3 <sup>a</sup>	4
	Small	3 <sup>a</sup>				

<sup>a</sup> Reduced spacing to 2.5 nmi allowed when certain conditions are met

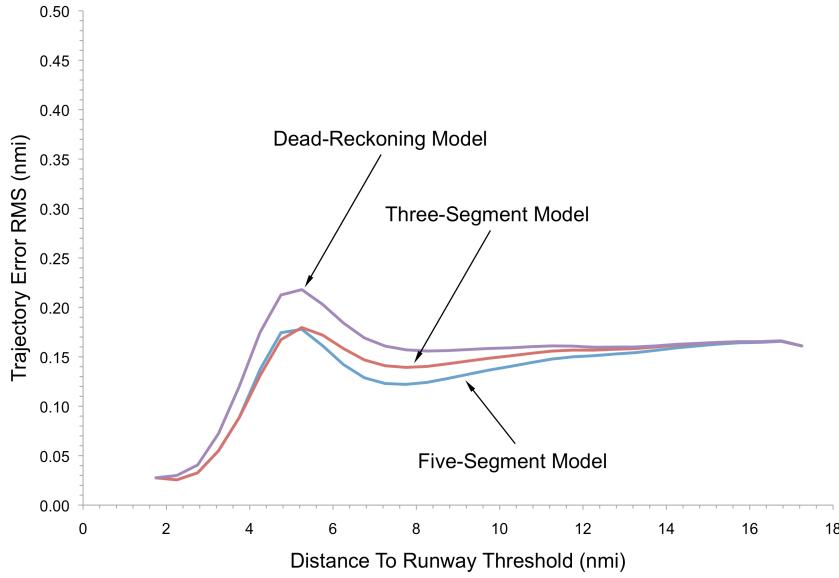
## V. Results

The trajectory prediction accuracy of each arrival flight and the separation prediction accuracy of each pair of arrival flights in every traffic sample were calculated. Approximately 7 million radar track pairs were analyzed. All of these results were used to rank the performance of the different trajectory models in terms of their probabilities of true and false detection. This section discusses those results in detail.

### A. Trajectory prediction accuracy along the final approach course

A limiting factor for compression monitoring is the degree to which an aircraft's trajectory along the final approach course can be predicted. The trajectory errors of the models described in Sec. IV(C) were calculated for each radar track. To isolate the effects of the trajectory model from the other components of the compression monitoring algorithm, the analysis of trajectory accuracy used the weight class landing speed model, and did not adjust the landing speed for airport elevation. The trajectory models were used to determine an aircraft's predicted position 45 seconds ahead of its track. The aircraft's actual position at that time was determined by interpolation between a pair of its later tracks. The difference in these positions was defined as the trajectory error. For statistical analysis purposes, the tracks were grouped by the aircraft's distance to the runway threshold using 0.5 nmi bins along the final approach course. Fig. 7 shows the RMS values of the trajectory errors for the different trajectory models. The results are shown for all airports collectively; results for the individual airports show the same overall behavior.

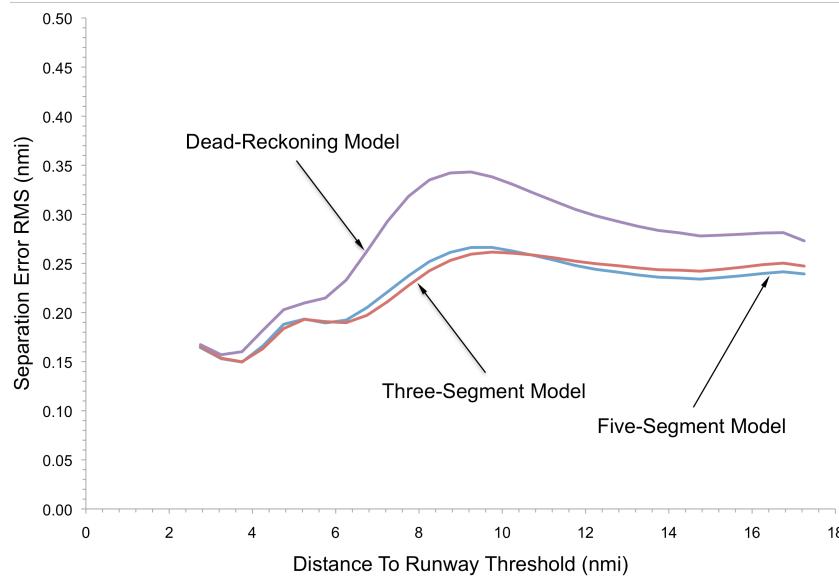
All of the models' trajectory errors have pronounced peaks centered around 4-6 nmi but generally exhibit constant error growth farther from the runway threshold. This result is consistent with the large amount of variability in the location where each aircraft begins slowing to its landing speed. The models exhibit noticeably difference performance between 6 and 12 nmi from the runway threshold. Along this region of the final approach course, the five-segment model is the best performing model, followed by the three-segment model, and finally the dead-reckoning model. The five-segment model's trajectory error is approximately 5-10% less than the three-segment model's error; the three-segment model's trajectory error is approximately 10-20% less than the dead-reckoning model's error. Inspection of the models' trajectory errors shows that the landing and final approach course speed constraints improve the prediction accuracy by reducing both its mean and variance upstream of the speed constraints.



**Fig. 7 Comparison of trajectory errors along the final approach course for different trajectory models**

#### B. Separation prediction accuracy along the final approach course

Another limiting factor for compression monitoring is the degree to which trajectory errors are correlated between the leader and trailer so that an aircraft pair's in-trail separation along the final approach course can be predicted. The separation errors of the trajectory models described in Sec. IV(C) was also analyzed for each radar track. The analysis of separation errors used the same landing speed assumptions as the analysis of trajectory errors. The trajectory models were used to determine an aircraft pair's predicted separation 45 seconds ahead of the trailer's track. The aircraft pair's actual separation at that time was determined by interpolation between two pairs of later tracks – one pair for the leader and one pair for the trailer. The difference in these separations was defined as the separation error. For statistical analysis purposes, the tracks were grouped by the trailer's distance to the runway threshold using 0.5 nmi bins along the final approach course. Fig. 8 shows the RMS value of the separation errors for the different trajectory models. Data are not shown for tracks whose distance to the runway threshold was less than 2.5 nmi or more than 17.5 nmi due to an insufficient number of aircraft pairs. The results are shown for all airports collectively; results for the individual airports show the same overall behavior.



**Fig. 8 Comparison of separation errors along the final approach course for different trajectory models**

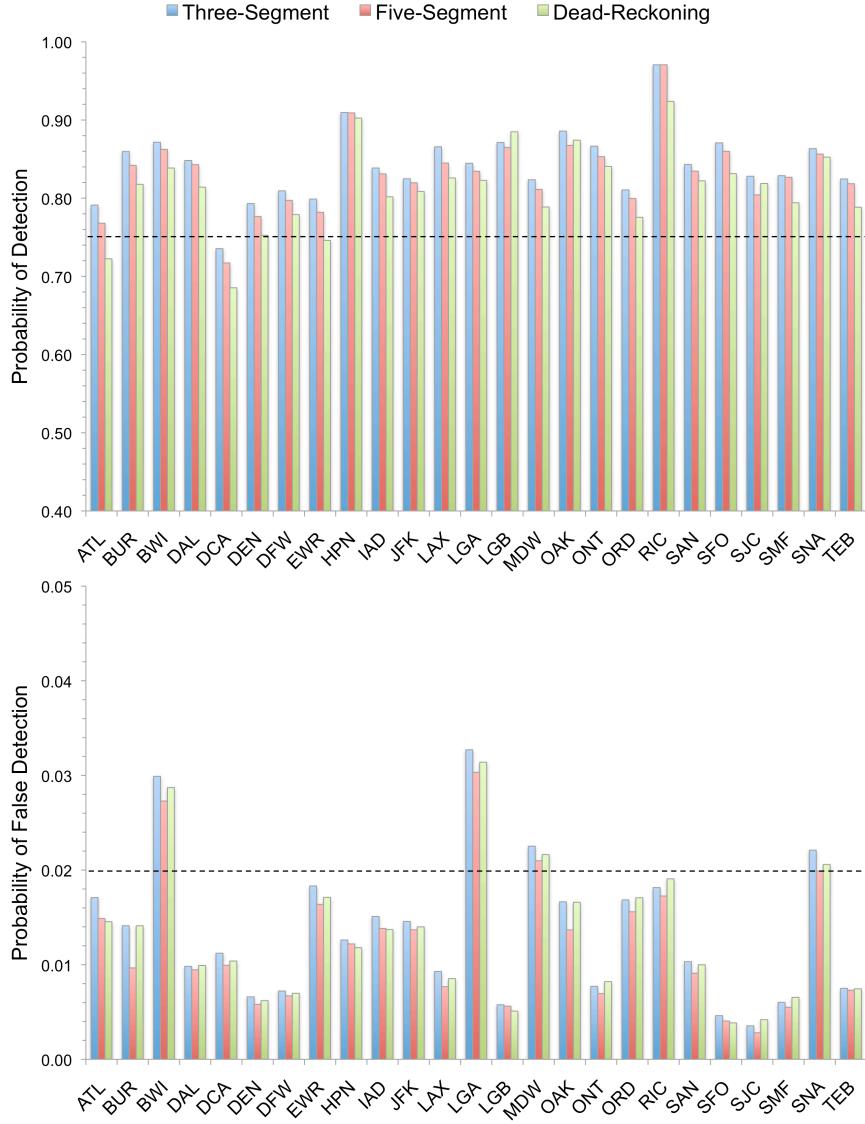
All of the models' separation errors have peaks centered around 8-10 nmi but generally exhibit constant error farther from the runway threshold. These peaks in separation error correspond to the peaks in the leader's trajectory error. All of the models' separation errors also have smaller peaks centered around 4-6 nmi. These peaks are the result of the peaks in the trailer's trajectory error. The three-segment and five-segment models perform equally well and are better than the dead-reckoning model. The three-segment and five-segment models' separation errors are approximately 20-30% less than the dead-reckoning model's error. At some high-density airports, the three-segment model's separation error is approximately 5% less than the five-segment model's error between 6-10 nmi. However, the three-segment model and five-segment model cannot be differentiated at most airports.

### C. Compression monitoring accuracy along final approach course

The results presented in Secs. V(A) and V(B) show that the trajectory errors will be a few tenths of nautical miles, and the separation errors roughly twice that amount, for 45-second predictions along the final approach course. However, the magnitude of the separation error is only one factor governing the performance of compression monitoring. The observed performance of different compression monitoring algorithms will be the combination of their separation errors and the traffic flow being monitored. The compression monitoring performance of the trajectory models described in Sec. IV(C) was also analyzed for each radar track. The analysis of compression accuracy used the same landing speed assumptions as the previous analyses, and additionally did not allow reduced (i.e., 2.5 nmi) in-trail separation. Two prediction intervals, 22 seconds and 45 seconds, were analyzed to understand how the trajectory models behaved as aircraft approached key ATPA prediction intervals. The 45-second prediction interval represents the earliest moment that an ATPA warning can be issued; the 22-second prediction interval represents the earliest moment that an ATPA alert can be issued.

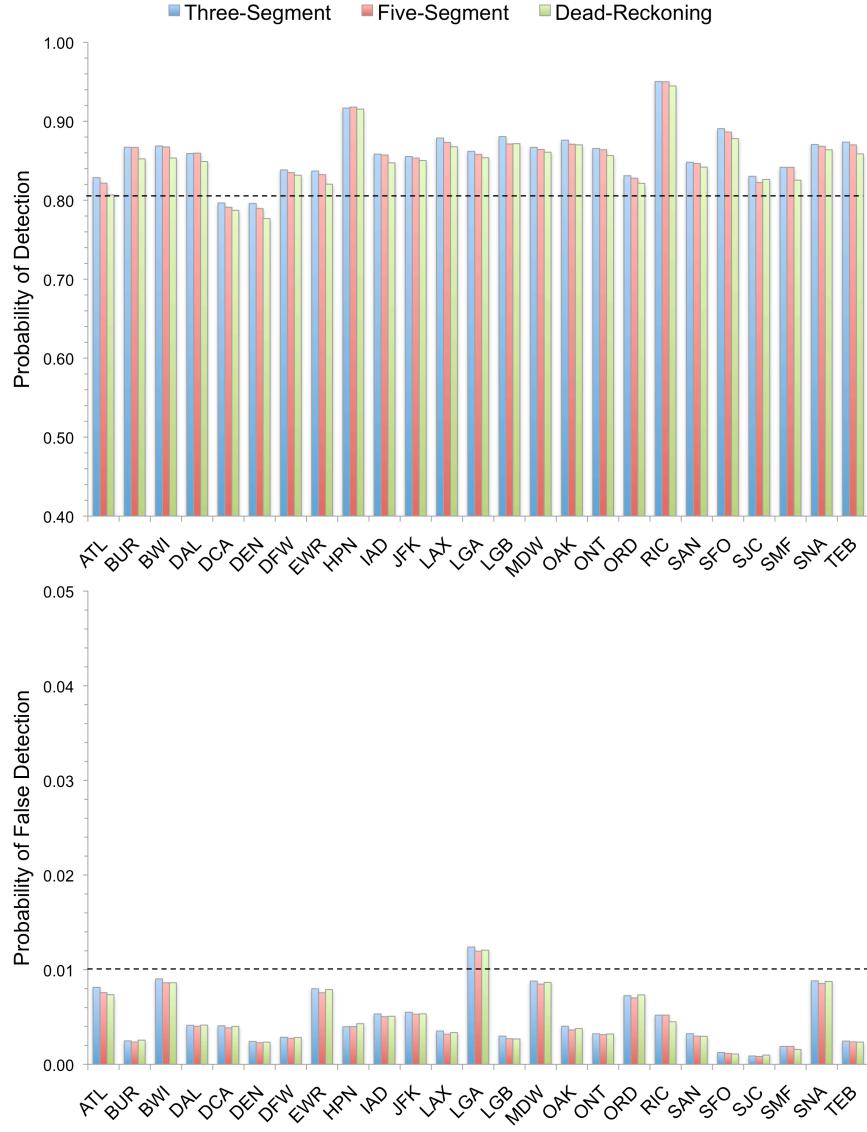
Two metrics were calculated to describe the compression monitoring performance: the probability of detection (POD) and the probability of false detection (POFD). In the context of this analysis, POD represents the fraction of radar tracks that were predicted to have a loss of separation at the prediction interval and did in fact have one. The probability of missed detection (POMD) is the inverse of the POD. Conversely, POFD represents the fraction of radar tracks that were predicted to have a loss of separation at the prediction interval and did not have one. Several caveats apply to the POD and POFD metrics used in this analysis. First, a loss of separation refers to an observation of actual in-trail separation less than the modeled amount. Operationally, the required in-trail separation will be dictated by airport and airspace configuration information provided by the controllers. This analysis assumed that basic wake separation standards were applicable. Many, if not all of the apparent losses of separation were likely the result of inaccurate estimates of the required separation, rather than true separation violations. Second, the POD is not the fraction of losses of separation that would eventually be predicted. Compression monitoring recurs for every radar track update, so a later radar track might yield a true but less timely compression warning or alert. Third, the POFD is not a precise measure of false detections because controllers might have intervened to avoid a loss of separation that was otherwise going to happen. Some of the apparent false detections will be nuisance alerts more generally. Finally, the POFD is calculated with respect to the fraction of radar tracks and not the fraction of aircraft pairs. Each aircraft pair can have multiple true or false detections. Later results (see Sec. V(F)) will discuss the compression monitoring performance with respect to aircraft pairs. These caveats notwithstanding, this study assumed that the relative behaviors of the difference compression monitoring algorithms are well described by the POD and POFD metrics.

Fig. 9 shows the POD and POFD at the 45-second prediction interval (hereafter, referred to as  $POD_{45}$  and  $POFD_{45}$ ) for the different trajectory models at the airports studied. The results are shown for multiple days at each airport collectively, but inspection of the results for individual days at each airport shows the same behavior across days. At the 45-second prediction interval, the trajectory models generate 50% more missed alerts than false alerts. For most airport/model combinations, the  $POD_{45}$  is between 0.75 and 0.85. In other words, there is a 75 to 85% chance of detecting a loss of separation 45 seconds ahead on the final approach course. Conversely, for most airports, the  $POFD_{45}$  is less than 0.02 (2%). A few airports, in particular BWI and LGA, have slightly higher  $POFD_{45}$  values. The specific cause of this behavior has not been determined. All of the trajectory models perform similarly in terms of both  $POD_{45}$  and  $POFD_{45}$  at each airport. However, the three-segment trajectory model does have a marginally higher  $POD_{45}$  for each airport. Its  $POD_{45}$  is approximately 0.01-0.02 (1-2%) higher than the five-segment model's  $POD_{45}$ , and 0.02-0.04 (2-4%) higher than the dead-reckoning model's  $POD_{45}$ . Unlike  $POD_{45}$ , all of the models have nearly identical  $POFD_{45}$  values for each airport.



**Fig. 9 Comparison of compression monitoring algorithm performance at the warning prediction interval (45 seconds) using the probability of detection (top) and the probability of false detection (bottom)**

Fig. 10 show the POD and POFD at the 22-second prediction interval (hereafter, referred to as  $POD_{22}$  and  $POFD_{22}$ ) for the different trajectory models at the airports studied. Again, the results are shown for multiple days at each airport collectively, but inspection of the results for individual days at each airport shows the same behavior across days. At the 22-second prediction interval, the trajectory models generate two times more missed alerts than false alerts. For most airports, the  $POD_{22}$  is 1 to 5% higher than the  $POD_{45}$  for all of the models. However, this means that there is still a 10-20% chance of not detecting a loss of separation 22 seconds ahead on the final approach course. The dead-reckoning model, as expected, showed the largest improvement, followed by the five-segment trajectory model and the three-segment trajectory model. For all airports except LGA, the  $POFD_{22}$  is less than 1% for all models. All of the trajectory models perform even more similarly in terms of both  $POD_{22}$  and  $POFD_{22}$  at each individual airport. The three-segment trajectory model no longer has a marginally higher  $POD_{22}$  for each airport. Its  $POD_{22}$  is now less than 0.01 (1%) higher than the five-segment model's  $POD_{22}$ , and only 0.01-0.02 (1-2%) higher than the dead-reckoning model's  $POD_{22}$ . Like  $POFD_{45}$ , all of the models have nearly identical  $POFD_{22}$  values for each airport.



**Fig. 10 Comparison of compression monitoring algorithm performance at the alerting prediction interval (22 seconds) using the probability of detection (top) and the probability of false detection (bottom)**

#### D. Effect of landing speed model on compression monitoring accuracy

The effect of the landing speed model on the compression monitoring accuracy was analyzed. In order to isolate the effects of the landing speed model from the other components of the compression monitoring algorithm, the analysis of its impact used the three-segment trajectory model, did not adjust the landing speed for airport elevation, and did not allow reduced in-trail separation. The three landing speed models described in Sec. IV(D) were analyzed: the actual landing speed (defined as the ground speed of the flight's last radar track before the runway threshold), the landing speed based upon weight class, and the landing speed based upon engine type. The POD and POFD metrics described above were used to quantify any improvements associated with the different landing speed predictions.

Qualitatively, there is little difference in the compression monitoring accuracy between the landing speed models. In general, the POD for the actual landing speed model is less than 0.016 (1.6%) higher than the weight class model, and the weight class model is less than 0.007 (0.7%) higher than the engine type model. The amount of improvement in POD is generally 3-5 times smaller than the improvement in POD associated with the trajectory

model. Like the POFD variation between trajectory models, all of the landing speed models have nearly identical POFD values for each airport.

#### E. Effect of airport elevation on compression monitoring accuracy

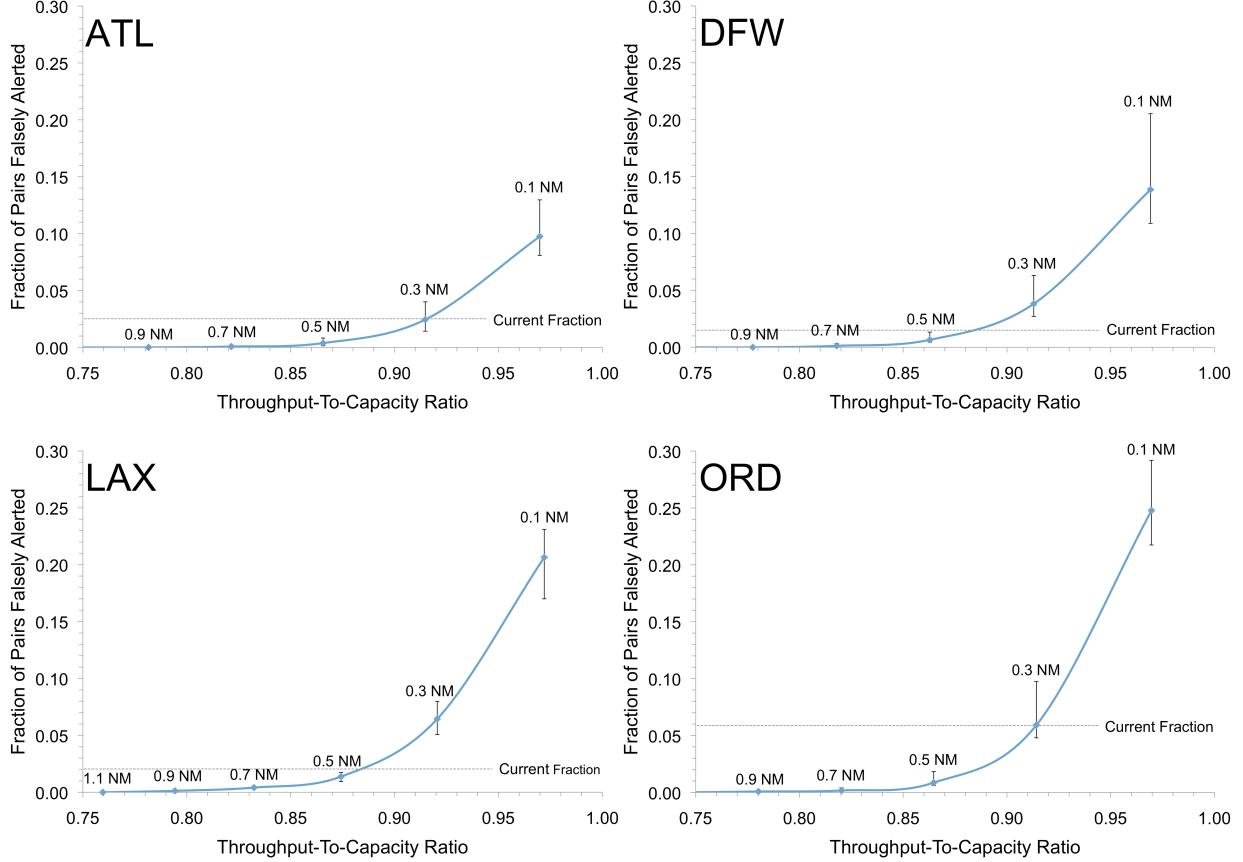
For a given indicated airspeed, the associated ground speed increases by approximately 1.4 knots per 1,000 feet of pressure altitude. The FAA's ATPA tool increases the aircraft's modeled landing speed to account for this natural increase of ground speed with airport elevation. The effect of the elevation adjustment on the compression monitoring accuracy was analyzed. In order to isolate the effects of the elevation adjustment from the other components of the compression monitoring algorithm, the analysis of its impact used the three-segment trajectory model and weight class landing speed model, and did not allow reduced in-trail separation. The elevation adjustment was either enabled or disabled for all airports. The POD and POFD metrics described above were used to quantify any improvements associated with the elevation adjustment.

Qualitatively, the elevation adjustment had an unexpectedly small impact. In general, the POD decreased 0.002 (0.2%) when the elevation adjustment was enabled. This result was initially unexpected, but can be traced to the three-segment trajectory model itself. The three-segment trajectory model prescribes the end of landing speed deceleration segment rather than its start. Therefore, the increased landing speed associated with the elevation adjustment shortens the deceleration segment and moves it closer to the runway threshold. As a result, the three-segment model behaves more like the dead-reckoning model (i.e., less accurately). Like the POFD variation between landing speed models, the POFD remained unchanged when the elevation adjustment was enabled.

#### F. Effect of traffic throughput on compression monitoring accuracy

Finally, the number of aircraft pairs triggering compression warnings was analyzed to understand how frequently controllers would be presented with false alarms. This analysis was performed for both today's traffic as well as artificially compressed traffic to model increased throughput. Throughput was varied by temporally translating each of the trailer's radar tracks to achieve a prescribed excess in-trail separation as the leader crossed the runway threshold. The analysis of aircraft pairs used the three-segment trajectory model and the weight class landing speed model, did not adjust landing speed for airport elevation, and did not allow reduced in-trail separation. The three-segment trajectory model was chosen because it is most similar to the trajectory model used by FAA's ATPA tool, and it was the highest performing model in this study. The 45-second prediction interval was analyzed, since false alerts are naturally more common at the longer prediction interval. A single metric was used to describe the compression monitoring performance: the probability of false pairs (POFP). In the context of this analysis, POFP represents the fraction of aircraft pairs that were predicted for one or more radar tracks to have a loss of separation at the prediction interval and did not have one. POFP is related to, but not the same as, POFD because multiple radar tracks will be associated with each aircraft pair.

Fig. 11 shows the median daily POFP values for the four busiest airports in the NAS - ATL, DFW, LAX, and ORD. These airports were examined because their traffic levels make compression monitoring most desired, but also most prone to excess false alarms. The dotted lines indicate each airport's median daily POFP for the days studied (i.e., current POFP). The current POFP is lowest for DFW (0.015) and highest for ORD (0.059). In other words, the compression monitoring algorithm generated false compression warnings for 1.5% of DFW arrivals and 5.9% of ORD arrivals. The prescribed excess in-trail separation (indicated by the labels along the curves) was varied from 0.1 nmi to 1.1 nmi. The excess in-trail separation was translated to a throughput-to-capacity ratio using each airport's mean required in-trail separation. The solid lines indicate the airport's median daily POFP for the prescribed excess in-trail separation (i.e., future POFP values). The bars indicate the 25<sup>th</sup> percentile and 75<sup>th</sup> percentile daily POFP values of the future POFP across the days studied at each airport. These results can be interpreted in two ways. They indicate the frequency of false compression warnings when operations are maintained at a particular throughput-to-capacity ratio. Also, they indicate the likelihood of a false compression warning for any pair of aircraft given a particular amount of excess in-trail separation at the runway threshold.



**Fig. 11 Comparison of compression monitoring algorithm performance for current and increased traffic demand at ATL, DFW, LAX, and ORD**

## VI. Discussion

The analyses focused on the variation of trajectory prediction errors, in-trail separation errors, and compression monitoring errors for today's and future higher throughput traffic scenarios. The analyses also evaluated the effectiveness of several improvements associated with variations of the trajectory models, including a reduction of the prediction interval, use of different landing speed models, and an adjustment of the landing speed based upon airport elevation.

Three trajectory models were compared: a dead-reckoning model that maintained current ground speed, a three-segment model that enforced a landing speed constraint, and a five-segment model that enforced both a final approach course speed constraint and a landing speed constraint. Comparison of the RMS values of trajectory prediction error for each of the models suggests that the five-segment model performed best, followed by the three-segment model and then the dead-reckoning model. (See Fig. 7) However, the inherent spatial correlation of the trajectory prediction errors of the three-segment and five-segment models causes their RMS values of separation error to be nearly identical, but still consistently better than the dead-reckoning model. (See Fig. 8) While the five-segment model has the smallest separation error, the natural behavior of the traffic flow along the final approach course causes the three-segment model to have the highest POD with only a minor increase in its POFD<sub>45</sub> when compared to the five-segment trajectory model. (See Fig. 9) For example, at ATL, the five-segment trajectory model has a POD<sub>45</sub> of 0.76 and a POFD<sub>45</sub> of 0.17, while the three-segment trajectory model has a POD<sub>45</sub> of 0.79 and a POFD<sub>45</sub> of 0.020. The three-segment model's single speed constraint allows the algorithm to be more responsive to changes in the aircraft's current ground speed than the five-segment model, and at the same time, it allows the algorithm to capture the effect of the downstream deceleration to the landing speed.

The difference across models is modest but consistent across days. Examination of the daily POD for each airport shows that the three-segment model has the highest POD on the most number of days at every airport studied. In fact, at many airports, and in particular at high-density airports like ATL, DFW, LAX, and ORD, the three-segment model has the highest score on more than 90% of the days studied. This consistency across both days

and airports further strengthens the assertion that the three-segment model is most appropriate compression monitoring algorithm.

The reduction of the prediction interval from 45 seconds to 22 seconds does not substantially increase the POD or decrease the POFD. The  $POD_{45}$  values of the three-segment model are 0.75-0.85 for all of the airports studied. (See Fig. 9); the  $POD_{22}$  values of the three-segment model are 0.80-0.90 for those same airports. (See Fig. 10) Similarly, the  $POFD_{45}$  values of the three-segment model are less than 2% for most airports, while the  $POFD_{22}$  values are less than 1%. Further reductions of the prediction interval are not likely to provide sufficient lead time to resolve the loss of separation with a speed reduction. For example, aircraft slowing at the nominal deceleration rate of 0.8 knots per second would need more than 12 seconds (nearly three radar track updates) to eliminate a 10 knot speed differential; a 20 knot speed differential could not be eliminated in 22 seconds.

The use of different landing speed models and the adjustment of the landing speed based upon the airport elevation does not provide any significant improvement or degradation of the  $POD_{45}$  and  $POFD_{45}$  values of the three-segment model. These results can be explained intuitively. The trajectory models' use of a nominal deceleration rate isolates the impact of the specific landing speed to the leader's last few radar tracks just prior to the runway threshold. Also, the landing speed models achieve very similar RMS values for landing speed error, and are essentially equivalent for many aircraft types. Lastly, the effect of airport elevation on separation prediction, like the effect of airport winds, is significantly correlated between flights operating in-trail of each other. Therefore, there will be some reduction of trajectory prediction error and an increase in estimated time-of-arrival accuracy, but improvements of separation accuracy and compression monitoring performance are not likely.

Finally, the number of falsely alerted aircraft pairs, examined at the four busiest airports in the NAS – ATL, DFW, LAX, and ORD, shows considerable sensitivity to increased traffic throughput. (See Fig. 11) These results illustrate several key points related to the performance of the compression monitoring algorithm. First, the variability of the current POFP is unexpectedly large across these four airports. It ranges from 0.015 (1.5%) at DFW to 0.059 (5.9%) at ORD. Both the range of values and magnitude, particularly at ORD, mean that controller acceptance of the compression monitoring algorithms will vary widely across airports. Second, the mean future POFP and its variance grow substantially as excess in-trail separation is reduced below 0.5 nmi. For example, the future POFP for DFW with an excess separation of 0.1 nmi has a mean value of 14% with upper and lower quartiles of 21% and 11%. Under these conditions, DFW controllers would receive false alerts for more than 21% of the aircraft pairs on one-quarter of the days. These results suggest that a compression monitoring algorithm that does not incorporate new information will exhibit sizeable false alert rates. The ability of controllers to use the compression monitoring tool to increase the achievable throughput at high-density airports, like ATL, DFW, LAX, and ORD, remains in doubt.

## VII. Conclusions

This study analyzed the performance of several compression monitoring algorithms using recorded flight plan and radar track data for approximately 480,000 flights on the final approach courses of 14 OEP35 airports, as well as 11 major satellite airports, at eight busy TRACONs in the NAS. The number of individual radar track pairs analyzed exceeded 7 million. Five specific conclusions are made regarding compression monitoring performance for potential algorithms compatible with today's air traffic automation systems.

- 1) The compression monitoring performance is best for the three-segment trajectory model that strikes a balance between probability of detection and probability of false detection. Its trajectory error and separation error are consistently less than the dead-reckoning trajectory model's errors.
- 2) The compression monitoring performance is modestly improved when the prediction interval is reduced from 45 seconds to 22 seconds. Prediction intervals less than 22 seconds are impractical since they would not provide enough alert lead time for controllers to intervene with speed control alone.
- 3) The compression monitoring performance is slightly better for the weight class landing speed model than the engine type landing speed model. In general, a precise landing speed estimate is not needed, and enforcement of any landing speed constraint improves the separation prediction.
- 4) The compression monitoring performance is not improved when the landing speed estimate is adjusted by airport elevation. The effects of airport elevation are strongly correlated and do not affect separation error.

5) The compression monitoring performance will degrade appreciably when typical excess in-trail separation is reduced below 0.5 nmi, regardless of its trajectory model. At high-density airports, the probability of false aircraft pairs will exceed 10% when the excess in-trail separation is reduced below 0.1 nmi.

### Acknowledgements

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