

FLIGHT MANAGEMENT SYSTEM PREDICTION AND EXECUTION OF IDLE-THRUST DESCENTS

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Abstract

To enable arriving aircraft to fly optimized descents computed by the flight management system (FMS) in congested airspace, ground automation must accurately predict descent trajectories. To support development of the predictor and its uncertainty models, descents from cruise to the meter fix were executed in a B737-700 simulator with a commercial FMS using vertical navigation. The FMS computed the intended descent path for a specified speed profile assuming idle thrust after top of descent (TOD), and then it controlled the avionics without human intervention. The test matrix varied aircraft weight, descent speed, and wind conditions. The first analysis in this paper determined the effect of the test matrix parameters on the FMS computation of TOD. Increasing weight by 10,000 lb moved TOD about 4.5 nmi farther from the meter fix, increasing along-track wind by 25 kt moved it about 4.6 nmi farther away, and varying the descent speed from 250 KCAS to 320 KCAS moved the TOD about 25 nmi. The execution of the descents was analyzed by comparing simulator state data to the specified speed profile and to the FMS predictions. The FMS generally flew its predicted three-dimensional trajectory accurately, with altitude error less than 200 ft. It engaged the throttle if the speed dropped 15 KCAS below the target speed but allowed the speed to increase arbitrarily above the target unless it reached a performance limit. In the runs with descent speed too slow but correct wind conditions, the FMS meter fix arrival time prediction error was as large as 37 sec. Along-track wind error of 25 kt resulted in a meter fix arrival time error of roughly 30 sec if the target descent speed was met. The data from this analysis are used to estimate accuracy requirements for the ground automation system.

Introduction

In congestion today, controllers direct aircraft to descend in steps. Since air density, and hence drag, increase as the aircraft descends, significant reductions in fuel consumption and emissions would result if aircraft stayed at cruise altitude longer and then descended smoothly at idle thrust. The flight management system (FMS) on a large jet can compute the location of top of descent (TOD) assuming an idle-thrust descent. To

merge aircraft, however, controllers impose level flight segments, which make it much easier for them to estimate the relative speeds of two aircraft given their calibrated airspeed (CAS). Three-Dimensional Path Arrival Management (3DPAM) enables arriving aircraft to fly optimized descents computed by the FMS in congested airspace, using procedures that do not require a data link [1]. The 3DPAM ground automation must accurately predict descent trajectories to ensure there are no conflicts and to provide situation awareness to controllers. In addition to predicting the meter fix arrival time accurately to ensure lateral separation, accurate prediction of the vertical profile is essential to ensure vertical separation from aircraft at different altitudes, including crossing traffic. This paper discusses some aspects of these prediction accuracy requirements.

In the 3DPAM concept, the FMS will be given the descent speed profile and the speed and altitude at the unknown TOD location and at the meter fix. Assuming idle thrust in the descent, the FMS will compute the vertical profile and fly it with minimal human intervention. In this study, such descents were flown in a B737-700 simulator with a commercial FMS and no human intervention. The test matrix varied aircraft weight, descent speed, and wind conditions to determine their effect on FMS prediction and execution of the descent. FMS prediction and aircraft simulator state data were recorded and analyzed. No ground-based trajectory predictor was used for the analysis in this paper. Instead, the FMS prediction was used as a proxy.

Due to the potential fuel savings and emissions reductions, enabling continuous descents is being pursued by several research groups [2,3,4,5,6]. Most of the previous error analysis has focused on the distribution of the difference between operational arrival time at a waypoint and its prediction by the FMS or ground automation. A few such as [2,5] have also considered the operational TOD prediction error. Using a simulator in the current research simplifies understanding how individual factors affect FMS predictions, which is beneficial in specifying accuracy requirements for the factors. Furthermore, throttle and pitch angle data provide insight into the FMS control procedures. Tong, Boyle, and Warren [3] and Herndon et al. [7,8] also used simulators with commer-

cial FMSs but analyzed the effects of different factors.

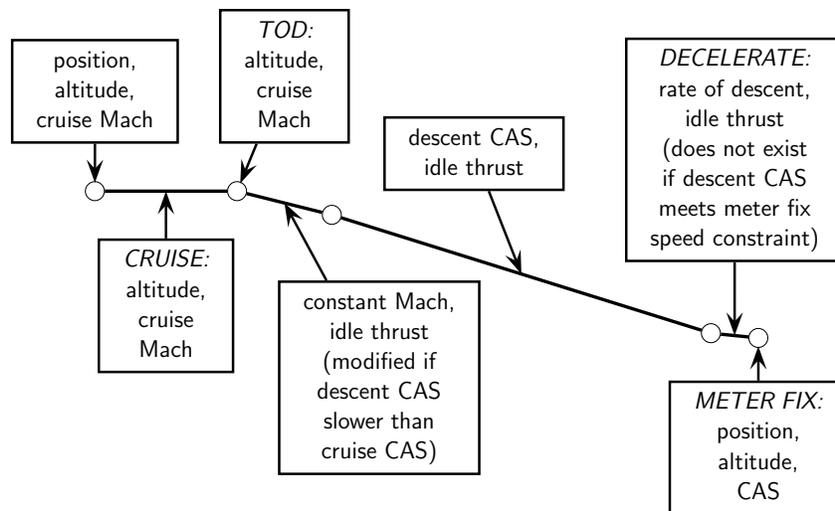
The first analysis reported in this paper determines the effect of the test matrix parameters on the FMS prediction of TOD location. Since the FMS flew the descents without human intervention, this prediction is very close to its actual location. Therefore, the variation in the FMS TOD location for a given test matrix parameter can be used to estimate a best-case accuracy requirement for that parameter for the ground predictor. Based on previous controller feedback, acceptable ground automation TOD prediction error is likely to be no larger than 5 nmi, and it is likely that no single source can contribute more than roughly 2 nmi of error.

The second analysis in this research considers the FMS execution error. First, the simulator aircraft speed profile is compared with the speed profile specified to the FMS. If the simulator model exactly matched the FMS model, the simulated trajectory would nearly satisfy the model and would be very close to the FMS prediction, with small differences due to errors in the autopilot system control algorithms. The reason this is not the case is unknown, but the simulation data give insight into FMS behavior in response to input errors that are likely to occur in operations. Based on the comparison of speeds, estimates are given of best-case ground predictor accuracy for the meter fix arrival time. To interpret these results, consider that the minimum separation requirement at the meter fix is 5 nmi, which is roughly 60 sec in zero wind at the meter fix speed and altitude constraints. Consequently, the ground automation probably needs to

predict the meter fix arrival time within about 20 sec.

Experiment Procedures

The experiments in this study were run in a Boeing 737-700 simulator operated by Boeing Phantom Works. The simulator is custom-built and includes a commercial FMS. The simulator is used in developing procedures, not in pilot training. The FMS used both lateral and vertical navigation (VNAV). To compute its descent trajectory, the FMS used the constraints shown in Figure 1, which uniquely determine the trajectory. The parameters shown in each box are specified for that segment or that point of the descent. In brief, the FMS assumed idle thrust from TOD to the meter fix, and it used the speed profile, which will be specified in 3DPAM by the controller for both cruise and descent. The FMS also used two meter fix constraints: altitude 11,000 ft and speed 250 kt CAS (KCAS). In Figure 1, the first segment in the descent has constant Mach number, which is the same as the cruise Mach number. As the altitude decreases, the CAS increases until it reaches the target descent CAS, which will be specified by the controller in 3DPAM. The next segment is then flown at that CAS. Finally, if the descent CAS is faster than the meter fix speed constraint, the aircraft pitches up to decelerate to that constraint. If target descent CAS is slower than the cruise CAS, however, the aircraft first decelerates at idle thrust while maintaining level flight or close to it, and then it pitches down to maintain the target descent speed at idle thrust.



The horizontal trajectory was the same nearly-straight standard arrival route in all simulation runs. Each run started at least 100 nmi from the meter fix in cruise at 37,000 ft. To set up the descent in the FMS in these experiments, the waypoints were entered, “ECON MODE” was selected to specify an idle-thrust descent, and the FMS-computed descent speed was overridden by manually entering the desired descent speed, which will be specified by the controller in 3DPAM. The cruise Mach number was determined by the FMS based on a user-specified parameter, but it was generally between 0.79 and 0.80 during cruise. The simulation runs continued below the meter fix, but analysis included only data to the meter fix.

In operations, the pilot may use throttle or spoilers to stay close to the intended descent speed profile, but there was no human intervention in these experiments after programming the FMS. Since the FMS cannot control the speed brakes, they were not used in these experiments. The FMS can and did, however, engage the throttle to correct descent speed in some runs when it was too slow. Thus, the descent was not necessarily flown entirely at idle thrust, but the FMS computed it assuming it would be.

Two different sets of conditions were used, shown in Table 1 and Table 2. The former describes nine runs, while the latter describes 22 runs. Five of the entries in the two sets were duplicates and run twice. All the trajectories are described by the schematic in Figure 1 except those with descent speed 250 KCAS, which is slower than the cruise speed. The test conditions were chosen to cover most of the expected operating conditions for descent speed and aircraft weight. The distribution of winds aloft and their forecast errors in the operational environment were unknown, so they were chosen somewhat arbitrarily. Since the horizontal trajectory is nearly straight, the wind fields used were actually constant in space and time with direction nearly parallel to the arrival route. The wind conditions labeled “in FMS” means the data entered into the descent wind page of the FMS.

Table 1. First Set of Test Conditions

Zero Winds in All Nine Runs		
250 KCAS 92,000 lb	250 KCAS 117,000 lb	250 KCAS 131,200 lb
280 KCAS 92,000 lb	280 KCAS 117,000 lb	280 KCAS 131,200 lb
320 KCAS 92,000 lb	320 KCAS 117,000 lb	320 KCAS 131,200 lb

Table 2. Second Set of Test Conditions

117,000 lb, Zero Winds, and One Speed Below	280 KCAS, Zero Winds, and One Weight Below	280 KCAS, 117,000 lb, and One Set of Wind Conditions Below
250 KCAS	92,000 lb	25 kt Tailwind in Simulator and FMS
260 KCAS	131,200 lb	50 kt Tailwind in Simulator and FMS
270 KCAS		25 kt Headwind in Simulator and FMS
290 KCAS		50 kt Headwind in Simulator and FMS
300 KCAS		25 kt Tailwind in Simulator, Zero Winds in FMS
310 KCAS		50 kt Tailwind in Simulator, Zero Winds in FMS
320 KCAS		25 kt Headwind in Simulator, Zero Winds in FMS
		50 kt Headwind in Simulator, Zero Winds in FMS
		Zero Winds in Simulator, 25 kt Tailwind in FMS
		Zero Winds in Simulator, 50 kt Tailwind in FMS
		Zero Winds in Simulator, 25 kt Headwind in FMS
		Zero Winds in Simulator, 50 kt Headwind in FMS

and One Run With 250 KCAS, 117,000 lb, Zero Winds

The fuel weights are not exact since they vary slightly between runs. Furthermore, the weights given are at the start of the simulation, and roughly 1000–1500 lb of fuel is burned in each run. Assuming the weights in *Jane's* [9], the light weight would include only 1000 lb of passengers, luggage, and cargo, since it includes 7000 lb of fuel. Furthermore, the heavy weight would be 2200 lb greater than the maximum landing weight. Therefore, the light and heavy weights are probably very close to the ends of the range of operational weights.

Data

This section briefly describes the simulated aircraft state data and Automatic Dependent Surveillance-Contract (ADS-C) messages Boeing provided for analysis.

The frequency of the simulator state data was about four per second. The latitude and longitude were in degrees with a precision of 0.01° . The altitude was barometric. The fields for flaps, landing gear handle, and speed brakes showed they were not used above the meter fix. Thrust and elevator position were not available. Since all the test runs accurately followed the same horizontal trajectory, analysis can be simplified by using path distance as the independent spatial variable. Computing path distance from the simulator state data required smoothing, however, because many state reports had exactly the same position due to the high frequency and low accuracy of the reported positions.

The time between ADS-C messages generally did not exceed 64 sec, but sometimes it was almost 200 sec. The only ADS-C data used in this analysis were the current position and the FMS trajectory predictions, which are in the “Intermediate Projected Intent Group.” Only the last message sent before the aircraft descended from cruise altitude was used. In the intent groups in this message, there are typically five points at or before the meter fix: current location, TOD, waypoint where there is a heading change of 4° , start of deceleration to meter fix speed constraint, and meter fix. For runs with descent speed 250 KCAS, the next to the last point is not included because deceleration is not required, but there is an additional point roughly 2 nmi after TOD. Each intent group contains the distance and true track from the previous group or from the current position for the first group, the predicted barometric altitude, and the predicted time to reach the point from the current position. The path

distance of each prediction point is computed for analysis by projecting the initial position onto the arrival route, computing its path distance relative to the meter fix, and adding the given distances between waypoints.

In the simulator state data, time is given as seconds since the start of the simulation. In the ADS-C messages, the current time is given as wallclock time. To compare predicted times to simulator times, the prediction time is synchronized to the simulator by using the simulator state record with smoothed path distance closest to the path distance of the ADS-C current position.

Effect of Test Matrix Parameters on FMS Prediction of TOD Location

The rest of this paper discusses the results of the data analysis. In this section, the separate effects of descent speed, weight, and wind on TOD location are investigated. The FMS prediction of the TOD location is critical because, as long as the FMS flies the descent, the actual TOD will be close to the FMS prediction. Therefore, even if the ground automation trajectory predictor has more accurate inputs or models than does the FMS, the ground prediction of TOD will rarely be closer to the actual TOD than is the FMS prediction. Furthermore, the FMS predictions of TOD location in these experiments are the same as they would have been in an operational environment.

In the introduction, we argued that the error in each input to the 3DPAM ground predictor probably should not result in an error in TOD location greater than 2 nmi. If a change of X in a certain parameter in the FMS predictor results in a change of 2 nmi in TOD location, then error exceeding X in that parameter in the ground predictor will likely result in the ground predictor's TOD location error commonly exceeding 2 nmi. This reasoning is used to estimate upper bounds on input errors for the 3DPAM ground predictor in the following subsections. However, these results are for only one particular aircraft type; and the effect of descent speed, weight, and wind will likely be different for other aircraft types — or even for a B737-700 with different engine type or other such variation. The results in this section are also helpful in validating the ground automation predictor.

Effect of Descent Speed and Aircraft Weight

Figure 2 shows the effect of descent speed and aircraft weight on the TOD computed by the FMS for the runs in which both the FMS and simulator used zero

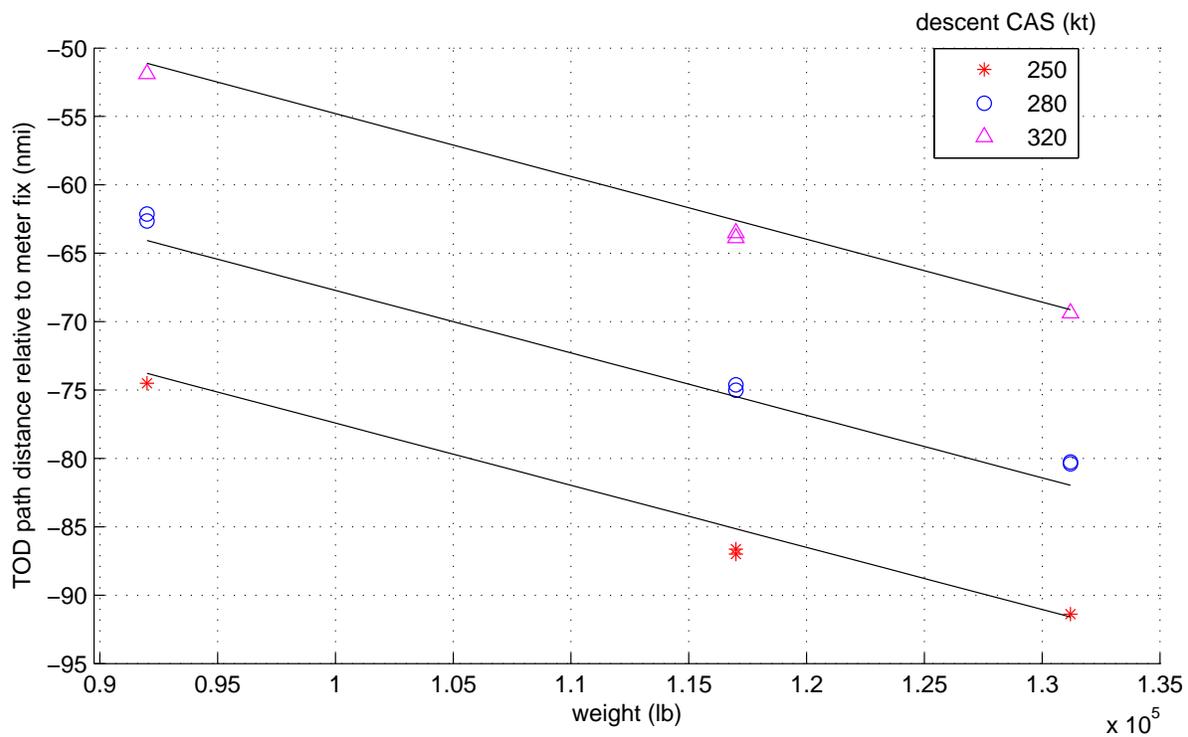
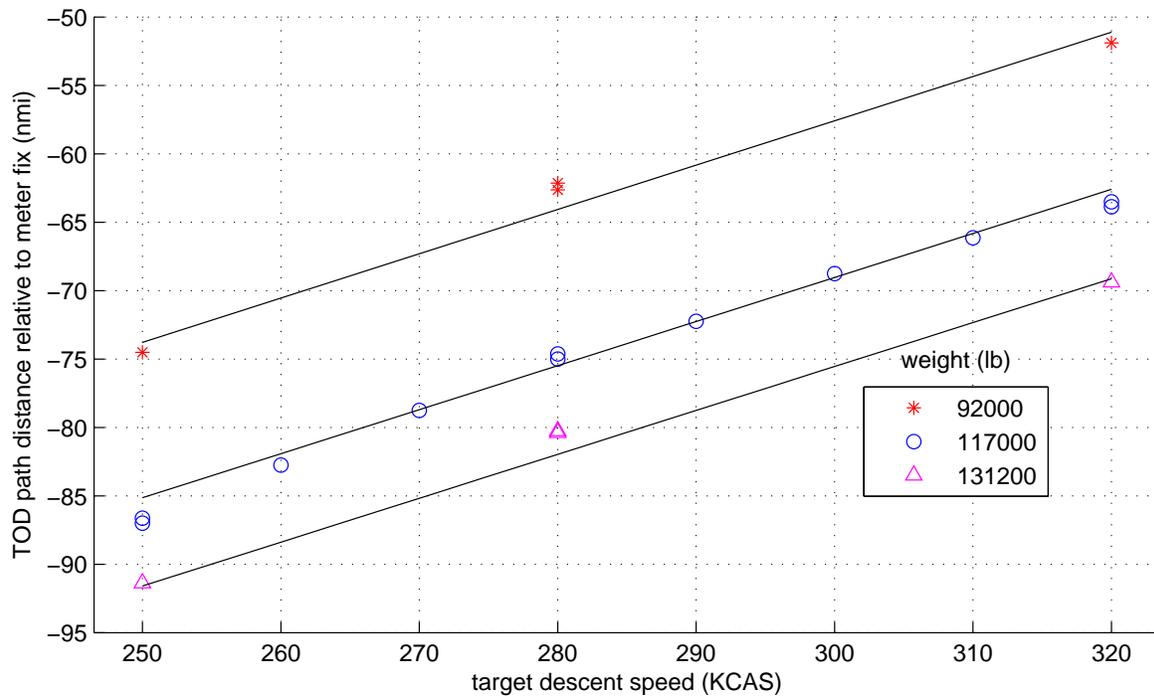


Figure 2. Effect of Speed, Weight on TOD

winds. To quantify the effect of descent speed and weight on TOD, approximate the TOD path distance by least squares fit to a bilinear polynomial. The lines in Figure 2 show the value of this approximation for the weights and descent speeds in these runs. The approximation fits the observations reasonably well, and the slopes of the lines are roughly the same in each plot. Therefore:

- For each 10,000 lb increase in weight, TOD is about 4.6 nmi farther from the meter fix. Assuming the 3DPAM ground predictor TOD error due to weight cannot exceed 2 nmi, the error in the weight used by the ground automation cannot exceed about 4000 lb.
- Increasing the descent speed by 10 KCAS moves TOD about 3.2 nmi closer to the meter fix. Assuming error in TOD due to speed cannot exceed 2 nmi, exchanging the descent speed between flight deck and ground is an essential part of the 3DPAM concept.

Effect of Wind

To characterize the effect of wind on TOD location, first consider the six simulator runs with nominal weight and descent speed and with the same winds used by the FMS and the simulator. The circles in Figure 3 show TOD path distance for these runs, and the line shows that this distance is linear in the along-track wind, with a 25-kt increase in the along-track wind moving the TOD location about 4.6 nmi farther from the meter fix.

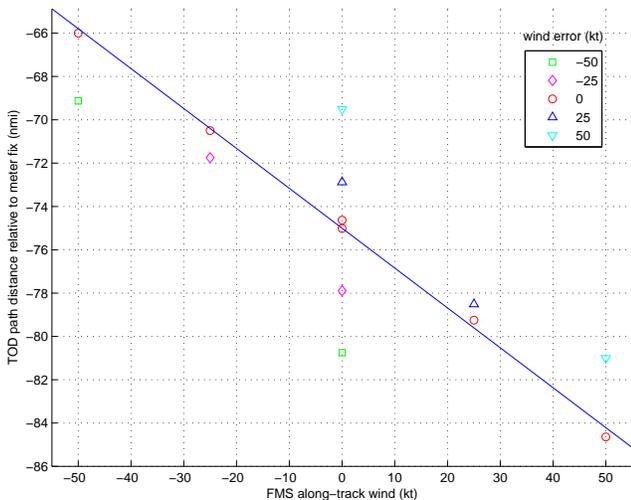


Figure 3. Effect of Wind on TOD

There is a simple explanation for the relationship between TOD and along-track wind. Since the wind in each run is constant over space and time and the speed constraints are given as airspeed, the parameters in the equations of motion relative to the air mass as well as in their constraints are the same in these six runs. Therefore, the flight path angle relative to the air mass is the same function of altitude in these runs, and it is also the same function of time relative to the meter fix time. The change in TOD path distance between any two of these runs is consequently equal to the difference in the distance the air mass moves relative to ground in the time required to descend from TOD to the meter fix. Due to small differences in the cruise speeds between runs, these descent times vary over 690–700 sec in these runs. Hence, a change of 25 kt in along-track wind should move TOD roughly ($695 \text{ sec} \times 25 \text{ kt} = 4.8 \text{ nmi}$), which agrees well with the regression line in Figure 3.

In an operational environment, the winds used by both the FMS and the ground automation will vary with altitude. If the variation is sufficiently small, however, the preceding argument suggests the absolute mean difference in the along-track wind speeds cannot exceed about 10 kt, again assuming the ground automation TOD prediction error due to any one source cannot exceed 2 nmi.

Now consider the runs in Table 2 in which the simulated winds were different than those entered into the FMS descent wind page. These are indicated by the markers other than the circles in Figure 3. The FMS TOD prediction depends upon the error in the winds entered into its descent wind page because the FMS blends that wind field with the current wind measurement, which in these experiments is a simulated pitot tube measurement. The blending algorithm is proprietary, so we cannot explain how the TOD location depends upon wind error. In 3DPAM, the ground automation is expected to use different wind forecast data than the FMS uses. If the absolute mean difference in along-track wind between them is 25 kt, Figure 3 suggests the difference in their TOD locations may be over 2 nmi.

Compliance With Speed Profile

The next goal is to compare the aircraft simulator speed, referred to as the actual speed, to the speed profile the FMS used in trajectory computation. As discussed in the introduction, the differences between them are due to unknown differences between the models in the FMS and the simulator. In operations, however, there will

generally be errors in the FMS inputs and in its aircraft performance model since aircraft of the same type generally have different performance characteristics. Feasibility of the 3DPAM concept depends upon the FMS behavior in response to the resulting deviations from its predicted four-dimensional trajectory. This behavior is characterized in this section and must be included in simulations in order to determine 3DPAM concept performance accurately. The section concludes with estimates of the change in meter fix arrival time due to the error in the actual speed profile.

Identifying Descent Segments in Simulator State Data

In order to compare the actual trajectory to the intended trajectory, the segments depicted in Figure 1 must be identified in the actual trajectory. While the transitions between segments are defined to be precise points here and in the FMS predicted trajectory, they are in reality time intervals over which controls and variables change smoothly. The algorithms outlined here, however, gave acceptable results in this analysis.

The cruise segment should include all data before TOD, but the data often contained transients at the start of each simulation. To handle this, estimate the cruise altitude by the mode of the recorded altitudes rounded to the nearest foot, and consider the set of records within 20 ft of cruise altitude. Find times T_1 and T_2 such that T_1 is as small as possible and such that reported altitude is nearly constant between T_1 and T_2 and nearly linear between T_2 and the end of this set. All reports before T_1 are ignored henceforth, and T_2 is TOD time.

If the descent CAS is 250 KCAS, the constant CAS segment ends at the meter fix because there is no deceleration to the meter fix constraint. The other endpoints of the constant CAS segment generally have significant jumps in the vertical speed. The general idea of the algorithm used here is to approximate the reported vertical speed by a piecewise linear function that captures the large jumps of interest but ignores spurious wiggles.

To identify the meter fix crossing point, first let s_f be the smallest horizontal distance from the trajectory to the meter fix. From the set of all records with horizontal distance s_f from the meter fix, choose the one that has altitude closest to the meter fix altitude constraint.

Constant Mach Segment

It does not appear that the FMS is trying to maintain constant Mach number but instead seems to be maintaining constant flight path angle. This reflects the fact that the FMS controls first to its intended three-dimensional trajectory. The variation in Mach number and the length of the segment are both small enough that the resulting prediction error is probably not significant.

Constant CAS Segment

In analyzing compliance with the target descent speed in the constant CAS segment, the runs generally fall into three categories: nominal weight and correct wind entered into FMS, heavy weight or simulator along-track wind smaller than entered into FMS, and light weight or simulator along-track wind larger than entered into FMS. The behavior of the FMS for each of these categories is described in the following subsections.

Nominal Weight and Correct Wind Entered Into FMS

Figure 4 shows the error in the speed profile over the constant CAS segment for the runs with nominal weight and with the same speed used by the FMS and the simulator. The speed is between 15 KCAS too slow and 5 KCAS too fast. The throttle is at idle setting except perhaps within 2–3 nmi of the ends of the segment.

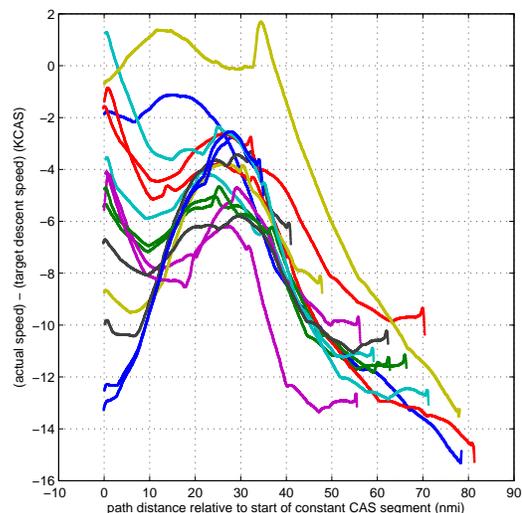


Figure 4. Good Speed Compliance

Heavy Weight or Simulator Along-track Wind Smaller Than Entered Into FMS

Figure 5 shows the error in the speed profile over the constant CAS segment for the runs with heavy weight or with the simulator along-track wind smaller than used by the FMS predictor, which means the aircraft encountered unexpected headwind or lack of expected tailwind. The speed became too slow and the FMS engaged the throttle in the constant CAS segment. In the run with heavy weight and target descent speed 320 KCAS, the FMS had already engaged the throttle in the constant Mach segment in order to get as fast as 310 KCAS, which it then maintained in the constant CAS segment. At the start of the constant CAS segment in the other trajectories in this category, the throttle is at idle setting, but the CAS then decreases to 15 KCAS too slow, at which time the FMS engages the throttle.

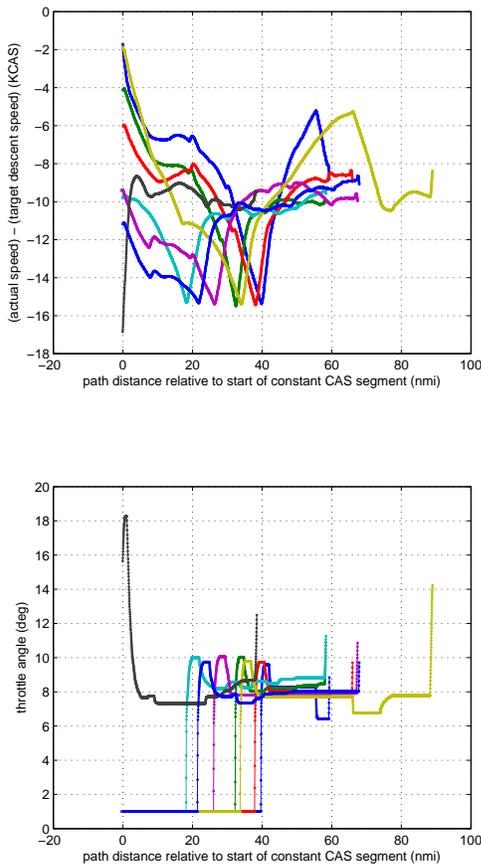


Figure 5. Speed Too Slow

Neither the flight path angle nor the pitch angle looks significantly different than for the previous category, which indicates the FMS did not use them to control speed before engaging the throttle. Once the throt-

tle is engaged, it appears the FMS controls to a speed 10 KCAS slower than the target speed. Furthermore, the throttle remains engaged all the way to the meter fix, even though the speed at the meter fix is 5–10 KCAS too fast except in the run with heavy weight and target descent speed 320 KCAS.

Light Weight or Simulator Along-track Wind Larger Than Entered Into FMS

Figure 6 shows the error in the speed profile over the constant CAS segment for the runs with light weight or with the simulator along-track wind larger than used by the FMS predictor, which means the aircraft encountered unexpected tailwind or lack of expected headwind. In the runs with light weight and the run with zero winds in the simulator but 50 kt headwind entered into the FMS, the speed became more than 15 KCAS too fast.

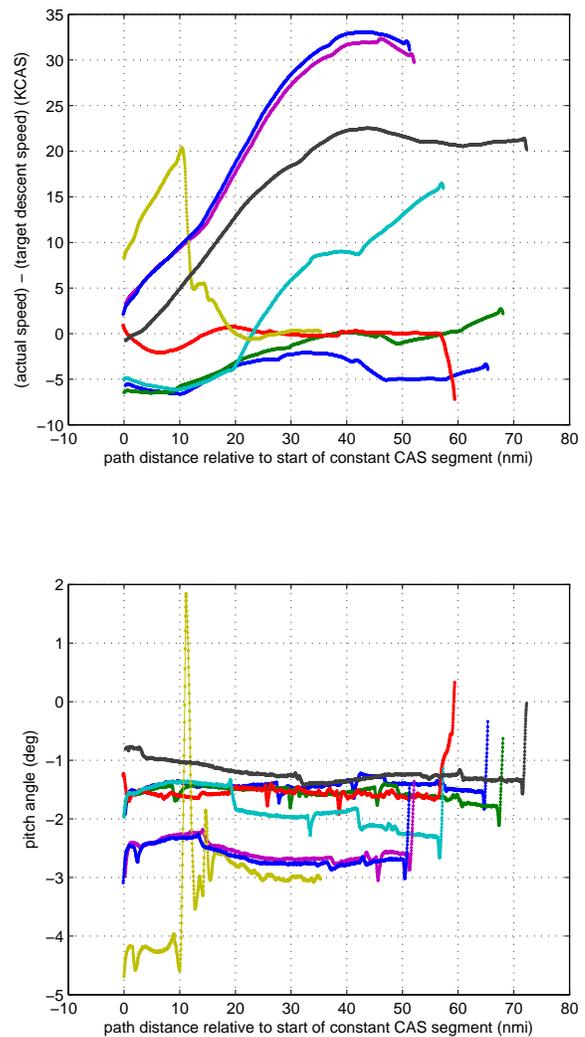


Figure 6. Speed Too Fast

While the FMS likely displayed an instruction to apply speed brakes, it does not appear to have done anything itself to control the speed except in one case. In the run with light weight and descent speed 320 KCAS, the FMS sharply increased the pitch angle and the flight path angle to decrease the speed when it approached 20 KCAS faster than the target speed. This is because it had reached its maximum operating velocity at that point. The FMS also disengaged VNAV mode at the same time and switched to maintaining the target descent speed.

On the other hand, the pitch angle actually decreased slightly in some of the other runs as the speed increased beyond 20 KCAS faster than the target speed. This illustrates that the FMS relies on the pilot to slow the aircraft using speed brakes while the FMS controls to its intended three-dimensional trajectory — unless an aircraft operating limit is reached.

Meter Fix Speed Constraint

Due to the imprecision in the reported positions, it is impossible to determine exactly when the trajectory crosses the meter fix. The algorithm used in this analysis to estimate the meter fix crossing point may make the altitude compliance seem slightly better (perhaps by 50 ft) than it really is whilst making the speed compliance seem worse.

At the meter fix, 15 of the trajectories were at or below the meter fix speed constraint of 250 KCAS, and another 10 were between 250 KCAS and 260 KCAS. The other runs, listed in Table 3, included all those with light weight as well as the two runs with zero winds in the simulator but headwind entered into the FMS. Given the behavior of these runs in the constant CAS segment, the failure to meet the meter fix speed constraint is not surprising except for the one with 25-kt headwind entered into the FMS.

Table 3. Meter Fix Speeds Too Fast

Run	Meter Fix Speed
Light Weight, Target 250-KCAS Descent	270 KCAS
Light Weight, Target 280-KCAS Descent (2 Runs)	282–283 KCAS
Light Weight, Target 320-KCAS Descent (Exited VNAV Mode)	320 KCAS
Zero Winds in Simulator, 25-kt Headwind in FMS	270 KCAS
Zero Winds in Simulator, 50-kt Headwind in FMS	271 KCAS

Implications for Meter Fix Arrival Time Prediction Accuracy

In 23 of the 31 runs in these experiments, the FMS used the correct input, so the errors in descent speed are caused by unknown differences between the aircraft models in the FMS and the simulator. In an operational 3DPAM environment, however, errors in FMS inputs, particularly wind, will necessarily exist. This section discusses how such errors will likely affect the accuracy of the ground predictor compared to the actual trajectory.

First consider the error in the FMS prediction of altitude. As already discussed, the run with light weight and descent speed 320 KCAS exited VNAV mode, so it is discarded from the analysis in this section. The run with zero winds in the simulator but 25-kt headwind entered into the FMS had actual trajectory as much as 800 ft higher than predicted by the FMS at given path distance and was 150 ft too high at the meter fix. The reason is unknown, especially considering that the run

with zero winds in the simulator but 50-kt headwind does not have this problem. The important point is that, in all the other runs, the FMS altitude prediction error was small:

- At the predicted TOD location, the altitude error is 0–350 ft.
- At the predicted start of the deceleration segment, the altitude error is –75 ft to 0 ft.
- The actual altitude at the meter fix was within 5 ft of the altitude constraint.

This confirms that the FMS usually follows its predicted three-dimensional trajectory accurately.

In fact, most of the altitude error at these points seems to be due to a simplification in the FMS model. The FMS apparently approximates changes in descent rate and other variables as instantaneous, which is not physically possible. Therefore, when executing the descent, the FMS anticipates the maneuver to allow the

time required to complete it. Most of the points at which FMS prediction data were available are points where the descent rate changes, so the overall FMS altitude prediction is probably more accurate than indicated here. Since the 3DPAM ground predictor is expected to use the same simplifications, it is unlikely to predict altitude more accurately than the FMS does.

The along-track error in a trajectory prediction is determined by the error in the predicted ground speed, which is in turn determined by the errors in predicted true airspeed and wind conditions. Since the descent speed profile in 3DPAM is specified as Mach number and CAS, the error in true airspeed depends upon the error in the predicted altitude profile as well as on the difference between the specified speed profile and actual. Since the actual vertical profile is close to that predicted by the FMS, the along-track error is determined almost completely by the error in maintaining the specified speed profile in those runs in which the FMS and simulator used the same wind conditions. This means the ground automation will probably not predict the meter fix arrival time more accurately than the FMS, assuming both are using correct wind forecasts.

Since the speed error is usually either positive or negative throughout the constant CAS segment in any run, the FMS along-track prediction error is generally worst at the meter fix, so that is the focus here. Of the runs without wind error, the ones with actual descent speed in the constant CAS segment within about 10 KCAS of the target speed seem to have actual meter fix arrival time within about 15 sec of the FMS prediction, whereas having actual speed within 15 KCAS of the target results in meter fix arrival time error as large as roughly 35 sec. The 3DPAM concept should consequently include instructions to the pilot to maintain descent speed within 10 KCAS of the target speed, assuming the requirement motivated in the introduction of 20-sec accuracy in meter fix arrival accuracy for the ground automation.

Finally, consider the effect of wind forecast error on the accuracy of the meter fix arrival time. Of the runs in which the FMS had incorrect wind inputs, the smallest CAS error occurred in the one with zero winds simulated but 25 kt headwind entered into the FMS. The error in the FMS prediction of meter fix arrival time was 35 sec. Unfortunately, this is also the run that had large error in the FMS prediction of altitude, which might affect meter fix arrival time accuracy as noted above. Also consider the two runs with zero winds entered into the FMS but simulated 25-kt wind speed:

Simulated 25-kt headwind. The actual meter fix arrival time was 51 sec later than predicted by the FMS, but this was compounded by the descent speed being slow enough that the FMS engaged the throttle.

Simulated 25-kt tailwind. The actual meter fix arrival time was 13 sec earlier than predicted by the FMS, but this was helped by the descent speed being about 5 KCAS too slow in the constant CAS segment.

It seems likely that 25-kt absolute mean along-track wind error in the ground automation will result in meter fix arrival time errors greater than 20 sec in some cases, although this needs to be investigated further. There is another point that is probably more important, however. If the ground predictor uses a wind forecast that is closer to the actual wind conditions, it will probably improve its prediction of path distance as a function of time. On the other hand, if the ground predictor uses a wind forecast that is closer to the wind conditions used by the FMS, the ground prediction of TOD will be more accurate. If there is a significant difference between the actual winds and the winds used by the FMS, this trade-off may need to be optimized.

Conclusions

Analysis of the FMS prediction of TOD location showed:

- For each 10,000-lb increase in weight, TOD is about 4.6 nmi farther from the meter fix.
- Increasing the descent speed by 10 KCAS moves TOD about 3.2 nmi closer to the meter fix.
- A 25-kt increase in the along-track wind moves TOD about 4.6 nmi farther from the meter fix.

Assuming the 3DPAM ground predictor TOD error due to any one factor cannot exceed 2 nmi, the difference between the ground predictor and FMS inputs cannot exceed 4000 lb in weight or 10 kt mean along-track wind speed. Furthermore, exchanging the descent speed between flight deck and ground seems to be an essential part of the 3DPAM concept. These are rough estimates, however, and are dependent upon the aircraft type.

Analysis of the simulator state data showed:

- The FMS usually follows its three-dimensional trajectory prediction accurately.
- If the descent speed drops to 15 KCAS below the target speed, the FMS engages the throttle but then seems to maintain descent speed 10 KCAS below the target speed for the most part. On the other

hand, the FMS allows the descent speed to increase arbitrarily above the target speed unless it reached a performance limit.

Comparison of the actual and FMS predictions of the meter fix arrival time showed that, in the absence of wind error in a predictor, maintaining speed within 10 KCAS of the speed profile used by the predictor probably keeps meter fix arrival time error under 20 sec, which may be necessary in 3DPAM. A 15-KCAS accuracy requirement does not meet this criterion, however. The results also indicate that error in the execution of the descent must be included in simulations to establish 3DPAM predictor accuracy requirements more rigorously.

Finally, suppose there is a significant difference between the actual winds and the winds used by the FMS. If the ground predictor uses a wind forecast that is closer to the actual wind conditions, it will probably improve its prediction of path distance as a function of time. On the other hand, if the ground predictor uses a wind forecast that is closer to the wind conditions used by the FMS, the ground prediction of TOD will be more accurate.

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