ANALYSIS OF ADVANCED FLIGHT MANAGEMENT SYSTEMS (FMSs), FLIGHT MANAGEMENT COMPUTER (FMC) FIELD OBSERVATIONS TRIALS, VERTICAL PATH

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Abstract

The differences in performance of various manufacturers' Flight Management Systems (FMSs) and their associated Flight Management Computers (FMCs) have the potential for significant impact on the air traffic control system. While Area Navigation (RNAV) and Required Navigation Performance (RNP) procedures and routes are designed according to criteria contained in Federal Aviation Administration (FAA) orders, FMCs are built to meet *Minimum Aviation System Performance Standards (MASPS)* [1] and the *Minimum Operational Performance Standards (MOPS)* [2] for area navigation systems, Technical Service Orders and Advisory Circulars. The expectation is the resulting performance of the aircraft FMC will meet the procedure design requirements identified in the FAA criteria.

The airspace design goal is procedures where aircraft operations result in repeatable and predictable paths. However, actual aircraft performance frequently does not match the expectations of the procedure designer. Studies referenced in this paper such as *Assessment of Operational Differences Among Flight Management Systems* [3], *Analysis of Advanced Flight Management Systems (FMSs)* [4] and *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials* [5] have shown that these differences result from variations in FMS equipment; variations and errors in data collection and processing; variations in pilot training and airline operating procedures; and variations in aircraft performance.

This paper presents the hypothesis that given a standardized performance-based (RNAV/RNP) procedure with coded altitudes, variations in vertical path performance will exist among the various FMC/FMS combinations that are tested. Controlled observations were made using twelve different test benches at five major FMC manufacturers and three full-motion simulators at the FAA and two airlines. This focus on vertical navigation (VNAV) path conformance follows the MITRE Corporation's analysis of lateral navigation (LNAV) path Conformance described in *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials* [5].

Introduction

The FAA is committed to transitioning to a performance-based National Airspace System (NAS). Performance-Based Navigation (PBN) is defined as navigation along a route, procedure, or within airspace that requires a specified minimum level of performance. Key concepts of this system are RNAV and RNP involving Instrument Approach Procedures (IAPs), terminal Standard Instrument Departures (SIDs), Standard Terminal Arrivals (STARs), and en route and oceanic procedures. RNAV and RNP procedures, which take advantage of advanced aircraft navigation capabilities, are expected to provide accurate and predictable paths; however, many procedures have not met the initial expectations of Air Traffic Control (ATC) and industry due to variations in the aircraft execution of those procedures.

The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) has supported the FAA in identifying and analyzing differences among widely used FMSs and in particular their associated FMCs. This report is part of a continuing effort beginning with *Assessment of*

Operational Differences Among Flight Management Systems [3] in 2004, to focus on the differences in how aircraft using different FMSs/FMCs execute specific procedures resulting in different tracks being flown by the aircraft.

In 2005, *Analysis of Advanced Flight Management Systems (FMSs)* [4] reported that there are four primary areas that contribute to variations in the aircraft RNAV paths:

1. FMC equipment installed on the aircraft
2. Procedure coding into FMC database
3. Aircraft to FMC interface and associated aircraft performance capabilities
4. Flight crew procedures

In 2006, *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials*, [5] focused on the first item; FMC equipment installed on the aircraft, and reported on the lateral path. This paper reports on the vertical path.

An extensive trial and data collection plan was developed to facilitate the trials and to make the collection effort minimal for a manufacturer. Manufacturers do not typically allow access to their developmental and test areas; however, agreements were developed to treat the data as proprietary and to disassociate analysis and reporting from the manufacturer's name. As a result, data from five of the major Flight Management Computer manufacturers as well a**s** three full motion simulators was obtained. The data was analyzed and the results are compiled in this document.

Scope

This paper describes the vertical navigation paths computed by flight management computers. The vertical path data was collected from twelve test benches at five major FMC manufacturers and three full motion simulators. It reports on the development, conduct, and results of Field Observations Trials which took place between February and April, 2007.

Background

Since the FAA began the development and implementation of RNAV procedures several years ago, ATC have had an expectation that the use of RNAV procedures would result in more accurate and predictable paths and less pilot-controller communications. For the most part, RNAV procedures have achieved these goals, but due to differences in ground speeds and variations in the performance of FMCs, track conformance has not been as good as expected. As procedures were implemented at different locations, it was identified almost immediately that while on RNAV procedures, aircraft flying at different speeds and differently equipped aircraft do not all fly lateral paths the same way, nor do they turn or climb or descend at the same point in space. The first observed differences involved lateral path construction, but vertical path construction is now becoming important as well to the future of PBN.

Existing Flight Management Systems have successfully automated the flight planning, navigation, lateral guidance and other control functions. Differences, especially differences in lateral guidance, were explored in *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials* [5] in 2006. The task of vertical guidance, or the FMS control of the vertical profile, and the ability of the associated FMCs to comply with speed and altitude constraints at waypoints in the various manufacturers FMCs have not been investigated to the same level. These variations in equipage are not only a problem of the differences in types of aircraft, where varied performance capabilities based on airframe and engines are expected, but many times the same type of aircraft type may also have differences. These differences may result from an aircraft manufacturer's use of different FMC in their FMSs. Not all FMSs are even equipped with VNAV and those that are equipped may vary in operation.

There are little regulatory criteria published for vertical path performance. RTCA DO-236 [1] states that for RNP RNAV, the tolerances for a flight along a specified vertical path is 160’ for 0’-5000’, 210’ for 5000’-29000’, and 260’ for 29000’-41,000’. The document provides extensive requirements for vertical path construction, and many FMCs meet these requirements. *Order 8260.52, Required Navigation Performance (RNP) Instrument Approach Procedure Construction* [6] establishes vertical performance requirements for RNP Special Aircraft and Aircrew Authorization Required (SAAAR) approaches based upon current altimetry systems and temperature related errors, but these documents do not have criteria relating to FMC path construction. *RNP Capability of FMC Equipped 737, Generation 3, D6-39067-3* [7] gives a good explanation, from the Boeing Company’s viewpoint, of RNP vertical criteria but with the exception of *FAA Order 8260.52* [6], none of the vertical requirements are binding on a FMC manufacturer. There are no mandatory vertical containment requirements (although there is an accuracy requirement) associated with operations designated as VNAV and no path definition for a climb since it is assumed to be strictly performance (engine/airframe) based.

MITRE’s intention with this study was to isolate vertical path construction differences, as well as operational differences, between various FMCs currently flying.

Field Observations Trial

Trial Plan Development

Starting with recommendations from previous analysis efforts, several investigative areas were considered for this report. As mentioned in the Introduction, there are four primary areas that contribute to variations in the aircraft lateral and vertical paths: FMC equipment installed on the aircraft, Procedure coding into FMC database, Aircraft to FMC interface and associated aircraft performance capabilities, and Flight crew procedures:

1. FMC equipment installed on the aircraft: The same type of aircraft may have FMCs from different manufacturers and/or different FMC models from the same manufacturer. Also as expected, different types of aircraft will have FMCs from different manufacturers installed.

2. Procedure coding into FMC database: Different versions of ARINC 424 used in the FMC, as well as database suppliers interpretation and coding of a procedure, can have an impact on how the aircraft complies with the LNAV and VNAV track.

3. Aircraft to FMC interface and associated aircraft performance capabilities: FMC Manufacturers often supply their systems to different aircraft manufacturers. The same model FMC may be installed in a Boeing aircraft and an Airbus aircraft where the aircraft performance requirements require the particular FMC model to be tailored. Some manufacturers offer differently tailored FMCs to different customers operating the same type aircraft. These different airframes when joined with different engine combinations will, as expected, have performance capabilities that differ; for example, acceleration, climb rate, maximum allowable bank angle, etc.

4. Flight crew procedures: Airline flight crews and general aviation crews will have extensive differences in training requirements and standards as well as different operating philosophies and procedures. For example, speed schedules may vary considerably and some flight crews may be instructed to use all available FMC and autopilot guidance and FMS automation provided while some operators explicitly limit what flight crews may use. These variations in flight crew operating procedures have not been fully examined.

Of these four areas, two and three were examined previously[1] and were found to have significant negative impact on the repeatability of LNAV and VNAV paths and based on

[1] Steinbach [3] and Herndon et al. [4]

recommendations in those reports the decision was made to focus on core functionality and examine differences in FMCs. A previous report[2] examined the lateral path (LNAV) and this report focuses on the vertical path (VNAV).

Goals of the trial plan:

1. Control all pertinent variables through standardized trial scenarios
2. Use procedures that are in use in the NAS today
3. Incorporate as many different manufacturers' FMCs as possible
4. Facilitate the trials and data collection process
5. Protect the data provided by the manufacturers

To successfully accomplish the goals of the trials, unprocessed data needed to be obtained. This data comes directly from manufactures' test bench computers, as all errors associated with atmosphere, sensors, and other peripheral systems can be eliminated, leaving the focus directly on the FMC. These "bench FMCs" are only available in the research and development labs of the manufacturers.

Manufacturer Participation

Five FMC manufacturers agreed to participate in the trials and data collection effort. These five manufactures provide over 90% of the FMC systems in service today. The bench observations involved simulating (on the bench testing device) an aircraft flying a high profile SID, STAR, and RNAV Approach, with pre-determined parameters recorded for each flight. At each manufacturing site, the same observation profile was accomplished.

Participating manufacturers and their associated FMC models are presented in Table 1.

Table 1. FMC Test Benches

Manufacturer	FMC	Aircraft
CMC Electronics	**CMA-900**	**B747-200**
Smiths Aerospace	**U10.6 MITRE Lab**	**B737-600**
Smiths Aerospace	**U10.6 sFMS**	**B737-600**
Thales Smiths	**FMS2**	**A320**
Honeywell	**Pegasus 2005**	**B767-300**
Honeywell	**AIMS Block Point 2005**	**B777-200**
Honeywell	**747-4 Load 16**	**B747-400**
Honeywell	**Primus EPIC**	**E-190**
Honeywell	**Primus EPIC**	**G-V**
Rockwell Collins	**FMS-4200**	**CRJ-700**
Universal Avionics	**UNS1-E**	**Citation II**

An addition to the manufacturer's field observations was the FAA's full motion simulator at the Mike Monroney Aeronautical Center in Oklahoma City. This simulator includes unique data collection equipment that makes it possible to record needed FMC output. The same data collection equipment was installed by the FAA on an airline's A320 simulator and a simulator manufacture installed special data collection equipment on another airline's A320 simulator, both of which were included in the trial. Aircraft simulators are generally not engineered for high fidelity data collection and use re-hosted FMCs. Full motion simulator participants are presented in Table 2.

Table 2. Full motion simulators

Airlines/Agency	FMC	Aircraft
JetBlue Airways	**Honeywell Pegasus 2005**	**A320**
United Airlines	**Honeywell Legacy 400K**	**A320**
FAA/AFS-440	**Smiths U10.5**	**B737-800**

Trial Plan

The plan, as presented to each manufacturer, provided the required information to setup the FMC and collects the required data. Procedures were chosen that would contain "AT," "AT or ABOVE," "AT or BELOW," and "WINDOW" altitude constraints and that would be time efficient. The plan was based on real world procedure data (from the 28 day navigation

[2] Herndon et al. [5]

database) for two airports and consisted of the BORDER FIVE DEPARTURE from San Diego (KSAN), Julian (JIL) Transition; PARADISE FOUR ARRIVAL, FUELR Transition; and the RNAV (GPS) RWY 25L at Los Angeles (KLAX). See Figure 1 for the plan view details. The route of flight, as presented on the "LEGS" page in the Control Data Unit (CDU) of the FMC was: KSAN RW27, POGY19, PGY, BROWS, JLI (FL240B), AMIGO, MUELR, DUEDD (16000'), JEROM (15000A), PDZ, TEJAY (12000A), ARNES (11000B11000A), SUZZI (9000A), FUELR (8000A), GAATE (5000A), HUNDA (3500A), LIMMA (1900'), MOSAE (1000A), KLAX RW25L (150').

The procedures were flown twice. The first flight was flown at a minimum Cost Index and the second flight was flown at a maximum Cost Index. For those FMCs which did not have the Cost Index function, the first flight was flown at a "reasonably slow" speed and the second flight was flown at a "reasonably fast" speed. In both cases, 250 knots Indicated Air Speed (IAS) was used below 10,000', the cruise altitude was 24,000', no wind conditions and the fuel load was appropriate for the approximately 32 minute flights.

The trial output parameters were selected for FMC internal data to be exported and in the case of the test benches, the flight was started using the aircraft, CDU and associated autopilot and flight director controls. The unprocessed data was recorded for subsequent analysis.

Figure 1. KLAX PARADISE FOUR ARRIVAL

Data Analysis

The FMS output parameters obtained from the manufacturers for analysis were recorded using 1-second time steps and included time, position, and altitude information characterizing a four-dimensional aircraft trajectory for each flight. The trajectories were evaluated using MITRE's Integrated Terminal Research Analysis and Evaluation Capabilities (iTRAEC) [8]. The ground tracks of all evaluated trajectories as well as their altitude and speed profiles are presented in Figure 2.

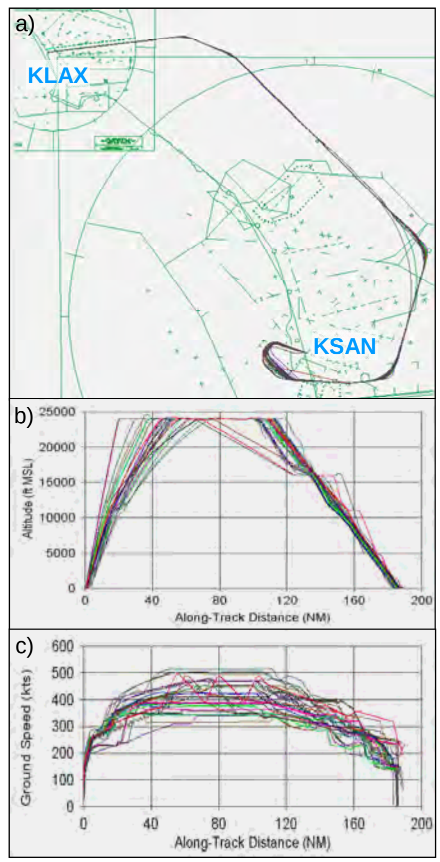

Figure 2. FMS trajectory (a) ground tracks and associated (b) altitude profiles and (c) speed profiles

Metrics

The analysis of the FMS trajectories involved three metrics that evaluated (1) how the realized trajectories compared to a MITRE-created common reference path, (2) how the location of the top-of-descent points of the trajectories compared, and (3) how the altitudes at which the trajectories crossed key waypoints compared during descent.

Vertical Path Comparison: The vertical path comparison metric was designed to quantify the vertical distance between points along a reference path and an FMS trajectory at common lateral locations. The same reference path was applied in the analysis and provided a common reference both laterally and vertically to which all FMS trajectories were compared. The reference path was constructed as a sequence of points spaced 0.1 NM apart starting at the touch-down-point and tracing upwards vertically along the procedure at an angle of 3 degrees (a typical glidepath angle) towards preceding waypoints. If a preceding waypoint was encountered before the altitude of the constraint specified for that waypoint had been reached, then the constraint altitude of the waypoint was adopted for the reference path altitude at the waypoint. If the altitude constraint of the preceding waypoint was reached before the lateral location of the waypoint, then the reference path continued along a level flight segment connecting the point on the reference path at which the altitude was reached to the waypoint at the waypoint constraint altitude. CAUTION: This reference path design was designed for simplicity and to provide a common reference for comparison and may or may not be representative of the trajectories built by any given FMC.

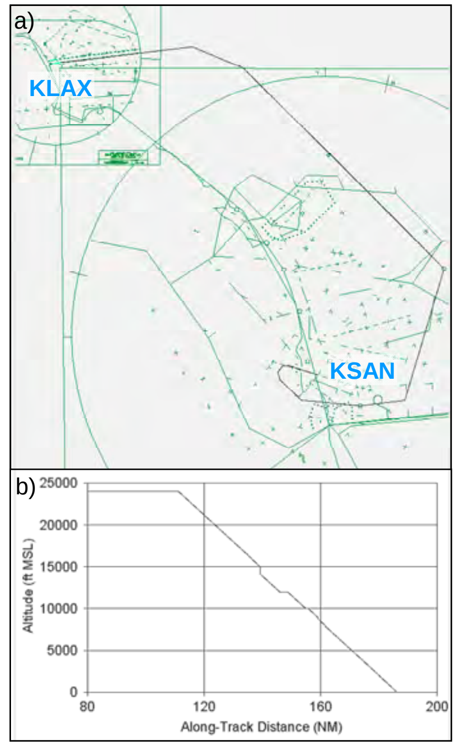

Figure 3. Reference path (a) ground track and (b) descent profile

The ground track of the reference path and its descent profile are illustrated in Figure 3. The vertical path comparison metric evaluated each point along the reference path, identified the closest lateral data point of each FMS trajectory, and measured the altitude difference between the reference path and the trajectory point.

Top-of-Descent (TOD**):** For each trajectory, the analysis identified the location of the Top-Of-Descent point. The location of the Top-of-Descent point was characterized by its geographic coordinates as well as by its distance along the ground track of the reference path and was identified by the geographic location of the point at which a FMS trajectory was observed to begin its initial descent from cruising altitude.

Waypoint Crossing Altitude: While the vertical path comparison analysis evaluated the proximity of the FMS altitudes to the reference path along the entirety of the path, the waypoint crossing analysis evaluated the altitude differences between the altitude constraints defined for key waypoints and the altitude actually realized by the FMS trajectory at the location of the waypoint. This analysis included JLI and waypoints that follow along the trial plan route up to MOSAE (see Figure 1).

Each FMS trajectory was evaluated separately and, for the purpose of presentation, the analysis results were grouped by the two operational scenarios evaluated in this study (FMS trajectories recorded in minimum and maximum Cost Index). For the purpose of Data Analysis the term minimum Cost Index will also reflect the Trial Plan's "slowest reasonable speed" and maximum Cost Index will reflect "fastest reasonable speed."

Analysis Results

Figure 4 presents the results of the vertical route comparison analysis. For each FMS trajectory, this metric evaluated the vertical distance between the trajectory and the reference vertical path at all points along the path. With the exception of two FMS trajectories in each scenario that started their initial descents early (see Figure 2), good agreement was observed in vertical path adherence up to points about 100 Nautical Mile (NM) along the route. At JLI, located approximately 80 NM along the route with an altitude constraint of FL240 or below, most FMS trajectories met the constraint closely. The majority of the trajectories were observed to start initial descent between points 100 to 115 NM along the route where trajectories were found to differ by as much as about 2000 feet (ft) in minimum Cost Index scenarios and up to about 4000 ft in maximum Cost Index scenarios. This is a function of the location of the TOD for the reference path. At these points along the route, the differences between FMS trajectories were seen to be largely due to differences in the locations of the top-of-descent points of the trajectories.

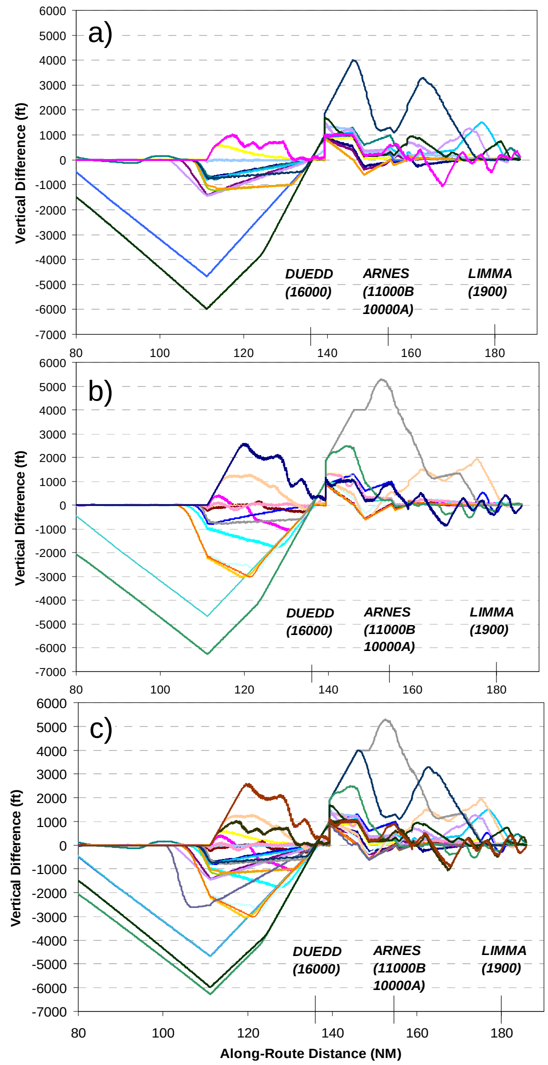

Figure 4. Vertical route comparison analysis illustrating altitude differences between FMS trajectories and the reference path recorded in (a) minimum Cost Index, (b) maximum Cost Index, and (c) both evaluation scenarios

Greater variability was observed between FMS trajectories recorded in maximum Cost Index scenarios. However, most trajectories were observed to vertically converge at the DUEDD waypoint with required crossing altitude of 16000 ft. The apparent discontinuities of the vertical path adherence results at points about 140 and 145 NM along the route were identified as analysis artifacts resulting from the construction of the reference path at the waypoint constraint (see Figure 3). Between

DUEDD and LIMMA vertical differences between FMS trajectories and the reference vertical path of up to about 5000 ft were observed.

Figure 5 presents the results of an evaluation of the variation, or spread, of observed FMS trajectory altitudes. Vertical distances between FMS trajectories and the reference path were taken as absolute values thus measuring the average absolute vertical deviation of FMS trajectories from the reference vertical path. The results indicate larger vertical spreads between FMS trajectories associated with maximum Cost Index scenarios at points along the reference path leading up to DUEDD as well as in the vicinity of ARNES waypoint. These observations can be viewed as evidence that aircraft operational differences such as speed differences and resulting energy management considerations during descent may contribute significantly to the altitude variation observed in the FMS trajectories.

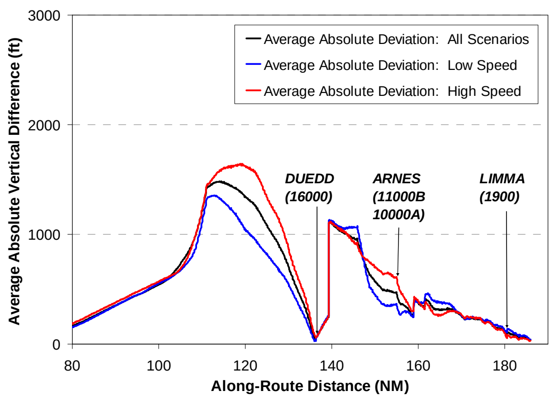

Figure 5. Average absolute value deviations of FMS trajectories from the reference vertical path

The locations of the top-of-descent points of all evaluated FMS trajectories are presented in Figure 6. In the figure, the Top-of-Descent points of trajectories of the minimum and maximum Cost Index scenarios are indicated by blue and red circles, respectively. The figure indicates that most top-of-descent points were observed within a 15 to 20-NM distance range along the route. The figure also illustrates that some top-of-descent points were observed at points significantly closer to the departure airport San Diego International Airport (KSAN). These findings are also illustrated in Figure 6. The figure shows a histogram of the top-of-descent point locations grouped into 5-NM wide distance bins along the route. While the majority of FMS trajectories were found to begin initial descent between 100 and 120 NM along the route, several FMS trajectories were

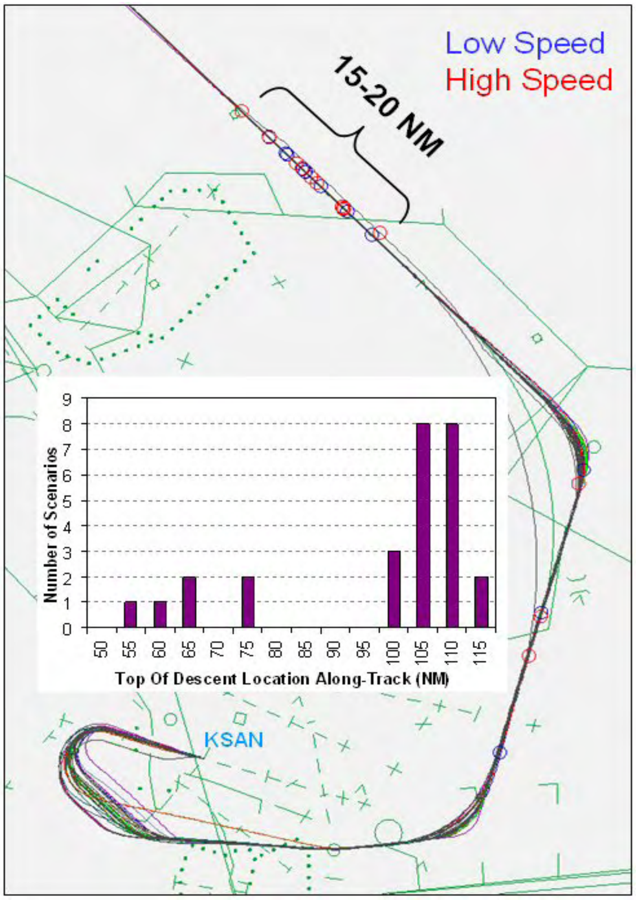

Figure 6. FMS trajectories and locations of associated top-of-descent points and histogram of the locations of top-of-descent points illustrating their distance along the route

seen to descend much earlier after traveling only 55 to 80 NM. These few early descents were observed in two systems, and were not a function of the Cost Index evaluation scenario. When an FMS was seen to result in early descents, the trajectories of both the minimum and maximum Cost Index scenarios were found to descend early.

Figure 7 illustrates the FMS track altitudes relative to the altitude constraints specified at the various waypoints defining the trial plan route (see Figure 1). For each FMS trajectory, the figure presents observed altitude differences between the trajectory and the published crossing altitude. At ARNES (11000B/10000A), altitude differences are plotted relative to the lower bound of the constraint. The results of the waypoint crossing analysis indicate that FMS track altitudes differed by up to several thousand feet at waypoints with At or Above type constraints. Observed crossing altitudes at waypoints with hard altitude constraints and along portions of FMS trajectories associated with the final approach segment were found to better conform to the published altitudes. Similar to the results of the vertical path comparison analysis, differences in speed profiles were found to contribute to the observed variations. The analysis results also identified some instances of FMS trajectories that violated particular altitude constraints. However, these violations were not found to be specific to any particular vendor or evaluation scenario.

In addition to the analysis of individual FMS trajectories, average absolute altitude differences between trajectory altitudes and the waypoint altitudes were evaluated for each Cost Index scenario. The results are presented in Figure 7. The average crossing altitude at TEJAY(12000A) was found to be about 800 feet higher than the published altitude, and was the largest average absolute difference observed at the waypoints. It is interesting to note that this observation coincides with a steeper than the typical descent angle between JEROM(15000A) and TEJAY if based on the lower altitude bounds at both waypoints. Figures 6 and 7 illustrate that FMS trajectory crossing altitudes better conformed to published altitudes at waypoints with hard constraints (DUEDD(16000) and LIMMA(1900)) where the average absolute value of the deviation from the constraint altitudes was less than 50 feet.

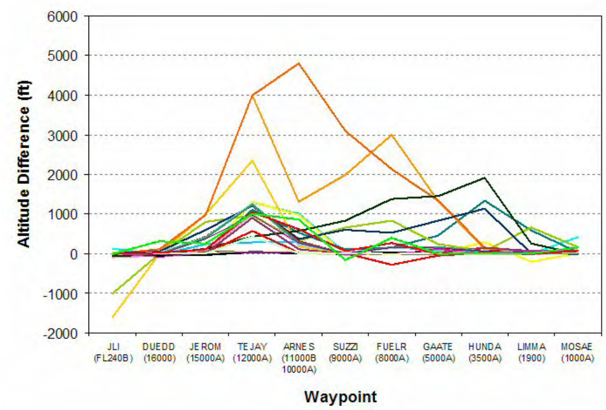

Figure 7. Average absolute value deviations of FMS trajectory altitudes from published altitude constraints at key waypoints defining the test plan route

Conclusions

In drawing conclusions from the data gathered during these tests and presented here, care must be taken to avoid drawing too strong a conclusion based on differences that may not be strictly FMS related. There are expected differences in the performance characteristics of the subject aircraft, as well as differences between automated VNAV and pilot controlled VNAV for instance. Further, one must remember how the vertical reference path was computed in reviewing the vertical differences and assessing their importance. Examining the data without regard to the underlying reasons for differences, however, was the primary purpose of this paper, since we want to draw conclusions relative to valid expectations for airspace and control based on the current generation of FMS and their operations. The following paragraphs represent what the authors believe are valid conclusions to be drawn from the data, with some cautionary notes as well.

One of the most noticeable variations was the few instances of very early top-of-descent points. These early descents produced the most deviation from the reference vertical path prior to the "AT" constraint of 16000' at DUEDD. They also lead to the higher deviations after other constraints. One can conclude here that while most FMS profiles tended to cluster in the location of TOD (figure 6), in actual operation there can be a wide difference. This has implications both for airspace and for air traffic control in terms of separation and intervention. A caution here is that while the differences were large, they are too large to be strictly the result of FMS modeled aircraft performance, so it is possible they were caused by how the FMS was used rather than what it might have done based on performance calculations. If one removes the outliers, the TOD points cluster around 107 NM, consistent with modern jet aircraft performance when flown to a near idle descent which is the optimum that FMSs with full VNAV compute for a descent path.

Altitude constraints were also of high importance / interest in these tests. There were three types encountered in the profile, AT, AT ABOVE and WINDOW (between). As noted in the analysis section, AT constraints were generally honored to within 50 feet, which is well within the bounds allowed in airspace design for baro-VNAV systems. Also, since the deviations were high (above the constraint), a valid conclusion would be that this type of constraint is safely handled by all systems. This is one of the more important conclusions drawn from these trials.

Examining the other two types of constraints, there were two instances of an AT ABOVE being violated by at least 100 feet, and two instances of the WINDOW constraint being violated, one a very large violation of 4000 feet. From the data, one cannot deduce the reasons, but it does point to the fact that some systems may have design issues with these types of constraints. A second conclusion can be drawn from this data is that the variability of aircraft altitudes above the AT ABOVE constraints is fairly broad. Often there is as much as 1000' variation. This has implications in airspace design, and needs to be considered by both ATC and FMS designers.

If one observes the vertical profiles shown in Figure 2, two more observations can be made. The climb profiles show more variability (spread) than do the descent profiles. There is a variation of nearly 50 NM along track in the top-of-climb points and discounting the seemingly out-of-place early descents, a variation of only about 10 NM in the TOD points. This points to a potential airspace concern when using RNAV (RNP) to integrate departure and arrival stream of traffic. The second observation (Figs 2 and 7) is that the descent profiles cluster more tightly below the 16000 foot constraint (disregarding the two major outliers), where if you look at a single altitude, the along track spread is 5 miles or less and if you look at a single along track location, the altitudes are no more than 1000' different. There are differing conclusions one can draw from this, depending on the goal; first, it would seem that allowing aircraft to pursue their unconstrained profiles provides adequate separation for terminal operations, or second, that if one wants to separate this descent profile from other profiles, perhaps tighter operation is necessary.

To summarize the conclusions then, we observe that:

1) Top of descent variation was tightly clustered independent of aircraft type with a few very dramatic outliers,
2) AT altitude constraints are met very well by all the systems,
3) AT ABOVE altitude constraints allow expected variations, with the exception of one system that violated a constraint,
4) WINDOW constraint was generally met, with again one notable exception,
5) Paths were more widely different for the climb profile than the descent profile,
6) The descent profiles flown could by themselves provide a means of separation of aircraft based on their dispersion.

Recommendations

Based on the observations & conclusions in the previous section, the authors make the following recommendations:

1) Given the manual intervention required on many systems, training should be developed for air crew procedures that support the "soft" constraint types in terms of their relationship to "hard"

constraints on the same descent path. How does one control to meet the full extent of the constraints and how close is good enough for the "soft" type? What relationship between constant IAS descents and constant vertical speed descents exists and how can it be used?

2) FAA should carefully review DO-236B FMC requirements for the vertical path construction and the performance requirements to assure that any criteria for aircraft qualification, operation or airspace / procedure design is consistent with the material there.

3) FMS manufacturers should review the data in this paper relative to the operation of their systems, and identify causes for the incorrectly handled constraints (where applicable), to correct any deficiencies. If they have not yet implemented full VNAV but intend to, they should work with FAA on item 2 to assure consistent operation.

4) FAA and/or the Performance-based Aviation Rulemaking Committee (PARC) FMS Standards Working Group should make recommendations for any further (beyond DO-236B) standardization deemed necessary to meet planned operational constraints using FMS vertical paths and control.

5) FAA should further study vertical aspects of FMS, particularly a comparison of the following:

    a. Unconstrained descent profiles variation between max and min cost index

    b. Fully constrained descent profiles (hard constraints with speeds?) and their variation from "a" above.

This study has been accomplished with the generous help of the FMS manufacturers, who donated their time and resources to generate the data. MITRE thanks them sincerely, and hopes that they will continue to support such efforts to make our airspace and operations safer and more efficient as we move toward taking much more advantage of the airborne capability of modern aircraft.

References

[1] RTCA, Special Committee 181, October 28, 2003, DO-236B, Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation, RTCA Incorporated, Washington, DC.

[2] RTCA, Special Committee 181, October 28, 2003, DO-283A, Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation, RTCA Incorporated, Washington, DC.

[3] Steinbach, D., June 30, 2004, *Assessment of Operational Differences Among Flight Management Systems,* F064-B04-032, The MITRE Corporation, McLean, VA.

[4] Herndon, A. A., et al., May 31, 2005, *Analysis of Advanced Flight Management Systems (FMSs),* F083-L05-009-001, The MITRE Corporation, McLean, VA.

[5] Herndon, A. A., et al., July 31, 2006, *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials*, F083-L06-030, The MITRE Corporation, McLean, VA.

[6] Federal Aviation Administration, June 3, 2005, Order 8260.52, Required Navigation Performance (RNP) Instrument Approach Procedure Construction, Washington, DC.

[7] BCAG Engineering, December 23, 2002, *RNP Capability of FMC Equipped 737, Generation 3, D6-39067-3*, The Boeing Company, Seattle, WA.

[8] Mayer, Ralf H., December 6, 2006, 1030 AM local, Estimating Operational Benefits of Aircraft Navigation and Air Traffic control Procedures Using an Integrated Aviation Modeling and Evaluation Platform, Proceedings of the 2006 Winter Simulation conference, Monterey, CA, pp. 1569 -1577.

Biographies

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