ANALYSIS OF ADVANCED FLIGHT MANAGEMENT SYSTEMS (FMS), FLIGHT MANAGEMENT COMPUTER (FMC) FIELD OBSERVATIONS TRIALS, RADIUS-TO-FIX PATH TERMINATORS

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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 and as such need to be examined and reexamined. While Area Navigation (RNAV) and Required Navigation Performance (RNP) procedures and routes are designed according to criteria contained in Federal Aviation Administration (FAA) orders, FMC manufacturers build their systems in accordance with *Minimum Aviation System Performance Standards (MASPS)* [1] and *Minimum Operational Performance Standards (MOPS)* [2] for area navigation systems, Technical Service Orders and Advisory Circulars. Despite the disconnect it is anticipated that the resulting performance of the aircraft FMC will meet the procedure design requirements identified in the FAA criteria.

The goal is procedures where aircraft operations meet expectations for repeatability and predictability to levels of performance sufficient to support performance based operations in the National Airspace System (NAS). Sometimes, due to the nearly independent development of procedure design criteria and aircraft performance standards, the paths of various aircraft on the same procedure do not overlap and do not match the expectancy 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], *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials, Lateral Path* [5], and *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials, Vertical Path* [6] have shown that these differences may result from any or all of the following: variations in FMC equipment installed on the aircraft; variations and errors in procedure coding in the FMC navigation database; variations in aircraft to FMC interface and associated aircraft performance capabilities; and variations in flight crew training and procedures.

The basic FMCs built by the major manufacturers and installed as the core of the FMC/FMS combinations in various airframe platforms will perform differently and this paper attempts to quantify those differences. It focuses on standard performance-based public RNAV (RNP) instrument approach procedures with coded *ARINC Navigation Systems Database Specification 424* [7], Radius-to-Fix path terminators (RF), also labeled as RF leg types, and their variations in performance. Criteria currently allows the use of RF leg types only in RNP Special Aircraft and Aircrew Authorization Required (SAAAR) procedures.

A Trial Plan was developed and controlled field observations trials were made using eleven test benches at seven major FMC manufacturers. The focus is on RF path terminators used in public procedures at Long Beach Daugherty Airport, California, and follows previous analysis of manufacturers' FMC lateral navigation (LNAV) path conformance described in *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials, Lateral Path* [5] and analysis of vertical navigation (VNAV) path conformance described in *Analysis of Advanced Flight Managements Systems (FMSs), FMC Field Observations Trials, Vertical Path* [6].

It is hoped that the results of this research will contribute to the eventual acceptance of RF usage in Basic RNP and RNAV criteria.

Introduction

The FAA is committed to transitioning to a performance-based 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 terminal Standard Instrument Departures (SIDs), Standard Terminal Arrivals (STARs), Instrument Approach Procedures (IAPs), and en route and oceanic 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 Flight Management Computers (FMCs). The FMC contains a navigation database and processes navigation sensor information. It interacts with the autopilot, flight director, autothrottle, and flight control computer and the integrated system is known as the FMS. 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/RNP paths:

1. FMC equipment installed on the aircraft
2. Procedure coding (errors) in the FMC navigation database
3. Aircraft to FMC interface and associated aircraft performance capabilities
4. Flight crew training and procedures

In 2006, *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trails, Lateral Path* [5] and in 2007, *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials, Vertical Path* [6] focused on the first item; FMC equipment installed on the aircraft and reported on lateral and vertical paths that did not include RF path terminators, also labeled RF leg types. This paper reports on the RF paths and terminators that currently may be used in instrument approaches as detailed in *ARINC Navigation Systems Database Specification 424* [7].

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 seven of the major Flight Management Computer manufacturers was obtained. The data was analyzed and the results are compiled in this document. The manufacturers reviewed this paper prior to publication.

Scope

This paper describes the Radius-to-Fix lateral and vertical paths computed by Flight Management Computers. The RF leg data was obtained from eleven test benches at seven major FMC manufacturers. It reports on the development, conduct, results and analysis of the Field Observations Trials which took place between February and May, 2008.

Background

Since the FAA began the development and implementation of RNAV procedures several years ago, air traffic controllers have had an expectation that the use of RNAV and RNP procedures would result in more accurate and predictable paths and less pilot-controller communications. For the most part, RNAV and RNP procedures have achieved these goals. However, due to differences in ground speeds and variations in the performance of FMCs such as the way various FMCs calculate distance to turn anticipation, 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 points in space. The first observed differences involved lateral path construction and then as vertical path construction became more important to the future of PBN, vertical differences were also observed. Differences, especially differences in lateral and vertical path were explored in *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trails, Lateral Path* [5] in 2006, and *Analysis of Advanced Flight Management Systems (FMSs), FMC Field Observations Trials, Vertical Path* [6] in 2007.

In the world of PBN the task of guidance, or the FMS control of the lateral and vertical profile, and the ability of the associated FMCs to comply with speed and altitude constraints at waypoints continues to be important to investigate. Variations in FMC equipage are not only a problem caused by 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 FMCs in the FMSs.

A next step in researching FMC differences is to investigate individual path terminators and how FMC's compute them. *ARINC Navigation Systems Database Specification 424* [7] Attachment 5 describes twenty-three path terminators or leg types such as Track-to-Fix (TF) where the concept is that the "Track" is the path and the "Fix" is the terminator. For this paper, the most repeatable turning path design element, the RF leg, was chosen for analysis. It is simple in design specifying a constant radius turn between two database fixes. The inbound and outbound paths are tangent to the arc and a center fix is also specified as shown in Figure 1.

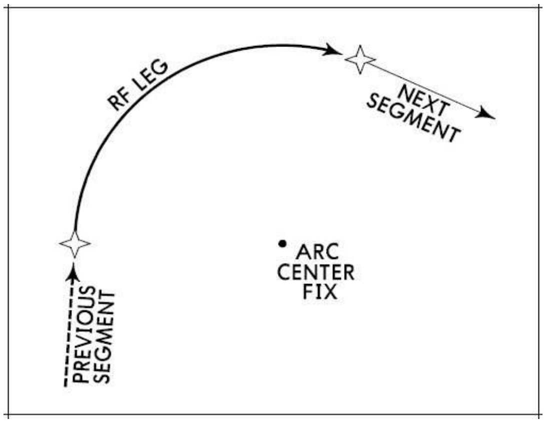

Figure 1. Radius-to-Fix Path Terminator[1]

The challenge for the FMC is to compute a path and direct the aircraft, via the flight control computer, to stay on the designed path under constantly changing wind direction and wind speeds requiring varying aircraft bank angles, typically using roll steering.

The RF path and its obstacle evaluation area (OEA) construction is currently defined in FAA *Order 8260.52, Required Navigation Performance (RNP) Instrument Approach Procedure Construction* [8] and FAA *Order 8260.54A, The United States Standard for Area Navigation* [9]. The minimum radius allowed is determined by a combination of the aircraft category for which the procedure is being designed, a limiting wind value, and a design bank angle control margin of five degrees. See Figure 2 for OEA construction.

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[1] ARINC 424 [7]

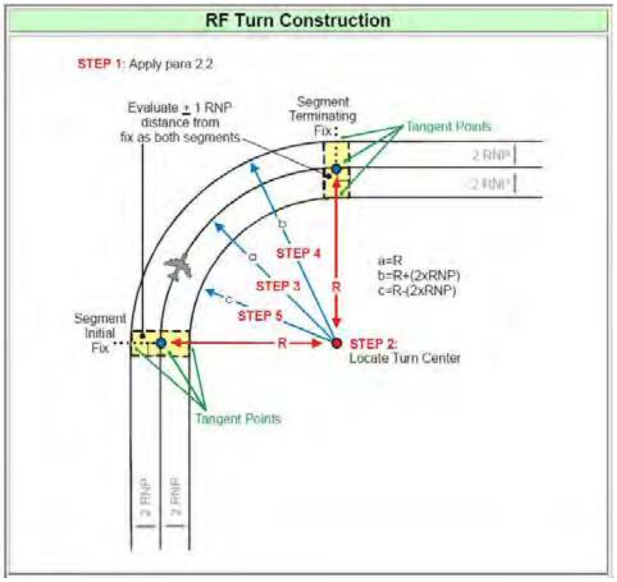

Figure 2. RF Turn Construction[2]

Today, the use of RF legs are only allowed operationally by *Advisory Circular 90-101, Approval Guidance for RNP Procedures with Special Aircraft and Aircrew Authorization Required (SAAAR)* [10] to RNP Special SAAAR approaches. The FAA considers an RF leg type as part of "advanced RNP" and therefore, requires special training for pilots. This report explores FMC RF path conformance and makes a case for inclusion of RF leg types in RNAV and Basic RNP.

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. These are FMC equipment installed on the aircraft, procedure coding in the FMC navigation 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 in the FMC navigation 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 Lateral Path (LNAV) and Vertical Path (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[3] and were found to have

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[2] Order 8260.52 [8]

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

significant negative impact on the repeatability of LNAV and VNAV paths and based on recommendations in those reports the decision was made to focus on core functionality and examine differences in FMCs. Previous reports[4] examined the LNAV and the VNAV paths. The intention of this report is to examine aircraft tracking on RF paths with the expectation that this type of turning path will be much more repeatable than the more unconstrained fly-by and fly-over transitions between inbound and outbound legs at a fix seen in previous comparisons. Examples of the use of the RF in RNP SAAAR Instrument Approach Procedures were needed that contained usage of the RF leg type in the final and missed approach segments and an example of sequential but reversed direction RF legs.

The methods of the trial plan were to:

1. Control all pertinent variables through standardized trial scenarios.
2. Use public 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 goal of the trials to directly compare different systems' RF performance, unprocessed data needed to be obtained. This data can only be obtained from manufacturers' test bench or test station computers (sometimes called System Integration Test Stations or SITS), 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

Seven FMC manufacturers agreed to participate in the trials and data collection effort. These seven manufacturers provide over 90% of the civil FMC systems in service today. 89% of airline aircraft in the NAS have at least one FMC installed. The bench observations involved simulating (on the bench testing device) an aircraft flying a public RNAV (RNP) approach with RF leg types, 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-9000	A300-600
GE Aviation	U10.6 sFMS	B737-600
Thales/GE	FMS2	A320
Honeywell	Pegasus 2005	B767-300
Honeywell	AIMS Version 14	B777-200
Honeywell	747-4 Load 16	B747-400
Honeywell	Primus EPIC Version 7.1	E-190
Honeywell	Primus EPIC Version 7.1	G-550
Rockwell Collins	FMS-6000	CL-604
Universal Avionics	UNS1-Ew SCN 1000.1	Citation II
Garmin	G1000	Embraer Phenom100

Trial Plan

The previously proven plan[5] was amended and presented to each manufacturer to provide the required information to setup the FMC and collect the required data. Procedures in the NAS were searched for published public RNP SAAAR approaches to satisfy the intentions stated previously. All the required RF leg types were found at one airport; Long Beach (Daugherty Field), California (KLGB).

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[4] Herndon et al. [5 & 6]

[5] Herndon et al. [5 & 6]

KLGB RNAV (RNP) Y Runway (RWY) 30 provided a RF leg in the missed approach segment. See Figure 3.

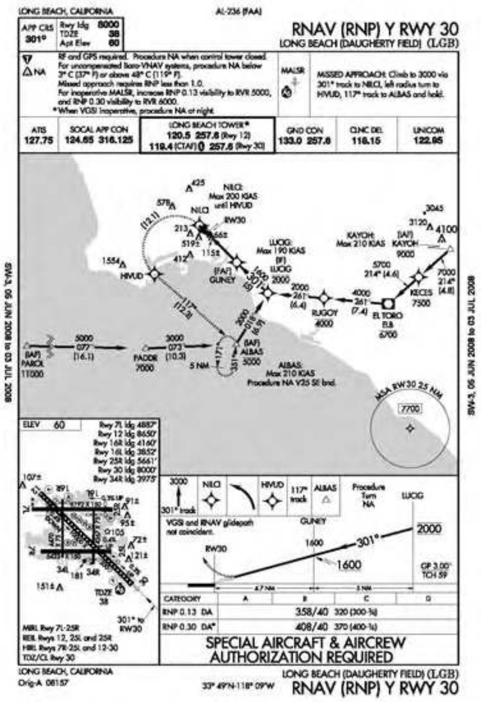

Figure 3. RF leg in the missed approach

KLGB RNAV (RNP) RWY 12 provided a RF leg in the final segment and RF legs in the missed approach. See Figure 4.

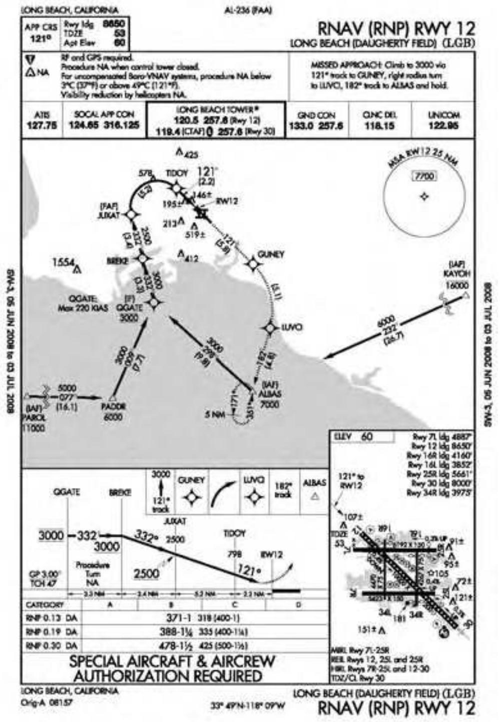

Figure 4. RF leg in the final segment

KLGB RNAV (RNP) RWY 25R provided sequenced reversed RF legs. See Figure 5.

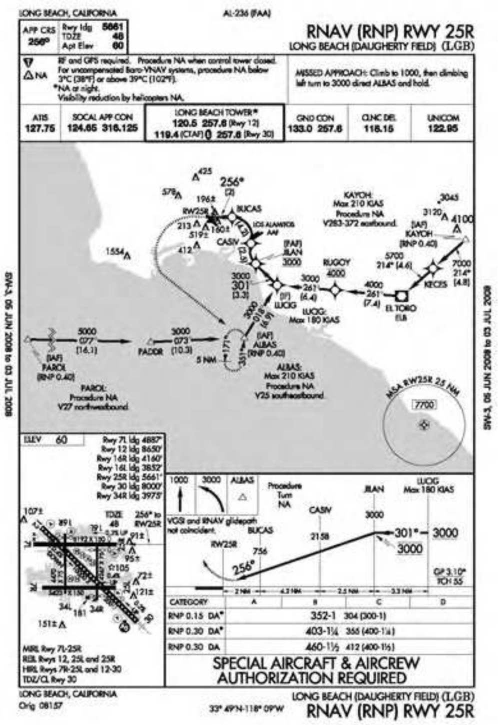

Figure 5. Sequential reversed RF legs

Each procedure was flown twice. The first flight was with no wind and a constant 150 knots Indicated Airspeed (IAS) for the final approach speed accelerating to 210 knots IAS in the missed approach. The second flight was with wind and the FMC was allowed to compute the final approach and missed approach speeds. The winds were chosen to represent the design wind speed (from the design winds table in FAA *Order 8260.52* [8]) in a direction that would maximize the aircraft ground speed at a point approximately midway through the turn. This resulted in values of 040° magnetic and 50 knots (040/50) for RNAV (RNP) Y RWY 30, 210/50 for RNAV (RNP) RWY 12, and 160/50 for RNAV (RNP) RWY 25R.

The trial output parameters were selected for FMC internal data to be exported, each flight was flown using the aircraft FMC Control Display Unit (CDU) and associated autopilot and flight director controls. The unprocessed data was recorded for subsequent analysis and will hereafter be referred to as an *FMS track*. "FMS track" label was chosen over "FMC track" because each manufacturer's test bench was flown using integral components (autopilot and flight director) of the FMS system.

Data Analysis

The FMS track 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.

In addition, FMS-record information such as aircraft roll angle was also collected. The trajectories were evaluated using MITRE's *Integrated Terminal Research Analysis and Evaluation Capabilities (iTRAEC)* [11]. Since the scope of the study is to understand FMS differences relating to RF leg execution, the analysis focuses on those portions of each FMS track during, and immediately before and after, the RF legs themselves. Ground track visualizations of the portions of the supplied FMS tracks occurring during the RF leg(s), as well as profile views of altitude and roll angle as a function of along-track distance, are included for tracks flying the RNAV (RNP) RWY 12, RNAV (RNP) RWY 25R, and RNAV (RNP) Y RWY 30 approaches in Figures 6, 7, and 8 respectively.

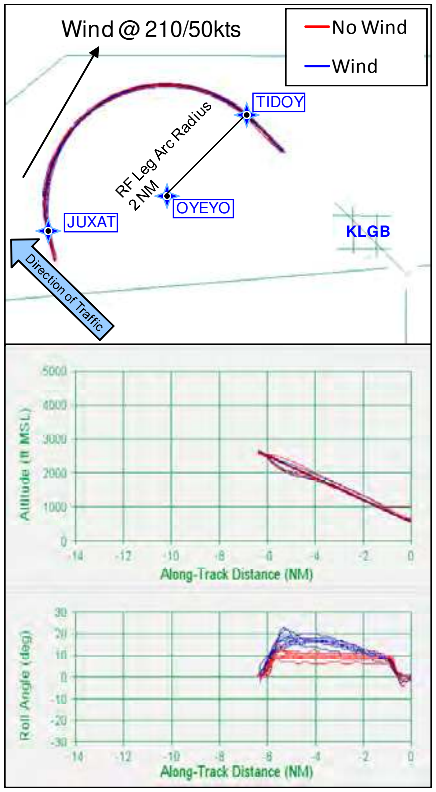

Figure 6. Runway 12 FMS Ground tracks, Altitude Profiles, and Roll Angle Profiles

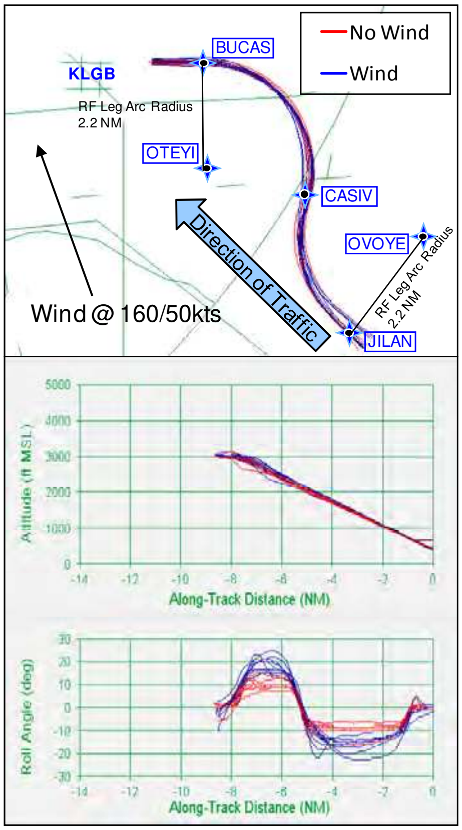

Figure 7. Runway 25R FMS Ground tracks, Altitude Profiles, and Roll Angle Profiles

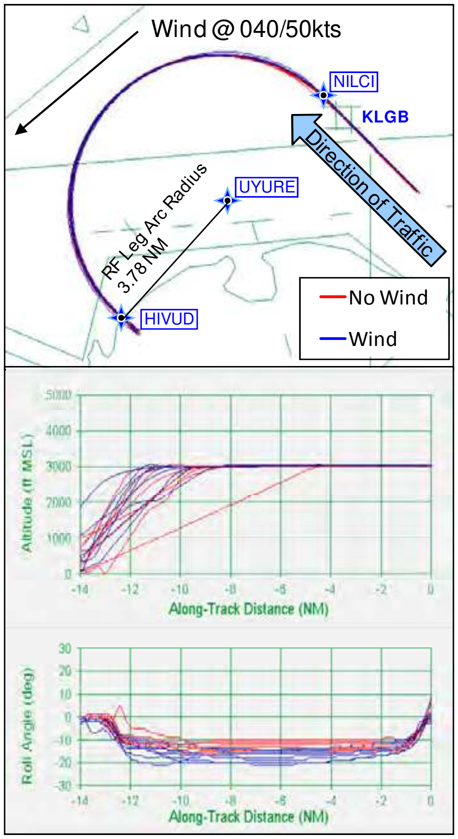

Figure 8. Runway 30 FMS Ground tracks, Altitude Profiles, and Roll Angle Profiles

Metrics

Analysis of the FMS track differences during RF turns involved four metrics that characterized:

1. The lateral distance of each track from the RF Arc Center Fix.
2. Vertical path comparison of each track through comparing the altitude difference between the FMS tracks and a MITRE-defined vertical reference route corresponding to the published glide path of the approaches.
3. The average missed approach climb gradient.
4. The average distance from the top-of-climb point to the missed approach fix for the missed approaches.

Lateral Distance from RF Arc Center: The lateral distance from the RF arc center metric was designed to quantify the lateral conformance of each FMS track in a way that related the FMS tracks to the track defined by the procedure design. This is unlike TF-TF transitions where the reference route is not defined by the procedure designer, but an area is set aside to accommodate all aircraft tracks as FMCs do not all execute that transition in the same way. Since the execution of an RF turn is defined by the arc radius of the RF leg, the chosen metric to represent lateral conformance during the RF leg was the distance between each FMS track point and the procedure's specified RF arc center fix (e.g., the UYURE waypoint for RNAV (RNP) Y RWY 30). The distance from the individual track to the specified RF arc center fix was considered individually for each track, in order to show variations at each point along-track for the FMS tracks. In addition, a distribution of the distances of each FMS track point from the RF arc center fix during the execution of the RF turn itself was created to characterize the performance of the entire data set during the RF turn and to highlight any differences between the scenarios flown with wind and without wind.

Vertical Path Comparison: The vertical path comparison analysis focused on the altitude difference of each track against the published glide paths of each of the approaches featuring RF turns during the approach: 3 degrees for the RNAV (RNP) RWY 12, and 3.1 degrees for the RNAV (RNP) RWY 25R approach. To construct the reference route used in the analysis, the tracks were ranked in order to choose the best conforming lateral track. This ranking was accomplished by computing the average absolute difference between the distance of each of the track's track points occurring during the RF leg(s) from the RF arc center and the published RF leg arc radius. Once the best conforming lateral track was chosen, applying the published glide path angle to the altitudes of the track produced the reference route to which all tracks were compared. 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. The vertical path comparison metric was calculated by iterating through the reference route's track points, and finding the closest track return laterally for each FMS track and recording the altitude difference from the reference route track point.

Missed Approach Climb Gradient: The RF leg for the RNAV (RNP) Y RWY 30 approach takes place during the missed approach segment, as opposed to the final approach RF legs featured in the RNAV (RNP) RWY 12 and RNAV (RNP) RWY 25R approaches. Since climb performance for aircraft varies significantly based on aircraft type (among many other factors), it was decided not to use the vertical path comparison approach of defining a common reference route to which all tracks would be compared for the approach featuring an RF leg during the missed approach climb out. Instead, the average climb gradient during the missed approach climb was computed for each FMS track by vendor. This was accomplished by calculating the total feet-per-nautical-mile increase for all consecutive increasing transponder returns until the missed approach top-of-climb point was reached. Inter-vendor comparisons as well as intra-vendor comparisons (between the wind and no wind scenarios) were performed on the average climb gradients.

Distance from Top-of-Climb to Missed Approach Point: This analysis measures the distance between the Missed Approach Point, ALBAS, and the identified missed approach top-of-climb point for each FMS track on the RNAV (RNP) Y RWY 30 approach. A histogram of the observed distances provides a visualization of the distribution of top-of-climb points in relation to their distance from ALBAS. In addition, the mean and standard deviation of this distance was computed

Analysis Results

The analysis of distance from the RF arc center fix (OYEYO) for each FMS track on the RNAV (RNP) RWY 12 approach is shown in Figure 9.

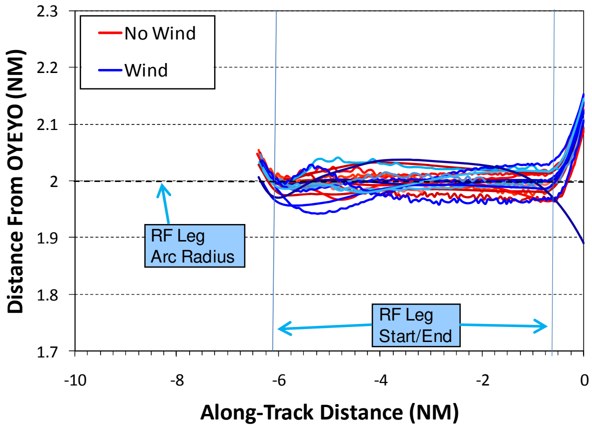

Figure 9. Runway 12 FMS Track Lateral Distance From RF Arc Center (OYEYO)

The RF turn for these tracks took place on final approach. The analysis shows that all tracks are within approximately 0.1 Nautical Mile (NM) of the nominal RF arc radius throughout the RF turn, and many are far closer. In addition, the effect of wind was not found to be significant on any of the tracks. The distributions of differences between the FMS track point distances from the RF arc center fix and the nominal arc radius (i.e., the distance of the FMS track point from the nominal RF leg) for wind and no wind scenarios are presented in Figure 10.

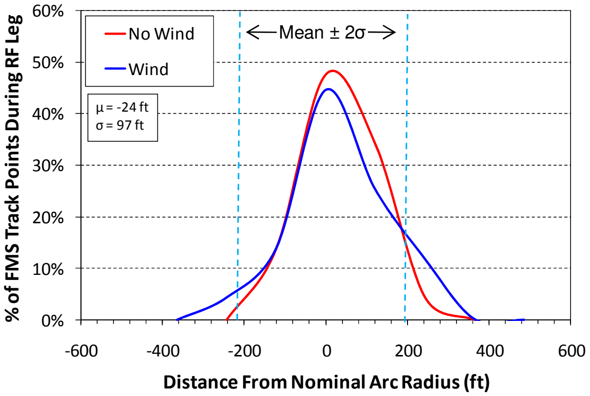

Figure 10. Distribution of Runway 12 FMS Track Point Distances From Nominal Arc Radius During RF Turn

All track points found along the RF leg were found to be no more than 400 feet (ft) away from the nominal arc radius. In addition, the mean value plus/minus 2 standard deviations bounds an area roughly 200 ft on either side of the nominal arc radius.

The analyses of distance from the RF arc center fixes (OVOYE and OTEYI) for each FMS track on the RNAV (RNP) RWY 25R approach are shown in Figures 11 and 12, respectively.

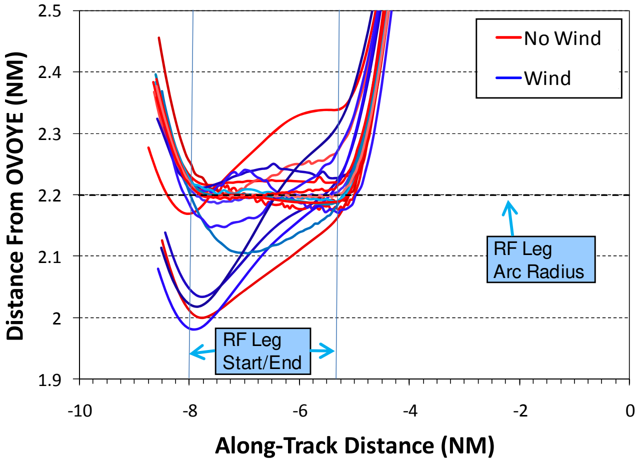

Figure 11. Runway 25R FMS Track Lateral Distance From First RF Arc Center (OVOYE)

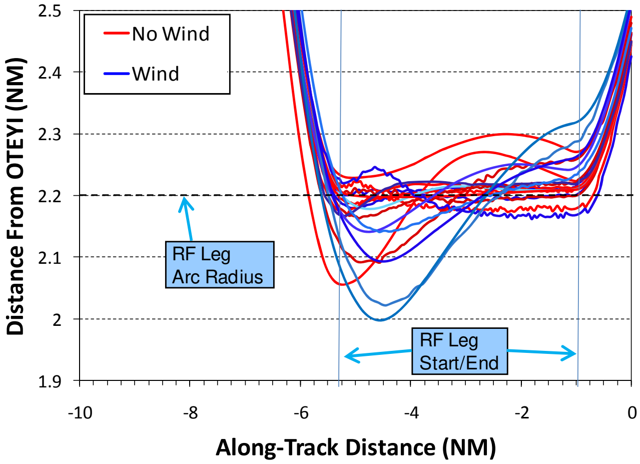

Figure 12. Runway 25R FMS Track Lateral Distance From Second RF Arc Center (OTEYI)

These tracks executed sequential reversed RF turns on final approach. While many tracks are again within approximately 0.1 NM of the nominal arc radius, for tracks recorded during both wind and no wind scenarios, there are several tracks flying the approach to Runway 25R which are up to approximately 0.2 NM away from the nominal arc radius. Note that this procedure has an option to fly it at RNP 0.15, so these aircraft would be required to execute a missed approach if flying that optional line of minima. Upon further investigation, these tracks were found to be tracks that overshot the turn from the previous leg starting at ALBAS onto the leg which intercepts the RF turn (see Figure 5). This relates to the previous analysis of TF transitions published two years ago and it is the same aircraft family which is overshooting the TF turn.[6] However, the error did not necessarily appear to propagate through to the second RF turn, as the number of tracks which stray from the nominal RF arc radius by more than 0.1 NM is fewer for the second RF leg. The distances from the nominal RF arc radius for track points during the RF turn for wind and no wind scenarios are presented in Figures 13 and 14 for the first and second of the reversed RF turns; respectively.

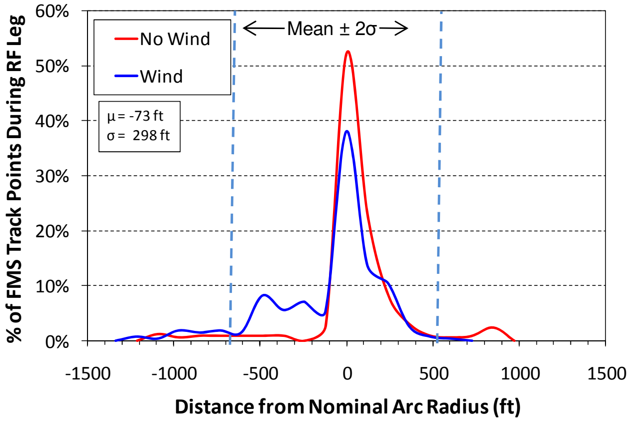

Figure 13. Distribution of Runway 25R FMS Track Point Distances From Nominal Arc Radius During First RF Turn

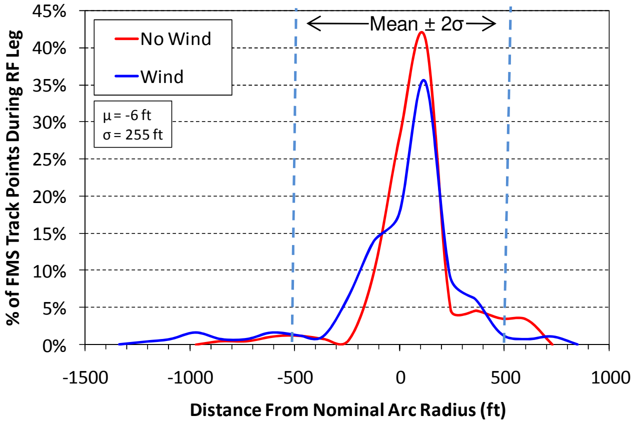

Figure 14. Distribution Of Runway 25R FMS Track Point Distances From Nominal Arc Radius During Second RF Turn

They show little variation due to the maximum winds allowed in the design of the procedure.

The analysis of distance from the RF arc center fix (UYURE) for each FMS track on the RNAV (RNP) RWY 30 approach is shown in Figure 15.

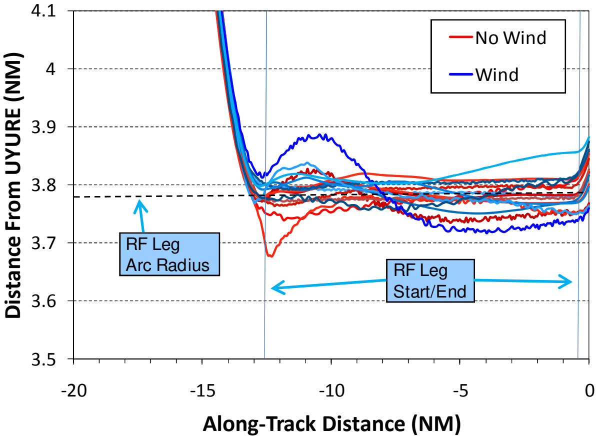

Figure 15. Runway 30 FMS Track Lateral Distance From RF Arc Center (UYURE)

The RF leg for this analysis takes place during the missed approach segment, meaning that the lateral conformance for the RF leg was measured for portions of the track where the aircraft executed a climb. The analysis shows that all tracks are within approximately 0.1 NM of the nominal RF arc radius throughout the RF turn, and many are far

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[6] Herndon et al. [5]

closer. In addition, the wind scenarios were not found to be significantly different than the scenarios without wind. Distributions of distances from the nominal RF arc radius for track points during the RF turn for wind and no wind scenarios are presented in Figure 16.

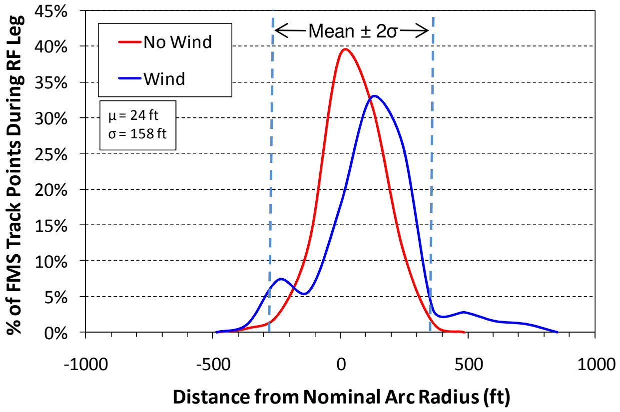

Figure 16. Distribution of Runway 30 FMS Track Point Distances From Nominal Arc Radius During RF Turn

The results of the vertical path comparison analysis for aircraft flying the RNAV (RNP) RWY 12 approach are presented in Figure 17.

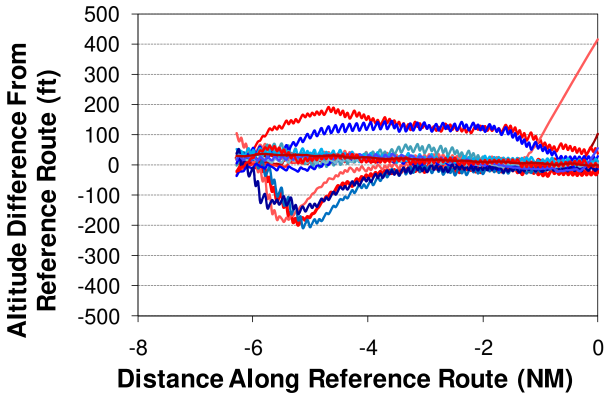

Figure 17. Altitude Difference Between Runway 12 FMS Tracks and Reference Route

With the exception of one outlier, all tracks remain within 200 ft vertically of the altitude at which they would have been had they perfectly followed the published glide path of 3 degrees.

The results of the vertical path comparison analysis for aircraft flying the RNAV (RNP) RWY 25R approach are presented in Figure 18.

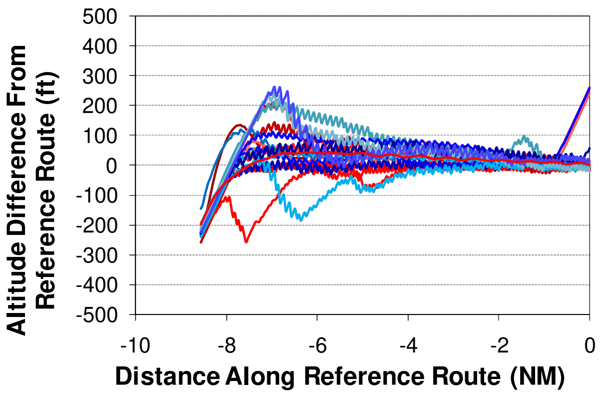

Figure 18. Altitude Difference Between Runway 25R FMS Tracks and Reference Route

All tracks remain within 300 ft vertically of the altitude at which they would have been had they perfectly followed the published glide path of 3.1 degrees. Again there appear to be two outliers at the end of the approach which appear to deviate from the reference route, else the comparison to the reference route would be closer within 6 miles of the end of the approach excepting the two outliers at roughly -0.75 NM along track, all tracks within 6 miles of the end of the approach are within 100 ft of the altitude at which they would have been had they followed the published glide path angle.

The average climb gradients during the missed approach for the FMS tracks flying the RNAV (RNP) Y RWY 30 approach by vendor and wind versus no wind scenario are presented in Figure 19.

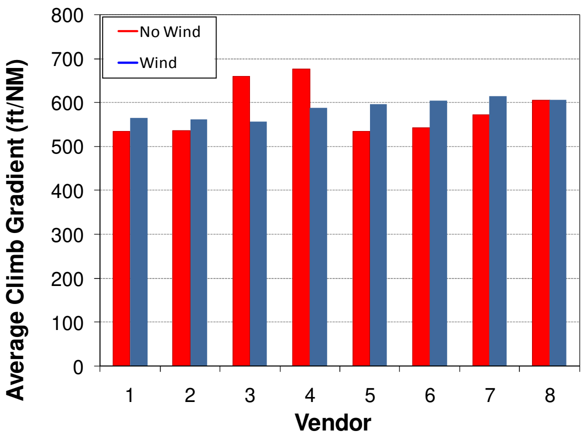

Figure 19. Average Climb Gradient During Missed Approach for Runway 30 FMS Tracks

The results show that the climb gradients are similar across vendors, and were also similar regardless of the presence of wind. Another metric of interest for missed approaches is the distance from the top-of-climb point to the missed approach point. A histogram of the distances from the top-of-climb to the missed approach point (ALBAS) for RNAV (RNP) Y RWY 30 is shown in Figure 20.

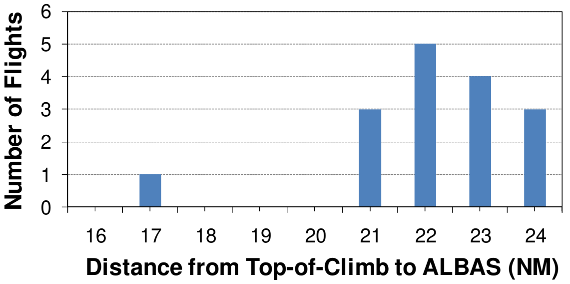

Figure 20. Histogram of Runway 30 FMS Track Distances From Top-Of-Climb to MAP (ALBAS)

With the exception of the one aircraft which reached its top-of-climb point 17 miles from ALBAS, all aircraft reach their top-of-climb point 21 to 24 miles away from ALBAS.

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 LNAV/VNAV and pilot controlled LNAV/VNAV. For instance, all of the flights were flown with LNAV using the autopilot; however, many were flown in a vertical speed mode controlled by the constraint at the initiation of the approach (those systems which do not have a full VNAV capability to fly the approach angle from the data base). These latter systems show some significant variation in Flight Technical Error (FTE) relative to the reference vertical path at the initiation of the descent which bears more investigation. FTE is the accuracy with which the aircraft is controlled as measured by the indicated aircraft position with respect to the command or desired position.[7]

There are three areas where the tests were examined in formulating conclusions for this paper:

1. Lateral path conformance to the RFs.
2. Vertical path conformance to the GP angle.
3. Missed approach climb performance through the RF.

First, an examination of the lateral path keeping ability of these systems showed a remarkable (and expected) conformance to the path and the RNP values. Looking at the distribution of lateral FTE for each of the RF segments showed that, with one set of exceptions, the FTE was maintained well within 1xRNP, which is the go-around criterion for RNP SAAAR procedures. The exceptions occurred on the reversed RF legs in the RWY 25R procedure, but perhaps not in the way one might have expected. Entry to this procedure was made from the missed approach holding fix, which resulted in a fairly sharp TF-TF turn to the leg preceding the RF initial fix. The same aircraft / FMC combinations that showed TF-TF turn overshoot before intercepting the outbound leg in the lateral tests two years ago[8], showed that same performance here, with the result that they were unable to return to the correct track prior to the initial fix of the first RF. In fact, the FTE they reached would have forced a go-around as it exceeded the RNP value for the procedure. This was an interesting link back to the previous testing, in effect validating that testing again, with a more problematic result. However, these systems were able to recover prior to the end of the first RF, so the sequential reversed RFs were inherently flyable by these systems as well. Also of significance in the lateral conformance was the fact that winds (worst case tailwind at the mid-point of the RF) had little to no effect on lateral path keeping. This is important to the debate over the conservative bank angle limits on design bank angle currently required by the criteria.[9] Lastly, it was shown that acceleration during the turning missed approach had

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[7] DO-236B [1]

[8] Herndon et al. [5]

[9] FAA Order 8260.52 [8]

no adverse effect on lateral tracking; another important conclusion. Overall, lateral conformance AND agreement between all the systems as to how to fly the RF was exceptional.

The second area of conclusions is in the vertical path conformance to the published GPA for the RFs in the approach side of these procedures (RWY 25R and RWY 12). The comparison method of using the most closely conforming lateral aircraft track as the vertical reference along path was defined to allow a standard comparison for all the tracks. Obviously this leaves the reference path showing zero deviation from the vertical path, so in that sense it could be misleading; however, the important factor is still the variation of vertical FTE especially near the initiation of each descent. The simple conclusion is that some of the systems far exceeded the budgeted FTE value from the Vertical Error Budget (VEB) for which the procedure was designed (200 ft versus design value of 75 ft 3 sigma). The VEB is a set of allowable values that contribute to the total error associated with a VNAV system.[10] This needs further investigation by the system designers to establish the root causes.

The final area of investigation relates to the missed approach climb out as mentioned above. There was no adverse impact to the tracking capability due to the acceleration during the climbing RF turn and it was shown that all the aircraft significantly exceeded the maximum climb gradient for which procedures may be designed. The criteria is nominally 200 ft/NM for design, and can be raised as high as 425 ft/NM, however, all the aircraft climbed at rates above 500 ft/NM.

In summary, RF path conformance for the FMC's was very good. Aircraft equipped with FMC's that process RF path terminators can be expected to remain within published tolerances on procedures containing RF leg types.

Recommendations

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

1. Based upon the comparison of RF performance to TF-TF performance, it is recommended that the preferred leg type for terminal area operations turns be defined, where able, by RF legs. This should include SIDS, STARS, approaches and transitions that occur within the terminal airspace.
2. Further standardization of TF-TF transitions should be studied as part of on-going work at the FAA/Industry Performance-Based Operations Aviation Rulemaking Committee (PARC) and other venues to provide for a more common implementation among manufacturer's FMCs.
3. An investigation of climb gradients permitted in the criteria based on modern aircraft capability should be initiated to determine whether the boundaries currently in the criteria are reflective of real aircraft performance.

The authors hope that this paper and the associated data will provide valuable assistance in moving forward to the performance-based NAS and will contribute to the eventual acceptance of RF usage in Basic RNP and RNAV criteria.

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