EVALUATION OF RNAV DEPARTURE OPERATIONS AT DALLAS FORT-WORTH INTERNATIONAL AIRPORT

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Abstract

On September 6, 2005 the Federal Aviation Administration (FAA) implemented revised Area Navigation (RNAV) departure procedures at Dallas-Fort Worth International Airport (DFW). The route structure of the procedures was designed to enable diverging departure operations that distribute departure traffic flows over a wider area of DFW's terminal airspace. Operational changes associated with the implementation were found to result in more efficient utilization of available runways and constrained airspace around the airport. This paper documents the results of comprehensive evaluations of observed operational changes. It reviews the design of the departure procedures and evaluates dependencies between DFW's two general implementation objectives of (1) realizing departure efficiency benefits while (2) maintaining the distance flown in terminal airspace. This paper describes the analysis methodology developed to evaluate operational changes using radar data. It presents pre- and post-implementation comparisons of benefit metrics characterizing the distance departing aircraft fly in terminal airspace and the continuity of observed departure climbs. The results show that DFW's gains in departure efficiency were realized without significantly impacting the flight distance and climb continuity of departure operations in DFW's terminal airspace.

Introduction

Incremental implementation of RNAV procedures increasingly leverages on-board navigation capabilities of advanced flight automation systems in terminal operations. These flight automation systems are currently available on the majority of commercial and corporate aircraft and implementation of the procedures promises more efficient utilization of available runways and constrained terminal airspaces surrounding major U.S. airports.

Prior to the implementation of RNAV departure procedures at DFW, terminal airspace and environmental constraints necessitated that the majority of aircraft departed DFW via a single initial heading from each primary departure runway. In post-implementation operations, the navigational conformance of aircraft flight paths to RNAV routes and reduced operational uncertainty generally associated with RNAV operations was found to support the design of two diverging route segments from each runway and to enable more efficient use of DFW's constrained departure airspace. Figure 1 illustrates the route design of DFW's RNAV departure procedures.

Implementation of the procedures and sequencing of successive flights by Air Traffic Control (ATC) for alternating use of diverging RNAV routes have resulted in increased airport departure capacity, improved throughput, and

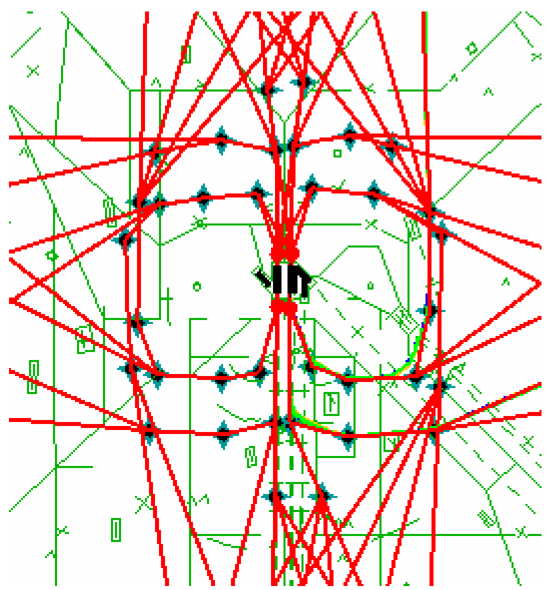

Figure 1. Detail of DFW's RNAV departure procedure design illustrating initially diverging route segments

reduced delay. Monte Carlo model evaluations of operational benefits associated with diverging departure operations were previously found to result in annual delay reduction benefits of $8.5 million to users and operators. A detailed description of the DFW's RNAV departure operations, the benefit mechanism, model analyses, and post-implementation evaluations are presented in Reference [1]. This paper presents evaluations of two operational changes also associated with the implementation of RNAV departure operations at DFW: (1) the distance aircraft were found to fly in terminal airspace and (2) the continuity of departure climb operations observed before and after implementation of RNAV departure procedures at DFW.

Operational Changes

A key operational change resulting from the implementation of RNAV departure procedures at DFW is associated with conducting diverging departure operations. This operational change reflects the airport's primary RNAV route design objective of improving the efficiency of departure operations. For this reason, the procedure design includes two diverging route segments from each primary runway in both North and South flow operational configuration. In both operational configurations, the route design is largely symmetrical with respect to a line of latitude approximately located mid-field of the airport (see Figure 1). The following discussion of operational changes assumes that the airport is operated in North flow configuration. Similar considerations also apply when the airport is operated in South flow configuration.

Flight Distance

Conventional departure operations, i.e. operations that were conducted exclusively prior to the implementation of RNAV procedures, rely on course guidance instructions provided by ATC. In terminal airspace, these control instructions typically comprise sequential assignments of aircraft headings that are issued to departing flights via voice communications. Timely issuance of successive clearances instructing aircraft to fly assigned headings, commonly referred to as *vectoring,* serves as a key control mechanism to continually ensure aircraft separation and to provide navigational guidance to points typically located about 40 nautical miles (NM) from the airport. These navigational points are often referred to as *departure fixes.* In conventional departure operations at DFW, aircraft reliance on on-board navigational course guidance is generally delayed until aircraft approach or cross a departure fix approximately located at the lateral boundary between terminal and en-route airspace. Figure 2 illustrates vector patterns typically associated with conventional departures and the route structure of RNAV departure procedures at DFW. The

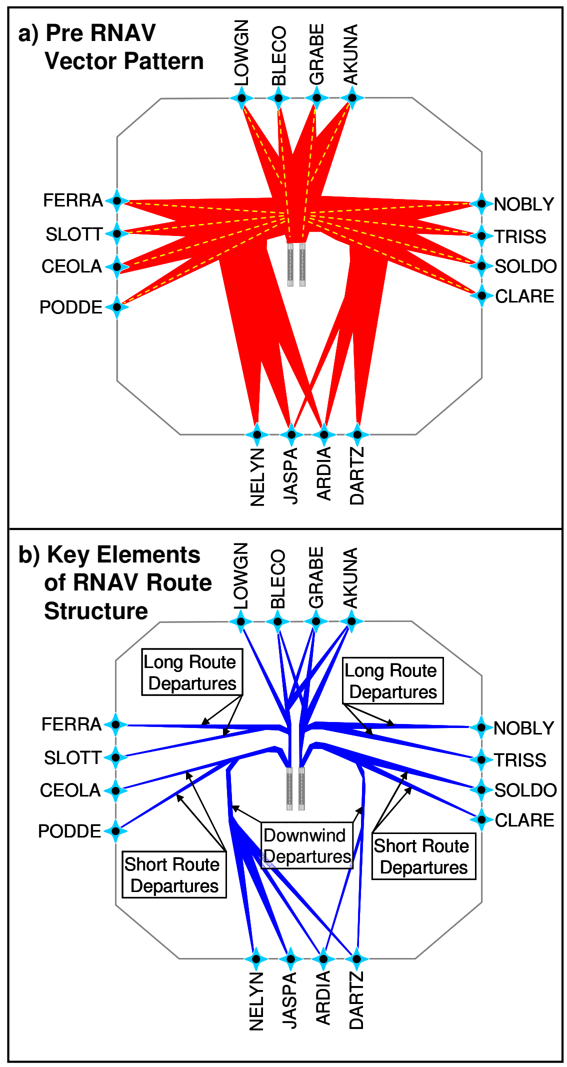

Figure 2. Illustration of typical vector patterns of (a) conventional departures and (b) RNAV departure paths (notional)

octagonal shape of the lateral terminal airspace boundary and the primary departure runways are outlined in the figure as well as the locations and names of DFW's 16 departure fixes. While about 22 percent of DFW departure operations are North-bound, the majority (about 65 percent) are routed over departure fixes located to the East (NOBLY, TRISS, SOLDO, CLARE) or West (FERRA, SLOTT, CEOLA, PODDE).

In conventional operations, virtually all jet aircraft depart DFW via a single initial heading from each primary departure runway. These initially North-bound headings are notionally indicated in Figure 2a by dashed lines. As the figure suggests, these departures proceed North-bound for about 5 to 6 NM. When reaching this distance from the runway ends, East- and West-bound departures are typically vectored on course to proceed toward a flight-planned departure fix. In the figure, the areas outlined in red approximately represent the area typically used by ATC to vector aircraft within terminal airspace.

As noted previously, a key operational change resulting from the implementation of RNAV departure procedures at DFW is associated with conducting diverging departure operations. Figure 2b illustrates the divergence of two initial route segments from each runway. As the figure suggests, East- and West-bound departures can be grouped in two classes depending upon the initial route segment of the departure procedure. Departures that are assigned RNAV procedures comprising initial straight-out segments proceed north-bound for about 10 to 11 NM before proceeding on course toward a departure fix. Since these departures continue North-bound for an additional 5 NM when compared to conventional operations, they are subsequently referred to as ***Long Route*** departures. Conversely, departures that are assigned RNAV procedures comprising an initially diverging segment fly North-bound for about 5 to 6 NM before proceeding on course toward a departure fix. Since these departures remain North-bound for a shorter distance (similar to conventional operations), they are subsequently referred to as ***Short Route*** departures.

It is interesting to note that the primary design objective of DFW's RNAV procedures was to enable diverging departure operations and to realize associated departure efficiency benefits for the airport. Full realization of these benefits requires a balanced use of Short Route and Long Route departures that maximizes the opportunities to conduct diverging departure operations, i.e. departure operations that make alternating use of the initially diverging routes. Due to the runway layout and DFW's primary demand for East- or West-bound departures, DFW anticipated that a significant number of departures would be assigned to Long Routes and devised an operational concept to mitigate the potential impact of its diverging departure operations on the distances flown in terminal airspace. This concept involved close monitoring of RNAV departures on Long Routes and issuing direct-to clearances whenever possible. Leveraging direct-to clearances to shortcut the 10 to 11 NM straight-out initial route segment, when possible, allowed expediting the turning on course of aircraft toward a departure fix.

This study aims to compare the efficiency benefits of diverging RNAV operations to the potential impact diverging operations may have on flight distances at DFW. It is important to note that the results presented here are specific to DFW and are not likely to apply to other airports as operational constraints including runway layouts, departure airspace geometries, RNAV route structures, and departure demands along cardinal departure headings typically vary significantly between airports.

Climb Continuity

Figure 3 illustrates the vector patterns and RNAV route structure shown in Figure 2 as well as selected traffic flows of aircraft arriving over DFW's North-West and North-East corner posts.

As can be seen by comparing Figure 3b to figure 3a, arriving aircraft joining the downwind legs are generally separated more widely from RNAV downwind departures. The greater operational segregation of arriving and departing traffic flows observed in RNAV operations can be expected to result in a reduction in potential conflicts between arriving and departing aircraft. Such potential conflicts typically require ATC to momentarily restrict the climb of a departing aircraft or the descent of an arrival and issue a clearance to maintain an intermediate altitude.

After an arriving aircraft no longer presents a factor for a departure, ATC may then instruct a departure to continue its climb and an arrival to continue its descent to the next lower altitude.

Given DFW's demand for East- and West-bound departure operations, Figure 3 also suggests that the potential for arrival-departure conflicts may be most pronounced between (1) aircraft arriving over the North-West or North-East corner posts when approaching the downwind legs and (2) East- and West-bound departures after they have turned on course to proceed toward a departure fix located along the airspace boundary. When approaching DFW's terminal airspace from the North, arriving aircraft are routinely assigned an altitude of 11,000 feet (ft) while East- and West-bound departures are generally cleared to climb and maintain an intermediate altitude of 10,000 ft. The potential for arrival-departure conflicts typically no longer exists once departures have crossed below the paths of the arrivals.

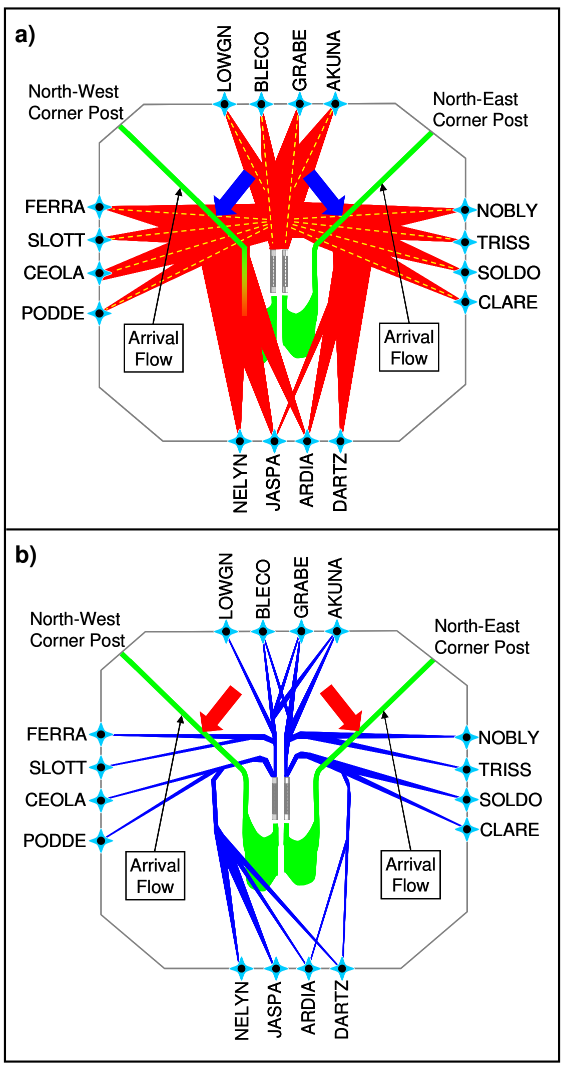

Figure 3. Key potential arrival-departure conflict areas of (a) conventional and (b) RNAV departure operations

In conventional operations, PODDE or CLARE departures were observed to have typically crossed below the paths of arrivals about 10 to 15 NM along their climb-out paths while FERRA and NOBLY departures generally cross the paths of arrivals after proceeding along their climb-out paths for about 15 to 20 NM (see Figure 3). On the other hand, DFW's RNAV Long Route departures are routed farther North and may not have completed turning on course before reaching points about 10 to 11 NM North of the departure ends of the runways. When crossing the arrival paths, these departures may have flown about 25 NM, i.e. up to about 5 NM longer than comparable conventional departures. This observation suggests a prolonged need for Long Route RNAV departure to level off at 10,000 ft potentially impacting the climb continuity of Long Route departures.

The following section describes the analysis methodologies that were developed to evaluate and quantify operational changes that are associated with conducting diverging departure operations. The analysis results are based on radar data of actual operations that were recorded before and after RNAV departure procedures became operational at DFW.

Evaluation of Operational Changes

A total of eleven days of Automated Radar Terminal System (ARTS) data comprising approximately 11,000 radar tracks of actual pre- and post-implementation operations were provided by DFW in Performance Data Analysis and Reporting System (PDARS) format and were evaluated in this study. The majority of pre-implementation data were recorded in July 2005. Post-implementation operations conducted about 2 months after the RNAV procedures became operational at DFW were recorded in November and December 2005. The data were pre-sorted to select jet operations associated with DFW departures from the appropriate primary runways and analyzed using MITRE's Integrated Terminal Research, Analysis, and Evaluation Capabilities (iTRAEC) tool [2]. The flight distance metric and climb continuity metric leveraged sequential radar position reports, generally referred to as a *radar tracks,* that characterize the location and motion of aircraft. The metrics are described in the following sections.

Flight Distance

For most departing aircraft, radar tracking information became first available when aircraft reached altitudes between the airport surface and 1,000 ft above ground level (AGL). In order to enable direct comparisons between radar tracks, iTRAEC supported extrapolating reported tracks to ensure all tracks commenced at a common line of longitude. On the other hand, most radar tracks were found to extend beyond the lateral boundary of DFW's terminal airspace (see Figure 2). Taking advantage of the rectangular geometry of the airspace, iTRAEC's track truncation feature supported discarding any portions of radar tracks that extended beyond lateral airspace boundaries from the analysis. These steps of the track preparation procedure ensured that all tracks began at a common line of longitude and ended at a lateral boundary of DFW's terminal airspace. This approach largely removed the track-to-track variability that is induced by the radar data acquisition system. Resulting differences in measured track lengths can be viewed as largely independent of automation system-induced variability and reflect the differences between actual operations, i.e. ATC vectored pre-implementation operations and RNAV-guided post-implementation operations.

The track length metric served to separately evaluate DFW operations in North flow and South flow configurations. In each operational configuration and for each day of recorded track data, track lengths were measured for all tracks associated with DFW's 16 departure fixes (see Figure 2). These measurements were carried out track-by-track and the results were averaged for each group of tracks associated with an individual departure fix. The numbers of tracks associated with individual departure fixes over all 11 days of recorded departure operations were used to obtain average fix loading information for each fix. Average track length and fix loading information derived for each departure fix then allowed for determining the average track length associated with all departure operations in either North or South flow operational configurations.

Climb Continuity

Climb continuity was evaluated using iTRAEC's altitude spectral analysis tools. The metric used in this analysis evaluates the average time associated with a track's climb through 100 ft of altitude. For each evaluated nominal altitude, this *Time-At-Altitude* metric characterizes the time an average departure occupies a block of altitude from 50 ft below to 50 ft above the nominal altitude. For all evaluated altitudes, the resulting series of average time values represents an altitude spectrum indicating both the average climb performance between level-offs as well as the average time in level flight at level-off altitudes. The average climb performance between level-offs is represented by the low-lying portions of the spectrum that form a smooth background distribution of measured time-at-altitude values. Parts of the spectrum that extend above the smooth distribution at a given altitude can be viewed as evidence of leveling off, i.e. aircraft remaining extended periods of time in level flight at that altitude.

The climb continuity analysis evaluated radar tracks of departure operations that displayed intent to climb. Tracks associated with operations in the local area and tracks that were found to level off at what could be identified as low final altitudes (below 18,000 ft) were excluded from the analysis. This analysis approach ensured that a level off identified by the analysis procedure was primarily induced by ATC and minimally dependent upon pilot preference.

Evaluation Results

Radar tracks recorded on four days of departure operations are illustrated in Figure 4. The tracks represent typical samples of recorded data and characterize the scenarios evaluated in this study. Track altitude information is encoded in the graphs using the color scheme shown in the legend. In the figure, departure tracks are seen to converge on one of DFW's departure fixes located at the lateral airspace boundary. ATC video map information illustrating the octagonal shape of the airspace boundary is also shown. The top and bottom rows of graphs depict tracks of North and South flow operations, respectively. The samples shown in the left column illustrate tracks recorded prior to implementation of RNAV departure procedures at DFW. The two columns on the right present radar tracks recorded after implementation of the procedures. The far-right column presents a sub-set of post-implementation tracks. These tracks were selected by requiring that a departing flight crossed key waypoints defining one of the various RNAV procedures. This selection of tracks illustrates typical radar tracks that may result if (1) RNAV participation were 100 percent and (2) ATC intervention to shorten flight distances of departure operations (by providing direct-to clearances enabling short-cuts to subsequent waypoints) were minimized.

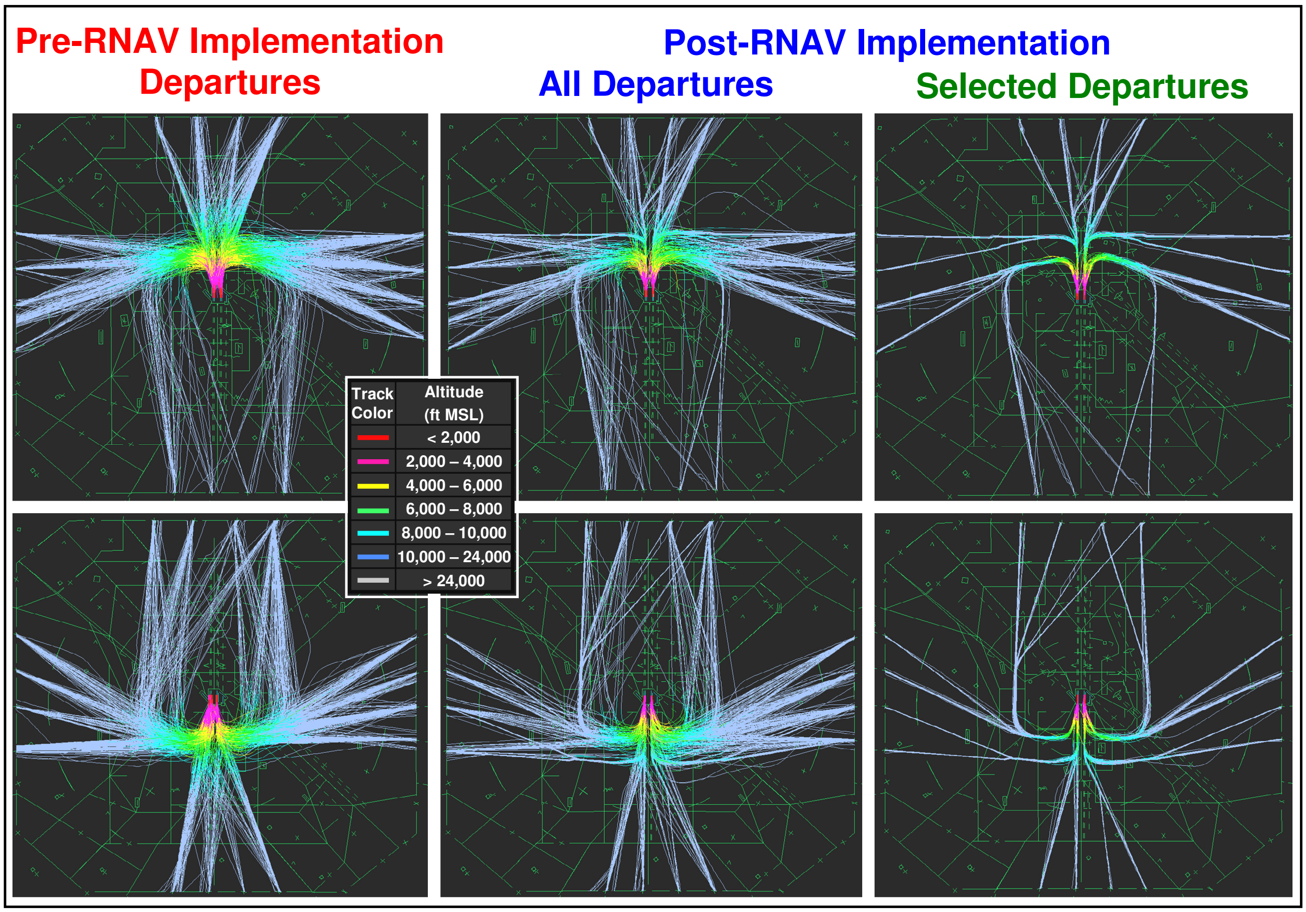

Figure 4. Radar tracks recorded on four days of departure operations illustrating operational scenarios evaluated in this study

Flight Distance

Results of track length analyses are illustrated in Figure 5. For each departure fix, average track lengths are shown on the left and fix loading information on the right vertical axes of the graphs. Taking North flow operations as an example, the results suggest little to no change in track lengths associated with the implementation of RNAV procedures for North-bound departures via LOWGN, BLECO, GRABE, or AKUNA (see Figure 2). Average track lengths of East- and West-bound departures via NOBLY, TRISS, FERRA, or SLOTT (Long Route) are seen to be longer in post-RNAV implementation operations. On the other hand, generally shorter track lengths are observed for departures via SOLDO, CLARE, PODDE, or CEOLA (Short Route). The figure also illustrates that downwind departures generally benefit from the RNAV implementation resulting in shorter observed track lengths for these departures. Similar considerations also apply to South-flow operations.

Comparing all measured track lengths shown in Figure 5, the results indicate that average post-implementation distances flown by departures bound for fixes associated with *Short Routes* are shorter by about 0.8 to 1.4 NM and distances flown by departures bound for fixes associated with *Long Routes* are longer by about 1.8 to 3.0 NM.

The track length analysis of departures associated with individual departure fixes was extended to determine the changes in the average track length associated with all departure operations at the airport. For each fix, the product was taken of the associated average track length and fix loading. The sum of all such products was divided by the total number of evaluated tracks (sum of all fix loads) to derive the average track length associated with departure operations at DFW. The results are summarized in Figure 6.

Comparing pre- and post-implementation track lengths associated with all departure operation at the airport, the results suggest that the average post-implementation distance flown in terminal airspace is longer by about 0.2 NM when the airport is operated in North flow configuration and 0.3 NM longer when in South flow configuration.

Considering that a typical distance flown within the lateral boundaries of DFW's terminal airspace was observed to be about 45 NM, the relatively small post-implementation increase in distance flown suggests largely successful execution of DFW's operational concept to mitigate the potential impact of its diverging departure operations on the distances flown. As stated above, this concept involved close monitoring of RNAV

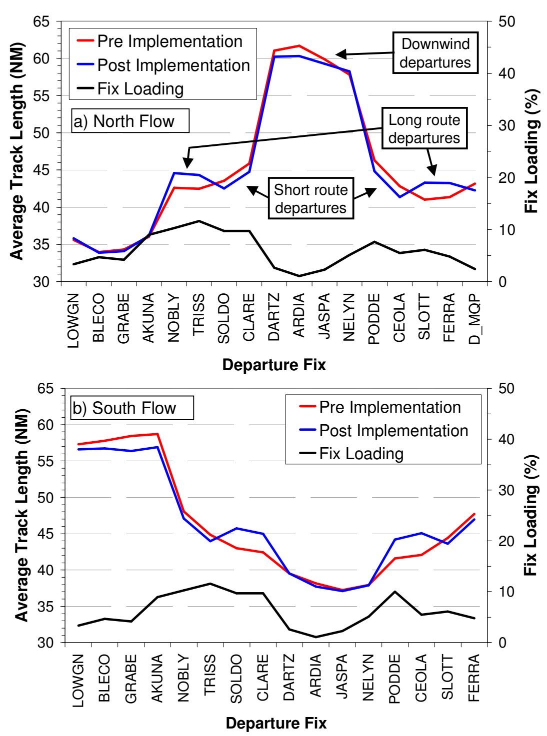

Figure 5. Average lengths of radar tracks associated with DFW departure fixes

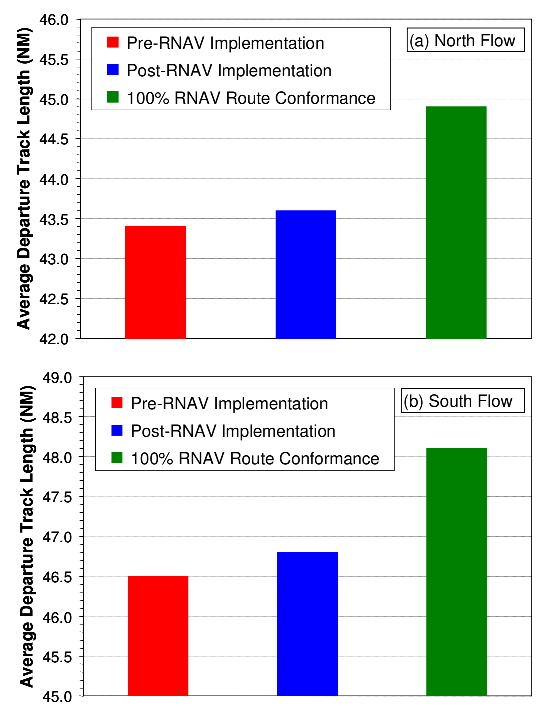

Figure 6. Average lengths of radar tracks associated with DFW departure operations

departures (primarily those on Long Routes) and issuing direct-to clearances whenever possible. In order to evaluate the effectiveness of the operational concept, sub-sets of post-implementation data were analyzed. For this analysis, tracks were selected by requiring that a departing flight crossed key waypoints defining the various RNAV procedures (see Figure 4). The remaining tracks then represent RNAV departure operations characterized by minimal ATC mitigation to expedite departure operations in terminal airspace (see Figure 4).

The results of this additional analysis are presented in green color (100% RNAV Route Conformance) in the bar graphs of Figure 6. It is important to keep in mind that these results intend to provide track length estimates for hypothetical scenarios defined by conditions of (1) 100 percent RNAV participation and (2) minimal ATC mitigation in terminal operations at DFW. For operations conducted under these conditions, the results suggest that average distances flown in post-implementation operations could be expected to increase by 1.5 NM and 1.6 NM when the airport is operated in North flow and South flow configurations, respectively. The observation that these values significantly exceed the track lengths actually measured in post-implementation operations can be viewed as evidence of the effectiveness of DFW's operational concept that was implemented to mitigate the potential impact of diverging departure operations on the flight distances within its terminal airspace.

Climb Continuity

Results of climb continuity analyses are illustrated in Figure 7. The figure presents results of the altitude spectral analysis of DFW departure operations in North flow and South flow operational configurations. Comparing the results for the two configurations, it is interesting to note that the best climb rates were observed in the data at altitudes between 5,000 and 7,000 ft. At these altitudes, the data indicate an average climb performance of about 2.3 seconds per 100 ft or about 2,600 ft per minute. At these altitudes, largely continuous climb behavior can be inferred from the smoothness of the observed distribution.

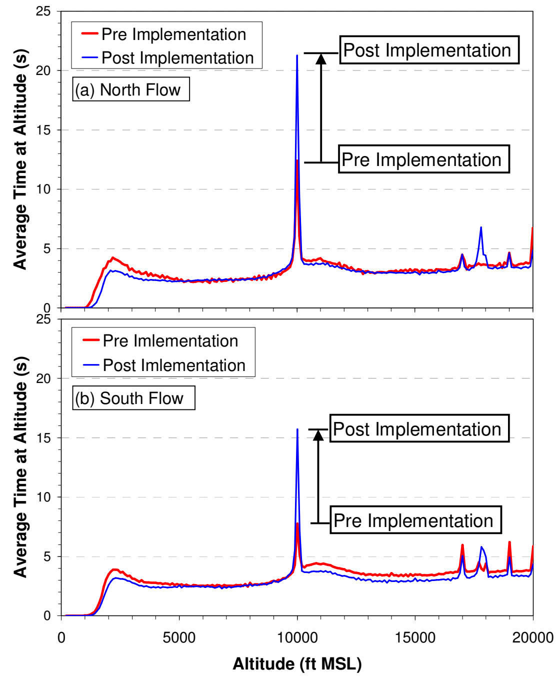

Figure 7. Climb continuity of DFW departure operations in (a) North flow and (b) South flow operational configurations

At lower altitudes, the distributions also suggest that the post-implementation climb performance generally exceeded the climb performance observed in pre-implementation operations. Assuming no significant changes in the fleet mix operating at DFW, this observation is consistent with meteorological conditions characterized by lower density altitudes in November/December when compared to meteorological conditions in July when the pre-implementation data were recorded.

At 10,000 ft, the distributions shown in Figure 7 feature average Time-At-Altitude values in excess of the smooth background level observed at all other altitudes up to and including 16,000 ft. This feature of the distributions represents not only the momentary reduction in climb rates associated with aircraft acceleration from typically 250 knots indicated airspeed to a greater en-route climb airspeeds, but also additional time aircraft remain, on average, in level flight at this altitude. This time in level flight can be determined from the altitude spectra shown in Figure 7. The analysis suggests that departure climbs were generally less continuous in North flow operational configuration when compared to South flow operations. Furthermore, post-implementation operations were found to remain about 12 seconds longer in level flight at 10,000 ft when compared to pre-implementation operations.

Interpretation of the altitude analysis results requires consideration of the possible interplay between meteorological conditions affecting climb performance and airspace constraints that may result from the need to de-conflict arrival and departure operations as discussed above in the Operational Changes section. As noted previously (see Figure 3), the potential for arrival-departure conflicts is likely to be most pronounced between (1) aircraft arriving over the North-West or North-East corner posts when approaching the downwind legs and (2) East- and West-bound departures after they have turned on course to proceed toward a departure fix along the airspace boundary. For this reason, DFW routinely assigns an altitude of 11,000 ft to arriving aircraft while East- and West-bound departures are generally cleared to climb and maintain an intermediate altitude of 10,000 ft. Thus, the potential for arrival-departure conflicts typically remains until departures have crossed below the paths of the arrivals (see Figure 3). This consideration may suggests a prolonged need for Long Route RNAV departure to level off at 10,000 ft potentially impacting the climb continuity of Long Route departures. In order to further investigate the role Long Route departures play in the changes observed in departure climb continuity at 10,000 ft, additional departure fix-specific altitude spectral analyses were carried out.

Figure 8 illustrates typical arrival and departure tracks of pre- and post-RNAV implementation operations at DFW. Arrows indicate the locations where key East- and West-bound departures were observed to typically cross below the paths of arrivals from the North when the airport is operated in the North flow configuration. In post-implementation operations, these points have moved farther East and West due to the more northerly routing of Long Route departures. The figure also illustrates similarities that exist between the vector patterns of conventional East- and West-bound departures and Short Route departure tracks.

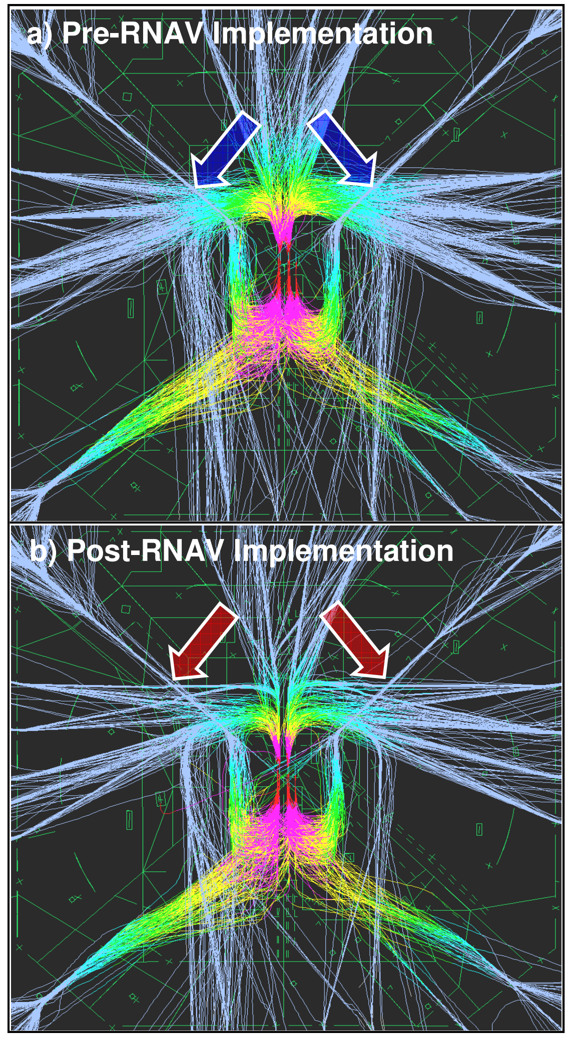

Figure 8. Radar tracks recorded before and after implementation of RNAV departure operations

The additional climb continuity analyses were carried out selectively for Short and Long Route departures of post-implementation operations and equivalent conventional departures involving the same departure fixes. The analysis was based on data recorded during both North and South flow operations and the results are presented in Figure 9. When compared to equivalent conventional departures, post-implementation Short Route departures were found to remain about 5 seconds longer in level flight at 10,000 ft.

Due to the geometric similarities between conventional East- and West-bound departures and post-implementation Short Route departures noted above, the 5-second difference in level-off time observed in the data can be attributed to differences in initial climb performance (also evidenced in the data) due to varying meteorological conditions present during the recording of data in July and November 2005. As lower density altitudes or stronger head wind components generally enable climbs with steeper gradients, operations under such conditions can be expected to reach the assigned altitude of 10,000 ft in a shorter distance. Because the locations of arrival flows were found to remain unchanged and departing aircraft continue to be required to cross underneath arriving aircraft before departure climbs can be resumed, reaching 10,000 ft of altitude in shorter distances would typically require prolonged periods of level flight under such conditions.

As shown in Figure 9, post-implementation Long Route departures were found to remain about 31 seconds longer in level flight at 10,000 ft than equivalent conventional departures. If the 5-second difference observed in the case of Short Route departures is viewed to reflect the impact of

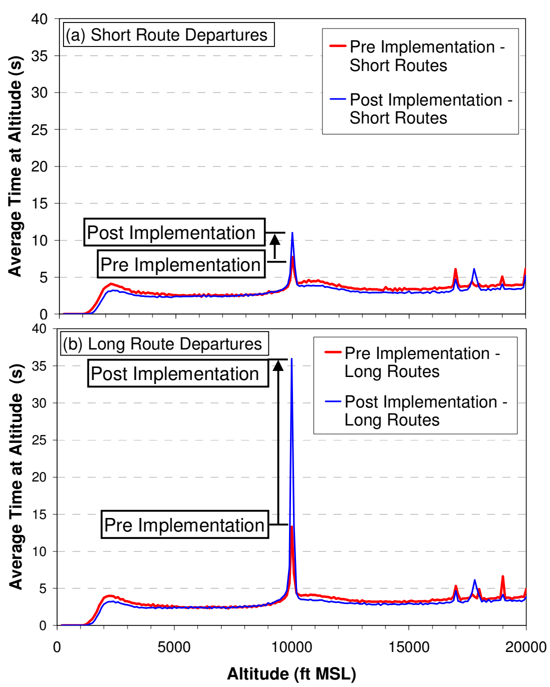

Figure 9. Climb continuity comparison of selected post-implementation operations and equivalent conventional departures

seasonally varying meteorological conditions throughout the climb to 10,000 ft, an estimate for a seasonally adjusted change in level-off time of Long Route departures can be derived. Based on this assumption, the seasonally adjusted change in level-off time of about 26 seconds can be viewed as confirmation that Long Route departures figure prominently in the changes observed in departure climb continuity at 10,000 ft.

While Long Route departures were found to contribute significantly to the observed changes in the overall average climb continuity at DFW (see Figure 7), the 5 to 6 month time span between the recording of pre- and post-implementation data and the lack of data to further characterize seasonal impacts currently preclude a more detailed determination of changes in climb continuity. However, given the seasonal trend from higher (July) to lower density altitudes (November and December) represented in the data, the climb continuity analysis results can be viewed to establish an upper bound on the change in climb continuity at 10,000 ft of 12 seconds that was found to be associated with DFW implementing RNAV departure procedures and conducting diverging departure operations.

As noted previously, the flight distance and departure climb continuity results presented here are specific to DFW operations and are not likely to apply to other airports as operational constraints including runway layouts, departure airspace geometries, RNAV route structures, and departure demands along cardinal departure headings typically vary significantly between airports.

Impact of Operational Changes

The operational impact of observed changes in the distance flown by aircraft departing DFW and the continuity of departure climbs at 10,000 ft was estimated using iTRAEC's fuel burn evaluation capability. MITRE's iTRAEC fuel burn evaluation capability is based on Eurocontrol's Base of Aircraft Data (BADA) which provides performance and fuel flow parameters for 84 aircraft types commonly used in corporate and commercial air carrier operations [3]. The cost impact was derived from observed operational changes in flight distance and climb continuity and Aircraft Direct Operating Cost (ADOC) estimates. This CAASD estimate was based on FAA APO guidance for estimating aircraft operating costs and 2005 fleet mix data for DFW [4].

Due to the uncertainty regarding the seasonal dependence of observed changes in climb continuity noted above, the analysis was limited to providing an estimate of an upper bound of the operational impact. The analysis was found to suggest an upper bound of the cost impact to users and operators of $1 million annually associated with observed changes in the distance flown by aircraft departing DFW and the continuity of departure climbs at 10,000 ft. It is interesting to compare this estimate of the operational impact to departure delay reduction benefits reported previously [1]. Implementation of RNAV departure procedures and ATC sequencing of successive flights for alternating use of diverging routes were found to result in increased airport departure capacity, improved throughput, and reduced delay with benefits to users and operators of $8.5 million annually. These results demonstrate that DFW's RNAV implementation goal of realizing overall operational benefits was achieved and that the resulting balance of annual benefits of over $7 million to users and operators strongly supports RNAV departure operations at DFW.

Summary

The operational objective of leveraging diverging departure operations as a benefit mechanism required that DFW's RNAV procedure design includes diverging initial route segments from each primary runway that effectively distribute departure traffic flows over a wider area of its terminal airspace. Implementation of RNAV departure procedures and sequencing of successive flights for alternating use of diverging routes was previously found to result in increased airport departure capacity, improved throughput, and reduced delay with benefits to users and operators of $8.5 million annually.

Post-implementation evaluations were carried out to investigate observed operational changes associated with RNAV departure operations involving the distance flown and climb continuity within DFW's terminal airspace and to estimate operational benefits.

The results of the evaluations have shown that implementation of the RNAV route structure entailed a moderate increase of 0.2 NM and 0.3 NM in the average distance flown per departure depending upon the airport's operational configuration. This observation was found to largely validate the effectiveness of DFW's RNAV operational concept that was implemented to mitigate the potential impact of more widely distributed traffic flows within its terminal airspace.

The evaluation of departure climb continuity at 10,000 ft was found to indicate a minor increase in the time aircraft remain, on average, in level flight at this altitude. While the available data were found to be insufficient to correct for seasonal effects, a likely upper bound of additional 12 seconds in level flight per departure was established as associated with DFW's implementation of RNAV departure procedures and conducting diverging departure operations.

The evaluation results demonstrate that DFW's RNAV implementation goal of realizing overall operational benefits was achieved and that the resulting balance of annual benefits of over $7 million to users and operators strongly supports RNAV departure operations at DFW.

The results of the study presented here establish that incremental implementation of RNAV departure procedures can provide significant benefits to users and operators and firmly support further terminal RNAV procedure design optimization and implementation at DFW and other airports.

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References

[1] Mayer, Ralf H., Greg Juro, September 2006, *Departure Efficiency Benefits of Terminal RNAV Operations at Dallas-Fort Worth International Airport,* Conference Proceedings, AIAA Aviation Technology, Integrations and Operations Conference, Wichita, KS.

[2] Mayer, Ralf H., December 2006, *Estimating Operational Benefits of Aircraft Navigation and Air Traffic Control Procedures Using an Integrated Aviation Modeling and Evaluation Platform,* Conference Proceedings, Winter Simulation Conference, Portland, OR.

[3] Eurocontrol, 2004, *Base of Aircraft Data (BADA 3.5)*, The EUROCONTROL Experimental Centre, Brétigny, France. http://www.eurocontrol.fr/projects/bada

[4]Federal Aviation Administration Office of Aviation Policy and Plans, December 1999, *FAA Airport Benefit-Cost Analysis Guidance*, Washington, DC.

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