ANALYSIS OF DIVERGENCES FROM AREA NAVIGATION DEPARTURE ROUTES AT DFW AIRPORT

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Abstract

The Next Generation Air Transportation System (NextGen) calls for the extensive use of trajectory management for aircraft to achieve precision flight paths [1]. To understand, develop, and model systems that support these NextGen operations, especially in the terminal area, NASA is looking at today's precision operations to gain insight into the expected behavior. This paper documents characteristics of aircraft that are both on and vectored from routes in the execution of area navigation (RNAV) precision departures to support precision modeling and provide for NextGen super density operations research. Dallas/Fort Worth International Airport (DFW) was selected for this case study as these kinds of precise departure procedures have been in daily use there for years.

One-third of DFW RNAV departures encounter some form of vectoring away from the defined RNAV routes. The majority of these, about one-quarter of the departures, are given direct routings that bypass fixes on the route and shorten the distance flown within the Terminal Radar Approach Control (TRACON). These divergences primarily result from controllers taking advantage of opportunities in the airborne traffic, similar to direct-to routing in enroute airspace [2], and are not the result of departure sequencing or avoiding loss of separation. During the planning of the RNAV procedures, some of this vectoring was expected and even encouraged, but the number of aircraft so affected has grown over time.

Pilots and air traffic controllers use the precision navigation capability required for the RNAV departure procedures to bypass portions of the routes. While this is applicable to DFW alone, it is a reminder that the human elements in the system frequently find new and innovative uses for elements of the procedures, or the technology behind them. The numbers of aircraft vectored in the course of RNAV departure operations is comparable to those departing with reduced spacing, the main benefit of the original RNAV implementation. The data presented here demonstrate the flexibility of the procedures as currently used.

Motivation

As part of a broad plan to improve the efficiency of the national airspace system, the Federal Aviation Administration is in the process of implementing RNAV departure procedures at a number of major airports in the United States [3]. Aircraft that file for RNAV departures must be equipped to fly an RNAV 1 route, which requires a total system error of not more than 1 NM for 95% of the total flight time [4].

DFW began routinely using these procedures in November 2005. The volume of RNAV departure operations following the creation of these procedures validates their utility, and nothing has required any significant change in their layout. These procedures have reached a state of maturity at DFW, and can serve as a test case of what might occur as more of these precision operations are implemented throughout the national airspace system. It also follows that simulations of advanced terminal airspace operations concepts should expand upon the best operations of what has already been implemented and practiced day-to-day at DFW.

Given the success of these procedures at DFW, the large number of aircraft radar tracks that do not fall within the bounds of the specified departure routes is an under-documented characteristic. Having controllers grant direct flight to fixes on the RNAV routes was accepted at the time the routes were designed to offset the longer distances that some aircraft flew in executing these procedures [5]. This aspect of DFW operations is not well understood in the research community, whereas the use of diverging headings to reduce time between departures is the better-known benefit. Both features need quantification. The goal of this paper, then, is to provide the characteristics of divergences from RNAV departure procedures as currently practiced at DFW, to develop an understanding towards their modeling and simulation. Operational aspects learned from examining divergences at DFW could be applicable to other metroplex procedures involving an explicit Required Navigational Performance (RNP).

Background

D10 TRACON is centered on DFW. Dallas Love Field (DAL), the closest airport, is the next largest of more than 30 other airfields within its bounds. D10 essentially consists of a square approximately 60 miles on each side, and controls aircraft within its boundaries up to 17,000 feet. Departures from D10 leave through the north, south, east, and west gates (sides) of the TRACON, while arrival traffic passes over fixes on the corners of this square.

Currently, sixteen procedures define RNAV 1 routes from the departure runway thresholds to the fixes where aircraft transition from the D10 TRACON to Fort Worth Air Route Traffic Control Center (ARTCC) airspace, also known as ZFW. Departures from DAL and other airports, as well as propeller and non-RNAV DFW departures, also fly over these boundary fixes, but they receive vectoring from D10 controllers and do not use routes that require the aircraft to use equipment meeting an explicit RNP. Based on data collected at the NASA/FAA North Texas Research Station, approximately 790 of 840 departures a day (94%) from DFW use an RNAV procedure.

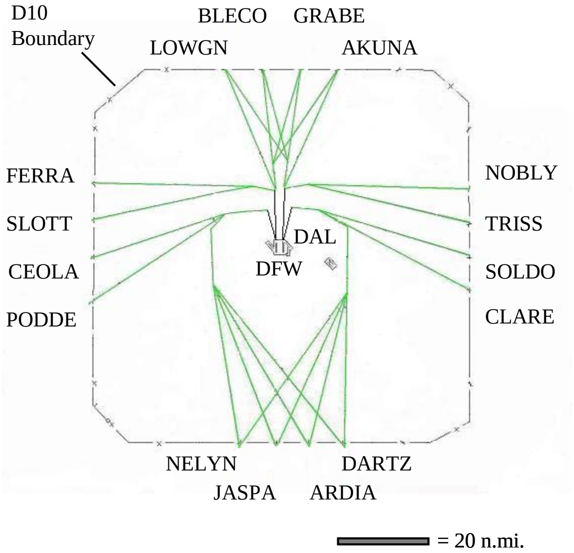


Figure 1. RNAV Departure Routes for North Flow

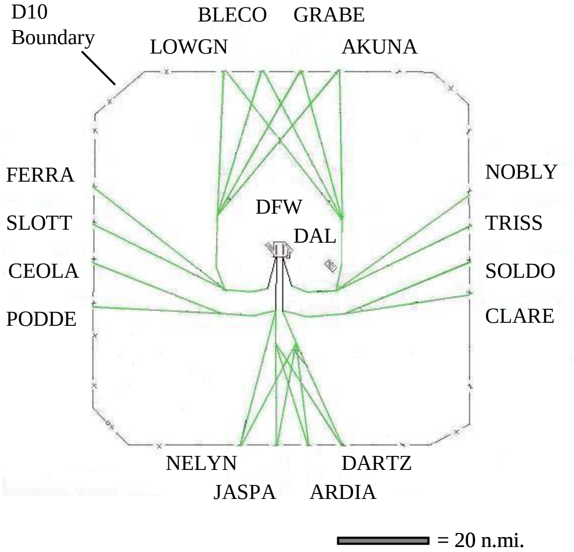


Figure 2. RNAV Departure Routes for South Flow

Each RNAV procedure defines routes for north and south flow airport configurations, that is, the aircraft direction at takeoff, from four potential departure runways. Figure 1 shows the combined routes for the RNAV departures in north flow, and Figure 2 shows those for south flow. Note that several procedures in each flow direction share common route segments. For example, Figure 2 shows that departures for SOLDO and CLARE use portions of the same route, and also share a fix common to the south gate departures leaving the eastern runway of the airport. Similarly, departures headed for the north gate that leave from the eastern runway use a segment of the route that departures to NOBLY and TRISS use as well. Aircraft on the initial segments of these two sets of routes, starting from the runway threshold, have heading angles fifteen degrees apart. In periods of high demand, the controllers alternate departures from the runway so that the subsequent aircraft is on a different initial segment than the preceding aircraft; these are termed *divergent heading departures*. In this case, less distance is required between departing aircraft than conventional operations. Departures from the same runway that have filed the same RNAV route, or that have routes with the same initial segment in common, are termed *non-divergent heading departures*. While routes for the western gates from the east side runways (and vice versa) exist, they are not used frequently, and differ only in the way aircraft reach the first fix on each route. Past studies have examined the departure efficiencies resulting from aircraft using RNAV procedures [5, 6]. In the first study, Mayer, Haltli, and Klein showed the initial RNAV procedure implementation at DFW did improve the efficiency of the airport. The authors found that, for aircraft following the RNAV departure routes, the distance flown varied from a decrease of 0.8 NM to an increase of 3.0 NM, compared to pre-RNAV implementation. Taking into account all departures, including those that received direct-to routing in the course of flying the RNAV procedure, the average increased distance was 0.2 to 0.3 NM. In the second study, Mayer and Sprong found that capacity gains of about 10 additional departures per hour and per runway are possible when RNAV procedure designs enable airports to conduct divergent heading departure operations.

RNAV departure traffic at DFW is a mix of "non-vectored" and "vectored" traffic. "Vectored" traffic in this case means that the aircraft flight plan includes the RNAV departure route, but air traffic controllers alter the route during the execution of the procedure. Figure 3, assembled from a mosaic of ASDE-X (surface and low altitude), ARTS IIIe and Host data, shows typical ground tracks for aircraft using the AKUNA RNAV departure route in south flow over the course of a single day. The designed RNAV routes from the inboard DFW runways appear with a one nautical mile bound on either side of it, as shown by the gray rectangles. Clearly, a large number of aircraft have been vectored both before and beyond the 90-degree turn in the route originating from the east-side runway. All the tracks leaving the west-side runway eventually turn inside the designed route, flying a shortened distance to the TRACON boundary. While most of the tracks converge on the AKUNA fix, a number of aircraft do not cross it, and appear to cross the TRACON boundary at a number of locations.

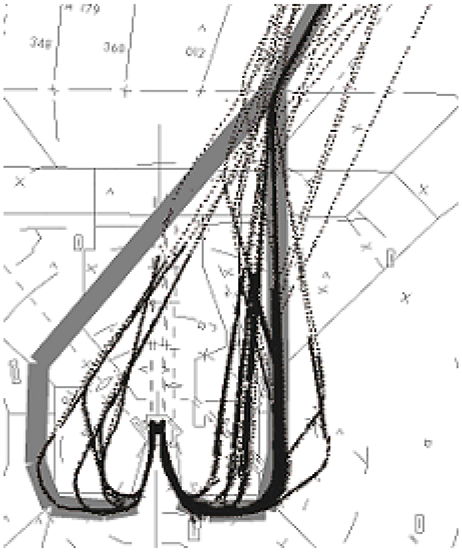


Figure 3. AKUNA Tracks in South Flow

Figure 4 shows tracks for a day of PODDE departures in south flow, while Figure 5 shows PODDE departures over the course of a north flow day. Examination of the tracks shows a wide fan ahead of the 90-degree turn in the route in Figure 4, and, as the case was with AKUNA, a number of tracks do not cross over the PODDE fix. Figure 5 shows this to a lesser extent, although one track clearly turns to the south and travels a number of miles off the route before turning west again.

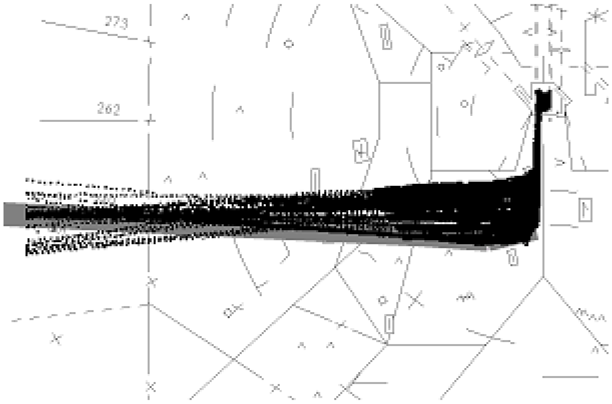


Figure 4. PODDE Tracks in South Flow

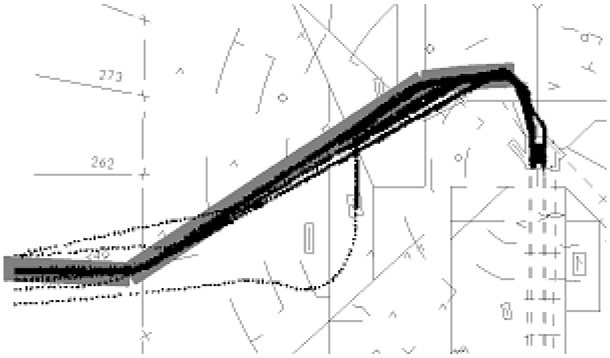


Figure 5. PODDE Tracks in North Flow

These examples show that, despite the precision implied for an aircraft filing for and expecting to execute an RNAV departure, actual operations frequently include extensive vectoring in the course of flying through D10. This is consistent with the operating concept for DFW RNAV departures, stemming from the design of the routes [5]. To effectively understand and model all departure operations at a large airport like DFW, it is therefore necessary to quantify how many aircraft encounter vectoring in the course of executing RNAV departures, and what impact this has in predicting when aircraft are going to transition from TRACON to ARTCC airspace.

Methodology

To study off-nominal routing of aircraft that have filed RNAV departure procedures from DFW, data was chosen to minimize other factors that might affect routing decisions made by air traffic control or requested by pilots.

The days were selected for their uniformity of departure flow direction and absence of limiting climatic activities in or near the TRACON. Ten days were selected to be the representative sample set. For the study, a day is defined as 24 hours of data commencing at 0600 UTC, or local midnight time. The dates range from October 16, 2008 through December 29, 2008, as shown in Table 1.

Table 1. Dates for Departure Analysis

Airport Configuration, All Runways Available	Date (2008)
North Flow, VFR (S4V)	November 27
	November 30
	December 1
	December 11
South Flow, VFR (N4V)	November 25
	December 7
	December 28
	December 29
North Flow, IFR (N4I)	October 16
South Flow, IFR (S4I)	November 23

The selected days are comprised of five south flow and five north flow days. The Visual Flight Rules (VFR) notation indicates clear conditions at the airport, while Instrument Flight Rules (IFR) indicates cloud cover. The IFR days used in this study did not feature rain or other events at DFW that inhibited the flow of traffic. The “4” notation indicates that all arrival runways were in use, as per normal operating conditions. The number of RNAV departures from DFW for each day was consistent. For nine days of the ten days, the range of daily RNAV departures was 773 to 810. The remaining day only had 561 RNAV departures, because it was Thanksgiving Day, November 27, 2008.

The decision to use very recent data when this study started meant that the ten days were all seasonally cooler days (about 30 to 60 degrees Fahrenheit). As temperature and humidity both adversely impact aircraft climb performance, a climb rate comparison using an eleventh day was performed. The details of this day and a convective weather day will be discussed in a later section.

Data available for this study included DFW ASDE-X (surface and low-altitude tracks collected from a mulitlateration system), DFW TRACON ARTS IIIe data, and ZFW Host data. The Surface Operations Data Analysis and Adaptation (SODAA) tool was used for data extraction and analysis [7].

Data and Analysis

The first of the sections that follow presents the DFW departure demand for the ten days studied, showing consistent operations. The next section describes the kinds of lateral variations observed in the data, followed by a discussion of departure altitudes at the TRACON boundary. The last two sections take departure sequencing into account. The first shows that the number of RNAV departures vectored is comparable to those encountering a reduced departure interval from RNAV departure implementation, while the last investigates possible correlations between vectoring and departure sequence.

Departure Demand

This section begins with an overview of the data, showing which RNAV departure procedures are most commonly used and any dependency on flow direction. Combining all of the RNAV departure data from the ten days listed in Table 1, Figure 6 shows the distribution of these flights by filed RNAV departure procedure. The eight-sided box reflects the general layout of the DFW TRACON boundary. The names of the departure fixes appear inside the figure, arranged in their relative location around the periphery. The length of the bar near each name represents the total departure demand for that departure procedure, and this total appears explicitly at the far end of each bar. Figure 7 shows the analogous depictions for these data on a daily basis, arranged by flow condition. The total RNAV departures for each date appear inside each box.

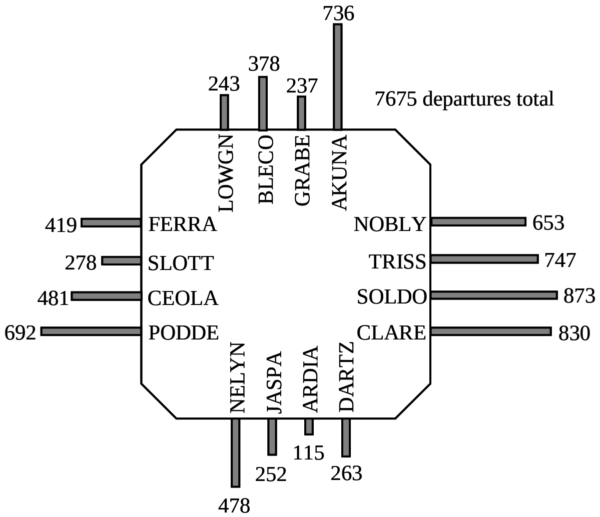


Figure 6. Departure Demand for Ten Days

Comparing Figure 6 to Figure 7 reveals that the distribution of total RNAV demand reflects the daily demand, and the individual diagrams in Figure 7 show little variation in this distribution due to overall traffic level or flow direction. Departures over six fixes (AKUNA on the north gate, NOBLY, TRISS, SOLDO, CLARE on the east gate, and PODDE on the west gate) comprise just over half of the total. The eastern gate sees a consistently higher demand than the other gates, reflecting the heavy traffic for cities to the east, while demand for the southern gate (and in particular, ARDIA) is the least. D10 used four departure fixes per gate prior to the implementation of the RNAV procedures, so that the number of gates per side and their spacing were not influenced by departure demand. The disparate demand seen for PODDE and AKUNA relative to other same-gate fixes reflects the current mix of traffic. The increase in regional jet operations has changed the allocation of departures to these fixes over time.

In general, the demand for each departure procedure is consistent across the ten selected days. Variations in which aircraft are vectored from their routes will likely not depend on a change in demand for particular routes. Traffic patterns on days where convective weather or other events possibly impacted TRACON traffic can be compared to these distributions to quickly assess how departure demand for that event shifts from the "typical" distributions shown here.

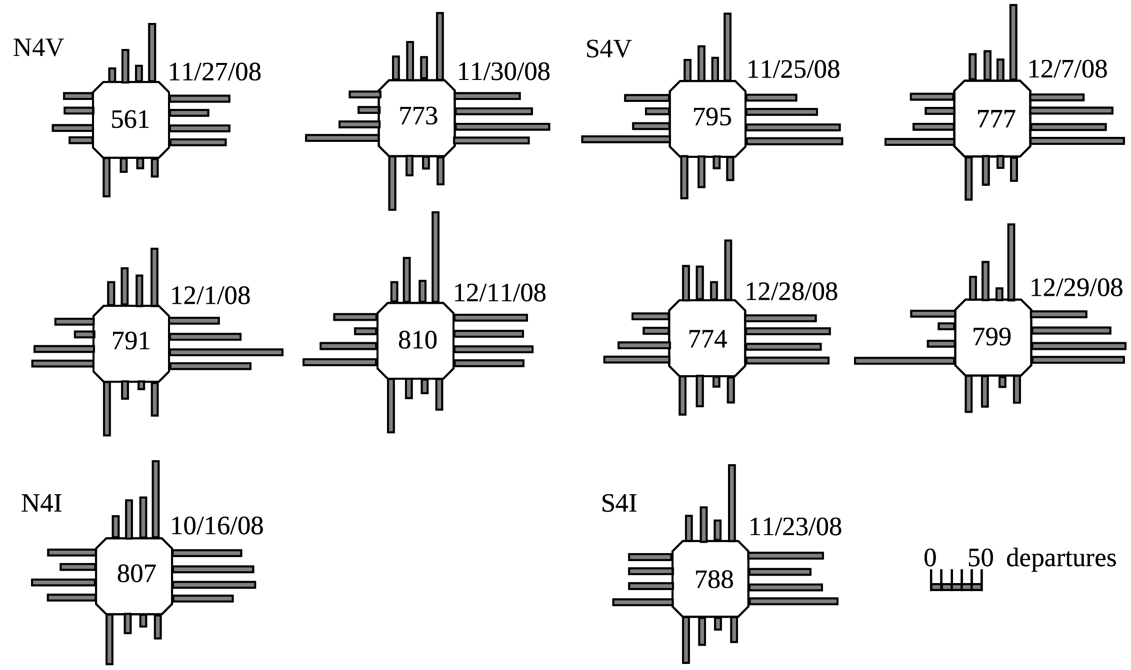


Figure 7. Demand by Date and Airport Configuration

Lateral Distribution of Tracks

In studying lateral variations of the traffic from the published RNAV routes, the off-route departure tracks (that is, tracks well outside the one nautical mile bound defined in the RNAV procedures) were categorized into three groups for expediency. First, some tracks passed to the inside of turns in the RNAV routes, shortening the distance traveled or bypassing fixes altogether. Other tracks did not pass over the TRACON boundary fix listed in the procedure, instead leading directly to a fix beyond the TRACON. A third category consisted of tracks inside the TRACON that were longer than those defined in the procedures, executing wider than expected turns. In this section, these departure variations will be tallied for each day of the study and discussed. Note all of these tracks fall from a half-mile to several miles from the expected location. Also, a few tracks fit more than one category (for example, an aircraft flew a route that bypassed a fix within the TRACON, returned to the RNAV route, and then bypassed the fix on the boundary). These aircraft were counted in each applicable category, but appeared infrequently enough that "double counting" did not significantly alter the trends in the data.

Shortened Routes

Using the same kind of "box and bar" presentations as in Figures 6 and 7, Figure 8 shows the number of aircraft that flew a route shorter than that defined in the RNAV procedure. These plots (with dark gray bars) are superimposed over a lightened version of Figure 7 so that differences in demand become readily apparent. The number of shortened departure tracks and its percentage of the total RNAV departure demand for that day appear in the center of each box. The aggregate number of departures in this category is 1,902, or 24.8% of the total departures.

Airport flow direction impacts the chance of flying a shortened departure route. 13% to 27% of the RNAV departures in north flow flew a shortened route, while 26% to 36% of the south flow departures have this characteristic. In north flow, the routes to the northern fixes on the east and west gates (NOBLY and TRISS on the east side, FERRA and SLOTT on the west) receive a disproportionate share of these "direct to" vectors– 367 out of 697, or 52.7 %. In south flow, this condition applies to SOLDO and CLARE on the east side and PODDE and CEOLA departures on the west side. The proportion of short cuts for these routes is even greater in this case (801 out of 1205, or 66.5%).

As noted before, these direct flights were to be granted by the controllers "whenever possible," specifically on the longer east-west routes [5]. Figure 8 shows not only that this is frequent, but that it also applies to all of the RNAV procedures. The controllers' perceptions of providing the best service

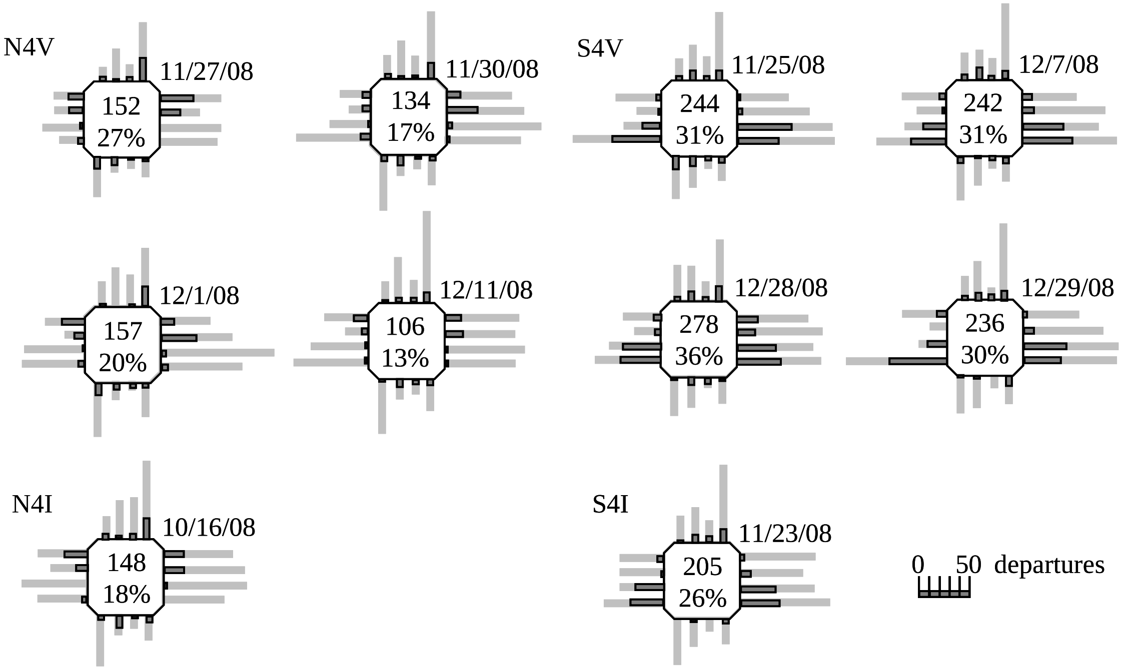


Figure 8. Departures That Flew a Shortened Route

have led to shortening departure routes whenever possible.

Aircraft crews can easily accommodate these kinds of changes because the controllers clear the aircraft directly to fixes that are already part of the RNAV procedure route; the crew simply removes the fixes to be bypassed from the route in the Flight Management System (FMS). The aircraft will fly to the designated fix and fly what remains of the route with the same precision specified in the RNAV procedure, and this expectation allows the air traffic controller to quickly assess the modified route for conflicting aircraft. The controller can issue this change with a minimal amount of verbal communication.

Examining the south flow cases first, and revisiting the routes shown in Figure 2, most of these tracks for CLARE, SOLDO, PODDE, and CEOLA fall three to five miles inside the turn that the procedure defines, and often fall on the common portion of the route that the northern and eastern RNAV procedures use (in these cases TRISS, NOBLY, AKUNA, and GRABE for the east side of the airport, SLOTT, FERRA, LOWGN, and BLECO for the west). The tracks for PODDE in Figure 4 illustrate this clearly. The pairs CLARE/SOLDO and CEOLA/PODDE have a portion of their route in common, so that one geometric shortcut can apply to each pair of procedures. Shortened routes are significantly less common for NOBLY, TRISS, SLOTT and FERRA because turning these aircraft inside their RNAV route could bring them into conflict with descending arrival traffic. These arrivals pass between this portion of the RNAV route and DFW, heading north (the “downwind” leg), before turning 180 degrees and acquiring the final approach into DFW. Typically these east- and west-gate departures reach 10,000 feet near these turns, and controllers must hold them at that altitude because DFW arrivals from the southeast and southwest descend and hold 11,000 feet in the same area before turning north.

The mirror image of these routes and the limiting effect of the DFW arrival traffic also appear in the north flow plots. The data show, however, that fewer shortened tracks appear in north flow. This is not only true for the total number of flights, but appears also in a smaller percentage of departures to the east receiving these short cuts (NOBLY and TRISS) as compared to the west (SLOTT and FERRA). In north flow, departures from DAL, which lies a few miles east and slightly south of DFW airport and has runways which are aligned northwest and southeast, climb and turn in the same vicinity as DFW flights that could potentially fly a shortened route. This is not the case in south flow, where DAL departures would generally fly below the DFW departures turning from south to east. Note that NOBLY and AKUNA tracks have proportionally more of these short cuts on November 27, which might reflect a reduction in DAL departures. The impact of DAL traffic must be more carefully studied in the development of DFW departure models.

Shortened tracks for departures through the north and south gates show less consistency with flow direction. Intuitively, the relatively short distance to the TRACON boundary and the straight routes to the boundary fixes limit opportunities for shortening the routes for south-bound flights in south flow and north-bound flights in north flow. Nonetheless, AKUNA departures receive a number of shortened routes in north flow, probably as a result of controllers perceiving that this action provides the best service.

From 19% to 29% of departures to the gate opposite the flow direction, for example RNAV routes leading to the north gate in south flow, benefit from shortened routes. As mentioned before, arrival traffic usually prevents controllers from tightening the large turn in these RNAV routes. Once these departures are past the arrival traffic, however, the controllers can clear the aircraft to bypass a few of the remaining fixes on the route, as illustrated in Figure 3. The reduced track length is more significant than that for an east- or west-bound departure. Frequently this kind of route change is coupled to an early handoff of the aircraft from the TRACON controller to an ARTCC controller, as discussed in a later section on altitude. This is consistent with the direct routing envisioned in the design of the procedures, even though the intent was to improve service for the dominant east-west departures, not the north-south routes [5].

In summary, which departures receive shortened departure routes depends on flow direction, in combination with distance from runway threshold to TRACON boundary. The arrival traffic streams and the proximity of departure traffic from other airports also limit opportunities for controllers to shorten these routes. Over time, the air traffic controllers have found frequent opportunities to reduce the distance RNAV departure aircraft fly in the TRACON. Actual benefit in terms of time saved would be difficult to determine without other information, such as wind, maneuvers to avoid potential conflicts, and detailed climb data.

Bypassed Boundary Fixes

Figure 9 shows how the number of aircraft that bypassed the fixes on the boundary of the TRACON compares to the daily RNAV departure demand. In these cases, controllers are clearing aircraft to fixes on their filed route that are beyond the boundary of the TRACON. Akin to direct routing when aircraft are in enroute airspace, this premature termination of the RNAV procedure results in a shortened route overall and potential time savings. After receiving handoff from the TRACON, the ARTCC controller can provide conflict-free direct routing in these cases.

The data indicate that 11% to 16% of RNAV departures in north flow bypass fixes on the TRACON boundary, while 6% to 11% of these departures receive this potential benefit in south flow. The total number of departures that fit this category is 775, which is 10.1% of the operations over the ten days. North-gate departures in south flow and south-gate departures in north flow appear to benefit the most often. Within D10, all of the north and south routes are longer than those going east and west, which allows the aircraft time to climb. As a result, the majority of these aircraft climb out of TRACON airspace (17,000 feet) before crossing the TRACON boundary. The higher demand for the northern routes might account for the greater percentage of direct routings outside the TRACON. These flights are flying longer distance to major cities north of the Dallas/Fort Worth area. Flights to the south are generally going to other cities within Texas, and this might limit the opportunity for ZFW-issued direct routes.

One consistent exception to the north-south departure trend benefit is that PODDE departures in north flow often receive direct routing to fixes west of the TRACON. These routing opportunities are probably available because this airspace is less crowded than its counterpart to the east. This kind of direct routing may have been unanticipated in the initial design of the RNAV routes (or at least has gone unmentioned), and once again illustrates perceived service improvement evolving from a somewhat different traffic management concept.

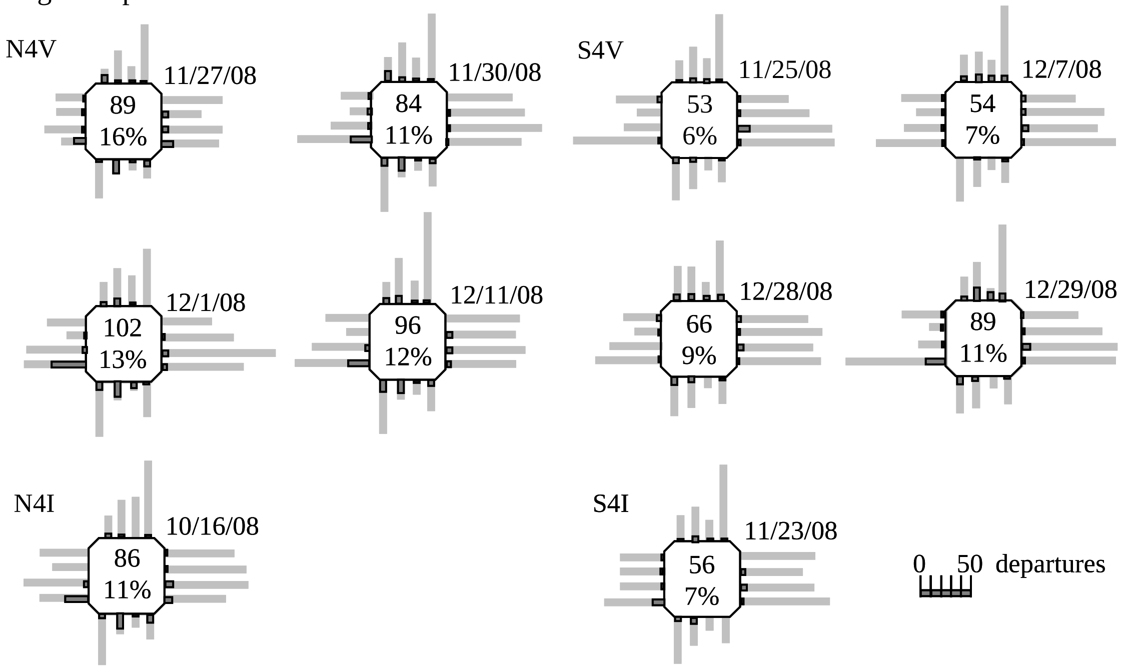


Figure 9. Departures That Bypassed Boundary Fixes

Extended Routes

Figure 10 covers the last set of lateral track data, those aircraft that flew routes longer than those defined in the RNAV procedures. The figure shows that 0.4% to 3.1% of the daily departures were affected, but no consistent trends associated with flow direction or with filed procedure appear. Over the course of ten days, 104 aircraft flew extended routes, or 1.4% of the total number of RNAV departures.

Detailed examination of the track data revealed that some of the aircraft sent on these extended legs and wide turns (in particular, aircraft heading for the north gate in south flow and the south gate in north flow) were climbing more rapidly than departures on the same route ahead of them. Once clear of overhead arrival flows, directing the higher-performing aircraft to the outside of the route allows them to climb unimpeded, without overtaking aircraft ahead of them. Therefore, the greater distance flown is traded off against a more rapid (and possibly uninterrupted) climb.

Other than noting their existence, it is difficult to assess exactly what events were causing aircraft to take these actions. In terms of modeling, these might be considered "in the noise", depending on the level of simulation fidelity.

Altitude Profiles

Unlike the one nautical mile bound on lateral tracking, the RNAV departure procedures specify only minimum altitudes for each portion of the route inside the TRACON. Altitude limits are left to the controller to specify based on other traffic and the altitude limit of the sector. The TRACON controllers ask the crews to contact ZFW at approximately 14,000 feet, and ZFW generally takes the handoff of the departing aircraft between that altitude and 17,000 feet.

The ten days of departure data revealed that all the aircraft quickly climbed upon departing DFW, and in fact the minimum altitude specified in the RNAV procedures was never an issue. The majority of the departures to the east and west gates climb to 10,000 feet, hold this altitude until past the stream of arrival traffic above them at 11,000 feet, and then continue to climb. Most departure aircraft, passing vertically through the upper limit of TRACON control, have been handed off to ZFW before cross-

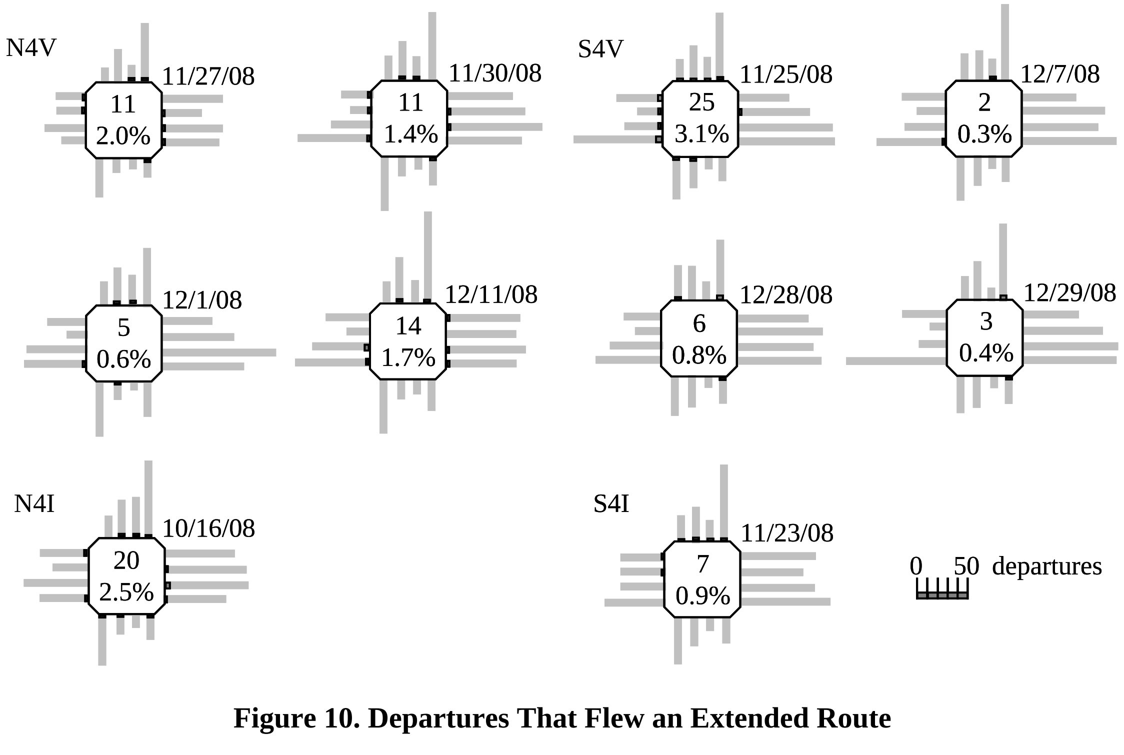


Figure 10. Departures That Flew an Extended Route

ing the sides of the TRACON itself. An altitude distribution typical of east- and west-gate departures for all ten days of collected data appears in a histogram in Figure 11, which shows the altitudes of PODDE departures at the point these aircraft tracks passed nearest that fix. The dashed line at 17,000 feet represents the vertical limit of TRACON control. 87% of these aircraft are at or above 17,000 feet in this figure.

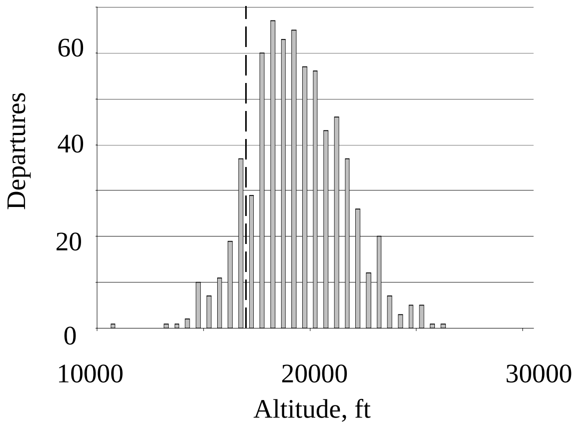


Figure 11. Departure Altitudes at PODDE Fix

Altitudes for departures through the north and south gates show variation with direction of the flow. Figure 12 shows a bimodal distribution for AKUNA departures, which is typical for the north and south departure procedures. 53% of the departures are at or above 17,000 feet upon reaching AKUNA in north flow, but 96% are at or above this altitude in south flow. The south flow departures climb over a greater distance and for a greater amount of time than the north flow departures before reaching the north boundary of the TRACON. These data reinforce the point that the north and south departures that bypass the TRACON boundary fixes are receiving flight plan amendments from the ARTCC controllers who are providing direct routing through the surrounding enroute traffic.

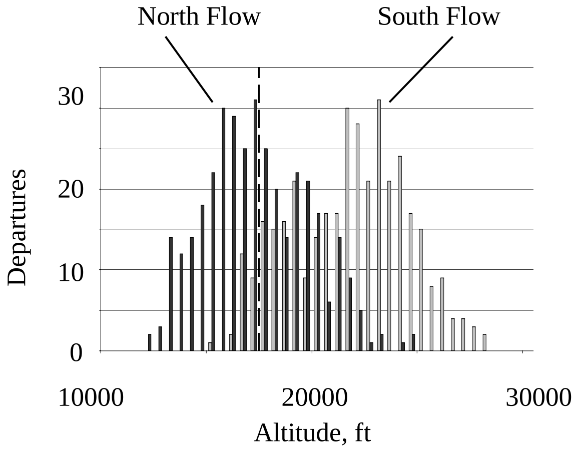


Figure 12. Departure Altitudes at AKUNA Fix

Frequency of Vectoring Compared to Divergent Heading Departures

As stated earlier, decreased time between takeoffs, as enabled through RNAV departures using divergent headings, is one benefit of these operations. This section will attempt to assess how many divergent heading operations associated with RNAV implementation actually occur, to determine how the number incidents of vectoring incidents compare. Measuring the impacts of each feature to operations is beyond the scope of this work.

An aircraft about to use a divergent heading departure can cleared for takeoff as soon as the departure that just used the runway is airborne and one nautical mile (6000 feet) ahead [8]. Taking advantage of ASDE-X surface data and SODAA, the departure sequence and the time between aircraft to cross the end of the runway was extracted from the ten days of collected data. Filed RNAV departure plan was the basis for determining if a subsequent departure was on a diverging or non-diverging departure heading. Figure 13 shows the aggregate result. Given no incidents involving loss of separation in the data, it must be assumed that the controllers were releasing these aircraft with the proper spacing, no matter how small the time between some of the departures.

Starting from the right of the Figure 13, the departures in each ten-second block consist of a roughly equal mix of aircraft on divergent and non-divergent headings, until the time between departures drops to 2:40. This amount of time between departures is so large that departure heading is of no consequence. From this point, the non-divergent departures peak with 1:50 between them. More departures with less time between them represents an increase in takeoff demand, but the departure sequencing here might reflect an insufficient "mix" of departures to warrant alternating based on departure heading, or perhaps enough space develops between departures that it still is not necessary to alternate departures. From this point, non-divergent heading operations decrease as the divergent heading departures reach their own peak at one minute, implying that further reductions in time between departures necessitates divergent heading operations.

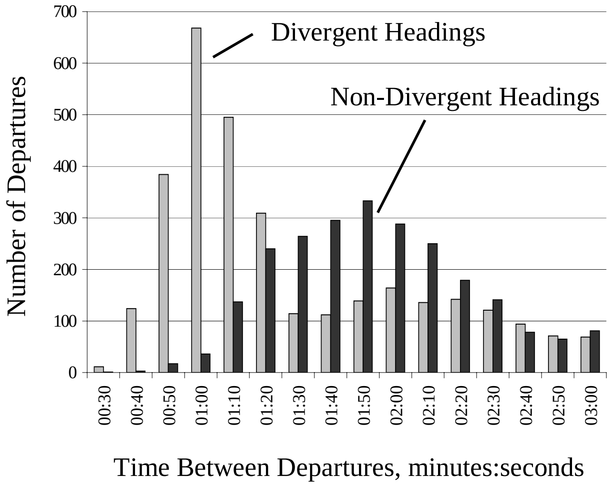


Figure 13. Impact of Departure Sequence

One interesting feature is that these histograms cross somewhere between one minute twenty seconds and one minute thirty seconds. Equal numbers of departures on divergent and non-divergent headings are taking off with this time interval between them. Also noteworthy is that some departures on non-divergent headings are still occurring with one minute between them, although the numbers are relatively small. One way of quantifying the reduction in time between departures attributable to implementation of RNAV procedures and the aircraft so affected is to base the assessment on this crossover point. In other words, assume that the time interval reduction attributable to the use of divergent heading departures is the difference between each time interval and this crossover point, about one minute 25 seconds. If all the divergent heading departures to the left of this point in Figure 13 were feasible because of the RNAV departure procedures, 1,991 aircraft from the ten days analyzed, or 25.9% of the departures, had a total of 45,295 seconds reduced in time between them, an average of 23.4 seconds.

In this analysis, the number of aircraft receiving reduced time between departures because of the RNAV departure operations is comparable to those receiving direct routing in the TRACON airspace (1,902 departures). While the potential benefits are altogether different (departure throughput for the former, reduced distance flown in the latter), both features of these departures impact a significant and nearly equal number of operations. Clearly the vectoring that occurs in the course of RNAV departures is worth studying in greater detail in both current and future work.

Departure Volume and Sequence

Given the number of RNAV departures that are vectored, the following analysis examined the departure sequencing to determine if this influenced the way controllers handled the aircraft in flight. This study attempted to determine if aircraft were vectored to avoid overtakes, or if the sequencing of the departures determined which aircraft received shortened routes.

From the ten days of data collected, groups of departures on non-divergent headings that departed two minutes or less apart were studied. 2,799 departures met these criteria.

As this was an exhaustive track-by-track examination and little change was observed in the tracks, time limited the analysis to the first three days of data. This yielded 837 aircraft in 341 groups, or 30% of all the departures that met the criteria.

The tracks were categorized in a manner similar to those in Figures 7 through 10. Additional categories were introduced to note whether a vectored departure was the first of a group, or a departure following another aircraft of the same group. Any aircraft that might have been directed away from the route because of possibly overtaking of a previous departure were also noted. A summary of these data appears in Table 2.

The majority (68.8%) of these departures flew non-vectored RNAV departure routes. The proportion of departures that flew shortened routes (23.4%), bypassed boundary fixes (5.5%), and flew extended routes (2%) are all within the ranges seen in the full ten day set of collected data. Only two aircraft appeared to have been vectored away from their RNAV route to avoid an overtaking a slower departure ahead of them, an insignificant number. Additionally, the first aircraft in a group of departures appears to have no better chance at flying a shortened route than the other aircraft in the same group.

Table 2. Impact of Departure Sequence

	Number of:			Shortened Route		Bypassed Boundary Fix		Extended Route		
Date	**Groups**	**Aircraft**	**Non-Vectored**	**First**	**Later**	**First**	**Later**	**First**	**Later**	**Overtake Avoided**
10/16	128	319	250	20	21	13	9	2	3	1
11/23	115	281	183	36	43	6	8	1	3	1
11/25	98	237	143	40	36	5	5	3	5	0
Total	341	837	576	96	100	24	22	6	11	2

These data show that, given the current state of procedures and demand at DFW, the sequence and frequency of departures from a particular runway have virtually no impact on whether or not a departure is vectored from its route. This implies that the airborne traffic (arrivals, merging departures from other airports) plays the key role in determining the opportunity for vectoring an RNAV aircraft, and not other aircraft executing their RNAV departures.More importantly, the characteristics of the departures that are vectored appear unaffected by departure volume. At the higher level of departure demand, the controllers are still providing the same kind of vectoring to the RNAV departures that they do in lower volume periods.

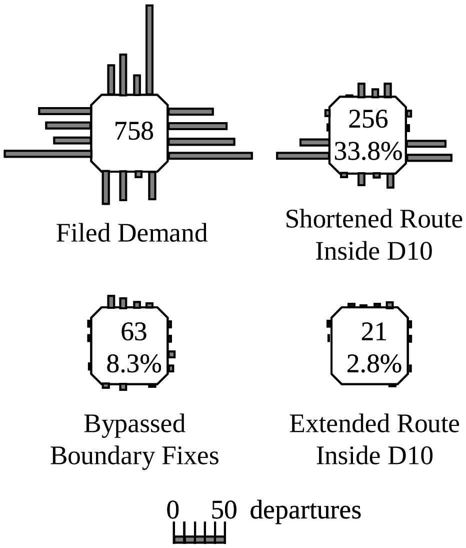
In terms of future system design for the terminal airspace, nothing in these data indicate the volume itself would alter the tendency of the air traffic controllers to change the way they handle precise departures. The observed vectoring is a means to attempt better service, and not to prevent loss of separation.

Weather Effects

This section discusses the impact that environmental conditions have on RNAV departure operations. Given weather variability, the results in this section should be regarded as qualitative descriptions of how the trajectories change, rather than definitive results applicable to all scenarios.

High Temperature

As noted previously, the data initially collected for this study included cool fall and winter days. Temperatures on June 27, 2009, however, reached 105 degrees Fahrenheit, with moderate humidity. DFW remained in a south flow configuration throughout the day, so it provided an opportunity to examine the effect of density altitude on the departure operations. Figure 14, covering the 758 departures that day in the format of Figures 7 through 10, shows that the distribution of RNAV departures and the number of flights vectored are comparable to the five south flow days previously studied. Altitude data, however, revealed that aircraft were reaching 17000 feet, the vertical limit of TRACON authority, about five miles further along their departure routes compared to the "cool weather" data, a result of heat reducing climb performance. This implies a delayed handoff from TRACON to ARTCC compared to the previous data for rapid-climbing aircraft. While this point is important for trajectory modeling, Figure 14 shows the temperature had no real impact on departure operations.



Filed Demand

Shortened Route Inside D10

Bypassed Boundary Fixes

Extended Route Inside D10

Figure 14. Departure Operations on a Hot Day

Convective Weather

June 29, 2009 was an unusual day that featured convective weather in and around D10. Despite storms that developed north of DFW airport in the morning hours and moved to the east, they did not pass over the airport. Consequently, DFW maintained an unimpeded north flow configuration throughout the day, but controllers did have to vector traffic around convective weather.

Figure 15, again in the form used previously in this paper, illustrates how the RNAV departures were vectored in the DFW airspace. This figure differs from the others in two ways. First, the day was split into five sections. The early morning hours (5:00 to 10:59 UTC) were excluded because the number of flights was insignificant. The remaining four sections illustrate the actions of the controllers in responding to the moving storms. Secondly, some data fell into a category that was unnecessary for the other analyses; specifically, some aircraft that filed procedures for one gate of the TRACON actually left the TRACON over a different gate. These extensive changes show the difference in what procedures were available when flight plans were filed versus what procedures the controllers had to exclude because of the weather at the time of takeoff. Some of the departures in this new category might not truly be using RNAV procedures at this point, but they are included as the procedures appeared in their flight plan. One consequence of splitting the day in this manner is that some departures are counted in more than one section. For example, an aircraft that is airborne twelve minutes before the end of one split but still in the TRACON for the following split actually appears in each segment. Therefore, numerical comparisons should be limited to diagrams within each time slice (that is, reading across the figure). Qualitative changes in the traffic, however, can still be read from one time slice to the next. The percentages that appear in each diagram are based on the number of departures in that time segment alone.

The day commenced with storms to the north of the airport, near the Red River valley (the border between Oklahoma and Texas). Figure 16 illustrates the movement of the storms for selected times of the day. The 11:00 to 14:59 UTC section of Figure 15 shows that, of the flights departing to the north, none flew a shortened route; most were vectored to fixes beyond the TRACON boundary, and a significant proportion of the AKUNA departures were actually sent to a different gate (east). More east and west departures bypassed the transition fixes on the TRACON boundary compared to typical conditions, while departures to the south were unaffected. This

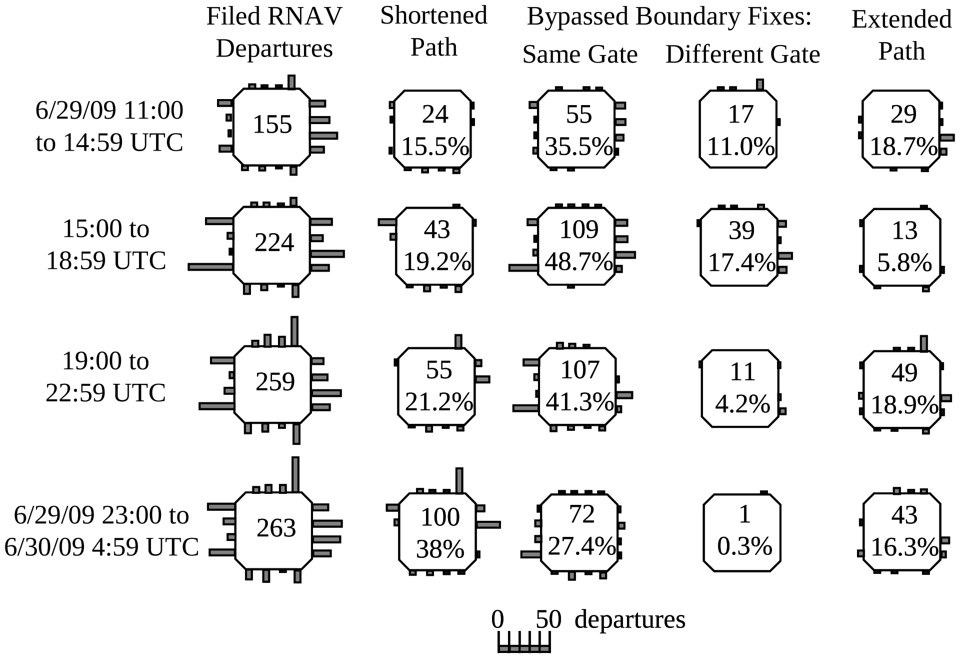
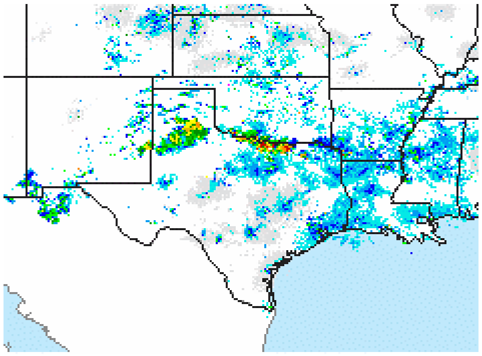
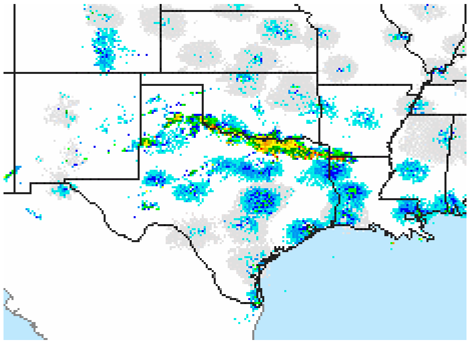


Figure 15. Impact of Convective Weather

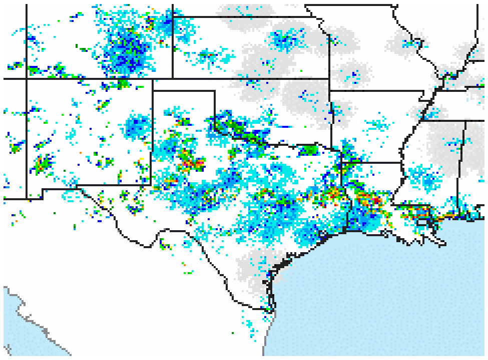
reflects how controllers compensate for the movement of the storm. If convective weather appears over a boundary fix, aircraft are typically directed to other fixes on the same gate. Should weather develop that blankets all the fixes on a boundary of the TRACON, controllers will send the aircraft to an entirely different gate while minimizing the distance added to the route.



1300 UTC



1600 UTC



2000 UTC

Figure 16. Weather on June 29, 2009 [9]

Between 15:00 and 18:59 UTC, Figure 16 shows that the storms moved to the northeast and east of the airport, and both the north and east gate departures were being vectored away from the boundary fixes. Controllers sent a number of east gate departures to the south gate in response to both weather and demand. The next time section shows that weather still impacted departures through the east gate, but proportionally more traffic was able to leave through these gates. Normal operations resumed in the last time segment as the storms dissipated.

This example illustrates the dynamic response of the controllers to changing weather. These kinds of actions are typical; yet predicting the percentage of flights affected in such a situation would require a detailed analysis of current and predicted storm position.

Conclusions

While the original design of the DFW RNAV procedures made increased departure throughput its goal, aircraft direct routing within D10 was anticipated as a means to shorten some of the departure routes. Controllers have acted upon this operational consideration, and in the execution of the procedures today as many aircraft receive direct routing as those that encounter reduced time between departures. To summarize the data examined:

- Approximately one out of three RNAV departures will be directed away from a portion of the route in the TRACON. Most of these (about 25% of all departures) result from the air traffic controllers attempting to shorten flight distances by providing direct clearances that bypass fixes along the route.
- About 10% of the RNAV departures bypass fixes on the TRACON boundary. These aircraft are receiving direct routing, often from ARTCC controllers, to fixes on their route beyond the TRACON.
- Aircraft vectoring is generally done to shorten the RNAV departure routes, and as opportunities in the airborne traffic allow. Presently, its occurrence does not vary with departure volume.
- Extensive vectoring occurs when convective weather closes fixes on the TRACON-ARTCC boundary.

Consequently, future automation tools attempting to benefit from the RNAV departure procedures currently in place cannot presume that aircraft transitioning to ARTCC airspace are following the RNAV routes. Rather, the tools must provide flexibility to account for air traffic control decisions that attempt to take advantage of opportunities for a perceived service benefit.

Future RNP-dependent concepts anticipate operational innovations, as the evolving RNAV operations at DFW illustrate by example. Allowing flexibility not only for traffic volume and convective weather, but also for human ingenuity in exploiting the technology used in new procedures promotes ideas for possible follow-on airspace management concepts.

Areas for future work derived from this study include assessing the possible benefits associated with the direct-to routings in the TRACON. Eventually, these benefits could be traded off against particular departure sequences, predicted arrival traffic, and the presence of convective weather.

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