

Benefits Analysis of Multi-Center Dynamic Weather Routes

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Dynamic weather routes are flight plan corrections that can provide airborne flights more than user-specified minutes of flying-time savings, compared to their current flight plan. These routes are computed from the aircraft's current location to a flight plan fix downstream (within a predefined limit region), while avoiding forecasted convective weather regions. The Dynamic Weather Routes automation has been continuously running with live air traffic data for a field evaluation at the American Airlines Integrated Operations Center in Fort Worth, TX since July 31, 2012, where flights within the Fort Worth Air Route Traffic Control Center are evaluated for time savings. This paper extends the methodology to all Centers in United States and presents benefits analysis of Dynamic Weather Routes automation, if it was implemented in multiple airspace Centers individually and concurrently. The current computation of dynamic weather routes requires a limit rectangle so that a downstream capture fix can be selected, preventing very large route changes spanning several Centers. In this paper, first, a method of computing a limit polygon (as opposed to a rectangle used for Fort Worth Center) is described for each of the 20 Centers in the National Airspace System. The Future ATM Concepts Evaluation Tool, a nationwide simulation and analysis tool, is used for this purpose. After a comparison of results with the Center-based Dynamic Weather Routes automation in Fort Worth Center, results are presented for 11 Centers in the contiguous United States. These Centers are generally most impacted by convective weather. A breakdown of individual Center and airline savings is presented and the results indicate an overall average savings of about 10 minutes of flying time are obtained per flight.

I. Introduction

DURING convective weather events, aircraft are routed around weather cells by the Federal Aviation Administration (FAA) traffic managers. Often, these reroutes introduce large deviations from the nominally filed flight plans. Some of the reroutes may have been imposed four- to six-hours before the flight gets near the constrained location, and often are either unnecessary or excessive as the weather and traffic conditions evolve. Dispatchers planning the flight an hour and a half to two hours before departure time (with less accurate weather information) may file some of these routes with larger than necessary deviations around forecasted weather. It is possible to find shorter routes for some of the flights once airborne, which can result in significant savings of time and fuel for the flight operator. To do so would also be beneficial for the environment due to reduced emissions. The Dynamic Weather Routes (DWR) automation has been developed and tested for Fort Worth Center (ZFW), as presented in McNally et al.¹, and Sheth et al.^{2,3} McNally et al.¹ developed DWR for near-term, trajectory-based

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operations. In that research, the benefits of removing excessive deviations from filed flight plans and sending flights on more direct routes while avoiding forecasted convective weather regions are presented. The DWR concept uses ground-based automation to automatically identify simple amendments to en route flight plans that can save a user-specified number of flying minutes by implementing more efficient routes around convective weather. More details on the DWR automation are provided in Section II.B. The airline would benefit from the smaller deviation around weather for fuel and time savings, and improved schedule integrity.⁴ The air traffic manager would find this beneficial during severe weather events because regions of airspace in the vicinity of weather become congested. Sheth et al.^{2,3} demonstrated that the proposed weather avoidance concept helps alleviate congestion by directing some flights along dynamically generated weather avoidance routes, and reduces environmental impact of flights. However, this work has focused on one Center and the benefits of DWR automation at a national level have not been analyzed.

In this paper, a multi-Center benefits analysis is presented for such weather avoidance routes. Using the Future ATM Concepts Evaluation Tool (FACET), a National Airspace System (NAS)-based simulation and analysis tool, first, a comparison of number of flights and time savings results for ZFW are presented. Second, results are presented for 11 Centers, which are generally most impacted by convective weather. Lastly, an alternate method is presented for treating all the Centers together based on current day operational procedures. In this last case, dynamic weather routes spanning across several Centers can be handled simultaneously providing larger potential time savings, rather than treated individually for each Center independently as in the second case.

The rest of the paper is as follows. Section II briefly presents the Dynamic Weather Routes operational concept and the automation process. In Section III, the NAS Constraint Evaluation and Notification Tool (NASCENT) automation based on FACET, is described. Section IV describes the differences between the Center-based DWR and NAS-based NASCENT automations. A comparison of results between DWR and NASCENT is presented next in Section V. The benefits analysis results for 11 Centers using NASCENT are presented in Section VI. Section VII describes an alternate method for handling multiple Centers. Some concluding remarks are presented at the end.

II. Dynamic Weather Routes (DWR)

A. Operational Concept

DWR, a trajectory automation system developed earlier, continuously analyzes airborne flights in en route airspace to find time and fuel saving corrections to inefficient convective weather reroutes. The system could help airline dispatchers and FAA traffic managers and controllers find more efficient routes around convective weather. Simple weather avoidance routes (or dynamic weather routes) are automatically proposed to an airline dispatcher and updated every 12 seconds using the DWR automation. DWR is an integrated system with the Center-TRACON Automation System (CTAS)⁵ and the Future ATM Concepts Evaluation Tool (FACET).⁶ Flights that can save more than a user-specified amount of wind-corrected flying time, e.g., five minutes, using a reroute, are posted to an advisory list on the dispatcher's display. An interactive trial planner function enables users to visualize the proposed reroute, modify it if necessary, and evaluate critical parameters such as potential flying time savings, proximity to current and predicted weather, traffic conflicts, downstream sector congestion, Special Activity Airspace (SAA) traversal, and FAA imposed reroutes. The last three are computed using FACET. The DWR system is ideally suited for air/ground data link communication but can be used with current operational procedures.

The three main assumptions of the DWR system are as follows:

1. It is not always necessary to fly a weather avoidance reroute completely as planned. If weather has changed, or a more efficient route around weather exists, then flight crew could request a reroute.
2. Airline dispatchers, FAA traffic managers and controllers are busy during weather events, and without automation, might not notice opportunities for more efficient weather avoidance routes.
3. Named fixes or waypoints may be communicated by voice, but auxiliary waypoints defined in fix-radial-distance (FRD or latitude/longitude) format are prone to voice communication error and should be communicated only via data link.

The DWR automation has been running live at American Airlines' Integrated Operations Center in Fort Worth, TX since July 31, 2012. The field test evaluation and the automation process are described in McNally et al.⁷ The environmental emissions reduction and other benefits of DWR were presented in Sheth et al.⁴

B. DWR Automation Process

In Figure 1 below, the solid line shows the current active flight plan that the aircraft is flying on. The middle dotted line is the reference route between the current location of aircraft and a downstream return capture fix. The dashed line is the newly created DWR with one auxiliary waypoint, which could be a fix-radial-distance (FRD) point (triangle) or a nearby named fix (filled circles). The integrated DWR system analyzes the current active flight plan for a “dog-leg” and looks for opportunities to reduce the travel time while avoiding forecasted convective weather model polygons. The process is described in detail in Refs. 1 and 7.

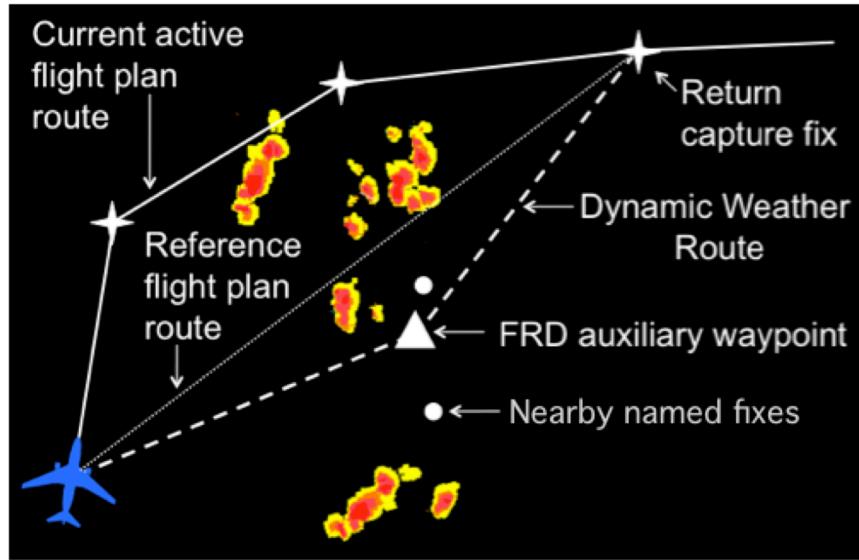


Figure 1. DWR automation schematic.

III. NAS Constraint Evaluation and Notification Tool (NASCENT)

In order to analyze the feasibility of dynamic weather routes, CTAS and FACET architectures were integrated for DWR automation. Both these software architectures have been in development at NASA Ames Research Center for many years. CTAS and FACET software are connected through an interface, which allows them to communicate bi-directionally to exchange flight plans, sector congestion and other relevant information.

CTAS is a high fidelity simulation environment handling aircraft within a single Center of the National Airspace System (NAS). FACET is a NAS-based medium level fidelity data analysis and simulation system. CTAS reads in FAA provided (12-second update) Center Host computer data, while FACET reads in FAA provided (one-minute update) Aircraft Situation Display to Industry (ASDI) or Enhanced Traffic Management System (ETMS)⁸ air traffic data. In order to study the benefits of multi-Center dynamic weather routes, the CTAS system would need to be run for as many Centers as the analysis was desired. This is a significant effort in maintaining, say 20 CTAS systems, as well as integrating data across the Center boundaries. Thus, the computations for creating dynamic weather routes across several Centers in the NAS were solely performed within FACET software, with new automation called the NAS Constraint Evaluation and Notification Tool (NASCENT). This system is not connected to CTAS.

NASCENT is the automation within FACET, used for the benefits analysis reported in this paper. NASCENT employs the NAS-wide simulation and analysis capability of FACET, along with weather avoidance algorithms therein. Henceforth, NASCENT will be referred to as an independent automation system, similar to DWR. For individual flights, NASCENT uses the aircraft performance tables specified by the Base of Aircraft Data⁹ for computing climb, cruise and descent trajectories. Similar to the original DWR automation, reference routes are created that save more than a user-specified number (e.g., five minutes) of flying-time savings. The return capture fix for the reference route is the last fix on the current flight plan within a limit region. These routes are checked against the weather avoidance polygons and auxiliary waypoints are added as necessary to avoid modeled weather. The wind-corrected flying-time savings are recorded for each flight.

Figure 2 shows the primary display for NASCENT. The main window at top left shows the Centers and state boundaries, the limit polygon (cyan) for Atlanta Center (ZTL), and some (yellow) convective weather polygons at the southeast corner of ZTL limit polygon. It also shows the current flight plan and the proposed time-saving route

for flight DAL928 in Denver Center flying from DEN to LGA. The ZTL limit polygon is displayed to demonstrate that analysis is being done in other Centers concurrently, while the flight (DAL928) in Denver Center is shown as being analyzed. The two windows on right show the sector congestion along the current flight plan (top) and the proposed route (middle) for DAL928. The small window below that shows an imposed reroute by the FAA for flights departing from DEN and arriving at LGA. The smaller window at bottom left shows the list of flights for which weather avoidance routes are proposed that save more than five minutes of flying time. The window at bottom right shows the Original (current), Reference, and NASCENT (proposed) route details for the flight.

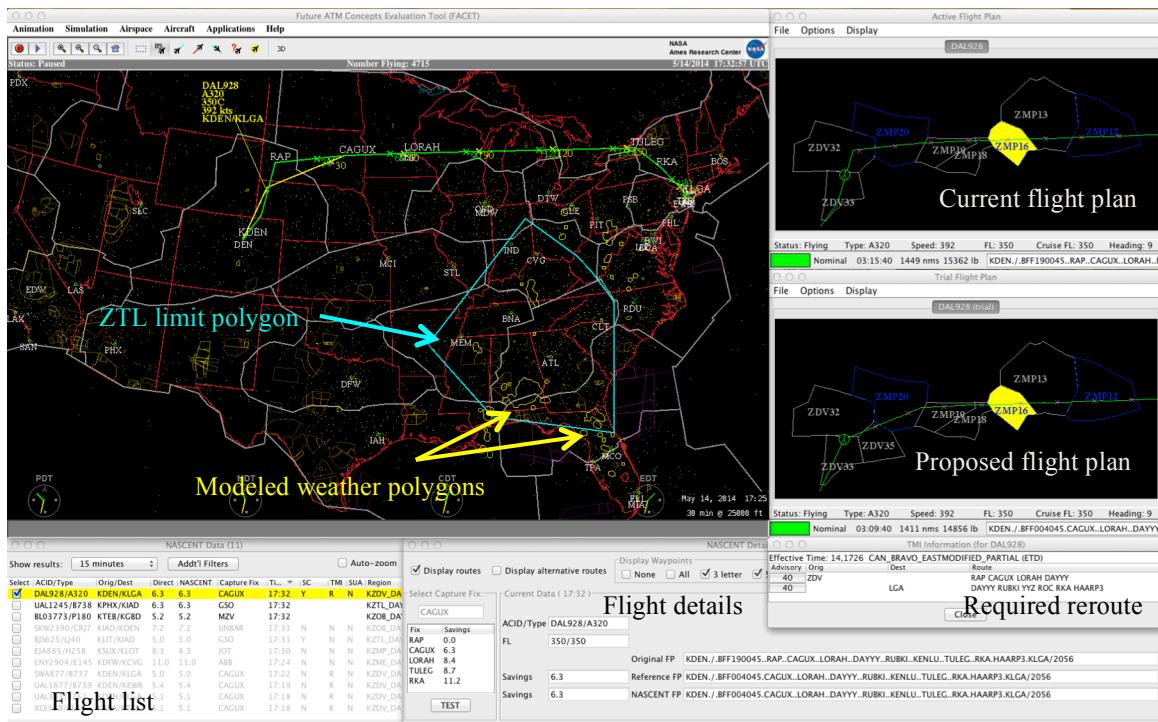


Figure 2. A snapshot of NASCENT display

IV. Differences between DWR and NASCENT

There are several differences between the way single-Center DWR and multiple-Center NASCENT automations work. The main differences include scope of dynamic weather route analysis (one Center vs. several Centers) and air traffic data rates (12-second vs. one-minute). For finding other Center dynamic weather routes, the differences are mainly in finding the capture fix and computing the weather avoidance routes. The different use of limit region to find the capture fix is described first and then the avoidance algorithm differences are presented next.

1. Computation of Limit Region

In the single-Center DWR automation, a limit rectangle is used to find the return capture fix for the reference route. A limit rectangle determines the furthest fix a controller is likely to send a flight direct to. For the Fort Worth Center (ZFW), this limit rectangle was created with about 200 nmi from each latitudinal and longitudinal minima and maxima from the ZFW boundary. To conduct benefits analysis for multiple Centers, a limit region for each Center is required. To achieve this, five months of plan data were processed. The size of the limit regions depend on how far downstream the direct clearances were granted by each Center within the five-months of data. Each flight plan in the data was searched to evaluate if a flight was given a direct clearance to a downstream fix. The format chosen for these direct clearances were of the form orig./.abc#####..pqr.lmn.....trf.star1.dest. Here, orig is the origin airport, abc##### is the fix-radial-distance (FRD) of the aircraft current position, pqr is the direct route cleared fix, lmn is another fix further downstream, trf is the transition fix (if present in flight plan), and star1 is the arrival route (if present in flight plan) from the transition fix to the destination airport, dest. These clearances were recorded for each Center. A list was created of how frequently each direct route cleared fix was used. The top 70%

of the most frequently used fixes from the list were used to create a limiting convex hull polygon. Again, the last fix on the flight plan within the limit polygons is used as the return capture fix for computing the reference route.

Figure 3(a) displays the original limit rectangle used for single-Center (ZFW) DWR automation and the convex hull limit polygon created using the approach just described. The vertices that make up the convex hull (e.g., ILC) are shown as well. In Fig. 3(b), convex hull limit polygons for Denver (ZDV), Cleveland (ZOB), and Atlanta (ZTL) are shown.

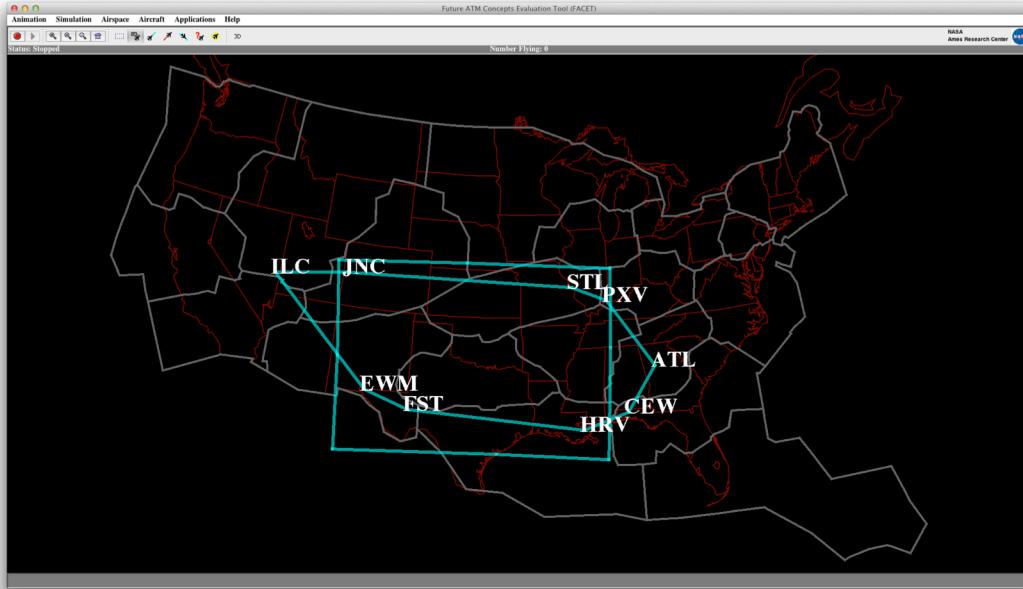


Figure 3 (a). Display of limit polygon and limit rectangle for Fort Worth Center. The corner fixes which make up the convex hull (e.g., ILC, EWM, PXV, etc.) are shown.

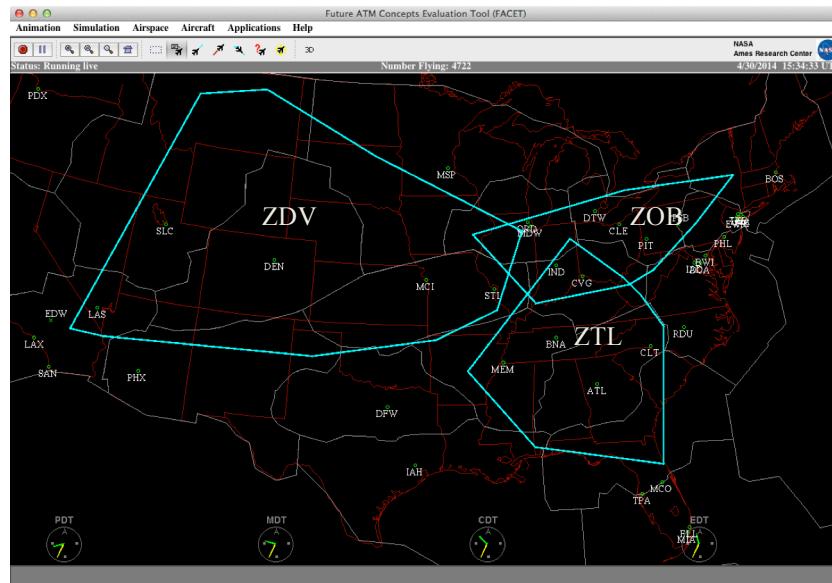


Figure 3 (b). Display of limit polygons for Denver (ZDV), Cleveland (ZOB), and Atlanta (ZTL) Centers.

Centers are shown. These polygons were created for each of the Centers in the NAS but just three samples are shown here for clarity. It is observed that due to the congested traffic within ZOB Center, the convex polygon is much smaller than the ZDV Center, where there is more flexibility for sending flights further out.

Even though the NAS-based analysis will be computed with the newly created limit polygons based on the five-month data analysis, a comparison was desired with the Center-based DWR computations to ensure consistency. This is described in Section V.

2. Weather Polygon Avoidance Algorithm

In the DWR automation, weather avoidance algorithm of the Automated Airspace Concept¹⁰ is used for ZFW. In NASCENT, the weather avoidance algorithm described in Sridhar et al.¹¹ was used with modifications. In the Ref. 11 algorithm, the first polygon in the flight's path was avoided but additional polygons downstream were not handled concurrently. In this research, a convex hull was formed around the first Convective Weather Avoidance Model (CWAM)¹² 70% pilot deviation probability weather polygon and was inflated by (user-specified) 20 nmi buffer at each vertex. For the DWR automation, the additional buffer was not applied because the CWAM model provides a probability of pilot deviation for storm intensity and height. In NASCENT, this buffer is used to be conservative and to implicitly include FAA required 20 nmi distance from weather. If any two inflated polygons in the flight's path (at the same altitude and the same forecast time) intersected, they were merged into a single polygon and a convex hull was created around the newly merged polygon. The avoidance algorithm created a route around this modified polygon.

If a flight was climbing, the NASCENT avoidance algorithm used the filed altitude weather contours for avoidance. This is a deviation from the DWR automation, which calculates avoidance routes based on polygons available at the current altitude and higher altitudes, as the flight climbs to flight plan altitude. If the current position of the aircraft or the capture fix falls within the temporally relevant CWAM weather polygon, no avoidance route is calculated. The DWR solution always has up to two added auxiliary waypoints. The NASCENT automation does not restrict the number of added auxiliary waypoints. However, in rare (less than fifty in over five thousand) cases, more than two waypoints were added, due to merging of intersecting weather polygons.

V. Comparison of DWR and NASCENT Results

The NASCENT system was run to play back recorded NAS-based real air traffic data and to compare it with DWR results. Thirty days with largest time savings proposed in DWR automation for ZFW were chosen. Data for 13 of the top 30 days were chosen for this analysis. The remaining days were not used due to either missing weather or air traffic data, or due to number of available flights for comparison. It should be noted that those 13 days had significant convective weather activity in ZFW and neighboring Centers. The 13 days were February 10, March 31, April 2, 10, 17, 18, May, 21, 24, 31, June 1, 6, 9, and September 28 of 2013. For each of those days, the data were run for a 24-hour period from 7 UTC to 7 UTC the following day.

All of the proposed dynamic weather routes for flights in ZFW were obtained from the DWR automation for the 13 days. Air traffic data were run in NASCENT and proposed dynamic weather routes for all flights in ZFW were recorded. Then, a comparison for each AAL flight was conducted between the two automations. It was observed that there were some flights captured in the DWR automation that were not present in the NASCENT system, and vice versa. However, there were a large number of flights common to both the systems, all of which were included in the comparison results. The flights that were not common to one or the other automation were classified in several categories to learn the differences between the two systems. The uncommon set of flights was due to several reasons. These are:

- different flight plan and update rate issues of ASDI (one-minute) vs. Host data (12-second),
- differences in handling by the avoidance algorithms,
- avoidance of weather at current vs. filed altitude (as noted earlier),
- minor difference in the selection of limit rectangle due to spherical and projected coordinate systems,
- few instances of differences in modeling of climb trajectories,
- presence of temporary altitudes in Host data used in DWR,
- occasional modification of minimum flying-time savings from five minutes to a different value,
- ignorance of flight if the current position is inside a weather polygon (in NASCENT), and
- absence of a ‘maneuver start point’ feature (in NASCENT).

An example of the weather avoidance routes observed within DWR and NASCENT is shown in Fig. 4. A flight, AAL980 going from Dallas/Ft. Worth (DFW) airport to Lima, Peru (SPIM) is shown. The current flight plan route takes the flight from current position (FRD: ABI078123) to ABI to VUH, and continues along the route to its destination. This route is shown in green in the top image, and shown as the Original FP in the bottom image. The DWR automation route, shown in cyan, proposes current position to SAT to VUH, with rest of route unchanged. The NASCENT route, shown in yellow, proposes current position to BIDME to PALMS to VUH, with rest of route

unchanged. An important difference in the avoidance modeling of the two approaches is revealed here. NASCENT uses 20 nmi inflated polygons for avoidance, whereas DWR uses the original CWAM polygons. The route from SAT to VUH could cross a 20 nmi distance around the weather region. Both systems, however, propose routes that are more efficient in terms of avoiding weather, as well as saving time over the current flight plan.

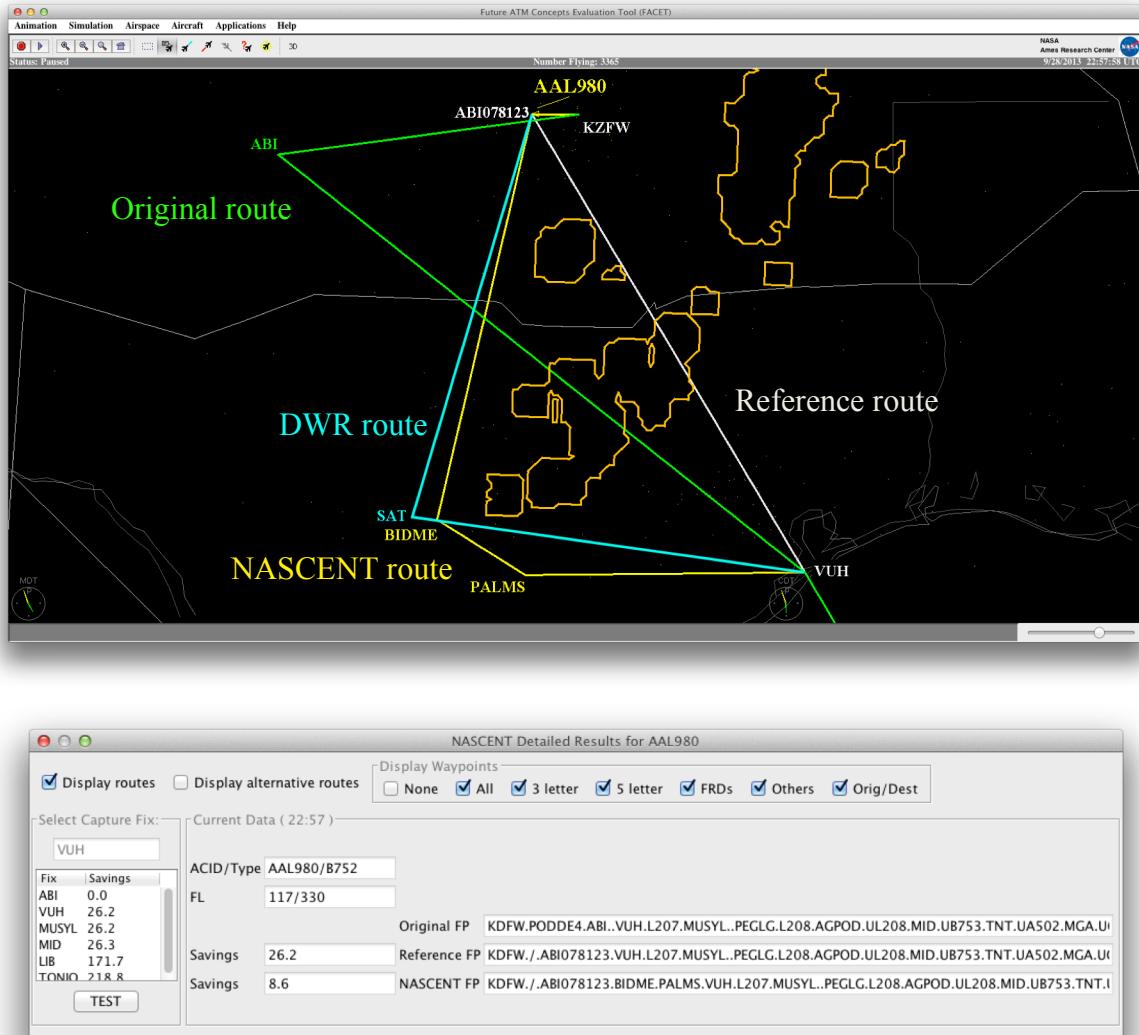


Figure 4. A comparison of dynamic weather routes computed by DWR and NASCENT systems. In the top image, the current flight plan is shown in green, the reference route is shown in gray, the DWR route in cyan, and the NASCENT route in yellow. The route strings are shown in the bottom image.

All proposed dynamic weather routes from both systems were compared for time savings along the reference route, the weather avoidance route, and for the number of auxiliary waypoints added for weather avoidance. Figure 5 shows the difference in potential flying-time savings between DWR and NASCENT systems for 43 common flights on April 2, 2013. Figure 5 (top) shows the difference in time savings for reference routes for same flights as proposed by DWR and NASCENT. The bottom image shows the difference in avoidance routes. Although the flight ids don't correspond between the two images, the same flight ids exist in each of the images. Figure 5 top and bottom images show that the difference in flying-time savings are less than five minutes and the average (shown by the blue lines) is around one-minute, which is the resolution of NASCENT air traffic data input.

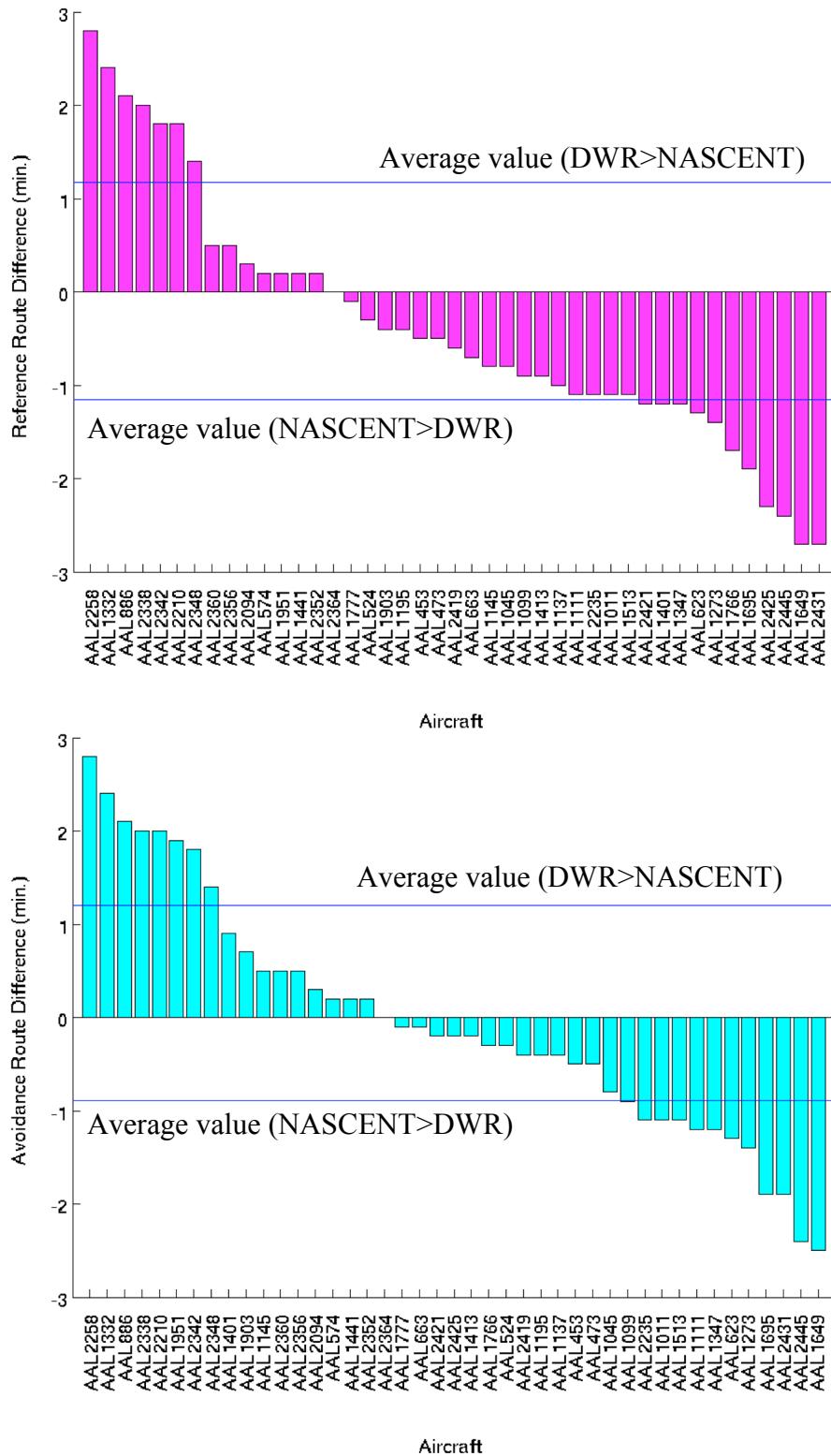
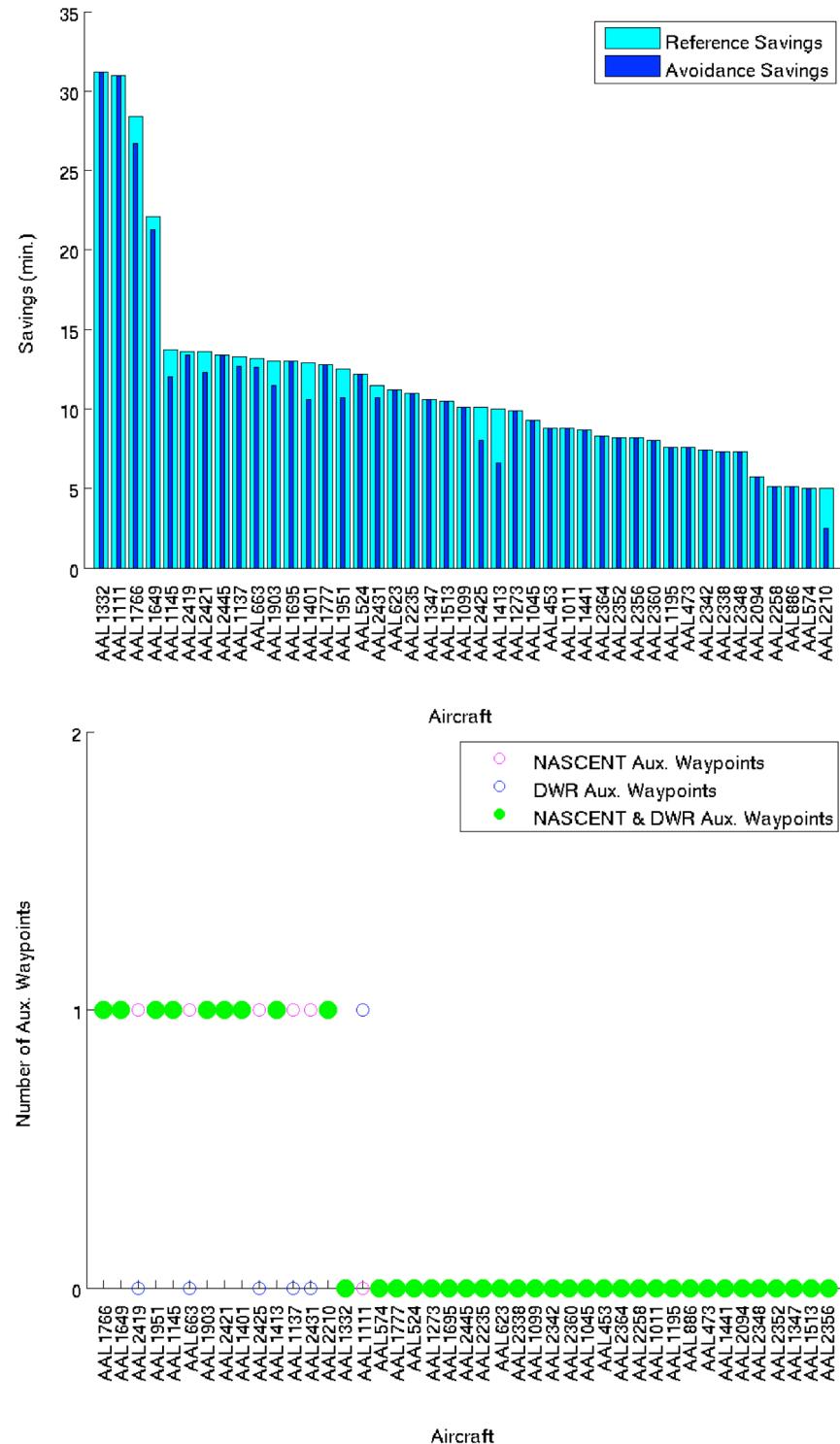


Figure 6 (top) shows the reference route (cyan) and avoidance route (dark blue) savings for the same 43 flights, but from NASCENT only. The differences in added auxiliary waypoints between DWR and NASCENT systems are shown in the bottom part of Fig. 6. The flights with same number of auxiliary waypoint in DWR and NASCENT are shown by green circles. When they differ, the number is shown with pink (NASCENT) and blue (DWR) circles.



It is seen that 29 out of the 43 flights don't have any auxiliary waypoint added in the NASCENT automation since the reference route can connect from current position to return capture fix without crossing any weather polygons. These can be identified in the top image as those where the dark blue bars are coincident at top with the cyan bar heights. This can also be observed by counting the green and pink circles at $y=0$ in the bottom part of Fig. 6.

VI. NASCENT Results for Eleven Centers

It was determined that with results presented in the previous Section, the NASCENT system was providing results that were close to those obtained by the DWR automation, barring the differences noted earlier. Therefore, the NASCENT system was run for the 13 days mentioned earlier, in 11 Centers concurrently. These 11 Centers are Albuquerque (ZAB), Atlanta (ZTL), Chicago (ZAU), Cleveland (ZOB), Denver (ZDV), Fort Worth (ZFW), Indianapolis (ZID), Jacksonville (ZJX), Kansas City (ZKC), Memphis (ZME), and Minneapolis (ZMP). All of these Centers are generally the most impacted by convective weather, and have more airspace to provide direct route clearances. Four Centers, Seattle (ZSE), Oakland (ZOA), Los Angeles (ZLA), and Salt Lake (ZLC) do not experience as much convective weather. New York Center (ZNY) is too congested for the weather avoidance routes to be useful. Houston (ZHU), Washington (ZDC), Boston (ZBW) and Miami (ZMA) Centers do not have much room of providing clearances of larger scale, providing more than five minutes of flying-time savings because of their boundary locations. It should be noted that the NASCENT analysis could be conducted in the remaining nine Centers as well, since the limit polygons for all Centers are available.

The results for all the 13 days of data are shown in Table 1, and Figs. 7 and 8 below. As noted earlier, these 13 days were selected because considerable savings were suggested by the DWR automation. During those days, significant convective weather was present in and around Fort Worth Center (ZFW) and Kansas City Center (ZKC). Therefore, maximum benefits are observed for ZFW, and neighboring Centers, ZKC, and ZME. The results are also presented for 12 airlines, which are American Airlines (AAL), Southwest Airlines (SWA), United Airlines (UAL), American Eagle Airlines (EGF), Delta Airlines (DAL), FedEx Express (FDX), US Airways (AWE), SkyWest Airlines (SKW), UPS Airlines (UPS), AirTran Airways (TRS), JetBlue Airways (JBU), and Alaska Airlines (ASA). Remaining airspace users are grouped into the "Other" category. Again, AAL, SWA, UAL (due to hub in Houston), and EGF demonstrate maximum benefits in Fig. 7 due to their large operations in and around ZFW. These results are wind-corrected savings between the reference or avoidance route and the original flight plan.

In Table 1, the number of flights in each scenario is presented along with the reference route and weather avoidance route savings. The savings are reported as total and average (based on number of flights) values. Since DWR automation was implemented for ZFW while the field test was being conducted at the American Airlines (AAL) Integrated Operations Center, the first two rows report numbers for ZFW and AAL. The third row reports results for AAL in all Centers, and results for all flights and all Centers are reported in the last row. It is observed that about 10 minutes of average avoidance routes savings are obtained when all Centers and all airlines are considered.

Table 1. NASCENT analysis results for number of flights and corresponding savings for 13 days of data.

Center Scenario	Number of flights	Total Reference Route Savings and Average (min., min./flight)	Total Avoidance Route Savings and Average (min., min./flight)
ZFW, Only AAL	449	6171, 13.74	5780, 12.87
ZFW, All flights	2018	24994, 12.39	23381, 11.59
All Centers, Only AAL	856	9790, 11.44	9276, 10.84
All Centers, All Airlines	5814	61524, 10.58	58802, 10.11

Fig. 7 shows the individual members of the total avoidance route savings results reported in last row, last column in Table 1. As mentioned before, ZFW, ZKC, and ZME have the largest pieces of the pie for Center-based savings. Similarly, AAL, SWA, UAL, and EGF have the largest Airline savings. Due to absence of weather in ZAB, location of ZJX, and size of ZOB, lower savings are observed there. The number of flights for ASA, JBU, TRS, UPS, and SKW are much lower than the rest of pie chart members, as they do not fly many flights in the Centers considered (e.g., ASA mainly flies in the northwest region of the country). Therefore, lower savings are seen for those.

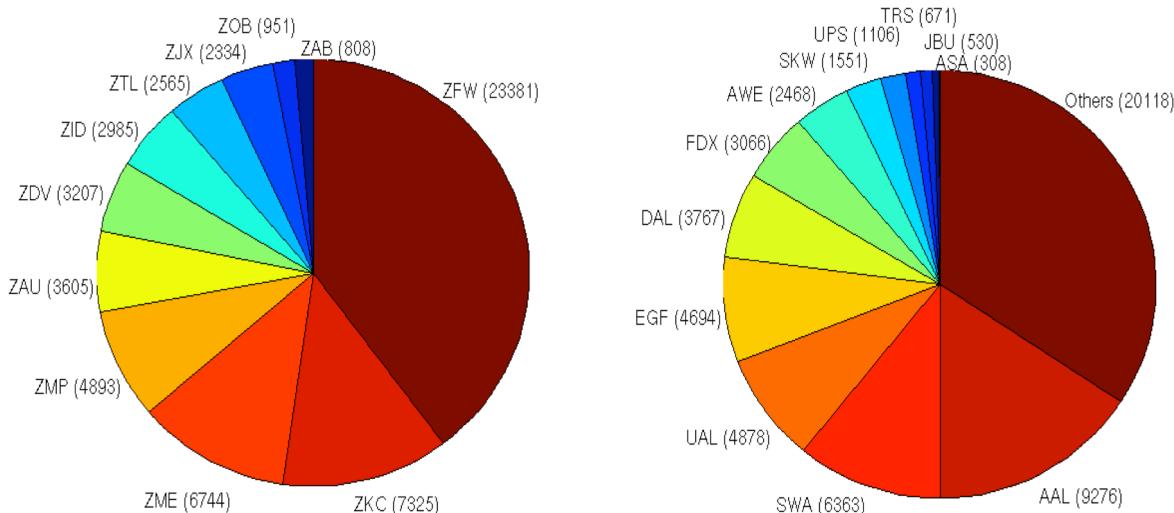


Figure 7. Avoidance route flying time saving minutes for all Centers (left) and all Airlines (right) for the 13 days of data.

Fig. 8 presents the average values of reference route and avoidance route savings for each of the pie chart members. It is interesting to note that even though the total savings for ZAB in Fig. 7 is about 3% of ZFW savings, the average savings are third largest. It should be noted though that all of the savings for ZAB come from reference routes, and no avoidance routes were proposed due to absence of weather. Similarly, even though ASA has the smallest time saving, which is about 3% of AAL savings, it has the second highest average of all airlines. These results indicate that even though there may not be too many flights for an airline in a specific Center, there are considerable average savings per flight available. Considering a rough estimate of \$100 per minute of flight, the numbers here indicate that on average, there may be up to \$1000 per proposed flight available as savings for Airlines. It should be noted that this analysis is dependent on the location of convective weather and the potential savings to airlines and Centers will vary with it. That analysis would use most-weather-related delay days rather than the 13 days used here, and will be considered in a future paper.

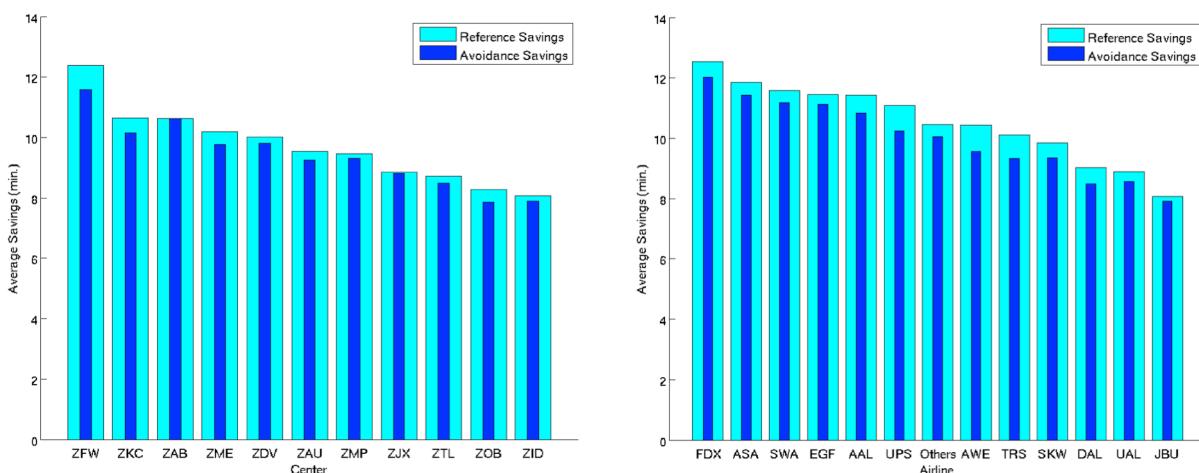


Figure 8. Average flying-time savings minutes for all Centers (left) and all Airlines (right).

An important result is for the longevity of potential savings as a function of time. Once a weather avoidance route is proposed for a flight, how long do the flying-time savings persist? This is important because the proposed route requires some time for request by pilot and clearance from the controller. This introduces a delay in activation of the route change, resulting in loss of potential savings benefit. The potential wind-corrected flying time savings for all flights on the NASCENT list are recorded as function of time. The decay of savings is shown in Fig. 9 for ZFW flights only for clarity. The thick black line shows the average of all the savings values (left y-axis). The thick green line shows the number of flights (right y-axis) the average savings was computed with. It is seen that between 30-35 minutes later about 10 minutes of savings, averaged over 500 flights, are still available. Another point to note, as shown by multiple colored lines, is that the rate of decay varies significantly from flight to flight. For some flights, the flying time savings decay quickly while for others, the savings persist for a longer time. This behavior is attributable to the geometry of the proposed route and the encountered winds.

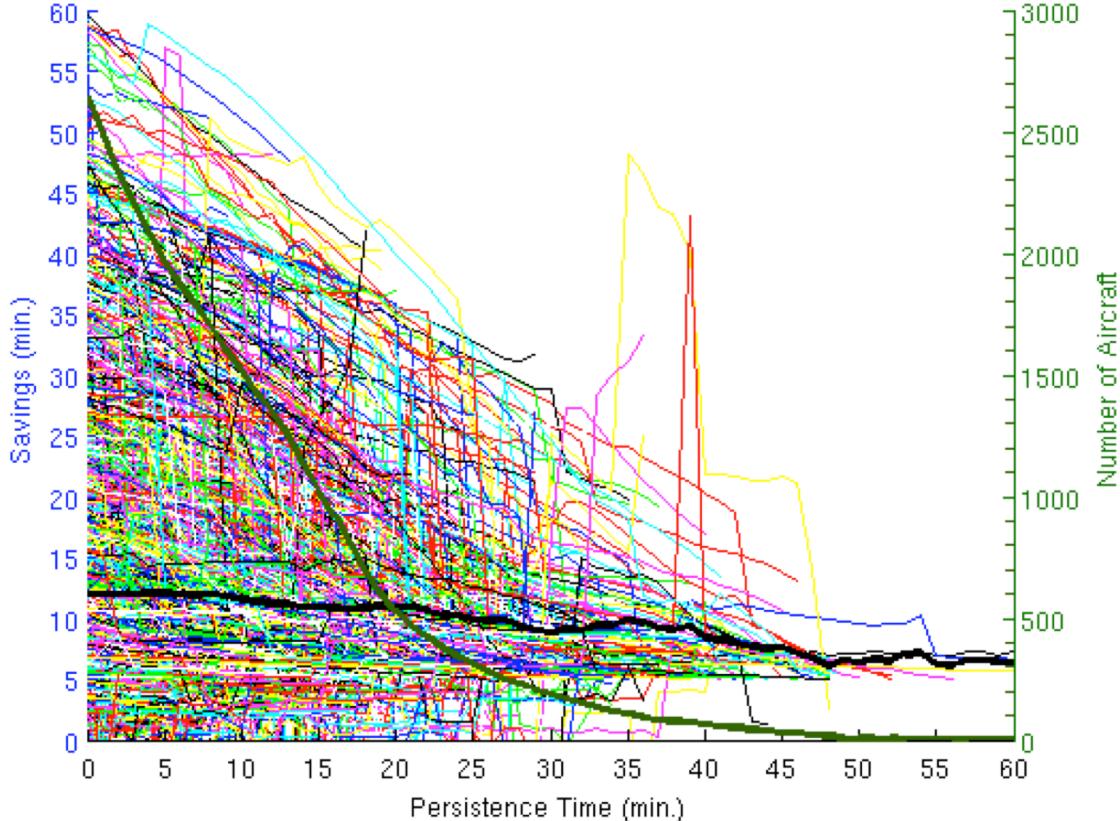


Figure 9. Longevity of flying-time savings for NASCENT proposed routes as a function of time for all flights in ZFW. Also shown are the average value (black) of savings and the number of flights (green) averaged over.

VII. Alternate Method for Handling Multiple Centers

So far in this paper, NASCENT results have been presented for multiple Centers. The analysis was performed for each flight with the return capture fix for the reference route selected based on the Center in which the flight was located. It is quite likely that due to the size of the convex hull limit polygons, the capture fix is far into a neighboring Center, or perhaps even in a Center beyond. See Fig. 3(b) for Denver Center limit polygon, where a flight at the southwest edge of ZDV could be cleared direct to a fix in Chicago Center bypassing Minneapolis Center altogether (since the Denver Center polygon covers lower part of Minneapolis Center and a third of Chicago Center). So, how far should a return capture fix be, for a flight to be sent direct to by automation? There are two approaches that can be studied. First is what has been done in this paper, where the last fix on the flight plan is within the limit polygon. Another approach is where the last fix is located in any tier one Center. This second approach would eliminate the need for an ad-hoc limit region since the boundaries of tier one Centers would become

the limit polygon (although in many cases, the limit polygon may not be a convex hull). The second approach is being studied and will be presented in the future.

The whole premise of a limit region is not to propose routes that take a flight direct across multiple Centers. However, if such savings are possible, the airline dispatcher may wish to know about the inefficiency in their flight plan. Figure 10 shows the limit polygons in cyan for Chicago Center at the top, Kansas City Center in the middle and Fort Worth Center at the bottom. The green route is the current flight plan for flight JZA113. Currently in Chicago Center (the Center boundaries are shown with gray lines), the flight finds reference route savings of 5.5 minutes (shown highlighted in yellow in bottom left window) capturing the fix COODY close to TUL in ZKC. This route is shown in yellow on main canvas. When the flight enters ZKC at IRK, it could get a direct clearance to CVE in ZFW. Subsequently, when the flight enters ZFW (just after TUL), it could get a direct clearance to BILEE in Houston Center. It is possible to compute the three clearances simultaneously and present them to the airline user. So, if it's possible, the user can gain maximum benefit of flying-time savings by identifying the inefficient "dog-legs" in the flight plan. Clearly, weather, sector congestion, and other airspace constraints along the path would have to be accounted for. Such an approach is also being researched currently and will be reported in a future publication.

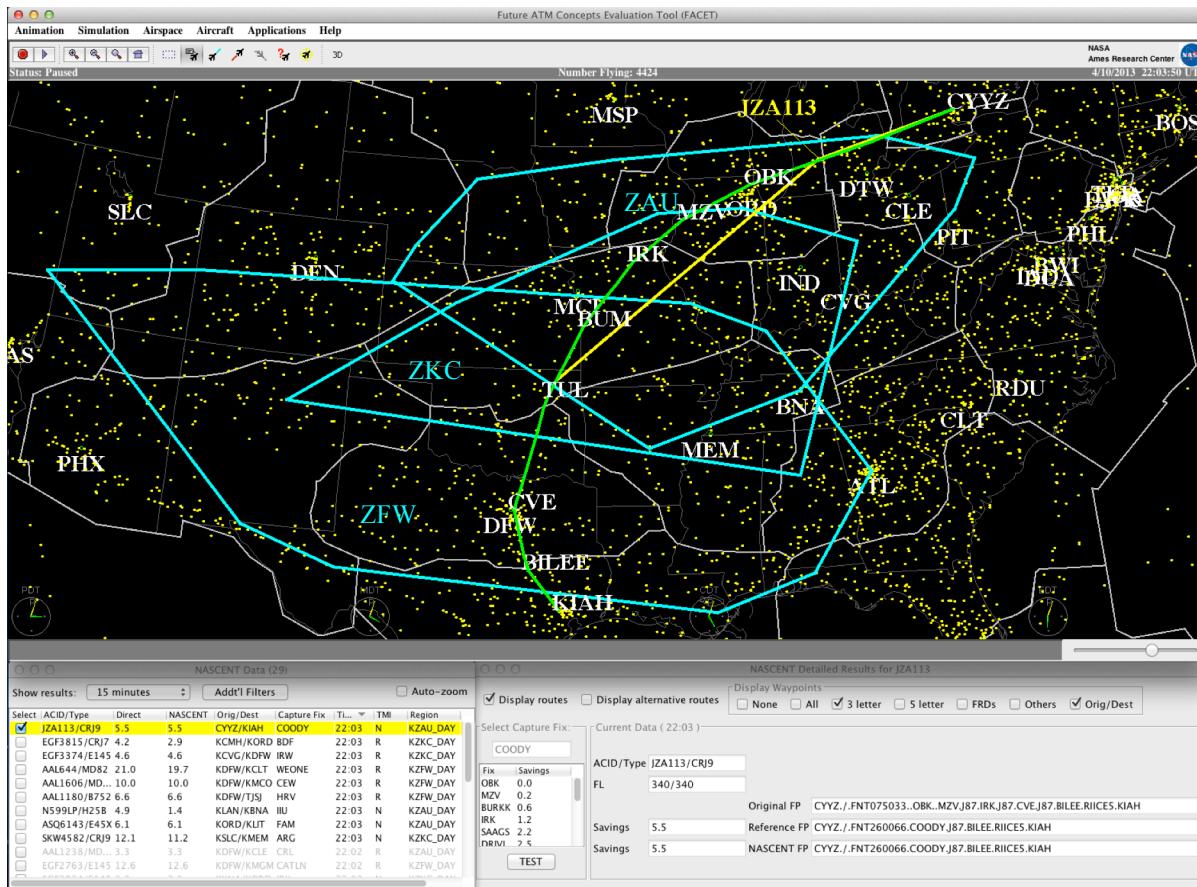


Figure 10. (a) A snapshot of NASCENT display for handling an alternate multiple Center approach.

VIII. Concluding Remarks

DWR computed weather avoidance routes can provide airborne flights more than a user-specified minutes of wind-corrected flying time savings. They are applied from the aircraft's current location to a flight plan fix downstream (within a predefined limit region), while avoiding forecasted convective weather regions. The Dynamic Weather Routes automation is currently adapted for flights within the Fort Worth Air Route Traffic Control Center. This paper presented the benefits of extending the Dynamic Weather Routes automation to multiple airspace Centers

individually and concurrently. A new application called National Airspace System Constraint Evaluation and Notification Tool (NASCENT), based on a nationwide simulation and analysis tool, was used for this purpose. The current computation of dynamic weather avoidance routes requires a limit rectangle so that a downstream return capture fix can be selected, preventing very large modified routes spanning several Centers. In this paper, first, a method of computing an operationally viable limit polygon (as opposed to a rectangle used for Fort Worth Center) for each of the 20 Centers was described. This empirical method produces limit regions that could be very large, depending on available airspace flexibility for clearing flights direct downstream. A comparison showed similar results with the Center-based DWR automation in Fort Worth Center. Then, results were presented for 11 Centers in the contiguous United States, which are generally impacted by significant convective weather. These results are for 13 Airlines over 13 days of NAS-based traffic in those 11 Centers. A breakdown of individual Center and Airline savings indicates an overall average of about 10 minutes of flying-time savings per flight for weather avoidance routes.

The focus of this paper was on computing the feasibility of flying-time savings across multiple Centers. An alternate method for computing dynamic weather routes across several Centers simultaneously was also presented at the end. This method addressed the questions of how far could the return capture fix be, and how efficient a filed flight plan can be, so the user can gain maximum benefit. Even though sector congestion Special Activity Area traversal, required reroutes, and fuel/emissions calculations are available within the NASCENT automation, they were considered beyond the scope of this paper, and will be reported in a future publication.

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References

- ¹McNally, D., Sheth, K., Gong, C., Love, J., Lee, C., Cheng, J., and Sahlman, S. "Dynamic Weather Routes: A Weather Avoidance Concept for Near-Term Trajectory-Based Operations," accepted for publication at the *International Council on Aeronautical Sciences*, Brisbane, Australia, Sep. 2012.
- ²Sheth, K., McNally, D., Petersen, J., Morando, A., and Shih, F., "Consideration of Strategic Airspace Constraints for Dynamic Weather Routes," *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Indianapolis, IN, Sep. 2012.
- ³Sheth, K., Sridhar, B., McNally, D., Petersen, J., "Strategic Airspace Constraint Analysis and Environmental Impact of Dynamic Weather Routes," *32nd Digital Avionics Systems Conference*, Syracuse, NY, Oct. 2013.
- ⁴Sridhar, B., Sheth, K., Smith, P., and Leber, W., "Migration of FACET from Simulation Environment to Dispatcher Decision Support System," *24th Digital Avionics Systems Conference*, Washington, D.C. 2005.
- ⁵McNally D, Engelland S, Bach R, Chan W, Brasil, C, Gong C, Frey J, Vincent D. Operational Evaluation of the Direct-To Controller Tool, *Proc 4th USA/Europe Air Traffic Management R&D Seminar (ATM2001)*, Santa Fe, New Mexico, 2001.
- ⁶Bilimoria, K. D., Sridhar, B., Chatterji, G., Sheth, K. S., and Grabbe, S., "FACET: Future ATM Concepts Evaluation Tool," *Air Traffic Control Quarterly*, Vol. 9, No. 1, 2001, pp. 1–20.
- ⁷McNally, D., Sheth, K., Gong, C., Borchers, P., Osborne, J., Keany, D., Scott, B., Smith, S., Sahlman, S., Lee, C., and Cheng, J., "Operational Evaluation of Dynamic Weather Routes at American Airlines," *10th USA/Europe Air Traffic Management Research and Development Seminar*, Chicago, IL, June. 2013.
- ⁸Volpe National Transportation Systems Center, "Enhanced Traffic Management System (ETMS) Functional Description," U.S. Dept. of Transportation, Cambridge, MA, Mar. 1999.
- ⁹Coverage of 2009 European Air Traffic for the Base of Aircraft Data (BADA) – Revision 3.8, Eurocontrol Experimental Center (EEC) Technical/Scientific Report No. 2010-08, European Organization for the Safety of Air Navigation, July 2010.
- ¹⁰Erzberger H, Lauderdale T, Chu Y. Automated Conflict Resolution, Arrival Management and Weather Avoidance for ATM, *Proc 27th International Congress of the Aeronautical Sciences*, Nice, France, 2010.
- ¹¹Sridhar, B., Chatterji, G., Grabbe, S., and Sheth, K., "Integration of Traffic Flow Management Decisions," *AIAA Guidance, Navigation, and Control (GN&C) Conference*, Monterey, CA, Aug. 2002.
- ¹²Matthews M, and DeLaura R., "Assessment and Interpretation of En Route Weather Avoidance Fields from the Convective Weather Avoidance Model," *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Fort Worth, Texas, Sep. 2010.