DYNAMIC WEATHER ROUTES: A WEATHER AVOIDANCE SYSTEM FOR NEAR-TERM TRAJECTORY-BASED OPERATIONS

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Abstract

A ground-based trajectory automation system was developed that continuously analyzes in-flight aircraft in en-route airspace to find time- and fuel-saving corrections to convective weather avoidance routes. The system could help airline dispatchers and Federal Aviation Administration (FAA) traffic managers and controllers find more efficient routes around convective weather. Simple reroutes - Dynamic Weather Routes (DWR) - are automatically proposed and updated every 12 sec. Interactive automation enables users to visualize reroutes and modify them if necessary, and evaluate flying time savings, proximity to weather, sector congestion, and traffic conflicts. Analysis of 14 hours of archived traffic and weather data from one US en-route Center (Fort Worth) over five convective weather days shows an average potential savings of about 10 min per flight for 171 flights. A sector congestion analysis shows that if all DWR routes were implemented, overall sector congestion as measured by the monitor/alert parameter would decrease due to the fact that aircraft are routed off standard weather-avoidance routes. The system is ideal for air/ground data link communication, but could also be used in today's operations.

1 Introduction

Weather is the leading cause of delay in the US National Airspace System, and convective weather accounts for 60% of weather-related delays [1]. Convective weather is common in the spring and summer months and can extend for hundreds of miles and reach altitudes well in excess of 40,000 feet. When weather is present or forecast along preferred flight routes, weather avoidance routes are planned and implemented, usually prior to take off. While aircraft are in flight, airline dispatchers and FAA traffic managers and controllers review weather updates and traffic flows to determine if and how flights may be rerouted to improve flow and reduce delay. However, real-time automation that continuously searchers for and proposes time- and fuel-efficient corrections to existing weather avoidance routes for in-flight aircraft is limited. And operators are busy during weather events and may miss workable opportunities for more efficient routes.

Related prior research applies the simulated annealing optimization method to dynamically generate operationally acceptable reroutes for flights that must deviate from their route due to weather [2]. DWR increases the number of eligible flights by searching for opportunities for more efficient weather-avoidance routes regardless of weather status on the current route.

Several trajectory automation functions were leveraged to implement the DWR concept and system. The Corridor Integrated Weather System (CIWS) and the Convective Weather Avoidance Model (CWAM) have been integrated with the Center/TRACON Automation System (CTAS) and together enable probing of flight trajectory predictions against growing and moving weather cells out to a two-hour time horizon [3,4,5]. The Direct-To tool, an element of CTAS, automatically analyzes in-flight aircraft in en-route airspace to find those that can save flying time while not deviating substantially from their current route of flight [6,7]. The automatic resolver element of the Advanced Airspace Concept (AAC) automation suite computes minimum-delay routes around modeled weather [8]. In this study the Future Air Traffic Management (ATM) Concepts Evaluation Tool (FACET) [9,10] is integrated with CTAS to determine the impact of proposed reroutes on downstream sector congestion.

DWR integrates the aforementioned trajectory automation functions [3-10] into a real-time system (see Fig. 1) that helps dispatchers and traffic managers identify and evaluate tactical corrections to existing weather-avoidance routes. The DWR system continuously analyzes in-flight aircraft in en-route airspace to find opportunities for time- and fuel-saving corrections to existing routes that avoid weather and don't interfere with other traffic flows or create conflicts. Flights where a reroute can save more than a user-specified amount of wind-corrected flying time, 5 min for example, are posted to a route advisory list on the user'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[1], proximity to current and predicted weather, traffic conflicts, and downstream sector congestion.

DWR is an ideal application for today's air/ground data link communication [11,12,13]. As described later (Section 5), the DWR system supports both voice and data communication. However, controllers are busy during weather events, and data communication reduces their workload, thereby increasing the likelihood that DWR routes are accepted by air traffic control (ATC). This is especially relevant for reroutes with inserted auxiliary waypoints as in the DWR concept. Without data communication, auxiliary waypoints must be located and verified by controllers and then input to the computer system by keyboard entry. Secondly, ATC provides weather advisories to pilots, but is not responsible for tactical separation of aircraft from weather. Today pilots request tactical deviations for weather. Consequently, controllers prefer that pilots request reroutes for weather, and data communication is ideal for requesting and coordinating specific reroutes, especially ones that include auxiliary waypoints.

The paper's objectives are to 1) describe the DWR concept and prototype system, 2) analyze performance using archived traffic and weather data, 3) compare benefits achievable with and without air/ground data communication, and 4) propose operating concepts for varying levels of automation including data link.

The paper opens with a list of important assumptions. The next section describes the DWR prototype system. A performance section examines potential flying time savings, sector congestion, and weather modeling using archived traffic and weather data from the FAA Fort Worth Air Route Traffic Control Center (ARTCC or Center) and national Airline Situation Display to Industry (ASDI) data. A brief description of operating concept options is presented, and the paper closes with a summary.

2 Assumptions

The following assumptions shape the DWR system and operating concept:

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

[1] In CTAS and the DWR system, flying time savings or delay figures are all wind-corrected.

3 Dynamic Weather Routes Prototype

Fig. 1 shows the prototype DWR system including its component functions and its primary inputs with their update rates. This section describes the contributions of each component and their integrated operation in the DWR system. Section 3.3 describes the real-time stepwise process built into the prototype DWR system to identify efficient tactical corrections to existing weather avoidance routes.

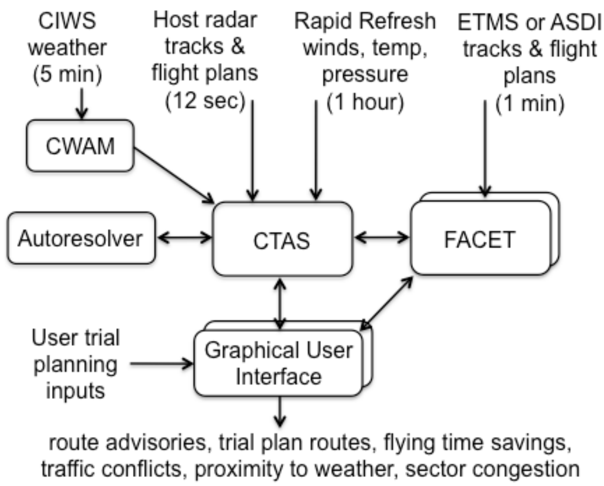

Fig. 1. Prototype DWR system

3.1 Trajectory automation system

The Center/TRACON Automation System (CTAS) configured for en-route Center operations [4,7] is the trajectory automation software baseline for DWR. CTAS computes 4D trajectory predictions (x, y, h, and time) for all Center flights using live or recorded data feeds. The primary inputs to CTAS are Center Host surveillance radar track messages updated every 12 sec, Center Host route and altitude flight plan intent messages as entered and updated by controllers, National Oceanic and Atmospheric Association (NOAA) Rapid Refresh atmospheric data, including wind forecasts, updated every 1 hour, and a database of aircraft performance models. All flight trajectories are updated every 12 sec upon receipt of fresh radar track and flight plan messages. The 12 sec Host track and flight plan updates are needed so that flight plan intent is up to date and traffic conflict detections are reliable. Trajectories include modeled top-of-climb and top-of-descent points and incorporate hourly Rapid Refresh wind updates which include wind variation with altitude.

CTAS includes real-time traffic conflict detection [4], convective weather conflict detection [5], time-based metering, and efficient descent advisory functions, all of which are supported by a single common CTAS trajectory engine. The convective weather modeling and conflict detection functionality and its configuration for the DWR system are described in more detail in the next section.

The CTAS trial planning function, a critical functionality for DWR, enables automated analysis of trial reroutes. The trial planning function, runs in two modes: fully automatic to support automated generation and analysis of reroute advisories [4,11,12,13], and interactive manual mode, to support user evaluation and modification of DWR route advisories or any other user-generated trial reroute [7,12,13]. Trial trajectories are tested for traffic conflicts, weather conflicts, and wind-corrected flying time savings or delay compared to the current nominal flight plan trajectory. Though not currently implemented for DWR, the system is easily extendable to test trial trajectories for conflict with time-based metering constraints.

3.2 Weather modeling and conflict detection

Convective weather forecasts for DWR are based on CIWS and CWAM, both developed at MIT/Lincoln Laboratory [3]. CIWS uses vertically integrated liquid (VIL) data and echo top data from NexRad weather radars to compute a 2-hour national convection forecast that is updated every 5 min and includes a 5-min forecast time step.

CWAM processes CIWS model outputs to predict the probability of pilot deviation for weather as a function of storm intensity, echo-tops, and look-ahead time. For a given CIWS forecast, pilot deviation probability is quantified using Weather Avoidance Fields (WAF), where a WAF defines a region around a weather cell that a specified percentage of pilots are expected to avoid. For example, 60% of pilots are expected to deviate around a 60% WAF. For a given weather cell and altitude, 70% WAF polygons are generally smaller with their boundaries closer to the weather cells than are 60% WAF polygons. Fig. 2 shows CIWS weather cells and their corresponding 60, 70, and 80% CWAM polygons at FL330 with zero min look ahead time.

CWAM is based on analysis of observed deviations by approximately 5,200 flights during archived weather events in the Northeastern US [3]. The methods implemented for DWR match those being used in the CWAM model that currently supports operational selection of departure routes during convective weather events in and around the New York TRACON [3, 14].

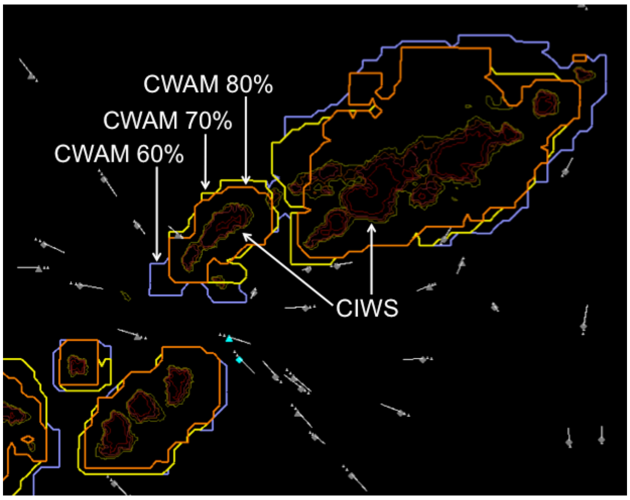

Fig. 2. DWR system screen capture showing CIWS cell and corresponding 60, 70, & 80% CWAM polygons for FL330 at zero min look-ahead time.

The DWR system downloads CIWS output data from MIT/Lincoln Laboratory every 5 min. The DWR system's CWAM processor then computes an updated set of 60, 70, and 80% WAF polygons every 5 min. Every polygon in each CWAM model set (60, 70, and 80%) has associated with it a look-ahead time in 5 min intervals out to 2 hours, and a flight level ranging from FL250 to FL450 in 1,000 ft increments. CWAM updates are read into CTAS every 5 min, and integrated with the trajectory modeling and automation such that conflicts between nominal trajectories, or trial plan trajectories, and CWAM weather polygons are automatically detected correctly accounting for the movement of traffic and weather over time [5]. The WAF value is a run-time parameter and selected at DWR system start up. The default WAF for this analysis is 70%.

3.3 Route advisory algorithm

The DWR route advisory algorithm and system are depicted graphically in Figs. 3 and 4, and described in detail in this section. The automation steps are repeated every 12 sec using fresh trajectory updates to identify flights that meet the criteria for a DWR route advisory. Flight IDs and DWR route summary information are posted to a list on the user's display (see Fig 7). The list updates every 12 sec.

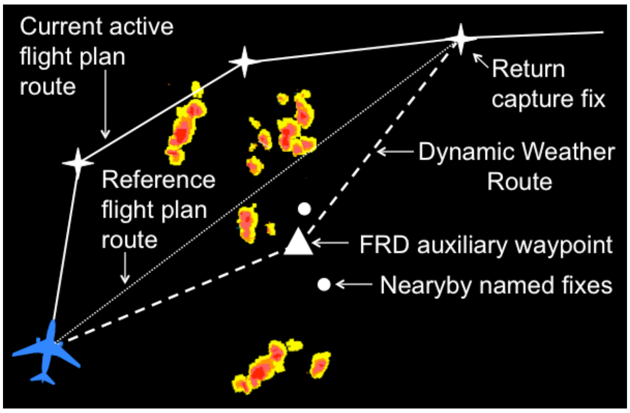

Fig. 3. DWR automation concept.

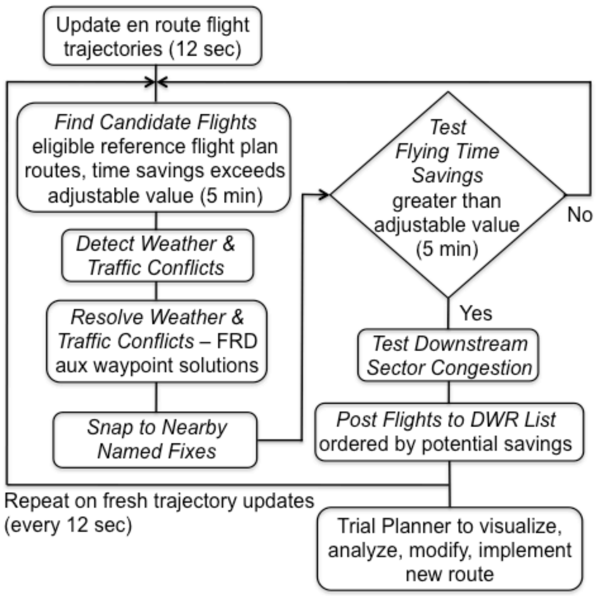

Fig. 4. DWR automation steps.

Step 1. Find Candidate Flights. Automatically analyze the most recent trajectory updates to find flights that could potentially benefit from a more efficient routing around weather. The objective is two fold. First, find flights with large course changes or 'dog-legs' in their current flight plan routes. Second, for each of these flights, identify a reference flight plan route that eliminates the dog-leg and returns the aircraft to its current route of flight at some downstream return capture fix (see Fig 3). The reference flight plan is not necessarily weather and traffic conflict-free at this point. It is however, a more desirable route and later automation steps will determine necessary adjustments to enable a conflict-free route that is as close as possible to the reference route.

The presence of a large course change or dog-leg in a downstream route of flight is a strong indication that the flight is on a route previously implemented for weather avoidance. The return capture fix is an existing fix on the current route of flight. The reference flight plan route - not the current active flight plan route - is the basis for resolving weather and traffic conflicts using the autoresolver described in Step 3. The notion of a reference flight plan is based on the important assumption that in cases where large dog-legs are present in the current route of flight, the flight might be eligible for a reroute. If weather is not present, or if it has changed since the current active flight plan was implemented, then the aircraft should be able to fly something closer to the reference flight plan instead of the current flight plan.

The reference flight plan route could be a direct route to a suitable downstream fix, a wind-optimal route to a downstream fix, or a route to a more efficient standard arrival route (STAR) into the destination airport, or some other user-preferred route. The distinguishing characteristic of the reference route is that it is a routing that is substantially more favorable than the current flight plan and would likely be acceptable if there were no weather. The reference flight plan route will always reflect a relatively large wind-corrected flying time savings relative to the current flight plan route.

In this analysis the Direct-To algorithm and its associated trajectory automation as implemented in CTAS [7,4] are applied to identify flights with large dog-legs in their current flight plan route. The Direct-To route then becomes the reference flight plan route. Direct-To automation automatically finds direct routes to downstream fixes that can save one or more min flying time, wind-corrected. For the DWR system, a flight with a large dog-leg is one where the flying time savings to a downstream fix is greater than a critical trigger value, 5 min for example. The trigger value is adjustable by the user based on workload, airspace, and other factors.

Eligible downstream capture fixes are limited so as not to propose a direct route that takes an aircraft substantially off its current route of flight [6,7]. For this analysis, and as shown in Fig. 5, the direct route capture fix is the furthest downstream flight plan fix that satisfies all of the following criteria:

- inside a limit rectangle,
- last fix before the Standard Arrival Route,
- 100 nmi or more from destination airport.

The limit rectangle is adaptable and may be adjusted as appropriate for the particular Center airspace. For example, the limit rectangle for a US East coast Center will likely be smaller or have one or all of its boundaries (North, South, East, West) closer to the home Center boundary. Alternatively, the direct route capture fix may be selected as a function of routing between city pairs [6,7]. Capture fix selection limits are determined by local Center experts and part of operational adaptation for the local Center. In this analysis the 700 x 1,000 nmi limit rectangle used in [7] and indicated in Fig. 5 is applied. In the current DWR implementation arrival flights nearing their destination airports in the home Center are not analyzed.

Fig. 5 also illustrates the point that DWR routes are tactical corrections to existing routes and generally impact routing in the local Center and the immediate neighboring Centers. If additional impacting weather exists on the flight plan further downstream, 2-3 Centers downstream for example, DWR automation in the downstream Centers analyze the flight and may propose DWR routes appropriate for those Centers.

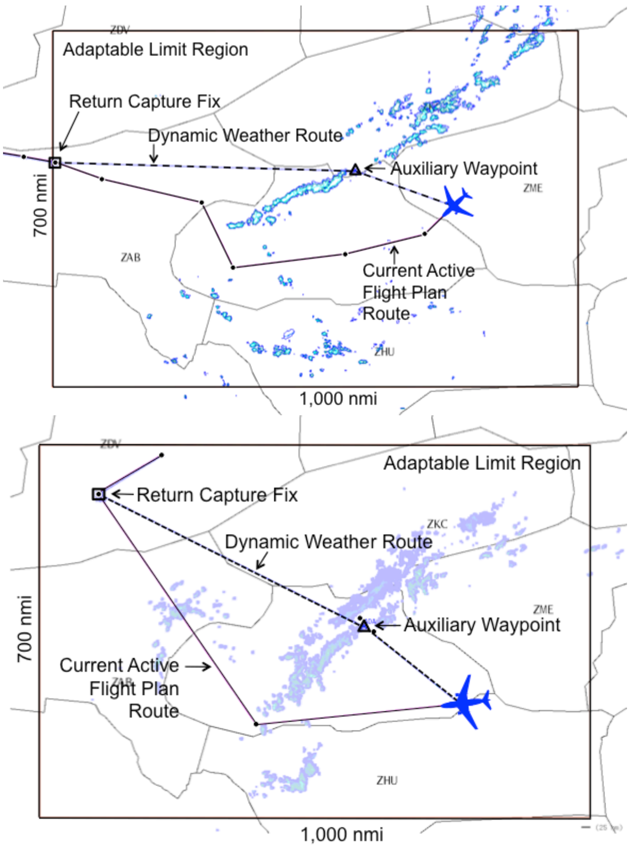

Fig. 5. Limit rectangle for capture fix selection

Step 2. Detect Weather and Traffic Conflicts. Any direct route trajectory that meets the limit rectangle and time savings criteria described in Step 1 is automatically tested for conflict with modeled weather and traffic. If no weather or traffic conflicts exist, Steps 3-5 are skipped, the direct route is tested for Sector Congestion (Step 6) and the DWR advisory is posted to the DWR List (Step 7) as a reroute direct to the downstream capture fix with no auxiliary waypoints.

Step 3. Resolve Weather and Traffic Conflicts. If weather or traffic conflicts are detected on the reference flight plan trajectory in Step 2, the autoresolver [8] attempts to find a minimum-delay reroute, relative to the reference flight plan. In the current implementation two DWR solutions are attempted, one that resolves modeled weather only, and a second that computes an integrated solution that resolves both weather and traffic conflicts. Weather conflicts are resolved on a 60 min time horizon; traffic conflicts are resolved on an 12 min time horizon (see Table 1). Since weather avoidance accounts for most of the delay in air traffic operations, two solutions are computed, and users can configure the system to post weather-only or integrated weather and traffic solutions. Either way, the trial planner enables users to see all detected weather and traffic conflicts.

Fig. 6 is a screen capture from the DWR system display showing a sample trial plan trajectory from an actual Fort Worth Center traffic and weather scenario (September 2, 2010). This example, which is not a DWR route advisory, was chosen to illustrate the integrated detection of traffic and weather conflicts on the trial trajectory. The current-time CIWS weather is shown along with the CWAM polygon (70% WAF) that first conflicts with the trial plan route trajectory. In this case the trial plan trajectory first conflicts with the 15 min forecast CWAM polygon so that polygon is displayed in bold (orange).

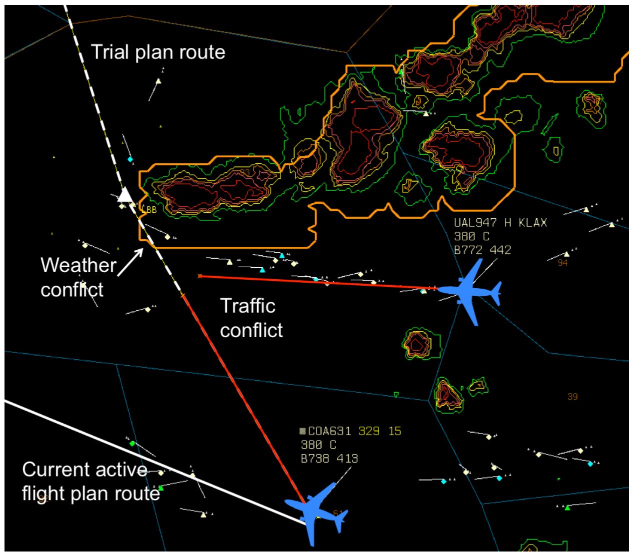

Fig. 6. DWR system screen capture showing weather and traffic conflicts detected.

DWR routes are formed by inserting auxiliary waypoints, up to two in this implementation, between current track position and the direct route capture fix. Candidate solutions are sent to the trajectory engine (CTAS) and tested for flying time delay relative to reference flight plan. The solution that results in the minimum flying time delay relative to the reference flight plan and meets the weather, or weather and traffic constraints is selected for further analysis.

Auxiliary waypoints are first computed in the x-y coordinate frame for the home Center, then converted to fix-radial-distance (FRD) format relative to a nearby named fix. Named fixes are based on the FAA 56-day adaptation [15], supplemented with fixes from the national En-Route Automation Modernization (ERAM) adaptation data base [16] and the Navigation Reference System (NRS) [17]. Nearby named fixes are selected according to the following search ordering:

- Capture fix if distance <= 100 nmi, or
- Nearest flight plan fix if distance <= 100 nmi, or
- Nearest non-NRS nearby fix if distance <= 100 nmi, or else
- Closest flight plan fix (even if distance > 100 nmi).

Step 4. Snap to Nearby Named Fixes. Since solutions that include auxiliary waypoints defined in terms of FRDs are suitable only for data link applications, neighboring DWR solutions where FRD waypoints are replaced with nearby named fixes are automatically computed. Using the FRD auxiliary waypoint solution computed in Step 3 as a starting point, the automation attempts to find that combination of nearby named fixes that when used in place of their respective FRD waypoints still do not cause the flight trajectory to conflict with modeled weather, or weather and traffic. In this analysis 'nearby' is defined to be within 25 nmi of the FRD auxiliary waypoint. The named fix trajectory that is minimum delay relative to the FRD trajectory, and does not conflict with weather, or weather and traffic, is selected as the nearby named fix solution.

Step 5. Test Flying Time Savings. Test the DWR solutions computed in Step 3 (FRD solution) and Step 4 (Snap To Fix solution) for potential flying time savings relative to the actual current flight plan trajectory. If the time to fly along the DWR route (either FRD or Snap to Fix depending on selected mode) saves more than parameter minutes (e.g., 5 min), continue on to Steps 6 and 7. If not, stop; do not post this flight to the DWR List.

Step 6. Test Downstream Sector Congestion. For all flights that meet the minimum flying time savings criteria in Step 5, their DWR trajectories and their actual current flight plan trajectories are probed for downstream sector congestion. If a DWR route would take an aircraft directly into a congested sector, the reroute would likely be unacceptable from an ATC perspective. Alternatively, if the current active flight plan has the aircraft flying into congested airspace, while the DWR route takes the flight out of congested airspace, the DWR might be preferable and ease congestion.

FACET software is used for computing downstream sector congestion. FACET is a National Airspace System (NAS)-based data analysis and simulation system, which reads in FAA provided air traffic data. The aircraft paths are simulated, with NOAA Rapid Refresh one, two, three, and six-hour winds, to fly along their nominal flight plans as filed with the FAA, using the Base of Aircraft Data (BADA) [18] look up tables for aircraft performance. The aircraft location at each one-minute step for a two-hour period is added to corresponding sector counts. The monitor/alert parameter (MAP) values are obtained from the FAA as well. Each aircraft's current flight plan route and the DWR proposed route is checked for travel through congested sectors. This can be seen in two windows at right in Fig. 8. The upper window shows the current flight plan traversing through one red and two yellow sectors. The sector is depicted red if at least MAP number of aircraft are predicted to travel through that sector, and are airborne at the time the prediction is made. If some of the aircraft are on the ground but the total number of aircraft traveling through a sector are over MAP value, then the sector is depicted yellow. The bottom right window in Fig. 8 shows that the proposed DWR route is not affected by congestion at all. As soon as a DWR route is computed by CTAS, FACET computes and provides the sector congestion information indicated in the two windows on the right (Fig. 8). The user (either a flight dispatcher or a traffic manager) at this point can look at the congestion information and decide based on their requirement whether the DWR route is acceptable from a congestion point of view.

Step 7. Post Flights to DWR List. Post the flight ID, potential flying time savings, and other pertinent information to a list on the user's display (DWR List). Options to display advisories and enable trial planning from the flight data block are also available and well suited to air traffic control displays [7,12,13]. The alerting value for posting a solution to the DWR List is adjustable by the user based on their workload, potential flying time savings benefit, and other factors. The list is configurable to display FRD solutions or snap-to-named-fix solutions.


Dynamic Weather Routes

TP	ACID/TYP	DEP/DST	DRCT	DWR	FIX/VIA	TR	SC	WX
☐	UAL561/A319	MSY/DEN	16.3	15.0	HBU/1	8	OK	OK
☐	FFT383/A319	KFLL/KDEN	14.2	12.2	HBU/1	6	OK	OK
☐	FFT675/A319	KMCO/KDEN	13.9	10.8	HBU/1	13	OK	OK
☐	AAL2411/B752	KDFW/KLAX	13.2	12.1	ALIBY/1	OK	OK	OK
☐	AAL1143/MD82	DFW/OMA	11.3	10.7	SGF/1	OK	OK	OK
☐	TCF7671/E170	KATL/KDEN	9.4	9.4	HBU	OK	OK	OK
☐	SWA418/B737	KJAX/KLAS	9.3	6.5	GUP/2	OK	SC	OK
☐	CPZ5663/E170	DFW/MSP	9.2	9.2	SGF	OK	OK	OK
☐	TCF7518/E170	KSAT/KORD	9.0	9.0	BAYLI	OK	OK	OK
☐	SKW4727/CRJ9	DFW/SLC	6.9	6.9	JNC	OK	OK	OK
☐	AAL1821/B738	KMIA/KLAS	6.6	5.4	GUP/1	OK	SC	OK
☐	AAL1157/MD83	DFW/SEA	6.2	5.6	JNC/2	OK	OK	OK

Fig. 7. DWR List

Fig. 7 shows a screen shot of the DWR List. The list is ordered by potential DWR route flying time savings. List information includes the aircraft call sign and type, the departure and destination airports, the direct route and DWR savings in minutes, the return capture fix and the number of auxiliary waypoints in the DWR solution. Also shown for each list entry are traffic (TR), sector load (SC), and weather (WX) conflict status indicators. A number in the TR column indicates minutes to a detected conflict on the DWR route. An "SC" entry in the SC column is color coded yellow or red indicating the DWR route is predicted to pass through a sector in yellow or red monitor/alert status.

In the current DWR software list entries must have a direct route savings of 5 min or more, but their DWR savings may be less than 5 min (but not less than 1 min). This display logic is selected at this stage in the development so that all solutions triggered by cases with 5 min direct route savings are visible to developers and users regardless of their DWR savings. As described later, this is also relevant to the analysis results in Section 4.1.

3.4 Trial planner

The Trial Planner is the user's primary tool for evaluating DWR route advisories. An interactive rapid-feedback trial planner tool enables users to quickly and easily visualize the proposed DWR route and modify it if necessary. Trial planning functions are common in air traffic management automation applications and are integral parts of many automation systems. A point and click action in the "TP" box to the left of the flight ID in the DWR List (Fig 7) initializes the trial planner with the advised DWR route. Fig. 8 shows the DWR graphical user interface display with a route trial plan that has been initialized by clicking the DWR List.

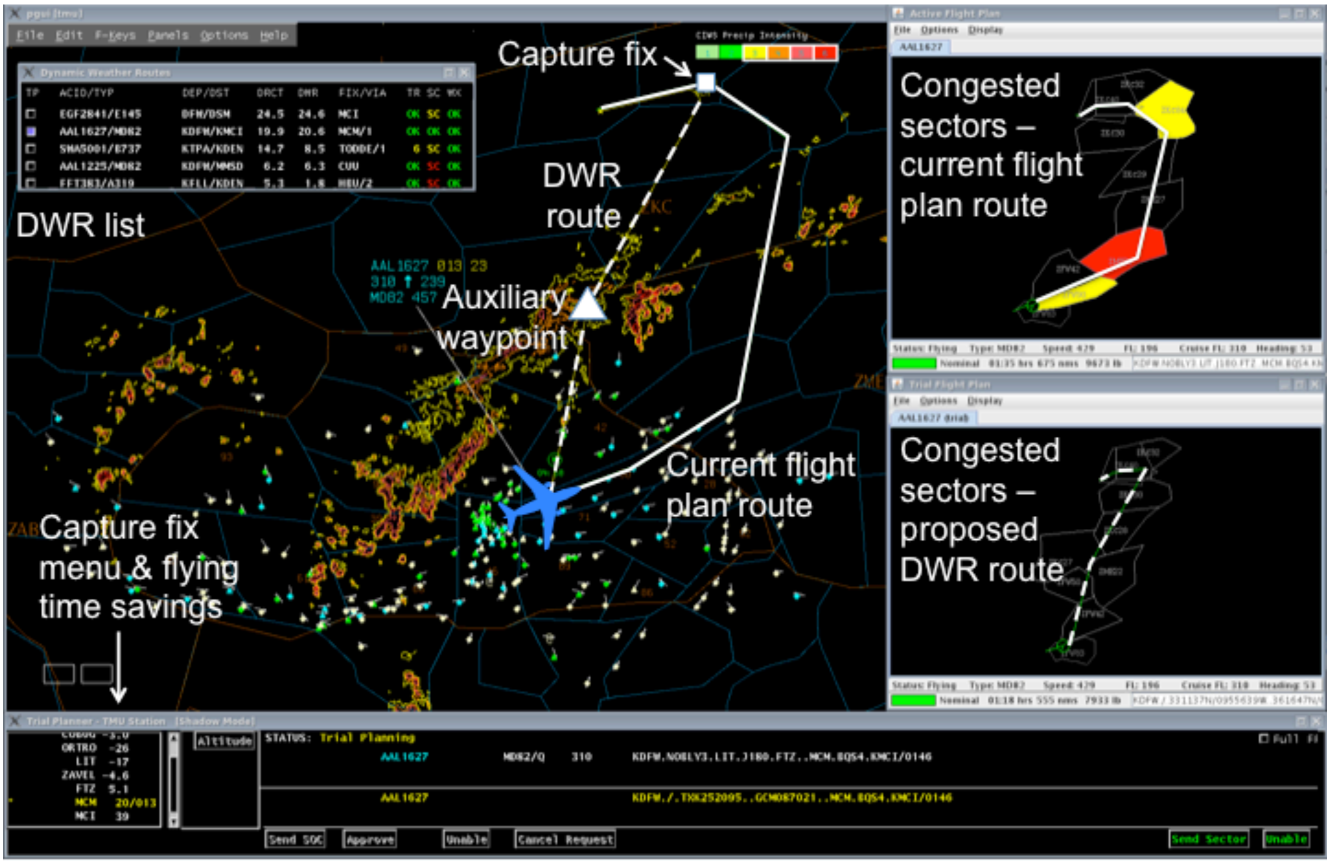

Fig. 8. DWR system graphical user interface. User clicks DWR list to activate trial plan for advised route. Click capture fix menu to change capture fix. Click and drag auxiliary waypoint to adjust DWR route or snap to nearby named fix. Traffic and weather conflict status, flying time savings, and downstream sector congestion information update in real-time as user adjusts trial plan route.

4 Performance

The DWR system described in Section 3 is implemented in software using CTAS and FACET. The system runs with either live or recorded traffic and weather feeds as its inputs. In this section potential flying time savings, downstream sector congestion, and weather modeling performance are analyzed. The analysis is based on archived recordings of actual en-route Center traffic from the Fort Worth Center airspace, national ASDI Class II traffic data, and time synchronized CIWS and CWAM weather model data.

Table 1 lists DWR system configuration parameters and their default values used in this analysis. The 70% WAF value was chosen because it represents the best tradeoff between probability of correctly and falsely predicting a pilot deviation for weather [3]. The 5 min trigger value for DWR analysis was selected because observations of Forth Worth Center traffic show that reroutes with five or more min savings are almost always due to convective weather. The 60 min weather time horizon was selected based on experience with weather forecast accuracy vs. time horizon. The maximum initial course change (85 deg), and limits on course changes between added auxiliary waypoints (70 deg) prevent the DWR system from suggesting operationally undesirable reroutes. Traffic conflict detection and resolution look-ahead parameters are those that have been used in recent automated traffic conflict detection and resolution studies [8,11]. Since CWAM models convective weather at altitudes between FL250 and FL450, a flight must have a flight plan altitude of FL250 or greater to be considered by the DWR route advisory algorithm (Section 3.3).

Five traffic samples were selected for analysis based on observed impact of weather on Fort Worth Center traffic (see Table 2).

Table 1. DWR system run-time parameters

Parameter Description	Default Value
CWAM WAF value	70%
Reference route time savings required to trigger DWR analysis	5 min
Weather detection/resolution time horizon	60 min
Traffic detection time horizon	8 min
Traffic resolution time horizon	12 min
Maximum initial course change relative to current Host flight plan	85 deg
Maximum course change between auxiliary waypoints and capture fix	70 deg
Minimum flight plan altitude	FL250

4.1 Potential flying time savings

The first route advisory to appear in the DWR List (Fig. 7) for any given flight is usually the one with the maximum potential flying time savings for that flight. This is intuitive since potential savings bleeds off as flights progress along active flight plan routes that include large dog legs. Small variations in the weather autoresolver solutions sometimes cause potential DWR savings to increase following the first successful solution, but generally potential savings decreases over time. In this analysis the following two additional constraints are applied in order for a DWR solution to be considered successful:

- Track altitude >= FL250,
- Three consecutive DWR solutions in 45 sec with track altitude >= FL250.

Fig. 9 (top) shows potential savings for the first successful DWR solution for a given flight ID over the 2.5 hour period on May 14, 2010. Yellow bars indicate solutions with residual traffic conflicts. The x-axis (in Figs. 9, 10, and 11) indicates the number of unique flights for which DWR routes were computed. Fig. 9 (bottom) shows the number of auxiliary waypoints that are inserted for the DWR solution. The number of auxiliary waypoints required for a successful DWR solution is one measure of reroute complexity. The results in Fig. 9 are for DWR solutions that resolve weather conflicts only. Fig. 10 shows the same metrics for flights where an integrated solution to both weather and traffic conflicts is computed.

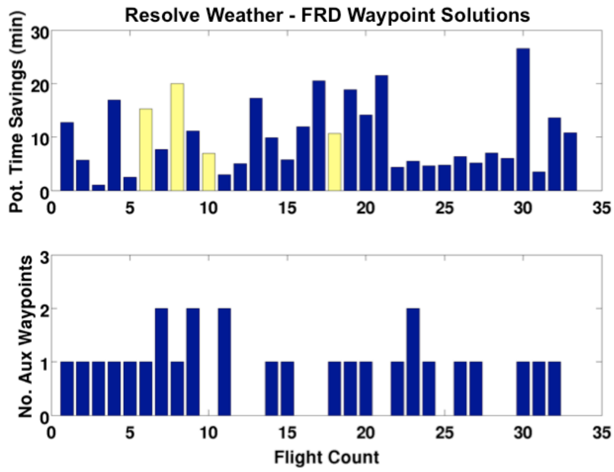

Fig. 9. Potential flying time savings and number of auxiliary waypoints for resolve-weather-only DWR solutions. Fort Worth Center traffic, May 14, 2010, 1400-1630 UTC.

Note that most solutions require one auxiliary waypoint, while some require two and a some are direct routes with no auxiliary waypoints. Also note that the integrated weather and traffic solutions do not have much impact on savings or the number of auxiliary waypoints. This is due to the fact that route changes to avoid weather have a relatively large impact on flying time, e.g., on the order of minutes, while changes to resolve traffic conflicts have a smaller impact on flying time, e.g., 10s of sec.

Table 2. DWR potential flying time savings analysis results, Fort Worth Center airspace, WAF 70%.

DWR Potential Time Savings				FRD Resolve Weather Only Solutions		FRD Resolve Weather & Traffic Solutions		Snap to Fix Resolve Weather Only Solutions	
Sample	Date	Start Time UTC	Stop Time UTC	flights	Flying Time Savings (min) min/max/avg/tot	flights	Flying Time Savings (min) min/max/avg/tot	flights	Flying Time Savings (min) min/max/avg/tot
1	5/14/2010	1400	1630	33	1.0/27/10.2/337	32	1.0/27/10.2/327	31	1.6/27/10.3/318
2	6/9/2010	1700	2025	50	3.2/30/10.9/543	50	3.2/30/10.8/542	50	1.8/30/10.7/536
3	6/24/2010	2000	2200	11	6.1/28/11.5/127	11	6.1/28/11.4/126	8	3.9/17/9.7/78
4	9/2/2010	2300	0205	41	1.6/30/8.1/330	41	1.6/30/8.0/328	36	0.7/26/8.1/293
5	3/19/2012	2300	0200	36	1.0/30/10.1/364	36	1.0/30/10.1/364	34	1.0/30/10.1/343

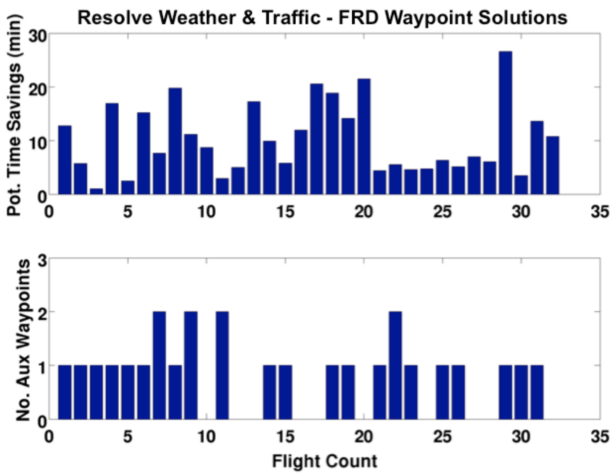

Fig. 10. Potential flying time savings and number of auxiliary waypoints for resolve weather and traffic solutions. Fort Worth Center traffic, May 14, 2010, 1400-1630 UTC.

Since the resolve-weather solutions use FRD auxiliary waypoints and the corresponding snap-to-fix solutions use named fixes, comparing their time savings for common DWR solutions provides a direct comparison between savings achievable with data link and savings achievable using voice-based operations where FRD solutions are not usable. Fig. 11 shows potential flying time savings vs. flight count for FRD weather-only solutions (top graph) and their associated snap-to-fix solutions (bottom graph). Fig. 11 also indicates cases where snap-to solutions had residual traffic conflicts (yellow bars) and residual weather conflicts (orange bar).

Table 2 summarizes the resolve-weather-only, resolve-weather-and-traffic, and the snap-to-named-fix results for the May 14, 2010 traffic sample and the four other traffic samples processed in this analysis. Listed in the table are the number of flights for which successful DWR solutions were computed over each traffic sample. Also listed are the minimum and maximum potential savings at the first successful DWR solution, and the average and total savings considering all DWR flights.

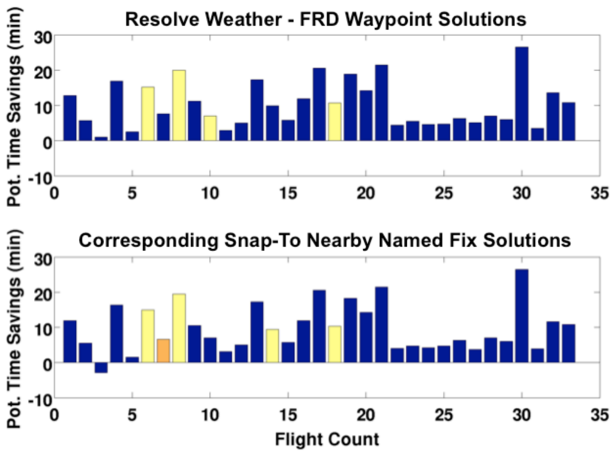

Fig. 11. Comparison of potential flying time savings for FRD waypoint and corresponding snap to fix solutions. Fort Worth Center traffic, May 14, 2010, 1400-1630 UTC.

The results (5/14/2010) show that the number of successful solutions drops from 33 to 31, and overall savings drops from 337 min to 318 min, but the average savings per flight is about the same at 10.2 and 10.3 min per flight. Clearly these data and those from other days analyzed (Table 2) indicate not much difference between FRD and snap to named fix solutions. However, the number of named fixes actually usable by an airline or air traffic control is likely smaller than the total number of fixes in the adaptation data base. An analysis of operationally usable fixes is ongoing, but beyond the scope of this paper.

4.2 Track miles analysis

Flights for which DWR routes are computed are analyzed using ASDI track data to examine actual flight tracks downstream of the first successful DWR advisory. The difference between the proposed DWR flight trajectory and the actual track is one metric for assessing potential benefit. For example, if the flight actually received a reroute that realized much of the DWR savings, then the DWR benefit would be decreased.

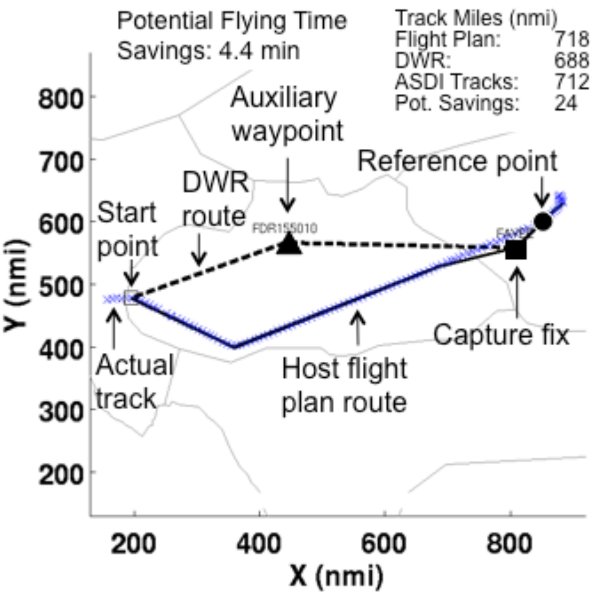

Fig. 12. Track miles analysis, sample flight

Fig. 12 shows a flight from Tucson, Arizona to Memphis, Tennessee taken from the May 14, 2010 traffic sample. The Host flight plan (solid line), the first successful DWR route (dashed line), and the capture fix are shown. Also shown are the actual ASDI tracks (blue 'X's) for the flight. In this case the Eastbound flight stayed mostly on the original Host flight plan but, as indicated by the ASDI track data, received a short direct route near the boundary of Fort Worth and Memphis Centers.

In order to compare actual track miles to DWR track miles a downstream reference point is identified where the actual track merges back to the flight plan route. This reference point is nominally the DWR capture fix, but often, especially during weather events, flights deviate or change their routing following the point where the first DWR route is posted to the list (Fig 7). The capture fix and all flight plan fixes downstream of the capture fix are tested to find the fix with the closest ASDI track. That fix and its associated ASDI track are the reference points for the track miles analysis. Note in Fig. 12 how the actual track data rejoin the flight plan at the reference point. The track miles distance from the DWR start point to the reference fix along the DWR route is subtracted from the actual track miles flown from the DWR start point to the reference track point. A positive value indicates a potential savings.

Fig. 13 shows potential track miles savings for each flight that received a DWR advisory in the May 14, 2010 traffic sample. Negative values indicate the flight flew a shorter distance than it would have had it flown the DWR trajectory. The data show that even considering events downstream of the DWR advisory, most flights indicate a potential savings in track miles.

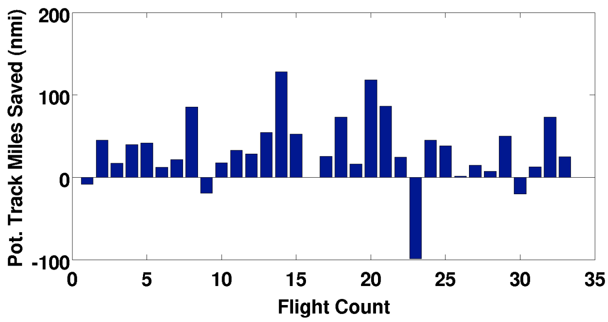

Fig. 13. Potential savings in track miles. May 14, 2010 traffic sample.

4.3 Downstream sector congestion

Using FACET's sector congestion analysis (described in Section 3.3, Step 6 above), the newly suggested DWR routes and the nominal flight plans were compared. As described earlier, the flight routes are shown in two different windows for the user to see (as shown in Fig. 8 above).

For the recorded Class II ASDI data on May 14, 2010 and September 2, 2010, two types of analyses were performed using FACET. First, a comparison of encountering sector congestion for the nominal flight plan route and the DWR route was performed. Congestion is defined as the number of aircraft exceeding the nominal MAP value. Then, the number of sector congestion occurrences for the two routes were computed. Details for September 2, 2010 and additional days are presented in [19].

Out of 32 flights selected for potential savings, 10 would have benefitted from a sector congestion perspective had they flown along the DWR route. Those flights encountered congested sectors during their as-flown tracks, but not on their DWR routes. Two flights would have encountered congestion on the DWR route but did not encounter congestion along their as-flown path.

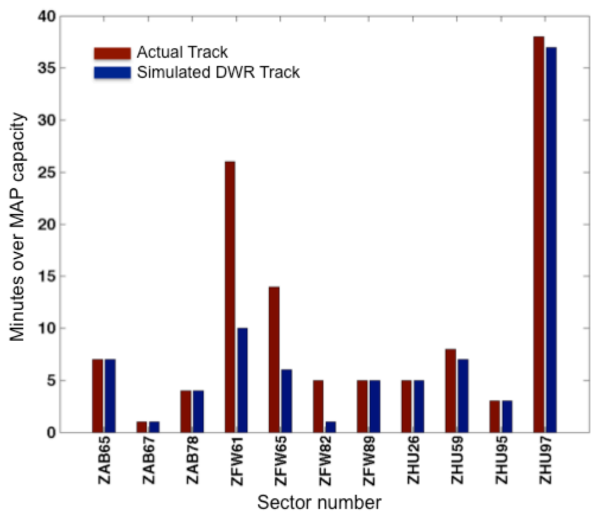

Fig. 14. Number of one-minute instances when sectors went over MAP value for the as flown case (red) and for the simulated DWR route case (blue). May 14, 2010 traffic sample.

One of the main questions to answer from the FAA's perspective is that if all of the flights for which DWR routes were proposed were to fly along those routes, would the state of the system be worse from a traffic congestion perspective? Fig. 14 attempts to answer that question using data from the May 14, 2010 traffic sample. Fig. 14 presents the number of one-minute occurrences of congestion in the Fort Worth Center and its four neighboring Centers (Albuquerque, Kansas City, Memphis, and Houston). The red bars represent the number of instances any of the sectors in those Centers go over nominal MAP value while the aircraft were flying their current filed flight plans. The blue bars represent the same value when all the aircraft flew their first suggested DWR routes. It is clearly seen that all the sectors in the five Centers fared equally or better when the aircraft flew the DWR routes. The data in Fig. 14 suggest that DWR trajectories result in a 35% reduction (in 11 sectors) in time spent over capacity. For the September 2, 2010 data, DWR trajectories resulted in 55% reduction (in 8 sectors) in time spent over capacity.

4.4 Frequency of DWR advisories

Another important question from an FAA perspective is how often might a single controller get a request for a DWR reroute? The frequency of DWR route advisories for individual flights and the distribution of DWR routes across different airspace sectors is a measure of controller workload associated with DWR. Fig. 15 plots the first occurrence of a DWR route advisory for a new flight ID over time in 15 min time bins and by en-route sector ownership. Each vertical bar indicates the

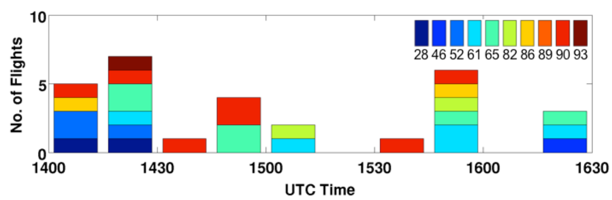

Fig. 15. Frequency and sector ownership of new DWR routes in Forth Worth Center. May 14, 2010 traffic sample.

number of flights in Fort Worth Center that received a new DWR route advisory during the 15 min time interval. The color coding indicates the en-route sector number that has track control of the flight at the time the DWR route was first posted. Fig. 15 shows that the highest frequency of new DWR advisories for any one sector is two per sector in a 15 min period. These cases occur during the 1400-1415 (Sector 46), 1415-1430 (Sector 65), 1445-1500 (Sectors 65 & 90), and 1545-1600 (Sector 61) time periods.

An examination of the DWR advisories for all five traffic samples (Table 2) indicates that the worst case situation occurs in the September 2, 2010 sample where DWR advisories for three new flights occur during one 15 min interval in the 3 hr and 5 min traffic sample.

Though controller workload depends on many factors, and is generally higher during weather, the frequency of DWR route advisories indicated in Fig. 15 and the other four traffic samples does not seem overwhelming.

4.5 Weather avoidance metric

The DWR solutions described in Section 4.1 were analyzed to determine if the DWR trajectory would have remained free of weather conflicts over the planning horizon (60 min) had the aircraft actually flown the DWR route. For the purposes of this analysis the zero look-ahead forecast, i.e., the 'nowcast,' is assumed to be true weather. Therefore, the analysis determines if DWR trajectories remain clear of nowcast CWAM weather.

Nowcast CWAM weather is determined by applying CWAM modeling described in Section 3.2 to actual observed CIWS weather (i.e., not forecast weather) at the current time. Each point in time along the DWR trajectory (at 10 sec intervals) is checked for encounters with nowcast weather corresponding to the same time within 25 nmi of each DWR trajectory point. For example, the predicted position of the flight along the DWR trajectory at 1620 UTC is checked for encounters with the nowcast weather at 1620 UTC. If a CWAM polygon is detected within 25 nmi, additional analysis is performed to determine if that polygon can be paired with another on the opposite side of the flight path to form a gap. Paired polygons are considered to be part of a gap if they are within 50 nmi of each other and on opposite sides of the flight path. If a polygon is detected within 25 nmi on one side of the flight path, but not on the other, the distance from the trajectory point to the polygon is a buffer. If a trajectory point is found to be inside a nowcast polygon, the trajectory is in conflict with the nowcast weather. If there is no nowcast weather within 25 nmi on either side of the trajectory point that point is said to be free of weather encounters.

Once all DWR trajectory points for a specific flight are analyzed for weather encounters, the worst case nowcast weather encounter is logged. In order of severity, the worst case encounter is a flight through a narrow gap, followed by nowcast weather conflicts and buffers. Fig. 16 illustrates the nowcast weather analysis for a specific flight. The nowcast CWAM polygons are shown with a solid black line, while the corresponding forecasted CWAM polygons are shown with a dashed gray line. The forecast polygons were those forecasted, and avoided, at the time when the DWR route was computed, and are shown here for reference. The "X" is the point of the closest encounter with nowcast polygons.

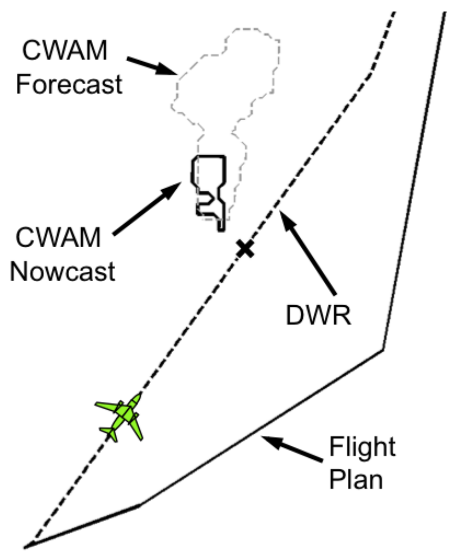

Fig. 16. Nowcast weather analysis example

Fig. 17 illustrates a nowcast weather metric for cases where the DWR trajectory does not conflict with the nowcast weather. Note the distinction between a buffer and a gap. A buffer encounter has nowcast weather within 25 nmi on one side of the flight path, but the distance to the nearest nowcast polygon on the other side is more than 50 nmi. In the gap encounter, the distance between polygons on either side of the flight path is 50 nmi or less. A red-yellow-green color scheme is used to indicate severity of the encounter and used later in Fig. 20 to distinguish nowcast encounter results for all flights.

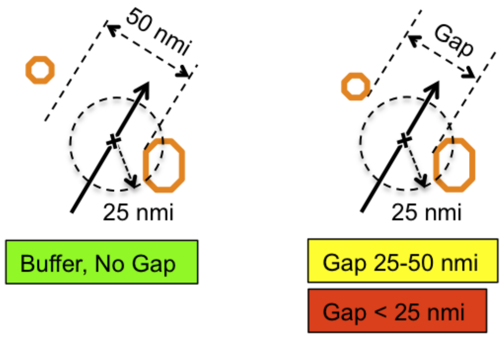

Fig. 17. Nowcast buffer and gap metrics for no weather conflict

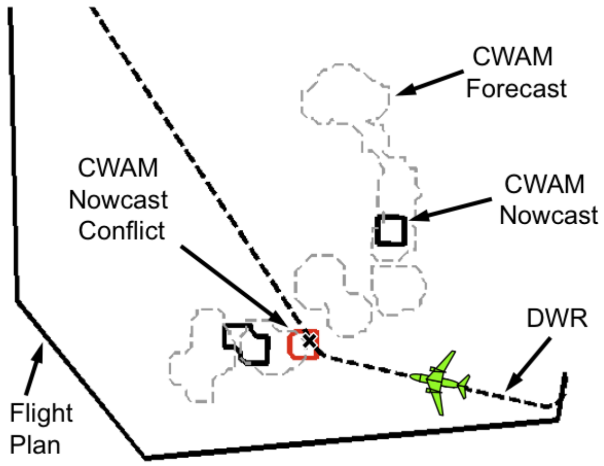

Fig. 18. Nowcast weather conflict example.

When the DWR trajectory conflicts with a nowcast CWAM polygon as in Fig. 18, the distance required to deviate around the weather is calculated before buffer and gap measurements are applied. The required deviation distance typically corresponds to the direction of minimum deviation unless that direction results in an encounter with additional weather or narrow gaps. In this case, the required deviation is to the right. This deviation to the right causes the aircraft to fly through a gap. The nowcast metrics for cases when a deviation around weather is required are illustrated in Fig. 19.

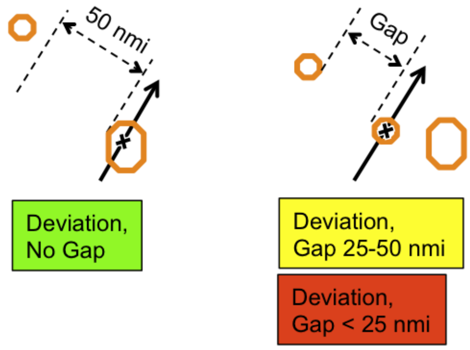

Fig 19. Nowcast buffer and gap metrics with weather conflict and required deviation

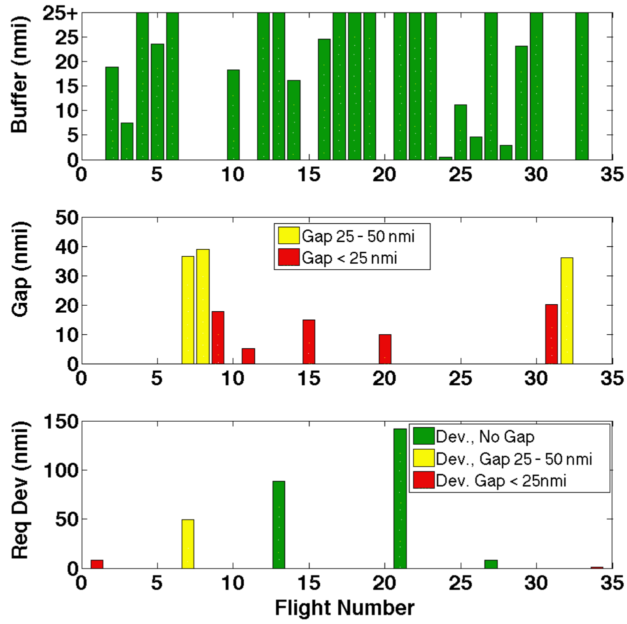

Fig. 20. Summary of nowcast weather metric.

The nowcast metrics for each DWR trajectory in the May 14, 2010 traffic sample are summarized in Fig. 20. Each flight has associated with it a buffer (top graph) or gap (middle graph) distance. If the DWR trajectory conflicted with nowcast weather, a required deviation (bottom graph) is also reported. It should be noted that the current deviation metric logic determines the required deviation around the initial weather cell conflict only and does not consider deviations around resulting secondary conflicts. The large required deviation of over 140 nmi reported for flight number 21 corresponds to the direction opposite of the minimum deviation because the minimum deviation results in secondary weather conflicts.

The plots in Fig. 20 together form a quantitative weather avoidance metric that incorporates buffers, gaps, and required deviation for cases where un-modeled weather turns up on the DWR route. A downstream deviation on the DWR route likely does not pose a safety hazard, and retains much of the DWR savings, as long as there is room to deviate without flying through narrow gaps (e.g., Flight 27). The autoresolver logic is now being improved to better detect and reject DWR solutions that indicate flight through narrow gaps. This should help eliminate the gap cases in Fig 20. Further development of the nowcast weather metric is ongoing.

5 Operating Concepts

The DWR system (Fig. 1) supports mixed data link equipage operations and is configurable for varying levels of ground automation at airline System Operation Centers and FAA en-route Centers. Fig. 21 depicts operating concepts and automation levels ranging from today's voice-based operations to the use of currently available air/ground data link, e.g., Future Air Navigation System with Controller-Pilot Data Link Communication (FANS/CPDLC) [11,12,13].

In the baseline voice operations (Concept 1) airline dispatchers use DWR to identify reroutes, and uplink them to flight crews via ACARS. Pilots evaluate proposed routes and request reroutes from Center controllers using today's procedures. Voice operations are restricted to the use of named fixes for auxiliary waypoints. The system alerts dispatchers to routes that transit congested sectors (and active special use airspace) and consequently may not be workable.

The next level of automation (Concept 2), still voice-based, assumes some level of automated reroute coordination between airline dispatchers and Traffic Management Coordinators (TMCs) at the local Center Traffic Management Unit (TMU). Simulation results suggest that if a Center controller receives a reroute request that they know has been coordinated with their Center TMU, the flight is more likely to get cleared on the new route [13]. An extension of this (Concept 3) is to send the coordinated reroute from the TMU to the sector position which has track control of the flight. Trial planning functions at the sector position, including those already available at the D-Side sector position, enable controllers to visualize, evaluate, and implement pre-coordinated reroutes.

The use of air/ground data link communication (Concept 4) would further reduce pilot and controller workload and remove the requirement that auxiliary waypoints be restricted to named fixes.

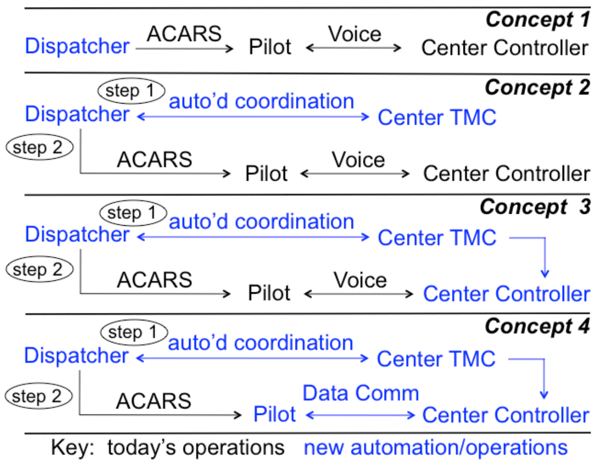

Fig. 21. DWR operating concepts

6 Summary

A ground-based trajectory automation system that continuously analyzes flights in en-route Center airspace to find simple time- and fuel-saving corrections to existing weather avoidance routes has been developed and tested in the laboratory.

The DWR system is based on integration of the Center/TRACON Automation System (CTAS), the Convective Weather Avoidance Model (CWAM), and the Future ATM Concepts Evaluation Tool (FACET). Automation enables users to evaluate flying time, traffic conflicts, weather avoidance, and downstream sector congestion when considering reroutes.

Based on analysis of 14 hours of Fort Worth Center traffic over five convective weather days, DWR routes were found for 171 flights with an average savings of about 10 min per flight.

Analysis of downstream sector counts in the home Center (Fort Worth) and its immediate neighboring Centers (Kansas City, Memphis, Houston, Albuquerque) shows that if all aircraft were to fly DWR routes, sector congestion as measured by the monitor/alert parameter would decrease. Taking aircraft off of standardized weather routes can reduce congestion during weather events.

Analysis of weather modeling performance uncovered metrics for characterizing the severity of weather encounters in terms of gaps, deviations, and buffers. A reroute that ultimately requires a small deviation is likely still beneficial since small deviations typically result in small delays relative to the overall savings of the DWR route.

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