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Dynamic Arrival Routes: A Trajectory-Based Weather Avoidance System for Merging Arrivals and Metering

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Convective weather can cause arrival traffic to fly less efficient weather avoidance routes and is the primary cause for time-based metering to be discontinued. Dynamic Arrival Routes (DAR) is a trajectory-based weather avoidance system that is designed to help improve arrival traffic flow when weather is present. The DAR system continuously analyzes airborne arrival flights for opportunities to reroute them to more efficient arrival routes or around weather that is predicted to be on their current flight plan early enough to allow the arrival time-based metering system to adjust its times of arrival for the presence of weather. Analysis of 93 hours of actual traffic over 12 different days from Fort Worth Center showed DAR proposed more efficient arrival reroutes for 352 arrival flights for an average time savings of 12.3 minutes per flight at a look-ahead time of 60 minutes from the meter fix. DAR also identified 642 arrival flights with a need to deviate around weather and proposed weather avoidance routes that were analytically shown to remain weather-free 83 percent of the time for a look-ahead time of 30 minutes from the meter fix.

I. Introduction

RECENT strides towards a future Next Generation Air Transportation System (NextGen) have seen NASA transfer a number of concepts and technologies that promise to improve the FAA's Time-Based Flow Management (TBFM) system.[1-4] These improvements include enhancements to the current time-based metering system, known as the Traffic Management Advisor (TMA), which facilitates the efficient flow of arrival traffic into congested airports. In this context, a flight is classified as an arrival if it is approximately 60 minutes from landing at a major destination airport (i.e., airport with metering program). Studies have shown that weather is one of the primary causes for time-based metering to be discontinued.[5] One reason for this is due to the current TBFM system's inability to adjust its predicted times of arrival for aircraft that need to deviate around weather. In this situation, controllers will likely revert back to miles-in-trail (MIT) operations, a simpler but less efficient method of managing arrival traffic flow into a congested airport.[6] In order to preempt potential disruption in the arrival flow and metering, arrival flights may be routed to a different but often less efficient arrival route to avoid forecasted weather hours before the flight would arrive (i.e., a time when weather forecasting error is high). Even if weather does not impact the arrival route or fails to materialize as forecasted, arrival flights will often continue to fly these less efficient arrival routes because the current Traffic Flow Management System (TFMS) and TBFM system cannot remedy these routing inefficiencies.

Related research addressing convective weather impacts on arrivals include the Arrival Route Status and Impact (ARSI) concept developed by Massachusetts Institute of Technology Lincoln Laboratory (MITLL).[7] The ARSI concept is the arrival counterpart to MITLL's operationally tested Route Availability Planning Tool (RAPT),[8,9] which predicts departure route blockage/availability due to convective weather. Both ARSI and RAPT are limited to informing users of route availability for static, pre-defined arrival and departure routes, respectively. Neither concept has weather avoidance rerouting functionality. A dynamic programming tree-based algorithm and associated concept of operations for dynamic rerouting around weather was proposed and evaluated in simulation for controller and pilot acceptablility.[10,11] However, this simulation did not evaluate the performance of the weather avoidance algorithm itself.

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An ongoing FAA research project referred to as Optimized Route Capability (ORC) seeks to assist traffic flow managers in proactively rerouting arrival traffic in response to changing operational demand (i.e., volume that exceeds an airport's arrival rate).[12] Current ORC development analyzes meter fix loading and looks for opportunities to intelligently offload arrival fix demand to underutilized arrival routes.[13] Although meter fix load imbalance may be due to the presence of convective weather, ORC does not directly address weather and instead relies on the user to assess weather impacts.

Dynamic Weather Routes (DWR) is a NASA developed tool that incorporates trajectory-based weather avoidance technology to continuously search for more efficient routes for airborne flights in en route airspace. The DWR tool proposes time-saving, weather-free reroutes for departures and overflights, but does not do the same for arrivals. It has been successfully tested as an Airline Operations Center/Dispatcher application in a field trial with American Airlines.[14-16]

This paper describes the development of Dynamic Arrival Routes (DAR), a trajectory-based system that leverages DWR technology to provide two new functions to help improve arrival traffic flows when weather is impacting arrival routing into major airports. First, DAR identifies flights that could be rerouted to more efficient routes that may have been previously impacted by weather. Secondly, when weather is impacting the standard arrival routing, DAR proposes simple arrival route corrections that enable aircraft to stay on their flight plan while avoiding weather. The DAR system proposes reroutes early enough to allow the time-based metering system to adjust its predicted times of arrival before the arrival schedule is frozen (i.e., freeze horizon). As a result, metering operations can be sustained in the presence of weather because the arrival schedule accounts for the need of arrival flights to deviate around weather. The DAR system shares many of the same core processes including the trajectory synthesizer used by other NASA technologies transferred to the FAA, thus, potentially simplifying integration with NextGen systems.

A detailed description of the DAR system and its algorithms is provided in Section II and includes notional examples of each of the two new DAR functions. Actual scenario examples taken from the Fort Worth Air Route Traffic Control Center (ARTCC) are used to illustrate DAR functionality and are analyzed for system benefits and performance in Section III. The paper closes in Section IV with concluding remarks which summarize the new functionality introduced by the DAR system and its associated benefits to arrival traffic flow management.

II. System Description

The DAR system is a derivative of DWR that leverages the trajectory automation developed under DWR to provide two new functions to help improve arrival traffic flow when weather is impacting arrival routes into major airports. With the exception of the Future ATM Concepts Evaluation Tool (FACET) that is used by DWR to analyze reroute effects on sector congestion, DAR shares all the same software components including the traffic display, the trail planner interface, and the trajectory-based weather avoidance technology. DAR has been integrated with arrival scheduling components currently being used by TMA in order to allow the user to evaluate the impact of proposed DAR reroutes on arrival scheduling. Key aspects of the DAR system are described in more detail in the following sections.

A. Dynamic Arrival Routes Algorithms

The primary difference between DAR and DWR are the algorithms used to identify candidate arrival flights and calculate reroutes under arrival routing constraints. Both systems update trajectories for all flights every 12 seconds (i.e., radar track update rate). The DAR algorithm adds two new functions that continuously analyze the trajectories of airborne arrival flights for DAR candidates that may fall into the following two rerouting scenarios. First, DAR looks for opportunities to reroute arrivals to more efficient, time-saving arrival routes that save at least 5 minutes (user defined) of wind-corrected flight time. If a time-saving reroute cannot be found, DAR probes the current flight plan of the arrival for convective weather conflicts. If a weather conflict is found, DAR proposes a reroute that will allow the arrival to avoid the weather. Once DAR candidates are found, they are posted to a list on the user interface where the user can select, examine, and modify the proposed DAR, if desired. Each DAR scenario as well as the DAR list is described in detail in the following sections.

1. Opportunities for more efficient arrival routes

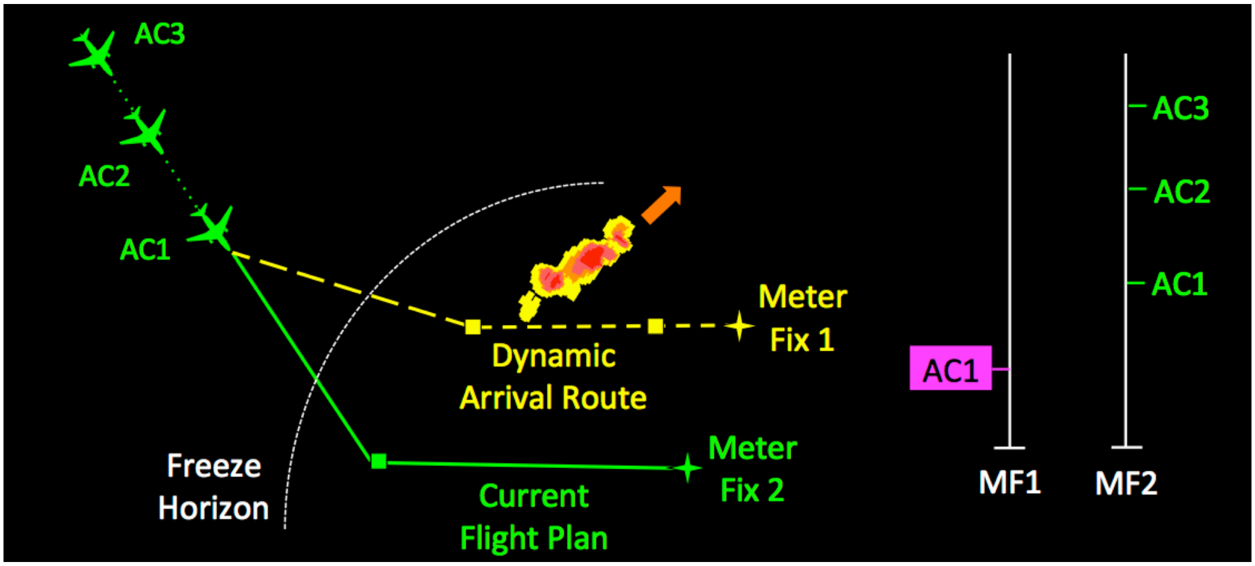

Figure 1. Identifying opportunities for more efficient arrival routes

When weather is forecasted to disrupt the flow of arrival traffic into a meter fix, traffic managers must often route arrival flights to a different meter fix via alternate, but more inefficient, arrival routes (i.e., Standard Terminal Arrival Route or STAR) to preempt potential disruption. These preemptive routing decisions are typically made hours before the flight is expected to arrive, a time when weather forecasting uncertainty is high.

The DAR algorithm is designed to ensure arrival flights are on their most efficient route. Currently, DAR assesses arrival route efficiency in terms of flight time. Other arrival route efficiency metrics such as meter fix loading could also be considered in the future. The notional example shown in Figure 1 depicts three arrival flights with flight plans that route them over Meter Fix 2 (MF2) with the assumption that the STAR to Meter Fix 1, the preferred route, was predicted to be blocked by convective weather at the time flight plans were originally filed. A simplified arrival scheduling timeline is also shown on the right side of Figure 1. The scheduled time of arrival (STA) for the three flights are shown in green on the simplified timeline for MF2. As a key DAR concept element in this example, all three flights have yet to reach the arrival scheduling freeze horizon, and therefore, could be rerouted early enough for the time-based metering system to adjust its times of arrival. Currently, DAR does not analyze arrivals that have passed the arrival scheduling freeze horizon.

The DAR algorithm builds a series of trial trajectories direct to the start of every published STAR transition leading to the next nearest meter fix for each arrival. Each of these potential DAR trajectories are checked for weather conflicts. DAR considers an arrival as a time-saving reroute candidate if a direct weather-free route to a published STAR transition can be found that saves more than 5 minutes of wind corrected flying time. If multiple trajectories for a given arrival meet these criteria, DAR selects the trajectory with the most time saving. A trial estimated time of arrival (ETA) is also calculated for each DAR candidate so that the arrival scheduling impact can be evaluated. Figure 1 shows the trial DAR ETA in magenta on the appropriate meter fix timeline. Example arrival flight AC1 is shown to arrive earlier than scheduled on under utilized alternate meter fix MF1.

Currently, DAR is limited to checking STARs leading to the next nearest meter fix not on the same gate as the current meter fix for potential time-savings reroutes options and does not actively consider time-based metering impacts in its rerouting solution. Work to expand potential DAR time-saving route options is ongoing. Incorporating arrival scheduling constraints into the DAR solution is planned for the future.

2. Route corrections for weather impacted arrival routes

Studies have shown weather is one of the primary causes for time-based metering to be discontinued. When deviation around convective weather is required, actual arrival traffic can be observed deviating in an ad hoc manner. Moreover, the flight plans of these arrivals may not be updated to reflect this deviation, possibly as a result of increased controller workload when convective weather is present. As a result, the arrival scheduler (e.g., TBFM system) is unaware of the flights' intent to deviate and, therefore, would be unable to adjust the times of arrival appropriately.

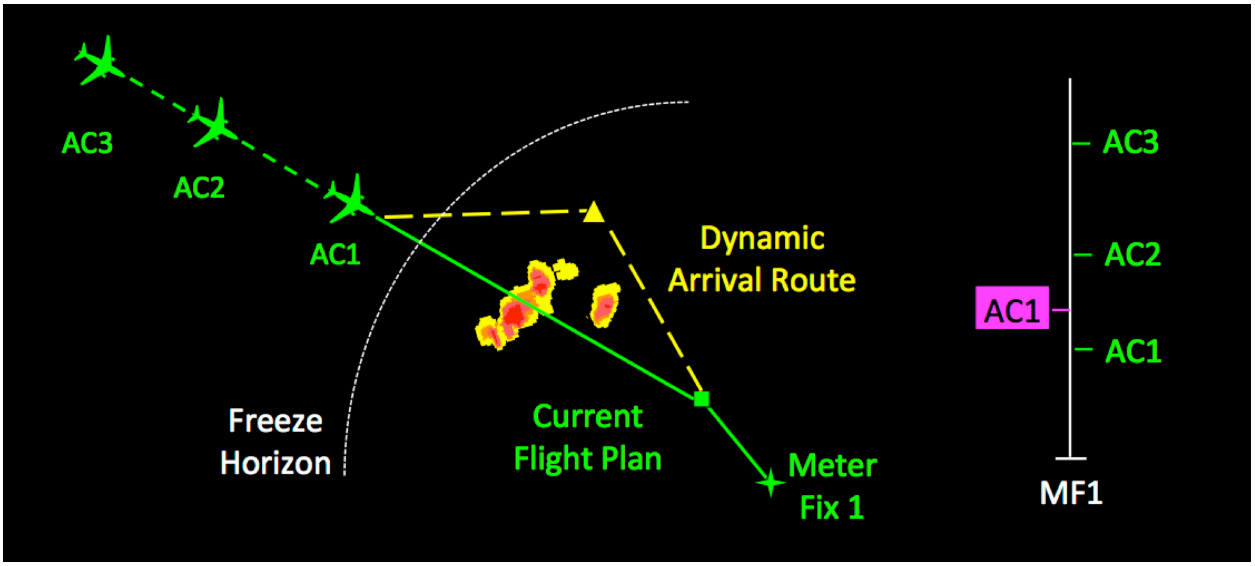

Figure 2. Identifying route corrections for weather-impacted arrival routes

The DAR algorithm analyzes the current flight plans of arrivals for the need to deviate around weather and calculates weather avoidance reroutes if necessary. This weather deviation analysis only occurs for arrivals that have not been identified by DAR as candidates for rerouting to more efficient arrival routes by the functionality described earlier. Figure 2 is a notional example to be used to describe the DAR weather avoidance algorithm. Convective weather is shown to be in conflict with the current flight plan of example arrival flight AC1 represented by the green line and, therefore, will need to deviate. The scheduled times of arrival based on the current flight plans of the three example flights are shown on the simplified arrival scheduling timeline on the right. As with the notional example shown earlier, a key DAR concept element is reinforced by the fact the weather conflict with the example flight is detected before the flight has reached the arrival scheduling freeze horizon, thus, allowing time for the arrival scheduler to adjust its scheduled times of arrival to a DAR weather avoidance reroute.

Once a weather conflict is detected, the DAR algorithm will calculate a route around the weather. The DAR weather avoidance algorithm is based on the successfully field tested DWR algorithm. The typical weather reroute proposed by this iterative weather avoidance algorithm is direct to a downstream capture fix via one or more auxiliary waypoints (if needed). DAR limits the eligible downstream capture fixes to the intersections of the STAR transitions prior to the meter fix (i.e., no direct routing to the meter fix). A single auxiliary waypoint is shown on the DAR as a yellow triangle in Figure 2. The algorithm establishes its location by calculating a series of trajectories that deviate around each side of the weather by an incremental distance. The trajectory that avoids the weather with least amount of delay is selected as the DAR candidate. Auxiliary waypoint locations are calculated generically (i.e., fix-radial-distance or FRD format). In order to facilitate voice operations, an auxiliary waypoint can be moved or "snapped" to the nearest named fix that maintains a weather-free route. The trial ETA of the proposed DAR weather deviation route is also calculated and is displayed on the example timeline in magenta. In this example, the DAR reroute would delay the arrival AC1 with respect to the weather conflicted initial scheduled time of arrival.

3. DAR List

Dynamic Arrival Routes

TP	ACID/TYPE	DEP/TRAN.STAR.DEST	SAV	TRANS.STAR/AUX	STATUS
☐	SWA2795/B737	KELP/INK.JEN9.KDAL	-2.9	JEN.JEN9/1	OK
☐	EJM36/F2TH	KVNY/TQA.JEN9.KDAL	-2.7	JEN.JEN9/2	OK
☐	EGF2776/E135	MMSP/LOA.CQY7.KDFW	6.9	SAT.JUMBO3	ALT
☐	AAL2446/B763	KLAX/INK.JEN9.KDFW	-2.9	JEN.JEN9/1	OK
☐	AAL1228/B738	KSNA/INK.JEN9.KDFW	-3.1	JEN.JEN9/1	OK
☐	AAL1242/MD82	KDEN/JEN.JEN9.KDFW	18.5	TXO.UKW2	ALT
☐	VRD714/A320	KSFO/JEN.JEN9.KDFW	8.4	TXO.UKW2	ALT

Figure 3. DAR List

All DAR candidates found by the algorithm are posted on the DAR list, an example of which is shown in Figure 3. The DAR candidate callsigns and aircraft types are shown in the second column under the heading "ACID/TYPE." The example DAR list in Figure 3 shows all DAR candidates, but can be filtered by airline if being used in an airline operation center application. The DAR list is sorted by destination airport, then by current STAR and transition, and finally by time savings. The flights departure airport, current arrival route information, and destination airport are shown in the third column. Current arrival route information includes the name of the STAR and its transition fix.

Information with respect to the proposed DAR reroute is shown in the three columns on the right of the list. The "STATUS" column indicates the type of DAR reroute. The "ALT" status is a time-savings reroute to an alternate STAR/meter fix, while "OK" status indicates a weather conflict was found on the flight's current route and a weather avoidance route was successfully found. Arrival route and number of auxiliary waypoints in the proposed DAR is shown under the column heading "TRANS.STAR/AUX." Time savings or delay for the DAR route is listed under "SAV." For example, a weather conflict was detected along the current flight plan of SWA2795 and a DAR weather avoidance reroute with one auxiliary waypoint was proposed which would result in a delay of 2.9 minutes. The DAR for AAL1242 proposes a reroute from the Glen Rose arrival (JEN9) to an alternate arrival route, the BOWIE arrival via the Texico transition (TXO.UKW2) for a time savings of 18.5 minutes. The "TP" buttons on the left side of the DAR list allows the user to select and display the proposed DAR in the trial planner interface, examples of which will be shown in subsequent sections.

B. Weather Model

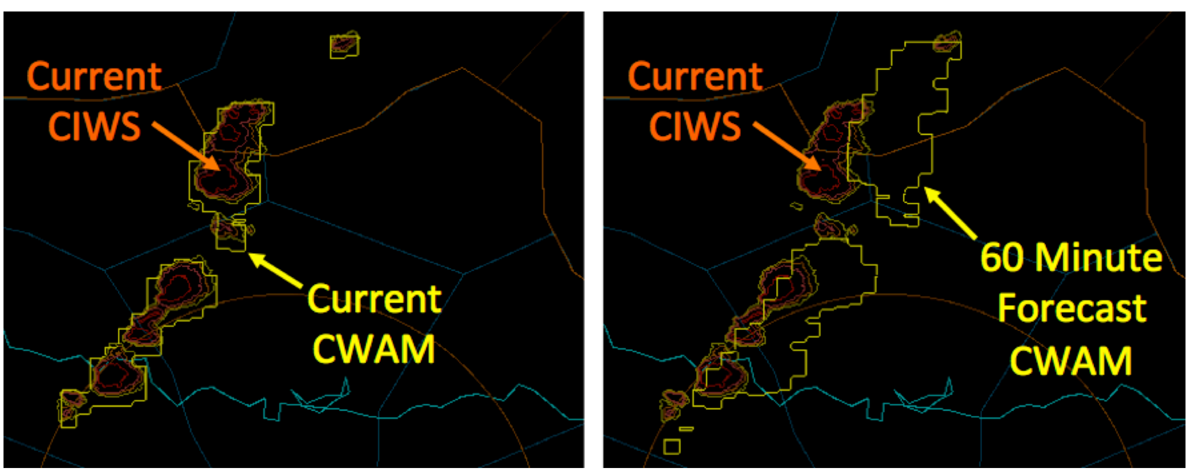

Figure 4. Example of the Terminal Area Convective Weather Avoidance Model (CWAM)

The DAR system utilizes the Convective Weather Avoidance Model (CWAM) developed by MITLL.[8] CWAM is a probabilistic model of pilot deviation around weather. Current and forecasted weather data consisting of vertically integrated liquid (VIL, a measure of precipitation intensity) and echo tops from the Corridor Integrated

Weather System (CIWS) are inputs to the CWAM model. Weather is forecasted for two hours and is updated every five minutes. The resulting output is referred to as Weather Avoidance Fields (WAF), polygons representing regions around weather that a certain percentage of pilots are predicted to avoid. For example, a 70 percent WAF (currently used by DAR) represents a region which 70 percent of pilots are predicted to avoid (Figure 4). The picture on the left shows the current CIWS weather and the CWAM polygons for the same time, while the picture on the right shows the corresponding CWAM polygon for a 60-minute forecast.

Modeling of WAF differs as a function of airspace operations, so MITLL has created two variants of CWAM, en route and terminal, for specific applications. NASA's DWR which proposes reroutes for airborne departure and overflights uses the en route version of CWAM where echo top height is the dominant factor. As a result, the en route variant of CWAM allows for flights to "top" or fly over WAFs. MITLL's ARSI and its departure counterpart RAPT are designed to be applied to flights transitioning to/from the terminal area. VIL intensity is the dominant factor in the terminal area version of CWAM. The WAFs modeled by terminal variant of CWAM are not a function of altitude and only represent the probability of pilots to deviate around weather laterally. Currently, only the terminal area variant of the CWAM model is implemented in DAR because DAR's primary focus is to improve arrival flow to the meter fix when convective weather is present. Because DAR may propose reroutes well before the arrival flight begins transitioning to terminal airspace, integration of the terminal CWAM model with the en route CWAM model is planned.

III. Actual Scenario Examples and Analysis

This section uses actual scenario examples of observed traffic at Fort Worth ARTCC (ZFW) to illustrate how the DAR system identifies candidates for more efficient arrival routes or corrections to weather impacted arrival routes. First, each actual scenario is described in detail. Then, examples of the DAR system working on the scenario are shown, followed by an analysis of the DAR system's performance for the specific type of scenario. Aggregate DAR system performance was based on the analysis of 93 hours of traffic over 12 different days when convective weather was present at ZFW between March 23, 2013 and September 6, 2014.

A. Rerouting to More Efficient Arrival Routes

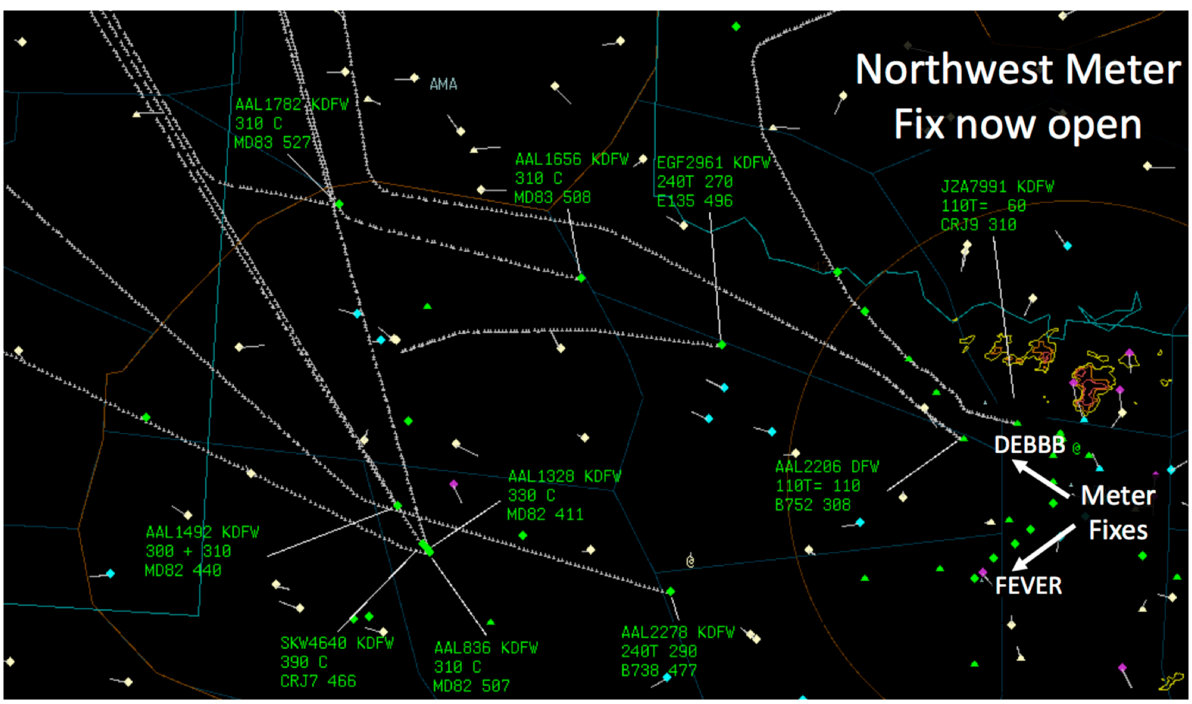

Figure 5. Example of Fort Worth Center arrival flights remaining on inefficient alternate arrival routes, March 23, 2013.

Arrival flights must routinely be routed to less efficient alternate arrival routes when their preferred route is predicted to be disrupted by convective weather. Observation of actual arrival traffic found that many flights continue to unnecessarily fly inefficient alternate routes after the weather has cleared and is no longer an issue.

Figure 5 depicts an actual example of this scenario at ZFW from March 23, 2013. Convective weather that was originally predicted to block arrival routes to the meter fix DEBBB, northwest of Dallas-Fort Worth International Airport (DFW), has moved to the east and is no longer a factor. Moreover, several flights (e.g., JZA7991) can be seen arriving via DEBBB. Despite this, six flights that originated from destinations northwest of DFW can be observed lining up for arrival into the southwest meter fix FEVER (e.g., AAL2278 and AAL1492). Typically, these flights would arrive via the northwest meter fix DEBBB. In addition, arrival scheduling timelines (i.e., TMA) for meter fixes DEBBB and FEVER shown in Figure 6 indicate a meter fix load imbalance with the current flight plan routes just before the scheduling freeze horizon (scheduled times of arrival for aircraft in blue have already been frozen), resulting in additional delay and potential increase in controller workload. The green numbers to the right of the yellow aircraft callsigns indicate the delay required by each flight to meet the scheduled time of arrival. In the 10-minute period highlighted in Figure 6, there are six flights scheduled to arrive at the meter fix FEVER that need to be delayed by at least one minute while only one aircraft scheduled to arrive at the preferred meter fix DEBBB needs to be delayed.

The DAR functionality described in the Section IIA.1 continuously seeks out opportunities to reroute arrival flights to more efficient arrival routes. Figure 7 shows a screenshot of the DAR system working on the actual scenario described above at an instance approximately 30 minutes earlier. The DAR system has identified 21 flights that are candidates for rerouting to more efficient alternate arrival routes. In this example, arrival flight AAL1492 has been selected from the DAR list (highlighted in yellow), and its trial plan has been displayed on the user interface. At approximately one hour before AAL1492 was scheduled to reach the southwest meter fix FEVER, DAR identified a more efficient arrival route to the northwest meter fix DEBBB that was predicted to save 12 minutes of flying time. In addition to the display of the DAR route, its effect on arrival scheduling can be assessed because the DAR system has been integrated with the arrival scheduling timeline. The ETA of the trial DAR for

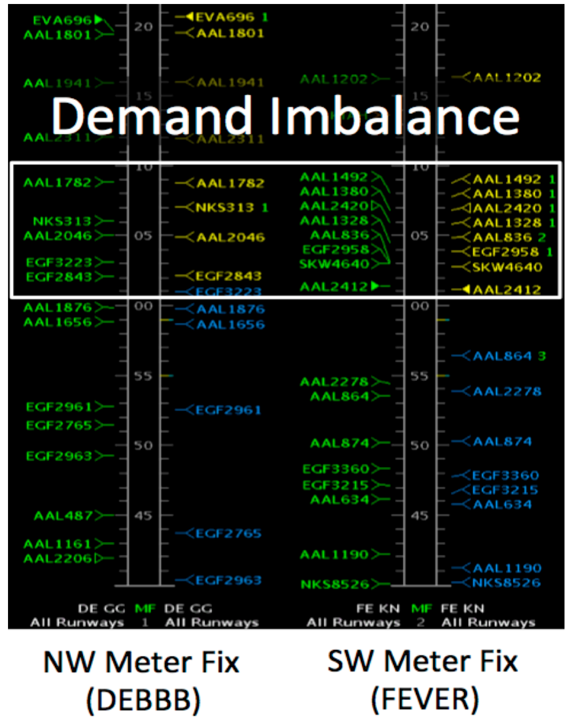

Figure 6. Example of meter fix load imbalance resulting from flights remaining on alternate arrival routes

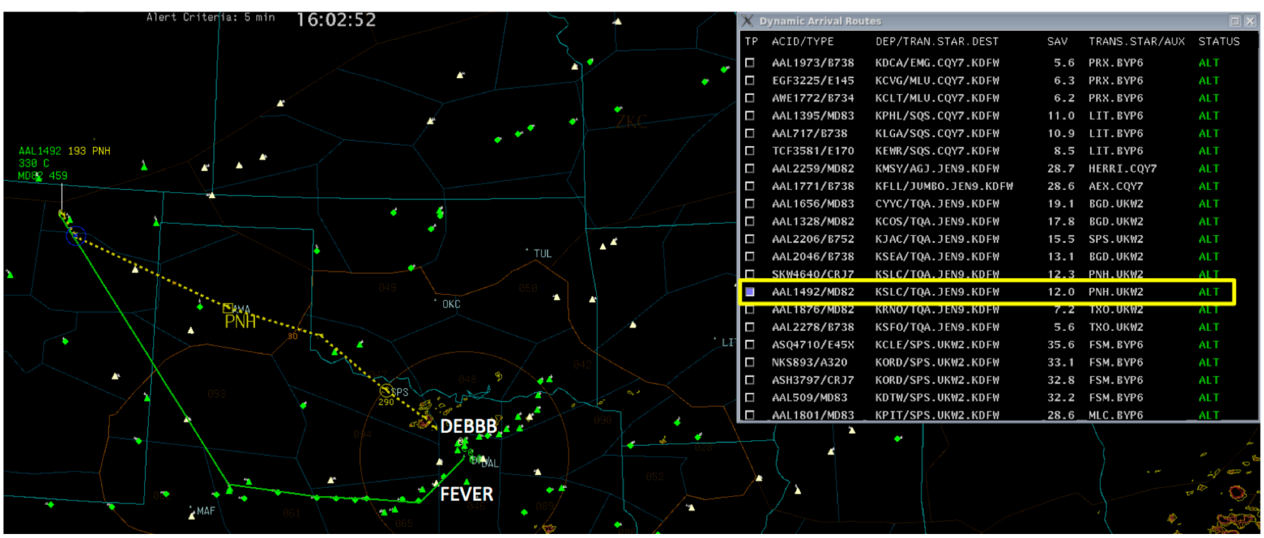

Figure 7. Actual DAR candidate for rerouting to a more efficient alternate arrival route

AAL1492 is displayed on the appropriate arrival scheduling timeline (Figure 8) when a trial plan is activated. The current STA and ETA are shown in magenta, and the DAR ETA is shown in inverse magenta. If the graphical trial planner is used to modify the proposed DAR (e.g., path stretch), the DAR ETA will rapidly update to reflect the route modification. Currently, the DAR system only displays the ETA of the proposed DAR and does not yet use ETA when calculating a solution. Additional integration of the DAR algorithm with the arrival scheduler is planned for the future.

The potential time savings for DAR alternate arrival routes was determined by measuring the time savings for the first "validated" DAR for each unique flight no more than 60 minutes from the meter fix. Because of noise and/or uncertainty in actual data, a DAR may be posted on the list then disappear following the next trajectory update. A validated DAR is one that remains on the DAR list for 3 out of 4 updates. This ensures the analysis is based on DAR advisories that have a level of persistence and certainty. A maximum look-ahead time horizon of 60 minutes from the meter fix was chosen for this analysis, which corresponds to the typical length of the arrival scheduling timeline. Potential time savings results for the example day of March 23, 2013 (1400-2200 UTC) are shown in Figure 9. The DAR system identified time-saving reroutes to more efficient alternate arrival routes for 93 unique flights with an average of 13.9 minutes per flight, 1295 minutes total.

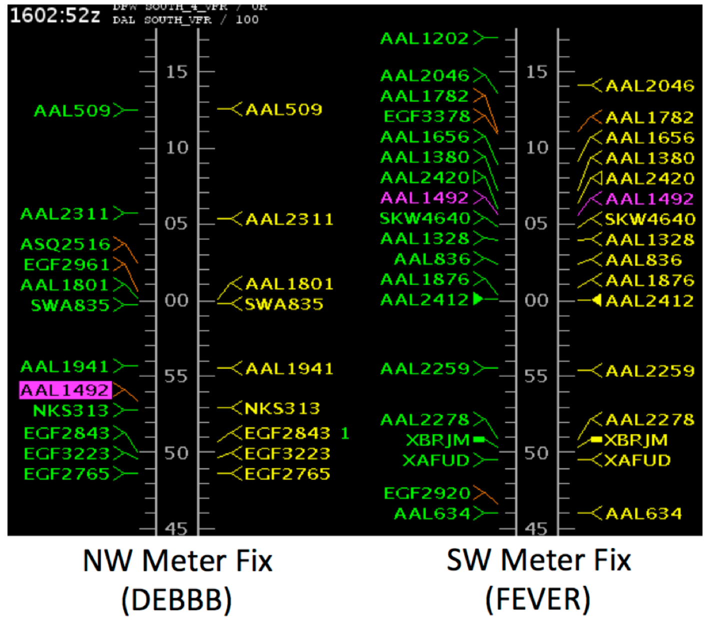

Figure 8. Estimated time of arrival (ETA) to alternate meter fix for DAR candidate

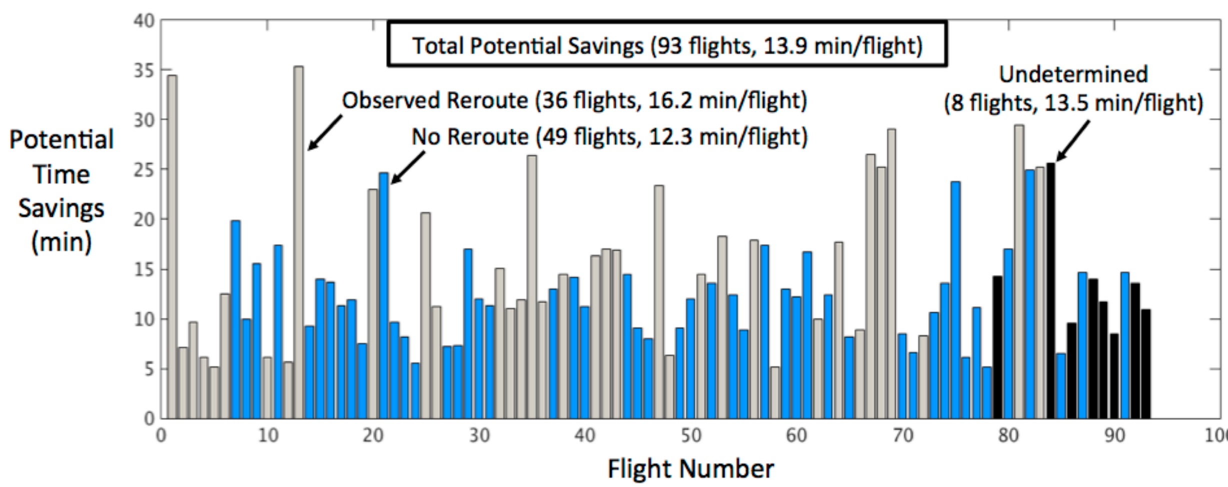

Figure 9. Potential time savings for DAR alternate arrival routes for March 23, 2013 (look-ahead time of 60 minutes from meter fix)

Controllers in today's operations will reroute some flights onto more efficient arrival routes without the assistance of a system such as DAR. Two such controller reroutes for flights AAL1656 and AAL1782 can be observed in Figure 5. In order to determine the net potential DAR time savings after accounting for controller initiated reroutes, each DAR flight was analyzed to determine which arrival routes they actually flew. For those flights that flew past the meter fix, 49 flights (53 percent) remained on their original inefficient flight plan, i.e., no observed reroute. This set of flights had an average time savings of 12.3 minutes per flight, which represents the net potential DAR time savings after controller reroutes are accounted for. Reroutes to different arrival routes were observed for 36 flights (39 percent). Of these rerouted flights, 23 (or 64 percent) were routed to the same meter fix recommended by DAR. The final arrival routes of 8 flights were undetermined primarily because the flights did not pass the meter fix before the data recording ended. In one case, the final arrival route could not be parsed. A summary of the total potential time savings and net potential time savings for 12 days of recorded traffic when convective weather was present in ZFW is shown in Figure 10. The total potential time savings for 352 unique flights was 4337 minutes for an average of 12.3 minutes per flight. After accounting for controller reroutes, the total net potential time savings was 2733 minutes for 234 flights with no observed reroutes for an average of 11.7 minutes per flight.

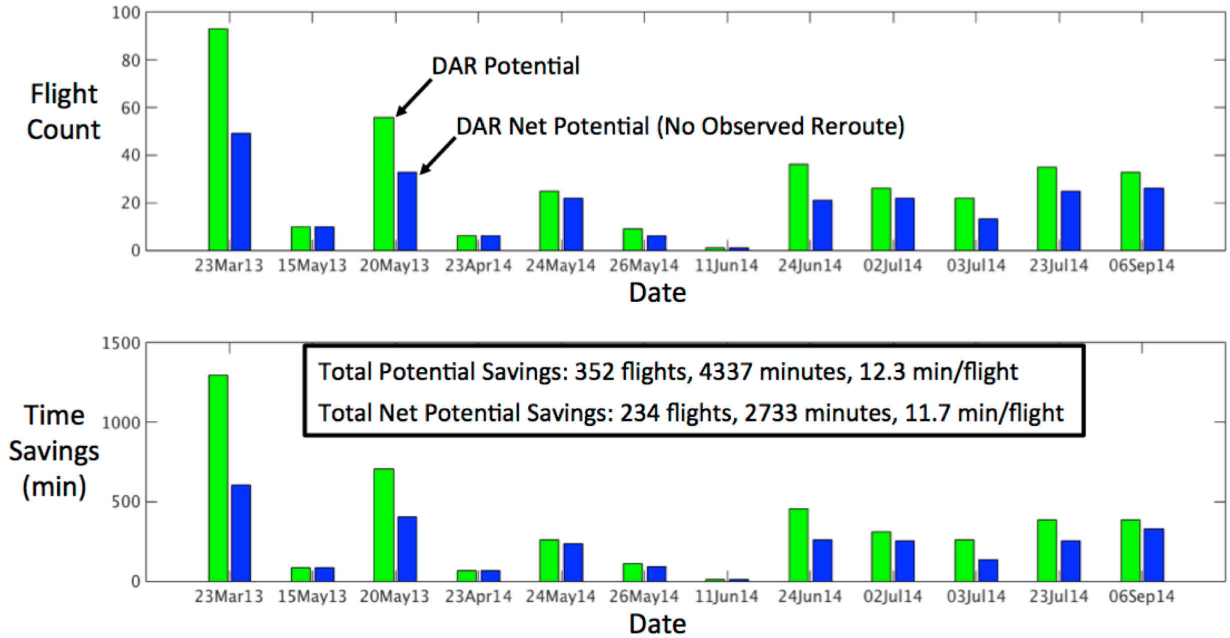

Figure 10. Time savings summary of DAR alternate arrival routes for a look-ahead time of 60 minutes from meter fix

B. Route corrections for weather along current arrival flight plan

Arrival flights can often be observed deviating off their flight plan to avoid weather in an ad hoc manner, well after the flight has crossed the arrival scheduling freeze horizon. Such deviations would not be reflected in the scheduled times of arrival and was cited as one of the primary reasons for metering to be discontinued.[5] An actual example from Forth Worth Air Route Traffic Control Center (ZFW) in Figure 11 shows track histories of three arrival flights flying the Bowie Two (UKW2) STAR to the DEBBB meter fix. The arrival flight EGF2716 can be seen flying a trajectory approximately 20 nmi further south than the two flights arriving before and after it (AAL1848 and EGF3426, respectively). Flight EGF2716 is also deviating off its intended flight plan, represented by the green line, by approximately 20 nmi.

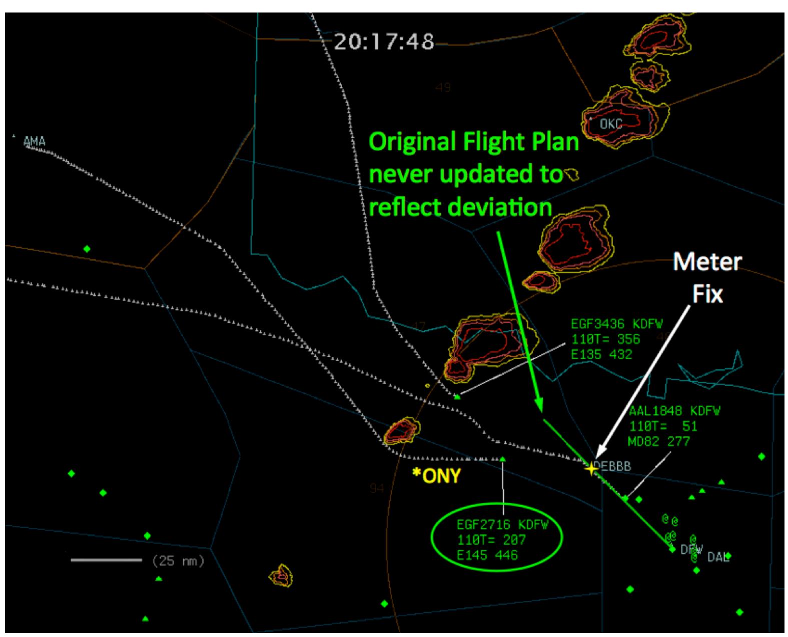

Figure 11. Deviation of actual arrival flights around weather

The DAR algorithm predicts the need for arrival flights to deviate around weather and proposes weather-free reroutes early enough for the arrival scheduling system to adjust their predicted times of arrival. Trajectories are calculated for all flights based on their current flight plan and are updated every 12 seconds with the latest track and flight plan information. These trajectories are continuously analyzed by DAR's weather conflict detection algorithm. Arrival flights with predicted weather conflicts are expected to deviate, and thus identified as reroute candidates by DAR if they have not passed the arrival scheduling freeze horizon.

An example of this functionality is shown in Figure 12 using the same arrival flight EGF2716 described above but at an earlier time, 30 minutes before its predicted time of arrival to the meter fix DEBBB. This is approximately 10 minutes before the arrival scheduling freeze horizon, ample time for the flight to be rerouted and the scheduled time of arrival to be adjusted. The current flight plan trajectory shown with a dashed yellow line conflicts with a forecasted CWAM weather polygon shown in orange. Note that the forecasted movement of the weather to the east can be seen when comparing current weather and the forecasted CWAM polygon.

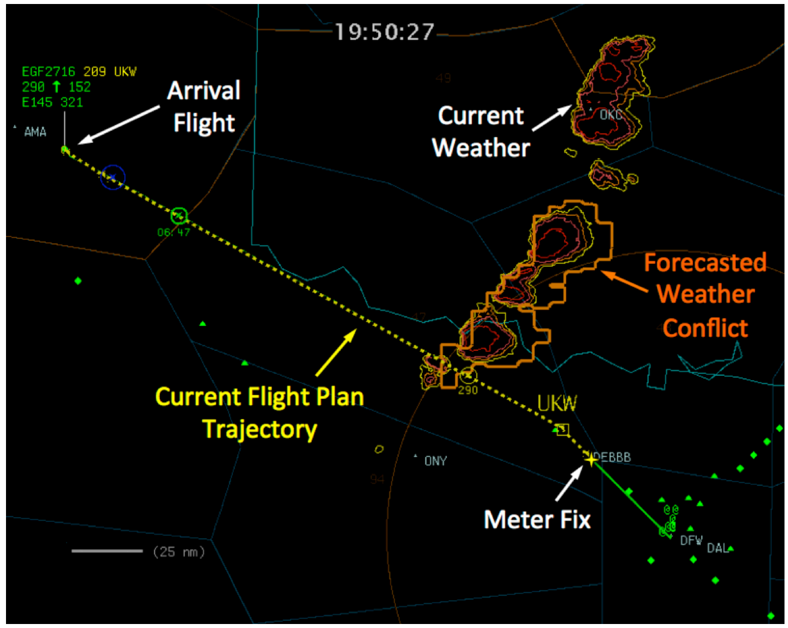

Figure 12. DAR candidate arrival flight with need to deviate around weather

Once an arrival flight has been identified as a DAR candidate, an iterative algorithm derived from the DWR application is used to find a weather-free reroute. Currently, the DAR system proposes the route with the least amount of delay selected from a set of weather-free routes calculated by the iterative algorithm. Other route selection criteria such as minimum deviation and metering/spacing constraints are to be considered in the future. The proposed DAR reroute for flight EGF2716 is shown in Figure 13. The green line represents the currently filed flight plan, while the dashed yellow line now represents the proposed DAR reroute. A nearby CWAM weather polygon within 25 nmi of the yellow proposed DAR reroute trajectory is shown by the dotted blue line. In this example, the DAR reroute is from the aircraft's current position, direct to fix UKW via a single auxiliary waypoint specified in fix-radial-distance format (FRD), e.g., UKW270047. The DAR system also has a mode more suitable for voice communications which will "snap-to" or substitute the FRD auxiliary waypoint for a named fix if a weather-free substitute can be found (e.g., ONY).

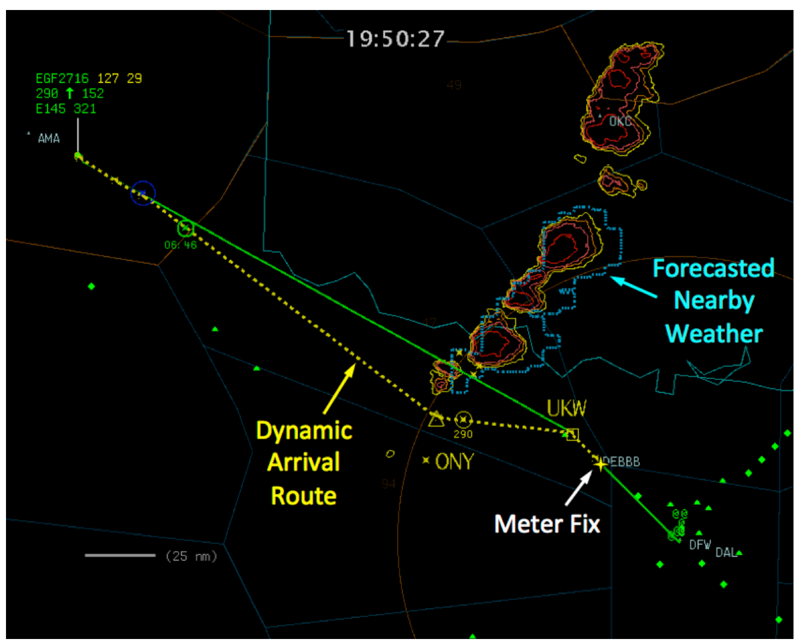

Figure 13. Dynamic Arrival Route correction for weather impacted arrival route

Analysis of the 12 test days for a look-ahead time of 30 minutes from the meter fix showed there were 642 validated DAR candidates that needed to deviate for weather (Figure 14). As described earlier, a DAR candidate must remain on the DAR list for 3 out of 4 trajectory updates in order to be counted as validated. The look-ahead time for this analysis is 30 minutes from the meter fix, approximately 10 minutes before the scheduling time horizon, ample time for a controller to reroute the arrival for weather before the arrival schedule is frozen.

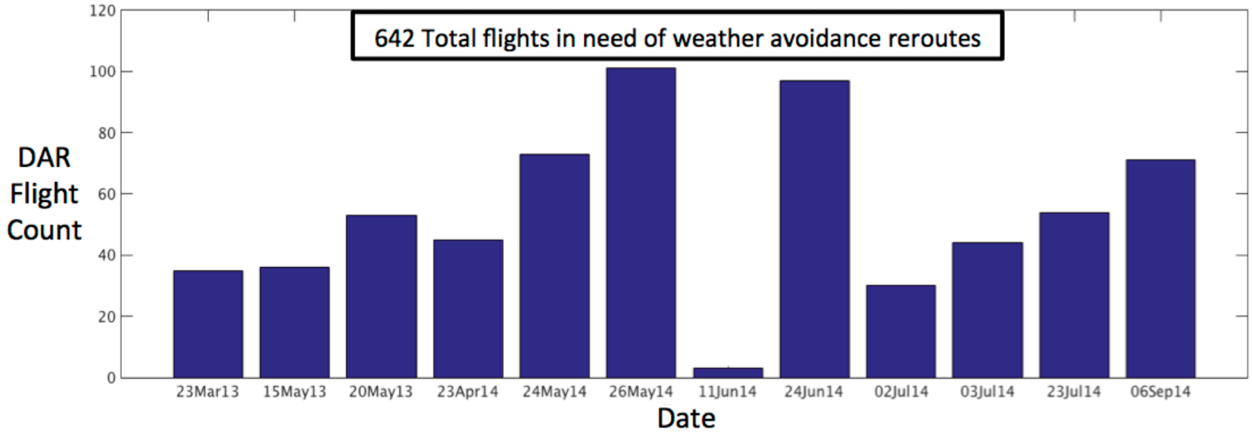

Figure 14. Summary of DAR weather avoidance candidates for a look-ahead time of 30 minutes from the meter fix.

An analysis of DAR was performed to evaluate the system's accuracy in predicting the need for arrival flights to deviate around weather and to assess if the resulting DAR reroute remained weather-free. The DAR system accuracy is a function of trajectory prediction and weather forecasting errors. A trajectory-based methodology called "nowcast" weather analysis was developed to measure the impact of weather forecasting error on the trajectories predicted by DAR. Figure 15 shows how this methodology is applied to the flight plan trajectory for the EGF2716 example described above. In this example, the flight plan trajectory calculated at current time t_0 has a conflict with forecasted weather at time t_n depicted by the red dashed polygon. Assuming the aircraft flies the trajectory as predicted, the methodology compares the predicted aircraft position at each time along the trajectory to actual nowcast (i.e., non-forecasted) weather. For the example shown in Figure 15, the aircraft's predicted location along the trajectory at time t_n has a conflict with the nowcast weather at the same time t_n, represented by the solid red polygon. Hence, the nowcast analysis records this as an accurately predicted weather conflict. The nowcast analysis methodology is also applied to the analysis of proposed DAR reroutes. In this case, however, an accurate DAR reroute would be one that remained weather-free as predicted.

The DAR system accuracy with the CWAM weather model described in Section IIB was evaluated using 93 hours of actual arrival traffic from 12 different days when convective weather was present at ZFW for look-ahead times ranging from 20 to 60 minutes from the meter fix. In this analysis, look-ahead time with respect to time to the meter fix was used in order to provide a performance metric relative to arrival scheduling operations. A summary of nowcast analysis results as a function of time to the meter fix is shown in Figure 16. At

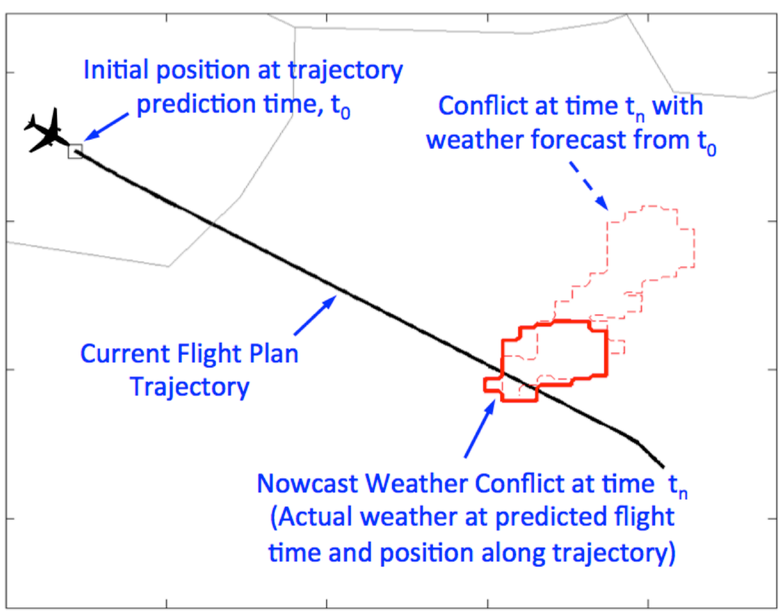

Figure 15. Nowcast analysis methodology for weather conflict prediction accuracy

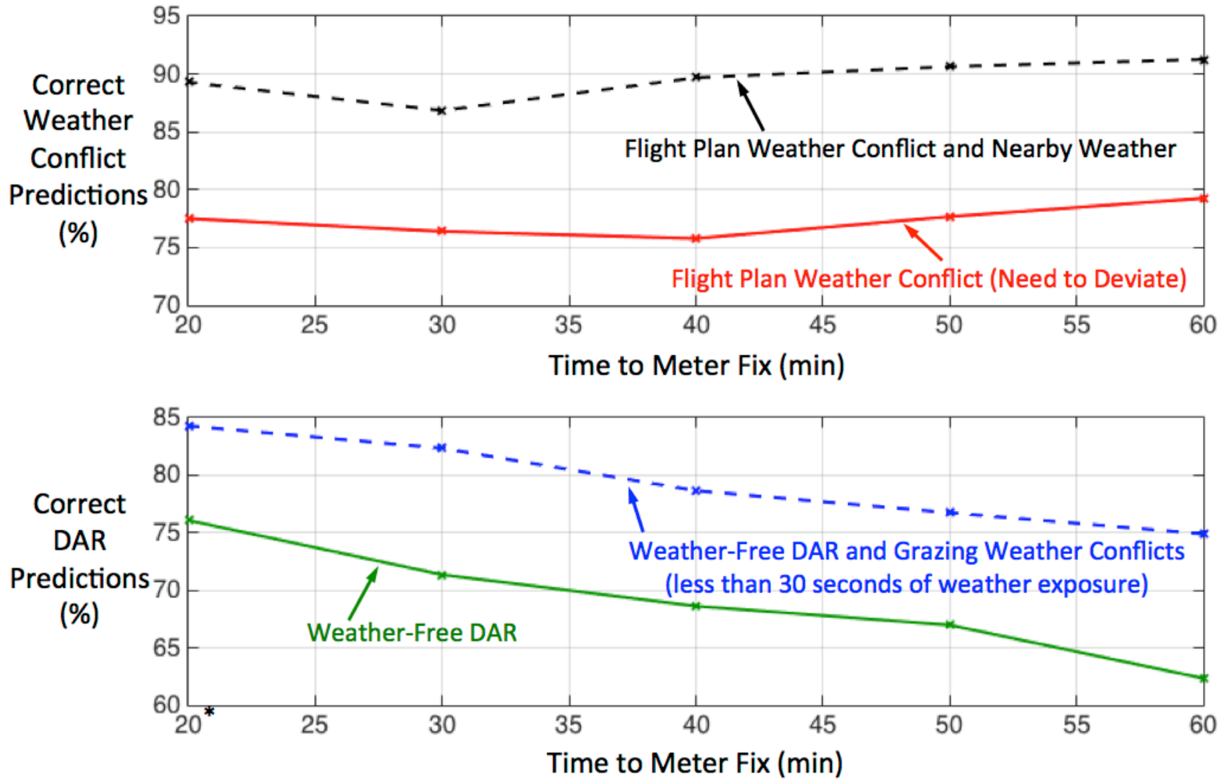

Figure 16. Nowcast analysis results for weather conflict prediction and weather-free DAR accuracy. Note: 20 minutes to the meter fix approximates the scheduling freeze horizon.

this time, the DAR algorithm is not fully integrated with the actual arrival scheduling system, so 20 minutes from the meter fix is used to approximate the scheduling freeze horizon. The red line on the upper plot shows the accuracy of flight plan weather conflict predictions (i.e., need to deviate). The nowcast analysis shows the DAR system accurately predicted a weather conflict approximately 76 percent of the time at 30 minutes to the meter fix (i.e., 10 minutes before the approximated scheduling freeze horizon). This weather conflict detection metric strictly measures detection accuracy based on the presence of a nowcast conflict. Because of weather forecasting error, forecasted conflicts with weather polygons may turn out to be nearby nowcast weather, thus not measured as a successful conflict prediction. If the presence of nearby nowcast weather is accounted for,

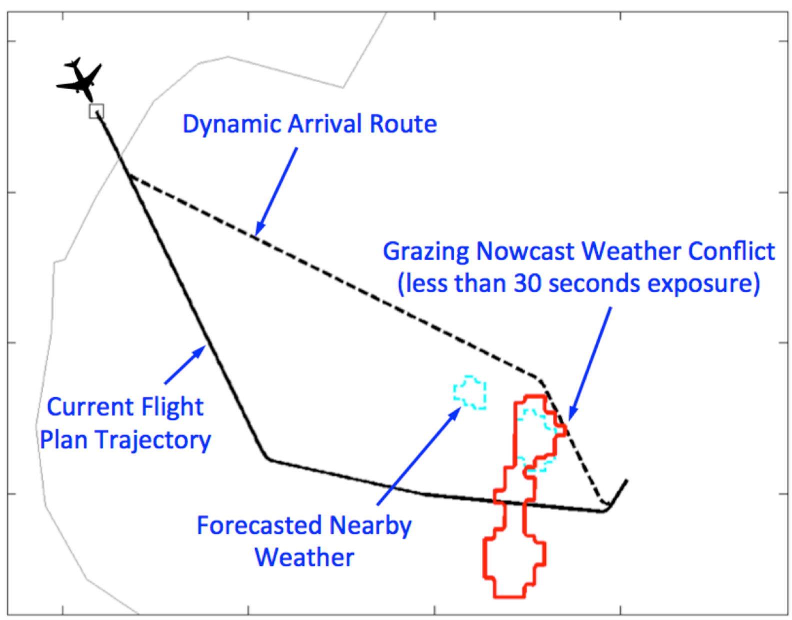

Figure. 17 DAR reroute with a grazing Nowcast weather conflict

then the dashed black line in Figure 16 shows DAR accurately predicted the need to deviate approximately 86 percent of the time at 30 minutes from the meter fix in the presence of weather forecasting error.

The lower plot in Figure 16 shows how often the proposed DAR reroutes remained weather-free. The solid green line shows DAR reroutes remained weather-free 71 percent of the time when predicted 30 minutes from the meter fix. After further detailed analysis, many DAR reroutes were found to have grazed the nowcast weather. A grazing weather conflict was defined to be a conflict with less than 30 seconds of exposure to weather. Figure 17 shows an example of a DAR reroute which was predicted to avoid the forecasted nearby weather approximately 30 minutes away. The corresponding nowcast analysis showed the reroute would have grazed the weather. Although these cases are weather conflicts by the strictest definition, minimal deviation would be required operationally. If minimal deviations due to grazing weather conflicts were considered operationally acceptable, the blue dashed line in Figure 16 shows the success rate of DAR reroutes would increase from 71 to 83 percent at 30 minutes from the meter fix, or 10 minutes before the approximated scheduling freeze horizon.

IV. Concluding Remarks

This paper described the development of a trajectory-based weather avoidance system for merging arrivals and metering called Dynamic Arrival Routes (DAR). The DAR system is designed to facilitate efficient arrival routing and robust metering in the presence of convective weather. The DAR algorithm first looks for opportunities to reroute arrivals to more efficient routes. If a more efficient arrival route is not found, DAR then probes the current arrival flight plan for weather conflicts and, if necessary, proposes a reroute around weather early enough to allow the arrival time-based metering system to adjust its scheduled times of arrival. As a result, metering operations can be sustained because weather deviations can be accounted for in the arrival schedule.

The DAR system performance was evaluated with 93 hours of actual Fort Worth Center traffic over 12 different days when convective weather was present at ZFW between March 23, 2013 and September 6, 2014. The DAR system identified more efficient reroutes for 352 arrival flights at a look-ahead time of 60 minutes from the meter fix for a total potential time savings of 4337 minutes or 12.3 minutes per flight. Some arrival flights receive more efficient reroutes in today's operations without the assistance of a system such as DAR. When actual observed reroutes for this set of DAR flights were accounted for, the net potential time savings was 2733 minutes for 234 flights or 11.7 minutes per flight.

The DAR system also proposed 642 weather avoidance routes for arrival flights with a need to deviate around weather at a look-ahead time of 30 minutes from the meter fix. Nowcast weather analysis of the proposed weather avoidance routes showed DAR could accurately predict the need to deviate 86 percent of the time in the presence of weather forecasting error. This analysis also showed DAR could calculate reroutes that effectively remain weather-free (i.e., minimal deviation) 83 percent of the time for a look-ahead time of 30 minutes from the meter fix, or approximately 10 minutes from the scheduling freeze horizon.

The integration of the DAR algorithm with the arrival scheduling timeline (e.g., TMA) provided the user with a capability to visualize the proposed DAR estimated time of arrival (ETA) and assess its impact on arrival scheduling before implementing the reroute. A graphical trial planner interface also allows the user to modify the proposed DAR and, consequently, its ETA if desired.

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