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The Route Availability Planning Tool (RAPT): Evaluation of Departure Management Decision Support in New York during the 2008 Convective Weather Season*

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***Abstract*— Severe weather avoidance programs (SWAP) due to convective weather are common in many of the busiest terminal areas in the US National Airspace System (NAS). In order to make efficient use of available airspace in rapidly evolving convective weather, it is necessary to predict the impacts of the weather on key resources (e.g., departure and arrival routes and fixes), with frequent updates as the weather changes. Currently, this prediction is a mental process that imposes a significant cognitive burden on air traffic managers. As a result, air traffic management in SWAP is often inconsistent and decisions result in less than optimal performance.**

The Route Availability Planning Tool (RAPT) is a prototype automated decision support tool, intended to help air traffic managers in convective weather SWAP, by predicting the impacts of convective weather on departure routes. Originally deployed in New York in August, 2002, RAPT has recently undergone two field evaluations (2007 and 2008) in order to test and refine its concept of operations, evaluate the accuracy and usefulness of its decision guidance, and estimate observed and potential delay reduction benefits that may be achieved as a result of its use.

This paper presents the results of the 2008 performance evaluation, focusing on the concept of operations and the quality of decision support guidance. A second paper [1] presents analyses of delay reduction benefits and the operational decision making environment in which RAPT is deployed.

Keywords – Decision support, departure management, route Availability Planning Tool (RAPT), weather impact, convective weather

I. Introduction

There is a critical need for improved departure management during convective weather events in the highly congested airspace in the Northeast and upper Midwest United States. An early study of the New York Integrated Terminal Weather System (ITWS) prototype [2] identified the need for improved departure management in New York, and suggested that small increases in airport departure rates during SWAP could result in significant delay reduction. Departure delays continue to be a major problem at New York airports, and their effects can cascade across the entire National Airspace System (NAS) as surface gridlock necessitates airborne holding, ground delays and ground stops of inbound traffic [3].

The ability to predict impacts of convective weather on future departures is a fundamental need in departure management that is extremely difficult to do without automated support. It requires projection into the future of three-dimensional thunderstorms and flight trajectories to determine the nature and severity of the weather that departing flights will encounter. Once the intersection of weather and flight trajectory is determined, it is necessary to estimate the likelihood and amount of deviation that may be required to avoid weather encountered along the route. Without automated decision support, this prediction is done mentally, imposing a significant cognitive burden on air traffic managers. As a result, departure management during SWAP is often inconsistent and inefficient. Detailed studies of New York operations in 2007 [4] found that there were often missed departure opportunities during SWAP.

The Route Availability Planning Tool (RAPT) [5][6] is an automated decision support tool (DST) intended to help air traffic managers and airline dispatchers determine the specific departure routes and times that will be affected by operationally significant convective weather. RAPT assigns a blockage status color - RED (blocked), YELLOW (partial or uncertain blockage), DARK GREEN (insignificant weather encountered) or GREEN (clear) - to each route for departure times up to 30 minutes into the future. Based on RAPT guidance, air traffic managers can quickly determine if and when specific routes are free of significant convective weather

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impacts and available for use. To our knowledge, it is the only tool of its kind currently in operational use.

In the summer of 2007, a comprehensive field evaluation of RAPT performance found that RAPT guidance provided a generally accurate assessment of route availability [6], and that significant delay reduction benefits could be achieved as a result of RAPT usage [4]. These studies also found that over-sensitivity to small-scale features of the input weather forecasts occasionally resulted in poor or unstable RAPT guidance, which, in turn, reduced user confidence and realization of potential benefits. In order to improve the robustness of RAPT guidance, the RAPT route blockage algorithm was significantly redesigned, and a new version was deployed operationally in July, 2008.

A second field study was performed in 2008 to evaluate the RAPT concept of operations, the quality of RAPT guidance, and the observed and potential delay reductions achievable as a result of RAPT usage. This paper presents an analysis of the accuracy of RAPT guidance and its ability to support the operational concept. RAPT, its operational concept and route blockage algorithm are described. The accuracy and operational relevance of RAPT guidance is evaluated, based on an analysis of several case days from the summer of 2008. Finally, enhancements planned for deployment in 2009 are presented. A second paper [1], also based on the field evaluation, presents an analysis of observed benefits, missed opportunities and the operational decision making environment in which RAPT is deployed.

II. RAPT DESCRIPTION

RAPT is intended to reduce departure delays by automatically identifying opportunities for efficient, proactive and consistent use of available departure routes. RAPT calculates route blockage along departure routes that are defined by four-dimensional, modeled flight trajectories that extend out to 60 minutes flight time. Trajectory points are calculated at one minute intervals.

Flight trajectories have four phases – climb, transition, near en route and en route – that reflect flight altitude and airspace complexity. Routes are defined by 'blockage boxes' centered on the trajectory points, and box length and width are functions of the flight phase. The lengths are set to approximately two minutes flight distance, and the widths reflect the route density and the ability of air traffic control to maneuver flights around convective weather in the region traversed during the flight phase. Typically, routes are wide during the climb and transition phases (inside the TRACON), become narrower in the near en route phase where departure and arrival routes are densely packed (ZNY and northern ZDC), and widen again in the en route phase where routes are not so densely packed (ZOB and southern ZDC). Figure 1 illustrates RAPT departure routes.

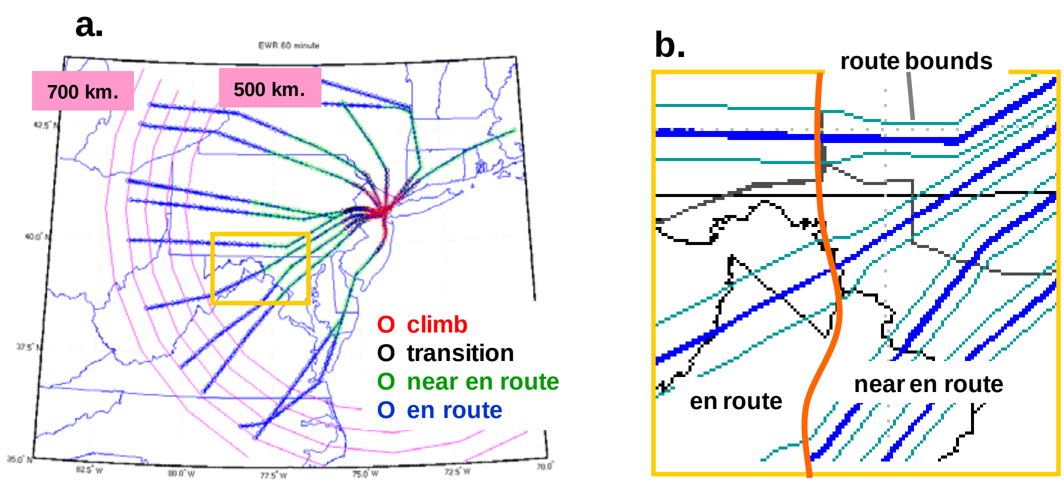

Figure 1. RAPT departure routes (a) and inset showing different route widths in near en route and en route airspace.

Figure 2 illustrates the RAPT algorithm. Vertically integrated liquid (VIL) and echo tops forecasts from the Corridor Integrated Weather System (CIWS) [7] are input to a Weather Avoidance Field (WAF) generator that estimates the probability of pilot deviation at each pixel in the RAPT domain. VIL provides a measure of precipitation intensity and the echo tops give an estimate of storm height, both of which are important factors in determining the severity of convective weather. The WAF in the TRACON is based on a heuristic convective weather avoidance model (CWAM), in which VIL intensity is the dominant factor. In en route airspace, the WAF is based on an en route CWAM [8], in which echo top height is dominant. Transition between TRACON and en route WAF occurs over a 20 km range (between 80 and 100 km from Newark International airport), in which WAF deviation probabilities are a range-weighted average between TRACON and en route WAF. WAF predictions are generated at five minute intervals, in synchronization with the CIWS forecast updates.

The route blockage algorithm [9][10] calculates a route blockage at each trajectory point as a function of the WAF deviation probabilities inside the blockage box for the point. The route blockage, a number between 0 and 1, is converted to a blockage status - RED (blocked), YELLOW (partial or uncertain blockage), DARK GREEN (insignificant weather encountered) and GREEN (clear) - using thresholds from a two dimensional 'deviation sensitivity field'. The deviation sensitivity field reflects the disruption to air traffic in different regions of the RAPT domain that could result from an unexpected pilot deviation outside the blockage box. It provides a rudimentary estimate of decision risk. Deviation sensitivity is highest (i.e., blockage thresholds are lowest) near highly congested regions of the RAPT domain (e.g., near departure fixes) and lowest in far en route space where airspace is less congested.

The departure status assigned to a particular route and departure time is the worst blockage status encountered along the departure trajectory. The blockage location is the trajectory phase where the worst blockage status on the departure trajectory first occurs (the 'first worst' blockage encountered). The departure status timeline for a route (the 'RAPT timeline') is the sequence of status triplets [route blockage status, blockage location, echo top height at the blockage location] for each departure time from T0 (the current time) to T0 + 30 minutes, in one minute intervals. RAPT combines departure statuses into 5 minute 'bins' for the operational display, where the status of the bin is set to the worst (most restrictive) blockage in the bin. Note that weather forecasts are needed out to 90 minutes to support RAPT timeline generation (30 minute departure time look-ahead + 60 minute departure flight trajectories).

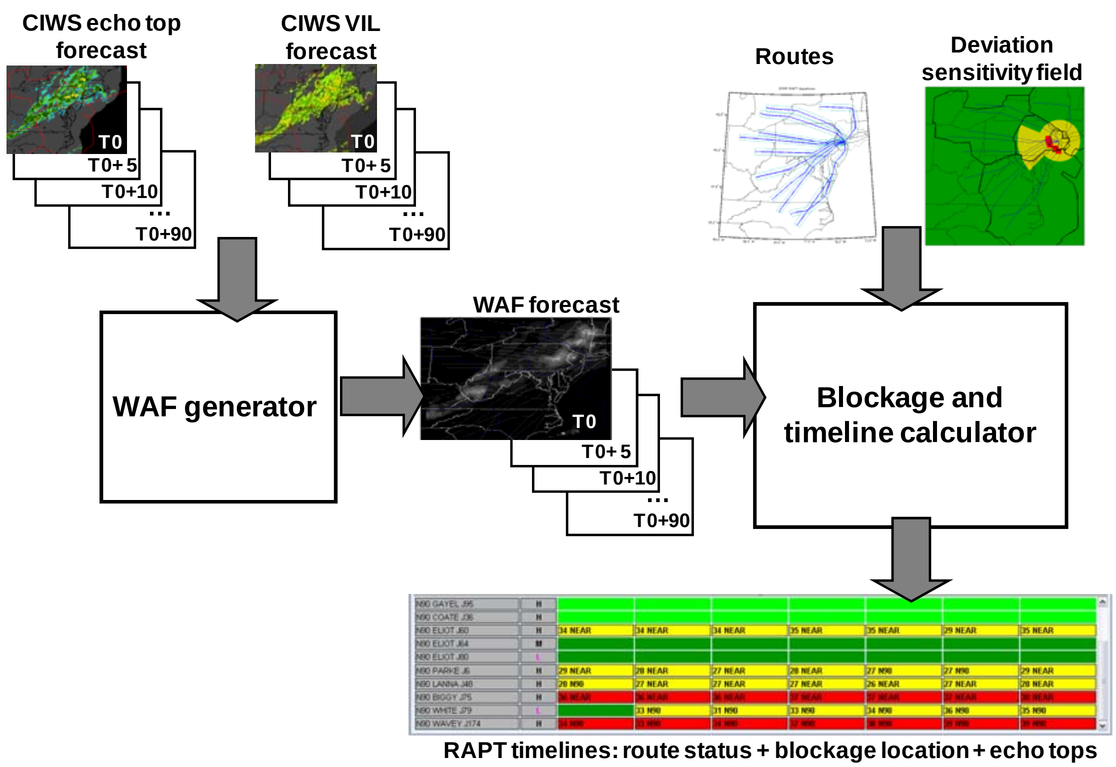

Figure 2. RAPT algorithm overview.

The RAPT user interface (figure 3) displays the RAPT timelines and a weather animation window. Each row of the timeline display corresponds to a departure route. Each column corresponds to a future departure time, starting at the current time and extending up to 30 minutes into the future in five minute intervals. The color of each timeline bin represents the departure status for the route and departure time. YELLOW and RED bins have text annotations giving the trajectory phase and the echo top height of the blockage location. The animation window overlays predicted locations of departing aircraft on forecasts of VIL or echo tops. Other CIWS product information, such as observed cloud-to-ground lightning strikes, can also be displayed.

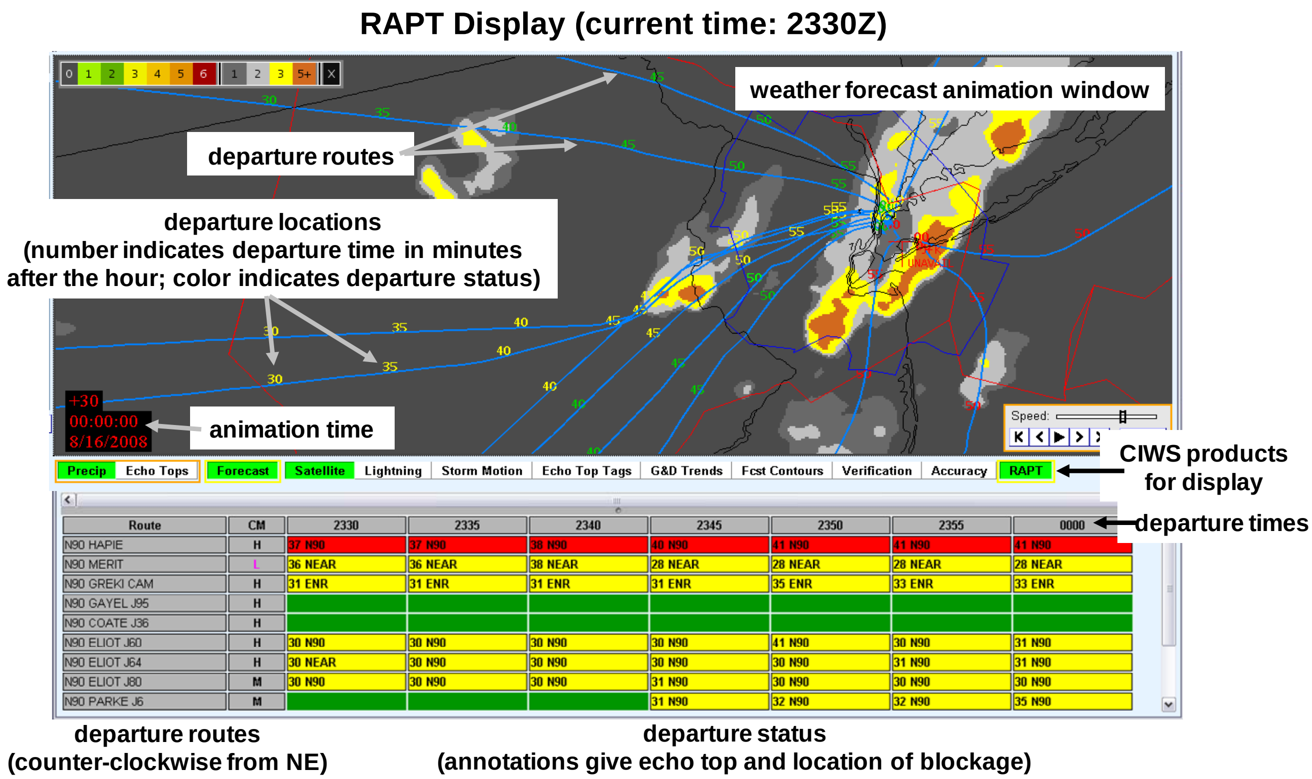

Figure 3. RAPT user interface.

RAPT usage is intended to improve departure efficiency by supporting more proactive decision making. The RAPT concept of operations can be summarized as follows:

- GREEN means GO! When weather impacts clear from a route and RAPT departure status goes from RED to GREEN ('post impact GREEN' or PIG), reopen the route with no weather-related restrictions. The RAPT concept of operations generally considers both GREEN and DARK GREEN as opportunities to go. However, since DARK GREEN implies the presence of some weather along the route, it is anticipated that users may wish to use their judgment in deciding whether to open the route with or without restrictions. As users gain confidence and experience with RAPT guidance, this portion of the concept of operations will be expanded to "GREEN and DARK GREEN mean GO!"
- RED means STOP! When a departure status turns RED, severely restrict the route and begin planning reroutes for the affected departures.
- YELLOW with improving trend or low echo top means RELEASE UNDER GUIDANCE. If the route is already open, consider increasing flow. If the route is currently closed, reopen with restrictions.
- YELLOW with deteriorating trend means INCREASE RESTRICTIONS. If traffic is flowing, consider imposing restrictions begin planning reroutes.

In order to implement the RAPT concept of operations, traffic managers must be confident that RAPT guidance accurately reflects operational reality. RAPT must reliably identify PIGs and REDs. RAPT should identify trends needed to support decision making under YELLOW conditions, particularly when weather is evolving. The distribution of RAPT to all participants in the departure management process should reduce the effort needed to coordinate departure management decisions and enable initiation of proactive decision making by any participant in the decision making chain.

III. PERFORMANCE EVALUATION FROM 2008

In order to determine the operational accuracy of RAPT guidance, plots of observed traffic were compared to RAPT departure status. These comparisons confirmed the accuracy of the RAPT blockage model in most instances and identified circumstances where RAPT performed poorly. Figures 4-7 illustrate several comparisons.

Figure 4 shows the impacts of scattered thunderstorms on several RAPT departure routes. Departure traffic is unimpeded on GREEN routes (J95, J36 and J80) through clear air or over very weak, low-topped convective storms. YELLOW routes (J6, J48) are impacted by more vigorous convection (echo tops to 25-30 kft), and traffic is running "2-as-1" (reduced departure streams for both routes are merged to avoid weather impacts near the TRACON, then separated onto the individual routes once the weather is cleared). Traffic is also running on J60 (YELLOW). The RED route (J75) is blocked by vigorous level 5 convection with echo tops up to 40 kft., and no traffic is observed on the route. Overall, RAPT guidance appears to match departure operations well.

Figure 5 presents an illustration of the impacts of two thunderstorm cells as the storms grow. RAPT initially assigns a status of DARK GREEN to J48, where there is sufficient space to accommodate weather-avoiding maneuvers. J75, which passes through the gap between the cells, is marked YELLOW. Observed traffic appears to confirm the accuracy of the guidance. As the cells grow, the maneuvering room on J48 is decreased, turning its status YELLOW, and the gap between the cells closes, turning J75 RED. Observed traffic validates the RAPT guidance; although a flight is passing through the remaining gap on J75, the next departure is beginning to circle and hold, potentially disrupting departure traffic on several routes.

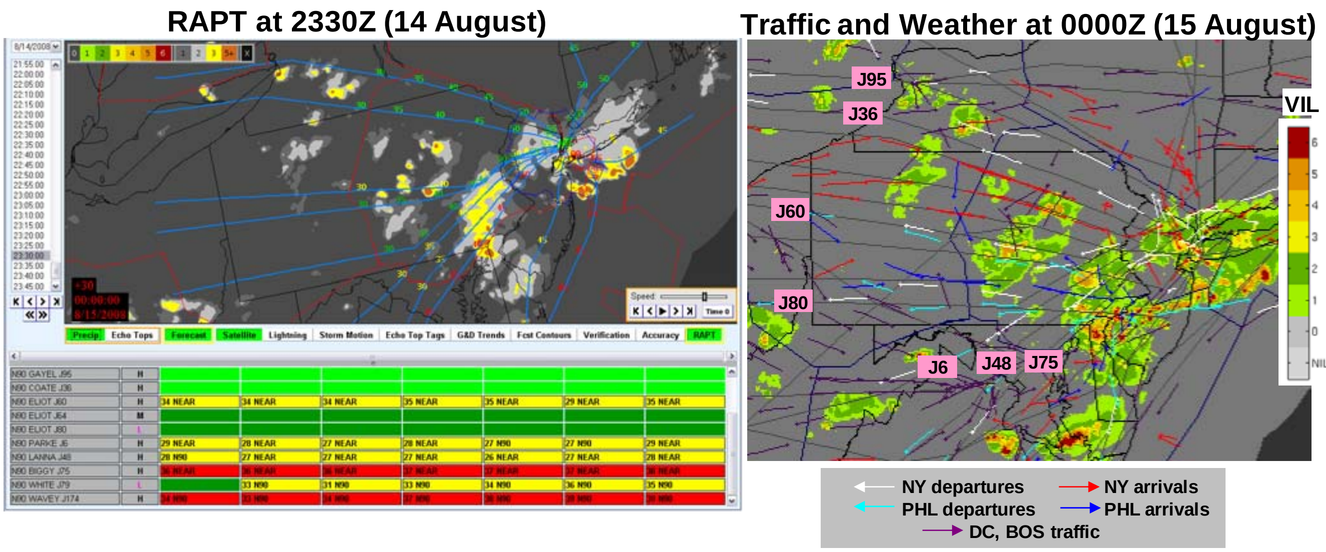

Figure 4. Illustration of RAPT guidance, compared to observed departure traffic. Overall, RAPT guidance appears to match departure operations well.

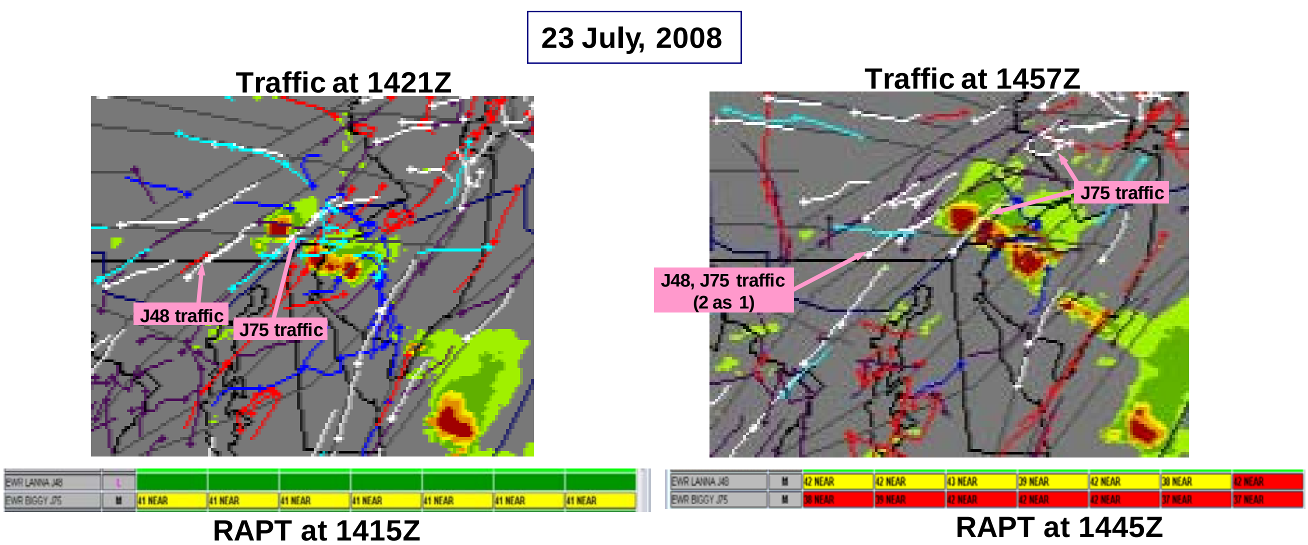

Figure 5. Illustration of RAPT guidance on growing isolated cells. As cells grow larger and stronger, closing down available maneuvering space, RAPT guidance deteriorates (from GREEN to YELLOW to RED), reflecting decreases in departure traffic. Note departures beginning t o hold on the illustration at right.

RAPT over-warned in circumstances where its route blockage model failed to capture the full range of operational flexibility in vectoring aircraft around weather. Figure 6 shows traffic in far en route airspace deviating far outside the RAPT route boundary to avoid convective weather. In figure 7, four different traffic streams are merged in the TRACON to avoid intense convection before splitting onto different airways in en route airspace. Departure status on all four routes is RED.

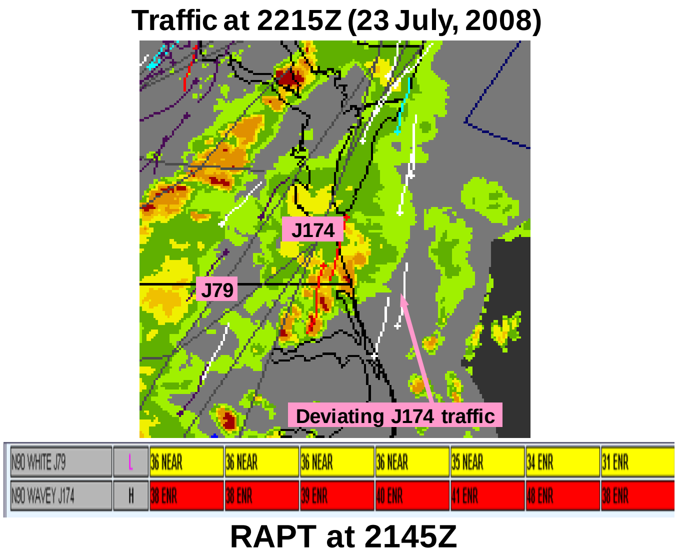

Figure 6. RAPT over-warning in far en route airspace, where aircraft have significant room to deviate to avoid weather.

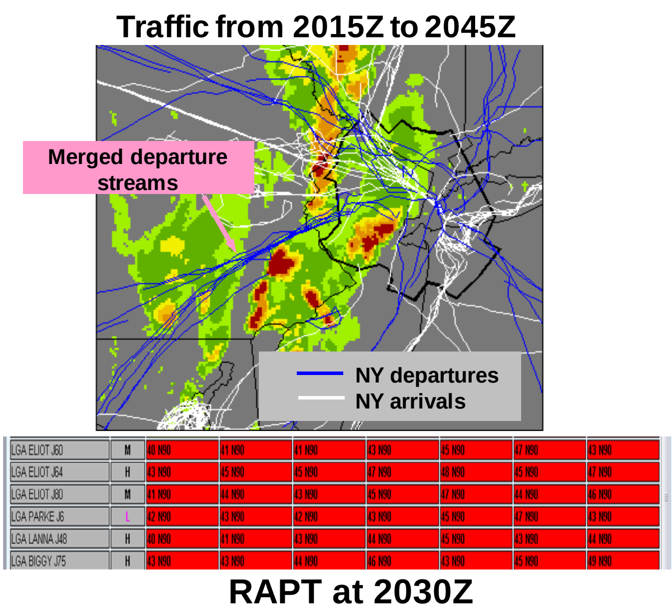

Figure 7. RAPT over-warning near TRACON boundary. TRACON air traffic control has considerable flexibility in vectoring aircraft to avoid weather. In this example, several departure streams are merged into a single stream to avoid weather impacts on the nominal departure routes.

In order to gain a more comprehensive view of RAPT performance, day-long summaries of RAPT guidance and departure traffic were analyzed for four SWAP days (20 July, 23 July, 10 August and 15 August). Figure 8 shows the history of RAPT departure status and departure counts through the BIGGY departure fix onto airway J75 for 10 August, 2008. Departures stop around 1430Z, as weather impacts turn the RAPT guidance RED. Departures begin in earnest around 1830Z, during a prolonged period of RAPT YELLOW, stopping again around 2100Z, when RAPT guidance turns RED. Finally, a steady stream of departures begins around 2200Z as RAPT guidance turns YELLOW, and continues as RAPT turns GREEN around 2330Z. This correlation between RAPT guidance and departures was observed on several departure routes during the four case days.

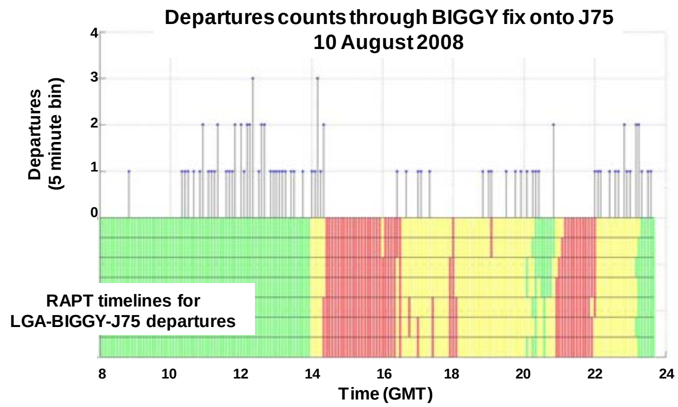

Figure 8. Day-long summary of departures through departure fix BIGGY onto airway J75 (upper panel). Lower panel shows RAPT timelines, as they were updated every five minutes during the day. Timelines are turned 'sideways'; departure time T0 is at the top and departure times increase (T0+5, T0+10, etc.) as one moves downward.

Figure 9 presents the cumulative departures from Newark International Airport (EWR) onto all RAPT departure routes for a fair weather day (20 August, 2008) and for the SWAP day on 10 August. The fair weather curve is colored sky blue; the curve for 10 August is colored by the average value of the status for all RAPT routes. During the period of highest weather impacts (reds, oranges and yellows between 1600 and 2100Z), the departure rate for all EWR RAPT routes falls far short of fair weather operations and the departure backlog (the difference between the fair weather and weather-impacted curves) increases significantly. Departure rates begin to approach fair weather norms after 2200Z, when the RAPT status turns green. RAPT accurately identifies both the onset and clearing of severe convective weather impacts, providing the information needed to support proactive decision making. Impact trends (improving and deteriorating conditions) are also apparent.

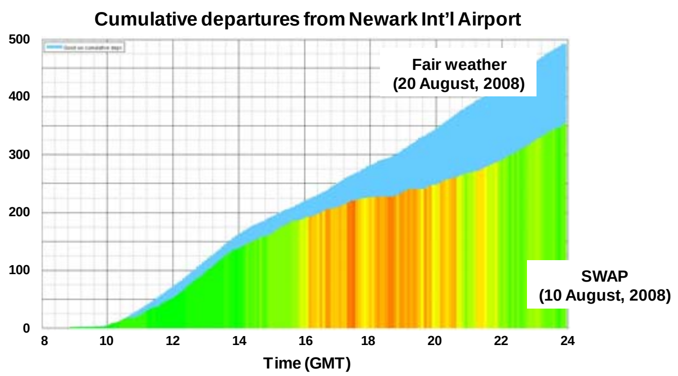

Figure 9. Comparison of cumulative departure from Newark International Airport (EWR) on fair weather day (blue) with a day with significant convective impacts (colors). Impacted colors indicated average RAPT blockage status of all RAPT departure routes for EWR.

Figure 10 summarizes the correlation between RAPT guidance and departure traffic for the three major New York airports for the four case days (three days for JFK). The figure shows histograms of departure counts per half-hour on all routes with blockage status RED, YELLOW, DARK GREEN, GREEN (excluding PIGs) and PIGs, normalized to the total number of half-hour periods of each route status (given in the number at the top of each distribution on the figure). The route status for a half-hour period was defined as the median departure status for that period. For example, to determine the status for departures from EWR through departure fix COATE onto airway J36 for the period from 1830Z to 1900Z, the route status for each minute (1830, 1831, 1832, …, 1859) in the interval are considered. If there were 3 GREEN, 4 DARK GREEN, 14 YELLOW and 9 RED, the median status for the half-hour block was YELLOW. The departure count for the period is simply the total number of departures on the route during the half-hour, determined using flight plan data from the Enhanced Traffic Management System (ETMS).

For this statistical analysis, the definition of PIGs is somewhat different than that used in the detailed study of operations presented in [1]. Here, a PIG is defined as a GREEN status that follows a RED status (either directly or after some intervening period of YELLOW), where both the GREEN and RED status are determined from the half-hour median described in the previous paragraph. The differences are warranted by the requirements of the different analyses (coarse-grained statistical validation vs. fine-grained analysis of individual departure release decisions). In practice, both methods identified a similar set of PIGs.

RAPT guidance correlates well with operational performance. No departures were released during 80% of all RED conditions observed on those four days; departure rates of two or more per half-hour were observed during only 10% of all RED conditions. The percentage of periods with higher departure rates – 2 or more per half-hour - steadily increases as conditions improve from RED (10%) to YELLOW (23%) to DARK GREEN (31%) to GREEN (37%).

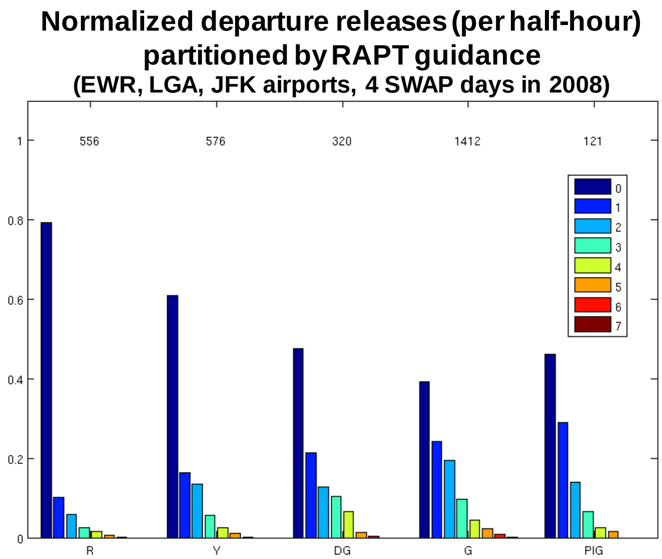

Figure 10. Distributions of departure counts per half-hour as a function of RAPT status. Numbers at the top of each distribution give the total number of half-hour periods with the route status for which the distribution is calculated.

A comparison of departure rates during non-PIG GREENs and PIGs shows that departure rates during PIGs are generally lower than during non-PIG GREEN operations. Departure counts of 2 or more flights were observed during approximately 37% of all GREEN periods, and only 25% of all PIGs. This result is not surprising – in fact, it is the one of the primary motivations for RAPT. Increasing departure rates during PIGs is a critical need of departure management during SWAP. After significant weather impacts clear, departure backlogs must be cleared as quickly as possible to avoid surface gridlock conditions that can cause disruption of air traffic to spread through the NAS. However, planning and staging the resumption of high volume operations after weather impacts pass can be difficult, and improving departure throughput by early identification of opportunities to reopen closed departure route is a major element of the RAPT concept of operations. A recent study [1] analyzed post-impact operations during the summer of 2008 in New York in detail, and found significant opportunities to improve departure throughput during PIGs that were clearly identified by RAPT.

IV. PLANNED ENHANCEMENTS

Post-event analysis of RAPT performance has demonstrated that RAPT guidance correlates well with operational reality. RAPT predictions of the onset and clearing of weather impacts (REDs, GREENs and Post-impact GREENS (PIGs)) provide useful information to air traffic managers that can support more proactive and consistent decision making. However, discussions with operational users suggest that RAPT usage would improve if RAPT provided explicit information about weather impact trends (particularly during YELLOW periods), real time RAPT forecast scores and more clarity in the operational display.

Figure 11 illustrates these enhancements on the planned 2009 user interface, developed in discussions during a user focus group meeting in December, 2008. Weather impact trends for each departure route are identified as 'improving' (upward arrow), 'deteriorating' (downward arrow) or 'stable' (right-pointing arrow). Trends are based on the history of impacts over the previous half-hour. A 'PIG timer' gives the time, in minutes, since the weather impacts have cleared the route. Users can 'drill down' to see detailed trend information by clicking on the trend arrow. The trend information includes the previous 30 minute history of RAPT status and echo top heights encountered along the departure route, and a text message that reminds the user of the action that is suggested by the RAPT concept of operations under the current conditions. An improved route timeline display filter enables users to display only the departure routes that are of interest.

RAPT forecast scores, based on the route blockage scoring algorithm presented in [10], are calculated for each of the regions that include the major departure routes in the RAPT domain. The blockage score takes into account the spatial scale and orientation of the routes and their geometric relationship to the weather. Both the trend and forecast algorithms are subjects of ongoing research and development.

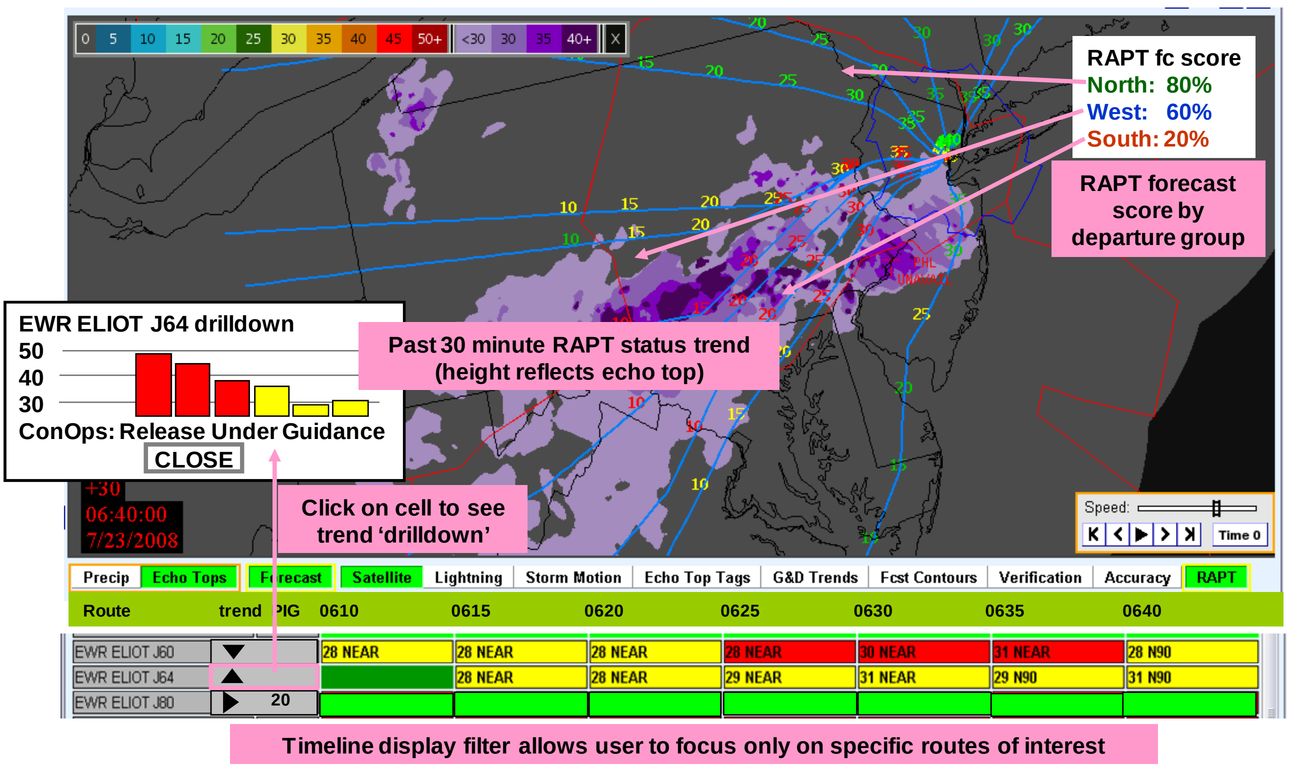

Figure 11. Proposed RAPT user interface for 2009.

V. Conclusions

The Route Availability Planning Tool (RAPT) is a prototype automated decision support tool that has been deployed in the New York area to help air traffic managers make departure decisions in convective weather SWAP. It predicts the impacts of convective weather on departure routes, providing a departure status (RED is blocked, GREEN is clear, DARK GREEN is insignificant impact and YELLOW is partially blocked or uncertain) for future departure times (up to 30 minutes) on specific departure routes. The RAPT concept of operations is to enable proactive departure management decision making based on RAPT departure status predictions: plan reroutes for departure routes that are turning RED, reopen closed departure routes that are turning GREEN after weather impacts, and use trend information to support advanced planning when route impacts are YELLOW.

The effectiveness of RAPT depends on the quality of its departure status predictions, which are based upon forecasts of precipitation intensity and echo top height, and an operational model that defines departure routes and route blockage. The operational accuracy of RAPT guidance was evaluated over several convective weather SWAP days in the summer of 2008. The evaluation was based on detailed analysis of observed departure traffic and RAPT guidance during several storm impacts, comprehensive timelines of weather impacts and departure counts on individual routes and complete airports, and a comparison of aggregate departure statistics over the four SWAP days studied, partitioned by RAPT guidance (RED, YELLOW, DARK GREEN, GREEN (excluding Post-impact GREEN), post-impact GREEN (PIG)).

RAPT guidance correlated well with observed departure rates on the four SWAP days studied. On RED routes, departures were completely shut down approximately 80% of the time, and rates greater than one departure per half-hour were observed only 10% of the time. Departure rates increased as RAPT status improved from RED to GREEN (excluding PIGs). Departure rates on PIG routes were generally lower than rates on GREEN (excluding PIGs) routes. A primary goal of RAPT is to improve departure throughput during these critical, post impact recovery periods, by helping air traffic managers to identify opportunities to plan, stage and execute the timely reopening of departure routes closed by convective weather impacts. RAPT identification of PIGs and trends leading to PIGs is sufficiently robust to support this goal.

Several enhancements will be deployed in 2009 to improve the effectiveness of RAPT. Explicit identification of weather impact trends (improving, deteriorating or stable) will provide additional guidance to help air traffic managers begin planning traffic management initiatives (route reopening, proactive reroutes, etc.) in response to changing weather impacts. Improved RAPT timeline display filtering will allow users to focus only on the specific routes of interest at any given time. An explicit RAPT forecast score will enable traffic managers to evaluate the quality of RAPT guidance and manage risks associated with RAPT-based decisions. Finally, RAPT guidance will be explicitly tied to specific operational actions suggested in the concept of operations.

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Author Biography

Rich DeLaura is a staff scientist at MIT Lincoln Laboratory in Lexington, MA. He holds an A.B degree in chemistry and physics from Harvard University in Cambridge, MA (1977). He has struggled mightily over the past decade to unravel the mysteries of pilot decision-making in convective weather, the impacts of convective weather on both en route and terminal area operations, and effective, weather-aware decision support for air traffic management.

Michael Robinson received his B.S. and M.S. degrees in meteorology from the State University of New York, College at Oswego and Texas A&M University, respectively.

He is a staff member at MIT Lincoln Laboratory. He is involved in research efforts to quantify the operational benefits of weather-ATM systems. He has led several field studies investigating the operational utility of convective weather decision support tools at air traffic management facilities. He is also investigating improved training techniques for weather-ATM systems.

Ngaire Underhill received her B.A. in Computer Science and Economics from Smith College. She is a staff member at MIT Lincoln Laboratory, working to develop statistical analyses of the correlations between weather and commercial airline departures for the development and evaluation of decision support tools.