2.1 EVALUATION OF WEATHER IMPACT MODELS IN DEPARTURE MANAGEMENT DECISION SUPPORT: OPERATIONAL PERFORMANCE OF THE ROUTE AVAILABILITY PLANNING TOOL (RAPT) PROTOTYPE[†]

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There is a critical need for improved departure management during convective weather events in the highly congested airspace in the Northeast and upper Midwest. An early study (Allan, 2001) of the New York Integrated Terminal Weather System (ITWS) prototype suggested that small increases in New York airport departure rates during Severe Weather Avoidance Programs (SWAP) could result in significant delay reduction. More recently, the 2006 annual FAA System Review identified improved departure management in the New York area during SWAP as a critical need in the East and Midwest regions. Departure delays at New York airports can cascade across the entire National Airspace System (NAS), as surface gridlock and reduced gate availability necessitate a reduction of arrival traffic and increased airborne holding and ground delays.

The ability to predict impacts of convective weather on future departures is a fundamental need in departure management. The Route Availability Planning Tool (RAPT) (DeLaura, 2003) is an automated decision support tool (DST) intended to help air traffic controllers and airline dispatchers determine the specific departure routes and departure times that will be affected by operationally significant convective weather. RAPT helps users to determine when departure routes or fixes should be opened or closed and to identify alternative departure routes that are free of convective weather. RAPT assigns a status color - RED (blocked), YELLOW (impacted), DARK GREEN (insignificant weather encountered) or GREEN (clear) - to each route for future departure times up to 30 minutes into the future. The status is determined by combining the deterministic precipitation and echo top forecasts from the Corridor Integrated Weather System (CIWS) with a route blockage algorithm that incorporates a model for departure airspace usage. The airspace usage model includes departure route definitions that take into account route density and average departure trajectories. The route blockage model calculates the severity of convective weather impact on departure traffic along the first 60 minutes of flight time of the departure route. RAPT also includes a user display.

RAPT became operational in August 2002, and has evolved in response to feedback from operational users and post event analysis of performance. The operational model and display were revised in 2007 to address shortcomings observed in the most recent RAPT performance evaluation (DeLaura, 2006). A 'morning after' web site (RAPT Evaluation and Post-Event Analysis Tool, or REPEAT) was added to provide traffic and weather visualizations to support post-event analysis of New York area departure operations.

In this paper, the revised RAPT algorithm and display are described and evaluated. The fidelity of the RAPT operational model is assessed by comparing RAPT departure status with observed departure flows (i.e., trajectories, weather avoidance maneuvers and storm penetrations) on several days when convective weather SWAPs were in effect in New York. Real-time in-situ observations at RAPT facilities (described in a companion paper at this conference; Robinson, 2008), user feedback from RAPT playbacks and the REPEAT web site are used to support this post-event evaluation. For example, real time observations provide the time and operational rationale for a specific departure route closure identified in the traffic flow analysis. This information is necessary to identify closures or flow restrictions that are the result of factors outside of the current RAPT algorithm domain

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(e.g., traffic restrictions due to volume, downstream congestion, etc.). Real time observations are also used to identify specific times when critical, weather-related operational decisions were made. The RAPT guidance at these critical decision points is analyzed to determine if RAPT provided information that enabled (or could have enabled, had it been used) more timely or effective decisions.

The effect of forecast uncertainty on RAPT performance is also examined, particularly in convective weather situations where the location, severity and operational impact were difficult to predict. Strategies that mitigated risks associated with forecast uncertainty are presented. These include the use of additional information provided in the RAPT display, such as echo top heights encountered along the departure route, to confirm or modify RAPT guidance and the consideration of the departure status of two or more adjacent routes to 'average out' variations in the departure status timelines.

1. INTRODUCTION

With funding from the Port Authority of New York / New Jersey (PANYNJ), RAPT was initially developed and deployed in 2002 to address a need for improved departure management that was identified in the benefits analysis of the prototype Integrated Terminal Weather System (ITWS) in New York (Allan, 2001). RAPT was initially designed to reduce the cognitive load needed to determine the impact of convective weather on departure routes up to one hour in the future (30 minute departure look-ahead plus 30 minutes flight time) by automatically calculating the intersection of departure trajectories with the forecast positions of moving and evolving convective weather.

Implicit in the operational concept were several assumptions about route blockage and departure management. Route blockage was modeled as a step function of the overlap of level 3 precipitation contours and a series of contiguous fixed route segments that defined the departure route. A route was RED if the level 3 contour blocked the complete width of any route segment; GREEN if no level 3 contour touched any route segment, and YELLOW otherwise. Departure release decisions were assumed to be made jointly by the airport towers, New York TRACON and local airline dispatchers, and dependent only on the weather in the New York TRACON and ARTCC.

RAPT has evolved to incorporate lessons learned in operational testing. In 2003, the fixed route segments that defined departure routes were replaced by a 'traveling box' centered on each point of the departure trajectory. The route blockage algorithm was revised to calculate blockage as a weighted average of all precipitation forecast pixels in the traveling box, where pixel weights were determined by their distance from the route center. In 2004, the echo top height was added to the blockage algorithm to reduce over-warning where departing flights were able to fly over storms on routes that RAPT considered blocked (DeLaura, 2003). In 2006, the definition of departure routes was again revised to better model the observed operational constraints on traffic flow. Routes were widened and route widths were made a function of route density and complexity. The route blockage model was revised to include an estimate of the width of passable airspace traversing each traveling box. Again, these changes were introduced to reduce observed RAPT over-warning due to its overly restrictive route definition (DeLaura, 2006).

It was also recognized that the New York ARTCC, and to a lesser extent neighboring downstream ARTCCs (particularly Cleveland and Washington, DC), were key participants in making decisions to open, close or reroute departure traffic flows in convective weather SWAP. As a result, RAPT was deployed to users in neighboring ARTCCs and RAPT departure trajectories were extended to one hour flight time to provide additional route impact information to downstream users.

In the summer of 2007, we performed an extensive review of RAPT performance, supported by real-time in-situ observations at several air traffic control facilities. Weather, traffic and site observations from eleven days of operations with significant convective weather impacts in July, August and September were analyzed. RAPT performance was examined to evaluate the fidelity of the RAPT blockage model, the usefulness of RAPT guidance and the validity of RAPT operational concepts. Presented in the following sections are a detailed description of the RAPT algorithm deployed in 2007 and the results of the RAPT performance analysis.

2. THE RAPT ALGORITHM AND DISPLAY

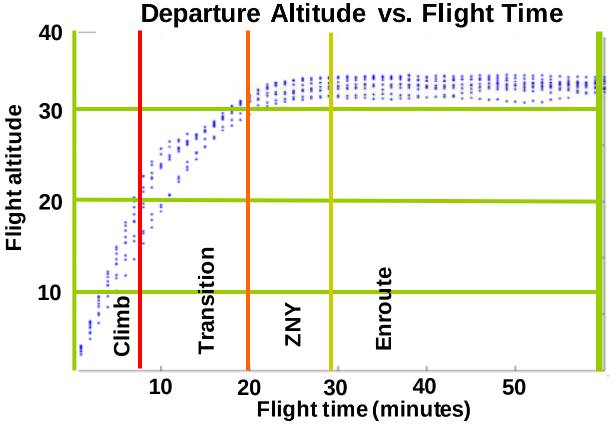
RAPT calculates route blockage along departure routes that are based on statistically averaged, 60 minute, four-dimensional (4D) departure flight trajectories. Trajectory points are calculated at one minute intervals. Flight trajectories have four phases – climb, transition, near enroute and enroute – that reflect flight altitude and airspace complexity. Routes are defined by boxes centered on the trajectory points, whose 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 enroute phase where departure and arrival routes are densely packed (ZNY and northern ZDC) and widen again in the enroute phase where routes are not so densely packed (ZOB and southern ZDC). Figure 1 illustrates the RAPT departure trajectory definitions.

Route blockage, a number between 0 and 1, is calculated for each box along a given route and thresholded to one of the four blockage status colors. The status for a particular departure route at a given departure time is the highest blockage encountered by the flight trajectory that starts at the departure time.

The Corridor Integrated Weather System (CIWS) provides forecast grids of precipitation intensity based on Vertically Integrated Liquid (VIL) and echo top heights that are used in the RAPT blockage calculation. Pixel values in the VIL forecast range from 0 to 254 and represent a feature interest level that is mapped into Video Integrated Processor (VIP) levels of precipitation intensity for display (Troxel, 1990). Note that the VIL forecast provides greater resolution of precipitation intensity than the 6 levels of the VIP scale. The echo tops forecast predicts echo top heights at each pixel in the grid to the nearest 1000 feet. Forecasts have a spatial resolution of 1 km and a temporal resolution of 5 minutes. Forecasts are updated every 5 minutes. RAPT uses forecasts out to 90 minutes into the future (30 minute departure look-ahead plus 60 minutes flight time).

Route blockage is calculated at each trajectory point based on the weather inside the route box centered on the trajectory point. It is a linear combination of three factors: VIL intensity (I), echo top height (H) and passable width (W) (Figure 2). Intensity is a spatially weighted average of all VIL pixels greater than or equal to VIP level 1, where the weights are higher toward the center of the route box and lower toward the edges. Weights are an algorithm parameter.

a) Departure trajectory altitude profile



b) Departure route plan view

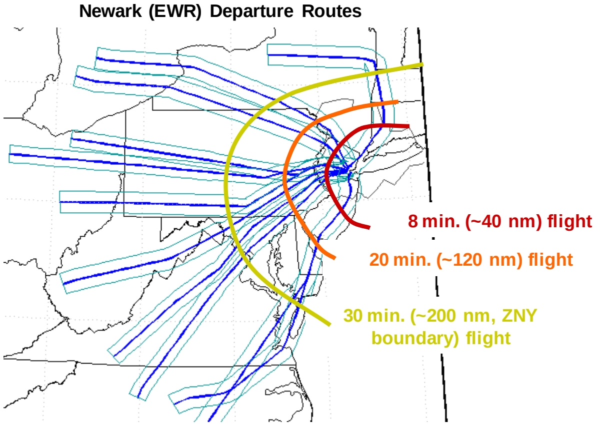


Figure 1. RAPT departure route definitions. Departure trajectory altitude vs. time profile (a) and departure route plan view (b) are illustrated.

I = Sum (over all pixels >= level 1) (Pixel weight * (VIL – Level 1 threshold) / (Level 3 threshold – Level 1 threshold))

The echo top height (H) is the median of all valid echo top pixels in the box. The passable width (in km) is an algorithm parameter that was set to 10 km during the operational test. Its contribution to blockage is calculated as

W = Passable width – Greatest width between level 3 VIL pixels

The calculated blockage is
$B = a * I + b * E + c * W$

where a, b and c are algorithm parameters that are functions of the departure trajectory phase, and B is clipped to the [0,1] interval.

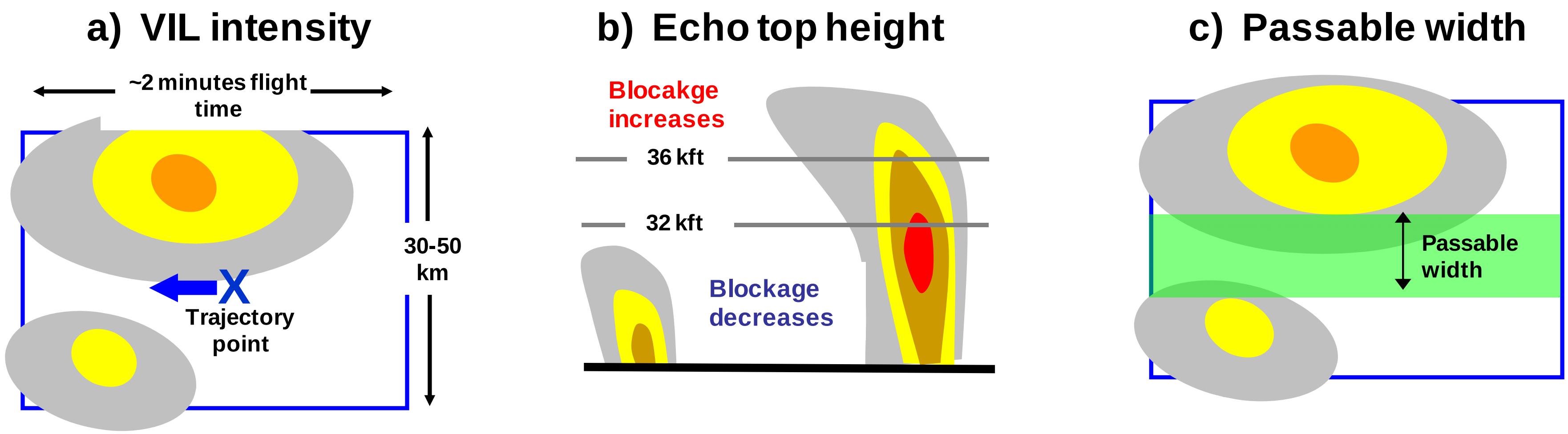
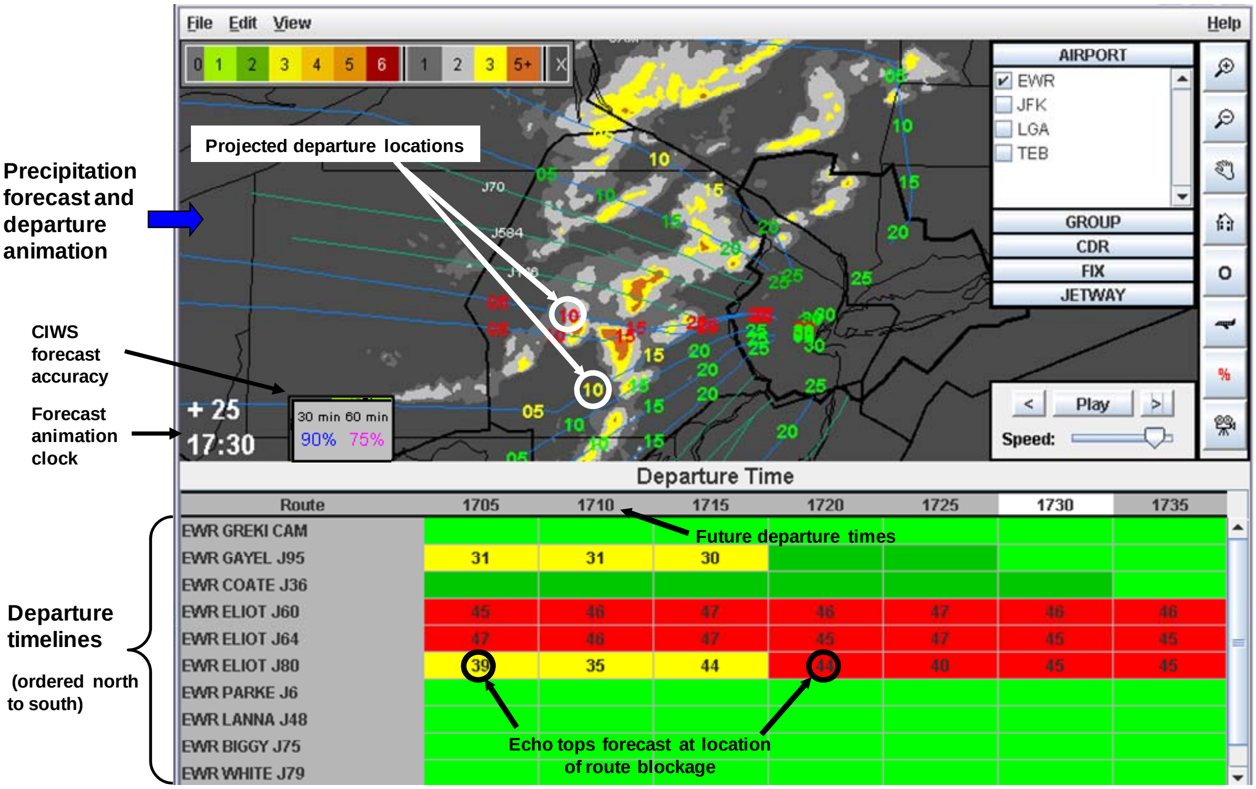


Figure 2. RAPT route blockage algorithm. Figures (a) is an overhead view of the departure route box (blue box) that surrounds a single trajectory point in a RAPT departure trajectory (the blue X in the middle of the box). The VIL intensity term in the blockage score a weighted average of the VIL values at each pixel in the box, with pixels near the center having higher weights than those near the edges. Figure (b) illustrates the concept for echo top height contribution. Route blockage decreases linearly with echo top height where echo tops are less than 32 kft and increases linearly where they exceed 36 kft. Between 32 and 36 kft, the echo tops contribution to blockage is 0. Figure (c) illustrates the definition of the passable width, which is the widest longitudinal path that traverse the route box without any level 3 VIL pixels (shown as yellow regions in the figure).

The RAPT display, illustrated in Figure 3, provides a RAPT departure status table and a weather forecast animation window. Each row in the table ('departure status timeline') provides the status of future departures along a particular route. The routes are ordered from north to south. Each column in the table represents a future departure time. Each cell in the table is colored according to the departure status for a particular departure time and route as described above. YELLOW and RED cells include a number that gives the median echo top encountered along the route at the point of blockage. They may also include an 'ENR' notation that indicates that the blockage occurred beyond the first 30 minutes of flight time, in 'enroute' airspace.

The weather forecast animation window shows an animated loop of the precipitation forecast, with the animation of RAPT departures overlaid. Each animated departure is represented as a 2 digit number, which gives the departure time as minutes after the hour. The color of the number matches the RAPT status (GREEN, DARK GREEN, YELLOW or RED). The animation window provides users with additional information that can help them evaluate the reliability of departure status given in the RAPT departure status timelines.



Departure Time

Route	1705	1710	1715	1720	1725	1730	1735
EWR GREKI CAM							
EWR GAYEL J95	31	31	30				
EWR COATE J36							
EWR ELIOT J60	45	46	47	46	47	46	46
EWR ELIOT J64	47	46	47	45	47	45	45
EWR ELIOT J80	39	35	44	44	40	45	45
EWR PARKE J6							
EWR LANNA J48							
EWR BIGGY J75							
EWR WHITE J79							

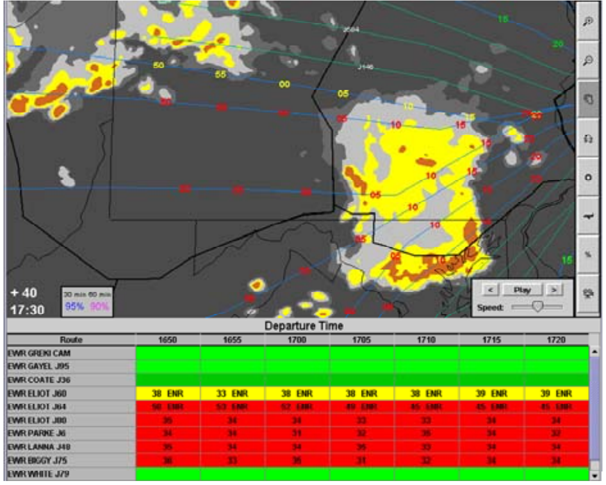
Figure 3. RAPT display. RAPT was available to users as a window on the CIWS situational display or as a stand-alone web-based client application.

3. EVALUATION RESULTS

The RAPT performance evaluation focused on three critical areas: validity of the RAPT operational concept, operational fidelity and improvements needed to increase the realization of RAPT benefits. In assessing the validity of the RAPT operational concepts, we sought to determine if RAPT provided the information needed to realize the benefits that RAPT is intended to provide: better timing of route openings and closings, small but significant increases in departure rates and improved surface management and inter-facility coordination. Operational fidelity is the measure of the 'correctness' of the RAPT blockage algorithm; verifying that traffic could not flow when routes were RED and that it could flow when they were GREEN. Identifying improvements required the consideration of several factors, including the timeliness, applicability and reliability of RAPT guidance.

Operational fidelity was evaluated by comparing actual traffic – either individual departure trajectories or departure traffic flows – to RAPT departure status. In general, the RAPT blockage algorithm performed best in circumstances where there is moderate or high weather coverage. Examples of such weather include solid or 'gappy' squall lines, low-topped stratiform weather or convective cells embedded in regions whose weather was characterized by level 1 or 2 VIL, even when the convection was unorganized and difficult to predict with a high degree of accuracy (see Figure 4).

a) RAPT at 1650Z



Departure Time

Route	1650	1655	1700	1705	1710	1715	1720
EWR GREKI CAM							
EWR GAYEL J95							
EWR COATE J36							
EWR ELIOT J60	38 ENR	33 ENR	38 ENR	38 ENR	38 ENR	39 ENR	39 ENR
EWR ELIOT J64	50 ENR	53 ENR	52 ENR	49 ENR	45 ENR	45 ENR	45 ENR
EWR ELIOT J80	35	34	34	33	33	34	34
EWR PARKE J6	34	34	31	32	36	34	32
EWR LANNA J48	35	34	34	35	33	34	34
EWR BIGGY J75	38	33	36	31	32	34	34
EWR WHITE J79							

b) Weather and traffic at 1730Z

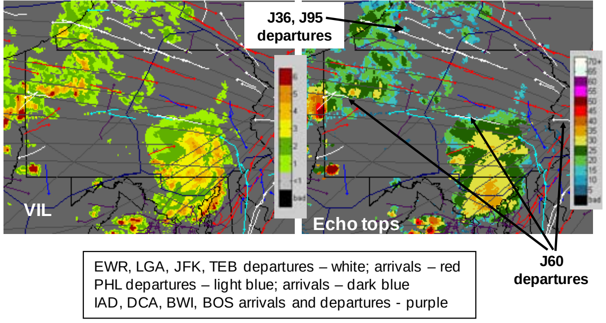
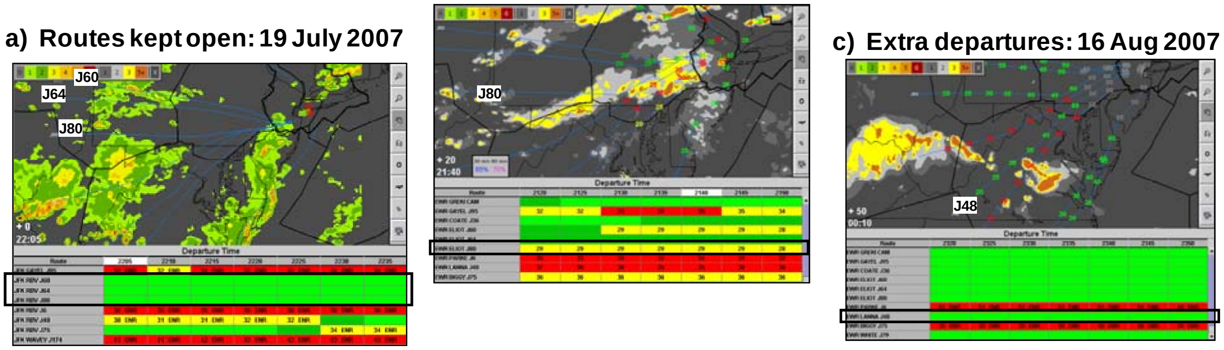


Figure 4. Illustration of high operational fidelity in RAPT departure status. RAPT departure status forecasts at 1650Z (a) and observed weather and departure traffic at 1730Z (b). RAPT shows northern departure routes J95 and J36 as GREEN or DARK GREEN, indicating minimal impact due to convective weather; steady departure streams in (b) confirm the guidance. J60 is YELLOW, due to scattered convection in enroute airspace; reduced departure stream in (b) confirms the guidance. J64 is RED, blocked by a large, intense cell in enroute airspace; departure routes to the southwest (J80, J6, J48 and J75) are all RED due to convection in ZNY ARTCC; figure (b) shows PHL departures (light blue) avoiding blockage in ZNY and confirms that all southwest departures routes are closed. Example is from 9 August, 2007.

The RAPT performance evaluation found many examples where RAPT guidance matches operational decisions. However, if RAPT does nothing more that confirm decisions that air traffic managers already make, it does not provide any benefit. Unfortunately, it is not easy to evaluate RAPT's operational fidelity when its guidance does not match observed operations. If RAPT status turns GREEN and no departure traffic is observed, did RAPT identify a valid opportunity to open a route proactively that was missed by air traffic managers? Were there other operational concerns (downstream volume constraints, possibility of arrivals deviating into departure airspace, etc.), not readily apparent in the traffic data, that caused air traffic managers to restrict the departure flow? In order to ascertain RAPT's fidelity in these hypothetical circumstances, it is necessary to corroborate the data analysis with site observations that provide direct evidence of RAPT usage to make decisions that users might not have made otherwise, or provide evidence that no other operational concerns were responsible for the observed course of action.

Figure 5 presents three illustrations of benefits arising from documented proactive RAPT usage. In Figure 5a, JFK air traffic control was concerned that the Robbinsville fix (RBV) was in danger of being closed by convective weather. If the fix were closed, they would have to move several queued departures off the runway to avoid stalling and possibly gridlocking the departure queue. However, resequencing the departure queue is a costly operation that they would rather avoid. Controllers consulted RAPT to see that the RBV fixes were predicted to remain open. As a result, they avoided the need to resequence the departure queue and moved the departures out through RBV. Figure 5b presents an example where the New York TRACON, observing that the departure status on airway J80 has moved from RED to YELLOW and noting that the forecast echo tops along the route were below 30,000 feet, requested that the New York ARTCC reopen J80 and the route was reopened. In Figure 5c, the New York ARTCC saw an opportunity to release departures along J48 between impacts of moving storm cells, and three extra departures were successfully released into the gap.


b) Early route opening: 05 July 2007

a) Routes kept open: 19 July 2007

c) Extra departures: 16 Aug 2007

Figure 5. Illustrations of documented RAPT usage. Successful uses of RAPT to make proactive decisions confirm operational fidelity of RAPT algorithm. Black boxes highlight relevant RAPT departure status timelines. In figure (a), departure routes J60, J64 and J80 from JFK airport through the RBV departure fix are kept open since RAPT forecast minimal impact from decaying storm. In figure (b), departure route J80 is opened because RAPT shows YELLOW status with low echo tops (below 30 kft). In figure (c), three extra departures are release along J48 as RAPT predicts a gap between storm impacts.

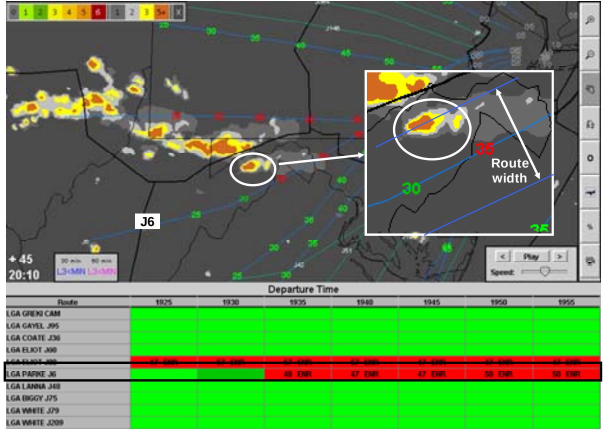
RAPT was not always so prescient. RAPT tended to fail, usually by over-warning, where small, strong isolated cells or high-gradient edges of larger cells were present near the edges of route boundaries. Since RAPT uses only valid pixels to characterize weather in the route box (pixels that are 'null', indicating lack of radar return, valid forecast or edited data, are not included in the intensity or echo top height calculations), it often overestimated the impact of such weather. This failure mode became more evident with the introduction of wider routes in 2007, as the route boundaries now extended several miles to either side of the center of the route and severe weather at greater distance influenced the route blockage calculation. Figure 6 illustrates this failure, where the leading edge of a strong, high topped cell just crosses the route boundary, resulting in RAPT blockage on a route where traffic continues to run unimpeded. Even though only a small portion of the route is impacted by the weather, the contribution of the high echo tops and strong precipitation intensity dominate the blockage calculation.

If RAPT is to be used to anticipate route openings and closings, users must develop confidence in the fidelity of its blockage model, and RAPT must provide users with the information they need to determine when to believe and when to ignore RAPT guidance. RAPT must answer the two most commonly asked questions in the field, "Why is it telling me this?" and "How do I know it's right?" RAPT must be transparent, readily providing information to the user that explains its guidance. It also should provide the user with some objective measure of its performance.

The 2007 implementation of RAPT was not particularly transparent. The blockage score calculation is highly non-linear and is not easily approximated by any rule of thumb. In circumstances like those illustrated in Figure 6, users were confused as to why RAPT showed

RED when the weather was so far from the route, and RAPT did not provide any additional explanation to help them understand. Potential ways to explain RAPT guidance in such situations include the ability to show the route boundaries on the animation display and to identify where RAPT thought the blockage was occurring.

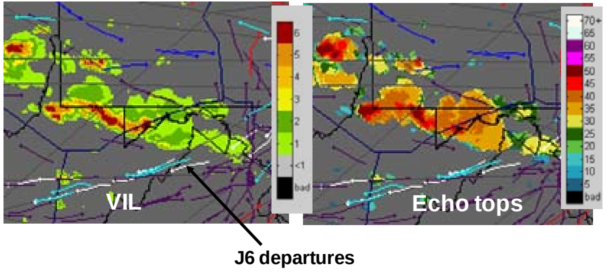
a) RAPT at 1925Z



Departure Time

Route	1925	1930	1935	1940	1945	1950	1955
LGA GREKI CAM	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA GAYEL J95	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA COATE J36	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA ELIOT J60	🟩	🟩	🟩	🟩	🟩	🟩	🟩
[illegible]	[illegible] ENR	[illegible] ENR	[illegible] ENR	[illegible] ENR	[illegible] ENR	[illegible] ENR	[illegible] ENR
LGA PARKE J6	🟩	🟩	48 ENR	47 ENR	47 ENR	50 ENR	50 ENR
LGA LANNA J48	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA BIGGY J75	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA WHITE J79	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA WHITE J209	🟩	🟩	🟩	🟩	🟩	🟩	🟩

b) Weather and traffic at 2010Z

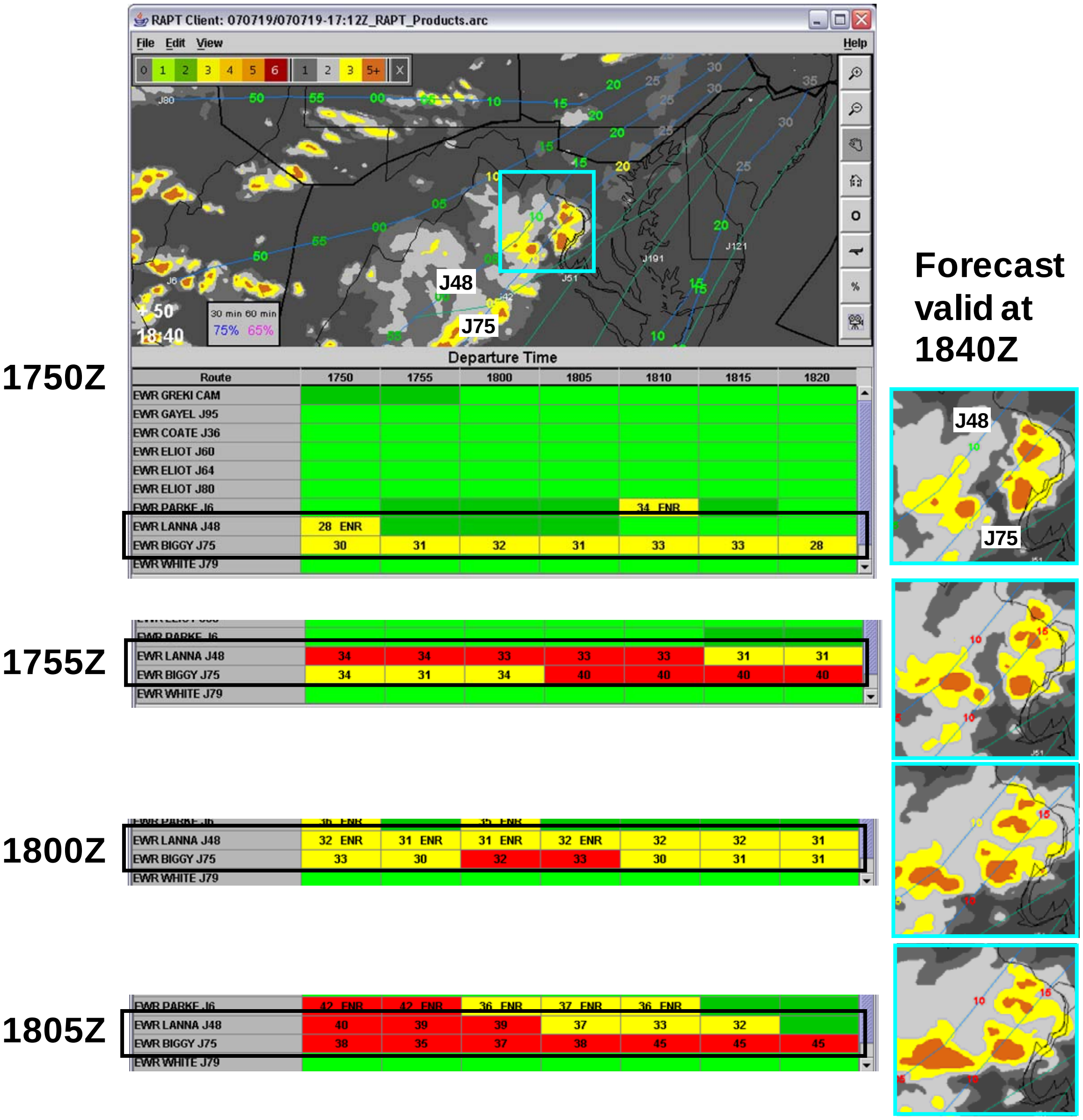


EWR, LGA, JFK, TEB departures – white; arrivals – red
PHL departures – light blue; arrivals – dark blue
IAD, DCA, BWI, BOS arrivals and departures - purple

Figure 6. Illustrations of poor operational performance. At 1925Z, RAPT shows J6 departure closing down at 1935Z as a small, intense cell crosses the route boundary. Weather and traffic at 2010Z show traffic stream on J6 continuing uninterrupted as there is still sufficient room to avoid the weather without deviating outside of route boundaries Example is from 8 August, 2007.

Some form of explicit RAPT confidence metric is needed to help users quickly evaluate the quality of RAPT guidance. In principal, it is straightforward to calculate a RAPT forecast score: compare the RAPT blockage calculated from the forecast with the blockage calculated from true weather. However, such a score has little value in real time operations because it provides a measure of past performance (forecast scores will be at least 90 minutes old), not a prediction of future performance. Furthermore, the RAPT forecast performance is not well correlated over time, due to the dynamic nature of convective weather, particularly at the small scales involved in calculating RAPT route blockages. Lacking a reliable measure of confidence, users in 2007 were required to develop their own rules of thumb to evaluate the quality of RAPT guidance, a difficult task with such a complex and unfamiliar tool.

RAPT was also not sufficiently robust in the face of highly uncertain forecasts of small-scale weather features (on the order of route widths) in dynamically changing convective weather. The problem is illustrated in Figure 7. The leading edge of a cluster of strong, unorganized cells is impacting departure airways J48 and J75. There is significant forecast uncertainty, and as forecasts are updated, the position and motion of the cells change. Because of the location and strength of the cells, even small changes in the forecast result in significant changes in RAPT blockage, as the successive RAPT departure timelines illustrate. This forecast instability is a result of a sort of ‘impedance mismatch’ between the weather forecast and the RAPT algorithm: RAPT is over-sensitive to small, strong weather features and the temporal correlation between successive weather forecasts is greater than RAPT expects. This over-sensitivity became more problematic in 2007, when RAPT departure routes were widened significantly and changes in the CIWS forecasts resulted in reduced correlation between features in successive forecasts. In any event, such instability has an easily predictable effect on user confidence – RAPT is not useful if the user cannot determine when its guidance is reliable.



1750Z

Route	1750	1755	1800	1805	1810	1815	1820
EWR GREKI CAM							
EWR GAYEL J95							
EWR COATE J36							
EWR ELIOT J60							
EWR ELIOT J64							
EWR ELIOT J80							
EWR PARKE J6					34 ENR		
EWR LANNA J48	28 ENR						
EWR BIGGY J75	30	31	32	31	33	33	28
EWR WHITE J79							

1755Z

EWR PARKE J6							
EWR LANNA J48	34	34	33	33	33	31	31
EWR BIGGY J75	34	31	34	40	40	40	40
EWR WHITE J79							

1800Z

EWR LANNA J48	32 ENR	31 ENR	31 ENR	32 ENR	32	32	31
EWR BIGGY J75	33	30	32	33	30	31	31
EWR WHITE J79							

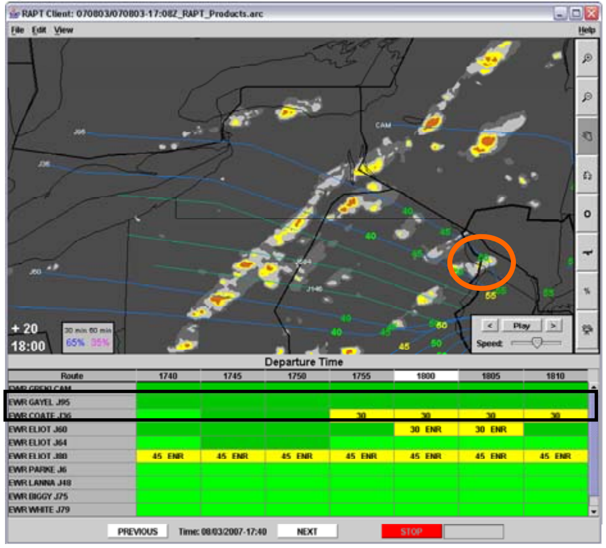
1805Z

EWR PARKE J6	42 ENR	42 ENR	36 ENR	37 ENR	36 ENR		
EWR LANNA J48	40	39	39	37	33	32	
EWR BIGGY J75	38	35	37	38	45	45	45
EWR WHITE J79							

Figure 7. Departure status timeline instability as a result of forecast uncertainty. As weather features change unpredictably with successive forecast updates, RAPT departure status along routes J48 and J75 changes significantly. Example is from 19 July, 2007.

Even when the weather forecast consistently locates the weather features correctly, the RAPT departure status prediction is also sensitive to errors in forecast intensity, as shown in Figure 8. In this example, the echo tops forecast correctly locates the cell responsible for the route blockage, but underestimates the echo top height by several thousand feet, resulting in significant RAPT under-warning.

a) RAPT, CIWS VIL forecast at 1740Z

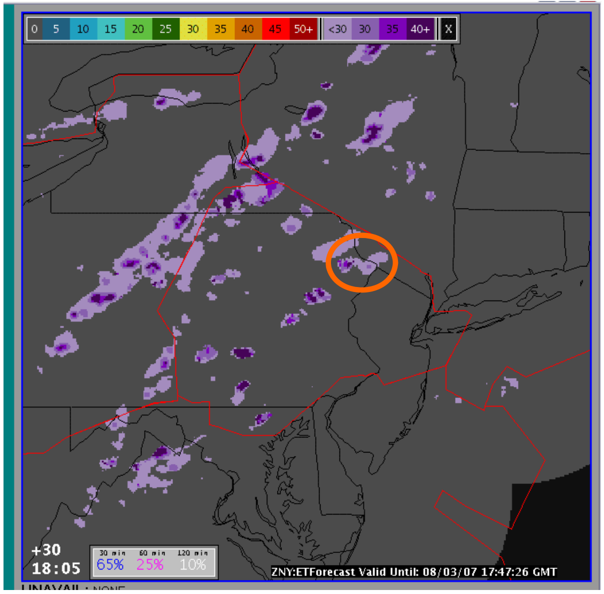


Departure Time

Route	1740	1745	1750	1755	1800	1805	1810
EWR GREKI CAM	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR GAYEL J95	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR COATE J36	🟩	🟩	🟩	30	30	30	30
EWR ELIOT J60	🟩	🟩	🟩	🟩	30 ENR	30 ENR	🟩
EWR ELIOT J64	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR ELIOT J80	45 ENR	45 ENR	45 ENR	45 ENR	45 ENR	45 ENR	45 ENR
EWR PARKE J6	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR LANNA J48	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR BIGGY J75	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR WHITE J79	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Time: 08/03/2007-17:40

b) CIWS echo top forecast at 1735Z



c) Weather and traffic at 1800Z

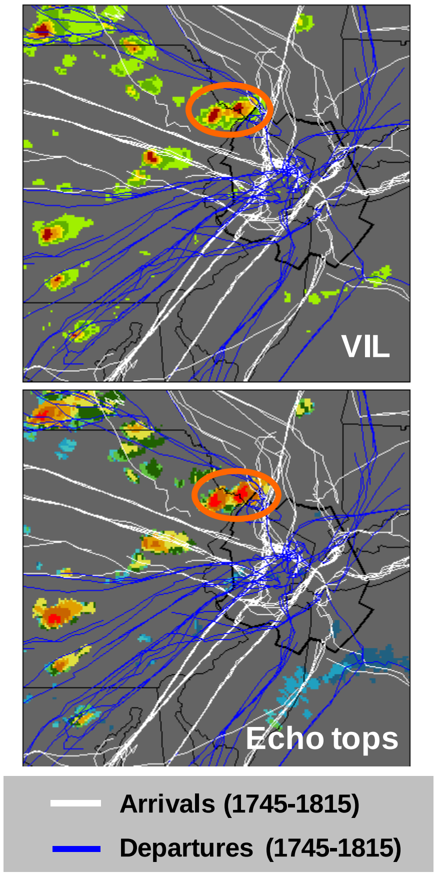
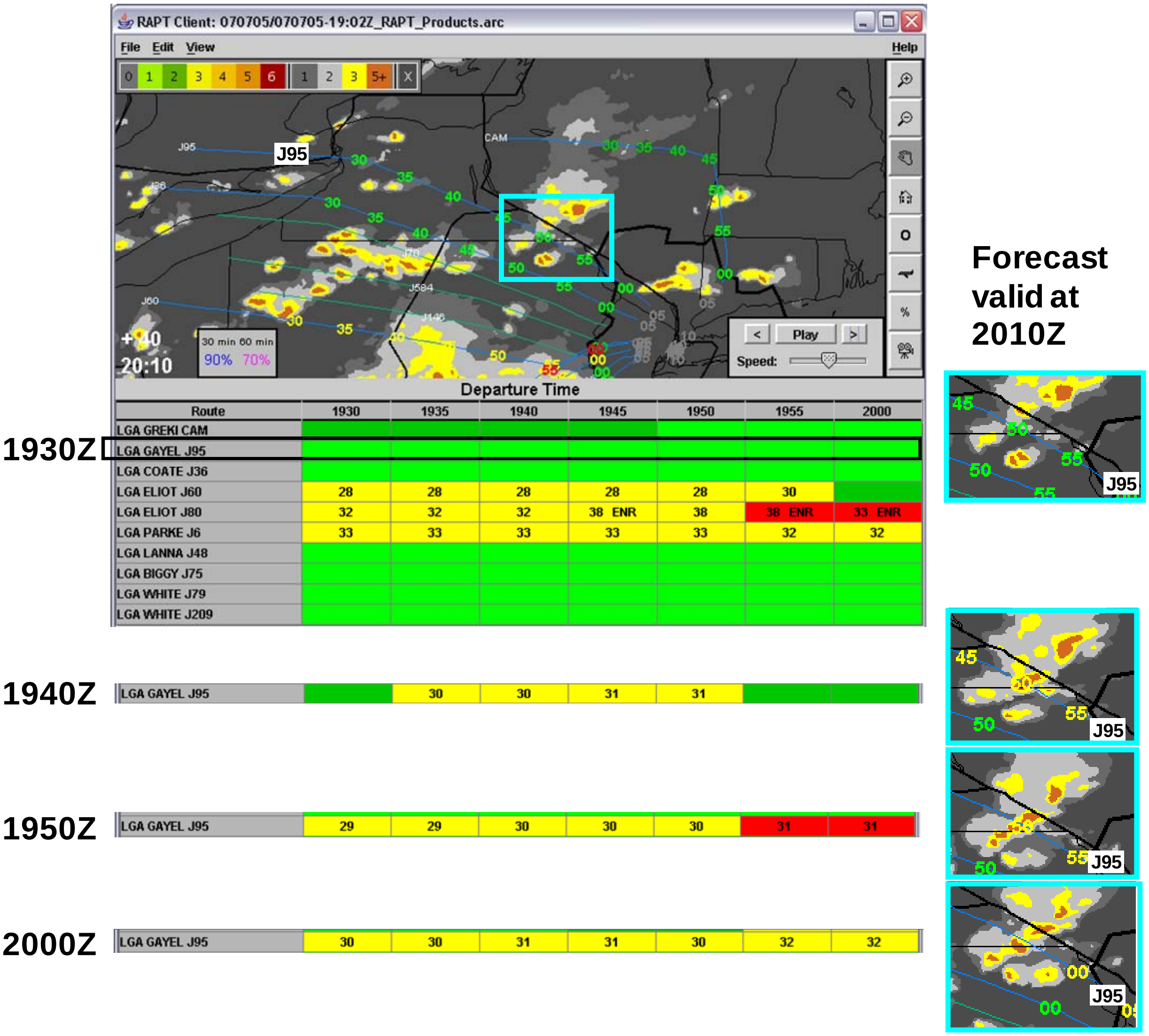


Figure 8. Impact of small scale forecast intensity errors on RAPT guidance. RAPT timeline and CIWS VIL forecast at 1740Z (a) and CIWS echo top forecast at 1735Z (b) show small, low intensity cells impacting departure routes J95 and J36 (orange oval). Note the low forecast accuracy scores (in magenta) for the 30 minute (65% for both VIL and echo tops) and the 60 minute (35% and 25%, respectively) forecasts. Actual weather and traffic (c) show strong cells causing departure traffic to deviate to the north and east to avoid the cells. Example is from 3 August, 2007.

RAPT did provide information that enabled users to reduce the risk associated with forecast uncertainty. The echo top altitudes in the RAPT departure timeline display provided information that enabled users to ‘smooth out’ variations in the RAPT departure status timelines, as illustrated in Figure 9. In this example, the decision was made to release a pathfinder along airway J95 based on RAPT showing GREEN at 1930Z. Two pathfinders were identified and given departure times in the range between 1950 – 2000Z. The RAPT forecast update showed J95 departures in the time range between 1950 and 2005Z had changed to YELLOW and later departures to RED, causing air traffic managers to reconsider the decision. However, the manager also noted that RAPT was predicting low echo tops (around 30 kft) along the flight route, suggesting that the flights could successfully navigate the departure route. The decision was made to release the pathfinders as planned, and they departed successfully.



1930Z

Departure Time

Route	1930	1935	1940	1945	1950	1955	2000
LGA GREKI CAM	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA GAYEL J95	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA COATE J36	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA ELIOT J60	28	28	28	28	28	30	🟩
LGA ELIOT J80	32	32	32	38 ENR	38	38 ENR	33 ENR
LGA PARKE J6	33	33	33	33	33	32	32
LGA LANNA J48	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA BIGGY J75	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA WHITE J79	🟩	🟩	🟩	🟩	🟩	🟩	🟩
LGA WHITE J209	🟩	🟩	🟩	🟩	🟩	🟩	🟩

1940Z

LGA GAYEL J95	🟩	30	30	31	31	🟩	🟩

1950Z

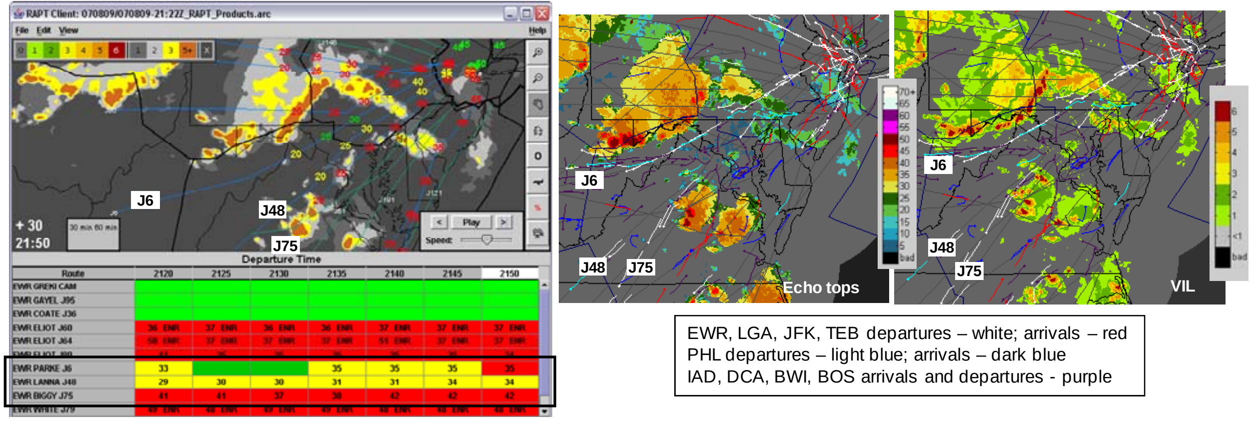
LGA GAYEL J95	29	29	30	30	30	31	31

2000Z

LGA GAYEL J95	30	30	31	31	30	32	32

Figure 9. Illustration of risk mitigation in RAPT using echo top height information. A decision was made at 1930Z to release a pathfiner along J95 from LaGuardia airport some time between 1950 and 2000Z, based on GREEN RAPT status for the route (RAPT display at top). RAPT status from subsequent forecasts (1940Z, 1950Z) indicate first YELLOW and then RED status for the route. However, noting the consistently low echo top heights forecast (between 29 and 31 kft.), air traffic managers decided to stay with the plan, and pathfinders were successfully released from both LaGuardia and Newark airports between 1950 and 2000Z. Example is from 5 July, 2007.

A second risk mitigation strategy was to mentally 'average' departure route status from adjacent routes when there was significant variation in their departure status timelines. RAPT timeline 'signatures', such as those illustrated in Figure 10, indicate opportunities for risk-hedging departure management strategies such as combined 'two as one' and 'three as one' departure operations. In these operations, two or three adjacent departure streams are merged into a single reduced-capacity traffic flow that is vectored around the storm. As departing flights clear the storm, they split from the merged flow to return to their filed flight plan. Two or three-as-one operations are frequently employed in the New York area terminal airspace to keep departures flowing when there are persistent gaps in local convective weather can be exploited.



a) RAPT at 2120Z

b) Weather and traffic at 2150Z

Route	2120	2125	2130	2135	2140	2145	2150
EWR GREKI CAM	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR GAYEL J95	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR COATE J36	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EWR ELIOT J60	36 ENR	37 ENR	36 ENR	36 ENR	37 ENR	37 ENR	37 ENR
EWR ELIOT J64	58 ENR	37 ENR	37 ENR	37 ENR	51 ENR	37 ENR	37 ENR
EWR ELIOT J80	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
EWR PARKE J6	33	🟩	🟩	35	35	35	35
EWR LANNA J48	29	30	30	31	31	34	34
EWR BIGGY J75	41	41	37	38	42	42	42
EWR WHITE J79	49 ENR	48 ENR	49 ENR	49 ENR	48 ENR	48 ENR	48 ENR

EWR, LGA, JFK, TEB departures – white; arrivals – red
PHL departures – light blue; arrivals – dark blue
IAD, DCA, BWI, BOS arrivals and departures - purple

Figure 10. Using RAPT to identify opportunities for '2 as 1' and '3 as 1' operations. RAPT status timeline 'triplet' for departures along J6, J48 and J75 show a mixture of GREEN, YELLOW and RED status for adjacent departure routes at 2120Z (a). Observed traffic at 2150Z (b) shows J48 and J75 departure flows running 'as 1' to avoid severe weather in northern VA before splitting apart in central VA. Example comes from 9 August, 2007.

4. CONCLUSIONS

RAPT combines a model for the usage of departure airspace in the New York area with CIWS forecasts of precipitation intensity and echo top height to predict the impact of convective weather on future departures in the first 60 minutes of flight time. An extensive operational test of RAPT performance was carried out in the summer of 2007 to evaluate the validity of the RAPT operational concepts and the quality of its impact predictions and decision support guidance.

The operational testing confirmed the validity of the RAPT operational concepts. Field observers noted successful RAPT usage at several facilities over the course of the study and found that RAPT guidance was operationally sound and timely in many circumstances. Overall, RAPT performance was best in circumstances where convection was embedded in larger regions of stratiform or low level precipitation. RAPT performed poorly in regions where route impacts were due to weather characterized by a large spatial gradient in the VIL or echo top prediction fields caused by small, strong isolated cells or the leading edge of intense convection.

The RAPT evaluation identified three needs that must be addressed in order to ensure that the potential benefits of RAPT usage are realized: improved operational fidelity, a more transparent blockage algorithm whose outputs can be readily explained to users and more robustness in the face of forecast uncertainty and real-time estimates of forecast confidence. Over time, the RAPT algorithm has grown 'organically' to address specific operational issues as they have been identified and the algorithm has become unnecessarily complicated and over-tuned to specific blockage scenarios. A near term RAPT development goal is to simplify the route blockage algorithm and reduce its sensitivity to small changes in the echo top forecast. Explicit rules of thumb can be developed to explain RAPT departure status and made available to users in real-time. Planned reductions in sensitivity to small changes in weather forecasts should improve both the operational fidelity and robustness of the RAPT blockage algorithm.

The real-time estimation of RAPT confidence given some measure of forecast uncertainty is a difficult problem. Route blockage requires the analysis of a set of specific ensembles of hundreds of forecast pixels (weather within the boundaries of a route) to determine both the severity of the weather and the likelihood that a passable route through the weather can be found. Estimating the uncertainty in route blockage given measures of forecast uncertainty such as error estimates for each pixel is virtually impossible. Furthermore, critical characteristics of forecasts, such as the spatial correlation between forecast pixels and the relative magnitude of different forecast errors (motion, storm growth, decay, etc.), are not well understood. More research is needed to understand and characterize weather forecast uncertainty in a way that can be readily translated into route blockage uncertainty.

5. REFERENCES

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