ROUTE SELECTION DECISION SUPPORT IN CONVECTIVE WEATHER: A CASE STUDY OF THE EFFECTS OF WEATHER AND OPERATIONAL ASSUMPTIONS ON DEPARTURE THROUGHPUT

Richard DeLaura and Shawn Allan, MIT Lincoln Laboratory, Lexington, MA

Abstract

This paper presents a detailed study of a convective weather event affecting the northeastern United States on 19 April 2002: its impacts on departure throughput, the response of traffic managers and an analysis of the potential effects of decision support on system performance. We compare actual departure throughput to what may have been achieved using the Route Availability Planning Tool (RAPT), a prototype decision support tool. We examine two questions: Can decision support identify opportunities to release departures that were missed during the event? How is route selection guidance affected by the operational model incorporated into the decision support tool? By "operational model", we mean three things: the choice of weather forecast information used to define hazards (precipitation, echo tops, etc.), the model for how airspace is used (route definition and allocation) and the assessment of the likelihood that a given route is passable. We focus our analysis on the operational model only; we eliminate weather forecast uncertainty as a factor in the analysis by running RAPT using the actual observed weather as the forecast ('perfect' forecast).

Results show that decision support based on perfect forecasts is sensitive to all three elements of the operational model. The sensitivity to weather metrics became evident when we compared decision support based upon perfect forecasts of level 3 vertically integrated liquid (VIL) to that based upon VIL plus storm echo tops. Traffic managers were at times able to move more aircraft by abandoning nominal routing than if they had used nominal routing with perfect weather information. The assessment of route availability will, at times, be ambiguous; different interpretations of that assessment lead to decisions that result in significant differences in departure throughput. These results suggest that for traffic flow management tools, a realistic operational model may be at least as important as the frequently discussed problem of weather forecast uncertainty.

Introduction

Allan et al. [1] found that departure delays at EWR were frequently larger than arrival delays on days when convective weather was disrupting operations both in the terminal and enroute environment around New York. A second study of the FAA Integrated Terminal Weather System (ITWS) in New York [2] identified higher departure rates during SWAPs as the most effective mechanism for reducing convective weather delay. This study also recommended the development of integrated weather information/traffic management tools that focus on both departures and arrivals. As a result, the Route Availability Planning Tool (RAPT) was developed to assist with the planning of departure routing during convective weather events impacting New York airports. This tool was deployed to users for testing during late summer 2002 and continues to be used at present.

New York airports operate within perhaps the most restricted and complex airspace in the United States. Mondolini and Lilang [5] used fractal applications to define a fractal metric that captured the complexity of many ARTCCs in the United States. Both the New York ARTCC and TRACON ranked at the top of the list for complexity. Beaton et al. [3] examined the unique characteristics of New York airspace. Using a clustering technique, they found that New York and its surrounding area had the greatest density of airport operations in the United States. Their study also showed that because of this density, lateral variability of traffic flows was heavily restricted and holding typically had to occur in centers outside of the NY ARTCC, especially in ZDC. They reported that there was

little alternate routing available when convective weather closed routes because of the lack of airspace. These results demonstrate the need to minimize the time for which these routes are unused as much as possible during convective events, making a route-based departure planning tool especially useful.

There are many complex factors that come into play when deciding if a plane can be released for departure. Often weather hundreds of miles away is a deciding factor [4]. Coordination between facilities along the flight path is crucial. Airline economies are important. Interpretation of forecast uncertainties and agreement about what constitutes weather hazard play a significant role.

In order to tailor decision support tools such as RAPT and Automation-assisted Weather Problem Resolution (AWPR) [10] to meet the needs of traffic managers, it is very important to know where and why opportunities are lost to move aircraft during convective weather, and how those currently lost opportunities might be realized through new technologies. To accomplish this, we present a case study of a convective weather event affecting New York airports on 19 April 2002.

Case Analysis

Selection of weather event
This case was attractive because the impacts of convective weather in the eastern USA were confined to within approximately 600 km of the New York airports. The limited extent of the storm eliminates distant weather conditions as a factor affecting departure throughput. The storms initially formed around 1400 in eastern Ohio and West Virginia and tracked towards the east, clearing New York City at approximately 2200. The routes that were analyzed in this study extend to the boundaries of the region that fully enclosed the weather event during this period of time. The case also featured a large gap in a line of storms that appeared to be underutilized.

The analysis was performed for departures out of EWR, LGA, and TEB and focused on the four major westbound jet routes out of New York: J80, J6, J48, and J48. Since the Ohio valley and

Appalachians are convective initiation hot spots, and since storms almost always track from west to east, these departure flows out of New York are the most heavily impacted by thunderstorms during the convective season. Multi-hour delays to many individual flights are the norm when even one of these routes is shut down due to hazardous weather.

Overview of RAPT
RAPT combines a hazardous weather forecast with statistically determined departure paths to predict the availability of specific departures, along a given route, in the future. In the initial operational prototype, we use the 60-minute Terminal Convective Weather Forecast (TCWF) from ITWS in New York City. TCWF predicts two-dimensional regions where there is a high likelihood of vertically integrated liquid content (VIL) $\geq$ level 3 [8,12]. For a discussion of the benefits of using VIL over more conventional precipitation intensity metrics, please see Robinson et al. [9]. In this study, we use a 'perfect' forecast consisting of the actual observed VIL as the hazardous weather metric, to eliminate the effects of forecast uncertainty on decision support.

Departure paths are defined as 8 km. wide, two-dimensional corridors, centered on the mean departure trajectory (one minute sampling resolution), which is calculated using Enhanced Traffic Management System (ETMS) data from several days of clear air operations. Departure path flight times were set to 45 minutes, resulting in departure paths that were long enough to capture all weather impacts.

RAPT takes advantage of the fact that an individual flight may be blocked at one departure time but not another. Likewise, flights from various airports in the same vicinity may not be blocked at the same times. As an example, consider two aircraft ready to depart along departure route J80 at 1400 UTC (hereafter all times will be in UTC). A thunderstorm will first block J80 at a particular location at 1420 and will clear that location at 1430. If an aircraft takes off at LGA at 1400 and takes 31 minutes to reach the location of impact, it will never encounter the thunderstorm, which has moved off. Another aircraft may depart from EWR at 1400 and take 25 minutes to reach the location of impact; it

will encounter the thunderstorm. Thus, at 1400, the route is thus open for an LGA departure, but not for one from EWR. These calculations of 4D aircraft locations and thunderstorm locations are difficult for traffic managers to perform in the midst of a busy severe weather event.

RAPT assigns a status of BLOCKED, IMPACTED, CLEAR, or UNKNOWN to future departures by intersecting their trajectories with predicted regions of hazardous weather. A departure is BLOCKED if the VIL level 3 contour completely blocks any route segment at the time when the departure is flying through the segment. A departure is CLEAR if no route segment along the departure trajectory is touched by the VIL level 3 contours. A departure is IMPACTED if there is a partial intersection of the VIL level 3 contours along the departure trajectory. Departures that cannot be completed before the end of the forecast period are assigned the UNKNOWN status, unless they are found to be BLOCKED or IMPACTED by any of the available forecast times. The intersection algorithm is depicted in figure 1.

RAPT produces a departure timeline for each departure route in the airspace that gives the status of future departures along the route. When RAPT receives a new forecast, it produces a new set of departure timelines. The RAPT display shows a table of the departure timelines and an animation loop showing the hazardous weather forecast with future departure trajectories superimposed. The animation loop provides critical information that enables the users to refine the guidance that RAPT is supplying by presenting the complete context – weather forecast and projected flight path – that is used to determine route status. It particular, it is intended to provide the means by which users can make operational decisions in cases where the route status is IMPACTED.

For this analysis, we produced a single 'truth' timeline through the duration of the event for each departure route studied. The truth timelines were based on 'perfect' forecasts (observed weather); the status for every departure is fixed for the event and does not change as the 'perfect' forecast is updated. Figure 2 shows an example of truth timelines from

both RAPT and eRAPT, for all 4 westbound departures routes out of LaGuardia airport.
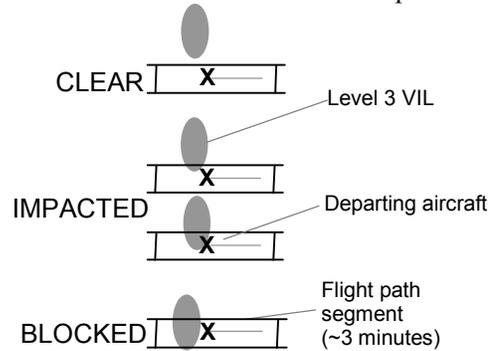
Figure 1. RAPT route status. Depiction of CLEAR, IMPACTED and BLOCKED departures shows how weather encounters are assigned to decision categories. Note the range of weather encounters that are IMPACTED.
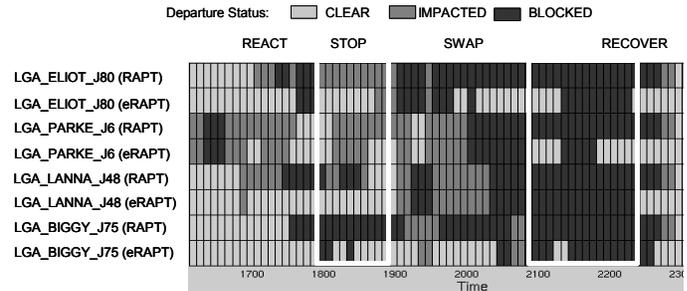
Figure 2. RAPT route timelines. Departure status timelines for 4 westbound routes out of LGA, using 'perfect' forecast, are shown for both RAPT (VIL only) and eRAPT (VIL plus echo tops < 24 Kft.). Routes are ordered north to south. White boxes indicate periods where fewer than 2 departures per hour were released. Note that the x axis indicates *departure* time.

The operational prototype of RAPT uses two-dimensional forecast contours and departure paths. For the purposes of this study, we created an 'enhanced' RAPT (eRAPT) algorithm that adds echo top information to determine if departures can fly *over* regions of hazardous weather. For each BLOCKED or IMPACTED departure, we calculated the maximum echo top along the trajectory, starting at a flight time of 20 minutes. By this point in the trajectory, most departures have reached a high enough altitude that flyovers are

3

possible. If the maximum echo top was less than 24,000 feet, the departure status was set to CLEAR. Note that eRAPT cannot decrease the number of available departure times for a given route. It can only increase it or leave it unchanged.

Methodology

Route selection decision support has two components: weather forecast and operational model. The effectiveness of decision support is determined by the quality of the weather forecast, the accuracy of the operational model and the interaction between the two. Decision support based on a poor forecast may still be useful if the operational model accounts for forecast error properly; likewise, a poor operational model will yield poor decision support even if it is based upon a perfect forecast. Vigeant-Langlois and Hansman [11] provide a more detailed and comprehensive framework that relates weather data to operational needs.

A complete study of the impact of RAPT on route selection and departure throughput requires analysis of the quality of the weather forecast, the automated departure status prediction algorithm, user interface and user response to the guidance provided by the system in an operational context. Sufficient data is not yet available from operational testing to support such an analysis. In this study, we examine only the effects of the operational model on the automated portion of RAPT (i.e., determination of departure route status). We ran the RAPT algorithm using the 'true' (observed) VIL and echo tops as the forecast, producing a single 'truth' departure timeline for each route through the duration of the event. This eliminates weather forecast uncertainty as a factor in the automated determination of departure route status. The assessment of route status predictions is therefore a function only of the operational model; in particular, route definition, choice of hazardous weather metric and determination of route status.

We compare actual departure throughput and estimated throughput using RAPT and eRAPT. Throughput estimation highlights a difficulty with the RAPT departure status algorithm. The IMPACTED status, although clearly defined in algorithmic terms, is highly ambiguous in the operational, decision-making context. Some IMPACTED departures may be passable, others blocked, depending upon the degree of blockage and severity of storm. This ambiguity became readily apparent once RAPT was deployed. Users often viewed the IMPACTED status as either over-warning or under-warning, and had a difficult time interpreting the meaning of IMPACTED in the operational context.

In light of this difficulty, we chose to calculate two different throughputs for each RAPT algorithm: an upper bound (assume that *all* IMPACTED routes are passable), and a lower bound (*no* IMPACTED routes are passable).

In order to calculate departure queues and the hypothetical RAPT throughputs we needed to determine the departure schedule and the number of departures possible using RAPT route availability guidance. We approximated the departure schedule for each route by using departure flight plans from the same weekday the following week, when there was no weather impact. Scheduled departures on each route were grouped into 30-minute time bins.

We determined the number of departures possible (D) using RAPT in the following way:

1) No departure queue. For each route, the RAPT route availability is checked for each scheduled departure in the time bin along that route. If the route is available for the scheduled departure, the departure is released and added to the departure total for the route (D_i).

2) Existing departure queue. If there is a queue of departures waiting to be released, the number of departures along a given route will be increased beyond the number of scheduled departures, if possible, to reduce the queue. The number of departures possible along each route during a particular time bin are determined as follows:

i) Determine the route capacity, C, for the current time bin. To find C, we look at the corresponding time bin from the

normal day to find N, the maximum number of departures along any route for the given time bin. We set $C = N$.

ii) For each route, determine the maximum number of departures possible, D_m. We determine the fraction of the time bin that RAPT declares the route CLEAR (f). $D_m = f \cdot C$, rounded down to the nearest integer.

iii) For each route, determine the number of departures waiting to go, D_q:

D_q = (queue at start of the time bin) + (departures scheduled for the time bin)

iv) For each route, $D_i = \min(D_m, D_q)$.

3) D = sum of (D_i) for all departure routes.

Analysis of traffic management for the event

The total time period can be roughly divided into four phases of traffic planning: REACT (1600-1800), STOP (1800-1900), SWAP (1900-2200), and RECOVERY (2200-2300). Weather impact and ATC performance differ markedly in each phase. Figures 3 and 4 compare actual departure counts to hypothetical departure counts using eRAPT and RAPT with a perfect forecast. We show two bounds—the upper bound using IMPACT=CLEAR, and the lower bound using IMPACT=BLOCK. Table 1 summarizes these results, showing the average and maximum departure queue size for the whole event.

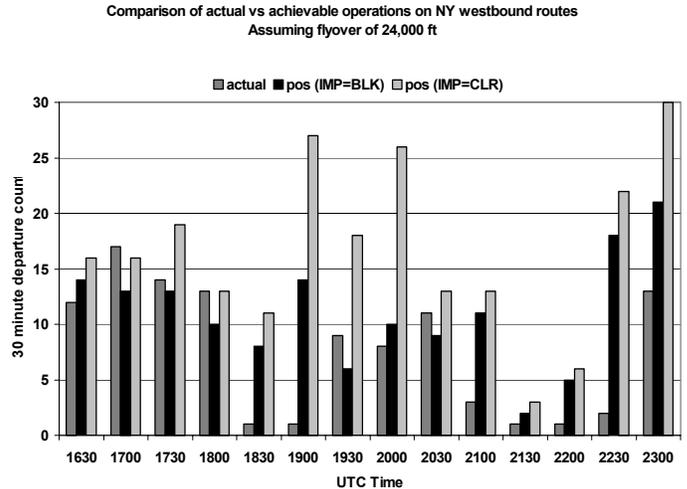| Departure Queue	average	eRAPT average	RAPT average	max	eRAPT max	RAPT max
Actual	38			109		
IMPACT=BLOCK		30	68		71	161
IMPACT=CLEAR		5	20		24	71

Table 1. Departure queue lengths.

Figure 3. Departure counts. Possible counts are hypothetical departure counts, assuming use of eRAPT (route availability based on level 3 VIL + echo tops). Black bars (IMP=BLK) represent the lower bound, light gray, the upper bound.
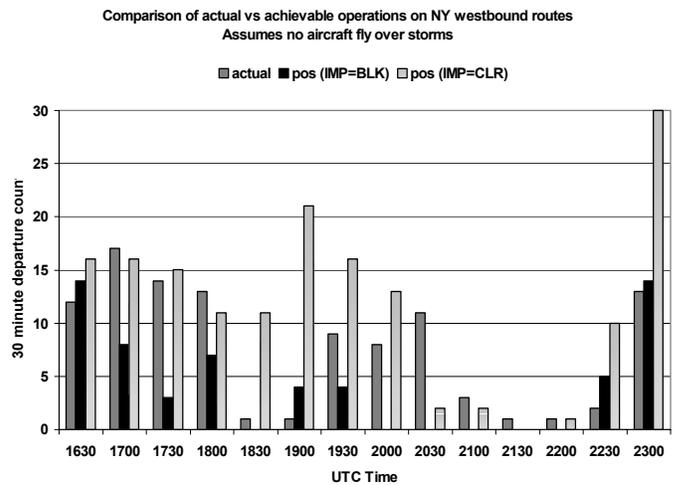

Figure 4. Departure counts. Same as figure 3, except that possible counts are based on the use of RAPT (level 3 VIL only).

It is evident that the lower bound criteria for determining route status is too conservative; in all four phases the actual traffic movement was greater than the hypothetical lower bound.   The upper bound agrees more closely with the actual departure movement but is clearly sensitive to the inclusion of

echo tops in defining the weather hazard metric. Although the upper bound using eRAPT is likely too optimistic with an average departure queue of only five over the period, ATC personnel have told us that it is not unusual for pilots to fly over low echo tops and our departure path data appears to support this idea (see fig. 7, for example). In any event, what these results demonstrate is that lost opportunity estimates are sensitive both to the choice of a hazard metric and the method of determining if a route is passable. Future studies will need to better define both of these measures.

In analyzing the actual departure throughput, it was necessary to look at arrivals as well. We did this to verify that departure space was not used for arrivals and to ensure that comparisons between actual and theoretical departure rates were valid. At no time during the event were departure routes used to bring in arrivals.

REACT phase

In the *REACT* phase, weather had formed about 400km east of EWR and was affecting J6, J48, and J75. To the north, a second area of thunderstorms was slightly north of J80. Figure 5 shows that traffic levels remained high during the two-hour period, and nominal routes were closely followed within 200km of EWR. However, significant deviations around the southern branch of weather were occurring. The airspace is less congested in that region, and one can infer that deviations were allowed due to lower complexity of the airspace.

Neither RAPT nor eRAPT appears to identify any missed opportunities during this phase. During this period, ATC identified gaps in the approaching storm and effectively routed traffic through them. However, it is possible that increased workload during this phase resulted in excessive fatigue which led to a total shutdown of departures in the next hour. A decision support tool that reduces ATC workload during this phase could reduce fatigue, making it possible to sustain this high level of efficiency for a longer period of time.
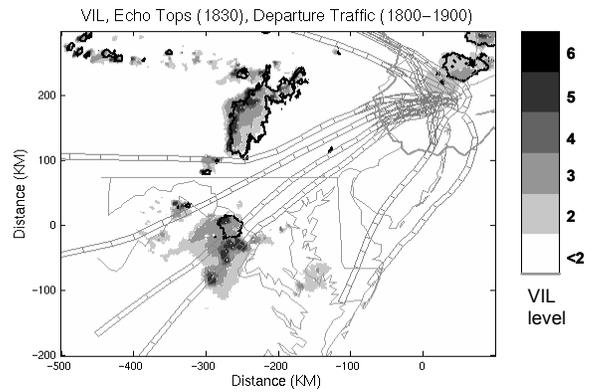
STOP phase

In the *STOP* phase (figure 6), no departures were released on the westbound routes for one full hour despite the existence of a large gap in the line of thunderstorms. Departures continued to use northern and southern routes during this period.

It appears that a significant amount of delay was incurred unnecessarily during this phase. The same gap that was present in this period was also present in the REACT phase and was used effectively. Gaps were also utilized at later times. The TCWF forecast that was available to users accurately predicted both the extent and location of the storm throughout the period. This suggests that traffic managers continued to be aware of the departure opportunities that were available and that lack of weather information was not the cause of the stop.
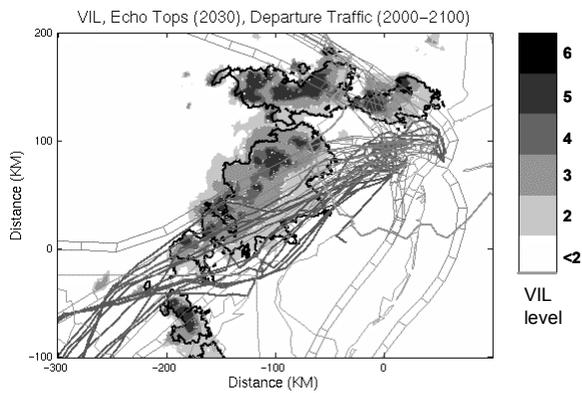
An examination of traffic logs for this period does not reveal the reason for the stop, but the logs indicate that the coordination hot line between traffic control centers was activated at the beginning of this phase. This suggests that traffic managers saw the need to formulate a plan to deal with the storms rapidly encroaching on NY airspace. Fatigue may also have been a factor. In our conversations with tower and TRACON managers, they have noted that fatigue often has a significant impact on controller performance in hazardous weather events. It is possible that the combination of planning workload and fatigue may have led to the decision to shut down departures completely even though there continued to be opportunities to release departures.

VIL, Echo Tops (1730), Departure Traffic (1700–1800)

VIL, Echo Tops (1830), Departure Traffic (1800–1900)
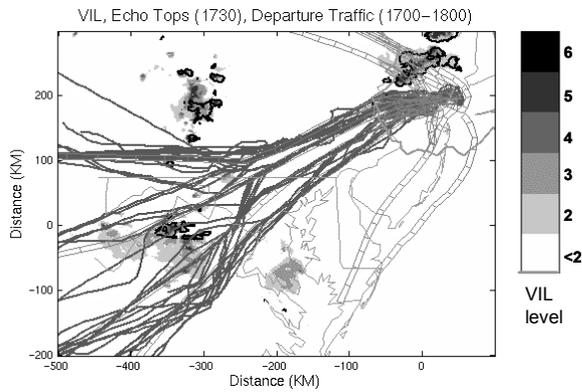
Figure 5. Weather and departures during the *REACT* phase. The storm is growing, approximately 200 km. from the TRACON boundary. Departures on the 3 southernmost westbound routes follow nominal routes closely until they approach the storm cell in the southwest corner. From this point, about 150 km. into the flight path, they deviate widely, in an effort to avoid the high echo tops and level 3 VIL in the cell.

Figure 6. Weather and departures during the *STOP* phase. The storm has grown and moved approximately 50 km. closer to the TRACON, but passable gaps remain. We do not know why there were no departures during this period.

VIL, Echo Tops (2030), Departure Traffic (2000–2100)

VIL, Echo Tops (2230), Departure Traffic (2200–2300)

Figure 7. Weather and departures during the *SWAP* phase. The northern and southern cells have grown and merged, closing the gap to the west of the airports, and the storm has reached the western boundary of the TRACON. Nominal departure routes have been abandoned, as traffic diverts to the south to avoid high echo tops and level 2 and 3 VIL. It appears that several departures penetrate level 3 VIL and high tops, but this must be verified by analyzing individual departure paths. Note that eRAPT, as it was configured, consider echo tops > 24 Kft. passable if VIL < level 3.
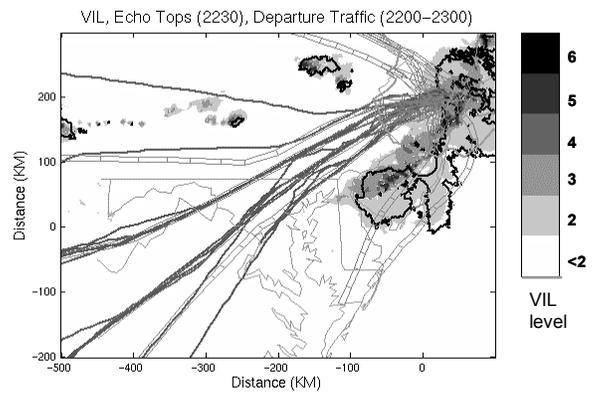
Figure 8. Weather and departures during the *RECOVER* phase. All 4 westbound routes are now completely clear, and operations have returned to normal, albeit somewhat slowly. The first departures were released at approximately 2230, which corresponds to the time of the VIL and echo top fields shown. Departure rates increased rapidly through this phase, but did not reach normal levels until 2330, indicating that traffic managers may not have had sufficient information or opportunity to prepare for the re-opening of the westbound routes.

Both RAPT and eRAPT suggest a much greater capacity during this period than was actually utilized. Since ATC was able to take advantage of similar departure opportunities both earlier and later in the event, we surmise that other factors – fatigue and collaborative planning load – led to the missed opportunity. In this circumstance, decision support can be helpful in two ways: by supporting collaborative planning, thereby reducing the time and workload associated with it, and by reducing traffic-routing workload, which would reduce fatigue and make it possible to maintain some level of throughput while plans are being formulated.

SWAP phase

In the *SWAP* phase (figure 7), the weather was moving rapidly towards the New York TRACON (N90). It is evident that nominal routes to the west were abandoned completely in order to thread effectively through the gap in the line. All departures were routed over the PARKE fix in this phase and vectored between storms. Airspace was used very effectively as a result.

RAPT and eRAPT performance was difficult to interpret during this phase, because their operational model does not take into account the possibility of dynamic routing through the airspace. RAPT guidance was overly conservative, with level 3 VIL blocking all routes throughout much of the period (see figs. 2, 7). Guidance from eRAPT appears to be more useful. Figure 2 indicates that eRAPT determines that the southernmost and northernmost routes (BIGGY_J75 and ELIOT_J80) are both passable, and, in fact, this guidance corresponds well with the actual use of departure airspace.

Throughout the first three phases of the event, estimated departure counts using eRAPT significantly exceed those using RAPT. Early in the event, this is due to the fact that level 3 cells forming to the west are not yet accompanied by high echo tops, and are therefore deemed passable by eRAPT. Later in the event, eRAPT declares departures along ELIOT_J80 to be passable because those departures pass through the *trailing* edge of the storm, where echo tops have decayed but level 3

VIL still remains. Figure 7 shows a few departures flying through this region.

RECOVER phase

In the *RECOVER* phase, the line of storms has moved past the NY airports (figure 8). Nominal routes are being used once again, with the exception of J80, which is still being impacted by thunderstorms well to the west.

Actual departure rates increase rapidly throughout the period, but lag the RAPT and eRAPT projected rates throughout the period. Clearly, the increased throughput in RAPT and eRAPT is not due to their ability to discover routing opportunities that were missed by ATC. It is more likely that traffic managers did not have sufficient time to prepare aircraft on the ground for timely departures as soon as departure routes opened back up. Decision support may improve efficiency during this phase if it accurately predicts when departure routes will reopen, and is integrated with ground management tools so that it can aid traffic managers and airline dispatchers in preparing aircraft for departure.

Conclusions

All three elements of the operational model – choice of forecast, route definition and allocation and determination of route status – have substantial impact on decision support quality and value.

1) **Two-dimensional forecast products do not supply sufficient information about the operational impact of hazardous weather.** In this instance, the use of a 2D map of a quasi-three dimensional product (VIL) resulted in route selection guidance that, in some cases, was too conservative and closed routes that were passable and in other cases, declared as passable regions that pilots consistently avoided. The inclusion of echo tops data resulted in more realistic and effective guidance and agrees with other studies that have shown that pilot deviation behavior is not well predicted using a 2-D representation of weather [6,7].

2) **Static route definition does not capture the full range of operational use of available airspace.** In certain circumstances, pilots may deviate substantially from published routes in order to make the most effective use of available airspace. However, decision support may become ambiguous and confusing if routes change dynamically and automatically in response to circumstances. In the worst case, decision support may become worthless if automatic changes in route definitions assume routes that differ substantially from reality. An optimal strategy for route definition must still be determined.

3) **Decision support must supply users with the means to make operational decisions when guidance is ambiguous.** In RAPT, the IMPACTED route status does not imply a clear operational decision. Table 1 and figures 3 and 4 show that there are major differences in departure rates associated with different interpretations of the IMPACTED route status. Operational users have been reluctant to use the display movie loop to resolve the ambiguity in these cases. Hence, we are working to improve both the determination and presentation of route status by reducing ambiguity and improving the tools that help resolve ambiguous guidance when it occurs.

4) **Decision support must do more than supply information about developing weather and an operational model that relates the weather to ATC needs.** During the STOP phase, it was clear that ATC had the information it needed to make efficient use of the departure airspace, but did not use it. We don't know why this happened, but fatigue and collaborative planning workload may have been factors.

Increasing departure rates is a critical factor in reducing overall delay in crowded airspaces during convective weather events. Decision support tools that integrate weather forecasts with an operational

model can help increase departure throughput, but the performance of such tools is very sensitive to the hazardous weather metric, route definition and the way that route status is determined (passable or blocked) used in the operational model. Improving the operational model will require research to address several issues:

1) Choice of hazardous weather metric
2) Dynamic route definition
3) Strategies to minimize and/or mitigate the effects of ambiguity in route status predictions
4) Effects of different user interface elements
5) Potential benefits of integration with surface management systems
6) Understanding when and why routes are closed when readily available information indicates that they are available

We will address these and other operational issues in ongoing research, development and field trials in New York in the coming year.

References

[1] Allan, S.S., J.A. Beesley, J.E. Evans, and S.G. Gaddy, 2001, "Analysis of Delay Causality at Newark International Airport", *4th USA/Europe Air Traffic Management R&D Seminar*, Santa Fe, NM.

[2] Allan, S.S., S.G Gaddy, and J.E. Evans, and S.G. Gaddy, 2001, "Delay Causality and Reduction at the New York City Airports Using Terminal Weather Information Systems", MIT Lincoln Laboratory, Project Report ATC-291.

[3] Beaton, E., J. DeArmon, C. Wanke, and S. Miller, "New York Airspace Effects on Operations", *Journal of Air Traffic Control*, Vol. 42(2) 32-37.

[4] Evans, J.E., 2001, "Tactical Weather Decision Support to Complement "Strategic" Traffic Flow Management for Convective Weather", *4th USA/Europe Air Traffic Management R&D Seminar*, Santa Fe, NM.

[5] Mondolini, S., and D. Liang, 2001, "Airspace Fractal Dimensions and Applications", *4th USA/Europe Air Traffic Management R&D Seminar*, Santa Fe, NM.

[6] Rhoda, D., B.A. Kocab, and M.L. Pawlak, 2002, "Aircraft Encounters with Thunderstorms in Enroute vs. Terminal Airspace above Memphis, Tennessee", *American Meteorological Society 10th Conference on Aviation, Range, and Aerospace Meteorology*, Portland, OR, pp. 162-165.

[7] Rhoda, D. and M. Pawluk, 1999, "An Assessment of Thunderstorm Penetrations and Deviation by Commercial Aircraft in the Terminal Area", Project Report NASA/A-2, MIT Lincoln Laboratory.

[8] Theriault, K.E., M.M. Wolfson, W.J. Dupree, B.E. Forman, R.G. Hallowell, R.J. Johnson, and M.P. Moore, 2001, "TCWF Algorithm Assessment-Memphis 2000", MIT Lincoln Laboratory, Project Report ATC-297.

[9] Robinson, M., J.E. Evans, and B.C. Crowe, 2002, "En Route Weather Depiction Benefits of the NEXRAD Vertically Integrated Liquid Water Product Utilized by the Corridor Integrated Terminal Weather System", *American Meteorological Society 10th Conference on Aviation, Range, and Aerospace Meteorology*, Portland, OR, pp. 120-123.

[10] Sherry, J.E., C.G. Ball, S.M. Zobell, 2001, "Traffic Flow Management (TFM) Weather Rerouting", *4th USA/Europe Air Traffic Management R&D Seminar*, Santa Fe, NM.

[11] Vigeant-Langlois, L., and R. J. Hansman, 2002, "Trajectory-based Performance Assessment of Aviation Weather Information", *American Meteorological Society 10th Conference on Aviation, Range, and Aerospace Meteorology*, Portland, OR, pp. 136-139.

[12] Wolfson, M.M, B.E. Forman, R.G. Hallowell, and M.P. Moore, 1999, "The Growth and Decay Storm Tracker", *American Meteorological Society 79th Annual Meeting*, Dallas, TX.

---

*Corresponding author address: Rich DeLaura, MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420-9108; e-mail: richd@ll.mit.edu

Author Biography

Shawn Allan is an Associate Staff member at MIT Lincoln Laboratory and manager of the New York Integrated Terminal Weather System (ITWS) field site in Garden City, New York. Mr. Allan has a Masters degree in Atmospheric Science from McGill University and for the past five years has performed research on air traffic control operations in the presence of capacity restricting weather. He currently co-leads the RAPT project with Rich Delaura.

Rich DeLaura is an Associate Staff member at MIT Lincoln Laboratory. He has worked for several years developing algorithms and tools to analyze and detect aviation weather hazards. Mr. DeLaura has a Bachelors degree in Physics from Harvard University.