
Integrating Advanced Weather Forecast Technologies into Air Traffic Management Decision Support

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■ Explicit integration of aviation weather forecasts with the National Airspace System (NAS) structure is needed to improve the development and execution of operationally effective weather impact mitigation plans and has become increasingly important due to NAS congestion and associated increases in delay. This article considers several contemporary weather-air traffic management (ATM) integration applications: the use of probabilistic forecasts of visibility at San Francisco, the Route Availability Planning Tool to facilitate departures from the New York airports during thunderstorms, the estimation of en route capacity in convective weather, and the application of mixed-integer optimization techniques to air traffic management when the en route and terminal capacities are varying with time because of convective weather impacts. Our operational experience at San Francisco and New York coupled with very promising initial results of traffic flow optimizations suggests that weather-ATM integrated systems warrant significant research and development investment. However, they will need to be refined through rapid prototyping at facilities with supportive operational users.

AIRSPACE DEMAND has increased steadily in the last twenty years. Some major terminals and en route sectors are approaching maximum capacity with current technology and procedures. As noted in related articles in this issue of the *Journal*, thunderstorms in en route or terminal airspace or low clouds and impaired visibility at airports can reduce capacity significantly below today's demand levels, resulting in widespread delay events. Aviation planners anticipate a need for at least a twofold increase in the capacity of the air transportation system in the next twenty years [1]. To prevent disruptive delays during adverse weather, we must develop better weather forecasts and air traffic management (ATM) decision

support systems that facilitate the optimal utilization of the available capacity of weather-impacted airspace. Figure 1 shows the operational decision process for mitigation of adverse weather impacts.

Lincoln Laboratory's role in developing and prototyping integrated weather sensing and processing systems such as the Integrated Terminal Weather System (ITWS) [2, 3], the Corridor Integrated Weather System (CIWS) [4, 5] and the San Francisco stratus-cloud forecast system [6] has lead naturally to consideration of improving the air traffic management process. A major goal of the operational testing of these systems has been to understand in detail how their meteorological products and forecasts are used by the Federal

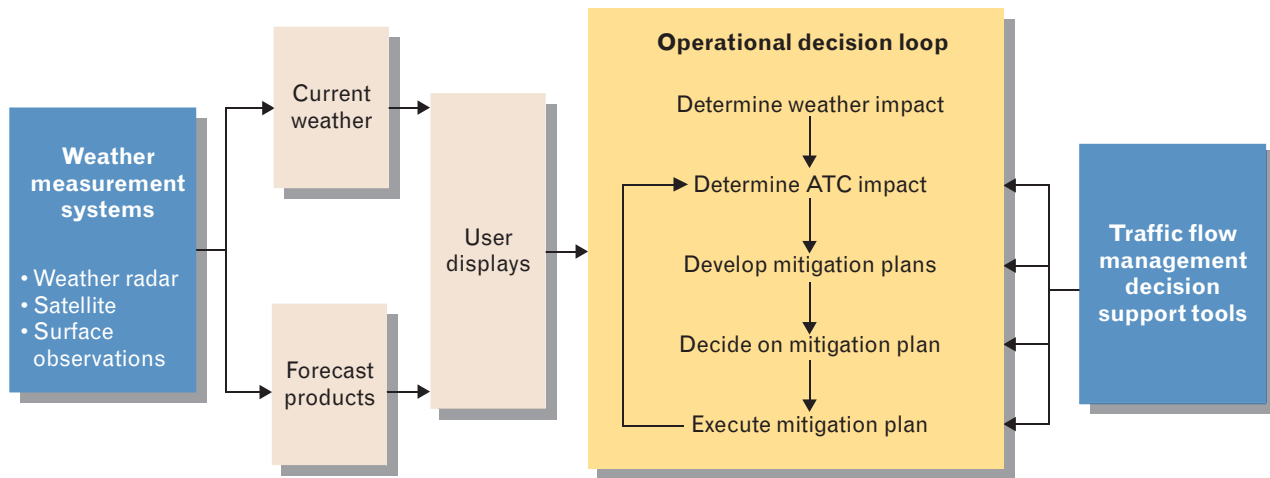


FIGURE 1. Decision process for use of weather products for air traffic management and/or flight planning. Delays are averted or minimized only if an appropriate mitigation plan is executed in a timely manner.

Aviation Administration (FAA) air traffic managers and airline operations personnel such as dispatchers to develop strategies for reroutes, ground and airborne delay programs, cancellations, and diversions.

Documented examples of improved operational decision making using these Lincoln Laboratory–developed systems are described in the references listed in the preceding paragraph. While the associated reductions in weather-related delay have been impressive, we have observed that the complexities of quantitatively assessing the impacts of weather on airspace capacity, developing candidate response strategies, and coordinating these strategies among multiple operational facilities often result in suboptimal response strategies. During situations when airspace demand exceeds capacity for a significant period of time, even modest increases in throughput—realizable by using better ATM strategies—can significantly decrease overall delay by limiting the length and duration of the aircraft queues that form.

In 1998, the Port Authority of New York and New Jersey funded a program at Lincoln Laboratory to establish an ITWS prototype supporting operations at the major New York City airports (Newark, LaGuardia and John F. Kennedy International Airport). Highly motivated FAA and airline personnel have worked closely with the Laboratory to adapt this prototype to the unique operational requirements of New York City’s highly congested terminal area. This interaction led to important insights into the mecha-

nisms of weather-related delay at *pacing* airports (those airports which control air traffic throughout a region) and the benefits derived from the ITWS products [7]. In addition, feedback from these operational users emphasized that purely meteorological products do not fully meet user needs and spurred the development of a simple but highly effective operational decision support system called the Route Availability Planning Tool (RAPT). As described later in this article, RAPT integrates three-dimensional (3D) convective weather forecasts from the CIWS with National Airspace System (NAS) structure information and an explicit model for pilot preferences in avoiding convective weather to predict the availability of the filed departure route and alternative departure routes for an aircraft. RAPT permits air traffic control (ATC) and airline decision makers to focus on managing departure scheduling as opposed to weather interpretation in the context of the NAS structure.

Insights gained from the operational testing of RAPT and our other integrated weather system prototypes continue to refine our appreciation of the challenges associated with translating meteorological diagnosis and forecast products into more operationally relevant terms. Broadly stated, more effective ATM during adverse weather requires enhancements in the following four areas.

(1) Continued improvement in forecasts of aviation-impacting meteorological conditions (e.g., thunderstorms, low ceiling and visibility) generated at fine

time steps that span the zero-to-six-hour window necessary for flight planning. These forecasts must include parameters that support quantitative characterization of airspace capacity.

(2) Models for *translating* the weather forecasts into time-varying estimates of the capacity reductions in affected en route sectors, terminal airspace, and airports. These estimates must include uncertainty bounds.

(3) Automatically generated, broad-area ATM strategies that utilize time-varying estimates of airspace capacity and demand to anticipate overload situations and suggest optimal reroute strategies or, when necessary, minimally disruptive ground or airborne delay programs.

(4) Application of modern statistical decision-making and risk-management techniques as a basis for developing ATM strategies, given probabilistic weather and airspace capacity forecasts.

In this article we discuss insights on the ATM challenge developed during ongoing operational prototyping of Lincoln Laboratory–integrated weather sensing and decision support systems, and recent work to develop more quantitative operational guidance, as just described. We begin with a discussion of Lincoln Laboratory’s experiences in operational prototyping of explicit capacity impact forecasts generated by the San Francisco stratus-forecast system and RAPT. Then we discuss our follow-on efforts to develop and validate more general airspace capacity models based on meteorological forecasts. We conclude with a description of preliminary efforts to develop and apply a robust optimization model for *post facto* performance assessment and real-time broad-area planning needs.

Operational Use of the San Francisco Ceiling/Visibility Capacity Forecasts

The Lincoln Laboratory San Francisco stratus-cloud forecast system deals with what in some respects is a relatively straightforward ATM problem [6]. The airport’s arrival acceptance rate can be one of two distinct values, depending on a well-defined meteorological condition (low-ceiling conditions from May through October due to the intrusion of marine stratus along the Pacific coast) at a specific location, the approach path to San Francisco.

The low cloud conditions prohibit dual paral-

lel landings of aircraft on the airport’s closely spaced parallel runways, thus effectively reducing the arrival capacity by a factor of two. The behavior of marine stratus evolves on a daily cycle, filling the San Francisco Bay region overnight, and dissipating during the daylight hours. Often the low-ceiling conditions persist throughout the morning. The FAA puts a ground-delay program into effect under these conditions, since the scheduled demand into San Francisco from mid-morning to early afternoon typically exceeds the San Francisco low-ceiling arrival capacity of approximately thirty aircraft per hour. These ground-delay programs delay departures at their origin such that the arrival flow for San Francisco matches the airport capacity. The result of the ground-delay program is a substantial number of delayed flights originating at airports as far away as Chicago.

The Lincoln Laboratory San Francisco forecast system uses physical and statistical models to provide an estimate of the most likely capacity transition time and estimates of the cumulative probability that the transition has occurred at each forecast time step. The original Lincoln Laboratory benefits projections for the San Francisco forecast system envisioned the proactive ending of these ground-delay programs so that there would no longer be a one-to-two-hour period when the low ceiling/visibility conditions had ended, but the rate of arrivals was much less than the actual airport capacity [8].

To date, however, there have been very few events in which a ground-delay program was cancelled proactively. The current FAA policy is to add two hours to the projected burn-off time to arrive at a ground-delay program cancellation time. If there is high confidence in the burn-off time, a higher airport acceptance rate—forty-five aircraft per hour, which is intermediate between the low capacity rate of thirty aircraft per hour and the fair-weather capacity of sixty per hour—is used to modify the ground-delay program for the two hours after the forecast burn-off time. Since the vast majority of stratus events dissipate well before two hours after the projected burn-off time, a significant fraction of the projected benefit from the San Francisco ceiling/visibility capacity forecast is not being achieved.

We have identified several key problems in the op-

erational utilization of what appears to be a technically successful probabilistic forecast. The first is that Air Route Traffic Control Center (ARTCC) operational users are concerned about the possibility of too many aircraft holding in Oakland center airspace. Effectively, they have assigned a very high cost to the possibility that an overly optimistic forecast will result in more planes arriving at San Francisco than can be accommodated with available capacity. Second, the FAA and airline-traffic flow management-unit personnel do not have academic training or practical experience in using probabilities for decision making. Indeed, important forecast information that would be needed to apply standard techniques for decision making under uncertainty is not being provided to the users by the current forecast.

Making decisions by using well-defined probability forecasts (probabilities that can be manipulated by the standard rules for probability use) involves the application of statistical decision theory. The key elements in the context of this problem are (1) the available actions (e.g., ground-delay program parameters); (2) the possible states of nature (the marine-stratus dissipation times); (3) the consequences for a given action taken when nature has some state (e.g., amount of delay, number of aircraft in a holding pattern); (4) the probability of the various possible states of nature, given some measurements (these probabilities for various states would be generated by the San Francisco forecast algorithm); and (5) the strategy used to choose between the actions, given the forecast probabilities [9].

It should be noted that there is extensive literature on optimizing ground-delay program parameters, given a probabilistic forecast of the future capacity. For example, A. Mukherjee and M. Hansen show contemporary results and provide references to the past literature [10]. These studies did not explicitly consider the cost to air traffic personnel from too many aircraft in a holding pattern (e.g., if the ground-delay program was ended proactively in error). In addition, they generally assume that the costs and benefits could be expressed by a combined metric such that the ground-delay program parameters could be optimized by using an expected loss criterion.

These considerations suggest that a substantially different, risk-management-based approach to pre-

sentation and use of the San Francisco probabilistic weather forecasts could increase their operational utility. Specifically, FAA traffic flow managers and airline operations managers need to be provided the expected consequences of ground-delay programs—given the forecast probability distribution of expected dissipation time. This operational consequences-oriented presentation would include key factors such as expected average delays, expected unnecessary avoidable delay, average holding time, and probabilities of various numbers of aircraft (e.g., ten, twenty, or thirty) in airborne holding within the Oakland ARTCC for various ground-delay program options.

In addition, we need to pay much more attention to how to mitigate the risk of very late stratus dissipation events that would cause an excessive number of holding aircraft. There are at least two elements to this risk mitigation: improved use of the daytime forecasts (e.g., 15Z, or 8 a.m. Pacific Daylight Time) to extend a ground-delay program that was put into effect in the predawn period (e.g., 13Z), and developing a fair and equitable system by which San Francisco-bound planes in a holding pattern would be diverted to an alternative airport in the event that the number of holding aircraft exceeds an agreed-upon threshold. It should be noted that the diversion option would have to be developed in collaboration with the airlines. This alternative approach to decision making with the San Francisco probabilistic forecast has been proposed by the Laboratory as an initiative for the FAA/Airline Collaborative Decision Making program [11].

The above experience in achieving operational benefits with what we would regard as a meteorologically successful probabilistic forecast for a situation in which the consequences of various actions are fairly well understood highlights the challenges ahead for the much more complicated problem of developing and utilizing probabilistic forecasts of chaotic convective weather capacity impacts.

Route Availability Planning Tool

Departure delays during thunderstorms have been identified as a significant problem in the NAS. The report of the FAA/Airline Severe Weather System Review identifies airport departures during a Severe Weather Avoidance Plan (SWAP) as one of the five

major NAS severe weather problems to be addressed [12]. Low departure rates when convective weather is within two hundred miles of the airports has been a major problem for years at the New York airports. S. Allan et al. found that increased departure rates when a SWAP was in effect provided the highest New York City ITWS delay reduction benefit during convective weather [7]. However, even with the ITWS in use, there were still major delays for departures, including situations of gridlock on the airport surface due to the arrival rate exceeding the departure rate for prolonged periods of time. A major problem was the long time required to execute the operational decision loop shown in Figure 1 under circumstances in which the departure capacity was rapidly changing due to convective weather.

On the basis of feedback from the New York Terminal Radar Approach Control (TRACON), Lincoln Laboratory developed a concept for a decision tool that would translate the convective forecasts into a prediction of the availability of departure routes as a function of takeoff times so that ATC and airline decision makers could focus on ATM for departures as opposed to interpreting ITWS thunderstorm forecasts relative to New York airspace structure.

The RAPT combines thunderstorm forecasts with an explicit model for pilot preferences in avoidance of convective weather, the structure of departure routes from the New York airports, and nominal flight times to various locations on a departure route. These forecasts help FAA traffic managers and airlines answer three questions: Will a candidate future departure encounter hazardous weather at some point along its intended path? Will there be opportunities to route the aircraft through significant gaps in evolving weather? If so, at what times can the aircraft depart to be able to utilize the gaps?

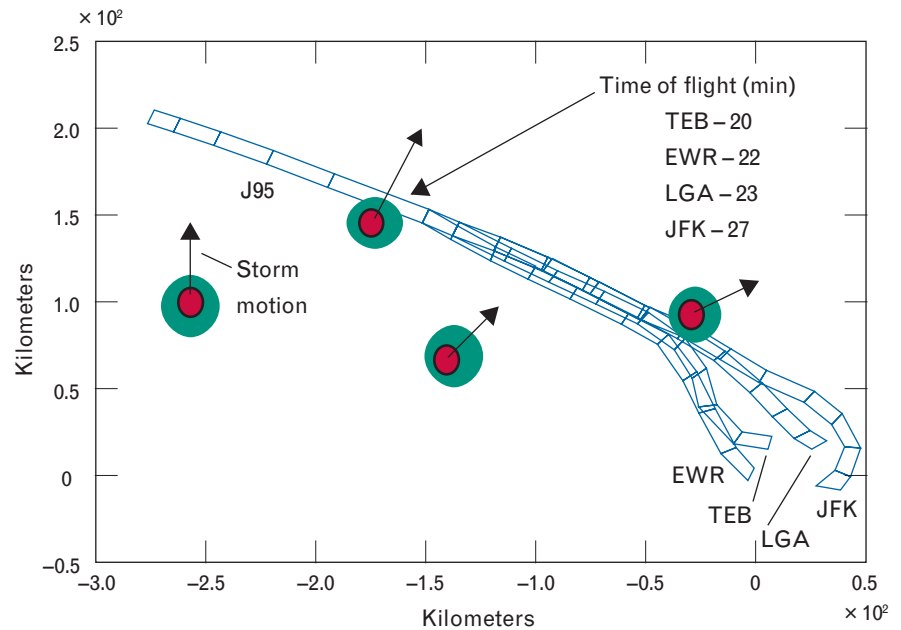


FIGURE 2. Potential interactions of released aircraft with thunderstorms in the New York City area. The challenge is determining aircraft/weather intersections along specific routes at times in the future. The question raised at various times is “If at this time an aircraft is released on this route, will it encounter hazardous weather?” The identification codes for the New York City region airports are TEB (Teterboro), EWR (Newark), LGA (LaGuardia), and JFK (Kennedy).

Previously, ATM personnel had to answer these questions by estimating flight profiles for departing aircraft and comparing these to the ITWS forecast of storm locations, as illustrated in Figure 2. RAPT automates these mentally taxing calculations, making accurate departure impact predictions readily available to the supervisors and air traffic flow managers for all the important routes in the airspace. The RAPT display shown in Figure 3 illustrates the tool’s usage for key westbound routes for the New York airspace.

Operational Insights Based on RAPT Field Evaluations

Operational evaluation of RAPT by New York City ITWS users commenced in August 2002 and has continued until the present. Our analysis of operational usage is based on data gathered from four different sources: (1) references to RAPT in operational logs; (2) interviews of air traffic control personnel; (3) direct observation of ATC operations in FAA facilities during convective weather events; and (4) unsolicited comments received from users via e-mail.

In 2003, traffic managers used RAPT primarily to

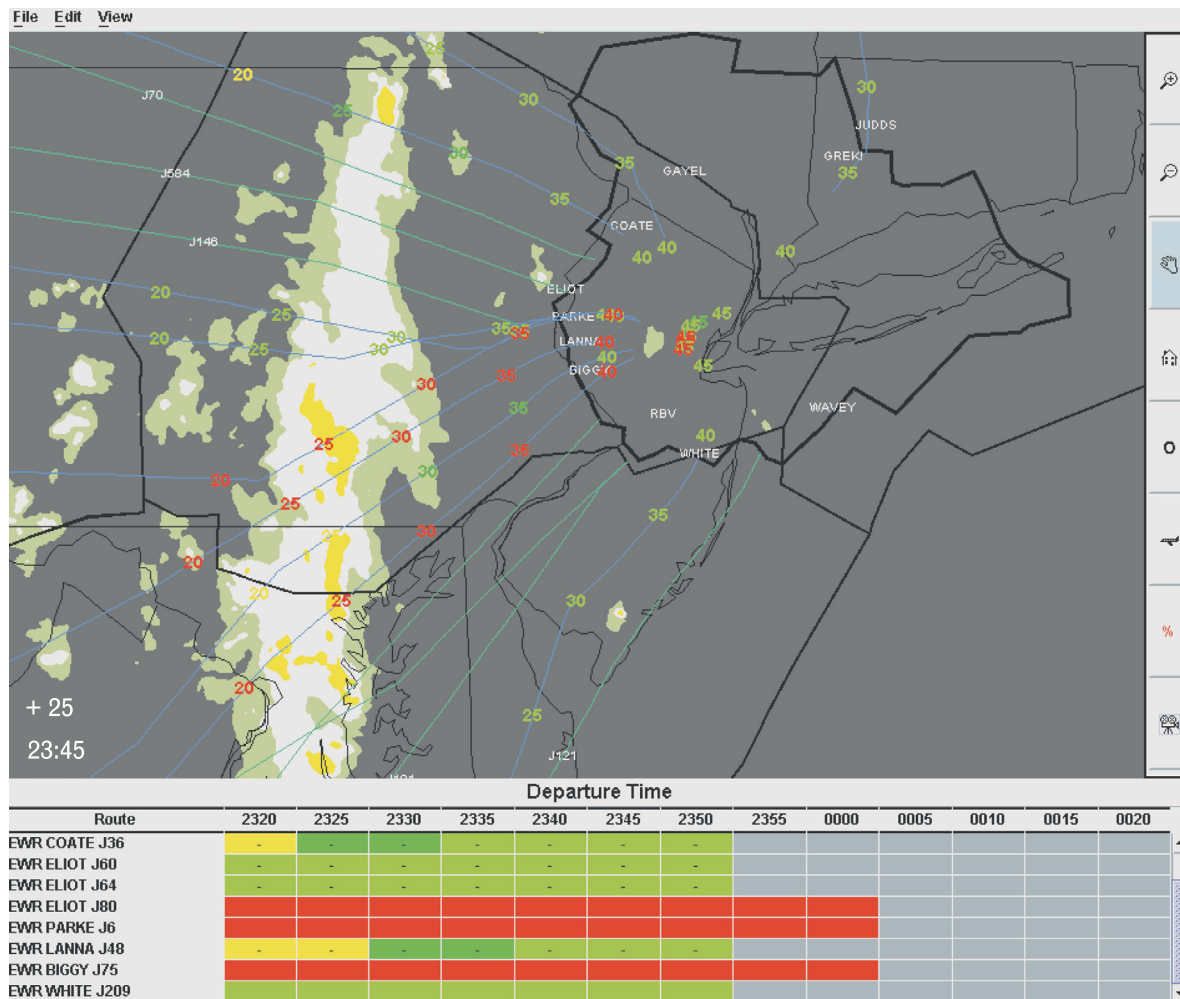


FIGURE 3. Route Availability Planning Tool (RAPT) display. The forecast movie loop display (upper region) shows animated hazardous weather forecast with projected departures (colored numbers) overlaid. The departure route status time line is shown in the lower region. Colored numbers in the animation correspond to future departure times and statuses shown in the time line. Red indicates a blocked departure, yellow shows impacted routes and times, dark green notes partially clear areas, and bright green indicates clear departures.

decide when to reopen jet routes that had been closed due to thunderstorms, or to avoid closing jet routes unnecessarily. User feedback from five specific incidents is instructive, as shown in Table 1. The specific operational parameters (e.g., how much earlier a closed route may be reopened on the basis of RAPT information, or the amount of capacity that may be available on a route that was kept open by using RAPT information) were used in a queue model to calculate departure delay reductions due to RAPT usage. The model results indicate that approximately 800 hours of airplane delay were saved from these five incidents.

On many occasions, however, RAPT showed routes

blocked due to thunderstorms, even when pilots could and did fly over the storms [13]. The erroneous indication of a blocked route arose because the RAPT 2003 real-time software did not consider the possibility of a departure overlying storms. Experience with the CIWS operational prototype [4] and studies of aircraft storm avoidance behavior [14] indicate that pilots will fly over storms if the aircraft is at least five thousand feet above the altitude of the weather radar echo top. The conclusion was that it was necessary to develop an explicit forecast of storm radar echo tops that would be used together with aircraft altitude information and storm reflectivity forecasts to determine

Table 1. Traffic Manager RAPT User Feedback from Specific Incidents

<i>Date</i>	<i>Feedback</i>
12 June 2003	"...at 2046 RAPT showed J80 was still available... were able to push twelve more departures as a result."
14 June 2003	"NY Air Route Traffic Control Center... used RAPT twice to open J75 and J48 twenty minutes earlier."
12 June 2003	"Three westbound routes consolidated and operated as a single departure route as needed according to... depiction given by RAPT."
5 July 2003	"Thirty extra departures as a result of leaving J80 open."
21 July 2003	"... all westbound departures would have been closed... credited RAPT for helping keep west gates open."

when and where departure routes would actually be blocked. An improved RAPT route-blockage model using forecasts of both radar echo tops and regions of high-reflectivity radar returns was deployed in 2004 and is currently in use.

Observations of RAPT usage in 2005 showed that additional issues need to be addressed if RAPT is to be fully successful. Although the use of the echo tops forecast greatly reduced the overwarning on route blockage, detailed modeling of pilot avoidance of thunderstorms by using the CIWS echo tops forecast has shown that additional storm severity features need to be considered in determining whether a jet route is blocked [15]. For example, planes have been observed to penetrate decaying thunderstorms that may still exhibit high radar echo tops but presumably not turbulence or other hazards to flight. Research is under way to improve the RAPT route blockage model by considering storm growth and decay as well as by using other storm vertical structure features.

Future RAPT Development Plans

A major impediment to increasing departure rates during SWAP is the willingness of en route ATC facilities to accept aircraft departing from New York City when there is convective weather in the ARTCC. One issue was that RAPT probed convective weather conflicts for only a limited portion of the aircraft routes through center airspace. This limitation arose because RAPT initially used only the one-hour thunderstorm forecasts provided by the New York City ITWS proto-

type. Utilizing the CIWS two-hour convective forecast could expand both the spatial extent of the departure routes probed by RAPT and the future departure time window. The use of longer lead-time forecasts will result in forecast uncertainty becoming more important as a factor in using RAPT, which will in turn warrant explicit consideration of forecast uncertainty in determining route blockage.

Another problem in RAPT usage by the ARTCC was coordination between the ATM unit and the area supervisors within the ARTCC that provide ATC separation services to departing aircraft. Although the Traffic Management Unit had a RAPT display, the area supervisors did not. The CIWS operational experience discussed in the companion article entitled "Corridor Integrated Weather System," by J.E. Evans and E.R. Ducot [5] in this issue suggests that the joint decision by the Traffic Management Unit and ARTCC area supervisors to accept higher departing aircraft rates would be facilitated if the area supervisors also had RAPT displays.

The current version of RAPT does not adequately provide support for the management of departures whose filed route is blocked. Neither does RAPT explicitly consider which flights are about to depart. Finding alternative routes for planes that are about to depart on a blocked route is important, since those planes may occupy locations on the taxiways that would block other aircraft from departing. Currently, the TRACON and ARTCCs must manually determine whether there are downstream congestion con-

straints associated with alternative routes. Also, the pilot and airline dispatch may be concerned about the extra flight distance associated with an alternative route. It clearly would be far more efficient if RAPT users were provided with an integrated analysis of all the departure constraints for alternative routes to the desired destination. Work is under way with the National Aeronautical and Space Administration (NASA) to develop an enhanced convective-weather departure management system that would enable the FAA and airline decision makers to rapidly determine the most viable alternative route to the desired destination.

Developing Models for the Impacts of Thunderstorms on en Route Airspace Capacity

The RAPT provides operational decision support based on binary (i.e., open or blocked) models for each specific departure route from New York City airports. Addressing larger-domain ATM problems requires that quantitative capacity impact models be developed for both en route and terminal airspace. This section describes initial work by B. Martin, R. DeLaura and J.E. Evans to develop forecast-based models for the impact of thunderstorms on en route sector capacity [16].

En route airspace is divided into sectors—volumes of airspace controlled by two-person teams charged with aircraft separation assurance, hand-offs to adjacent sectors, and weather advisories. En route sector capacities during fair-weather conditions are typically ten to fifteen aircraft, dictated by controller workload constraints. Airspace capacity during convective weather outbreaks is reduced as jet routes are blocked and/or planes must maneuver to avoid thunderstorm penetrations. Associated reductions in the numbers of aircraft that can safely be accommodated in an en route sector depend on the fine-scale interaction between air route structure and the complex, time-varying spatial distribution of thunderstorms. It is not currently possible to forecast even large-scale, long-lived thunderstorm systems with high precision beyond one to two hours. Smaller, air-mass thunderstorms may have lifetimes on the order of one hour or less so that even very short term (less than two hours) forecasts must be viewed as probabilistic for such storms.

Realistically, estimates of the future impacts of thunderstorms on airspace capacity must in many cas-

es be based on forecasts of the likely range of key storm parameters within areas where storms are forecast to occur. An example is the area probability currently provided by today's Collaborative Convective Forecast Product (CCFP) [17]. Loosely, this is to be interpreted as the probability that a specific location within the forecast region will be experiencing a convective storm with high radar reflectivity at the forecast-valid time. Equivalently, this probability can be interpreted as the fractional area within the forecast region that will be experiencing such a storm at the forecast-valid time. These probabilities can be estimated manually on the basis of the forecaster's interpretation of atmospheric convective potential, or they can be derived from numerical weather-prediction models by using multiple runs to form an ensemble of explicit forecasts, which are then converted to area probabilities. S. Weygandt and S. Benjamin discuss a zero-to-six-hour convective probability forecast based on numerical weather-prediction ensemble techniques [18].

Unfortunately, area probabilities alone are not readily translated into estimates of future airspace capacity reduction because the traffic flow impact is strongly dependent on the location, orientation, and spatial scale of the convection within the forecast area and the height of the thunderstorms. This dependency is illustrated in Figure 4, in which the route-blockage model described below has been used to estimate distributions of capacity reduction for different U.S. en route sectors, using an ensemble of similar thunderstorm cases—east-west-oriented line storms covering 30% to 50% of the sector. The distributions of blockage within individual sectors are broad, and they vary considerably among the sectors, indicating that details of the individual storms' structures and the sector air route structures have a strong impact on the amount of blockage. For example, four of the five major high-altitude jet routes in Cleveland Center sector 28 are also east-west oriented so that similarly oriented line storms are unlikely to block all the routes. In contrast, the major jet routes in Washington Center sector 12 run north-south, accounting for the significant probability that many or all routes will be blocked by east-west thunderstorm lines.

Multi-hour probabilistic convective forecasts must therefore provide estimates for many relevant storm

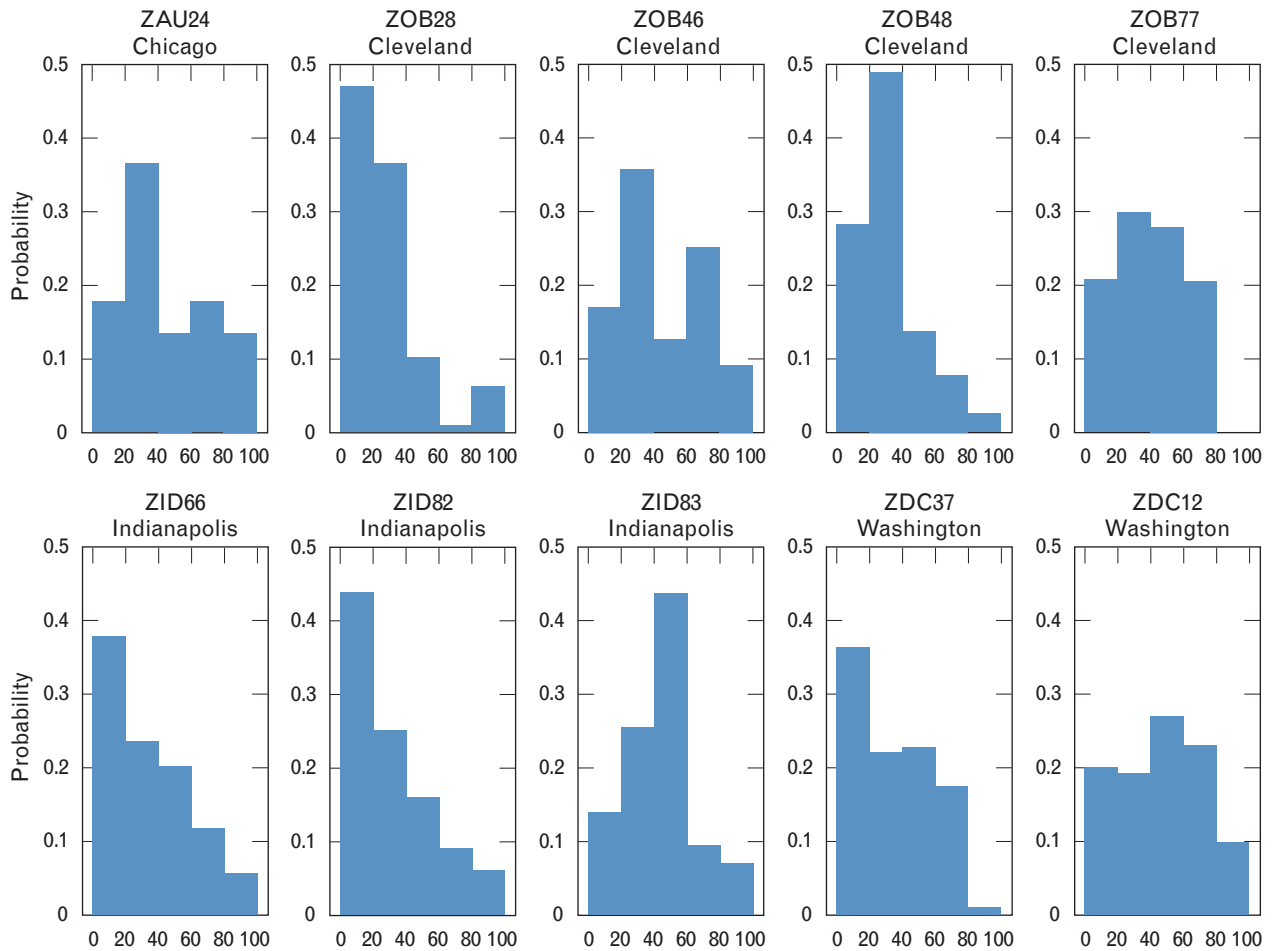


FIGURE 4. Distribution of the percentage of routes blocked in ten congested en route sectors in the northeastern United States. The distributions are for an ensemble of east-west-oriented line storms exhibiting area coverage within the sectors of 30 to 50%.

parameters, not simply fractional area coverage. In addition, it will be necessary to develop sector-specific models to translate the convective forecasts into estimates of capacity loss. Preliminary efforts to develop such models are described in the following paragraphs.

We used weather radar measurements of storm systems to calculate multi-parameter storm characterizations that could reasonably be generated by a forecast algorithm. Examples of such parameters include the fractional area coverages of storms with intense precipitation and/or high-altitude extent, parameters characterizing the type of storm (e.g., line storm, large thunderstorm complex, scattered small cells), and, in the case of line storms, the orientation of the line. High-resolution fields of vertically integrated liquid water content (VIL) and radar echo top, derived from

these same weather radar measurements, were then used to estimate the true reduction in sector capacity. Statistical models relating the forecastable storm parameters to the true capacity reductions were then developed by using the LnkNet pattern classification software package [19]. These statistical models were developed with 80% of the storm database described below: the remaining 20% was used to measure the performance of the models. The results of this exercise were a preliminary measure of skill for en route capacity reduction predictions based on probabilistic weather forecast parameters and an understanding of which weather parameters forecast algorithms should strive to estimate.

The ten ATC sectors referenced in Figure 4 were chosen for this model development because of differences in geographic location, size, route orientation,

and route complexity. These sectors include high traffic areas within the Indianapolis (ZID) and Cleveland (ZOB) centers, major north-south transit routes within the Washington (ZDC) center, and a Chicago (ZAU) center sector responsible for transcontinental traffic over the Midwest. A total of sixty high-altitude jet route segments within these sectors were utilized in developing the models. A database of twenty convective weather events, archived by using the CIWS prototype, was analyzed. The storm cases were chosen to represent a variety of weather types, structures, and orientations, relative to the en route sectors considered, and each had significant operational impact within the area considered.

We calculated a parameter referred to as fractional route blockage in order to estimate the true capacity reduction within each sector. Jet route segments within each sector were subdivided into lengths of roughly 55 km (0.5° latitude) and assigned a width of 8 km. A storm blockage score for each subdivided segment was determined via a linear combination of measured radar echo overlap parameters. These parameters capture the intensity of the radar echo, the extent (partial or total) to which the echo overlays the route segment and the altitude extent of the echo. The weighting factors were determined empirically through our study of RAPT operations in New York City airspace and interactions with FAA air traffic managers and controllers.

The blockage score for the route segment was taken to be the maximum of the subdivided segment blockage scores. Finally, the capacity reduction for the entire sector was taken as the fraction of jet routes through the sector whose blockage score exceeded a threshold.

The use of the maximum of the subdivided segment blockage scores determines an upper bound on the capacity loss on the route. If we consider the time variation of the subdivided segments blockage scores relative to the positions that an aircraft would be in as a function of time (i.e., determining whether there are four-dimensional intersections of the aircraft and convective cells), we generally obtain a higher effective capacity.

Figure 5 is a snapshot of true capacity reductions thus calculated in the ten en route sectors during a period of thunderstorm activity. Shown are the high-altitude jet routes used in the model and the averaged route blockage (i.e., capacity reduction) for each sector. The widths of the jet route lines denote the scheduled demand for each route at the time of this analysis. The significant sector-to-sector variation of capacity reflects the fine-scale interaction between the storm locations, heights, and jet route structure. Similar complexity in the time variation of sector capacity is also observed.

Table 2 summarizes the prediction skill of the capacity reduction model developed with the above methodology. The rows of the table correspond to subsets

Table 2. Statistical Capacity Model Validation Test

<i>True capacity reduction (%)</i>	<i>Number of cases</i>	<i>Coverage* VIL > convective weather threshold</i>	<i>Coverage* height > 25,000 ft</i>	<i>Best combination*</i>
0 to 20	21,287	88	92	97
20 to 40	2578	22	30	63
40 to 60	1691	26	23	64
60 to 80	884	29	27	68
80 to 100	515	44	29	85
Totals	26,955	78	78	91

* Correct predictions based on indicated storm parameters (%).

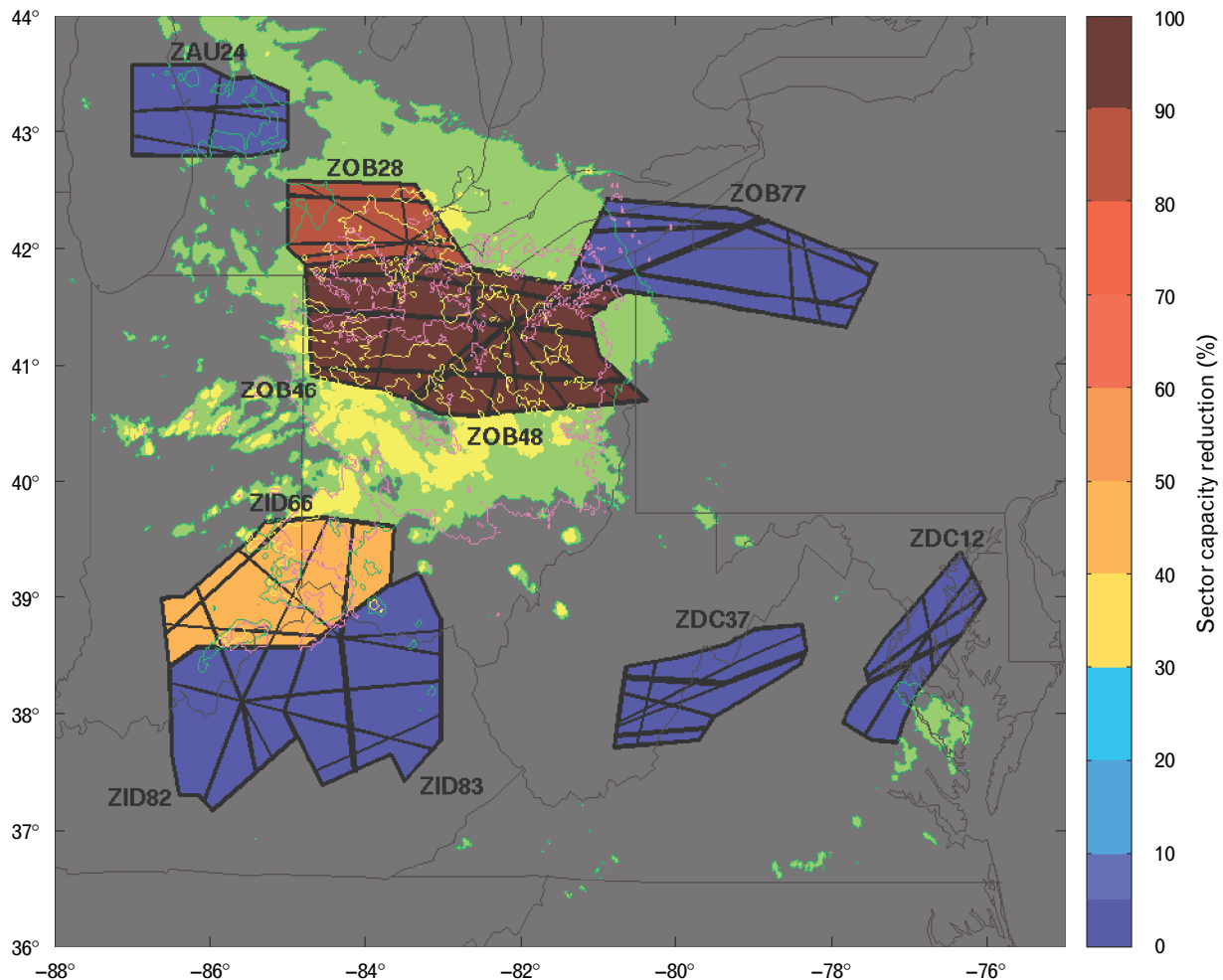


FIGURE 5. Output of the route-blockage-based sector capacity model. The input-weather-radar vertically integrated liquid (VIL) water content field is shown in green, with yellow denoting areas where the VIL exceeds the convective weather threshold. The purple contours are areas where radar error tops exceed 32,000 feet.

of the database in which calculated route blockage—our metric for true capacity reduction—is within the indicated interval. Shown in the first column are the number of storm cases in the database that fall into each category and, in the last three columns, the probability that this true capacity reduction is predicted by using the statistical models operating on the calculated storm parameters individually or in combination.

Models using only the coverage of high-intensity precipitation (VIL greater than the convective weather threshold) or of high-topped storms were able to correctly classify approximately ninety percent of the cases where actual route blockage was 0 to 20%, but provided poor performance for higher true capacity reductions. In contrast, the best multi-parameter ca-

capacity prediction models provided very good performance for the extreme route-blockage intervals and acceptable performance in the middle range of 20 to 80% actual route blockage. Better performance in this middle range may be expected when a larger storm database is analyzed.

Overall, this exercise conveys a fair amount of optimism that thunderstorm impacts on en route capacity can be estimated by using area parameters that can reasonably be expected to be provided by next-generation weather forecast models. Much additional work is needed, however, to refine and validate such models, to extend them to terminal airspace and airport domains, and to understand their application to a variety of specific ATM decision support tools.

ATM Optimization with Weather-Induced Capacity Constraints

This section discusses initial efforts to utilize estimates of thunderstorm-induced airspace capacity reductions to develop automated, broad-area ATM strategies. We are working with D. Bertsimas at MIT, who previously developed a mixed-integer programming (MIP) model that addresses this problem [20]. The NAS is characterized as a set of airports interconnected via en route sectors. Each airport and en route sector is assigned time-varying aircraft capacities. Individual flights are modeled as traversals of sectors forming paths between pairs of origin and destination airports. The model specifies the valid paths, along with minimum sector traversal times, so that aircraft speed is accounted for. The model solution yields not only the optimal cost

(in terms of minimal in-flight and ground delays) but also the flight plan for each flight—takeoff and landing times, and arrival times at each sector along its path. Using 1990s state-of-the-art MIP solvers and hardware, D. Bertsimas and S. Stock-Patterson showed that ATM problems of significant size (six major airports, with three thousand flights over a sixteen-hour period) could be solved optimally in only a few minutes of computation time [20].

We are utilizing this model in a *post facto* mode (that is, with perfect knowledge of how the weather evolved over time) to assess current ATM strategies in relation to the optimal solution. Several high-impact thunderstorm days in the CIWS domain during 2004 and 2005 are being analyzed for this purpose. For 16 July 2005, Figure 6 shows preliminary statistical comparisons between Aviation System Performance Met-

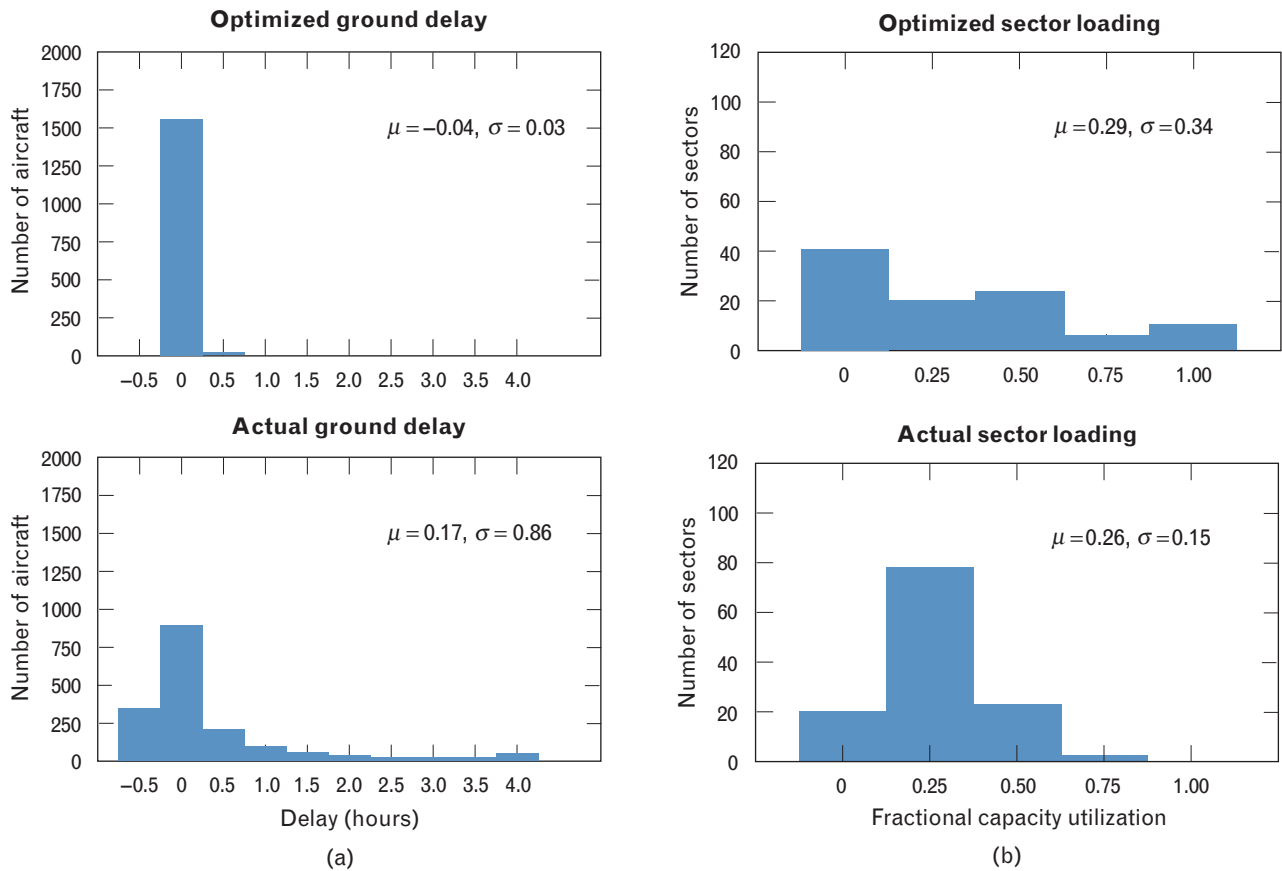
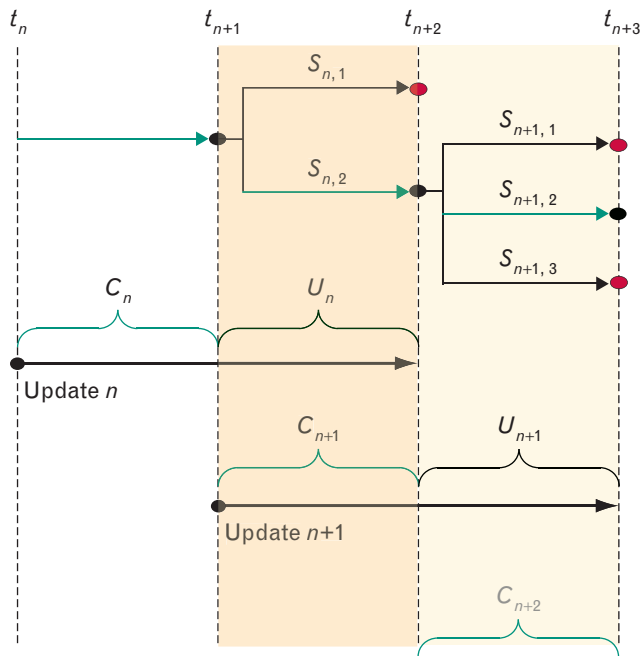


FIGURE 6. Optimization and actual ground delays and sector loading: (a) actual versus optimal ground-delay statistics for north-eastern United States airports on 16 July 2005; and (b) actual versus optimal fractional capacity utilization for en route sectors in northeastern United States airports on 16 July 2005. The Aviation System Performance Metrics (ASPM) data considered only the loss of en route capacity due to adverse weather conditions and did not model terminal capacity losses. In these graphs, μ is the mean value of the data and σ is the standard deviation.



Adaptive scheduling: updates at times $\{t_k\}$

At time t_n

- Capacity over interval C_n is certain, but uncertain over interval U_n .
- Scenarios $S_{n,1}, S_{n,2}$ are developed for interval t_n to t_{n+2} based on the t_n forecast.
- Optimal schedules developed for scenarios $S_{n,1}, S_{n,2}$ are identical over interval C_n , but diverge over interval U_n . Common portion is implemented over C_n .

At time t_{n+1}

- Airborne flights are on trajectories consistent with realized scenario ($S_{n,2}$).
- Updated forecast at t_{n+1} is used to generate scenarios $S_{n+1,1} \dots S_{n+1,3}$ developed for interval t_{n+1} to t_{n+3} .
- Common portion of schedules is implemented over C_{n+1} .

FIGURE 7. Adaptive multi-stage scheduling algorithm. Here, C_n indicates the current time period over which conditions are known, U_n is the uncertain future time interval, and $S_{n,i}$ are the proposed scenarios based on the current conditions.

rics (ASPM) data and the *post facto* optimal model run. Figure 6(a) shows that ground delays exceeding fifteen minutes affected 31% of the flights in the northeastern United States on this day, with 12% of the flights held for one hour or more. The model for an optimal ATM strategy resulted in a single flight experiencing a thirty-minute delay, with the remaining flights arriving on time. The dramatic performance improvement occurs because the modeled optimal ATM strategy utilizes a substantial fraction of the en route sectors at much nearer their maximum (weather constrained) capacity, as shown in Figure 6(b). Obviously, the modeled results are unrealistic, given that they assume perfect knowledge of the weather and associated capacity impacts. Further, we did not include terminal capacity losses in this initial exercise. This experiment indicates, however, that substantial reductions in weather-related delays may be possible with improved weather forecasts and more effective ATM response strategies.

With support from Lincoln Laboratory's Advanced Concepts Committee, we are generalizing this ATM optimization model to the real-time situation in which future capacity reductions are uncertain both because of errors in the weather forecasts and because of the associated airspace impact models. This is naturally a

multistage optimization problem with partial information revealed sequentially. It is sequential because we must specify directives for planes that are currently in the air or must take off in the current time period. The uncertainty is the capacity as affected by the weather. We have some idea of what the weather will do for the entire time horizon (the day), but we get an increasingly better picture as time progresses. That is, at 2:30 p.m. we have a better idea of what the weather will do at 3:00 than we did at 1:00 p.m.

Decisions that we make and implement immediately are good if they can be continued in a feasible and low-cost manner in the next time period. Therefore, the optimization process must have a notion of the future variables even while its only task is to output the current decisions.

A notion of adaptability is built in to the optimization in order to generate solutions that are not overly conservative. That is, the optimization must output decisions for the current time step, and then output alternative strategies, or policies for the future time steps, that depend on the updated weather forecasts. There is a natural trade-off between the optimality of the formulation, the computational complexity of obtaining a solution, and the level of risk associated

with the possibility that the realized future weather situation may be even worse than that assumed for the most pessimistic future policy.

We have recently begun work on the implementation of this algorithm, which is a natural extension of the Bertsimas-Stock-Patterson model to multiple future weather scenarios. This adaptive multistage scheduling algorithm, shown in Figure 7, includes the capability to update its solution periodically to account for new weather information. The algorithm is adaptive in the sense that it makes decisions that take into account a range of uncertainty in weather impacts on sector capacity, and multi-staged in the sense that it reoptimizes when weather updates are provided.

We plan to assess the utility of this algorithm with thunderstorm event data archived via the CIWS prototype. Actual weather, CIWS thunderstorm forecasts, and data on scheduled demand and implemented delay programs will be archived and analyzed to develop realistic estimates of the potential benefits of automated, objective ATM procedures. This analysis should clarify the extent to which objective ATM strategies based on imperfect weather forecasts and an associated set of alternative future strategies can improve over current human-specialist-developed strategies.

Summary and Conclusions

We have discussed key elements of an emerging aviation weather research area: the explicit integration of aviation weather forecasts with NAS structure to improve the effectiveness and timeliness of weather impact mitigation plans.

Our insights are based on operational experiences with Lincoln Laboratory–developed integrated weather sensing and processing systems, and derivative early prototypes of explicit ATM decision support tools such as the RAPT in New York City.

The technical components of this effort involve improving meteorological forecast skill, tailoring the forecast outputs to the problem of estimating airspace impacts, developing models to quantify airspace impacts, and prototyping automated tools that assist in the development of objective broad-area ATM strategies, given probabilistic weather forecasts.

Lincoln Laboratory studies and prototype demonstrations in this area are helping to define the weather-

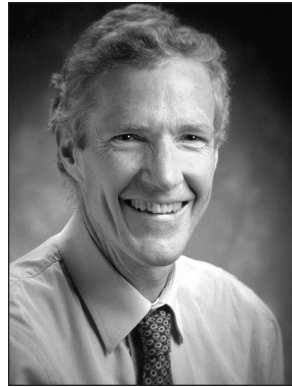
assimilated decision-making system that is envisioned as a key capability for the multi-agency Next Generation Air Transportation System [1]. The Laboratory's work in this area has involved continuing, operations-based evolution of both weather forecasts and models for weather impacts on the NAS. Our experience has been that the development of usable ATM technologies that address weather impacts must proceed via rapid prototyping at facilities whose users are highly motivated to participate in system evolution.

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