Air Traffic Management Decision Support During Convective Weather

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Flight delays caused by thunderstorms are a significant and growing problem for airlines and the flying public. Thunderstorms disrupt the structured, pre-planned flight routing and control process that is used to handle dense air traffic streams in congested airspace. Today's coping strategies are developed by traffic-flow management (TFM) specialists who interpret weather measurements and forecasts to develop delay and rerouting strategies. The effectiveness of these strategies is limited by the lack of quantitative models for the capacity impacts of thunderstorms, and by the difficulty of developing and executing timely response strategies during rapidly changing convective weather. In this article, we describe initial work to develop more effective response strategies. We first review insights gained during operational testing of a simple but highly effective Route Availability Planning Tool that can significantly reduce convective-weather-induced departure delays at congested airports. We then discuss work to develop core technical capabilities and applications that address broader TFM problems, including en route congestion. Objective models for airspace capacity reductions caused by thunderstorms are discussed, as is an associated scheduling algorithm that exploits the capacity estimates to develop broad-area TFM strategies that minimize delay. We conclude by discussing candidate real-time applications and airspace system performance analysis that is enabled by our weather-capacity models and optimal scheduling algorithm.

Thunderstorms are a dominant cause of commercial-aircraft delays in the United States and their impact is worsening, as shown in Figure 1. Although they are highly dynamic and are difficult to forecast over multi-hour time periods, these thunderstorms do not normally completely shut down airspace. Their effects, however, are fundamentally at odds with the structured, pre-planned flight-planning and control process that is the basis for today's Air Traffic Control (ATC) system. As airport and high-altitude jet route congestion increases because of overall growth in operations, commercial fleet transition from turbo-props to regional jets, and the introduction of very light business jets, thunderstorm-related delays are expected to increase rapidly. The Federal Aviation Administration's (FAA) Office for Strategic Planning has estimated that thunderstorm-related delay costs may completely offset airline profits within ten years unless significantly improved coping strategies are developed [1].

Today's thunderstorm response strategies are developed collaboratively by human traffic-flow management (TFM) specialists at FAA terminals, en route, and at national ATC facilities, and by ATC coordinators and dispatchers at airlines. The development of these strategies

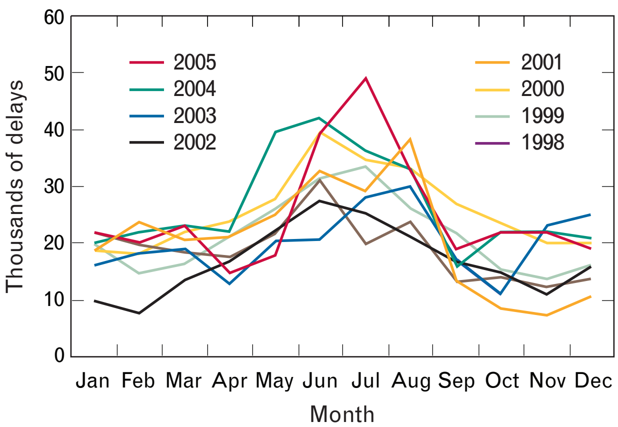

FIGURE 1. Commercial aircraft delays by month over the last eight years. The marked increase in spring and summer months reflects the impact of thunderstorms on en route and terminal airspace capacity.

is based on measurements and forecasts of thunderstorm locations, intensity, and movement relative to airports and jet routes. TFM specialists subjectively estimate the weather's impact on airspace capacity on the basis of the weather forecasts, then attempt to allocate this capacity by using corresponding estimates of current and future aircraft demand.

Experienced TFM specialists can execute effective short lead time (e.g., up to an hour) coping strategies, particularly when they have high-quality weather data such as that provided by the Laboratory's Corridor Integrated Weather System (CIWS) [2]. The specialists' capabilities to achieve near optimal results for longer lead times are limited by imperfect weather forecasts, associated uncertainties in available future capacity, and the lack of decision support tools to determine the implications of possible actions. As described by M.M. Wolfson and D.A. Clark, highly accurate thunderstorm forecasts cannot routinely be provided for time horizons beyond one to two hours [3]. In contrast, commercial-aircraft flight-planning horizons extend to eight hours or more.

Another major challenge is the limited time required to coordinate between multiple ATCs and airline decision makers when developing and implementing TFM strategies. Many of the opportunities to take advantage of variations in convective weather impacts (e.g., transient gaps in a squall line) are short lived. Hence, if the coordination time is too lengthy, opportunities to safely utilize the available capacity are missed.

The complexity of devising traffic-flow strategies that are near optimal for a given set of weather constraints is also a major problem. The system-wide implications of rerouting strategies are often simply too difficult to assess in real time because of the absence of quantitative estimates of current and future weather capacity impacts and objective guidance in balancing airspace capacity versus demand. As a result, TFM specialists frequently resort to pre-coordinated *playbook* strategies that reroute major traffic flows completely away from the weather-impacted areas. The airspace to which traffic is rerouted typically cannot accommodate all affected flights; thus a significant number of flights must be delayed on the ground or cancelled.

In this article, we discuss our initial efforts to develop *next-generation* Air Traffic Management (ATM) capabilities that build on the high-quality weather diagnostic and forecast products provided by CIWS. We review major Lincoln Laboratory aviation weather programs, describe associated insights into the need for more explicit ATM decision support, and discuss our initial technical development in this area. We conclude with a description of potential applications and discuss future strategies.

Insights Gained from Development of Integrated Weather Sensing Prototypes

During operational prototype testing of the Terminal Doppler Weather Radar (TDWR) in the early 1990s, Lincoln Laboratory researchers recognized that thunderstorm situational awareness provided by radar's broad-area surveillance allowed terminal air traffic controllers to improve decision making relative to openings/closings of runways, arrival and departure fixes, and other critical airspace assets. These insights spurred development of the Integrated Terminal Weather System (ITWS) [4], which was originally tested at moderate-density airports such as Orlando, Florida, and Memphis, Tennessee. Subsequent ITWS prototype operations at New York City (NYC) airports provided the opportunity to assess the TFM issues associated with thunderstorm impacts on highly congested airspace [5]. Specific insights included the following three issues. (1) The need to consider airspace constraints well beyond the NYC terminal area. Arrival and departure delays at NYC airports are significantly affected by operational constraints throughout the northeastern, north-central, and mid-Atlantic United States. (2) The importance of improving capabilities to expedite airport departures. During thunderstorm activity, deference to arriving aircraft may result in very long queues for departing aircraft, or even gridlock on the airport surface. (3) The need for operations-oriented decision support information, derived from meteorological forecast information *integrated* with airspace structure and flight-demand information.

Table 1. Glossary of Acronyms

ATC SCC	Air Traffic Control System Command Center
CIWS	Corridor Integrated Weather System
CTAS	Center/Tracon Automation System
DSP	Departure Sequencing Program
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FACET	NASA's Future Advanced Concept Evaluation Tool
FBO	Facilities-based operations
MIP	Mixed-integer program
MITRE	Mitre's Center for Advanced Aviation System Development
MSC	Meteorological Service of Canada
NAS	National Airspace System
RAPT	Route Available Planning Tool
SWIM	System-Wide Information Management
TRACON	Terminal Radar Approach Control
TMU	Traffic Management Unit

The recognition that flight delays at large airports are frequently caused by thunderstorms affecting en route airspace led to the development of the Laboratory's CIWS prototype. As shown in Figure 2, CIWS encompasses highly congested airspace in the northeastern quadrant of the United States. CIWS exploits a large sensor network (Doppler weather radars, environmental satellites, surface stations, lightning-detection sensors) to develop high-quality weather diagnostic and forecast products. These data are disseminated to all major FAA and airline facilities in its service area. CIWS products have been utilized effectively by TFM specialists to reduce thunderstorm flight delays [6].

In the context of this article, it is important to note that CIWS provides the Laboratory a key operational research environment for developing, implementing, and testing concepts for *integrated weather-ATM* decision making. Continuous, real-time operations provide archives of high-resolution raw weather data and associated forecast products, as well as operational information on ground and airborne delay programs. Lincoln Laboratory and FAA personnel periodically observe operational user decision making at multiple facilities in real time, and conduct structured, post-event debriefings to determine how CIWS products support effective TFM strategy development [7]. The Laboratory is *hardening* the CIWS prototype so that it can operate over the entire continental United States and serve as a technical exhibit for the FAA's next generation en route weather processor [2]. CIWS product improvement concepts developed as a result of ongoing operational testing can be readily inserted into this hardened prototype by way of frequent (three to six month) software builds.

An important example of a weather-informed ATM decision support tool that was developed as an outgrowth of ITWS and CIWS prototype testing is the Route Availability Planning Tool (RAPT) [8, 9]. RAPT was developed in coordination with NYC TFM specialists to facilitate the coordination of departures from NYC airports during convective weather. By solving the four-dimensional plane-storm intersection problem, the initial RAPT capability provided explicit guidance on times when an aircraft could depart on a route without encountering significant convective weather. In a number of cases, this decision support tool has been successful at helping to keep routes open and in facilitating the reopening of a route after a route blockage event ended. However, operational usage has shown that it is very important to quickly determine an alternative route for aircraft whose planned departure route is blocked. This avoids the situation where the departure queue for a runway is blocked by aircraft with *no route available*.

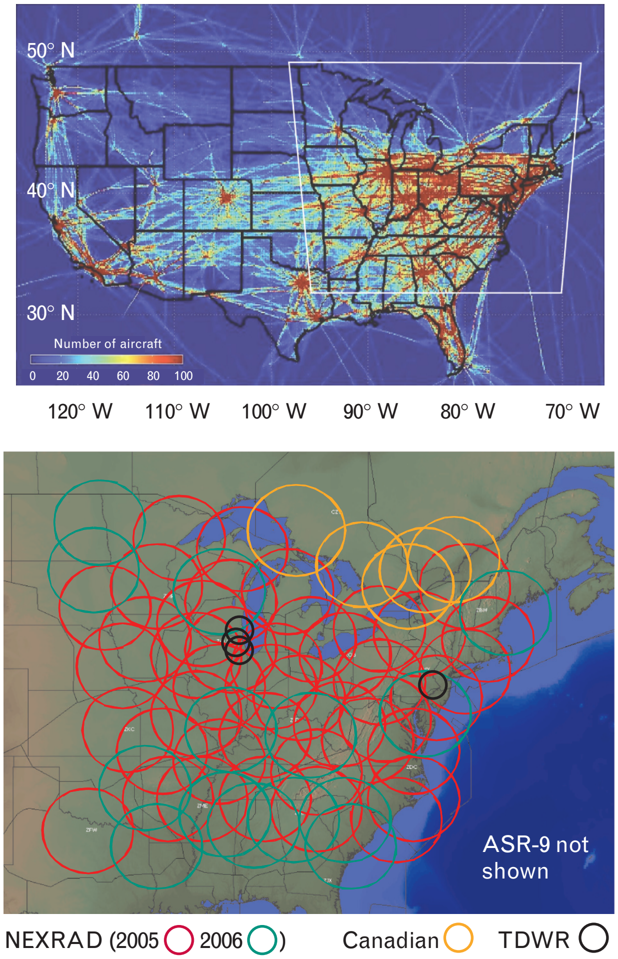

FIGURE 2. Corridor Integrated Weather System (CIWS). The upper figure shows the density of traffic in the United States over 24-hr, largely weather-free period beginning at 1000 GMT on 12 September 2002. Coverage of the CIWS prototype in 2005 is indicated by the white box. Note that aircraft are concentrated on defined routes as opposed to being more uniformly distributed. Both terminal and en route weather sensors utilized to create CIWS products are shown in the lower figure. The rapid update (30 second) Airport Surveillance Radars (ASR-9) are utilized to detect rapidly growing cells, while the Next Generation Weather Radar (NEXRAD), Terminal Doppler Weather Radar (TDWR), and Canadian radars provide information on 3-D storm structure and boundary layer winds. Data from lightning sensors and the Geosynchronous Operational Environmental satellite (GOES), not shown, are also utilized by CIWS. Dedicated display users include ATC SCC, Air Route Traffic Control Centers (ARTCC), TRACONs, and airlines (United, Continental, Southwest, Delta, FedEx, and JetBlue). Digital product customers include the weather-assimilated decision support tools (RAPT, CTAS, and FACET) and the experimental SWIM clients (e.g., Embry Riddle enhanced traffic display). Website users include most carrier/freight airlines, FAA headquarters, MITRE, NavCanada, MSC, the airline dispatch federation, FBOs, and the Department of Defense (U.S. Air Force and Navy). ARTCCs are located in Chicago, Cleveland, Indianapolis, Washington, D.C., Boston, New York, Minneapolis, and Kansas City. At the Cleveland, Washington, D.C., and Minneapolis ARTCCs, both TMU and controller supervisors had CIWS displays in 2005, whereas only the TMU has CIWS displays at the other ARTCCs.

The New York Terminal Radar Approach Control (TRACON) traffic management officer (TMO) recommended an enhanced capability in which the feasibility of flight-specific alternative routes for each aircraft in the departure queue could be readily accessed by decision makers. Figure 3 illustrates the use of RAPT and the Departure Sequencing Program (DSP) to determine that American Airlines Flight 1678 has filed for a departure route that will be blocked by convective weather at its projected wheels-up time. Pre-determined alternative coded departure routes (CDR) are evaluated by RAPT and NASA's Future Advanced Concept Evaluation Tool (FACET) to assess blockage by convective weather, incremental flight time, and potential downstream congestion constraints associated with each CDR. On the basis of this information, American Airlines and ATC can efficiently determine the best alternative to the filed route. Note that these enhanced departure management tools involve the integration of multiple types of information (CIWS forecasts, RAPT, DSP, FACET), thus suggesting the importance of a service-oriented architecture (SOA) as a basis for building advanced weather mitigation capabilities.

A key element in our development of weather-informed ATM decision tool concepts has been extensive interaction with FAA and airline TFM personnel. Interactions that revolve around ongoing training, benefits assessment, and prototype system enhancements have been crucial to our understanding of how candidate decision support technologies should be interfaced to human decision makers. Our interactions have emphasized that the need to achieve improved operational outcomes requires consideration of (1) the overall decision process, including who are the important users and what training is needed, (2) what is the pre-existing *baseline* of decision support (how new tools will augment the process), and (3) how we will measure the change in system performance.

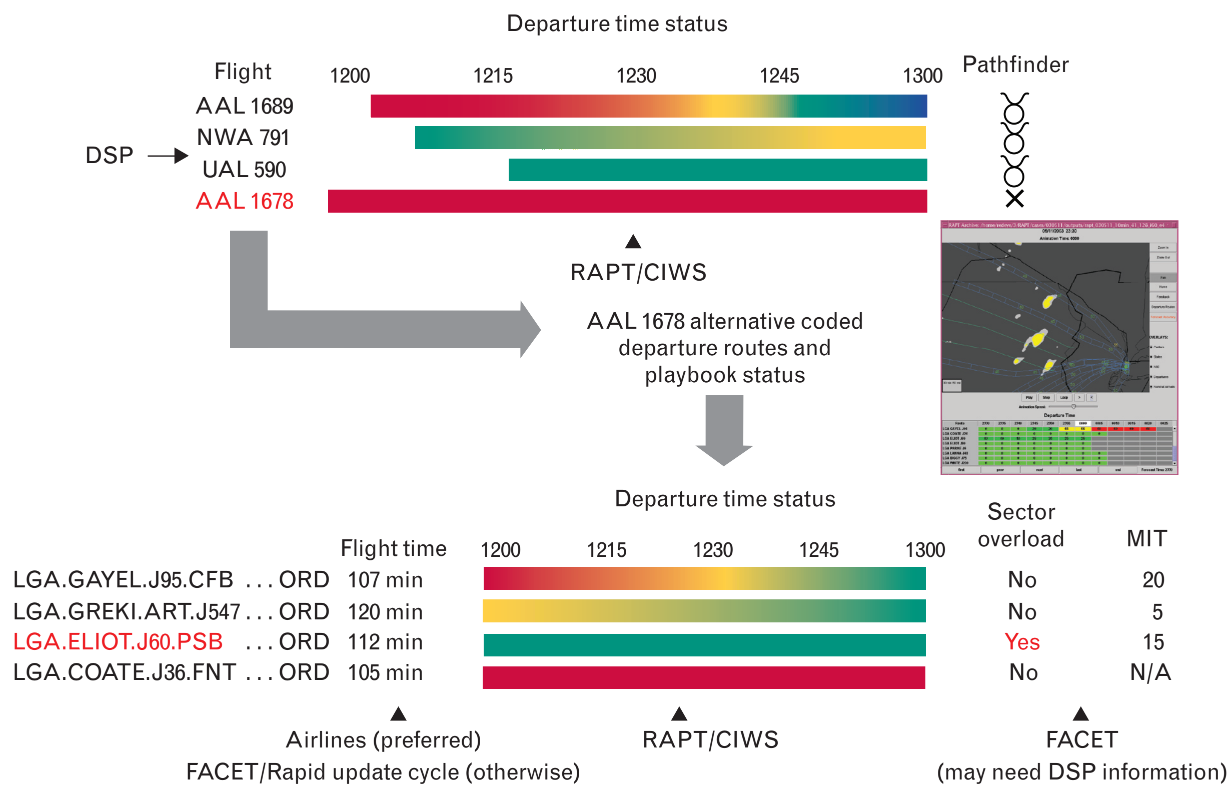

FIGURE 3. Integrated departure support tool for New York City (NYC) airports. The RAPT timeline status shows that the filed route for American Airlines flight 1678 will be blocked for the next hour. By selecting a flight, the user can display an automatically generated evaluation of alternative routes to the same destination for four key factors: route blockage, flying time, congestion in en route sector, and miles in trail constraints. The color bars indicate the status of a filed route (upper bars) and the status of alternative routes (lower bars) for the selected flight. Red denotes a route blocked at the indicated departure time, yellow denotes a partial blockage, and green indicates that the route is not blocked. The DSP shows four pending departures (American Airlines 1689, Northwest Airlines 791, United Airlines 590, and American 1678), two of which are showing delays on their filed departure routes. The lower bars show the alternative routes under consideration for AAL 1678. In this case AAL 1678 can depart any time during the hour indicated by using the Eliot departure fix.

Key Technical Development Activities

In this section, we describe three thrusts that address thunderstorm impacts on commercial aviation by the application of integrated sensing and decision support (ISDS) technology. These thrusts seek to develop (1) a cross-domain weather/TFM SOA; (2) quantitative estimates of the airspace capacity impacts of convective weather; and (3) objective ATM strategies based on estimates and associated uncertainties of the time-varying future capacity of terminal and en route airspace.

Service-Oriented Weather Decision-Support Architecture

J. Evans and E. Ducot discuss the complex inter-facility coordination that must be achieved to reroute aircraft in congested airspace in the northeastern United States [2]. Currently, the various decision makers do not generally have access to common weather products, and they certainly have no tools to provide consistent estimates of the weather's impact on airspace capacity. Meteorological products in use range from highly interactive workstations at Center Weather Service Unit positions in en route centers to simple radar reflectivity presentations available at controller radar positions. The most widely available decision support tool—the Enhanced Traffic Management System (ETMS)—utilizes software technology of the early 1990s era and is very difficult to upgrade as new capabilities are developed [10]. As a result, effective collaborative TFM decision making during complex, rapidly evolving weather impacts is hindered by difficulties in information access and sharing.

The FAA's System Wide Information Management

(SWIM) program seeks to develop an SOA that will support surveillance, weather observation and forecasting, TFM, and security functions by using open network-based communications, data formats, and information models. The Laboratory has played a leading role in developing initial demonstrations and a broader vision for the weather component of SWIM.

The benefits of an SOA are well recognized by both commercial and government IT organizations. Potential benefits to the aviation weather community include the following. (1) Consolidation of weather systems across the National Airspace System (NAS). As noted, numerous weather-processing and display systems are in use today, such that decision makers have to view a number of different displays to make decisions. In some cases, the decision makers do not have direct access to important information. (2) Implementation of new capabilities in an efficient manner, by providing *core* data delivery and weather algorithm services as building blocks for higher-level, mission-specific weather processing and TFM services. (3) Improved coupling between end-user decision support requirements and weather technology development due to the community-based system development required when implementing an SOA. (4) Increased interoperability with other agencies (National Weather Service, Department of Defense, Department of Homeland Security), and leveraging of SOA development conducted by those agencies.

The Laboratory previously conducted several SWIM weather demonstrations of a concept exploration nature, helping to establish the overall utility of net-centric weather dissemination. In addition, issues related to the simultaneous use of weather and aircraft surveillance data on a single network segment have been characterized, and a variety of candidate SOA technologies have been evaluated. A major expansion of this effort is under way to exploit maturing core infrastructure technologies to build towards the actual realization of the SWIM vision. Identifying the SOA technologies that are ready for real use, and coupling these technologies with demonstrated end-user capability improvements, is one technical thrust.

A second and perhaps more important activity is the design of the service-oriented architecture itself. Although a set of standard core services (e.g., Universal Description, Discovery and Integration [UDDI]–based discovery) will be provided and/or specified as part of SWIM, the services for any given community of interest are not specified. An up-front effort is needed to extract the common features from the system requirements and organize those features into a set of coherent, modular services. Without this structured initial design effort, it is possible that a largely point-to-point networked sensor architecture will be implemented, which, though certainly useful, would require significant downstream modification to recapture the full potential of an SOA.

In order to create this flexible service-oriented architecture, we will generate and analyze a core set of *use cases*—straightforward requirements consisting of brief text-based usage scenarios. The generated set will include a variety of known usage scenarios extracted from existing operational use of FAA weather systems, as well as a number of envisioned scenarios for the future net-centric NAS environment. The scenarios will cover the spectrum with respect to network topologies, data message size, message latency, and time (live versus archived access). Lincoln Laboratory will generate an initial core set of use cases, and publish them on a publicly accessible website.

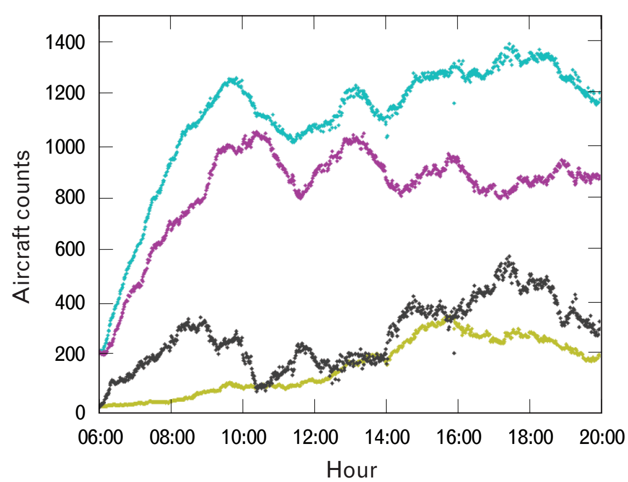

FIGURE 4. Measured and estimated thunderstorm-induced airspace capacity reductions. The blue curve is a three-day average during 2005 of fair-weather traffic counts for all en route sectors within the CIWS coverage area. The purple curve shows corresponding counts for 16 July 2005, a day with significant thunderstorm delays in the northeastern United States The difference between these two counts, a measure of the actual thunderstorm-related operations reduction, is shown in black, and the estimated capacity reductions, averaged over the CIWS domain, are in light green.

After gathering the use cases, we will perform a two-stage system analysis. First, the system-specific cases will be sorted into categories and generalized. The second step, essential to producing a flexible SOA design, is to break the cumulative desired functionality into a set of reusable software modules, the services in the SOA. These services will be used as the key building blocks for follow-on demonstration of net-centric weather capabilities.

Airspace Capacity Impact Models

Under NASA support, Lincoln Laboratory researchers are developing models that quantitatively estimate the impact of convective weather on terminal and en route capacity. The first stage of this modeling involves empirically based transformations of measured (or forecast) weather parameters into a weather avoidance field (WAF) [11, 12]. This WAF is a three-dimensional field representing the probability that a pilot will fly through a volume of airspace. The most effective inputs were shown to be weather radar-derived estimates of the vertically integrated precipitation intensity in a storm, and the height of the radar precipitation echo relative to the airplane's flight track.

B. Martin, J. Evans, and R. DeLaura have demonstrated the utilization of the WAF to estimate quantitatively the reduction in en route sector capacity caused by convective weather [13]. Jet route segments within each sector are 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 is 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 blockage score for the route segment is taken to be the maximum of the subdivided-segment blockage scores. Finally, the capacity reduction for the entire sector is taken as the fraction of jet routes through the sector whose blockage score exceeds a threshold.

Figure 4 compares the capacity reductions predicted by these models to actual airspace usage. The difference between the weather-affected counts and the fair-weather counts is a measure of the actual thunderstorm-related operations reduction. This difference is comparable to, but generally greater than, the estimated capacity reductions, averaged over the CIWS domain. This relationship is reasonable, given that ATC may not be able to take advantage of available airspace capacity in some en route sectors, because of weather or congestion constraints elsewhere in the system.

While this work is preliminary, it represents the first known effort to quantify the impacts of convective weather in terms that may be directly utilized in setting the parameters of TFM initiatives. We believe that this work, in combination with the ATM optimization techniques described in the following subsection, provides a basis for very substantial improvements in the ability to mitigate thunderstorm delays.

Optimizing Air Traffic Management Initiatives

As noted, the complexity of balancing airspace capacity and demand across many hundreds of airports and en route sectors, and the time-critical nature of the strategies that must be implemented, frequently results in the execution of TFM programs that do not take advantage of available airspace. In this section, we discuss an objective approach to developing real-time, broad-area ATM strategies that explicitly deals with uncertainty associated with imperfect weather forecasts.

We are working with Professor Dimitris Bertsimas at MIT, who previously developed a mixed-integer programming (MIP) model that addresses this problem [14]. The model characterizes the NAS 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 with 1 to 5 min time resolution as traversals of sectors forming paths between pairs of origin and destination airports. The model accounts for aircraft speed in specifying the valid paths and minimum sector traversal times. Not only does the model solution yield 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

* The use of the maximum of the subdivided-segment blockage scores upper-bounds the capacity loss on the route. If we consider the time variation of the subdivided-segment 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. This refinement to capacity calculations is used by RAPT and will be considered in follow-on studies [9].

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 by using only a few minutes of computation time [14].

With support from Lincoln Laboratory's Advanced Concepts Committee, we have generalized this ATM optimization model to the real-time situation in which future capacity reductions are uncertain because of errors both in the weather forecasts and in the associated airspace impact models. As illustrated in Figure 5, the weather and flight-demand data input to the optimization are updated nominally once per hour: this is the time interval over which accurate thunderstorm forecasts are generally possible. Flight-plan decisions that are output for the current hour must be compatible with the range of future weather-constrained capacity configurations dictated by forecast uncertainty. With this approach there is a natural trade-off between the optimality of the formulation and the level of risk associated with the possibility that the actual future weather situation may be even worse than that assumed for the most pessimistic future capacity forecast.

It has become clear that analogous resource scheduling challenges exist in constructing decision support tools in diverse mission areas across the Laboratory. In fact, we have recently begun a collaboration with MIT campus and members of the ISDS group to develop a modeling framework that will support the formulation of problems in areas as seemingly diverse as air traffic management and intelligence, surveillance, and reconnaissance (ISR) sensor tasking. We believe that the payoff in developing such a framework is in the ability to share strategies for overcoming the difficulties inherent in solving large real-time optimization problems.

Metrics Quantifying Benefits of Aviation Weather System Investments

As noted, thunderstorm-related delays in the NAS continue to grow in spite of the introduction of improved weather-forecasting technologies, operational weather platforms, and TFM support systems. As a result, we have found it extremely difficult to demonstrate the benefits of these technologies through direct comparison of system performance measurements such as the FAA's Aviation System Performance Metrics (ASPM) delay data [15]. This difficulty arises because airspace demand is increasing—particularly in high-altitude en route sectors—airspace structure and usage changes with time, and there are significant variations in the frequency, spatial structure, and severity of thunderstorm outbreaks. Most assessments to date have modeled system performance benefits on the basis of operational users' estimates of the type and frequency of improved TFM decisions made by using the system(s) under evaluation [5, 6, 15]. Although valuable, such user assessments cannot readily be related to measured NAS performance metrics (e.g., delays) and cannot quantify the benefit of improvements in

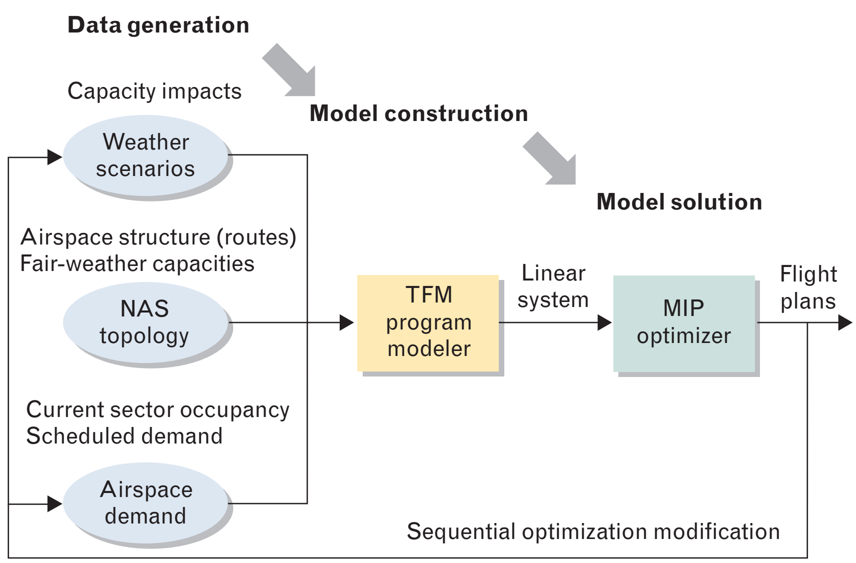

FIGURE 5. Block diagram of optimal scheduling algorithm. The algorithm is effected in three phases. In phase one, weather radar data is mapped into sector capacity impacts, and information is gathered on the location and intended flight plans for the existing air traffic (both en route and awaiting departure) within the NAS. In phase two, a MIP model of the current airspace situation is generated from the gathered data and a set of parametrized constraints representing the general air traffic flow problem. Finally, in phase three, the model is input to a commercial MIP optimizer, which generates flight plans for the aircraft under consideration.

the accuracy of the meteorological forecasts upon which TFM decisions are based.

Using the airspace capacity models and optimal scheduling algorithm described above, we have proposed a quantitative metric for thunderstorm operational impact that we term *unavoidable delay*. This metric explicitly accounts for the impact of the weather on airspace capacity, as well as NAS structure, demand, and achievable TFM strategies. As shown in Figure 6, unavoidable delay is an estimate of the minimum delay that could have been realized if future weather were known perfectly and optimal TFM were used. The difference between actual system delay and unavoidable delay reflects non-optimal traffic management decisions that result from both imperfect knowledge of current and future weather, and the challenges of executing fully effective response strategies during a highly dynamic convective weather event. We term this difference *maximum delay-reduction potential*.

The value of aviation weather system technology investments may be assessed by using these metrics to address the following three important questions. First, how do these metrics correlate with the structure, degree of organization, time duration, spatial extent, and geographic location of the thunderstorm systems? This analysis can establish relationships between the effectiveness of current thunderstorm-impact mitigation technologies and procedures, and specific measurable weather characteristics. For example, are greater delay-reduction benefits potentially achievable through improved capability to forecast and manage organized thunderstorm lines (e.g., squall lines) versus forecasting and managing disorganized (e.g., air mass) storms?

Second, how does the maximum delay-reduction potential vary with thunderstorm forecast accuracy, which changes considerably from day to day? This is a complicated issue, since the delays on a given day reflect both the weather severity on a day and the actions taken by ATC and airlines in response to forecasts for two different time scales (*strategic* 2 to 6 hr and *tactical* 0 to 2 hr forecasts). Hence, it will be necessary to stratify the analysis results as a function of accuracy of the various types of forecasts.

Third, how does *maximum delay-reduction potential* vary between airspace controlled by facilities with and without the advanced weather forecasting capabilities of ITWS and CIWS? This analysis will provide a performance-data-based assessment of the business case for advanced weather system deployments.

Assuming that the utility of the proposed metrics is

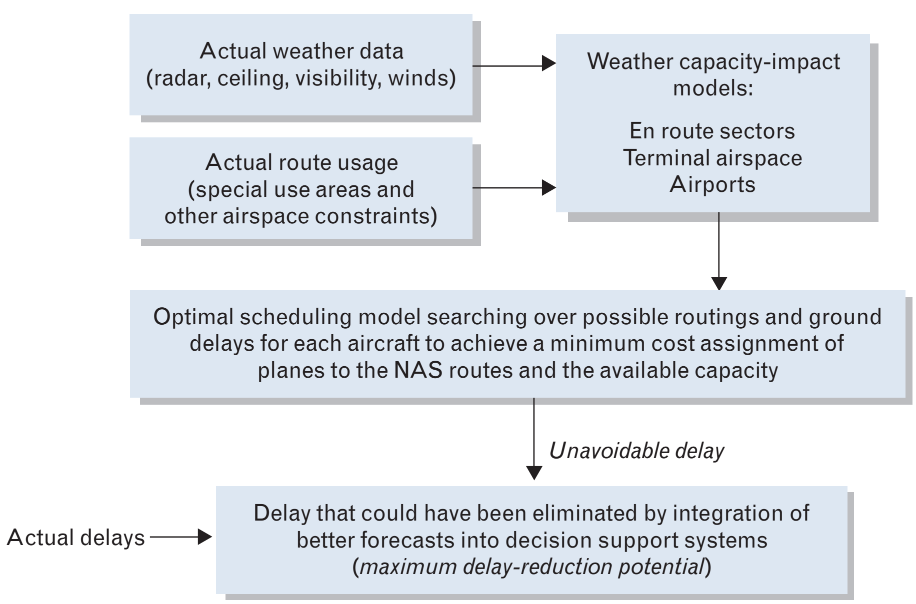

FIGURE 6. Measuring benefits of aviation weather decision support tools. We can combine the actual weather data and route usage, including any special-use airspaces, to model the optimal scheduling of aircraft and determine the levels of *unavoidable delay*. By comparing the actual delays with the unavoidable delays, we obtain the *maximum delay-reduction potential*.

clearly demonstrated, we expect that the results of this effort will include a recommendation as to how to routinely calculate these as FAA standard metrics for system performance during convective weather events, and as a guide for aviation weather investment decisions.

Expedited Airport Departures during Convective Weather

When convective weather blocks both departure and arrival routes, ATC will typically invoke Severe Weather Avoidance Procedures (SWAP) to manage the severe airspace congestion. Workload and safety concerns dictate that airport arrivals be given precedence over departures. If SWAP goes on long enough, gridlock on the airport surface can result.

The possibility of gridlock could be significantly reduced if there were a decision support tool to support a *departure flush* (DF) procedure* by which departures from airports with major departure delays and airport surface congestion could be given priority without unduly delaying other flights. The procedure consists of the following three steps: (1) determine which airports are to be given departure priority; (2) impose highly selective traffic management initiatives (TMI) for departures from lower-priority airports (for example, airports not currently experiencing extensive departure delays) so as to optimally alleviate the en route congestion that hinders the release of departures from the priority airports; and (3) release as many departures as feasible from the priority airports over a predetermined time interval, thereby alleviating surface congestion at the priority airports while not unnecessarily delaying flights from other airports.†

Depending on the duration of SWAP, the DF procedure may take place several times during the weather event, or only at its end. The DF procedure may also be appropriate in other (non-SWAP) situations when there is inadequate departure capacity relative to demand.

A major issue in implementing this procedure is the complexity of selecting and coordinating the traffic management initiatives for specific departures from the lower-priority airports. The en route sector-loading adjustments required to support the DF procedure may involve flights originating from multiple airports, which may be scheduled to depart over a period of time. A number of en route sectors may be involved, and evolving weather constraints can change available capacity in these sectors over the duration of the DF planning and execution cycle.

The airspace capacity models we described previously, when they are coupled to high-resolution thunderstorm forecasts such as those generated by CIWS, provide critical, quantitative information on airspace capacity constraints that affect DF implementation. Our real-time, efficient optimization algorithm based on the Bertsimas-Stock-Patterson formulation can develop plans for each departing aircraft at the various airports of concern, with 1 min time resolution [14]. This algorithm can search over multiple possible routes and departure times for each departure from both the high- and lower-priority airports to determine appropriate routes and departure times for all departures. The impact of arrivals on en route capacity can be considered as well.

We have proposed the development and demonstration of an automated DF decision support system (DST) for New York City airports that will allow TFM specialists to develop TMIs that maximize the benefits of the DF procedure while minimizing the impact of the TMIs on flights from the lower-priority airports. The optimization algorithm would model each flight in the system with one-minute time resolution, thus allowing for real-time development of pinpoint traffic management initiatives that have minimal impact at the lower-priority airports. Figure 7 illustrates this DST as applied to the commercial airports serving New York City (LGA, JFK, EWR), Boston, Massachusetts (BOS), Manchester, New Hampshire (MHT), and Philadelphia, Pennsylvania (PHL).

* The FAA/airline review of the 2005 NAS severe-weather operations had five breakout subgroups to discuss major problems during convective weather [16]. The airport departures during SWAP subgroup identified the need for a departure-flush decision support system.

† The major FAA operational initiative for the summer of 2004 was the growth without gridlock approach to coping with the loss of en route capacity due to convective weather [17]. This initiative is described as follows: "Any time the wait for takeoff hits 90 minutes at a United States airport, the FAA slows down departures from other airports so that the clogged airports can launch more jets." Also, express lanes are set up for the delayed flights. "…Storms in one part of the country might delay your flight even though it's sunny where you are, where you are going and even in-between." However, it was found that there was no practical way manually to determine how departures at other airports should be held to facilitate the departures from the clogged airports to proceed.

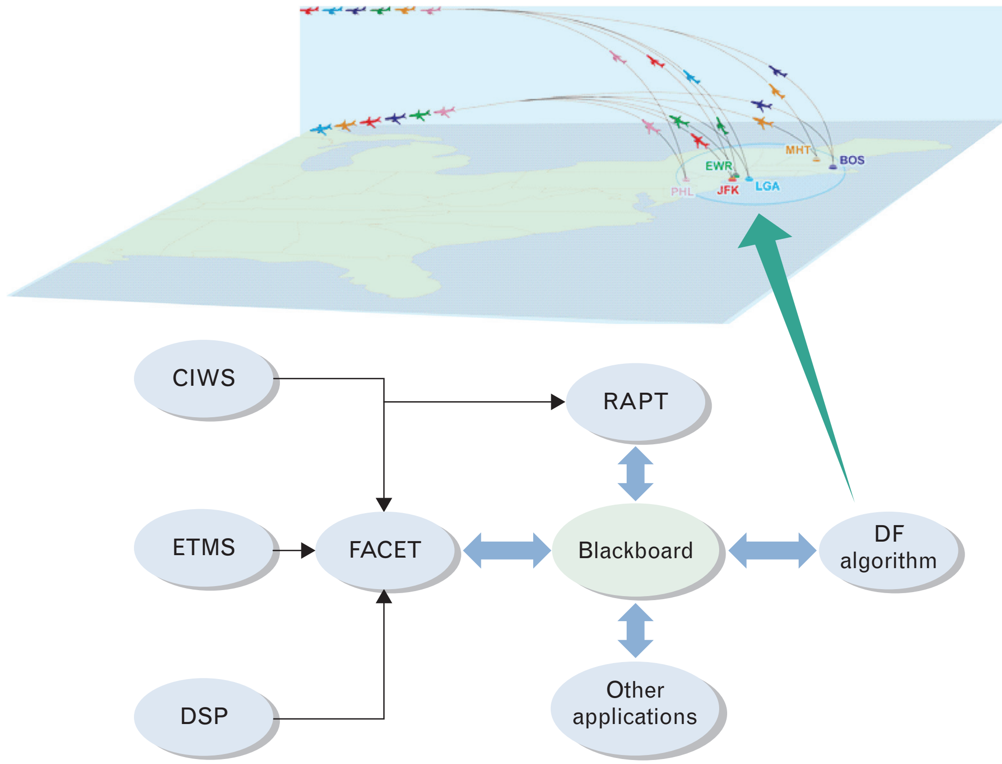

FIGURE 7. Departure flush (DF) decision support tool as applied to New York City airports. The releasing process for planes from the New York City airports involves flights originating from other airports within the northeast United States. ETMS stands for Enhanced Traffic Management Systems.

Components of the DF DST would include (1) real-time data on scheduled demand, current sector, and route loading constraints (these data will be monitored by using existing tools such as DSP, the Enhanced Traffic Management System [ETMS], and FACET); (2) weather impact forecasts derived from the CIWS and its associated RAPT; and (3) the departure flow algorithm, which is based on the optimal-scheduling algorithm described above. Note that this DST is essentially an expansion of that described earlier and shown in Figure 3. As such, it again points out that criticality of a more open service-oriented FAA weather system architecture as a basis for efficiently realizing necessary future capabilities.

Users would define airport prioritization criteria and acceptability limits for solutions developed by the DST. For example, an upper limit might be set for delay of individual flights at the low-priority airports. Alternatively, a nonlinear cost function for delays at the low-priority airports that captures the nonlinear impact of downstream delays might be utilized [18]. It would also be possible to have different delay-cost models for various departures (e.g., so that airline priorities for different flights could be directly considered).

We anticipate that this DST would significantly enhance the ability of FAA and airline TFM specialists to mitigate very high-impact-delay events at key airports in the congested United States northeast corridor. Planning, setup time, and workload for the DF procedure would be reduced through availability of consistent, optimized guidance for the TFM specialists at the different facilities involved. Appropriate DF-procedure consequence-analysis capability would be provided, including the facility for *what if* exploration of user-introduced modifications to the *optimal* set of TMIs.

Summary

Improving decision making for the mitigation of thunderstorm impacts on the aviation system represents an important application for ISDS technology. The need for improved decision making is currently urgent and is expected to be even more critical with expected future increases in flight demand. The rapidly changing nature of convective weather places a premium on making good decisions in a short amount of time. The good working relationships with operational users at a number of the key ATC facilities that have been established via the CIWS program offer the opportunity to explore innovative approaches to some very challenging problems via rapid prototype techniques. Practical applications of ISDS technology are being assessed operationally (e.g., the RAPT testing at New York) and we anticipate that much more sophisticated ISDS decision support approaches will be utilized in the near future.

The ATM/weather problem poses a very challenging, coupled scientific/operations-impact problem. Inherent uncertainty in multi-hour meteorological forecasts requires that corresponding future capacity uncertainty be characterized and accounted for in developing broad-area ATM strategies. The Laboratory's multidisciplinary approach to these problems is showing early promise in achieving significant capability enhancements.

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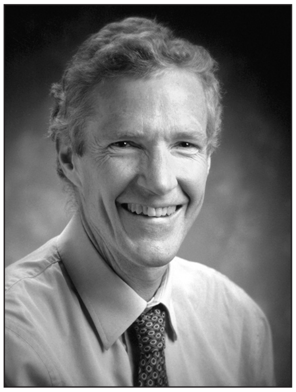

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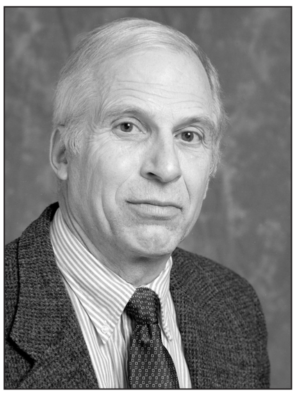

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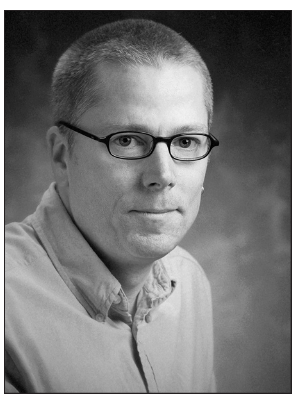

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