J3.3 IMPLICATIONS OF A SUCCESSFUL BENEFITS DEMONSTRATION FOR INTEGRATED WEATHER/AIR TRAFFIC MANAGEMENT (WX/ATM) SYSTEM DEVELOPMENT AND TESTING[†]

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1. INTRODUCTION

One of the major challenges in the US National Airspace System (NAS) today is improving the decisions made when adverse aviation weather occurs. Major increases in the usage of high altitude en route airspace by regional and corporate jets, coupled with greater use of "secondary" airports by low cost air carriers, have dramatically increased the complexity of operating the NAS during bad weather.

One potentially powerful approach to improving decision making is to explicitly combine aviation weather information with aviation system information to create an integrated weather/air traffic management (wx/ATM) system that improves the productivity of the NAS operators. However, it will not be enough to be able to develop the technology that could make system improvements possible; it has now become increasingly important to demonstrate quantitative user benefits for any new initiatives.

In this paper, we discuss the implications on the development and testing of wx/ATM systems of the need for a successful operational benefits demonstration of the new capability.

The paper proceeds as follows. In the next section, we discuss how an integrated wx/ATM system differs from the "conventional" aviation weather decision process. Section 3 describes current efforts by the FAA and the Office of Management and Budget (OMB) to appropriately consider operational benefits as a factor in investment decision making. Section 4 discusses key elements of an "operational benefits centric" approach to wx/ATM system development and testing. Sections 5 and 6 discuss two contemporary examples of integrated wx/ATM systems in the context of section 4. The paper concludes with a summary and recommendations.

2. INTEGRATED WX/ATM DECISION SYSTEMS

In the "conventional" approach to aviation decision making shown in Figure 1, the human users must determine the impact of the weather on the ATC system before a decision can be made. If decision support tools, such as the Cooperative Route Coordination Tool (CRCT) in the Enhanced Traffic Management System (ETMS), are used to aid in the execution of the conventional operational decision loop, the user must provide results from the impact assessment phase (e.g., Flow Constrained Areas) to the tools in order to take advantage of the decision guidance they provide. Although this approach has been successful in a number of specific applications, it is becoming clear that it is not adequate overall, since often the task of determining the weather impact manually can be extremely difficult. For example, it is increasingly necessary to both minimize the loss of the arrival "slots" at capacity-constrained airports and to take advantage of opportunities to insert a departure into an overall stream of en-route aircraft [FAA, 2005b]. The need is even more acute in severe convective weather since initial en route and/or terminal capacity loss due to weather can cause holding patterns that rapidly result in widespread NAS disruptions (Boone and Hollenberg, 2004).

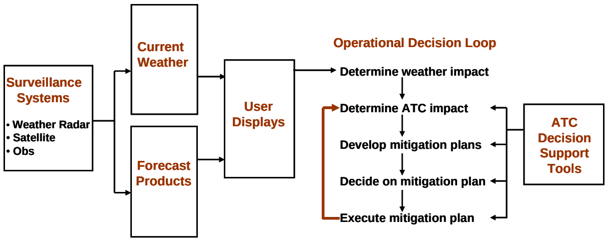

Figure 1. Decision process for use of weather products for air traffic management and/or flight planning

The new direction [e.g., as exemplified by the Joint Program Development Office (JDPO) initiatives to be discussed at this conference] is toward the development of integrated weather/air

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traffic management (wx/ATM) decision support systems as shown in Figure 2. In this approach, the weather products go directly into an explicit model of some element of the aviation system, which is embedded in a decision support tool. At a minimum, this integrated wx/ATM tool then determines the air traffic control (ATC) impact of the weather [e.g., as in the Route Availability Planning Tool (RAPT) discussed below] and may (depending on the degree of sophistication) generate mitigation plans, decide on a mitigation plan, and assist in the execution of the plan. Other non-integrated ATM decision support tools (DSTs) may assist in the decision elements that are not accomplished by the wx/ATM system, but the majority of the complex analysis is provided by the integrated system.

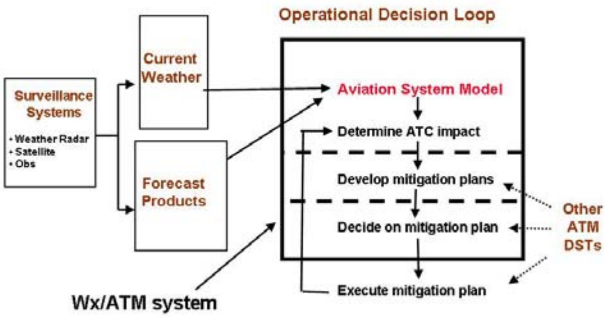

Figure 2. Decision process for use of weather products with an integrated wx/ATM system

Since an integrated wx/ATM system has an explicit model of some aspect of the ATM system, the ATC workload required to use the weather products to arrive at an appropriate ATM decision can be much lower[1] than with the conventional approach. There is a caveat however, in that the aviation model used in the wx/ATM system may not be appropriate for some weather situations. For example, a flight trajectory model might not be appropriate if there was significant turbulence due to a sheared vertical wind environment; the model for the blockage of a route by convective weather might not be appropriate fpr some types of storms. Under these circumstances, the user would need to compensate manually for the shortcomings of the model. In addition, if an integrated wx/ATM model makes errors on a given day due to a mismatch between the weather and the explicit aviation system model, it may keep making errors in situations where a human would recognize the problem and compensate.

Thus, the introduction of wx/ATM systems may create some different challenges in achieving successful operational use than was the case for "human centric" systems such as were shown in Figure 1.

3. INCREASED IMPORTANCE OF A QUANTITATIVE OPERATIONAL BENEFITS DEMONSTRATION

In an era of significant government and airline budget austerity for civil aviation investments, it is becoming increasingly important to quantitatively demonstrate the benefits to the operational user community of improvements such as integrated wx/ATM decision support tools[2].

The FAA and Office of Management and Budget (OMB) have increasingly stressed the importance of quantitative system performance metrics. For example, the new FAA Air Traffic Organization (ATO)[3] and the FAA Flight Plan 2004-08 (FAA, 2005a) both have quantitative performance metrics that are closely related to reducing convective weather delays. Additionally, the Office of Management and Budget (Office of Management and Budget, 2004) requires quantitative measures for system performance, an estimate of the baseline performance, the planned improvement to the baseline, and actual results achieved. Moreover, if an integrated ATM/wx system is to be part of a US government "capital "asset", then OMB circular A-11, section 300 covering acquisition of capital assets, may be applicable (Office of Management and Budget, 2004). This section calls for a computation of return on investment (ROI), which, in turn, is likely to require a quantitative estimate of delay reduction and/or safety benefits.

For FAA-procured systems, the analysis of benefits is carried out by the FAA investment analysis group (http://www.faa.gov/asd/ia-or/ia.htm).

The FAA benefits analyses can result in significant changes in the deployment of aviation weather decision support systems. For example, the acquisition of the last 12 Integrated Terminal Weather Systems (ITWS), out of a planned deployment of 37 systems, was deferred in 2004 due to questions raised as to whether or not the ITWS was achieving its anticipated delay

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[1] In addition, the wx/ATM system may be able to carry out much more detailed calculations than are practical or possible for a human.

[2] In some cases, it may even be important to demonstrate that benefits are likely to be achieved before the tool development will be funded.

[3] Performance metrics for ATO are provided on the ATO web site (http://ato.faa.gov/)

reduction benefits at deployed production ITWS sites.

4. KEY ELEMENTS OF AN "OPERATIONAL BENEFITS CENTRIC" APPROACH TO WX/ATM SYSTEM DEVELOPMENT AND TESTING

If demonstrating benefits is deemed important, then we would propose that the development and demonstration process for wx/ATM systems have:

(a) a specific set of supportive users seeking improved performance for certain relatively well understood weather situations, and

(b) reason to believe that if the decision making performance could be improved by currently exploitable scientific knowledge, measurable benefits would in fact be achieved.

The first element listed above has frequently been addressed by "rapid prototype" development processes, where a group of aviation system developers work in an iterative fashion with a group of users. This collaboration will be particularly important for the development of wx/ATM systems, since the users may have to communicate to the developer the critical elements of the aviation system model that are implicit in the wx/ATM system. The important difference in what we recommend is the addition of the second element, where one has identified users and a weather/ATM system usage situation in which quantitative end user benefits can be demonstrated.

In the remainder of this paper, we discuss the important aspects of the wx/ATM system development and testing process, which need to be considered if the end result is to be a successful "user benefits driven" demonstration. We begin with a sequence of questions:

First, what is the overall decision process for the effective use of the wx/ATM system if it is to have the desired quantifiable user benefit? If benefits are to be achieved, one must

(a) identify the important users, and

(b) develop training for these users that is oriented towards achieving measurable benefits.

Second, what is the preexisting "baseline" of aviation forecasts/decision processes that already exists to address the user needs? In most cases, there are already a number of weather information sources that can be viewed as providing a short term forecast [e.g., a Center Weather Service Unit (CWSU) meteorologist, persistence, or animation loops of the past weather]. How well do we understand how the "baseline" forecast and the associated user decision support system operate? How will the new wx/ATM system compare to the baseline? What are the training implications, if the new wx/ATM system is rather different than the "baseline"?

Third, how will we measure the change in system performance? For example, if the new wx/ATM system claims to help reduce delays and/or accidents, how will one address differences in the weather between the "before" and "after" time periods? How will one determine whether the wx/ATM system is in fact the key factor if there was a change?

The approach we have taken to this problem is to consider how the benefits considerations described above have been addressed in two current examples of wx/ATM systems:

(a) An air traffic automation system, which uses winds information to optimize sequencing of aircraft arriving at busy terminal areas, and

(b) A convective weather decision support tool, which combines convective weather forecasts and departure trajectory models to provide explicit guidance for departure times when there are Severe Weather Avoidance Procedures (SWAP) in effect near the departure airport.

Examples, showing the challenges of a following a successful operational benefits-centric approach to development, are drawn from experiences with two contemporary wx/ATM tool developments.

5. CENTER-TRACON AUTOMATION SYSTEM (CTAS) TRAFFIC MANAGEMENT ADVISOR (TMA)

A. System description

The Center air traffic controllers and Traffic Management Coordinators (TMCs) control arriving aircraft that enter the ARTCC from an adjacent ARTCC or depart from feeder airports within the

ARTCC[4]. On the basis of the current and future traffic flow, the TMC creates a plan to deliver the aircraft, safely separated, to the TRACON at a rate that is as close as possible to the capacity of the TRACON and destination airports. The TMC's plan consists of sequences and scheduled times of arrival (STAs) at the meter fix (blue triangles in Figure 3), published points that lie on the ARTCC-TRACON boundary. The ARTCC air traffic controllers issue clearances to the aircraft in the Center so that they cross the meter fixes at the STAs specified in the TMC's plan. Near the TRACON, the ARTCC controllers hand the aircraft off to the TRACON air traffic controllers.

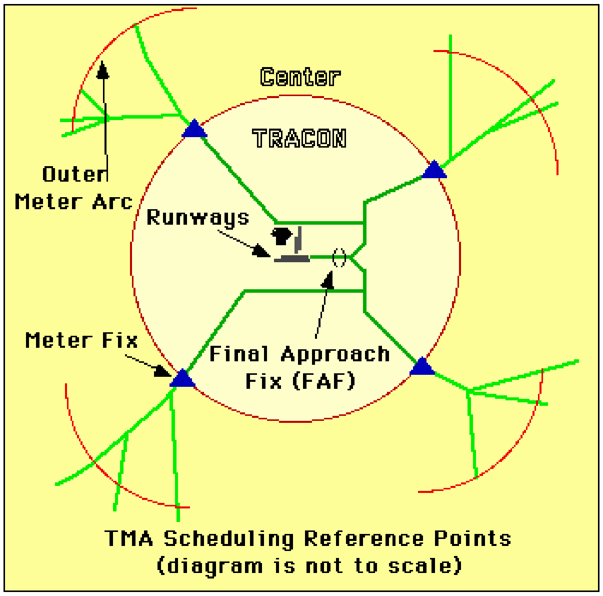

Figure 3. Key locations for CTAS TMA scheduling. The meter fixes (also known as arrival transition areas) are the blue triangles.

The arrival throughput of a capacity-constrained airport can be optimized if the arrival flows at the arrival fixes shown in Figure 3 can be appropriately spaced for the desired runway landing rate. Determining how the flight profiles of the individual arriving aircraft should be manipulated to achieve the desired sequence at the arrival fixes is quite challenging, since the aircraft arrive from many different directions and one must consider the impacts of winds aloft which will modify the flight times differently for different aircraft.

An important feature of TMA is its ability to sequence and schedule aircraft to the outer fix, meter fix, final approach fix, and runway threshold, in such a way as to maximize airport and TRACON capacity without compromising safety. In addition, TMA will assign the aircraft to runways to optimize the schedule. At the sector, en route controllers receive a TMA-list on their radar scopes, which displays the scheduled time of arrival (STA) at the meter fixes and the delays[5] that they need to absorb for certain aircraft to maintain adequate spacing.

The TMA planning activity takes place while the aircraft is in the ARTCC's airspace (approximately 40 to 200 miles from the arrival airport). Scheduling of some aircraft make take place before the aircraft have even entered the ARTCC's airspace, provided that aircraft's flight plan has been received by CTAS. TMA will update these sequences, schedules, and runway assignments constantly to adapt to changes in the traffic situation, changes in the environment, or in response to inputs by the TMCs.

In terms of the paradigm shown in Figure 2, the TMA determines the ATC impact of the winds and suggests a mitigation plan (e.g., speeding up or delaying a flight time of arrival at the meter fix and assigning the aircraft to a runway). However, the choice of how to accomplish a change in the meter fix crossing time is left to the controller.

Inputs to the TMA system include real-time radar track data, flight plan data, and a three-dimensional grid of wind speeds and directions. Winds information is clearly important if accurate runway sequences are to be generated. An error of about 5 m/s in the differential mean wind experienced by two aircraft over 20 minutes of flight time would cause a spacing error of 6 km. To put this error in perspective, narrow body jet aircraft typically land about 3 nmi (6 km) apart.

Currently, CTAS uses the Rapid Update Cycle (RUC) winds. Analyses of the accuracy of the winds estimates have been carried out in both en route and terminal airspace. Studies to determine the improvement in trajectory modeling resulting from the use of real-time aircraft reports of winds to augment RUC focused principally on en route airspace (Cole, et. al., 1999; Cole. et. al., 2000). These studies showed that adding near-real time aircraft reports to the model would significantly reduce the wind errors. However, there was no

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[4] The information in this paragraph (including Figure 3) and the next three paragraphs was derived from the CTAS description available at http://www.ctas.arc.nasa.gov/project_description/tma.html#overview

[5] The term “delay” here is the difference between the plane’s estimated time of arrival (ETA) at the meter fix and the TMA scheduled time of arrival (STA) at the meter fix.

explicit assessment of errors in time-to-fly to the meter fixes. Studies of the potential benefits for CTAS to ingest and use the ITWS terminal winds (Cole and Wilson, 1994; Cole and Kim, 1999) did consider time-to-fly errors on 7 days at Dallas/Ft. Worth where there was a large shear in the vertical. It was shown that the time-to-fly errors in a sheared environment from the use of RUC alone could have mean differences of as great as 80 seconds. There was no assessment of the impact of the time-to-flight errors on delay benefits metrics such as peak operations rate or airport acceptance rate.

B. *Operational Benefits of CTAS TMA in Adverse Weather Conditions.*

CTAS TMA was developed through "rapid prototype" testing at the Denver and Ft. Worth ARTCCs (ZDV and ZFW), with Ft. Worth continuing as a test site. The operational benefits of TMA at ZFW are discussed by (Swenson, et. al., 1999). Subsequent operational benefits assessments were carried out by the Free Flight Program. Typical results are summarized (Knorr and Post, 2003 and Free Flight Program, 2003) for a number of locations, including ZFW[6], as follows:

> An 5% increase in the airport acceptance rate (AAR) (weather conditions not stated) at Dallas (ZFW/DFW)
>
> A five aircraft per hour increase in the peak operations rate (weather conditions not stated) at Minneapolis (ZMP/MSP)
>
> A two aircraft per hour increase in the peak arrival rate at Atlanta (ZTL/ATL) with a 2 aircraft per hour increase in the AAR (weather conditions not stated).

It was also noted that TMA reduced airborne holding times, flight times, and departure delays for aircraft departing from within the ARTCC to the TMA equipped airport.

It appears from the published CTAS operational benefits assessments that TMA has focused initially on major airline hubs where the demand typically approaches or exceeds the capacity of the metering fixes on one or more of the arrival "banks" per day. They did not explicitly attempt to improve the effective capacity during adverse weather, which for CTAS TMA would be during periods where the winds aloft change rapidly (especially in the vertical plane) as a function of 3D location.

The emphasis on normal, fair weather performance is not surprising and probably reflects a difference in viewpoint between the ATM and weather communities. The ATM community views CTAS as an automation system for which weather (specifically winds) is an annoyance that must be considered. Since weather situations that significantly disrupt CTAS performance may occur only a few times per year, dealing with them fully has not been a priority in the effort to develop the currently-deployed tool. By contrast, the aviation weather community is very interested in adverse weather situations whenever they occur, since even if the events are infrequent, significant reductions in delays and/or improvements in safety can be obtained through improved aviation weather products.

The AAR increases shown in the Free Flight summary tables represent the average result over many months. Given that the number of days with significant vertical gradient in the horizontal the winds is on the order of 1-2 per month (see the ITWS discussion below), it is doubtful that one could differentiate the performance of TMA in these steep wind gradient situations from the "baseline[7]", due to the fact that TMA performance is calculated as an average over many months.

One can get some insights into the potential impacts of fully addressing wind variations in CTAS compared to the CTAS TMA "baseline" by examining what might be possible with a non-integrated aircraft merging and sequencing system in a situation where the winds vary rapidly with altitude. Specifically, the benefits of manual TMC use of gridded winds information during adverse terminal wind conditions to optimize the merging and sequencing of aircraft has been assessed to a degree in the New York Integrated Terminal Weather System (ITWS) operational benefits analysis.

Rapid changes in the horizontal wind field as a function of altitude can be a significant problem for arrival operations at New York, which results in significant delays. (Allan, et. al., 2001) discuss an example of a deepening upper level low that generated a shear of nearly 30 knots per 1000 feet

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[6] More recent operational benefits of TMA are available at the FAA Operational Planning Office Web site (www.faa.gov/programs/oep/v7/Library/)

[7] The "baseline" for CTAS TMA would probably be manual adjustments of the arrival stream in en route airspace using 3D winds information from plane reports and the Center Weather Service Unit (CWSU) meteorologists.

(about 10 m/s/km) at New York. This sheared environment necessitated a reduction in airport acceptance rate (AAR) from 36 to 32 at Newark International Airport (EWR) due to difficulties in merging and sequencing aircraft. Since an AAR of 36 is already much less than the demand, a reduction of another 4 aircraft can result in a large increase in delays.[8] The manual use of the ITWS gridded terminal winds products by the New York TRACON enabled the NY airports to raise the AAR by 3 aircraft per hour on the 13 days per year at New York with strong vertical wind gradients (Allan, et. al., 2001). The delay reduction associated with this higher AAR was estimated to be about 6,300 hours per year with a monetary value of approximately $ 40 M per year. The high value of the delay reduction associated with this use of terminal winds arose because there had already been a capacity loss and delays due to low ceilings and visibility alone. The fact that the delays were further increased by the loss of additional capacity due to the terminal winds is common and therefore numbers such as those provided above can be considered representative.

At Atlanta (Allan and Evans, 2005), the TRACON users of the ITWS indicated that they achieved an AAR increase of approximately 2 aircraft per hour in cases where there is a strong steep vertical gradient of horizontal winds (e.g., a low-level jet with winds out of the southwest). Such steep vertical gradients of the horizontal wind field typically occur at Atlanta approximately 13 times per year. The delay reduction associated with this AAR increase was estimated to be approximately 520 hours per year. To put this in perspective, we note that the AAR increase associated with the manual use of high resolution terminal winds at Atlanta is comparable to that associated with overall CTAS TMA use for that TRACON.

TMA has provided impressive enhancements in the effective capacity at a number of airports. However, the reported benefits analysis to date does not appear to have explicitly examined the performance in meteorological conditions in which manual merging and sequencing of planes is particularly difficult.

The ITWS operational experience has shown that strongly sheared winds aloft are a significant contributor to delays when the airport arrival capacity has been reduced to less than the scheduled demand by other meteorological factors (such as low ceilings and visibility and/or wet or snow covered runways). In such cases, relatively small increases in the airport acceptance rate (AAR) can yield major reductions in the delays.

It would be interesting to assess the TMA operational performance in these stressful meteorological conditions to determine whether TMA was achieving the AAR increases that have been observed in more benign meteorological conditions. We would recommend conducting real time observations of facility observations during such meteorological events to better understand how the TMA products are used operationally in such situations.

Let us now consider the various elements identified in section 4 for a successful "user benefits driven" demonstration in the context of CTAS TMA.

The first set of issues dealt with the decision process for effective use of the wx/ATM system including the important users and their training. To date, it appears that TMA has not considered a need to explicitly address the possible impact of vertically sheared winds in selection of the users and training.

Within the ARTCC, it appears that CTAS can accomplish its merging and sequencing task and deliver a smooth flow of traffic over the meter fixes, without explicitly addressing the impact of a highly sheared environment in either training or choice of users. If the regions of high wind shear (not captured by use of RUC winds alone) is in the ARTCC airspace, CTAS would observe that the expected times at which aircraft reached various points did not match with what had been anticipated and it would therefore recompute estimated time of arrival at the meter fix based on recent information. The controllers can see the changing ETA and the difference between the ETA and the STA, until the TMA software stops updating the ETA and STA for a flight[9]. How well this "partial" closed loop control by TMA and the controllers works in a case of rapidly changing winds with altitude would depend on the altitude region in the ARTCC where the high gradient occurs.

However, if the highly sheared wind environment is in the TRACON and is not captured by RUC (e.g., due to coarse resolution and/or the data used by RUC), there could be sizable errors in the time of flight computed by TMA from the meter fixes to the runways. Since

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[8] When the AAR is less than the demand, the delays are a strongly nonlinear function of both the AAR and the demand ([see, e.g., (Allan and Evans, 2005)].

[9] This "freeze" typically occurs when a plane enters a sector so as to minimize the number of modifications to a planes flight profile by the controller.

the aircraft spacing at the meter fix is intended to produce an appropriate flow of arrivals at the runways, errors in the flight time in the TRACON could result in difficulties in achieving the desired runway arrival streams.

Another factor in testing would be to determine a location for a test where there is reason to believe that there would be significant benefits from explicit operation of CTAS TMA as an integrated wx/ATM system. Dallas would not be our first recommendation for such a test because DFW has excess IMC runway capacity in most circumstances (e.g., at least three independent arrival runways). Rather, it would be seem better to consider an airport such as PHL or BOS which has insufficient runway capacity during low ceiling and visibility conditions even with benign wind environments. At either BOS or PHL, there would be a high benefit from providing a higher effective landing rate in situations where the capacity loss due to low ceiling/visibility conditions is being further reduced by the vertical gradient in the horizontal wind field.

One would like to compare the achieved runway landing rates, before and after TMA introduction, during coastal storms with high gradients in the horizontal winds. The biggest challenge in carrying out such comparison would be determining when in the "pre TMA" time period there was a coastal storm with a steep vertical gradient in the horizontal winds.

For PHL, one option for identifying such cases would be to obtain archives of the terminal winds product from the New York ITWS prototype, since that product covers the PHL terminal area and was in operation before the TMA informal use by the TMCs at PHL began in early 2004.[10] Hopefully, it would be possible to find similar cases where there are rapid changes in horizontal winds with altitude during the coastal storms in the PHL/New York region before and after TMA was operationally, albeit, to the best of our knowledge, no detailed studies of the repeatability of high shear events have been carried out. The New York ITWS terminal winds product does not cover BOS so it would be difficult to quantitatively determine when significant vertical shear was present before TMA was available to the Boston ARTCC TMCs.

The TMA timeline information is not being provided to the controllers managing the traffic into PHL nor BOS at this time, so it would be possible to assess the "baseline" performance before full TMA capability was deployed to these users.

6. ROUTE AVAILABILITY PLANNING TOOL (RAPT)

A. RAPT System Description

When severe convective weather causes a loss of airspace (especially ARTCC) capacity near major terminals, ATC typically gives priority to arrivals. As a result, the departure rates drop to well below the arrival rate, which in turn results in long departure delays and, at times, "gridlock" on the airport surface. [For example, in the summer of 2005, it was not unusual to have 90 to 180 minute departure delays during Severe Weather Avoidance Procedures (SWAP)]. There is an urgent need for a departure decision support aid that can take advantage of short lived opportunities to get departures out of airports, as well, including the optimization of the use of "pathfinder" aircraft that probe a route after the use of that route has been halted due to pilot reports of severe turbulence and/or pilot refusals to use the route.

RAPT uses the Corridor Integrated Weather System forecasts of reflectivity and echo tops (Wolfson, et. al., 2004; Dupree, et. al., this conference) with model trajectories[11] for aircraft departing from the New York airports to help FAA traffic managers and airlines answer the questions:

(a) Will a candidate future departure encounter hazardous weather at some point along its intended path?

(b) 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?

Historically ATC personnel have had to answer these questions by extrapolating the forecast of 3D storm locations and calculating the

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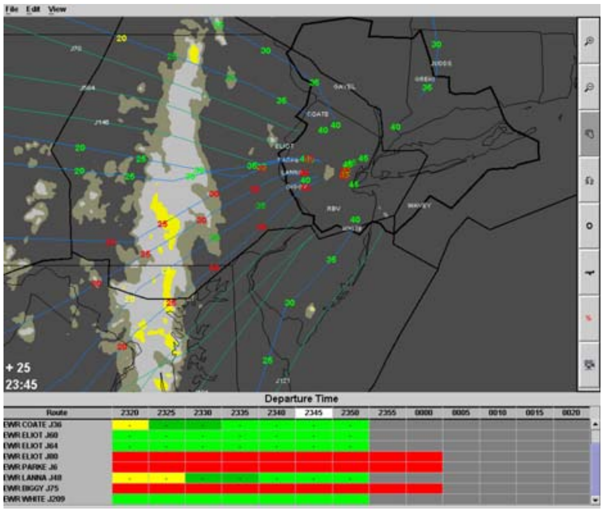
[10] The TMCs could see the TMA computed ETAs and STAs in real time for much of 2004, but were not officially allowed to use the information operationally. There was a several day period in Nov. 2004 during which the TMCs were allowed to use TMA at PHL operationally (http://www.ctas.arc.nasa.gov/media/20041215_release.html).

[11] That is, 3D locations of aircraft as a function of time after takeoff along the various major jet departure routes from the New York airports.

future aircraft 3D locations mentally for each planned departure time. RAPT automates these calculations, and provides convective weather impact predictions as a function of departure time (see Figure 4) to the supervisors and air traffic flow managers for all the important routes in the airspace.



Route	2320	2325	2330	2335	2340	2345	2350	2355	0000	0005	0010	0015	0020
EWR COATE J36	🟨	▩	▩	🟩	🟩	🟩	🟩						
EWR ELIOT J60	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
EWR ELIOT J64	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
EWR ELIOT J80	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥				
EWR PARKE J6	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥				
EWR LANNA J48	🟨	🟨	▩	▩	🟩	🟩	🟩						
EWR BIGGY J75	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥				
EWR WHITE J209	🟩	🟩	🟩	🟩	🟩	🟩	🟩						

Figure 4. Route Availability Planning Tool (RAPT) display as of summer 2005. Forecast movie loop display (upper half) shows an animated precipitation (VIL) intensity weather forecast with projected departure locations (colored numbers) superimposed. The departure route status timeline is shown in the lower half. Colored numbers in the animation correspond to future departure times and status information shown in the timeline. RED indicates a blocked departure, YELLOW impacted, DARK GREEN partially clear and BRIGHT GREEN clear. Dashes in the timeline indicated where departure status warning level has been reduced due to low echo tops.

B. *Operational Benefits of RAPT in Adverse Weather Conditions.*

The expectation was that RAPT would enable towers, TRACONs, ARTCCs and airlines to collaborate much more efficiently in achieving higher departure rates during Severe Weather Avoidance Procedures (SWAP). Since each RAPT user has identical guidance regarding route status for departures, confusion among facilities regarding availability of routes for departing aircraft should be significantly reduced. Additionally, safety would be enhanced by minimizing and optimizing the use of "pathfinders" to determine when the weather will no longer be adversely impacting a route.

Case studies of the departure rates during SWAP events at New York (table 1 below) and Chicago have shown that the achieved departure rate during SWAP is typically lower than the demand by a factor of two (which causes very large queue delays) and, that fairly modest increases in departure rate (e.g., an extra plane every 20 minutes) would provide operationally useful delay savings.

Hours of delay saved					
Throughput Increase	**EWR**	**LGA**	**JFK**	**TEB**	**N90**
+1 dep	50	50	50	30	**180**
+2 dep	95	90	90	60	**335**
+3 dep	135	130	130	90	**485**

Table 1. Departure delay savings, estimated using a queuing model, for the convective weather event on 29 June 2000 at New York. Thunderstorms in the New York area resulted in Severe Weather Avoidance Plans (SWAP) in effect for almost 8 hours. The column labeled "N90" is the total delay savings for New York TRACON, which controls departures from all four airports. Departure capacity increases were assumed constant at 1, 2, and 3 aircraft per hour respectively over an 8 hour period.

We see that by increasing the effective departure rates by as few as 3 aircraft per hour on this event at New York, one can achieve a significant reduction in departure delays. Figure 5 shows a similar calculation for a convective weather event at Chicago on 13 August 2002. Here again, increasing the departure rates by as few as 3 aircraft per hour would have significantly reduced the delays.

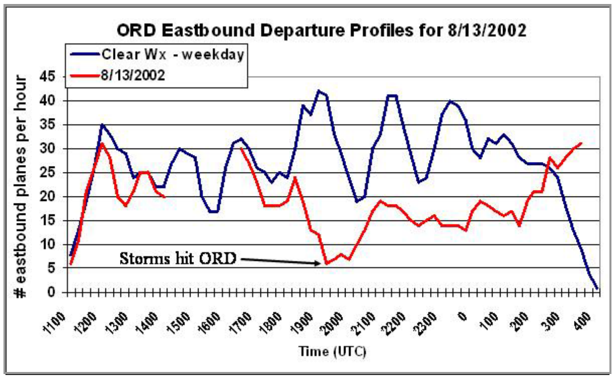


Figure 5. Comparison of fair weather departure rates (to the east from Chicago O'Hare airport) with the departure rates when storms moved over the airport. There were 267 hours of delay for ORD departures to the east after 1700 Z. Increasing the eastbound departure rate by 3 aircraft per hour would have reduced the delays by 25%.

Figure 5 also highlights the difficulty in ascertaining the use of a system such as RAPT by comparing the departure rates during convective weather events before and after RAPT was deployed. We see that variations in departure rates of 5-10 aircraft during a convective event are not unusual[12].

Several efforts have been made to gather quantitative RAPT benefits data. We will discuss them together to illustrate the challenges that arise. One common conclusion was that there is a need to improve:

(a) the aviation system model implicitly used in RAPT and/or,

(b) the match between the RAPT features and the user decision support environment.

RAPT was first used operationally in 2002. Displays were provided to the NY airport towers, the NY TRACON (N90), three en route centers (ZNY, ZDC and ZBW), the FAA Command Center (ATCSCC), Continental Airlines systems operation center in Houston and the Continental Airlines ramp tower at Newark. Post event interviews with the NY TRACON, and comparisons of the RAPT guidance with actual departure observations in 2002 (DeLaura and Allan, 2003), determined that there were significant problems with the RAPT model for departure operations during convective weather:

(a) The flight tracks from the departure runway to the departure fixes during convective weather in the TRACON deviated significantly from the fair weather routes. RAPT would correctly determine that the normal route was blocked, but erroneously conclude that departures were blocked. This problem was addressed initially by assuming a wider width for routes from the runway to the departure fixes.

(b) In the ARTCC portion of the flight, the aircraft were flying over storms that appeared to block the routes, if one based the assessment of blockage only the storm reflectivity. In order to address this issue, the aircraft departure model was augmented to include the aircraft altitude and an echo tops forecast, which was later incorporated into the Corridor Integrated Weather System (CIWS) [Dupree, et. al., this conference], was developed.

(c) In some cases ATC might combine a route that appeared to be blocked with one or two adjacent departure routes to create a single “virtual” departure route that had a much greater effective horizontal width. This greater effective route width would provide space for aircraft to deviate around storms without encountering other aircraft.[13]

In 2003, post event user interviews and/or observations at the NY ARTCC (ZNY) identified a number of occasions in which RAPT was useful:

June 12- ….”at 2046 RAPT showed J80 was still available….were able to push 12 more departures as a result”
June 14 – “ZNY … used RAPT twice to open J75 and J48 twenty minutes earlier”
June 21 – “Three westbound routes consolidated and changed as needed according to …depiction given by RAPT”
July 5 – “Thirty extra departures as a result of leaving J80 open”
July 21- “ …. All west bounds would have been closed… credit RAPT with helping keep the gates open….

The estimates of the delay reduction benefits that resulted from these particular cases are shown in Table 2. Other benefits were gathered in 2003, however users often could not provide enough information to allow modeling the benefit quantitatively.

RAPT saw increased usage in 2004, both by airlines and FAA traffic managers. We were able to determine, via remote monitoring of FAA user displays, how often RAPT was in use during convective weather events. At most facilities, they brought up the RAPT display during almost every convective weather event. Since the RAPT display is not a default capability, this deliberate selection of RAPT is considered significant.

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[12] Since there was a rapid increase in departures at the end of the weather event, we attribute the variation in departure rate seen in Figure 5 to changes in the convective weather rather than a lack of planes seeking to depart to the west.

[13] Combining routes in this way reduces the effective capacity of the routes, since now only a single string of departures is using airspace that previously supported multiple streams of departures.

Table 2: Delay reduction using queue models associated with 2003 RAPT benefits cases.

Date (2003)	Convective Weather Location(s)	User Identified Decision Made with RAPT	Hours of delay saved
June 12	West	Avert 1-hr route closure	52
June 14	North and west	Opened route early twice	106
June 21	North and west	Avert 1-hr route closure	159
July 5	West	Avert 2-hour route stoppage	119
July 21	North and west	Avert 2-hour route stoppage	240

RAPT was used almost daily at the Continental ramp tower in Newark to brief pilots who were taxiing on the runway and being held because their filed routes were blocked by thunderstorms. In addition, although the benefit is difficult to quantify, RAPT was frequently used to move and sequence aircraft on the taxiway. Towers at EWR and LGA also used RAPT extensively to sequence aircraft for take-off. For example, if RAPT indicated that a filed departure route might be closed down, the users could adjust the departure sequence to minimize disruption to the departure queue if the filed route were actually closed and the aircraft had to move out of the way.

Unfortunately, the collection of operational data at the NY ARTCC for purpose of quantifying the RAPT delay reduction benefits calculations was more difficult in 2004 than in 2003. In spring, 2004, NATCA informed the FAA management that they needed a formal agreement outlining procedures for RAPT training and usage. Efforts to draft an agreement continued through spring and summer 2004, but a resolution was not reached before the end of the convective season.

An exploratory analysis of RAPT benefits using the CIWS approach (i.e., multiple observers at ATC facilities during convective weather events) was conducted at New York in the summer of 2005. These results showed that there were yet more RAPT ATC model features that needed to be refined:

(a) The creativity of the NY TRACON[14] in devising “unconventional” routes from the departure runways to the departure fixes is such that simply increasing the effective width of the departure route in the RAPT software is not adequate. A different model, that considered the nature of the convective weather (e.g., squall line vs. disorganized convection) in assessing the likelihood that an aircraft could successfully fly from the airport to the departure fix, is most likely needed.

(b) RAPT guidance didn’t go far enough into en route airspace. Specifically, RAPT-provided guidance covers only about 20-30 minutes of flight time in en route airspace[15]. This placed too much burden on the ARTCC TMCs personnel to extrapolate the forecast of 3D storm locations manually and calculate the future aircraft 3D locations for each planned departure time for long look-ahead times. As a result, all too often, the ARTCC did not have time to carry out the manual extrapolation and, as a consequence, would not agree to accept a departure. The current plan is to begin to use longer forecast lead times, modifying the RAPT route blockage algorithm to better handle the uncertainty in the forecast storm locations at longer time horizon. It may also be necessary to accept that RAPT guidance will be useful for a smaller fraction of the overall population of SWAP convective events.

The experience at attempting to quantify the RAPT operational benefits has illustrated both the challenges in developing and deploying an integrated convective weather/ATM system and in obtaining quantitative operational data.

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[14] An important factor in this creativity was that the flight times within the TRACON were fairly short. Hence, the ATC workload in assessing future weather positions is fairly minimal when determining a feasible TRACON route to use for a plane that is about to take off.

[15] For a system such as RAPT, the sum of the departure time line on the surface and the flight time aloft must be less than or equal to the maximum lead time of the convective weather forecast that is being used. RAPT had focused on use of forecast lead times of no greater than 1 hour; hence, with a 30 minute departure time line, only allowed a 30 minute flight time through the TRACON and into en route airspace.

Apropos the questions posed in section 4:

(a) the overall decision process for accomplishing departures and the roles of the key users were not fully understood at the outset, and there is still some significant uncertainty. The TRACON and towers were clearly very interested in higher departure rates and have been very willing to use the RAPT guidance. However, after several years of studies at New York and the 2005 CIWS productivity study (Robinson and Evans, this conference), we have come to understand that the ARTCC decision making process is critical to the overall success of a system such as RAPT. The role of the area managers at the ARTCC in departure management appears from the CIWS productivity study to be very important. Moreover, the role of the airlines (especially major hub operators) in convincing the ARTCC that a departure can be safely handled may also be very important. The airlines clearly are very interested in expediting departures and appear in some cases to be able to get agreement for departures in situations where the towers and/or TRACON have been unsuccessful.

(b) the "baseline" system for RAPT was the use of ITWS forecasts to identify opportunities. Although the use of ITWS alone to expedite departures during SWAP in studies of ITWS benefits (Allan, et. al., 2001) was well understood; in retrospect, the RAPT development would have benefited from observations of decision making at all of the key facilities earlier on in the development process. For example, RAPT training at the ARTCC should have been emphasized more at the outset.

Measuring the change in system performance for RAPT could be achieved by post event analysis of flight tracks and weather, as well as via real time observations such as were begun in 2005. We recommend a combination of approaches, since it is clear that some elements of the overall RAPT design still warrant refinement (e.g., the route blockage model and tailoring the display to better address the ARTCC concerns regarding risks associated with agreeing to handle more departures). On the other hand, the analysis of post event flight tracks and weather can be accomplished by independent organizations, thus providing a higher credibility for the end benefits results.

7. SUMMARY

Integrated wx/ATM systems provide some interesting challenges in development and benefits assessment because there is a mixture of aviation weather product development and explicit modeling of some aspects of the aviation system itself. In a "conventional" ATM aviation weather decision making process, the developer generally worries only about the weather products and not the fidelity of the human user's model of the aviation system. With integrated systems, there must be more attention to both the weather products (e.g., forecast) quality <u>and</u> the aviation system model.

In our opinion, this important difference between integrated and non-integrated wx/ATM systems suggests a somewhat different approach to benefits quantification. At the outset, we have discussed the identification of the operational users that are most likely to generate the benefits and the tailoring <u>both</u> the forecasts and training to facilitate improved end user decision making. The experience with CIWS, ITWS and RAPT showed the importance of identifying as many of the key decision makers as possible (Evans, this conference). On the other hand, with an integrated wx/ATM system, it will be very important to involve operational users who have an interest in NAS system design, since it will be important for them to articulate what is needed to improve the aviation system model features. Thus, one wants both users with a significant operational need as well as interest in system design, at least for the initial product development.

Determining meteorological and/or operational situations that should generate significant benefits is also very important. For example, we suggested that the CTAS TMA testing consider some explicit testing to better determine the benefits in a highly sheared wind environment.

As in the case of "conventional" aviation weather decision support systems, the training needs to advise the end users on how to properly apply the output of the wx/ATM system to the operational decisions that they make on a daily basis, as well as providing information on:

- the basis of the combined system (that is, both the approach by which the weather products are generated and the aviation system model that is an implicit part of the wx/ATM system), as well as

- the use of the display.

Given the complexities of the basis for the integrated wx/ATM system, this training should include face-to-face training by a subject matter expert (SME) on the operational use of the integrated system so that the user can ask questions.

One element of the "baseline" analysis that we have not discussed here is determining how much of the existing weather delay is "avoidable" and to what extent the "avoidable" delay is being reduced by other systems. The issues here are identical to those for convectional aviation weather decision support systems such as discussed in (Evans, et. al., 2005). (Allan and Evans, 2005) provide estimates of the summer season weather delay in 2005. Determining how much of that delay is "avoidable" requires a NAS model that considers the capacities of terminals, en route sectors, and the optimal allocation of flights to the available capacity. Research is underway to develop such a model; its overall structure is discussed in (Weber, et. al., 2005).

Another important topic is how to normalize the performance metrics (e.g., delays) to deal with issues such as:

- finding comparable convective weather events (e.g., spatial patterns and time history of significant convective weather)
- compensating for changes in the NAS (e.g., demand, traffic mix, operational procedures, airline scheduling and automation capabilities), and
- determining the influence of other weather decision support systems [e.g., Collaborative Convective Forecast Product (CCFP) and the decision system that makes use of the CCFP].

Some of the practical problems in accomplishing this for convective weather decision support systems are discussed in (Allan and Evans, 2005) and (Evans, et. al., 2005).

Even if it is believed that the operational benefits of the wx/ATM system can be estimated by objective metrics, such as those used to assess TMA performance in the Free Flight studies, we would strongly recommend that when a system is introduced that there also be real time user facilities observations of the type used for CIWS. Although user inputs on their operational needs presumably were obtained in the initial system design, our experience has been that it is difficult a priori to anticipate all of the adverse aviation weather situations that would be of concern for an integrated system.

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