

P1.5 IMPROVING CONVECTIVE WEATHER OPERATIONS IN HIGHLY CONGESTED AIRSPACE WITH THE CORRIDOR INTEGRATED WEATHER SYSTEM (CIWS)*

J.E. Evans, K. Carusone, M.M. Wolfson, M. Robinson, E.R. Ducot, B. Crowe
MIT Lincoln Laboratory, Lexington, Massachusetts

1. INTRODUCTION

Reducing thunderstorm-related air traffic delays in congested airspace has become a major objective of the FAA, especially given the recent growth in convective delays. In 2000 and 2001, the key new initiative for reducing these convective weather delays was "strategic" traffic flow management (TFM). Users were given 2-, 4-, and 6-hour collaborative convective weather forecasts, and collaborative traffic routing plans were established via telecons attended by Air Traffic Control (ATC) and airline traffic managers. This "strategic" approach led to difficulties during a large fraction of the weather events because it was not possible to generate forecasts of convective weather at time horizons between 2 and 6 hours that were accurate enough to assess impacts on routes and capacity, and thereby accomplish effective TFM. During convective weather events, traffic managers tend to focus on tactical TFM [Huberdeau, 2004], yet they had relatively inaccurate current weather information and tactical forecasts.

The Corridor Integrated Weather System (CIWS) demonstration began in 2001. The objectives of the demonstration are to provide improved tactical air traffic management (ATM) decision support, via improved real time 3D products and accurate short-term convective weather forecasts, and to determine if this support is an operationally useful complement to "strategic" TFM. The current focus of the CIWS initiative is the highly congested airspace containing the Great Lakes and Northeast corridors, since that region offers the greatest potential for delay reduction benefits.

In this paper, we describe the current status of CIWS, including initial operational results of Air

Traffic Control (ATC) and airline use of the CIWS weather products. We begin with some CIWS background, describing the motivation for the program, the role of CIWS products in the overall convective weather planning process, and the functional domains in which CIWS products can provide operationally significant benefits. We then review the current CIWS capabilities, spatial coverage, sensors used, products, operational users, and integration with ATM systems. Next the detailed CIWS operational benefits study carried out in 2003 is summarized. Finally, we discuss the FAA plans for CIWS and near term enhancements to the system.

2. BACKGROUND

In 2004, as in past years, delays during the convective weather season continue to significantly exceed the delays in other seasons of the year (Figure 1). The current key FAA planning documents, along with the FAA 2004 operational initiatives, address convective weather delay in varying degrees.

The Operational Evolution Plan (OEP) identifies en route severe weather and airport weather conditions as two key problems that must be addressed if the U.S. air transportation system is to alleviate the growing gap between the demand for air transportation and the capacity to meet that demand. Most of the air traffic delay that is so costly to the airlines and the flying public is incurred during severe weather in the congested Great Lakes and Northeast Corridor region.

CIWS supports the FAA Flight Plan (FAA, 2003) principal safety objective of "reducing cabin injuries due to turbulence", as well as directly supporting all four of the enhanced capacity objectives:

- Increase airport capacity to provide a system that meets or exceeds air traffic demand.
- Improve efficient air traffic flow over land and sea.

*This work was sponsored by the Federal Aviation Administration under Air Force Contract F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Government.

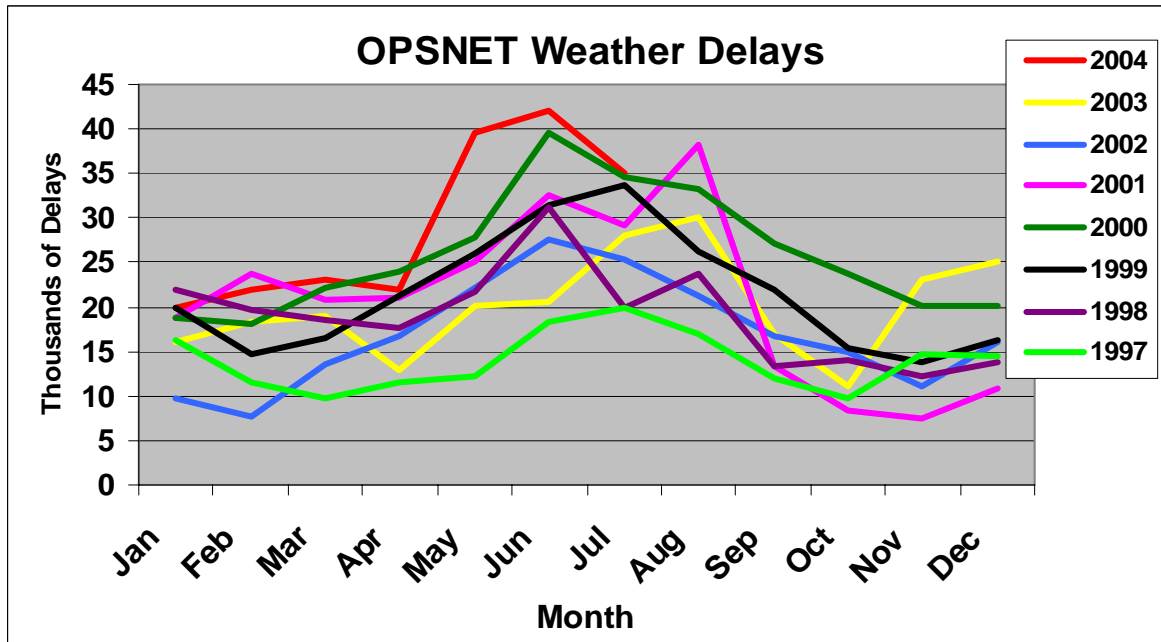


Figure 1. OPSNET delays by month.

- Increase or improve airspace capacity in the eight¹ major metropolitan areas and corridors that most affect total system delay: New York, Philadelphia, Boston, Chicago, Washington/Baltimore, Atlanta, Los Angeles Basin and San Francisco.
- Increase on-time performance of scheduled carriers.

An important operational initiative for the summer of 2004 is “growth without gridlock” to cope with the loss of en route capacity due to convective weather. This initiative is described (McCartney, 2004) as follows: “if the waiting time for takeoff hits 90 minutes at a U.S. airport, the FAA slows down departures from other airports so that the clogged airports can launch more jets. In addition, 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.”

Most en route weather decision support systems show only past or current storm locations. Moreover existing operational forecast products within en route airspace are limited. Two national-scale forecast products are provided by the Aviation Weather Center: the automated National Convective Weather Forecast (NCWF) 1-hour

forecast and the Collaborative Convective Forecast Product (CCFP) 2-, 4-, and 6-hour forecasts that are updated every two hours. While these products are helpful, the highly congested airspace requires accurate, timely, high-resolution weather information and forecasts to safely improve the tactical flow of air traffic during thunderstorms.

The approach defined for CIWS provides en route and terminal traffic flow managers with accurate, automated, rapid update-rate information on storm locations and echo tops, along with 2-hour animated growth and decay forecasts of storms. To do so, CIWS takes advantage of the high density of existing FAA, NWS and Environment Canada weather sensors and the FAA-funded research conducted on thunderstorm forecasting (Wolfson et. al., 2004). We hypothesize that the availability of these high quality weather products will allow managers to achieve more efficient tactical use of the airspace and therefore significantly reduce delay.

The CIWS “tactical” TFM products complement the longer-term “strategic” (2-6 hour) national CCFP forecasts also needed for flight planning and traffic flow management (Figure 2). Additionally, CIWS provides important enhancements to the precipitation products and forecast capability at all levels of air traffic management. Table 1 shows operational ATC

¹The CIWS demonstration system covered five of these eight designated metropolitan regions.

domains impacted by convective weather and improved by CIWS Products.
indicates how safety and efficiency can be

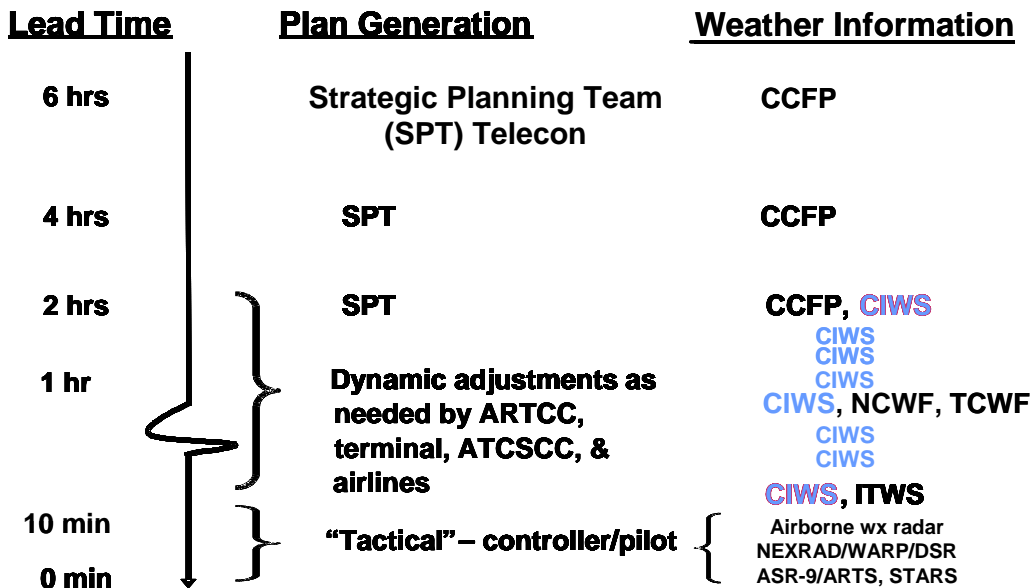


Figure 2. Use of various forecasts and weather information as a function of time for convective weather planning in congested airspace. The CIWS products are used to make dynamic adjustments to the strategic plans developed from longer term forecasts.

Table 1. Operational Air Traffic Domains and CIWS' Role in Decision Support.

Domain	Existing Systems *	CIWS Role	CIWS Demo 2002/2004
En route	WARP, ETMS, CCFP, NCWF, CWSU	Improve storm severity and echo tops information and provide 2-hour automated forecasts. Support ATM decision support systems such as ETMS and RAPT.	Yes
Major terminals	ITWS, TDWR, ASR-9	Improve long range weather surveillance and provide 2-hour forecasts. Support RAPT.	Yes
	WSP	Provide long range weather surveillance and 0-2 hour forecasts.	No
	None	Provide basic precipitation with 2-hour forecasts.	No

* Note: WARP is the Weather and Radar Processor. ETMS is the Enhanced Traffic Management System which is capable of displaying weather. CCFP is the Collaborative Convective Forecast Product. NCWF is the National Convective Weather Forecast. CWSU is the Center Weather Service Unit. ITWS is the Integrated Terminal Weather System. TDWR is the Terminal Doppler Weather Radar. RAPT is Route Availability Planning Tool. ASR-9 is the operational Airport Surveillance Radar. WSP is ASR-9 Weather Systems Processor.

3. CURRENT CIWS CAPABILITY

3.1 Coverage and Sensors

The radar sensors used for the CIWS demonstration system are shown in Figure 3. As of Summer 2004, CIWS ingests base data from 33 NEXRADs using a compression server developed under the Collaborative Radar Acquisition Field Test (CRAFT) project (Droegemeier, 2001), in

conjunction with the Local Data Manager (LDM) software package developed by Unidata. NEXRAD data are used to generate the VIL Mosaic product and to provide information on 3-D storm structure and boundary layer winds.

CIWS Sensor Coverage for 2004

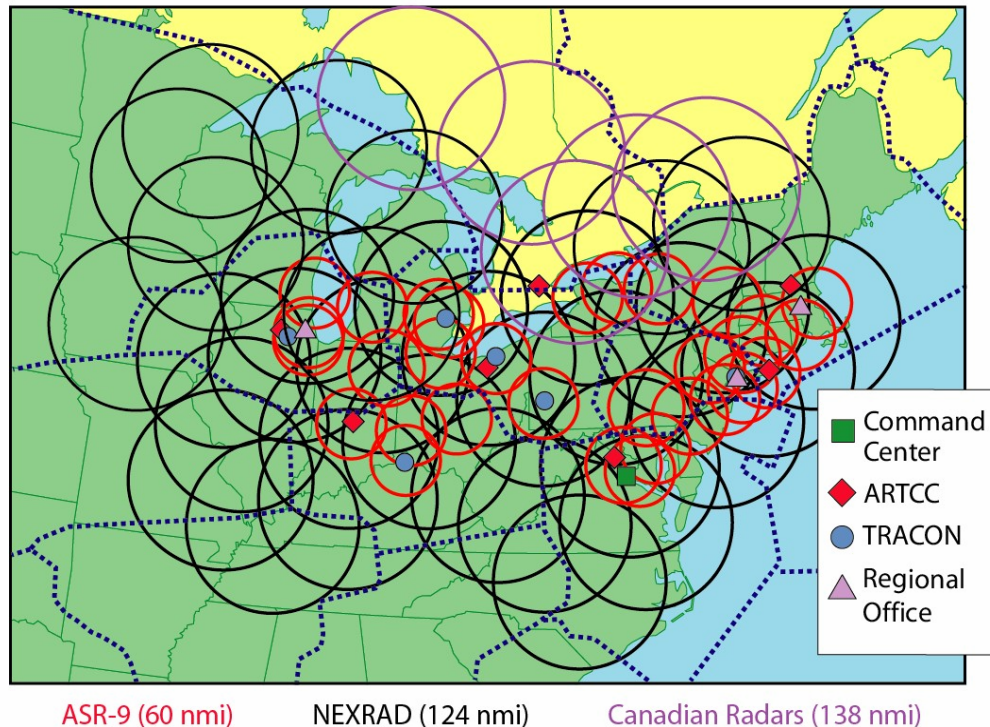


Figure 3. Terminal and en route weather sensors utilized to create the Corridor Integrated Weather System (CIWS) products in 2004.

In addition, CIWS uses base data from five Meteorological Service of Canada (MSC) weather radars. The MSC radars (Lapczak, 1999 and Paul, 2004) are C-band Doppler radars with typically a 1.1 degree beam width. The data from these radars are provided over the Internet to the CIWS processing system in Lexington, MA. The addition of the Canadian weather radars to the CIWS coverage is particularly operationally important because it provides coverage for the CAN playbook routes (Figure 4). These routes through Canada are used by U.S. air carrier aircraft when key east-west routes along the Great Lakes corridor are blocked by severe convective weather.

CIWS also takes advantage of the rapid update rate of the FAA ASR-9 radars. The ASR-9 is an S-band radar with a 5.0 by 1.4 degree fan beam that has a target channel to track aircraft, as well as an independent weather channel that provides six levels of reflectivity. The ASR-9 executes a weather volume scan every 12 seconds and the weather data are averaged to produce an update every 30 seconds. The rapid update rate of the ASR-9 radars is utilized to detect rapidly growing cells. There are 31 ASR-9 radars included in the ASR Mosaic product.

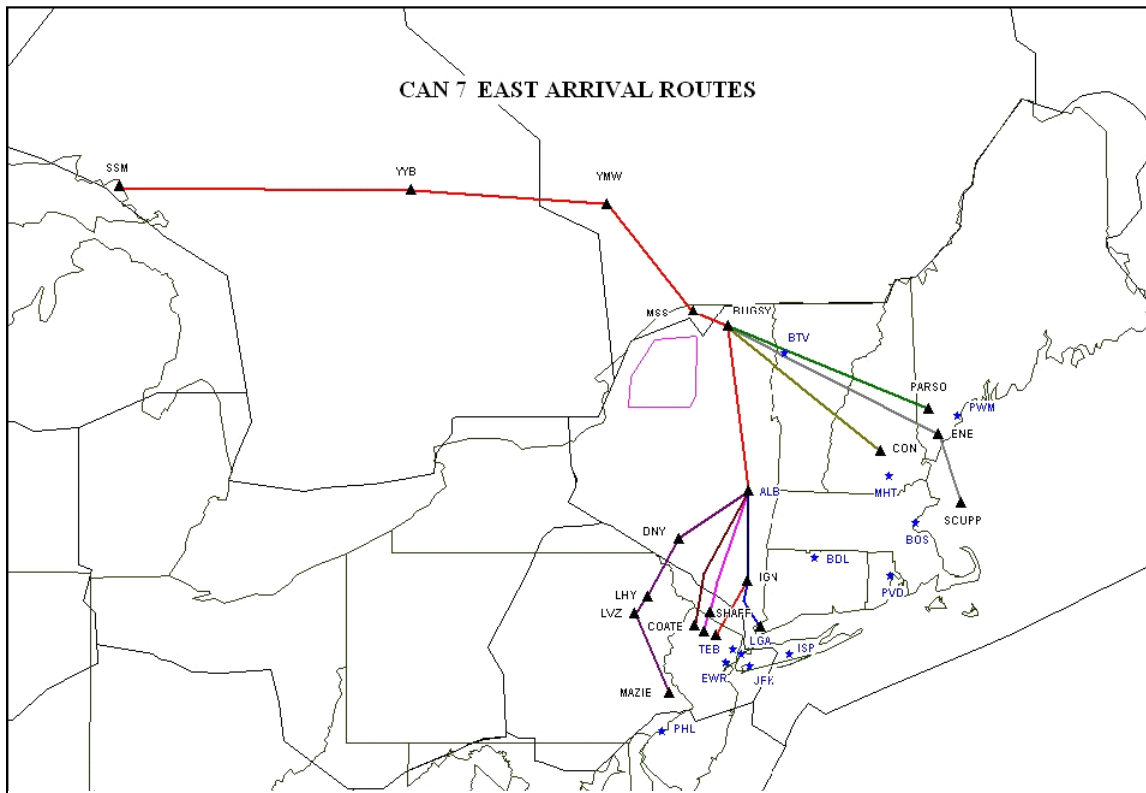


Figure 4. Example of a Canadian playbook route.

CIWS ingests Lightning data from the National Lightning Detection Network. This network detects cloud-to-ground strikes across the U.S. Visual and infrared satellite data from the Geostationary Operational Environmental Satellite (GOES)-East satellite are obtained via a downlink system located at Lincoln Laboratory.

3.2 Processing Architecture

Given the very large number of sensors, the wide area of operation, and the need for flexible and rapid system expansion, the communications infrastructure shown in Figure 5 is a very important feature of the CIWS demonstration system. In contrast to the Lincoln-operated Integrated Terminal Weather System (ITWS) demonstration systems in which dedicated point-to-point links were used, the CIWS demonstration system has successfully used a vendor-supplied frame relay network (Sprint). At each sensor or external user location, there is a local line to the frame relay packet switched network. A DS3 link connects the frame relay network to the real time product generation center at Lexington MA. The frame relay system has provided nearly 100% availability

of the communications infrastructure since the system began real time operations in May of 2001.

A network of Commercial Off-the-Shelf Unix and Linux workstations, located in Lexington, MA, provides the compute power for data ingest and product generation. To support the development of new algorithms, the system is designed to be modular and flexible. Algorithms can be assigned to individual workstations or sets of workstations to limit resource contention issues. Data are shared between algorithms by means of TCP/IP data streams and shared disks. Additional resources can be readily incorporated into the system by including new workstations in the network. Hardware failures can be easily and quickly resolved using hot spares. Web servers at Lincoln Laboratory provide Web browser-viewable products over the Internet and CDM-Net.

CIWS

2002-2003 Architecture

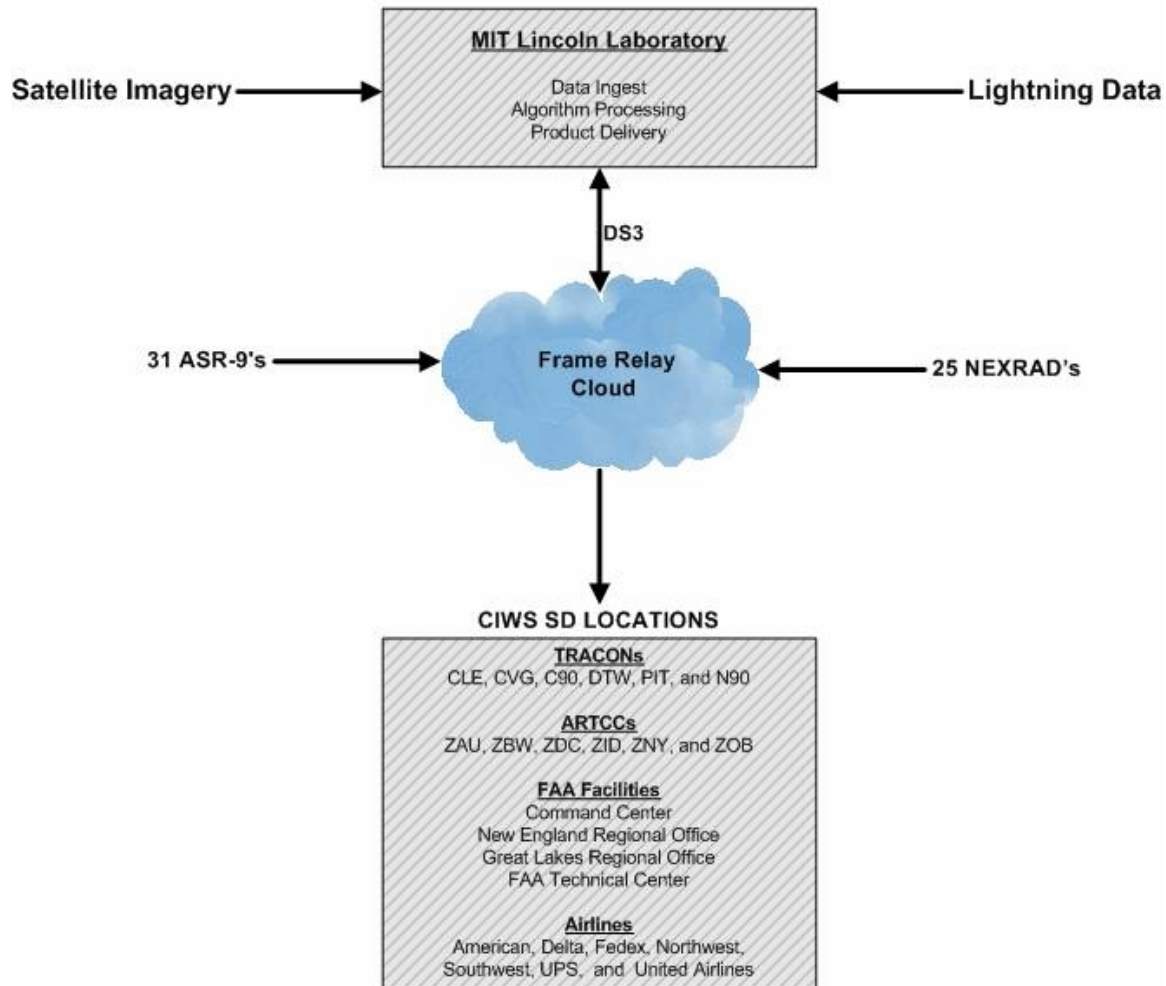


Figure 5. Communications architecture for CIWS 2002-03 demonstration system.

3.3 Product and Display Features

The CIWS weather products and dedicated situation display (SD) features are designed based on user feedback from the CIWS 2001-2003 demonstrations. Figure 6 shows the CIWS situation display as tested in 2004.

The CIWS Echo Tops product (Figure 6, upper left window) provides high-resolution (2 km) estimates of the height of storms that are much

more accurate than estimates available elsewhere. This product is used in conjunction with the radar-based precipitation data to permit aircraft to fly safely over storms that, based on storm reflectivity alone, would appear to block major jet routes. This significantly reduces aviation delays.

The CIWS VIL Mosaic product provides a high-resolution (2 km) estimate of vertically integrated liquid water (VIL) based on the

NEXRAD and MSC radar reflectivity data. The upper right window of Figure 6 shows the NEXRAD VIL mosaic product displayed with storm

motion vectors, satellite data, and two-hour forecast contours.

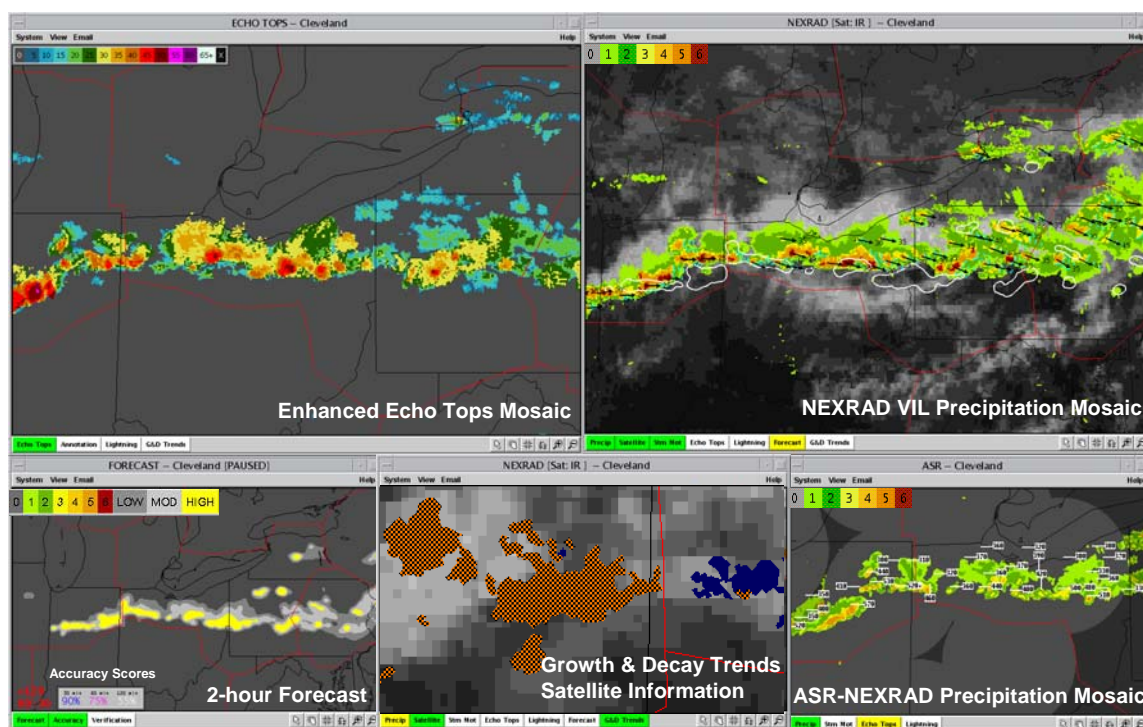


Figure 6. An example of the CIWS situation display.

The CIWS Regional Convective Weather Forecast (RCWF), now enhanced with Growth and Decay Trends (Wolfson et. al., 2004), provides two-hour animated forecasts in 15-minute intervals (lower left window). Key features of the forecast include the real time indication of forecast accuracy and an explicit depiction of areas of storm growth and decay.

The CIWS Growth and Decay Trends Product shows areas where storm growth or decay has been detected over the past 15 to 18 minutes. The product is not a forecast or estimate of future storm evolution, but rather a reliable diagnosis of recent storm behavior. Growth trend areas are depicted by an orange/black cross-hatched pattern while decay is shown as navy blue regions. This product is available as an overlay option for the VIL Mosaic and Echo Tops products (Figure 6, lower middle window).

The CIWS ASR Mosaic product is a representation of the location and intensity of weather from a mosaic many ASR-9 radars in the CIWS coverage area. These fan-beam

surveillance radars have a maximum range of 60 nmi, and thus do not completely cover the CIWS domain. For this reason, 1-km VIL Mosaic data are used to fill the mosaic image where ASR-9 coverage does not exist. The lower right window of Figure 6 shows the ASR Mosaic product with labels of echo top heights.

For both the VIL and ASR Mosaic products, the precipitation data from the various radars are advected to account for storm movement. This advection approach has been demonstrated to significantly improve the accuracy of the depiction of storm position (Proseus, 2003).

3.3 Operational Users

Full capability CIWS situation displays are provided to key Air Route Traffic Control Centers (ARTCCs) (Cleveland [ZOB], Washington, DC [ZDC], Chicago [ZAU], Boston [ZBW], New York [ZNY], Indianapolis [ZID], Minneapolis [ZMP], and Kansas City [ZKC]²), major terminals (New York

² ZMP and ZKC received dedicated SDs in July 2004.

City [N90], Chicago [C90], Detroit [DTW], Pittsburgh [PIT], Cleveland [CLE], and Cincinnati [CVG]), and the Air Traffic Control System Command Center (ATCSCC).

Within the ARTCCs, situation displays are generally located at the traffic management unit and the CWSU. At ZDC, situation displays are also in use at a number of area manager positions. Within the ATCSCC, CIWS displays were provided to the Severe Weather unit, the Weather Unit, and the Chicago/Minneapolis and Cleveland/New York/Boston sector manager positions. Additionally, real time dedicated displays were provided at the Great Lakes and New England regional offices.

Many of the major airlines³ have dedicated situation displays equivalent to the FAA displays. Nearly all major airline systems operations centers (SOCs) have access to the products via servers on the Internet.

4. INTEGRATION OF CIWS WITH AIR TRAFFIC MANAGEMENT (ATM) SYSTEMS

The reduction of convective weather-related delay in highly congested airspace, such as the CIWS domain in 2004, can only be achieved if the CIWS users can develop and execute appropriate weather impact mitigation plans in a timely manner. Figure 7 shows the key elements of this process. It is essential that the Operational Decision Loop be executed in a time period commensurate with a) the time scale over which the weather changes and b) the ability to accurately forecast the weather impact. If this cannot be achieved, then the plans that are executed will not be an appropriate solution for the weather situation.

The integration of CIWS with ATM systems (e.g., automation and TFM) is expected to be a major element of the CIWS development program in the coming years. An important first step in this process occurred in 2004 when the CIWS was interfaced to the RAPT demonstration system operating at New York (Allan et. al., 2004, DeLaura and Allan, 2003). This very important application addresses an urgent problem in the NAS (McCartney, 2004); increasing the departure rates from major airports when there is en route convective weather.

RAPT is the first of a new generation of decision support tools that combine state-of-the-art weather forecasts with operational flight data to help FAA traffic managers and airlines answer the questions:

- Will a candidate future departure encounter hazardous weather at some point along its intended path?
- Will there be opportunities to route the aircraft through significant gaps in evolving weather?

RAPT combines the CIWS forecasts and echo tops information with information on the departure route structure and typical flight times after takeoff. The objective is to provide an estimate of when planes may take off from an airport and not encounter significant convective weather along their departure trajectory. Previously, RAPT utilized the New York Integrated Terminal Weather System (ITWS) products. However, CIWS products are more appropriate for the RAPT application due to the greater spatial coverage of CIWS in en route airspace, the improved CIWS forecast capability, and the availability of CIWS echo tops information.

5. OPERATIONAL BENEFITS OF THE CIWS

The CIWS delay reduction benefits for 2003 were assessed by on-site observations and interviews during major convective weather events, end-of-season user interviews, and analysis of flight track data as discussed in Robinson et al. (2004) and Evans et al. (2004).

Estimates were made of the frequency of operational use of CIWS products at various facilities based on data obtained during 22 days of intensive facility operations. The delay reduction benefits associated with two operational scenarios were determined from case study analyses of detailed delay savings, using weather and flight track data together with delay reduction models (Figure 8). The case studies were carried out for randomly selected individual cases for each benefit category. These individual cases were identified from the observation “blitzes” and daily post-event phone interviews with users. Separate estimates were made for each ARTCC to account for differences in product usage, the nature of the weather, the ATC structure (e.g., routes, terminals, procedures), and demand. Details on this approach are discussed in Robinson et. al. (2004).

³ American, American Eagle, Continental, Delta, Federal Express, Jet Blue, Northwest, Southwest, United, UPS

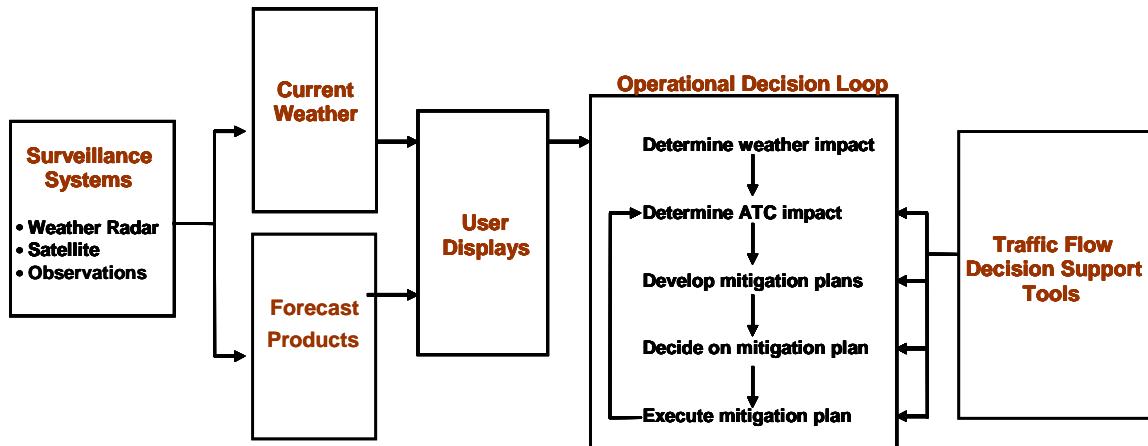


Figure 7. Overall convective weather impact mitigation process.

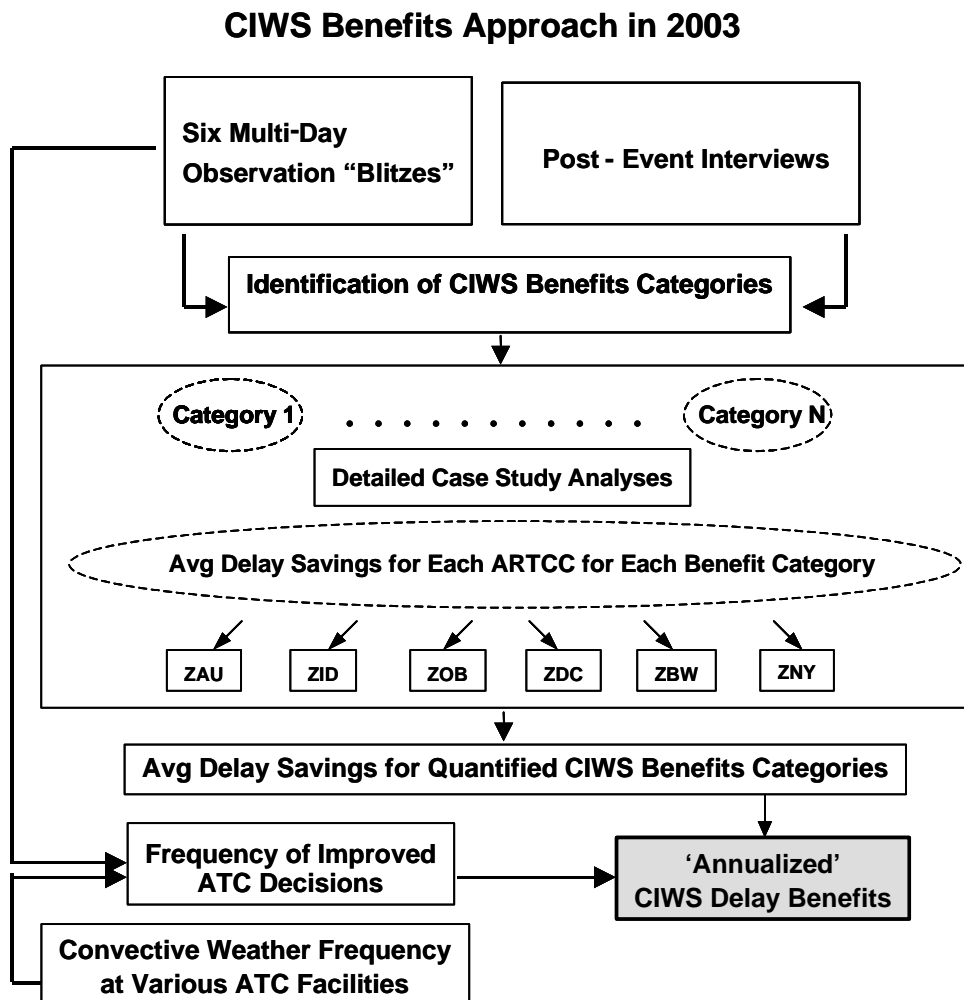


Figure 8. Approach used in 2003 to estimate the CIWS annual delay reduction benefits.

Sixteen unique benefits categories attributable to CIWS were identified (Figure 9). Estimated annual occurrences of each categorized benefit were quantified, along with annual delay savings for two primary benefits realized in en route airspace (Keeping Routes Open

Longer/Reopening Closed Routes Earlier and Proactive, Efficient Reroutes). The use of specific CIWS products during convective weather to assist in realizing these benefits was quantified as well (Figure 10).

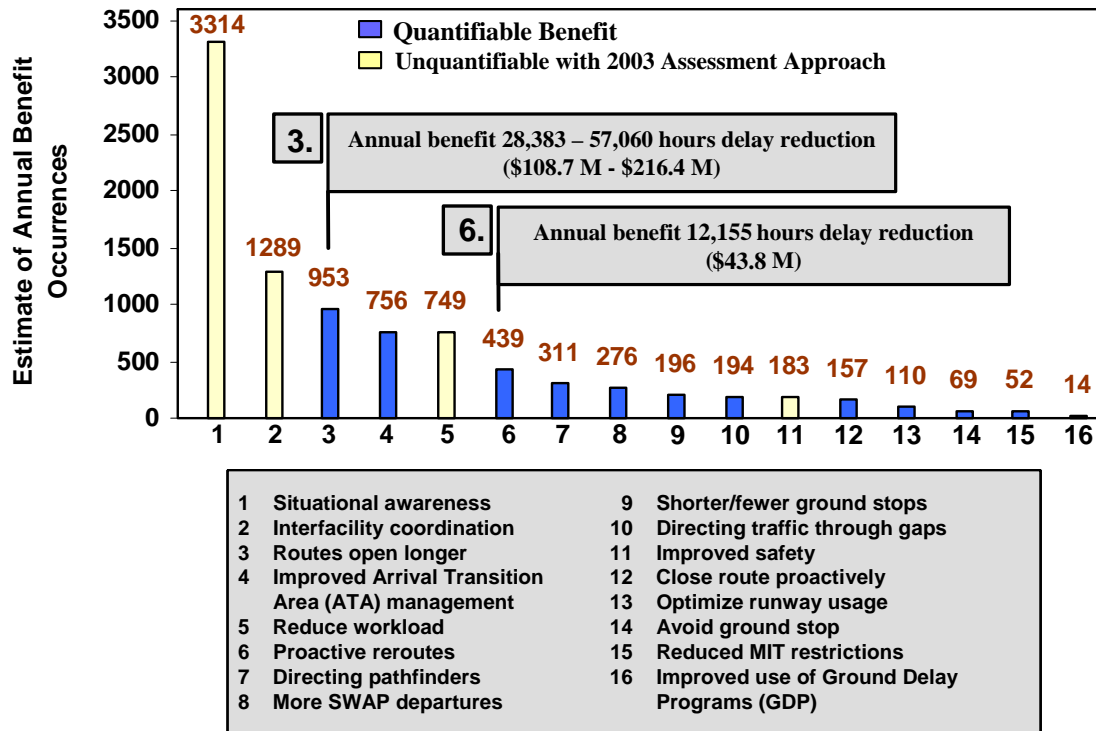


Figure 9. Estimated annual occurrences of identified CIWS benefits categories. Yellow bars denote unquantifiable benefits. Blue bars denote quantifiable benefits. Annual delay savings estimates associated with the two main categories examined in the initial benefits analyses (“Route kept open longer/reopened closed route earlier” and “Proactive, effective rerouting”) are shown.

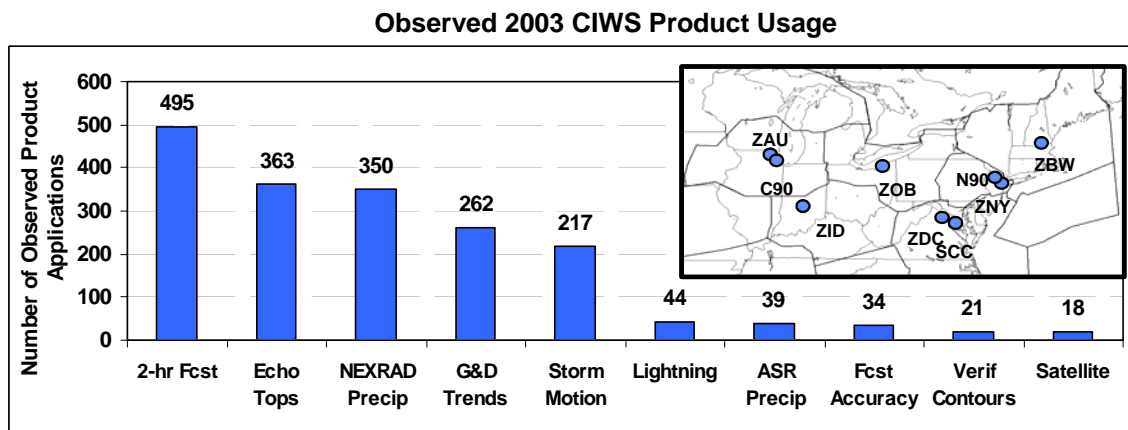


Figure 10. The number of observed applications of individual CIWS weather products at FAA facilities visited (inset) during 2003 convective weather events.

Inspection of convective weather-related delay statistics in 2022 and 2023 suggests that CIWS provided delay reductions (Figure 11). Several of the ARTCCs showing significant delay reduction benefits for keeping routes open longer/reopening closed routes earlier and proactive, efficient reroutes (e.g., ZOB and ZID) also showed significant reductions in the number of delay

events at the major airports (CVG, DTW, and PIT) within the ARTCC in 2023. These reductions in delay events were evident even though the number of convective storm events in the respective ARTCCs was constant or increased from 2022 to 2023.

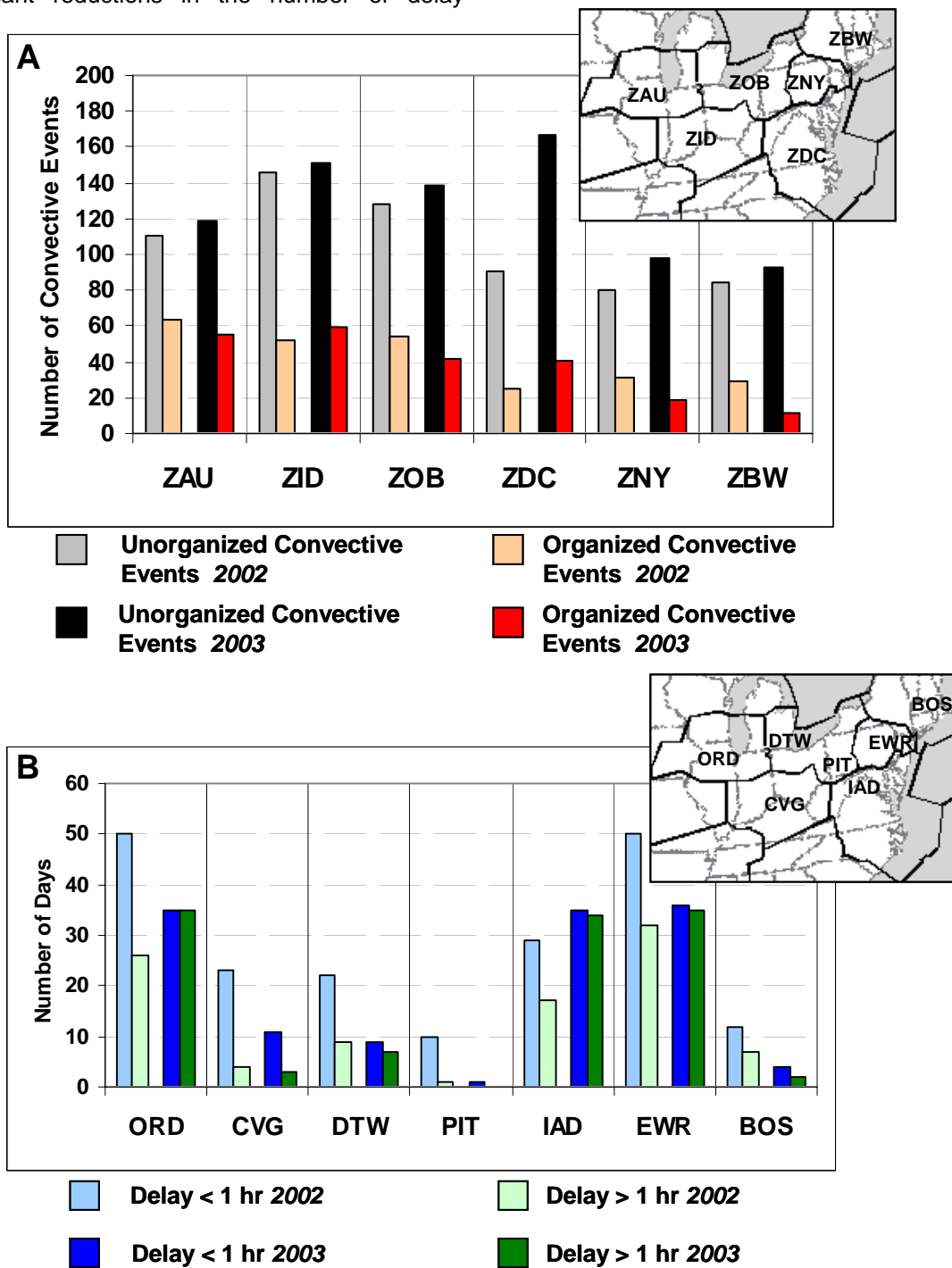


Figure 11. Comparison of 2022 and 2023 (A) convective weather events and (B) storm-related airport delays throughout the CIWS coverage area for May through August.

The overall number of delay events at Newark International Airport (EWR) dropped in 2003 even though the number of delay events with delays greater than one hour at EWR increased. Since other convective delay reduction systems (specifically RAPT) also began operation in 2003, it is unclear to what extent CIWS assisted in reducing the number of overall delay events at EWR.

Relative to 2002, there was significant decrease in delay events (over 66%) at Logan International Airport (BOS) in 2003. This can be attributed in part to ZBW's use of CIWS in 2003 and in part due to a 10% drop in overall storm activity.

The number of delay events at ORD with delays greater than one hour increased in 2003, while shorter delay events decreased. Within the ARTCC boundaries, the amount of convective activity was essentially the same during 2002 and 2003. However, the National Weather Service identified a 12% increase in thunderstorm days at ORD airport from 2002 to 2003. The increase in the number of delay events may reflect the increase in demand at ORD in 2003 and the particular nature of storm events in the two years, as well as a very significant change in the ORD operations procedures issues (e.g., rules governing the use of land and hold short operations [LAHSO] on wet runways).

6. PLANS FOR CIWS DEPLOYMENT

The FAA is currently conducting a study to determine whether the CIWS should become a fully operational element of the NAS. An important element of the study is estimating the benefits and costs of an operational CIWS. Key cost factors include determining a) whether CIWS should be a national system, b) how the products will be generated (and where), and c) how the products will be distributed to the users.

Figure 12 shows the initial concept for an operational capability. The products would be generated in a central location and then distributed to various user locations using FAA information dissemination systems. The architecture shown in Figure 12 is functionally similar to that of the CIWS demonstration system shown in Figure 4. The key difference is that the production system would use existing FAA system displays to provide the CIWS

products to users, as opposed to dedicated CIWS situation displays.⁴

Several approaches to data acquisition and product dissemination, which are being defined as part of an FAA concept exploration project to explore techniques for meeting the System Wide Information Management (SWIM) needs of the NAS, are being considered for CIWS. In 2005, it is anticipated that portions of the CIWS demonstration system will use data protocols and information models that illustrate SWIM concepts, while at the same time demonstrating the integration of RAPT with CIWS at New York and CIWS product use in small terminal facilities.

The benefits studies discussed above will be validated by analysis of flight tracks and delay statistics for convective weather events before and after the start of the CIWS demonstration. The delay reduction results for the domain shown in Figure 3 will be extrapolated to other regions of the NAS, based on studies of convective weather and congestion in key ARTCCs to the south and west of the current CIWS coverage.

An initial Joint Resources Council (JRC) investment decision (JRC-2A) for CIWS is currently planned for October 2004.

7. POTENTIAL NEAR TERM ENHANCEMENTS TO THE SUMMER 2004 CIWS FUNCTIONAL CAPABILITY

A number of enhancements to the CIWS capabilities, demonstrated offline in the summer of 2004, are under discussion for possible implementation in the real time system in the fall of 2004 and early spring of 2005. The RCWF product could be enhanced to provide forecasts of light precipitation to assist in traffic flow management during winter precipitation (Wolfson et. al., 2004). Since the current CIWS coverage includes most of the major terminals that have significant winter precipitation problems, this enhancement would be very useful during winter storms.

⁴ Due to scheduling problems that may arise between the CIWS deployment and enhancements to the various display systems shown in Figure 12, there may be a need for interim dedicated CIWS situation displays at some user locations when the production CIWS is deployed.

The echo tops decision support could be enhanced significantly by the spring 2005 storm season. A high priority user request is to provide movie loop animation of the past echo tops product. Additionally, an echo tops forecast could be added (Wolfson et. al., 2004).

If CIWS were to support a SWIM demonstration of CIWS products at Little Rock (AR), Jackson (MS) and Springfield (MO) in 2005, it would be necessary to extend the CIWS spatial coverage shown in Figure 3 to the west and southwest (including most of the Memphis en route center airspace).

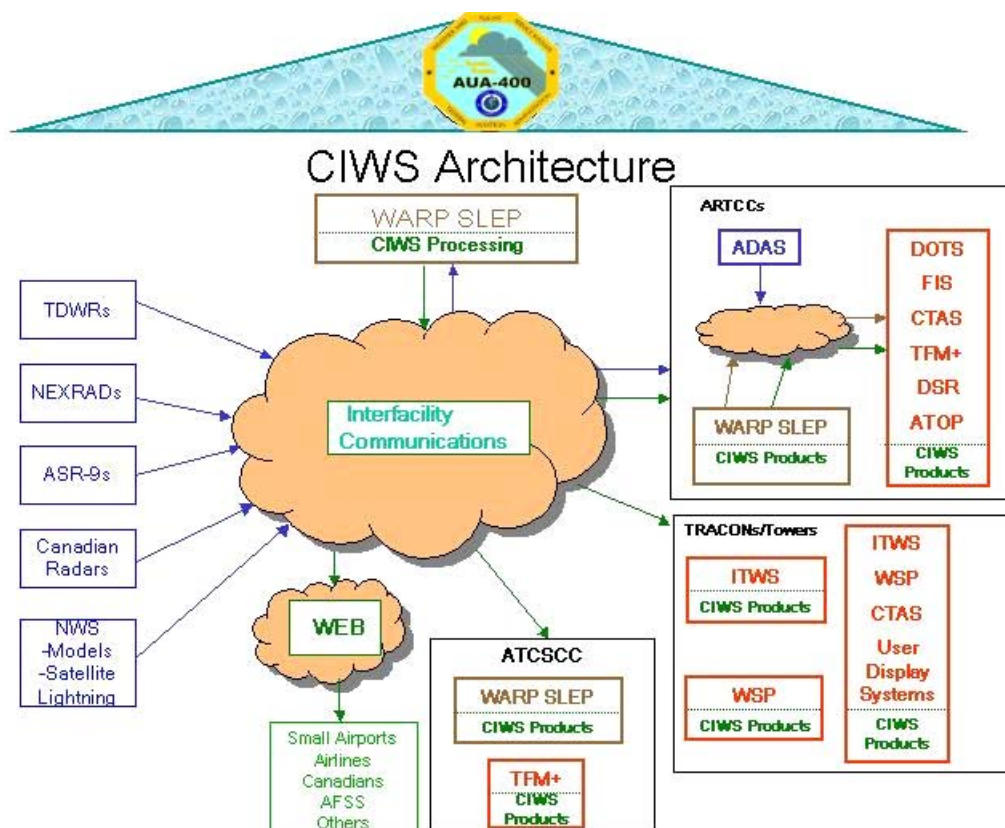


Figure 12. Candidate CIWS production system architecture as presented at CIWS Acquisition Review in August 2003 [Moy, 2003].

8. REFERENCES

Allan, S., R. DeLaura, B. Martin, D. Clark, and C. Gross, 2004: Advanced Terminal Weather Products Demonstration in New York, 11th Conference on Aviation, Range, and Aerospace Meteorology, Hyannis, MA

DeLaura, R., and S. Allan, 2003: Route Selection Decision Support in Convective Weather: A Case Study of the Effects of Weather and Operational Assumptions on Departure Throughput, 5th Eurocontrol/FAA ATM R&D Seminar, Budapest, Hungary, <http://atm2003.eurocontrol.fr/>

Droegemeier, K.K., K. Kelleher, T. Crum, J. Levit, S. Del Greco, L. Miller, C. Sinclair, M. Benner, D. Fulker, and H. Edmon, 2002: Project CRAFT: A Test Bed for Demonstrating the Real Time Acquisition and Archival of WSR-88D Level II Data, 18th International Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology., 13-17 January, Amer. Meteor. Soc., Orlando, Florida, 136-139

FAA, 2002: National Airspace System Operational Evolution Plan (OEP). A Foundation for Capacity Enhancement 2002-2013, Executive Summary, Version 5

FAA (2004): "Flight Plan 2004-08" (available at <http://www2.faa.gov/AboutFAA/FlightPlan.cfm>)

Huberdeau, M. and J. Gentry, 2004: Use of the Collaborative Convective Forecast Product in the Air Traffic Control Strategic Planning Process, ATCA Journal of ATC, April-June, pages 9-14

Lapczak, S., E. Aldcroft, M. Stanley-Jones, J. Scott, P. Joe, P. Van Rijn, M. Falla, A. Gagne, P. Ford, K. Reynolds and D. Hudak, 1999: The Canadian National Radar Project, 29th Conference on Radar Meteorology, Montreal, 327-330

McCartney, S., 2004: FAA Spreads Flight Delays More Widely, Wall Street Journal, 4 August 2004, p. D-1

Moy, R., 2003: Corridor Integrated Weather System (CIWS), FAA (AUA-460), 27 August 2003.

Paul, J., M. Falla, P. Van Rijn, L. Stamadianos, T. Falla, D. Magosse, L. Ing, and J. Dobson, 2004: Radar Data Processing for Severe Weather in the National Radar Project of Canada, 21st Conference on Severe Storms (Paper 4.13)

Proseus, E., 2002: Accuracy of Motion-Compensated NEXRAD Precipitation, MIT Lincoln Laboratory Project Report ATC-312 (26 June 2003).

Robinson, M., J. Evans, B. Crowe, D. Klinge-Wilson and S. Allan, 2004: CIWS Operational Benefits 2002-3: Initial Estimates of Convective Weather Delay Reduction, MIT Lincoln Laboratory Project Report ATC-313 (9 April 2004)

Wolfson, M.M., B.E. Forman, K.T. Calden, W.J. Dupree, R.J. Johnson Jr., R.A. Boldi, C.A. Wilson and P.E. Bieringer, 2004: Tactical 0-2 Hour Convective Weather Forecasts for FAA, 11th Conference on Aviation Range, and Aerospace Meteorology, Hyannis, MA