10.1 MULTI-RADAR INTEGRATION TO IMPROVE EN ROUTE AVIATION OPERATIONS IN SEVERE CONVECTIVE WEATHER

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1. Introduction*

Historically, the development of aviation weather products has focused on route selection by individual planes, with the principal emphasis being a safe, efficient route for an individual flight. However, it is now essential to consider the role of weather products in improving the effective capacity of the national airspace system.

In a substantial fraction of the US en route airspace, congestion from the user demand exceeding the fair weather capacity is a recurrent problem [OEP, 2002]. When convective weather causes the capacity in such regions to drop well below the fair weather capacity, delays go up dramatically, and the overall system flows may exhibit instability phenomena in which apparently small changes in capacity result in very large delays and disruptions[1].

The en route system can be viewed as a time varying network problem involving flights between multiple origin-destination (OD) pairs that use common airspace. Hence, when some sectors in en route airspace lose some or all of their normal capacity due to convective weather, the planes that would have used those sectors reroute to other sectors which results in additional traffic overloads in the other sectors, thus necessitating further rerouting and traffic flow adjustments.

The FAA Operational Evolution Plan (OEP)[2] identifies improved decision support for en route severe convective weather as a key problem 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 effective capacity of the current National Air System (NAS)

In this paper, we describe a major new FAA initiative, the Corridor Integrated Weather System (CIWS), to improve convective weather decision support for congested en route airspace <u>and</u> the terminals within that airspace through use of a large, heterogeneous network of weather sensing radars as well as many additional sensors.

The objective of the CIWS concept exploration is to determine the improvements in NAS performance that could be achieved by providing en route controllers, en route and major terminal traffic flow managers, and airline dispatch with accurate, fully automated high update-rate information on current and near term (0-2 hour) storm locations, severity and vertical structure so that they can achieve more efficient <u>tactical</u> use of the airspace. These “tactical” traffic flow management products will complement the longer-term (2-6 hr) forecasts that are also needed for flight planning and strategic traffic flow management.

Since balancing the en route traffic flows in the presence of time varying impacts on sector capacities by convective weather is essential if delays are to be reduced, an important element of the CIWS initiative is interfacing to and, in some cases providing, air traffic flow management (TFM) and airline dispatch decision support tools (DSTs).

2. Mission Needs/Operational Concept

The current en route convective weather decision support system is deficient on many time scales [Evans, 2001; Evans, et al., 2002]. Mosaics of NEXRAD products are the principal current source of information on storm locations and severity. NEXRAD product data anomalies (e.g., AP-induced ground clutter and system malfunctions) and the product timeliness have been a concern for the controllers. The current NEXRAD algorithm used to estimate storm echo tops generally underestimates the tops. Existing operational forecast products within en route airspace are limited. Most en route weather decision support systems such as WARP show only current and past storm locations. The Aviation Weather Center provides two products: 1) the National Convective Weather Forecast (NCWF) with one-hour forecast contours, and 2) the Collaborative Convective Weather Forecast Product (CCFP) 2,4, and 6-hour predictions that are updated every four hours. The spatial and time resolution of these forecast products is not adequate for congested airspace operations, and there is an urgent need to improve the product accuracy.

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[1] See, for example, scenario A at http://www.faa.gov/programs/oep/Archive/scenarios/scenarios.html

[2] see http://www.faa.gov/programs/oep/Archive/

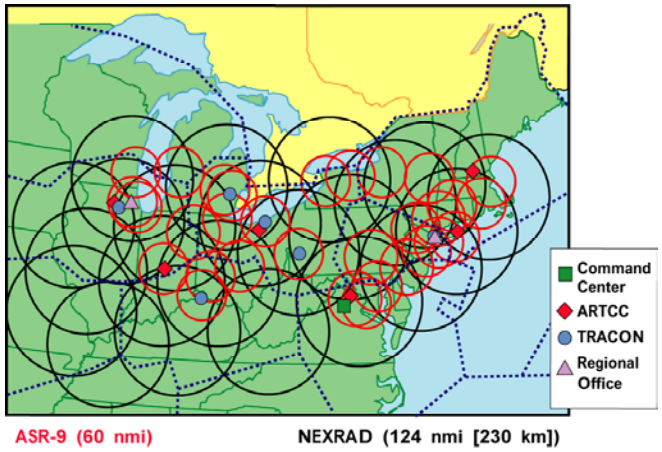

Figure 1. Coverage of radar sensors used for CIWS operational demonstrations in the summer of 2002.

To address this need for rapid updates in forecasts and timeliness of all weather products, the operational concept for the CIWS is full automation in the generation of all weather products with the products being provided directly to non-meteorologist FAA and airline users. Since these operational users must rapidly make traffic flow decisions, it is very important that there be a high integrity in all of the CIWS products to minimize the need for meteorological interpretation.

3. Approach to Achieving the Desired Operational Concept

The CIWS takes advantage of infrastructure enabling technologies such as wideband communications capability, dramatic increases in computational capability/cost ratio and Web browser capabilities. The bulk of the current tactical convective weather information systems (e.g., NEXRAD and WARP, and to a lesser degree ITWS) architecture and capability were dictated by the narrow band communications capability and relatively expensive computer capabilities available in the 1980's and early 1990's. These limitations placed major constraints on the complexity of automatic product generation systems, display product spatial resolution, update rate and features as well as the ability to provide information to a wide variety of users.

3.1 Choice of Sensors

It is essential to use <u>both</u> terminal and en route weather sensors to create the improved convective weather products for congested en route airspace [just as the Integrated Terminal Weather System (ITWS) has been very successful at using en route sensors to improve terminal operations)]. To significantly improve the effective rate at which the full surveillance volume is scanned, fan beam radars such as ASR-9s and ARSR-4s[3] can be used to provide a weather product with a volume update of at least once per minute. We see from fig. 1 that the ASR-9s have a very dense coverage in the highly congested Great Lakes and Northeast corridors. Additionally, the ASR-11s when deployed will further improve the region that is rapidly scanned. This much higher data rate is particularly important when there is air mass convection and/or "explosive" line storm development.

There are two key steps to improving forecast capability:

1. Better weather sensing, and
2. Improved algorithms for creating the storm severity products and forecasts.

The ability to predict the development of new cells in areas that are being used by en route traffic is critical for improved operations. A key factor in convective initiation is measurement of surface wind convergence. As shown in figure 2, by using both NEXRADs and TDWRs, it will be possible to do a much better job of surface convergence detection than with NEXRAD alone (especially near major terminal complexes such as New York/Philadelphia, the Washington DC area, near Chicago and in southern Ohio).[4]

[3] The ARSR-4s are long range L-band surveillance radars positioned around the perimeter of the country. They have a 6 VIP level output which is analogous to the terminal ASR-9 "weather channel". To date, the FAA has not yet made use of the ARSR-4 6-level precipitation product.

[4] It is also possible that the ASR-9 WSP gust front product may be useful for surface convergence detection.

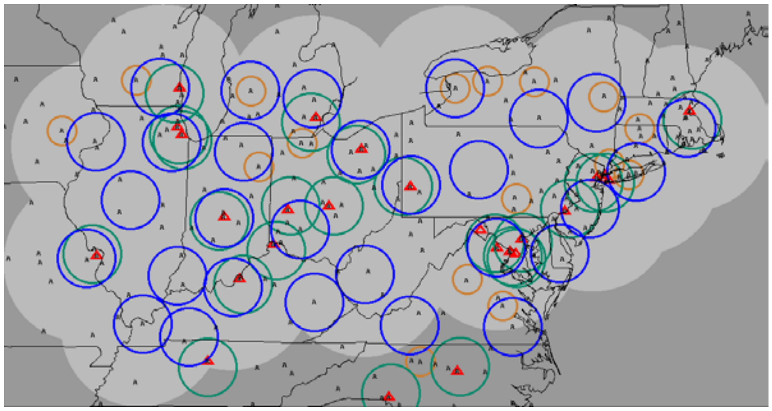

Figure 2. Surface winds coverage by NEXRAD (blue circles, 80 km range), TDWR (green circles, 80 km range), ASR-9 WSP (orange circles, 40 km range) and ASOS stations (A's) in CIWS Summer 2002 spatial domain. (The ITWS airports are indicated with red triangles.) Note the TDWR significantly enhances the low altitude coverage. The many gaps in surface winds coverage mean that it will be difficult to accurately predict new convective storm development in all locations; as a consequence, it is very important to have high update rates for storm sensing such as is provided by ASR-9, ASR-11 and ARSR-4.

3.2 Sensor Data Processing

The algorithms by which the various sensor data are processed and integrated are very important for a system that provides products directly to non-meteorologist users. Since NEXRAD is a key sensor for en route surveillance, the CIWS concept exploration should use full resolution base data from the NEXRAD to create intermediate and final products (e.g., reliably discriminating between AP and valid weather returns is very difficult using the current NEXRAD coarsely quantized "narrow band" base products)[5]. The concept exploration phase is focusing on vertically integrated liquid water (VIL) [Robinson, et. al, 2002] as precipitation product because VIL is a better indicator of storm severity and new growth and is less susceptible to AP and other data anomalies than other precipitation representations.

One of the significant issues to resolve in the CIWS development was the mitigation of the underestimated storm echo tops from the current NEXRAD echo tops algorithm. The radar echo tops are particularly important in the en route domain with the rapid transition to regional jets for commuter operations [Rhoda, et. al, 2002]. The current NEXRAD echo tops algorithm reports radar echo top as the height associated with the range and azimuth of the highest radar beam whose received power exceeds a fixed threshold (currently 18 dBZ). Hence, if a storm's true top lies between two beams such that the measured reflectivity is above the threshold at the lower beam and below the threshold at the higher beam, the reported altitude will be below the true altitude.

3.3 Mosaic Processing and Product Spatial Resolution

Since the congested corridors cover very large expanses, it is clear that radar mosaics will be necessary. The ITWS algorithms for comparing the various weather radar sensors to remove data artifacts such as AP [Evans and Ducot, 1994] can clearly be adapted to en route surveillance. In particular, it is important to compare the various data for a given spatial location for reasonableness rather than blindly taking the largest measured value for precipitation at that location.

One of the important issues in creating a NEXRAD mosaic is how to account for the motion of storms in the mosaic operation. Since NEXRADs typically have volume scan times of five to six minutes during precipitation and scan asynchronously, adjacent NEXRADs can observe a given storm at times that differ by as much as six minutes. If the storms are moving at 100 km per hr (not uncommon in the spring or fall), the observed location of a given cell can differ by as much as 10 km between adjacent radars. Hence, if no allowance is made for the motion of the storms, the spatial extent of a storm will be overestimated in the direction in which the storm is moving by considerable distances and the apparent location of the storm can change dramatically in short periods of time[6].

It is also very important to be able to identify precisely which routes (especially those feeding into and out of the terminals) are currently and will be impacted in future by adverse weather. Hence, for the CIWS, it is important to have at least 1 km spatial resolution near major terminals with no poorer than 2 km spatial resolution over the remainder of the coverage volume.

[5] See section IV b below for a discussion of the use of NEXRAD base data to address these NEXRAD data quality issues

[6] Particularly if the product used is a mosaic of surface tilts.

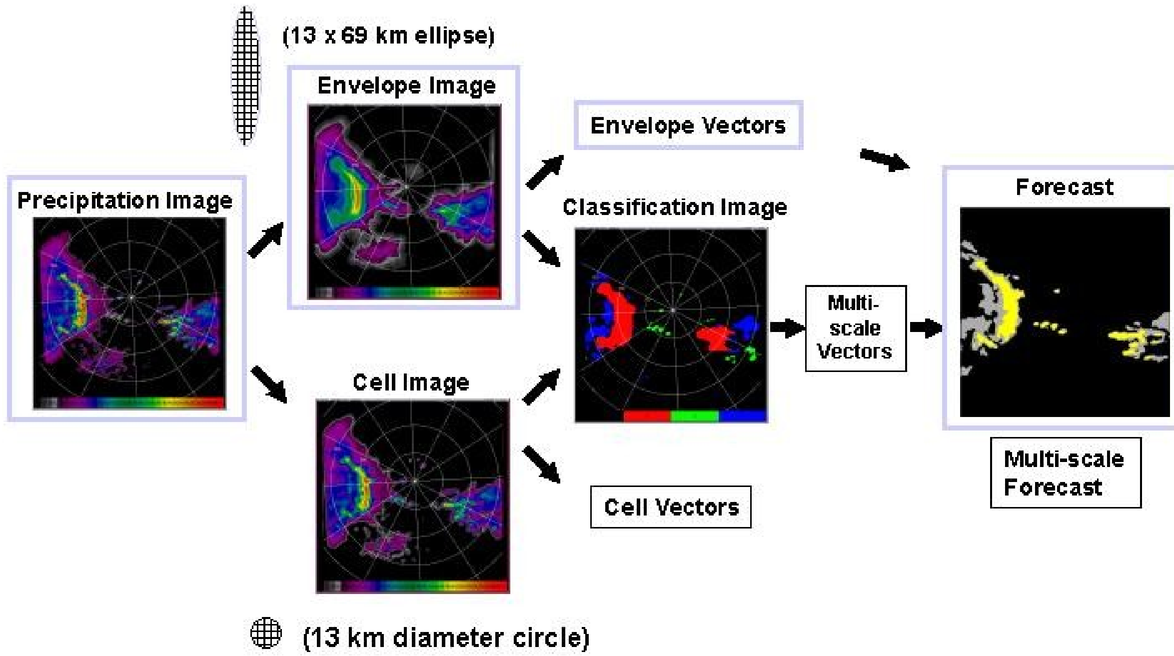

Figure 3. Multi-scale storm tracking/forecasting algorithm used in the CIWS summer 2002 operational demonstration. The radar return spatial structure is analyzed to determine the local character of the convective storms. Storm tracking is then optimized on a local basis to determine appropriate advection vectors.

3.4 Forecast Algorithms

Applicable contemporary automated forecast product technology is described in [Dupree, et al. 2002] and [Boldi, et al. 2002]. Key features in these algorithms are:

- Explicit estimation of storm growth and decay allow growth and decay trends to be incorporated into forecasts,
- Use of satellite data in conjunction with radar data,
- Scale separation technology to regionally classify precipitation by type so as to optimize performance on a regional basis (see fig. 3 below),
- Explicit consideration of small scale forcing (e.g., storm initiation, growth, and dissipation) during the 0 - 60 min forecast range and larger scale forcing (e.g. fronts) for the 60 - 120 min forecast range, and
- Real time metrics for the forecast accuracy that assist the user in estimating the forecast utility as a function of forecast time and location within the CIWS domain.

3.5 Common Situation Awareness between the Various FAA Facilities and Airline System Operations Centers

It has become clear from the ITWS experience that there needs to be common situational awareness between the key FAA facilities and the airlines [Evans and Ducot, 1994], [Maloney, et. al, 2002]. This is particularly important for decision making in congested en route airspace since:

1. rerouting planes between an Origin-Destination pair if the normal route is blocked by adverse weather is a significant element of en route ATM, and
2. a high level of congestion in fair weather means that convective weather impacts in one region of en route airspace can result in major traffic management problems in regions that are far away from the weather impacted area.

Additionally, airline dispatchers have critical responsibilities for the safety of flight in en route airspace [see (Evans, 2000)], and hence it is particularly important that they have real time access to products from systems such as CIWS.[7]

4. The CIWS Summer 2002 Demonstration System

4.1 System Architecture

Figure 4 shows the system architecture for the CIWS demonstration system in 2001-02. The desired radar base data is transferred at full data resolution via a

[7] It should be noted that at this time, airlines do not have access to the WARP weather products being used in the FAA en route centers. The airlines will receive access to the ITWS products over CDMnet [Mahoney, et. al., 2000]

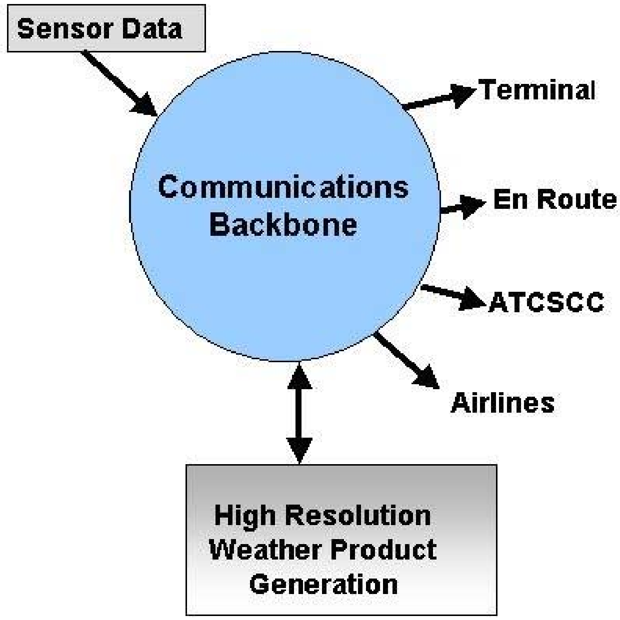

Figure 4. System architecture for CIWS operational demonstration in 2002. A frame relay network was used as the communications backbone.

frame relay network to a central location in Lexington, MA where the products are generated and monitored. This same network provides communications of the various products to FAA user displays. To provide higher reliability, redundant wide band dedicated lines connected the Lexington operations center to the frame relay access port in Boston MA[8].

The frame relay reliability over the two summers has been very high: the overall system availability has exceeded 0.999. The major cause of outages has been local phone line outages between an FAA site and the nearest frame relay access point.

4.2 Products

The processing capability and wide band communication links permit the generation and distribution of very high spatial resolution/rapidly updated precipitation, echo tops and forecast products shown in table 1 on the following page.

4.3 Data Quality Edited Precipitation

For the 2002 demonstration, two data quality checks were applied to the NEXRAD base data prior to the estimation of VIL and the generation of other products. The checks attempt to identify and mitigate two primary sources of data corruption: anomalous propagation (AP) and artifacts [Isaminger et al., 1997, Smalley and Bennett, 2002; Smalley et al., 2003]. The AP check assumes all radar returns are weather unless a combination of strong reflectivity and weak, coincident Doppler data are identified[9].

The detection of artifacts involves the identification of radials that exhibit a constant power function signature. This signature is noted by an increase of reflectivity with distance from the radar along a radial. NEXRAD system malfunctions typically result in bull's-eye or starburst echo patterns that exhibit this signature. Sun strobes associated with sunrise and sunset also exhibit this signature. These two classes of artifacts make up the vast majority contaminating NEXRAD data. The removal of the data artifacts along with AP mitigation provides an improved base data stream for the VIL computation and other CIWS uses of the NEXRAD base data. This improves the prospects for increased sensitivity to detect low reflectivity features such as convergence lines that are precursors to the growth of convective cells.

[8] Airlines provided point-to-point communications lines to an appropriate Lincoln Laboratory location (e.g., Lexington) if they wanted to access the CIWS products for a dedicated situation display.

[9] One deficiency observed with this method of AP removal is that it cannot be accomplished if the NEXRAD reflectivity measurement has no corresponding velocity measurement (e.g., due to range aliasing in the velocity channel). The new NEXRAD signal processors should alleviate this problem. Additionally, we are investigating the automatic use of GOES satellite data to aid in identifying AP.

Table 1
CIWS Product Update Rates and Technical Performance

Product	Data Sources	Product Update Interval (min.)	Product Spatial Resolution (km)	Typical Performance[1]
VIL mosaic precipitation	NEXRAD	2.5	2	----- -----
ASR9/VIL mosaic[2]	NEXRAD and ASR9 mosaic	1	1	----- -----
Echo Tops	NEXRAD	2.5	2	
Cell Motion	Precip. source	2.5	---	Within 10 knots for 90% of storms moving faster than 10 knots
Storm Extrapolated Position (SEP)	Precip. source	1 (ASR) 2.5 (NEXRAD)	0.5	Within 1 nmi 85% of time for 10 min. SEP and 65% of time for 20 min. SEP
Regional Convective Weather 2-hr Forecast (RCWF)	NEXRAD & GOES (TDWR and NWS Rapid Update Cycle Numerical Model in 2003)	5	1 (internal) 2 (display)	Performance varies with weather type; performance scores are updated every 5 minutes; verification contours are available on past weather
Satellite clouds	GOES	15	2 (day–vis) 4 (night-IR)	
Lightning strikes	National Lightning Detection Network	2	0.5	NLDN detects 80-90% of cloud-to-ground lightning[3]

1. Performance results from Klingle-Wilson (1995) unless otherwise noted.
2. ASR reflectivity is quality checked against TDWR (if accomplished by ITWS) and NEXRAD data.
3. Cummins, et al. (1998) and Idone, et al. (1998)

The data quality edited VIL products from each NEXRAD is advected to a common time prior to the mosaic formation using the ITWS storm cell tracker to determine appropriate cell advection velocities to use in various portions of each radar's coverage region.

AP-edited ASR-9 data [Evans and Ducot, 1994] and the NEXRAD VIL mosaic data are combined to provide a composite 1 km spatial resolution product that updates once per minute. Since the data from an individual ASR-9 updates every 30 seconds, updating the ASR-9 portion of the mosaic is straightforward.

The advection compensated NEXRAD VIL mosaic computation is redone every minute so that there will be minimal discontinuities between the ASR-9 storm locations and the NEXRAD storm locations at the interface between the two products.[10]

4.4 Echo Tops Algorithm

An improved echo tops algorithm has been developed for CIWS that better estimates the true storm echo tops by interpolation between the measured beam reflectivity of the two beams that bracket the desired threshold. It can be shown that this algorithm is particularly effective at reducing the large underestimation of radar echo tops that arises when the measured reflectivity in the upper beam is just below the desired threshold. In fig. 5, we compare the echo tops estimated using the new algorithm with the echo tops estimates using the current NEXRAD algorithm for a stratiform rain event observed in fall 2001.

4.5 Forecast Algorithms

Two separate storm tracking and forecast algorithms are used. The ITWS storm tracking algorithm is used to generate the storm motion vectors and 10- and 20 minute storm cell extrapolated positions provided on the ASR-9/NEXRAD VIL combined product.

The Regional Convective Weather Forecast (RCWF) is used to generate all of the longer lead-time forecast products. The RCWF has evolved considerably over the 2001-02 demonstration period as additional capabilities shown in fig. 3 were added to the initial structure.

10 Some discontinuities will exist as a result of storm growth and decay between the time that the NEXRAD made a volume scan and the ASR-9 fan beam scan of the same storm; however, the precipitation differences due to storm motion between those two times is minimized by the advection process.

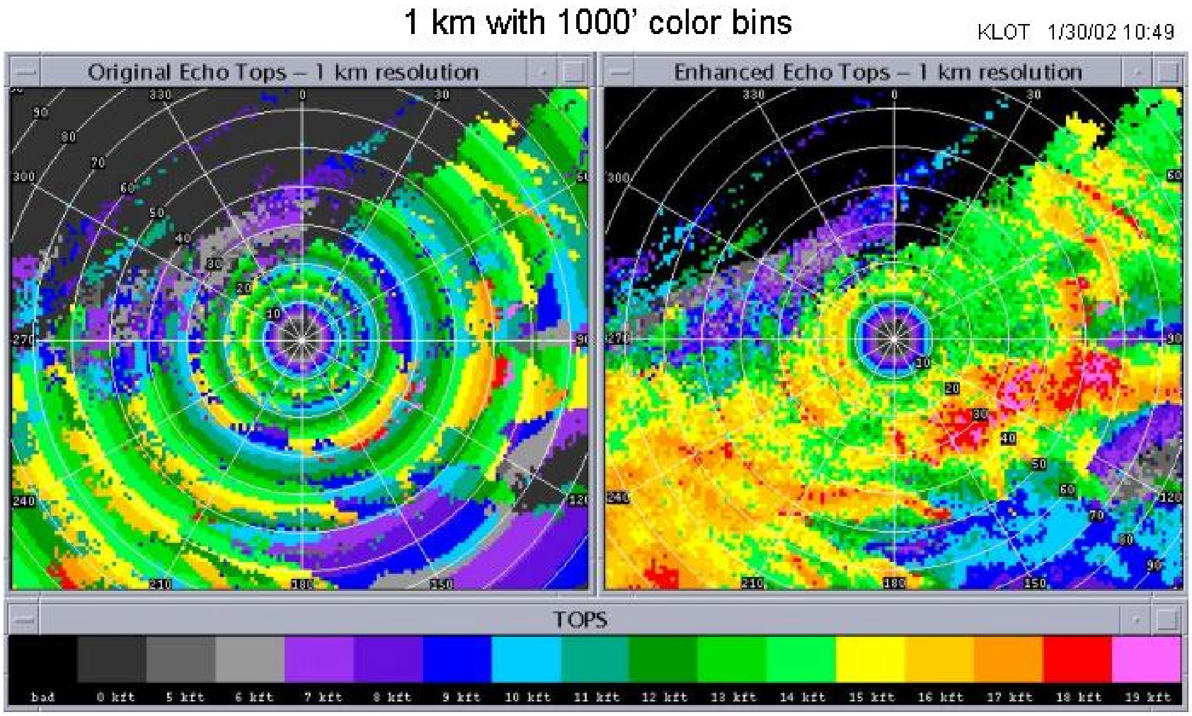

Figure 5. Comparison of echo tops computed using current operational NEXRAD algorithm (left) with echo tops computed using new algorithm (right) for a winter precipitation event on 30 January 2002. Note the meteorologically implausible circular oscillations in echo tops in the left hand window due to "stepping" between elevation tilts in the current NEXRAD algorithm. The enhanced echo tops are much more consistent with the expected tops in this stratiform precipitation event.

The RCWF now loops 60 min of past weather and 120 min of forecast weather in 15 min increments. The probabilistic forecast is depicted in three levels (low, moderate, and high probability) and represents a deterministic but fuzzy representation of the likely areas of level 3+ precipitation areas at each 15 min time in the future. The forecast is created at 1-km resolution across the corridor, but displayed at 2-km resolution owing to bandwidth limitations to the situation displays. The current input data are the individual NEXRAD VIL maps plus the corridor-wide mosaic, and the satellite data.

The RCWF algorithm provides multi-scale motion estimates on storms within the corridor. To do this, each weather region is classified as line storm, large cell, small cell, or stratiform. The most appropriate motion vectors for each storm type are applied based on different correlation tracking calculations (various degree of scale selection) and constraint of the vectors. The satellite data are used to locate growing cumulus clouds in a linear configuration, which could be indicative of growth along a forcing boundary. This conservative detector provides occasional growth evidence.

Early in FY'03, the RCWF algorithm will be augmented with growth and decay trending based primarily on VIL data, storm classification, and statistical models of storm evolution. Additional capabilities planned for FY'03 include explicit boundary layer forcing using the Machine Intelligent Gust Front Algorithm operating on all the NEXRADs (and a few TDWRs) in the corridor, additional satellite growth feature detectors, large scale forcing based on evidence in the national scale Rapid Update Cycle (RUC) numerical model, and feature detectors that capture diurnal and orographic forcing.

4.6 Displays

The initial concept exploration has sought to provide displays at key ARTCCs that lie within the congested corridors as well as the surrounding ARTCCs, the ATC System Command Center (ATCSCC), and the major TRACONs within the corridors. Color situation displays were provided at 6 key en route centers[11], the FAA's Command Center, and 6 TRACONs[12] between June of 2001 and March of 2002. By August of 2002, there were 30 dedicated CIWS displays at FAA facilities. Airline systems operations centers were provided access to the CIWS products via servers on the Internet and CDM-Net as well as having dedicated situation displays identical to the FAA user displays.

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11 Chicago, Cleveland, Boston, New York, Washington and Indianapolis

12 New York, Chicago, Detroit, Pittsburgh, Cincinnati, and Cleveland

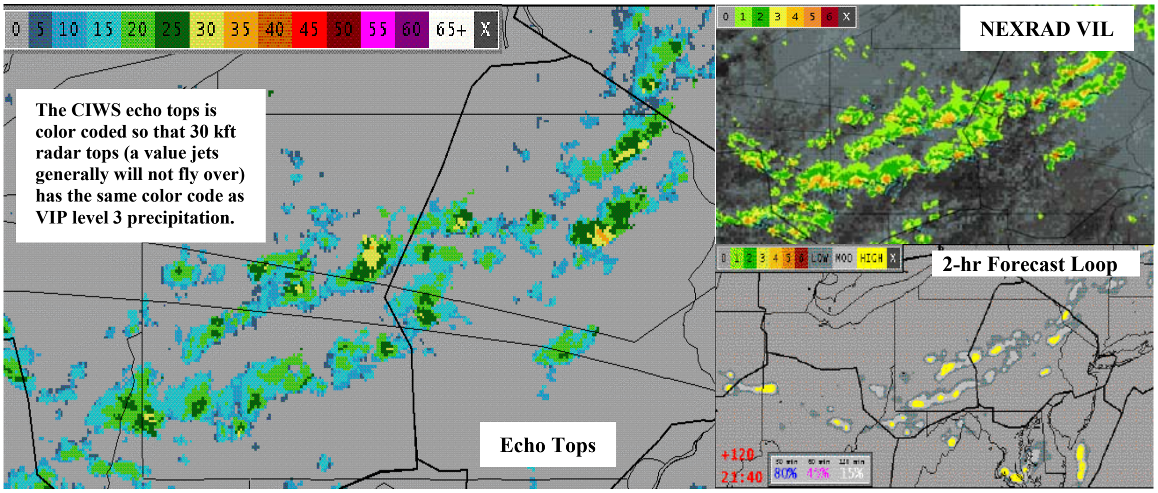

Figure 6. CIWS display during the severe weather event of 24 August 2002. The echo tops product is shown at the left and the NEXRAD VIL mosaic with visible satellite data background is shown at the top right. By viewing both windows, users could discern that high level VIL returns are associated with relatively low echo tops. The CIWS echo tops information permitted many aircraft to safely fly over the storms in Pennsylvania, thus significantly reducing aviation delays. The 2-hr Forecast Loop provides CIWS 15-120 minute animated forecasts (lower right hand window). A key feature is the real time indication of forecast accuracy.

The CIWS multi-windowed display is written in Java and utilizes the Hypertext transfer protocol (http) for data distribution. This technology has allowed rapid prototyping and implementation of display concepts for new products, portability between hardware platforms, and easy transfer to web-based browsers. CIWS displays are served by local or remote webservers which provide access to products as they are available.

The display (see fig. 6) has a number of innovative functional features to assist in air traffic management:

1. Since radar echo tops are a particularly important factor for en route flight routing with jets, the echo tops are portrayed with a 2 km spatial resolution that matches the precipitation spatial resolution and has the colors assigned in such a way as to facilitate air traffic management decision making. Since echo tops of 30 kft are a key “threshold” for storm avoidance by jets analogous to VIL level 3 precipitation, the echo tops color code for this flight level has been chosen to match the VIL level color code. This facilitates rapid traffic flow decision making by non-meteorologist users (e.g., if either the precipitation or echo tops colors in a given region are all blues or greens, pilots are likely to accept routing through that region).

2. Longer lead time Convective Weather forecasts are shown as a time loop over the past weather and into the future and the Forecast Accuracy product provides current accuracy evaluations in the same window.

3. GOES visible and IR satellite data is a user selectable background on the radar precipitation windows with the visible data provided during daylight periods and IR otherwise. Although this ability to overlay radar and satellite has been a common feature for many years for meteorologist workstations, this capability has not been provided in contemporary ATC decision support systems such as the ITWS.

4.7 Operational Usage

Operational usage of the CIWS products commenced in early July 2001. In April of 2002, the system started near-full-time operations (seven days per week, 24-hours per day with occasional downtimes for upgrades and maintenance). This schedule has continued through the 2002 storms season with several one-day shutdowns for software and hardware upgrades.

At ARTCCs, the CIWS displays typically have been provided at the TMU desk and the CWSU work area. As time evolved, additional TMU displays have been installed at all facilities [e.g., so that the TMU’s handling some key sectors had a separate display from the TMU that was participating in the FAA strategic planning team (SPT) teleconferences every 2-hours].

These CIWS displays typically are in close proximity to the existing Weather and Radar Processor (WARP) displays with NEXRAD mosaic composites at the same facilities. Additionally, the Enhanced Traffic Management System (ETMS) displays in the same vicinity have vendor-provided NEXRAD mosaics (different from the WARP mosaic). Hence, the operational users had multiple sources of information on severe convective weather that could and would differ as to weather location and severity.

With time, the ARTCC users generally have come to rely on the CIWS products as the more useful representation operationally, albeit there continue to be situations where the other products (i.e., WARP or ETMS) are used because the CIWS display is in an inconvenient location for that particular user.

The major TRACONs have had access to weather information on their ETMS display, but have not had access to the WARP convective weather information. At TRACONs, the CIWS displays are typically located in the TMU unit. At the New York TRACON, there were already two ITWS demonstration displays in the TMU area with the baseline ITWS products and the 1-hour Terminal Convective Weather Forecast (TCWF). Hence, the New York CIWS display was put next to the lead TMU position to facilitate participation in SPT discussions and coordination with the surrounding ARTCCs. Also, the Cincinnati TRACON has been provided two displays, one at the Controller In Charge (CIC) position and one at theTMU position.

The use of the CIWS for operational decision-making increased dramatically in 2002 over 2001 after the various users became convinced that the CIWS products were substantially more capable than their existing weather products. The en route decisions that were most frequently improved by the use of CIWS include:

a. recognizing opportunities for aircraft to fly over storms as opposed to having to be rerouted to other regions and/or held on the ground (this generally involved use of the echo tops products),
b. determining that routes need not be closed even though there was weather in the vicinity (this generally involved use of the high space/time resolution RCWF forecasts),
c. reopening routes 30-45 minutes earlier by using the RCWF forecasts to determine when the weather impacts on the routes would end, and
d. using a much smaller miles in trail (MIT) spacing on routes when there was weather in close proximity to the routes (this decision often involved a combined use of echo tops and the various storm forecast products).

Additionally, the TRACONs and en route centers were able to effectively coordinate actions to achieve nearly all of the delay-reducing terminal convective weather ATC decisions that had been identified previously in the ITWS program [Evans and Ducot, 1994; Allen, et. al, 2001]. A formal quantitative delay reduction assessment will be carried out in the fall of 2002 and the results published separately.

5. Near Term Plans

The CIWS initiative has several major new thrusts in the coming year: improvements in weather product capability and dissemination, transitioning to the beginning of implementation in the NAS, and integration with ATM decision support systems. We will briefly discuss each of these thrusts.

5.1 Improving Forecast Capability

In September of 2002, the 2-hr RCWF (Regional Convective Weather Forecast) contained: a) multi-scale tracking and b) satellite boundary growth. In the late fall of 2002, radar growth and decay trends based on trends in VIL structure will permit automatic decay of large storm systems as they evolve out to 2 hours and the ability to predict the growth of storms up to high level 3+ probability even when only weak VIL is currently present. Satellite based detectors of growth will be added on in early 2003.

The most significant upgrade will be the automated prediction of convective initiation based on evidence of convergence lines/gust fronts from the Machine Intelligent Gust Front Algorithm (MIGFA) on both NEXRAD and TDWR base data. The MIGFA has been very successfully used for gust front detection on TDWR base data for a number of years. Research has gone forth to port and adapt the MIGFA software to operate successfully with NEXRAD base data. Satellite information will be used to confirm that the boundary layer humidity and temperature will support the development of convection in areas where there are colliding convergence lines.

5.2 Providing High Quality Convective Weather Information for Small Terminals

The CIWS ability to provide high spatial resolution precipitation and forecast products over large domains enables CIWS to provide very high quality information on convective weather to both large and small airports over large areas using FAA intranets and the Internets with Web browsers as the user display engines. By taking advantage of the technology and operational concepts developed by the Medium Intensity Airport Weather System (MIAWS) initiative [Rappa, 2002], it should be possible to make very rapid progress at demonstrating a very effective, low cost way to improve safety at many of the FAA's small towered airports.

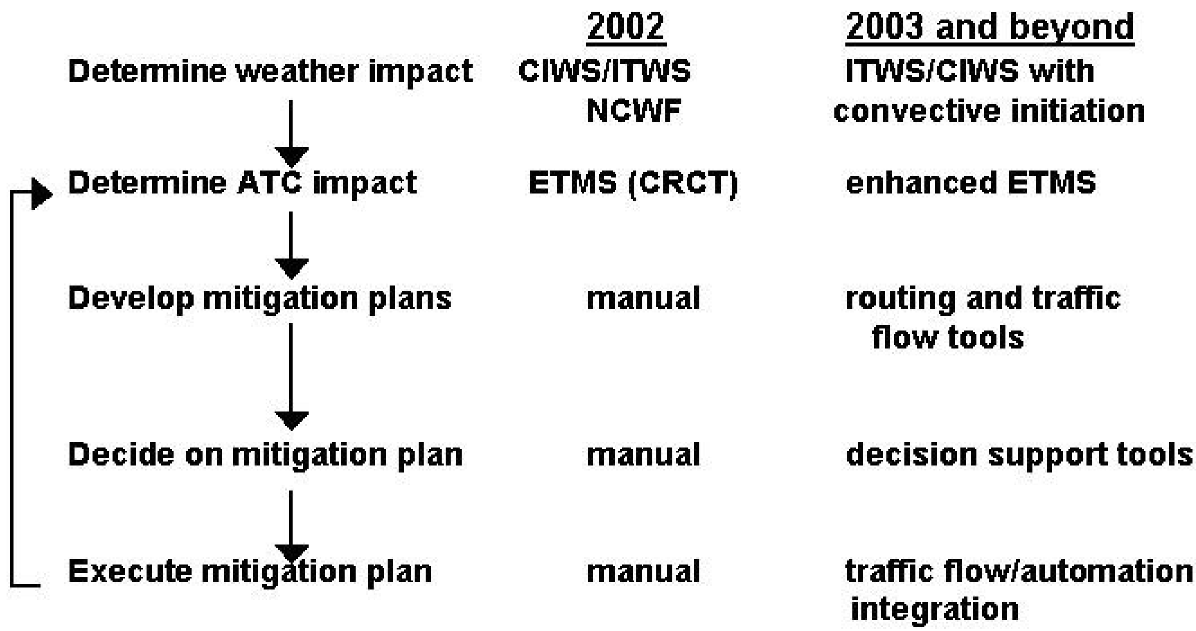

Figure 7. Overall decision support structure for improving air traffic operations when convective weather occurs in congested en route airspace. The systems used to develop and decide on mitigation plans must be able to address the time varying nature of the weather impacts and the time dynamics of the network response to changes in the traffic flows.

5.3 *Interfacing the CIWS to Air Traffic Management Decision Support Systems*

The CIWS weather products can only be successful in reducing the delays due to convective weather if the FAA and airline users are able to develop and implement effective mitigation plans. This is particularly challenging in en route airspace due to the complex dynamics of the network that were discussed in the introduction to this paper.

Figure 7 shows the key elements of moving from information on the weather impacts to achieving a successful response to the evolving convective weather. One of the most significant issues in developing the integrated decision support system shown in fig. 7 will be determining how uncertainty in the CIWS convective weather forecasts should be explicitly represented so that the various decision support tools and the human users can make meaningful decisions.

Most of the work to date in air traffic management has assumed perfect knowledge of the current and future sector and airport capacities. However, considering the difficulties in:

1. measuring boundary layer winds (recall fig. 2), and
2. accurately predicting the growth and decay of several generations of convective cells,

it is clear that the CIWS forecasts will have substantial uncertainties in the forecast weather for the foreseeable future (especially in the mid summer months that typically have the greatest number of convective weather delays). Hence, it will be necessary to develop air traffic management decision support systems that can explicitly handle uncertainty in capacity and route availability for longer tactical times (e.g., > 1 hour) with increasing accuracy in weather impact assessment at shorter lead times.

An initial concrete application for investigating these issues in 2003 will be the interface of the CIWS products to the Route Availability Planning Tool (RAPT) that has been developed by Lincoln Laboratory under the sponsorship of the Port Authority of New York and New Jersey. RAPT identifies times at which a plane may depart from a New York City major airport such that the plane would avoid intersecting convective weather in the terminal airspace and nearby en route airspace by determining whether there are intersections between the expected plane locations and the forecast storm locations.

5.4 *Investigation of Options for Operational Implementation*

If the delay benefits assessment discussed above shows that the CIWS approach would be cost-effective at reducing delays due to en route convective weather, the FAA plans to commence operational implementation.

An important consideration is the extent to which the CIWS products can be generated and displayed through use of existing en route, national and terminal decision support systems such as WARP, ITWS and ETMS.

One of the major issues to be addressed in the operational implementation study will be the system for product generation. WARP has access to NEXRADs that would be used in a CIWS. However, up to this point, the WARP has had fairly minimal automatic product generation capability (as contrasted with the ITWS). Hence, there are issues of expandability and architecture for a WARP product generator that will need to be examined in detail.

Another important architecture feature will be the allocation of processing capability between the CIWS product generator and the ITWS and NEXRAD product generators. For example, an ITWS associated with a large TRACON needs to mosaic ASR-9s. Should the CIWS mosaic the ITWS mosaics along with ASR-9s not associated with an ITWS or, should the CIWS mosaic all ASR-9s "from scratch"? Similar issues arise for the use of TDWR gust front information for storm convective initiation, and whether CIWS should access base data (as done in the CIWS demonstration systems) versus using the output of the NEXRAD ORPG.

Finally, there is the issue of communications and processing architecture for the CIWS. The centralized product generation system with a frame relay communications link used for the demonstration system has worked well, but there are several alternative communications systems and architectures already in use by the FAA that need to be considered. The operational WARP system accomplishes its processing on a regional basis with dedicated lines to each of the NEXRADs used by a WARP. In some cases, data from a NEXRAD must be accessed by several WARP product generators if each is to have the desired spatial coverage. It has been found in both the WARP and the CIWS programs that forming a large mosaic that has as many radars as possible overlapping a given region of desired coverage permits much more robust data quality editing than is possible in cases where there in only single radar coverage of a region.

6. Summary

Significantly improving the ability of the US en route system to cope with severe convective weather is a major FAA near term objective. This is a very challenging problem due to the very complicated dynamical behavior of the en route network flows when there are major capacity perturbations due to the convective weather. The problem is further complicated by the difficulty in accurately forecasting convective weather several hours in the future due to problems in sensing the surface boundary layer over the congested airspace and in accurately predicting several generations of convective storm growth and decay.

The CIWS initiative is tackling this problem by integrating data from a heterogeneous group of weather sensing radars and using advanced techniques for fully automated weather phenomena interpretation, tracking and forecasting. An initial demonstration system focusing on the Great Lakes and Northeast corridors has been successful in reducing delays through by providing information on storm severity, echo tops and 0-2 hour forecasts to major FAA facilities and airline systems operations centers. This system will be the springboard for major initiatives in convective weather forecasting and the development of fully integrated air traffic management decision support systems over the next few years. Work is commencing on determining the best approach to providing the CIWS functional capability by taking advantage of current NAS systems.

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