# NextGen Trajectory-Based Integration of Grid-Based Weather Avoidance Fields


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**ABSTRACT**

In anticipation of NextGen requirements for probing of aircraft to weather conflicts within automation systems such as En Route Automation (ERAM), Time-Based Flow Management (TBFM), Common Automated Radar Terminal System (CARTS), and Advanced Technologies & Oceanic Procedures (ATOP), we have been investigating trajectory based methods to integrate gridded weather avoidance fields such as may be available from the 4-dimensional (4-D) weather data cube/Single Authoritative Source (SAS) across multiple ATC domains. The components of our work include 1) Generation of 4-D prototype weather avoidance fields, 2) Retrieval of net-enabled weather data based on Corridor Integrated Weather System (CIWS) derived products using a System Wide Information Management (SWIM) service, 3) Development of a conflict detection service between a hazardous weather data grid and aircraft trajectories, and 4) Visualization of the interaction of weather products, the resulting weather avoidance field and aircraft trajectories. This paper describes the results of the generation, integration and visualization of 4-D trajectories with grid-based hazardous weather avoidance fields.



**KEY WORDS**

NextGen, weather avoidance, integration, trajectory based


## 1. Introduction

In 2007, the REsearch and Development Advisory Committee (REDAC), Report of the Weather-Air Traffic Management (ATM) Integration Working Group [1] provided research recommendations to the FAA for the integration of air traffic management and weather. Among the several recommendations ranging from Near-Term to Far-Term, we took note of three particular recommendations:

- Develop adaptive integrated ATM procedures for tactical trajectories (Mid Term – 2015)
Replace surrogate weather indicators with true measures of flight hazards Far Term (2015+), and
- Conduct research on gridded and scenario based probabilistic weather data for ATM decision tools (Far Term – 2015+)

According to the REDAC report, "integration is defined as translating traditional weather information into impact measures, such as capacity or flow rates and automatically or semi-automatically incorporating that data into traffic flow advisory information to improve the system capacity and safety in the face of weather hazards." However, we believe additional work is needed in representing hazardous weather within automation systems and having a common understanding among controllers, traffic managers, pilots, dispatchers, etc. on just what hazardous weather means before translating it to operational impacts. Thus, our definition of integration for the purposes of our research includes part of the REDAC definition. Before hazardous weather can be translated to ATM system capacity impacts for traffic flow management (TFM) collaborative decision making, it must first be ingested and represented within the automation system. This requires that there eventually be an agreed four dimensional (4-D) representation of various types of hazardous weather that could impact the ATC system. This weather data should be represented in a form consistent with the intended purpose of its use within the automation system. For example, since trajectory-based operations is a cornerstone of collaborative air traffic management (CATM), integrating weather information that can be evaluated collaboratively using trajectory tools allows for improved usability of the weather information for traffic flow decision making.

The work described in this paper documents the results of the generation, integration and visualization of 4-D trajectories with grid-based hazardous weather avoidance fields.

### 1.1 Previous Work

There are four areas of previous work that are key predecessors that have contributed to our research:
1) The 2005 NASA research on grid-based air traffic control strategic conflict detection [2]
2) The 2008 Convective Weather integration Demonstration at Daytona Beach NextGen Test Bed (DNTB) [3],
3) The 2009 MIT Lincoln Laboratory and Jack May work on convective weather avoidance fields [4] [5] [6], and
4) The 2008/2009 Lockheed Martin/ENSCO research on integrating weather into ATM [7] [8]

In 2005, Matt Jardin of NASA Ames Research Center published reference [2] on Grid-Based Strategic conflict detection. While the primary objective of the technique described in the paper was improved computational efficiency of pair-wise aircraft conflict evaluation, the technique was adaptable to weather application by using a stochastic model to represent weather and its movement uncertainty in the conflict grid.

In November 2008, a demonstration was held at the NextGen test bed facility located at Daytona Beach International Airport by the Integrated Airport Initiative (IAI). The IAI is a consortium formed by Lockheed Martin and Embry Riddle Aeronautical University (ERAU), to promote NextGen capabilities and accelerate their implementation into the National Airspace System (NAS). In this demonstration, consortium member Ensco, Inc. generated convective weather forecast using their version of the weather research and forecast (WRF) model. The forecast areas of convection were depicted as 3-D polygons on the ERAM D-side display. These polygons moved in space and time according to the forecast. The ERAM Conflict Probe was modified so that the trial plan trajectories would be "weather aware". In this sense, the weather areas were treated as special use airspace and the trial plan trajectories would "light up" indicating there was a conflict with a hazardous weather area. This highlighting of the trajectories was distinct from the mechanism currently used to highlight traffic conflicts. The demonstration met with mixed reviews. Controllers and TMU representatives commented that having a hazardous weather area depicted on the D-side would certainly improve weather situational awareness and improve coordination between the sectors and the TMU. On the other hand, some commented that the sector controllers should not re-route aircraft around weather using the weather hazard area depicted on the D-side display. Instead, the TMU should communicate weather re-route information to the sectors for implementation.

Regarding weather avoidance fields (WAFs), recent research has centered on the definition of convective WAFs. In an April 2009 presentation to the Joint Program Development Office (JPDO) Environmental Information working group, Jack May, former director of the National Weather Service's Aviation Weather Center proposed a working definition of a 3-D Convective Hazard Volume. Rich DeLaura and others at MIT Lincoln Laboratory have defined convective WAFs based on a convective weather avoidance model (CWAM) as a probability of pilot deviation around convective weather [5] [6]. The CWAM is based on statistics from NEXRAD radars and aircraft flight trajectories near convective weather [9].

The paper we published in the ATCA 2009 conference proceedings [8] described the concept of integrating weather into ATC automation decision support tools (DSTs) as one that should be trajectory-based. That is, to define weather as a

grid-based "trajectory-aware" object. The idea being that weather-aware DSTs would be applicable to not only En Route systems such as En Route Automation Modernization (ERAM) system, but to terminal, oceanic and traffic flow as well. The summary of our recommendations for the integration of trajectory based gridded weather were:
1) be applicable to multiple weather phenomena a) convective activity, b) Icing, c) Ceiling and Visibility hazards, d) Turbulence and e) volcanic ash
2) be applicable to multiple ATC domains including TFM, Oceanic, En Route, Terminal, Oceanic and Surface - thus supporting the NextGen Weather ConOps "common weather picture" concept
3) be modulated according to aircraft characteristics and mission
4) be adaptable to products evolving from ATM-Weather integration research by Mitre, MIT Lincoln Lab, NCAR or others (e.g., Consolidated Storm Prediction for Aviation (CoSPA) weather avoidance field) [10]
5) require a minimum training of ATC Controllers – do not want controllers to be meteorologists
6) be implementable, certifiable and deployable by 2015 – the timeframe for NextGen Weather Processor Initial Operating Capability (IOC).

### 1.2 Purpose for Undertaking Research

With an understanding of the research and prior work as described above, the concept of integrating a grid-based weather avoidance field into our ERAM DST was essentially different from how we currently provide tactical and strategic conflicts between aircraft, between aircraft to ground and aircraft to airspace. The use of a grid-based approach to conflict evaluation dictates an entirely new method and technique; one in which all WAFs are integrated into a single grid, and the trajectory conflict processing is done against that grid instead of against each individual WAF. Whether airspace definitions and aircraft trajectories can be stored in the same grid, and therefore allow the grid to be used for aircraft to aircraft and aircraft to airspace conflict detection, is the subject of future research.

For this year's research, we built upon the work described in last year's ATCA Paper by defining a grid-based convective WAF that could be represented within ATC automation that aircraft trajectories would be aware of. Generally, a WAF scores the hazard level associated with current and short term forecast weather (e.g., convective, turbulence, icing, etc. within a 30 minute time window)

## 2. Approach

The approach to this year's research comprised five components:
1) Generation of 4-D research-level convective WAF data;
2) Retrieval of net-enabled weather data based on Corridor Integrated Weather System (CIWS) derived products using a System Wide Information Management (SWIM) service;
3) Creation of a set of sample flight plans and trajectories using jet, turboprop and piston type aircraft types;
4) Development of a conflict detection service between WAFs and aircraft trajectories; and
5) Visualization of the interaction of source weather products, the resulting weather avoidance field, aircraft trajectories and aircraft-WAF conflicts.

### 2.1 Four Dimensional (4-D) WAF Data

For the purpose of trajectory integration, we postulate that a WAF be applicable to not only convective weather, but to other forms of potentially hazardous weather such as turbulence, icing, ash, ceiling/visibility. Thus, when considering a convective WAF definition as described in reference [5], how does one assign a probability of deviation to a WAF that can represent varying forms of hazardous weather (e.g., turbulence, icing, hail, etc.) as evaluated by pilots of varying experience flying aircraft of varying capabilities and missions subject to individual or company operating rules?

Current automation trajectory-to-airspace probes check the trajectory segments (modeled as great circle arc segments) for lateral and vertical penetration of the airspace boundaries. In order to modify our conflict probes from a geometric to a grid-based evaluation, we need a gridded 4-D WAF product. A 4-D WAF product includes the severity level and is defined horizontally by latitude/longitude, vertically by Echo Tops and temporally by the source system (i.e. CIWS) forecast time updates. Since gridded 4-D WAF fields were not available when the project began, ENSCO was consulted to generate prototype 3-D WAF data sets using CWIS Echo Tops (ET) and Vertically Integrated Liquid (VIL) in 1 km x 1 km resolution products [8]. Examples of VIL and ET products are shown in

Figures 1a and 1b. These are examples and not the data used in the work described here.

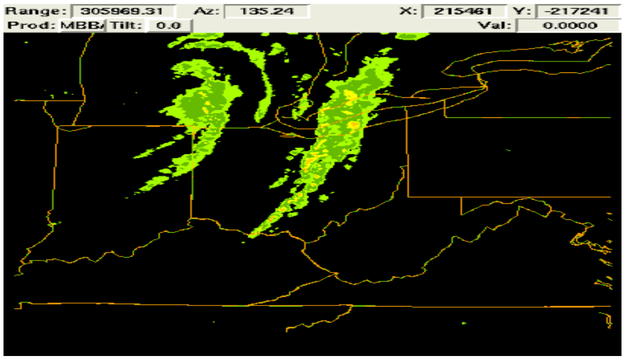


Figure 1a. CIWS 2-D VIL Example (Courtesy: MIT Lincoln Laboratory)

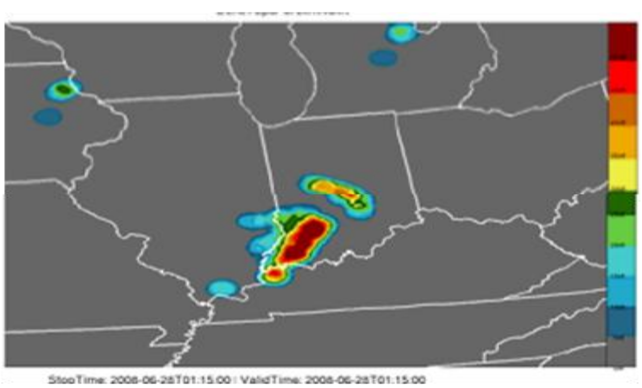

Figure 1b. CIWS 2-D ET Example (Courtesy: MIT Lincoln Laboratory)

***WAF Product Development***

To explain a bit further development of the prototype WAF products, consider the statistical analysis as reported by DeLaura et al [5]. The best single predictor of when a pilot will deviate around a storm is radar ET. This is not surprising considering that the ET correlates well with the overall updraft strength in a mature storm. The VIL is the next best predictor of deviation, again not surprisingly since it too correlates well with the updraft strength of a mature storm. Given that the VIL and ET appear to be the best predictors of aircraft deviations, systems such as the Integrated Terminal Weather System (ITWS) and CIWS produce forecasts of VIL and ET as well as an estimate of forecast accuracy. These forecasts are provided not only because the ET and VIL correlate with the updraft strength and thus the storm's intensity (and thus its overall danger to aviation), but also because pilots and other aviation users are accustomed to inferring storm danger from radar reflectivity. There is still a problem however; just how close can an aircraft fly to a given forecasted VIL and ET and remain safe including providing a comfortable ride for their passengers?

To define the total hazard volume associated with a given storm, we have developed an algorithm that scores the danger zone (i.e. WAF) according to the expected updraft intensity – as indicated by the forecast VIL and ET values. We believe this WAF would provide TFM decision support tools with more realistic traffic impact scenarios than simply the raw VIL and ET forecasts, and could also provide an alternative or supplement to the convective weather avoidance model (CWAM) as developed by MIT Lincoln Laboratory. [5]

Figure 2 depicts the mapping between VIL and ET values to the WAF level. In the figure the red area represents an "extreme risk," the orange area a "high risk," and the yellow area a "moderate risk." For this example, the clear area represents areas of both "no risk" and "slight risk." The mapping algorithm can be made flexible by using adaptable parameters that could be tuned for various climate regimes.

Lastly, incorporating the forecast confidence values presents one of the toughest challenges in how to represent confidence of the forecast WAFs to a tactical ATC display or a traffic flow management DST. In the case of a tactical ATC display, the conops for communicating hazardous areas as indicted by WAFs and their associated confidence to pilots requires further investigation. In the case of a traffic flow management DST, simply increasing the "buffer" distance around a region with a low-confidence is essentially today's practice using current tools which can lead to inefficient airspace planning for traffic flow. While confidence values for short time horizons (e.g., less than 1 hour) are relatively high, the confidence values for long term strategic time horizons (e.g., 1 – 6+ hours), tend toward relatively low – owing to the highly probabilistic nature of weather [10, 12]. Thus, a significant portion of future research in weather-ATM integration needs to consider not only the operations research aspects of weather avoidance route planning, but also the conops of dealing with forecast confidence values in strategic planning timeframes for TFM DSTs as well as ATC communication of tactical hazard conflicts to pilots.

| VIL | CR | Echo Tops (ft) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (0-256) | (dBZ) | 5,000 | 1,000 | 15,000 | 20,000 | 25,000 | 30,000 | 35,000 | 40,000 | 45,000 | 50,000 | 55,000 | 60,000 |
| 0-20 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21-36 | 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 37-56 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| 57-83 | 25 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 2 | 3 | 3 | 3 | 3 |
| 84-110 | 30 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 3 | 3 | 3 | 3 | 3 |
| 111-137 | 35 | 0 | 0 | 0 | 1 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 138-164 | 40 | 0 | 0 | 0 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 |
| 165-188 | 45 | 0 | 0 | 0 | 2 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 |
| 189-208 | 50 | 0 | 0 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 209-226 | 55 | 0 | 0 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 227-242 | 60 | 0 | 0 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| >242 | 65 | 0 | 0 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | WAF Level | | | | | | | | | | | | |
| | 4 | Extreme Risk (red) | | | | | | | | | | | |
| | 3 | High Risk (Amber) | | | | | | | | | | | |
| | 2 | Moderate Risk (green) | | | | | | | | | | | |
| | 1 | Slight Risk (blue) | | | | | | | | | | | |
| | 0 | (blank) | | | | | | | | | | | |

Figure 2. WAF Value Mapping from VIL and ET

We needed CIWS data for a sample day in the Denver region that had experienced convective activity. The Denver area was the area of choice as our prototype trajectory service included adaptation data similar to that used in the Denver area. To obtain the sample CIWS data, we turned to MIT Lincoln Laboratory for assistance. While Lincoln Lab researched sample data, we started to build a framework to "digitize" the Denver area airspace of interest as well as to develop a grid-based aircraft-to-WAF conflict service. We chose to limit the conflict look-ahead time to 30 minutes since beyond that time weather forecast uncertainties would need to be modeled. Thus, we required the WAF data set to include a current time data plus six additional forecast data sets where each data set corresponds to a 5 min future forecast. Since the CIWS VIL and ET products were 1 km x 1 km resolution, the resulting WAF data would also be 1 km x 1 km resolution. MIT Lincoln Lab graciously provided a sample data set shown in Figure 3 that included gridded VIL and ET in netCDF4 format. In addition to the VIL and ET data, Lincoln Lab also provided a prototype CoSPA convective WAF data set which we plan to integrate in the next phase of the project. An example of the combined WAF, ET data set is depicted in figure 4. This is a ¼ scale portable network graphics (PNG) image of the entire CIWS region with the hazard value plotted in subset area with an orange border that roughly corresponds to the area covered by the Denver ARTCC airspace. The Figure 4 map projection is different from the one in Figure 3. The red areas have both high VIL and ET and are thus most likely to be avoided by all aircraft. The blue areas have lower VIL and ET values that some aircraft may choose to penetrate. The gray areas have much lower VIL and ET values and thus are less likely to present an obstacle to air traffic.

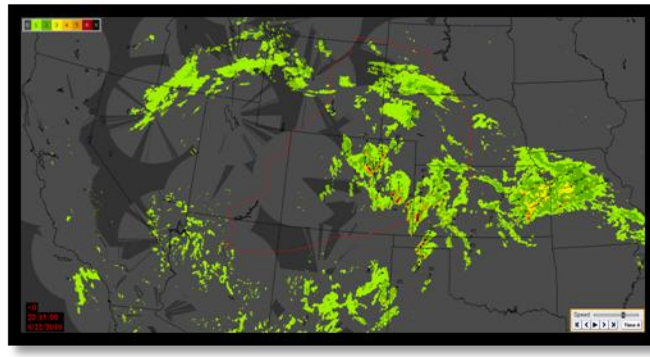

Figure 3. CIWS VIL Data Set from 2035z, April 22, 2010 (Courtesy: MIT Lincoln Laboratory)

From the 2-D ENSCO combined WAF-ET data set, LM created a 3-D WAF data set by extending the WAF value at a given grid point downward to the surface. We did this only for a convective WAF field to ensure that aircraft would not be routed under the convective weather. We would anticipate that such 3-D WAF data would eventually be published by the 4-D Weather Cube/SAS for a requested area of concern.

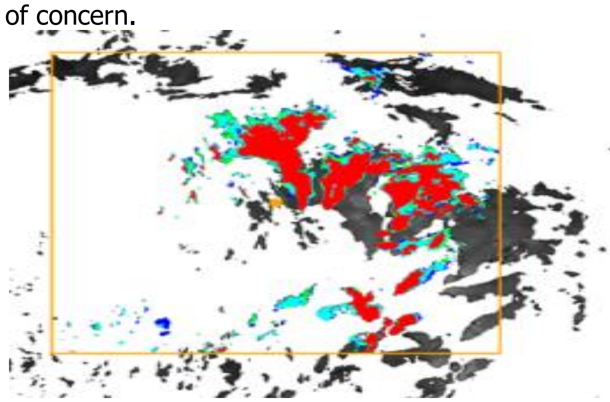

Figure 4. Combined 2-D WAF-ET Data Set

The process used to create the 3-D WAF was to consider a given grid cell and to extend the grid cell's WAF value from the surface up to and including the altitude of the grid's ET value. This array will be stored in netCDF4 format. Figure 5 depicts a Google Earth™ visualization of the 3-D WAF data.

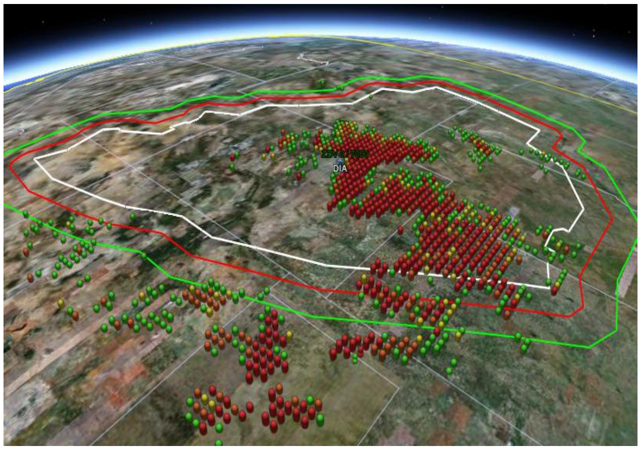


Figure 5. Visualization of 3-D WAF Array(10k x 10k)

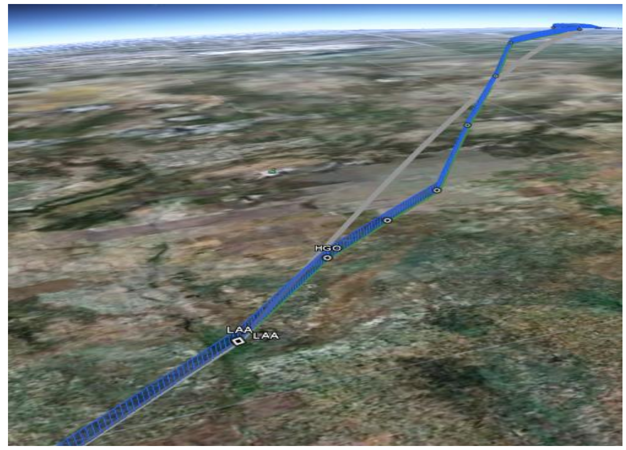


Figure 7. 4-D Trajectory

**2.2 Retrieval of net-enabled weather data based on CIWS SWIM service**

This portion of our project was deferred. Instead, we received sample CIWS data files from MIT Lincoln Lab and stored them locally. It would be our preference to retrieve data such as gridded WAF fields using a net centric format such as Weather Information Exchange Model (WXXM) over a NNEW/SWIM service.

**2.3 Flight Plan and Trajectory Prediction Service**

A simple service was created that either reads in existing flight plans or creates new flight plans and publishes those flight plans to a prototype trajectory prediction service, which converted the flight plans into NAS flight trajectories using a route conversion and trajectory generation algorithm similar to that used in the current en route automation system. See Figure 6.


Figure 6. Flight Plan/Trajectory Service Panel

Examples of a Seattle (SEA) –to- Dallas Ft. Worth (DFW) 4-D trajectory is shown by the blue wall in Figure 7. The trajectory is essentially the converted route with altitude cusps defining trajectory segments. The blue wall extends from the trajectory altitude down to the surface.

**2.4 Aircraft-WAF Conflict Detection (AWCD) Service**

The AWCD service and its interaction with other services used on this project is depicted in Figure 8. The AWCD uses the following generalized approach to detection of aircraft trajectory –to- WAF conflicts using a grid-based technique. At this time, the AWCD does not suggest alternate routes around the WAFs.

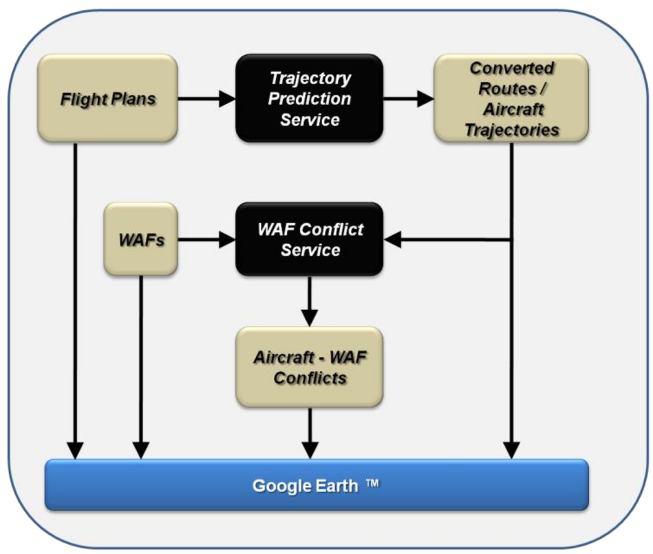


Figure 8. Aircraft-WAF Conflicts Service Block Diagram

1) <u>Digitize Airspace Containing Aircraft and WAFs</u>

We created a digitized volume of Denver's Air Route Traffic Control Center (ARTCC) Area of Responsibility (AOR) plus a 150 nm buffer. However, as a simplification for this project, the digitized volume is rectangular extending in height from MSL to 70,000 ft MSL. The airspace is digitized into an array of grid points where each grid point represents the center of a cell that is 1 km wide latitudinally by 1 km wide longitudinally and 1000 ft vertically.

2) Test for WAF Existence
Because we specified the sample data to include convective activity within the Denver ARTCC AOR, we assumed that WAFs exist in the Denver ARTCC AOR and thus, as another simplification, did not perform a test for WAF existence.

3) Bounding Volume Intersection Test (BVIT)
The BVIT is a first order test to determine if there is an intersection between an aircraft trajectory including its 3-D WAF buffer margins bounding volume (BV) and the WAF 3-D BV. The BVs would be created for each time increment.

4) Determine WAF Avoidance Margin Search Domain
To determine the WAF avoidance margin search domain, we need to establish the number of buffer cells surrounding the aircraft trajectory cell of interest at any time increment, that is, a cell occupied by an aircraft according to its trajectory at some time. The lateral search domain can be thought of as a single 2-D rectangular stereographic surface level plane consisting of three nested rectangular regions. The three nested avoidance regions can be visualized by considering a Russian wooden Matroshka doll that consists of rectangular regions at 5 km, 15 km and 20 km buffer margins latitudinally and longitudinally. The vertical search domain consists of nested vertical regions starting at the aircraft's current altitude extending above and below by 1000 ft, 3000 ft and 5000 ft margins.

The buffer margins referenced above were for research purposes only and not suggested to be used operationally. The actual buffer margins used operationally by pilots of general aviation or commercial airlines will be in accordance with their own personal weather minimums or company policy respectively. The Aeronautical Information Manual [11] suggests pilots avoid severe thunderstorms by at least 20 nm (i.e., ~ 40 km) laterally and by at least 1000 ft vertically for each 10 kts of wind speed at the cloud top. The margins described above were intended to be used as starting points in defining a pilot/company provided risk preference.

5) Search Algorithm to Determine AC-WAF Conflicts
Once the first order BV test passes, the detailed search algorithm begins using the WAF avoidance margin search domain. Each grid cell that the trajectory passes through is compared against the grid for the appropriate forecast time interval (there are grids at 5 minute intervals that represent time up to 30 minutes into the future). Any grid cell found to be within the WAF avoidance margin of the trajectory cell will cause a conflict to be generated. This algorithm allows different aircraft types or airline preferences to have different avoidance margins; for example, a cargo flight may be allowed to fly closer to a given level WAF than a passenger flight.

**2.5 Visualize Aircraft-WAF Conflicts**
Google Earth™ - a simple visualization tool, was selected to visualize the WAF, flight plans, trajectories and Aircraft-WAF conflicts. We selected Google Earth™ to avoid significant development and complication of the visualization function. This allowed us to focus on the content of the research that had more significant unknowns and risk. i.e., the WAF itself and the Aircraft-WAF conflict detection service. Google Earth™ has proved itself to be an effective visualization tool for all involved. When the search algorithm finds a WAF cell within the aircraft trajectory WAF buffer region, the trajectory segment for the corresponding trajectory cell at the time increment under evaluation is highlighted in a color corresponding to the trajectory buffer margin penetration and of the proximate WAF cell value. The output of the conflict service returns the subset of aircraft trajectory segments with a conflict including the value of the conflict (WAF 1-4). See Figure 9.

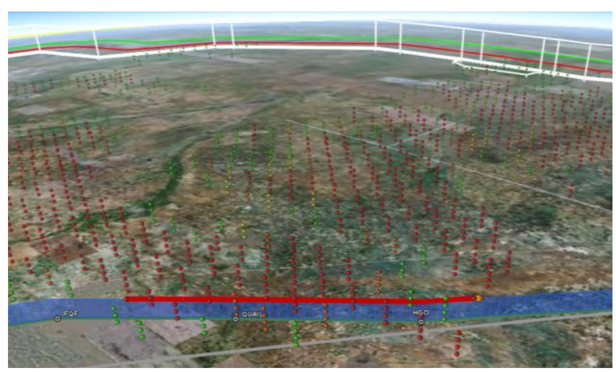

Figure 9. Aircraft - WAF Conflicts for SEA-DFW flight

## 3. Conclusion

Our work to date has demonstrated the viability of using a gridded representation of a hazardous weather product that may be published by the 4D weather cube. We have integrated this gridded representation with existing 4D trajectory models to detect conflicts in a way that can be tailored for aircraft types and operator preferences. We currently have used netCDF4 format for the weather products; future work will incorporate net-centric WXXM-based gridded models received from a NNEW/SWIM service when available.

Additionally, we look to the aviation weather science community for continued development of gridded hazardous weather products to be used in trajectory-based integration, that include other weather phenomena, specifically addressing the variability of the weather phenomena hazard, spatial resolution of the gridded representation and the temporal resolution of the product updates.

## Acknowledgements

The authors are grateful to MIT Lincoln Laboratory for providing sample CIWS data used in this project. We further acknowledge the work of Erik Magnuson of ENSCO and Lockheed Martin Engineering Interns Michael Robinson and Ben Owen.

## References

[1] Report of the Weather-ATM Integration Working Group, FAA Research, Engineering and Development Advisory Committee, October 3, 2007 http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/nextgen/research_tech_dev/research_planning/redac/reports/media/pdf/report_weather_atm_integration_working_group.pdf

[2] M.W. Burkle, T. Montgomery, The Integrated Airport – A NextGen Test Bed. *2008 ICNS Conference, Bethesda, MD May 2008*

[3] Jardin, Matt R, Grid-Based Air Traffic Control Strategic Conflict Detection, *AIAA Guidance, Navigation and Control Conference and Exhibit*, 15-18 August 2005, San Francisco, CA

[4] May, J., The concept of convective hazard volume, presentation given to JPDO Weather Working Group Environmental Information Team, April 3, 2009.

[5] R. DeLaura, M. Robinson, M. Pawlak, J. Evans, Modeling Convective Weather Avoidance in En Route Airspace. *13th Conference on Aviation, Range and Aerospace Meteorology (ARAM), Amer. Meteor. Soc.,* New Orleans, LA January 2008

[6] R. DeLaura, B. Crowe, R. Ferris, J. Love, and W. Chan, Comparing convective Weather Avoidance Models and Aircraft-based Data. *89th Annual Meeting of the American Meteorological Society: Aviation, Range and Aerospace Meteorology Special Symposium on Weather – Air Traffic Impacts,* Phoenix, AZ, January, 2009 *.*

[7] R. Avjian and J. Stobie, "NextGen En Route Weather Integration Strategies", *Proceedings of the ATCA 53rd Annual Conference and Exposition,* Washington, DC Nov 2008.

[8] R. Avjian, J. Stobie, Strategies for Air Traffic Management Integration of Hazardous Weather. *Proceedings of the ATCA 54th Annual Conference and Exposition,* Washington, DC October 2009

[9] Matthews, Michael P. and Rich DeLaura: "Evaluation of Enroute Convective Weather Avoidance Models Based on Planned and Observed Flights," *14th Conference on Aviation, Range, and Aerospace Meteorology (ARAM)*, Atlanta, GA, 2010

[10] CoSPA and Integration with ATM. Presentation by National Center for Atmospheric Research (NCAR) – Lockheed Martin Technical Interchange Meeting, July 30, 2008, Boulder, CO

[11] Federal Aviation Administration, *Aeronautical Information Manual*, February 11, 2010. http://www.faa.gov/air_traffic/publications/ATpubs/AIM/

[12] MIT Lincoln Laboratory, Roadmap for weather integration into traffic flow management modernization (TFM-M), Project Report ATC-347, MIT Lincoln Laboratory, Lexington, MA, 2009.http://www.avmet.com/CMS/CMSDocs%5CProject%20Report%20ATC-347.pdf