

MODELING WEATHER IN SIMULATION AND ANALYSIS

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Abstract

In the concept development and validation process, fast-time simulation and modeling exercises are performed to examine system performance, obtain initial assessments of potential benefits, and to identify potential problem areas where real-time simulation studies are necessary for further exploration^[1]. Despite the immense impact weather has on the National Airspace System (NAS), most simulation and analysis tools are unable to represent weather activity. This creates a large gap in the capabilities of future concept analysis such that potential benefits of some operational improvements cannot be quantified.

The FAA's Concept Analysis Branch (ANG-C41) developed a tool which uses high fidelity weather data to create weather polygons. These weather polygons provide a much more concise model to store and process in simulation and analysis tools. In a fast-time simulation environment, the weather polygons can be modeled as restricted airspace that moves across the NAS. This enables researchers to measure the impact of operational improvements on weather-related flight delays. The weather polygons can also be used in analytical tools such as ANG-C41's FliteViz4D. Incorporating the weather polygons into this tool allows the user to animate both air traffic and weather in one three-dimensional view. This is very useful when examining the impact of weather on air traffic.

In this paper, the Concept Analysis Branch describes the process of creating and using weather polygons for simulation and analysis activities. An example study is discussed where weather polygons are used to determine the impact of weather on flight efficiency in today's NAS. Finally, the weather polygons are tested in a fast-time simulation environment.

Introduction

The Next Generation Air Transportation System (NextGen) is the proposed solution to safety, capacity, and efficiency problems that is anticipated to result from an expected increase in air traffic. The Federal Aviation Administration (FAA) is primarily responsible for the implementation of NextGen which includes improvements to the management of flight operations, pilot and controller situational awareness, terminal environment flexibility, environmental impact, and weather prediction and avoidance. Convective weather is a significant cause of flight delay as aircraft must avoid severe weather to ensure safety. Multiple enhancements to weather prediction and avoidance techniques are included in the NextGen plan and are expected to reduce flight delays and safety hazards caused by convective weather.

Furthermore, the impact of weather on the National Airspace System (NAS) must be considered when analyzing NextGen concepts. Fast-time simulation and modeling exercises are performed to examine system performance, obtain initial assessments of potential benefits, and to identify potential problem areas where real-time simulation studies are necessary for further exploration^[1]. However, weather has traditionally been excluded from fast-time simulation studies due to its complexity in modeling. To satisfy a need for the capability to include weather in a fast-time environment, the FAA's Concept Analysis Branch (ANG-C41) developed a tool which creates weather polygons from recorded radar measures of convective activity. These polygons can then be used in fast-time simulation models and analysis tools.

Purpose

To measure the potential benefits of planned operational improvements, researchers must first understand current practices during flight, including weather avoidance. Data analyses can provide the

researcher with some knowledge of weather avoidance, but the ability to visualize the actual movements of aircraft around a weather event is invaluable. With the inclusion of weather in ANG-C41's tool FliteViz4D^[2], an analyst can view flights, airspace, and weather in three-dimensional space and easily examine patterns and anomalies. An example of the use of FliteViz4D will be detailed in later sections.

Given the known impacts weather has on flight operations, the capability to simulate weather in fast-time models is necessary to accurately evaluate NextGen concepts. Current simulation tools may consider wind conditions but are limited in their functionality for representing convective weather. Thus, ANG-C41 developed the capability to export convective weather polygons for use with current simulation models. We will show an example of how the weather polygon tool was used in a fast-time simulation model.

Background

There have been many studies which examine the current behavior of aircraft rerouting around weather. The methodologies and results of the studies described below provide a background of the research topic.

A study conducted by ISA Software explored the potential benefits of a multi-sector planner (MSP) role in the efficiency of the trajectory flow management (TFM) process during weather events. The study compared the total distance of a flight during a clear weather day with the total distance of the same flights when weather was present. Reportedly, 3.5% of more than 62,000 flights flew up to 200nm greater than originally planned during convective weather activity^[3]. The conclusions discussed opportunities for improvement in efficient TFM operations; however, the study included all flights, those affected and not affected by the weather, in the airspace since no method for identifying weather rerouted aircraft was available. Therefore, the MSP study results could be skewed since no other causes of flight vectoring were considered.

A Massachusetts Institute of Technology (MIT) graduate research thesis was conducted in 1999 to

determine distances between aircraft and precipitation of varying intensities. Distances were determined through pilot surveys and interviews as well as track data from the Dallas Fort-Worth area. The study concluded that aircraft increase their distance from weather as the intensity of the weather increases^[4]. Traffic levels and aviation technologies have changed since the study was performed; therefore, a follow-on study was appropriate. No visualization techniques or simulation were used in this study.

Another MIT Lincoln Lab (LL) study described an en route convective weather avoidance model that includes an algorithm to transform gridded, deterministic forecasts of radar echo top height and vertically integrated liquid (VIL – a measure of precipitation intensity) into three-dimensional weather avoidance fields. This algorithm was studied and led to the development of the ANG-C41 Weather Polygon Creator^[5].

Creating Weather Polygons

There are two main steps in creating weather polygons for use in fast-time simulation and analysis. First, researchers must obtain the weather data from meteorological professionals who acquire the data via sensors and other equipment. Second, the weather data is processed through a Weather Polygon Creator. The details of each step are below.

Weather Data

The first step in obtaining weather data is finding weather days with severe weather in the study's focus area. To do this, an analyst may view NEXRAD National Mosaic Reflectivity Images on the National Oceanic and Atmospheric Administration (NOAA) website. Users of the website can view animation of the weather maps per hour for a selected day to evaluate the location and severity of weather events. Figure 1 shows an example of a NEXRAD image from NOAA's website. Alternatively, a weather day may be chosen by following daily weather forecasts and preemptively deciding to record the weather when it is particularly convective.

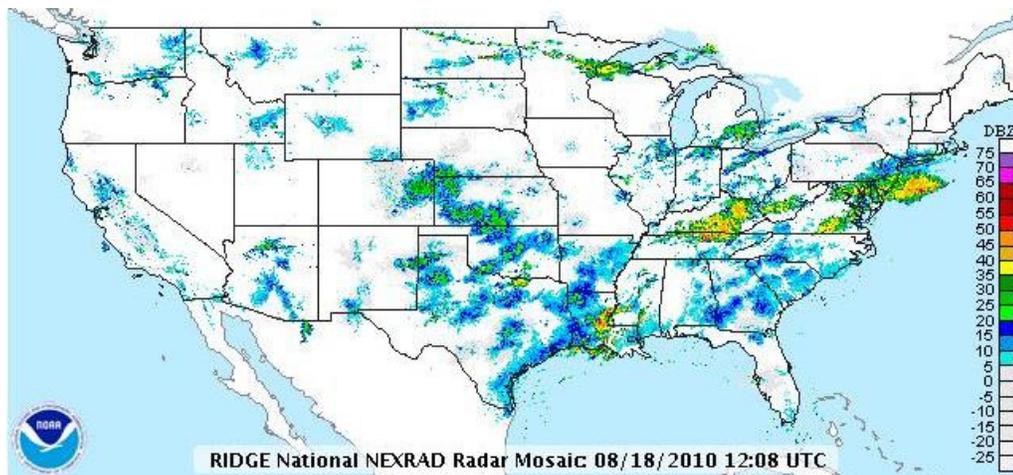


Figure 1. NEXRAD Weather Map for 8-18-2010⁶¹

Next, the type of data required for the study must be determined. Forecast weather data may be sufficient for a study involving a fictitious scenario, and multiple data sources may be available. However, if a historical event is to be evaluated, recorded weather data is required. ANG-C41 found that only one source provides high fidelity, recorded weather data for multiple altitude bands. Researchers in the FAA’s NAS Weather Group acquire Multi-Radar/Multi-Sensor (MRMS)^[7] weather data from NOAA and provide it to other FAA teams via a convenient website. Currently, the NAS Weather Group stores the MRMS data for ten days and users may download their data from the selection listed on the site.

The MRMS data is provided in a binary format called NetCDF¹. The data contains a four-dimensional array that has a single value of radar reflectivity measured in decibels relative to Z (dBZ²) at each time, latitude, longitude, and altitude combination. In 2010, data measurements were taken every 2.5 minutes at each 0.01 degrees in each direction, with 31 altitude levels ranging from 1,600 ft to 50,000 ft. Weather data from 2011-2013 provides these measurements every 2 minutes, and future versions of the tools are expected to provide data every 30 seconds. This grid of data covers the continental USA and the lower half of Canada, but it

is split into eight tiles in order to provide more manageable sizes (Figure 2).

Reflectivity values provided in the MRMS data can be translated to hazard levels that align with the National Convective Weather Forecast (NCWF) Hazard Levels as shown below in Table 1. This allows analysts to interpret and visualize the weather data in a more familiar manner.

Reflectivity (r) in dBZ	NCWF Hazard Level
$r < 30$	1
$30 \leq r < 41$	2
$41 \leq r < 46$	3
$46 \leq r < 50$	4
$50 \leq r < 57$	5
$r \geq 57$	6

Table 1. Hazard Level Definition of Reflectivity Values

¹ <http://www.unidata.ucar.edu/software/netcdf/>

² http://www.srh.noaa.gov/jetstream/append/glossary_d.htm

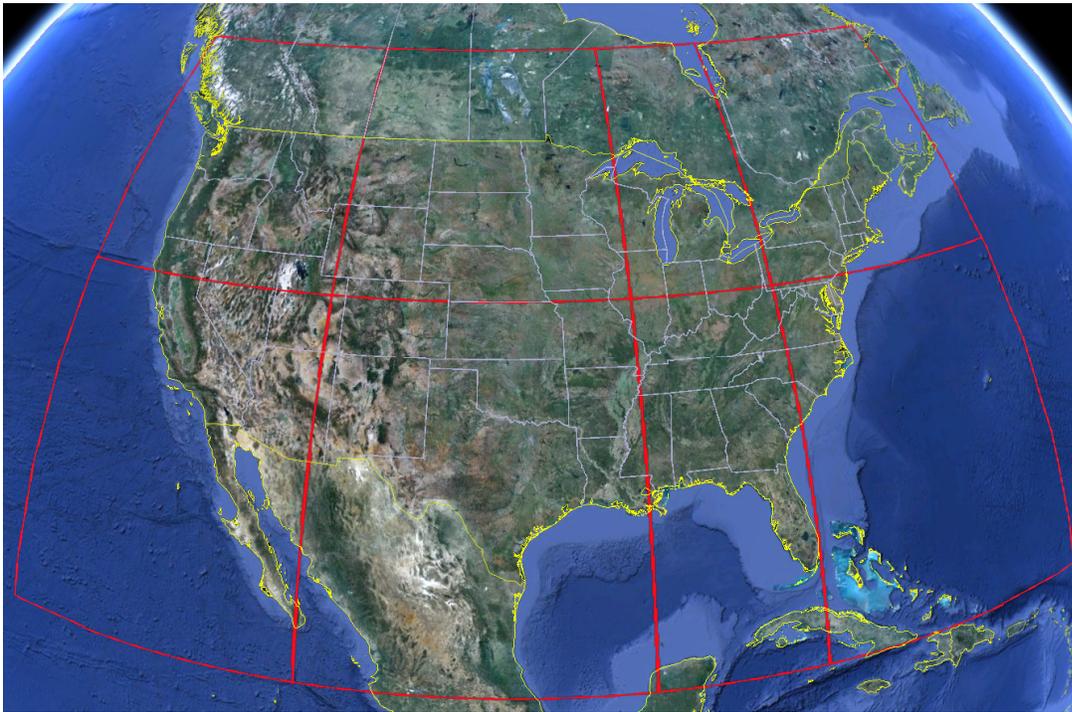


Figure 2. MRMS tiles overlaying the continental USA

Weather Polygon Creator

The descriptive detail of the convective weather contained in the MRMS data requires a large amount of storage and processing power to manage and use it for calculations or visualizations. To mitigate this limitation, ANG-C41 created a tool that transforms the essential information into polygon models.

The Weather Polygon Creator converts MRMS weather data into three-dimensional polygons to be used in fast-time simulations and other data processing tools. Since the MRMS data set is very large, the eight tiles (latitude-longitude grids illustrated in Figure 2) that comprise it are processed through the conversion tool individually. An MRMS file associated with each tile contains reflectivity values for 31 altitude bands at a point in time, with a file existing for every 2 or 2.5 minutes (depending on the year of the data). Several files can be processed concurrently.

During the conversion process, a polygon is created for each hazard level at each of the 31 altitude bands. Since there is a large amount of data,

only reflectivity values at or above 18 dBZ are used. This value represents light precipitation and is the minimum reflectivity value considered for the creation of echo tops; thus, reflectivity values below 18 dBZ are assumed to be negligible for aviation studies. A reflectivity value is assigned to each cell in the grid.

Within a specific altitude band, a cluster algorithm is used to group neighboring cells by reflectivity value. The algorithm groups cells with hazard level at or above the current level, starting with Level 1 and moving consecutively until Level 6. Figure 3 below illustrates this process. A polygon is created to encompass the cluster of cells for each hazard level, and the algorithm begins the same process for the next altitude band. The result is a collection of polygons at each altitude band that contains individual polygons representing weather at each hazard level. These polygons are stored in a database table and used in data processing and analysis tools including FliteViz4D.

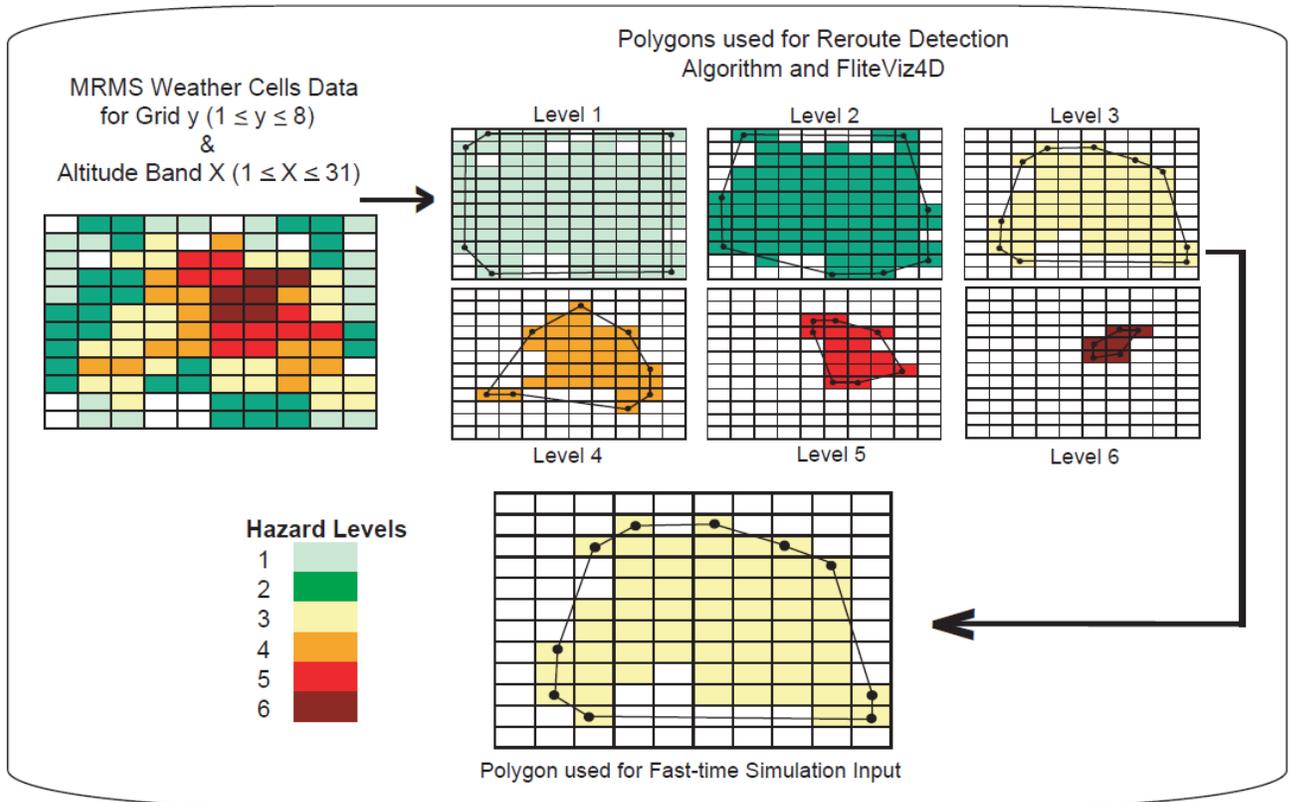


Figure 3. Weather Polygon Creator Process Diagram

In fast-time simulation, weather polygons can be used to force flights to reroute around the piece of airspace that is blocked by convective weather. For this purpose, only one polygon representing the boundary of severe weather is needed in order to model aircraft avoiding the weather. ANG-C41 considered convective weather severe if it possessed a hazard level of 3 or greater. Thus, the Weather Polygon Creator can group nested or combined polygons of hazard levels greater than 3 and create one polygon to represent severe weather.

This process is repeatable; data from another day or for another tile can be used as input to create new weather polygons. Once the tables have been populated, it is a simple process of formatting the data into the specific fast-time model file format to import the polygons into a fast-time simulation tool.

Using Weather Polygons

There are numerous benefits to creating weather polygons from raw data. First, stored polygons are

much smaller than stored raw weather data, reducing the amount of computer storage space and memory needed. Second, they can more easily be used to calculate flight metrics associated with the weather such as the number of flights which penetrated the weather, number of flights which deviated to avoid weather, and the minimum distance which flights flew near convective weather. Third, polygons are much easier to view in a three-dimensional visualization tool. Finally, polygons may be used in simulation tools to model the effect of weather on NAS operations.

Calculating Metrics in Analytical Tools

In 2010, ANG-C41 was tasked to examine the behavior of flights near convective weather. Once the weather data was gathered and converted into polygons, new tools were created and used to measure the proximity of flights to the weather polygons and to count how many aircraft rerouted to avoid the convective weather^[8].

This study focused on the Washington, DC (ZDC) and Indianapolis (ZID) Air Route Traffic Control Centers and utilized the MRMS weather data in tiles covering the majority of ZDC and ZID. The ZDC data contained 124 million measurements while ZID data contained 62 million measurements.

Two analyses were conducted in this study. The first analysis identified flights within 20nm^[9] of a weather polygon and calculated the minimum distance of each flight to each weather polygon. The second analysis identified flights that were rerouted to avoid weather and calculated the deviation from their planned route. Weather polygons enabled the use of new tools to efficiently perform these calculations. Some details of the use of these tools in the proximity to weather and weather reroute analyses are described below.

Proximity to Weather Analysis

One of the objectives of this study was to determine how close aircraft fly to different severity levels of weather. This analysis was particularly interested in aircraft that are not adhering to their current flight plan. Since the FAA recommends maintaining a safe 20nm distance from any weather, only flights within 20nm of weather were considered in this analysis.

A software application was developed to measure the distance of each flight to each severity level of weather for each recorded position of the flight. This tool was used to identify flights within 20nm of weather and provided the distance of each flight to the six hazard levels of weather at 10 second intervals. Analysts used a suite of in-house aircraft trajectory tools calculated for each 12-second radar surveillance track point on all flights to identify instances where a flight deviated from its current flight plan. Analysts identified the closest position at which each flight flew near the weather. The minimum distance to each level of weather was found for each flight, and the distribution of these results was reported.

Weather Reroute Analysis

Another objective of this study was to identify aircraft that were rerouted due to weather and to calculate the distance between the original route and the actual flight path.

To do this, the Reroute Detection Tool was used to identify weather reroutes, and accuracy metrics obtained from a suite of in-house trajectory tools were used to analyze the distance flown off the original route.

The Reroute Detection Tool algorithm was implemented in a program to automate the process. The steps of the algorithm are as follows:

1. Generate a new predicted trajectory at each route amendment that follows the route at the flight's current altitude and speed.
2. Calculate distance of each predicted trajectory point (10 second sample time) to each of the four most severe reflectivity level (3-6) polygons.
3. Flights that possess at least one predicted trajectory which penetrates a weather polygon of hazard level 3-6 are flagged as weather reroutes.
4. For each flight, find the trajectory that goes the furthest into the maximum reflectivity polygon. This trajectory will be compared against the actual flight path of the aircraft.

The key metric used for this analysis was horizontal deviation. This metric reflects the difference in horizontal location between the original route and the actual flown flight path at the same moment in time. Figure 4 below provides an illustration of the horizontal deviation, and details on the calculation of this metric can be found in "Implementation and Metrics for a Trajectory Prediction Validation Methodology."^[10]

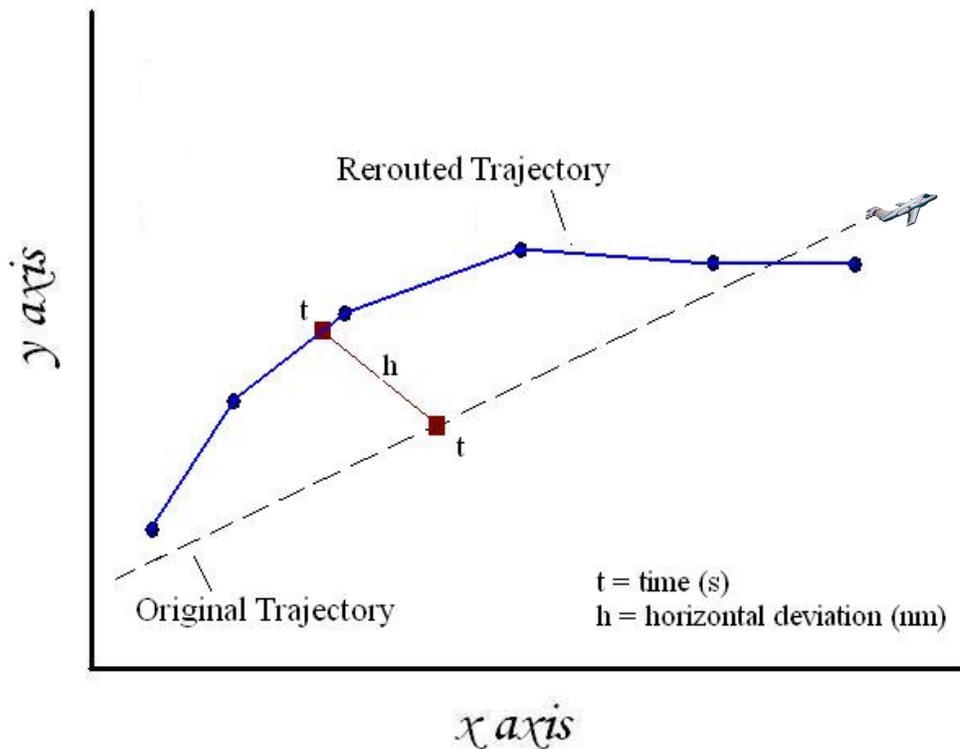


Figure 4. Horizontal Deviation Metric

The horizontal deviation for each flight was calculated every 10 seconds and recorded at each track point at which the original flight plan was inside a weather polygon of level 3 through 6. A large number of aircraft fly directly through weather at levels 1 and 2; these aircraft were not considered in this analysis since pilots do not typically reroute around such mild convective activity.

At each track point when the original flight path was predicted to enter the weather, the horizontal deviation of the actual flight path was calculated. Figure 5 below depicts this calculation. The maximum horizontal deviation for each flight was found and analyzed.

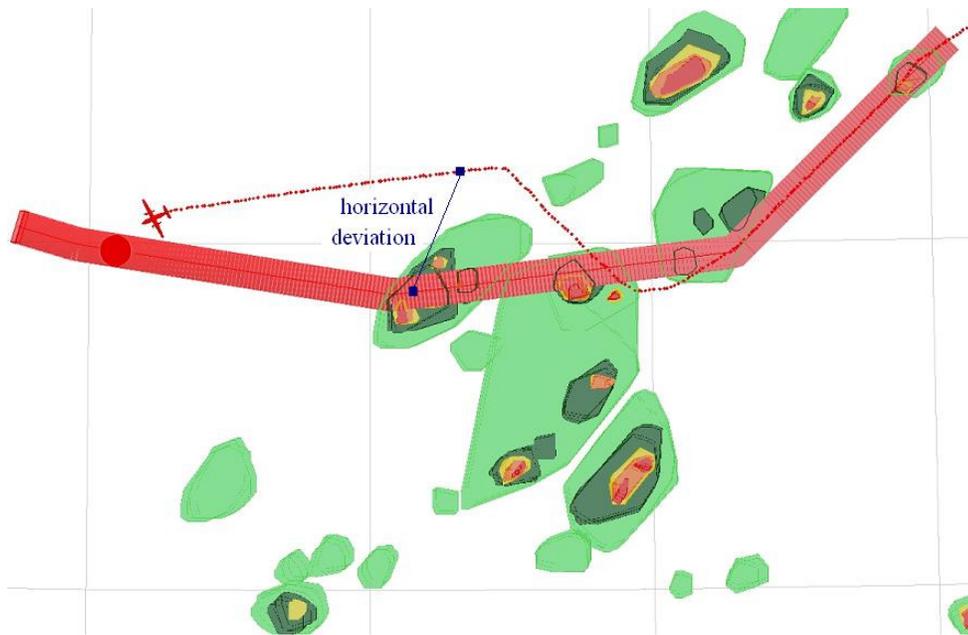


Figure 5. Horizontal Deviation of Weather Rerouted Flight showing Flight Plan (red, solid tube) and Actual Flight Path (red, dotted line)

Visualizing Weather in FliteViz4D

FliteViz4D is an interactive three-dimensional visualization tool for air traffic data built by ANG-C41. For the study described above, the capability was added for three-dimensional weather polygon visualization. Using this new option and its ability to show flight paths and trajectory predictions, users can view the air traffic data with the convective weather and see the reroutes from all angles with a high level of detail. The trajectory prediction display allows the analyst to see where the flight would have been if it had not rerouted around the weather. This tool was useful in validating the Reroute Detection Tool since the analyst could clearly see the aircraft avoid the

weather as the reroute occurs. FliteViz4D was also used to visualize the behavior of outliers in the proximity to weather analysis.

Figure 6 shows an example of one of the aircraft rerouting around the severe weather cells as it takes off. Since the reroute analysis only considers hazard levels of 3 through 6 (yellow, orange, red, and dark red), levels 1 and 2 are hidden in this visualization. The small, purple airplane is where the flight is located currently, and the diamond trail behind the aircraft is the actual flight path. The purple tube is the path the aircraft would have flown if it had not rerouted around the weather.

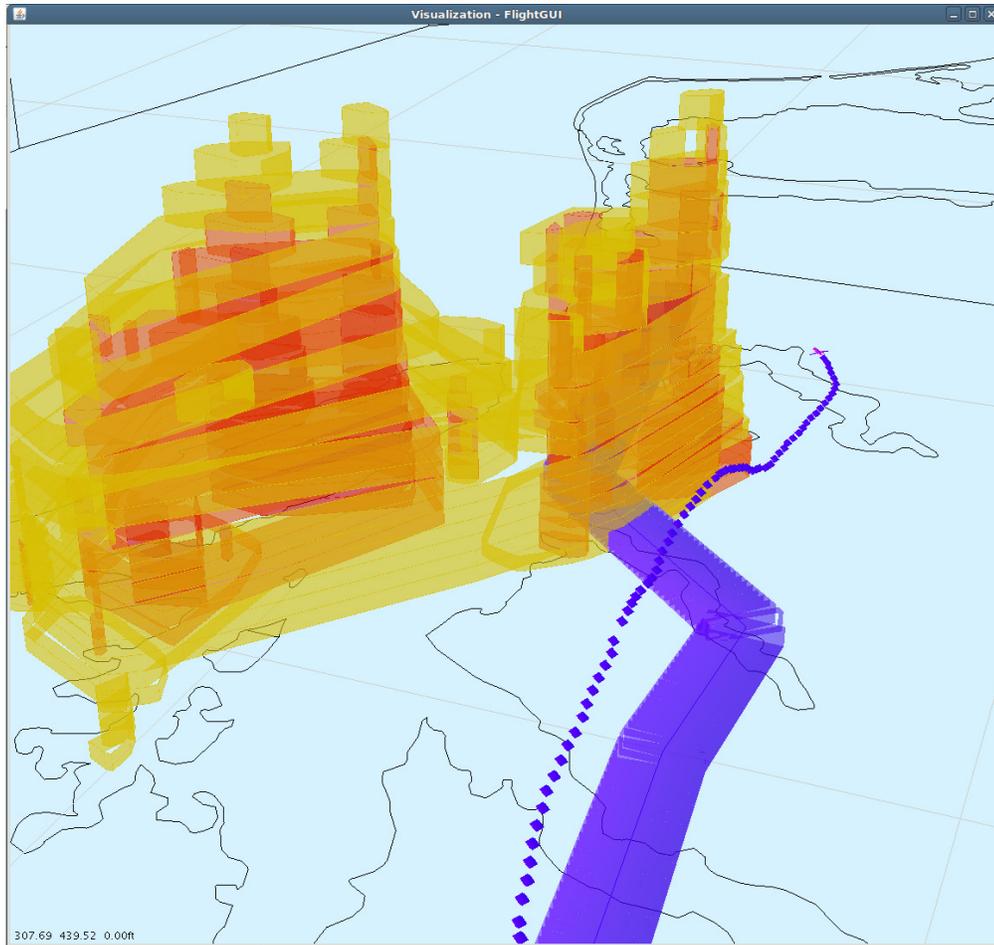


Figure 6. FliteViz4D Visualization of Flight (purple, dotted path) Deviating from Planned Route (purple, solid tube) to Avoid Severe Weather

Modeling Weather in Fast-Time Simulation

RAMS Plus is developed and supported by ISA Software and features 4-D flight profile calculation, 4-D sectorization, and 4-D spatial conflict detection and resolution (CD&R). Both enroute and terminal environments can be modeled in RAMS Plus, and traffic route flows and procedures can be easily modified by the analyst to fit any study. ANG-C41 uses RAMS Plus to define and evaluate potential benefits of NextGen concepts.

One of the key features in RAMS Plus is the ability to reroute around restricted zones such as Military Operations Areas (MOA) and Special Activity Airspace (SAA). By importing weather polygons created in the Weather Polygon Tool, ANG-C41 may use this feature to depict weather polygons as restricted zones. RAMS Plus can perform rerouting using user defined avoidance routes or automatically through the CD&R algorithms. For proof of concept, ANG-C41 elected to use the automated feature since defining an avoidance route around each polygon would be time consuming and inefficient.

To define the restricted zone(s), one must create polygons similarly defined as sectors with a boundary, floor, and ceiling. In addition, each polygon can be turned on or off by associating it with on and off times during the simulation. The creation of the polygons is performed by the Weather Polygon Creator defined above. When creating the polygons

the user can specify the duration and time interval to sample the data. For example, the proof of concept test uses a one hour sample of weather data with a ten minute update interval. Figure 7 is a screen shot of the RAMS plus test scenario depicting the Air Traffic Control (ATC) sector boundary (blue), flight tracks (white), and weather polygons (red).

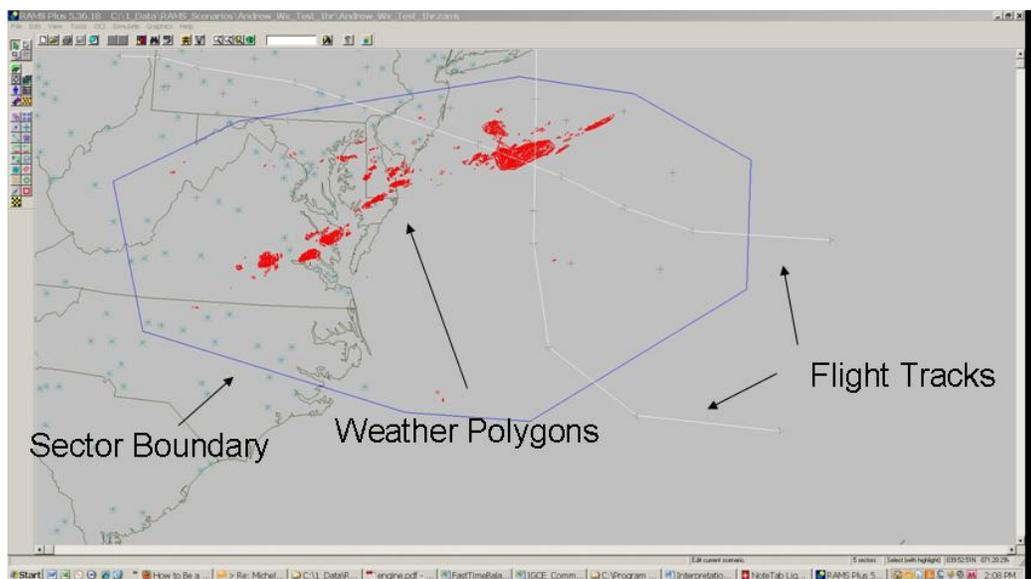


Figure 7. RAMS Plus Screen Shot with Weather Polygons

To test the proof of concept, a small traffic sample was created in which each aircraft's flight plan flew through the weather polygons. As the simulation progressed, the weather polygons turned on and off depicting the changes in the convective weather forecast. Once an aircraft entered a sector, RAMS Plus simulated controller actions, including CD&R. For this test RAMS Plus performed CD&R on both the restricted zones (weather polygons) and crossing traffic providing conflict free flight paths for the aircraft. ANG-C41 concluded that this was a sound test of using the polygon tool in conjunction with a fast-time simulation tool.

However, there were two limitations identified in using the polygon tool for fast-time simulation. These limitations were a byproduct of the high fidelity of the MRMS data. First, the number of

polygons created as restricted zones caused a degradation in RAMS Plus processing speed. Second, the number of polygons restricted the simulation time to one hour with ten minute intervals. To address these limitations, ANG-C41 will determine a method of describing the polygons in less detail. Some of these limitations were experienced and identified by NASA Ames Research Center^[11] when implementing weather polygons into the Airspace Concept Evaluation System (ACES).

Conclusion

In summary, the FAA's Concept Analysis Branch has filled a gap in the simulation and analysis community by developing the capability to model weather in analytical tools and fast-time simulation. While any gridded weather data may be represented

by the weather polygons, ANG-C41 has used the tool to transform convective weather data from NOAA's MRMS weather product into manageable weather polygons which can be used for numerous analyses and calculations. The polygons may also be used in fast-time simulations to represent weather in NextGen concept development and validation activities.

In an analysis of the efficiency of current weather avoidance operations, weather polygons were used in algorithms to calculate the distance of each flight from weather at different severity levels as well as to identify flights which rerouted to avoid moderate to severe convective weather. These weather polygons were added to the three-dimensional visualization tool FliteViz4D to allow researchers to animate air traffic and weather and identify patterns and anomalies within the data. The Concept Analysis Branch also demonstrated the use of weather polygons in the fast-time simulation model RAMS Plus. This capability enables the FAA to represent the impact of convective weather on NextGen operational improvements.

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