

# Studying NextGen Concepts with the Multi-Aircraft Control System

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**This paper describes new functionality recently added to the Multi Aircraft Control System (MACS) software. MACS is a comprehensive research platform used in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center that has been developed to increase the overall realism and flexibility of controller- and pilot-in-the loop air traffic simulations. The research focus in the AOL is on examining distributed air traffic operations in complex air/ground environments. MACS was originally developed to rapidly prototype new interfaces, displays, tools and operational concepts for managing air traffic and evaluating them from different perspectives. New capabilities have been added to MACS to better investigate NextGen concepts, including the capability to simulate airspaces that span multiple Air Route Traffic Control Centers (ARTCCs), and powerful tools for creating and editing custom traffic and weather scenarios.**

## Nomenclature

<i>AAC</i>	=	Advanced Airspace Concept
<i>ANSP</i>	=	Air Navigation Service Provider
<i>AOL</i>	=	Airspace Operations Laboratory
<i>ARMD</i>	=	Aeronautics Research Mission Directorate
<i>ARTCC</i>	=	Air Route Traffic Control Center
<i>ASDI</i>	=	Aircraft Situation Display to Industry
<i>ATC</i>	=	Air Traffic Control
<i>ATM</i>	=	Air Traffic Management
<i>CPDLC</i>	=	Controller-Pilot Data Link Communication
<i>DFW</i>	=	Dallas-Fort Worth airport
<i>DSR</i>	=	Display System Replacement
<i>ETMS</i>	=	Enhanced Traffic Management System
<i>FAA</i>	=	Federal Aviation Administration
<i>FMS</i>	=	Flight Management System
<i>HITL</i>	=	Human-In-The-Loop
<i>JPDO</i>	=	Joint Planning and Development Office
<i>MACS</i>	=	Multi Aircraft Control System
<i>NAS</i>	=	National Airspace System
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>NextGen</i>	=	Next Generation Air Transportation System
<i>RNAV</i>	=	Area Navigation
<i>SID</i>	=	Standard Instrument Departure

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*STAR* = Standard Terminal Arrival Route  
*SUA* = Special Use Airspace  
*TRACON* = Terminal RADAR Approach Control  
*TSAFE* = Tactical Separation-Assisted Flight Environment  
*VOR* = VHF Omni-directional Range  
*ZID* = Indianapolis ARTCC

## I. Introduction

The air traffic management (ATM) concepts defined in the Next Generation Air Transportation System (NextGen)<sup>1</sup> include a shift towards trajectory-based operations and larger planning horizons, aiming to become a more strategic and efficient transportation system. Because of this, the task of the Air Navigation Service Provider (ANSP) is expected to change significantly. The ANSP of NextGen will be less tactical, and focus on “the strategic management of traffic flows in high density airspace.” When also considering the predicted growth in traffic levels, it becomes possible that an ANSP will be managing complex flows of traffic over longer time horizons.

Research in NASA’s Airspace Operations Laboratory (AOL)<sup>2</sup> at the Ames Research Center uses the Multi-Aircraft Control System (MACS)<sup>3,5</sup> to investigate NextGen concepts through Human-In-The-Loop (HITL) simulation. The MACS software is used for building the appropriate air traffic environments and operator workstation prototypes to evaluate candidate roles and responsibilities, and see how controllers and pilots manage the traffic situation. The ongoing research associated with NextGen ATM operations has required that new capabilities be added to MACS in order to simulate the traffic scenarios necessary to appropriately test those concepts.

In this paper we present new capabilities implemented for the MACS software. Functionality is discussed to illustrate how MACS can be used as an effective tool for simulating prototype ATM working environments, producing research that addresses the human factors associated with operator roles and responsibilities, and the human/system/automation interaction issues inherent in NextGen concepts. Funding for this work was provided by NASA’s Aeronautics Research Mission Directorate (ARMD) and Airspace Systems research program.

## II. Simulation Infrastructure

Previous research conducted in the AOL has mostly looked at concepts focused around one major airport or taking place in a generic airspace. Full exploration of these concepts was achieved within just one Air Route Traffic Control Center (ARTCC), and typically only a few sectors within that ARTCC. By contrast, NextGen concepts that are more strategic and trajectory-based in nature need to be investigated on an appropriately larger scale, potentially ranging from one or two ARTCCs in the National Airspace System (NAS) to NAS-wide operations. However, being limited to examining concepts within just one ARTCC did not allow the AOL to easily study the issues pertaining to the coordination procedures between ARTCCs, coordination between neighboring metroplex airports, or the implications of a tested operational concept over long en route segments.

As the scale of the concepts being investigated grew, the requirements for those research activities evolved, creating a need to provide a simulation environment for large scenarios. In response, the capability to simulate an airspace that can extend across multiple ARTCCs has been implemented in MACS, enabling researchers to investigate “bigger” ATM concepts.

### A. Multiple ARTCCs

Before startup, MACS requires that an airspace be specified, so as to load the correct navigation database associated with that airspace. An airspace’s database includes several elements that collectively are referred to as an adaptation. At a minimum, a given adaptation will include waypoints, VORs, Navaids, sector boundaries, sector names, TRACON video maps, airways, jet routes, meter fixes, Special Use Airspaces (SUAs), published Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs), and airports and runways. Additionally, an airspace adaptation can include sector frequency assignments, published holding patterns, and TRACON RNAV route definitions.

In order to simulate multiple ARTCCs, the architecture used by MACS to load a database was modified to include parameters for a primary airspace adaptation as well as any number of auxiliary airspace adaptations. Inside a configuration file using the “Airspace Directory” parameter, the user specifies the primary airspace adaptation. If additional airspace adaptations are desired, the user can specify them using the “Secondary ARTCCs Directories” parameter.

Loading multiple airspace adaptations required that certain objects in the navigation databases be redefined. To avoid duplicate object names, more specific naming conventions were adopted in MACS. Sector names and runways were originally identified without reference to their specific ARTCC, such as “runway 18R” or “sector 91.” To be compatible with the multiple ARTCC architecture, a new naming convention was implemented that included the ARTCC as part of the object name. Taking from the previous example, the new object names would be “DFW18R” for the runway and “ZID\_91” for the sector. Although the new naming convention was necessary for loading multiple airspace adaptations, it was implemented in a way that maintained a level of flexibility and backwards-compatibility for specific situations. When controllers initiate the handoff of a plane from their sector to the next, they expect to only need to specify the two-digit sector number (e.g., 91). Even after the databases were changed to the new naming convention, this method of initiating handoffs was preserved in order to maintain consistency with the controller’s expectations of standard working procedures.

## **B. Traffic Levels**

When simulating a test airspace, regardless of size, the surrounding area’s traffic needs to be sufficiently populated so as to look realistic and not too sparse. If the traffic is too light, there can be a false lack of external pressure on the test airspace. When this requirement is applied to large airspaces spanning multiple ARTCCs, the traffic count of a simulation’s scenario files can become very high.

Processing the data for a simulation of 1,500 planes per hour can be resource-intensive for even above-average computers. A user-configurable option has been implemented in MACS that can dynamically adjust the data communication rates of flight state data. This functionality helps workstation computers to better cope with processing the large number of data messages when simulating several hundred aircraft. With this functionality, standard output rates (nominally 1sec updates) will apply when the total number of active aircraft is relatively small. As traffic levels increase, the output rate can be reduced to varying degrees depending on how many active aircraft are in the scenario.

## **C. Time Factor**

One of the primary reasons for simulating larger airspaces is to capture data from traffic scenarios spanning long en route flight segments, usually to observe how inter-facility coordination affected the traffic, and/or how strategic decisions early on played out over the long run. For example, a researcher may want to run a HITL simulation to investigate how effective en route speed adjustments (near Top Of Climb) are at delivering reasonably spaced streams of traffic to a TRACON meter fix at the Dallas-Fort Worth airport (DFW). For their experiment, the researcher may need to design traffic scenarios that follow flights from California to Texas, a trip that would take 3<sup>1/2</sup> hours in real-time. In order to obtain enough data for statistical analyses, such a study would become an enormous time commitment. A new capability has been added to MACS that can vary the time rate of a simulation from real-time to faster rates of up to 20x, and to slower rates as low as a virtual “pause.” This capability, combined with a configuration of multiple ARTCCs, could allow a researcher to staff test positions for ANSPs in both Northern and Southern California to manage the aircraft early in the en route phase of flight. The researcher could then speed up the simulation until the traffic approaches DFW, knowing that they could slow down to real-time or even pause the simulation to observe any interesting developments in the traffic. Lastly, the researcher would then slow the simulation back to real-time and staff test positions for ANSPs working the traffic arriving into DFW, finishing a complete end-to-end run much more quickly.

These new features in MACS will help to efficiently study large-scale traffic complexities such as inter-facility coordination, major traffic flow management initiatives, and multi-hour planning horizons. They also provide the robust simulation infrastructure necessary to investigate concepts on a scale that reflect the size and scope of NextGen ATM concepts.

## **III. The Scenario Editor**

Building effective traffic scenarios for ATM research is a central part of the simulation environment. This can often become a very time and labor-intensive task, requiring a significant amount of manual work to verify each aircraft’s initial position, filed flight plan, and its Flight Management System (FMS) routing information. Additionally, the traffic scenarios need to meet desired airspace characteristics in order to provide the appropriate background for testing a particular hypothesis. This can also be a cumbersome process, which involves carefully controlling sector counts throughout the run, controlling the nominal conflicts throughout the run, and matching general flow patterns to either real-world tracks or the custom needs of a simulation. Adding a time-based metering environment to the traffic scenarios can require even more work to crafting a good traffic scenario.

The scenario creation and editing tools in MACS have been redesigned to give users easier and more powerful ways to build traffic scenarios. Functions for selecting multiple aircraft and effecting common operations on that selection make otherwise slow editing tasks significantly more efficient. Weather can also play a big role in traffic scenarios, and new weather editing tools have been incorporated into MACS' scenario editing tools as well. These new tools help users to more easily see how custom-created weather patterns interact with a particular traffic scenario, allowing for multiple design iterations to occur quickly and easily.

### A. Editing Traffic Scenarios

Most often the starting point for creating traffic scenarios are captures of live traffic, through certain data feeds such as Enhanced Traffic Management System (ETMS) or Aircraft Situation Display to Industry (ASDI) data. This can be an effective method for replicating realistic flows and traffic patterns in a simulation, but getting the MACS scenario file completely correct can also become time-consuming.

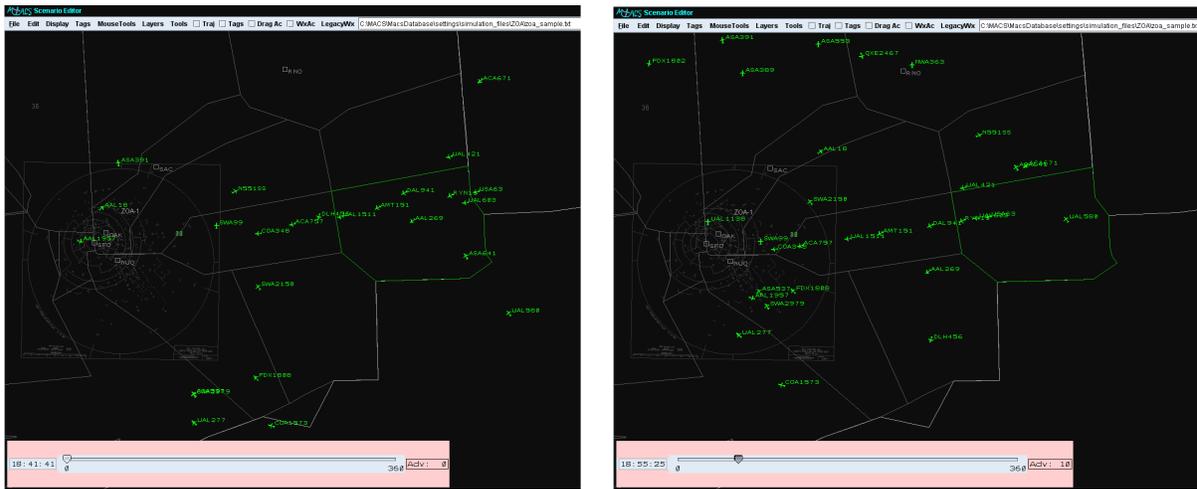
The data obtained from live traffic feeds typically consists of the filed flight plan, current location, callsign, and beacon code. This level of information unfortunately does not cover all the parameters needed for a simulation file. Current speed, climb speed, descent speed, approach speed, landing speed, current heading, and Mode Control Panel (MCP) target values, are necessary to correctly simulate an aircraft. Additionally, routing programmed in an aircraft's Flight Management System (FMS) can potentially differ from the filed flight plan, another parameter that is required for a MACS scenario file. When converting data from live traffic feeds, the Scenario Editor's automation goes beyond simply parsing the filed flight plan, and attempts to alleviate some of the "hand-editing" by automatically filling out the scenario files with the following functions:

- 1) Sets the FMS route to be equivalent to the ATC filed flight plan. The user can then later modify the routes if discrepancies between the two are desired.
- 2) Recognizes the airplane type and fills in any missing altitude, speed, and heading values. If any pre-existing values are found to be outside of the nominal performance envelope for an aircraft type, the Scenario Editor will also automatically substitute the nearest acceptable value.

With these actions already done by the automation, hand-editing would only be necessary for any flight plans or aircraft types that were not recognized by the Scenario Editor. Once identified, it is a straight-forward process of selecting a valid aircraft type and entering a new flight plan for those few aircraft. These capabilities significantly reduce the amount of time it takes to convert live data into complete traffic scenarios, making live data feeds an attractive option for creating scenario files.

Rather than creating entirely new scenarios for every simulation, a user may prefer to modify existing scenarios instead. The new Scenario Editor in MACS includes both graphic and tabular displays to provide simple methods for editing scenario files. The graphic display's appearance is that of a generic ATC display, capable of showing sectors, waypoints, jet routes, etc. An included time slider allows the user to view the scenario progress through time, giving the user visual feedback of the scenario's entire duration (see Figure1).

After loading an existing scenario file, the graphic display shows where all the aircraft will be when they become active in the simulation. With the time slider, the user can see if and when aircraft appear later in the scenario, and



**Figure 1.** The Scenario Editor's graphic display combines a generic ATC display with a time slider. The image on the left shows a scenario file's traffic at time-zero, whereas the image on the right shows the same traffic 10 minutes into the scenario.

also what the traffic picture might look like after aircraft reach their destination and are removed from the scenario.

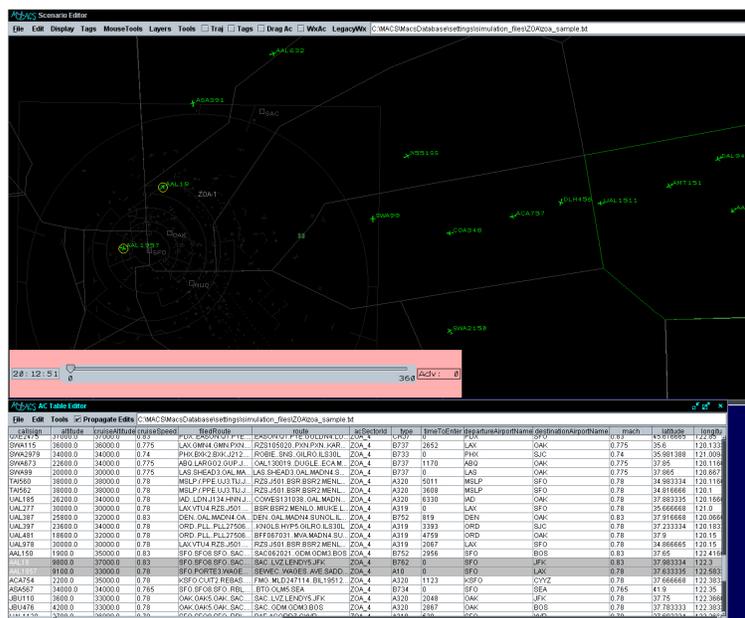
The editing tools in the Scenario Editor are designed to perform operations on the entire “selection,” which can consist of one or as many as all aircraft. Selecting aircraft can be done individually, or by entire areas such as ATC sectors or drawn selection rectangles. In cooperation with the ability to select multiple aircraft, the functions incorporated into the Scenario Editor can significantly speed up otherwise time-consuming tasks. As an example, a user could drag a selection rectangle to select all aircraft in a particular area. They could then display the current routes for those aircraft, and decide to move all aircraft further out. This can be accomplished either with the “Drag Aircraft” function for a drag-and-drop solution, or with the “Move Aircraft in Time” function to specify the number of seconds to move the aircraft forward or backwards along their route.

During a simulation, it may be desirable to have multiple variations of a base scenario file, as opposed to using the same scenario for every run. Typically the variations are small, so as to not turn the scenarios themselves into a major variable within an experiment. To create a variation of a scenario file, tools for “jiggling” traffic have been recently added to the Scenario Editor. Selected aircraft can be jiggled in speed, where the speed will be randomly modified by a specified jiggle factor (e.g., 0.02 mach or 30 knots). This same functionality also exists for altitude, initial latitude/longitude location, and the time-along-route function described above.

If smaller scenarios are needed, (i.e. training), the Scenario Editor’s “Decimate Aircraft” function is useful for easily reducing the number of aircraft in a scenario file. Aircraft can also be duplicated with the Scenario Editor, which can then be edited with the jiggling tools to quickly increase the number of aircraft in a scenario file, without having identical “waves” of traffic during a simulation. Additionally, to avoid the risk of identical callsigns in a simulation, the Scenario Editor has functionality that, when duplicating aircraft, automatically makes the callsigns of new aircraft unique.

Another method for selecting and editing aircraft is through the Scenario Editor’s tabular display (see Figure 2). The tabular display provides the user with a familiar spreadsheet interface to allow for sorting and simple arithmetic functions on scenario files. For example, through the tabular display, a user can highlight multiple aircraft (rows) and set the destination airport to be San Francisco as well as increase the descent speed by 20 knots for all selected aircraft. Having these features integrated into the Scenario Editor enables a user to do all editing, both graphically and via spreadsheet, without the need to switch back-and-forth between programs. The tabular display also incorporates basic automation to correctly propagate the changes of one field across other related fields. If a departure airport is changed for example, that change will also automatically update both the filed flight plan and FMS route fields, saving the user from having to make each change separately.

Simulations often bring specific requirements to a traffic scenario file, with a carefully controlled aircraft count being the most common. Current-day operations tend to work within the limits of a sector’s Monitor Alert Parameter (MAP), while some NextGen concepts are investigating double and triple those numbers. Validating a scenario file’s aircraft counts for a given sector historically involved running the simulation in real-time, and manually counting the number of aircraft at regular intervals. Adjustments to the scenario file were then made, and then the process was repeated until an appropriate traffic level was achieved. A function within the Scenario Editor avoids this time-consuming process by working with a Load Graph view in MACS to plot the number of aircraft inside a given sector over time (see Figure



3). Also available for counting conflicts over time, this functionality greatly reduces the time spent between design iterations, enabling users to make edits to the scenario and immediately re-plot the aircraft count data in the Load Graph to view the results of their modifications.

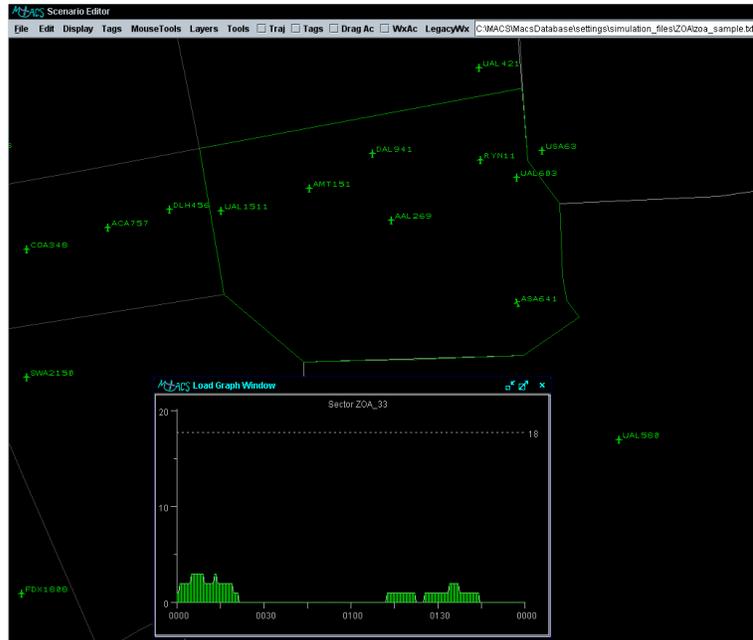
### B. Editing Weather Scenarios

Weather can be an important part of a simulation, and correctly coordinating weather with a scenario's traffic can be a challenge. Weather editing is a third component of the new Scenario Editor within MACS, and includes drawing functions and tools for highlighting weather-aircraft interactions (see Figure 4).

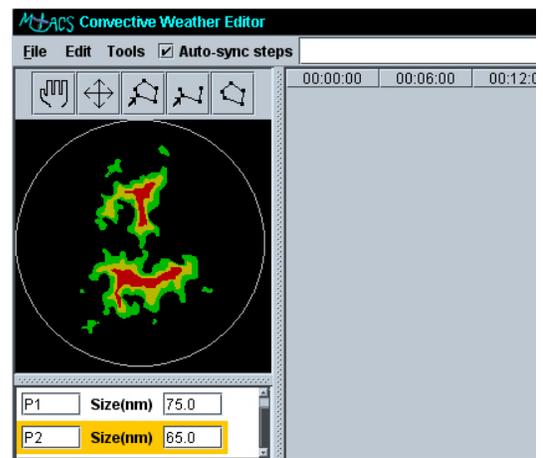
The Scenario Editor's weather editing interface defines weather as one or more patterns, which can be thought of as weather cells. Each pattern has parameters for altitude tops and bottoms, and consists of one or more polygons. Each polygon has a specified size and can be assigned an intensity of low, medium or high. The size parameter of a pattern's polygon(s) allows the same pattern to be the size of a large weather front spanning an entire region of the country, or as small as localized afternoon showers. This flexibility can save time by allowing the re-use of drawn weather patterns for different scenarios that may focus on very different scales in terms of area.

Drawing weather polygons in the weather editor display is done with simple, intuitive tools. With the "Add Polygon" tool, the user can click inside of a drawing area at each point a polygon vertex is wanted, and double-click to finish the polygon. Individual points can be selected and dragged so the user can alter the shape of the polygon. An "Add Points" function in the Scenario Editor will insert more vertices along the edges of the polygon, offering the user a finer-level of control over the polygon's shape. When making more complex weather patterns with multiple polygons, the user may want to adjust the location of a polygon relative to the others, in which case the "Select Polygon" tool is used, enabling an entire polygon to be selected and then dragged. Functions for loading archived patterns, as well as functions for deleting points, polygons, and patterns are also available in the weather editor display.

When the polygons of a weather pattern are done being edited, that pattern can be added to the Scenario Editor's graphic display, ready for an associated path to be defined. Similar to current-day weather displays on the radar screens of air traffic controllers, when a Scenario Editor's weather pattern moves along a path over time, it does so in steps, or incremental jumps. The size of these steps is nominally set to six minutes, but can be easily changed by the user. Each step within a pattern's path can be treated independently from the others, giving significant control over how weather patterns can morph over time. In addition to position updates between steps, the weather patterns can also be set to randomly rotate and change size and shape, approximating the natural movement of real weather cells. The ability to specify steps independently allows for patterns to suddenly



**Figure 3. With the Scenario Editor, a given scenario file's aircraft count data can easily be plotted in MACS' Load Graph view.**



**Figure 4. The weather editing display provides the interface for drawing weather polygons and patterns.**

increase or decrease their speed, and change in both size and shape as they move along their paths.

As an alternative to specifying the parameters for every step of a weather pattern's path, the Scenario Editor has the capability to automatically "fill-in" steps. With just the first step fully defined, selecting the "Auto Fill Steps" function can fill in any other selected steps within a given path. This function will preserve the nominal speed, direction, and altitude settings, but will slightly vary the size, rotation factor, and shape of the weather pattern's steps. Additionally, functions for randomizing steps have been incorporated into the Scenario Editor, which offer a one-click solution for generating completely new paths for a given weather pattern. The "Jiggle Steps" function can be used repeatedly or in combination with the "Undo" function, until a satisfactory path with desirable mutations between steps has emerged. This approach makes an otherwise labor-intensive task faster, more efficient, and also very flexible, greatly reducing the amount of time needed to generate quality weather scenarios.

Once weather patterns have been created and their paths defined, the Scenario Editor contains capabilities that enable the user to visualize, and optionally modify, the interactions between the traffic and the weather. An "Add Aircraft Flying Through Weather To Selection" function will recognize the path of any present weather patterns, and detect all instances throughout the scenario when aircraft penetrate the weather. The detection criteria can be configured to check for penetration of only certain intensities, to check within certain periods of time, and to assume a specified type of weather movement (e.g., static or step-wise). Aircraft that are predicted to penetrate weather will be automatically selected within the Scenario Editor's graphic and tabular displays, ready for modification with the editing tools. Additionally, the points of penetration for the entire scenario can be displayed, providing quick feedback to the user as to where the traffic could potentially interact with the weather. The penetration markers are also color-coded with the different weather intensity levels, identifying which intensity levels affected any of the aircraft in the scenario (see Figure 5).

The redesigned Scenario Editor in MACS provides several capabilities that make creating new and modifying existing scenario files a more efficient process. Producing quality scenario files that include customized traffic flows as well as dynamic weather can now be accomplished much faster and easier than before.

#### IV. Implementation of Automated Sector Operations

Large-scale HITL simulations can have high staffing requirements when several sectors all need to be staffed by either participant or confederate controllers. At the same time, several areas of research related to NextGen concepts call for traffic densities much higher than the levels of traffic seen today<sup>1</sup>. It is believed that automation will help a controller manage such high numbers of aircraft, but exactly how much or which parts of the radar control task will be given to future automation is still unknown. Both the NextGen research and simulation logistics issues have prompted AOL researchers to begin implementing capabilities supporting automated sector operations into MACS.

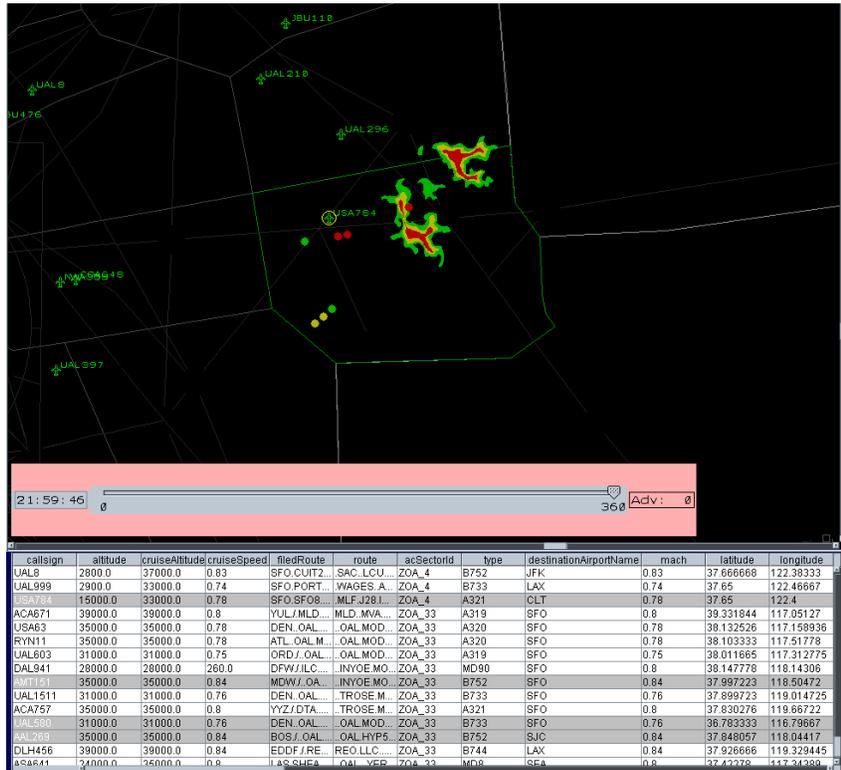


Figure 5. Functions within the Scenario Editor can identify which aircraft could penetrate weather, and highlight exactly where the traffic and the weather will interact.

A big step towards this goal was the recent integration of the Auto-Resolver and Tactical Separation Assisted Flight Environment (TSAFE) functions from the Advanced Airspace Concept (AAC)<sup>6</sup>. With only small changes to the assumptions about available surveillance information and the requirement for FMS-coupled Controller-Pilot Data Link Communication (CPDLC, or data-link), controller workstations in MACS have begun using machine-based separation assurance functions for managing traffic scenarios. Specifically, the AAC components provide automated conflict detection and resolution capabilities in both the strategic (medium-term) and tactical (short-term) domains. These new functions have recently been tested in HITL simulations partially under interactive modes<sup>7-9</sup>, but have also been operated as completely closed-loop operations.

Fully automated sector operations are not possible without addressing the more routine tasks of transfer of communications, handoffs, point-outs, climb and descent clearances, and pilot requests. Combined with data-link, functions within MACS can reliably automate the transfer of communication and handoff tasks. To date, point-outs and pilot requests can partially be managed by the automation, but more development and testing is still needed. Altitude clearances for climbs and descents can be handled with data-link when initiated as a down-link request from the pilot, and can also be automated procedurally. The procedural solution requires that a new set of flight rules be created that clears all aircraft flying under those flight rules to follow their FMS-computed vertical profile.

These methods of automating most of the radar controller's tasks associated with nominal sector operations will be further developed as part of an upcoming study that plans to have multiple radar positions controlled by automation rather than human operators.

## V. Concluding Remarks

The Multi Aircraft Control System (MACS) is a simulation platform developed in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center that encompasses high-fidelity interfaces for operator workstations, a robust architecture that allows for the study of large-scale NextGen concepts, powerful tools helping researchers create realistic, complex, and custom scenarios, and the capabilities needed for automated sector operations. This paper has described new functionality recently added to the MACS software that can simulate airspaces spanning multiple ARTCCs, new tools for creating and editing custom traffic and weather scenarios, and new functionality for automating tasks associated with nominal sector operations. These capabilities allow researchers to more effectively investigate the human/system/automation interactions crucial to the implementation of the NextGen.

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