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Human Factors Requirements for En Route Controller Weather Displays

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16. Abstract

Adverse weather conditions affect flight operations, overall, but are especially hazardous to general aviation (GA) aircraft. The primary weather hazards are icing, convective activity (i.e., thunderstorms), and reductions in ceiling/visibility. Because of information shortcomings in current en route operations, this research proposes weather display concepts for convective activity, ceiling/visibility, and icing information that meet controller needs. Our weather displays do this by providing operationally useful information that effectively enables the controller to transfer hazard information to the pilot. In addition to the weather displays, our concept involves an automated support system that tracks GA aircraft and hazardous weather areas. When the automated system detects a future conflict with an aircraft and a hazardous weather region (i.e., *no-go* area), the system alerts the controller about the aircraft and the hazard. Once alerted, the controller can either inform the pilot about the location and extent of the hazard (thereby enhancing cockpit decision making) or the controller can execute necessary weather avoidance actions. Taken together, the weather displays and automation support tool could work towards a reduction in weather-related GA accidents and provide information that enhances cockpit decision making.

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Executive Summary

Adverse weather conditions affect flight operations, overall, but are especially hazardous to small and light aircraft operations. Because small and light aircraft have limitations in maximum speed, altitude, and range, these pilots have a disadvantage when trying to avoid adverse weather conditions. The primary weather hazards for general aviation (GA) aircraft are icing, convective activity (i.e., thunderstorms), and inadvertent Visual Flight Rules flights into Instrument Meteorological Conditions. Although en route air traffic controllers can help pilots with weather requests, they are limited in the information available. The controllers often lack detailed and specific information regarding convective activity, icing, and ceiling/visibility conditions.

To address this shortcoming, we developed en route controller weather display concepts for convective activity, ceiling/visibility, and icing information that meet controller needs. They do this by providing operationally useful information that effectively enables the controller to transfer hazard information to the pilot. In addition to the weather displays, our concept involves an automated support system that tracks GA aircraft and hazardous weather areas. When the automated system detects a future conflict with an aircraft and a hazardous weather region (i.e., *no-go* area), the system alerts the controller about the aircraft and the hazard. Once alerted, the controller can either inform the pilot about the location and extent of the hazard, thereby enhancing cockpit decision making, or the controller can execute necessary weather avoidance actions.

Pertinent and sufficient data sources exist today that could meet controller requirements for severe weather avoidance and, when relayed to pilots, could enhance decision making in the cockpit. We do not yet have the capability to display these data sources graphically at the controller workstation. To initiate this development process, we include research requirements for each weather display. These will serve as input to the weather research program for the development of the displays. Once developed, these weather products will provide information that enhances cockpit decision making and works to reduce weather-related GA accidents.

1. INTRODUCTION

Adverse weather conditions affect flight operations, in general, but are especially hazardous to small and light aircraft operations. Because small and light aircraft have limitations in maximum speed, altitude, and range, these pilots have a disadvantage when trying to avoid adverse weather conditions. Although weather is not the only cause of crashes and accidents in general aviation (GA), adverse weather contributes to a significant share of these incidents (Groff & Price, 2006; Li & Baker, 2007; National Transportation Safety Board [NTSB], 2005; Wong, Pitfield, Caves, & Appleyard, 2006). For example, during 2004, 25% of all fatal weather accidents involved pilot encounters with thunderstorms (Aircraft Owners and Pilots Association [AOPA], 2006a, 2006b; NTSB, 2006b). Likewise, many fatal incidents have occurred as a consequence of aircraft icing (AOPA, 2002; Maynard & Sand, 1999; Politovich & Bernstein, 2006).

One way to illustrate the hazardous impact of weather is to review the GA accident statistics from the National Transportation Safety Board (NTSB, 2006a). Overall, NTSB cited weather conditions in 357 (21%) of the total number of GA accidents during 2003. During 2003, there were 1,628 accidents and 280 fatalities during Visual Meteorological Conditions (VMC). In the same year during Instrument Meteorological Conditions (IMC) when visibility, cloud distance, and ceiling are less than the minima for VMC, there were 100 accidents that resulted in 66 fatalities. This illustrates the impact of weather on GA in that only 17% of VMC accidents resulted in fatalities, whereas 66% of all IMC accidents were fatal. For all of these fatal GA accidents, the most frequently cited weather factors relate to conditions that create reduced visibility.

The visibility concept pertains to the farthest distance at which a pilot can discern an object. The ceiling concept encompasses the altitude to the nearest layer of clouds that obscures more than half the sky. Taken together, there are multiple factors that contribute to a ceiling and visibility problem (Herzegh et al., 2006; NTSB, 2006a). For example, fog, clouds, and obscurations all contribute to reduced visibility. Similarly, other phenomena such as haze, smoke, sand, dust, and sun glare can also be contributing factors. GA accidents caused by low ceiling and visibility can occur if pilots inadvertently encounter these conditions during flight. However, inexperienced Instrument Flight Rules (IFR) pilots who suddenly encounter reduced ceiling and visibility conditions are also at risk (Lenz, 2004). Commonly, these encounters result in a loss of control of the aircraft, or controlled flight into terrain.

Because adverse weather conditions can develop quickly and are somewhat unpredictable, it is vital for GA pilots to consider available weather information. Many sources are available for their pre-flight planning (Parson et al., 2005), such as the Internet (Carpenter & Brusda, 2006), automated flight service stations (Prinzo, Hendrix, & Hendrix, 2007), and various other weather information providers (Knecht, 2007). It is also important for pilots to monitor weather conditions while in flight (Knecht). For in-flight weather information, pilots can contact air traffic control (ATC) and request pertinent weather information and guidance (Ahlstrom, 2003).

Although air traffic controllers can help pilots with weather requests, they are limited in the information available. They often lack detailed and specific information for convective activity, icing, and ceiling/visibility conditions. For example, both en route and terminal controllers have text-based information for icing, ceiling, and visibility but no detailed graphical representation at their workstation. In the en route domain, supervisors can display this information graphically on an Enhanced Status Information System (ESIS) in each area of specialization. Controllers can access this information, but it is very general in nature, lacks important details, and may not be adequate to accommodate all pilot requests (Ahlstrom, 2007). Furthermore, the ESIS display is located on the end wall, in the area of specialization, some distance away from the controllers. When controllers use this display, they have to integrate information from the ESIS display (which can be 20 or more feet away) with information on their situation display. Although the ESIS display can be set up to provide useful information, it does not fulfill the human factors requirement for controller weather displays. In the terminal domain, advanced weather information displays are available at the supervisor workstation. However, the availability of these weather sources and the possibility for controllers to access this information varies from one terminal facility to the other (Ahlstrom, 2004). More detailed weather information from pilot reports (PIREPs) is available in both ATC domains, but these reports might not be available at all times or even for the relevant geographical areas.

1.1 Purpose

The main purpose of this study is to develop en route controller weather display concepts for convective activity (i.e., thunderstorms), ceiling/visibility, and icing information that meet controller needs and provide operationally useful information that effectively enables the controller to transfer hazard information to the pilot. An additional purpose is to explore suitable implementation techniques and phraseology examples for operational use and communication with pilots. If the outcome of this effort shows that available products cannot meet our display requirements, we have an additional goal to provide research requirements to the weather research program for the development of these displays.

2. METHOD

2.1 Working Group

At the beginning of the project, researchers put together a team that had the necessary knowledge and experience of en route air traffic operations, GA pilot operations, and aviation weather. Included in this team were three experienced GA pilots, one en route ATC Subject Matter Expert (SME), and several Engineering Research Psychologists and Software Engineers. In addition, the working group received input from an independent group of four en route SMEs.

2.2 Procedure

The weather display analysis and display prototyping took place in group settings over the course of the project. During these sessions, the working group analyzed controller information requirements for display information of convective activity (i.e., thunderstorms), ceiling/visibility, and icing conditions. Throughout the work sessions, the team used a scenario-based methodology to determine whether each weather display met controller information requirements. This implied a determination of a controller's ability to provide adequate weather avoidance operations and the controller's ability to provide relevant weather advisories to pilots when using the display. The team also focused on documented real-life GA weather accidents, discussing issues with controller and pilot weather situation awareness and shortcomings during weather-related communications.

2.3 Weather Data

In current en route operations, controllers use graphical representations of precipitation areas and text-based information for visibility, ceiling, and icing conditions (Ahlstrom, 2007). All text-based products require, to some degree, a mental interpretation and manipulation on part of the controller and do not usually allow a direct and effortless application (Ahlstrom, 2005). Therefore, the task of correlating text-based weather information with specific sector areas can be difficult and time consuming. On the other hand, a graphical representation of weather information generally provides a direct correlation between weather information and sector data. Although far from being implemented across the aviation weather domain, there is currently a transition in the display development from text-based weather products to graphical weather products (McCarthy, 2006).

Although few controller weather displays are available in current operations (Ahlstrom, 2003, 2007), many display examples and concepts are available for pilot operations (Stough & Martzaklis, 2002). One elegant example is the Helicopter Emergency Medical Services tool developed by Research Applications Laboratory researchers at the University Center for Atmospheric Research (UCAR). This tool provides, among many other things, a grid-based system that graphically depicts assessments for ceiling, visibility, and icing conditions. To assess the conditions between the reporting stations for Aviation Routine Weather Report and Terminal Area Forecast sites, the system interpolates and produces a best estimate of the likely conditions. By using this graphical tool, pilots could gain a quick overview of the likely weather situation at a given geographical location or at points along their intended line of flight. The tool provides an effortless and direct pick up of important weather constraints and does not require any mental elaboration by the user.

Because the tool provides precipitation, ceiling, visibility, icing, and flight category data in a graphical format, these data sets would be very useful for our display concept development. Therefore, we contacted the researchers at UCAR who generously provided us with weather data covering the Continental United States (CONUS). In the following, we provide a brief description of the weather data used for our prototype displays. More detailed information about the data sources, applications, and a user tutorial are available on the Web (http://weather.aero/hems/). For a review of the tool and weather data see Buehler (2007).

From the grid-based data, we created separate displays for Ceiling, Visibility, Flight Category, Icing, and Precipitation. The data grids for the Ceiling and Visibility Displays derive from observations, surface weather reports, and satellite data. The Ceiling Display shows the ceiling in feet above ground level for eight altitudes ranging from 0-5,000 feet. A ninth category shows areas containing obstructions. The Visibility Display shows the visibility in areas ranging from zero visibility to 10 miles of visibility. The Ceiling and Visibility grids provide data for a third grid used to create a Flight Category display.

The Flight Category Display codes areas according to Visual Flight Rules (VFR), Marginal VFR (MVFR), IFR, and Low IFR (LIFR). The Flight Category Display is based on data from certain cloud-base ceilings and horizontal surface-visibility values. The Ceiling, Visibility, and Flight Category Displays update approximately every 5 minutes. Because of data set limitations (e.g., due to the distance between measuring stations), these data grids have a maximal resolution of approximately 5 kilometers.

The Icing Display consists of two icing metrics: Icing Severity and Icing Probability. The Icing Severity combines many data sources, such as temperature, humidity, radar data, satellite, pilot reports, and observed surface weather to depict areas with none, trace, light, moderate, and heavy icing. The Icing Probability displays areas and their associated probability of icing from 5-85%.

Both the Icing Severity and Icing Probability information come from the Current Icing Product. The grid cell size for the Icing display is approximately 20 x 20 kilometers, and the display updates once every hour.

Finally, the Precipitation Display consists of a Next-Generation Weather Radar (NEXRAD) Data composite for the range 5-75 dBZ. This Precipitation Display updates approximately every 5 minutes and has a grid resolution of 1 square kilometer.

3. EN ROUTE WEATHER DISPLAY CONCEPTS

In the following sections, we define our weather display concepts with information requirements, illustrations, and phraseology examples. We derived controller weather display requirements from the control tasks and control strategies applicable to en route controllers during severe weather avoidance (Ahlstrom, 2004).

Control tasks define what a controller has to do when controlling an aircraft during different adverse weather phenomena (e.g., provide weather advisories, requesting PIREPs). Control strategies define the possible options that the controller has when performing these control tasks (e.g., climb, vector). For example, if an aircraft experiences in-flight icing, an en route controller can climb, descend, or vector the aircraft away from the hazardous area. In order to perform either one of these operations, however, the controller must have immediate information about the location of the hazard (in relation to the aircraft) as well as information about hazard-free areas. Furthermore, the weather information display must enable the controller to transfer information about the location and extent of hazardous areas to pilots to enhance decision making in the cockpit. If an Icing Display provides this information and allows the controller to select the appropriate action to transfer useful information to pilots, we can say that the display information satisfies the controller's operational requirements for icing avoidance. Conversely, if the Icing Display provides information that does not allow the controller to select and execute a control strategy or to transfer operationally useful information to pilots, it does *not* meet the controller's information requirements for icing avoidance.

To support the controller during active weather avoidance operations, our concept makes use of an automated support system that tracks GA aircraft and hazardous weather areas. If the automated system detects a future conflict with an aircraft and a hazardous weather region (i.e., "no-go" area), the system alerts the controllers about the aircraft and the hazard. In this situation, the support system allows the controller to display the hazard type, and the controller can either relay the information to the pilot or take the necessary control actions. In other situations, controllers will use the weather displays in various situations where pilots contact the controllers to request weather information. In these situations, the controllers need quick access to operationally relevant information for pilots.

For all the weather information displays, we have optimized the original data information for use by en route controllers. For example, the Flight Category data contains information that specifies regions of obscurations, VFR, MVFR, IFR, and LIFR conditions. This information is very important during pilot pre-flight planning because it gives a very quick overview of conditions that the pilot is likely to encounter during a flight. For an en route controller, the Flight Category Display only needs to display shaded regions for two categories. The first region is obscurations and the second region is a combination of all non-VFR regions into a single IFR area. Essentially, these shaded areas are no-go regions and all other areas are "go" regions for VFR aircraft, enhancing controller decision making during severe weather avoidance. Similarly, we combined data sources into fewer but more operationally relevant controller categories for the remainder of our display concepts.

Within the present framework, we assume that controllers communicate with pilots using radio. Today, various data-link applications are becoming more prevalent and could provide another means for communicating weather information in the future. However, the relay of weather information from the en route controller to the pilot does not require such means. The displays provide a quick look of hazardous areas that controllers can directly communicate to pilots. Furthermore, controllers use phraseology that is similar to the phraseology used in the field today to describe weather areas.

Finally, although weather data are available that would meet our weather information requirements, there are currently no displays available that would meet controller needs. Therefore, we have included research requirements for the development of each weather display (see section 5, *Summary of Research Requirements*). However, we want to emphasize that our display requirements are general examples. The display system needs to be flexible and allow adaptation to specific en route sector needs, depending on traffic patterns and geographical location. For example, the need for specific altitude strata for ceiling/visibility and icing information are likely to vary across the CONUS. In this report, our displays provide only generic examples of how to code each weather hazard to provide operationally meaningful information. In the current stage of display development, we have not specified color palettes for use on current en route systems. We merely use shaded color areas to demonstrate the display concepts, although guidelines for the use of color palettes and weather information on ATC displays are available (Ahlstrom & Arend, 2005).

3.1 Automated Weather Avoidance Support Tool

The weather concept displays provide the controller with quick-look information for aircraft hazards caused by reductions in ceiling and visibility, icing conditions, and convective activity. During weather avoidance operations, the controller actively uses this information to advise pilots of hazardous weather areas and to help pilots avoid these areas. However, these operations add additional requirements for the controller that could easily have detrimental effects on controller workload during operations in adverse weather conditions. Therefore, to support the controller during these operations, our weather avoidance concept includes an automated support tool. This tool automatically tracks GA aircraft, based on the aircraft type filed on the flight plan, and correlates this information with the 3D weather database to detect future conflicts between aircraft and weather hazards. The specific aircraft types included in the tracking are single-engine piston aircraft and light twin-engine aircraft under 6,000 lbs; generally, with or without limited weather detection capability and, in most cases, without deicing capability. The support tool alerts the controller by blinking the aircraft data block 20 minutes ahead of a predicted aircraft or hazard conflict. As soon as the automated support system generates an alert, the controller receives specific information about the weather hazard in a read-out window (moveable) on the situation display. The controller also has the option to display the specific weather hazard that the aircraft will encounter given its current flight path. This allows the controller to verify the situation and to take appropriate action in a timely manner. The controller can either inform the pilot about the location and extent of the hazard, thereby enhancing cockpit decision making, or execute necessary weather avoidance actions to avoid a conflict between the aircraft and the hazard.

3.2 Precipitation Display

For the Precipitation Display, we use NEXRAD data corresponding to moderate (30-40 dBZ), heavy (40-50 dBZ), and extreme (50+ dBZ) precipitation intensities (see Figure 1). The grid resolution of the precipitation information is 1 kilometers. The display allows the controller to select a specific altitude stratum that exactly corresponds to the vertical sector limits. This prevents the display of precipitation intensities that are outside of the controller's area of jurisdiction. The display allows the controller to independently select any combination of the three precipitation intensities.

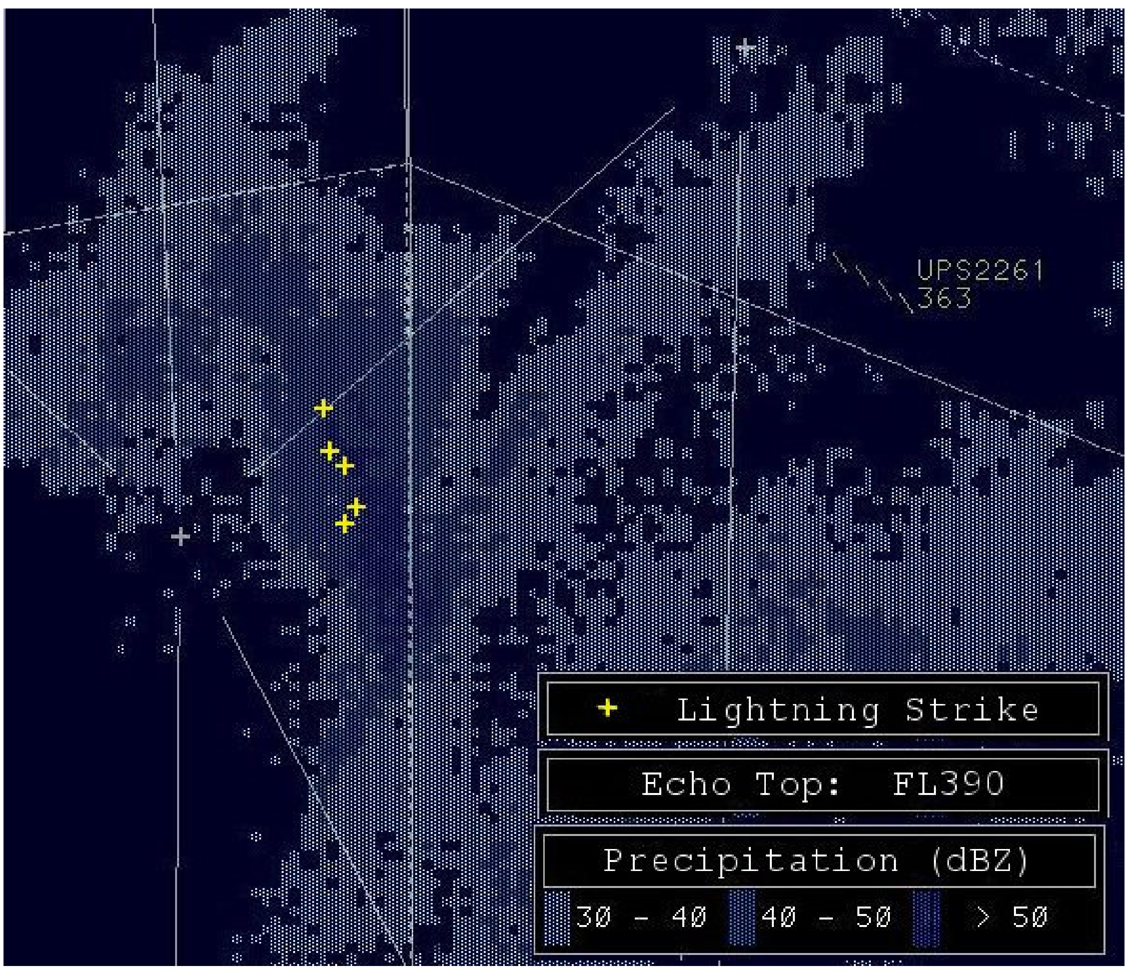

Figure 1. Precipitation Display.

Given the current problem with the en route precipitation display accuracy caused by winds and slow radar update rates (Ahlstrom & Dury, 2007), our prototype display makes use of all available wind information (i.e., real-time observations, satellite, radar, PIREPs) and previous NEXRAD updates to display extrapolations of precipitation locations once a minute. This improved precipitation display provides the controller with a more accurate display of precipitation locations, enhances the accuracy of controller weather avoidance operations, and improves the quality of weather advisories to pilots.

Cloud top information is very important for GA operations. In the field, the supervisor can tailor the ESIS to display echo top information in each area of specialization. However, this information is not available at the controller workstation. In our Precipitation Display concept, the controller can display grid-based echo top information along with the precipitation areas. Each bin in the grid is 2 x 2 kilometers and provides a single echo top value. After activating the echo top information, the controller can slew the cursor across the precipitation areas and display the echo top values in a moveable read-out window located on the situation display.

To provide information that is indicative of thunderstorms and convective activity, the controller can display lightning symbols that indicate a lightning strike (i.e., cloud-to-ground) at those locations within the past 15 minutes. The lightning symbols appear on the display for 15 minutes, after which they disappear. During this 15-minute interval, the size of each lightning symbol decreases twice; first after 5 minutes and then after 10 minutes**.**

3.2.1 Phraseology Example

The phraseology that en route controllers can use to communicate precipitation, lightning, and echo top information to pilots is as follows: *N123, heavy precipitation between ten o'clock and two o'clock, one five miles. Moving east at two zero knots, tops flight level three niner zero. Precipitation area is two five miles in diameter. Lightning displayed.*

3.2.2 Research Requirements for the Precipitation Display

As shown in Figure 1, the Precipitation Display contains features not currently available on en route controller displays. Therefore, there is a need to develop a Precipitation Display that meets the following requirements:

- Allows user-defined altitude strata that limit the display of precipitation intensities to the volume within the sector altitudes.
- Uses wind information and previous precipitation updates to extrapolate a best estimate of current intensity locations. The display of the precipitation intensities updates once a minute.
- Displays echo top information in association with the Precipitation Display.
- Shows symbols for cloud-to-ground lightning strikes on the Precipitation Display. Each symbol indicates that there has been a lightning strike at that location within the past 15 minutes. Each symbol *times out* after 15 minutes.

3.3 Ceiling Display

The graphical Ceiling Display in Figure 2 shows an example of two different shaded areas for ceilings that are below VFR minima (i.e., no-go regions). The first area shows ceilings below 500 feet, and the second area shows ceilings between 500-1,000 feet. Non-shaded areas on the situation display have a ceiling of more than 1,000 feet, which meets the ceiling minima for VFR operations (i.e., go regions). Alternatively, the Ceiling Display can be tailored to display all ceiling levels (in feet above the ground level) across the sector. The grid resolution for the ceiling data is 5 kilometers, and the display updates every 5 minutes.

Figure 2. Ceiling Display.

3.3.1 Phraseology Example

To communicate ceiling information to pilots, en route controllers can use the following phraseology: *N123, ceiling less than 500 feet between ten o'clock and two o'clock, one five miles.*

3.3.2 Research Requirements for the Ceiling Display

The Ceiling Display in Figure 2 is not available in current ATC operations. Therefore, there is a need to develop a Ceiling Display that shows shaded areas where ceilings are less than 500 feet and between 500-1,000 feet.

3.4 Visibility Display

The Visibility Display in Figure 3 shows an example of shaded regions for two visibility levels that are below VFR minima (i.e., no-go regions). The first region shows areas that have a visibility of less than 1 mile, and the second region shows areas that have a visibility between 1 mile and 3 miles. Non-shaded areas on the situation display have a visibility of more than 3 miles, which meets the visibility minima for VFR operations (i.e., go regions). Alternatively, the Visibility Display can be tailored to display all visibility conditions (in miles) across the sector. The Visibility Display has the same spatial resolution (5 kilometers) and update rate (every 5 minutes) as the Ceiling Display.

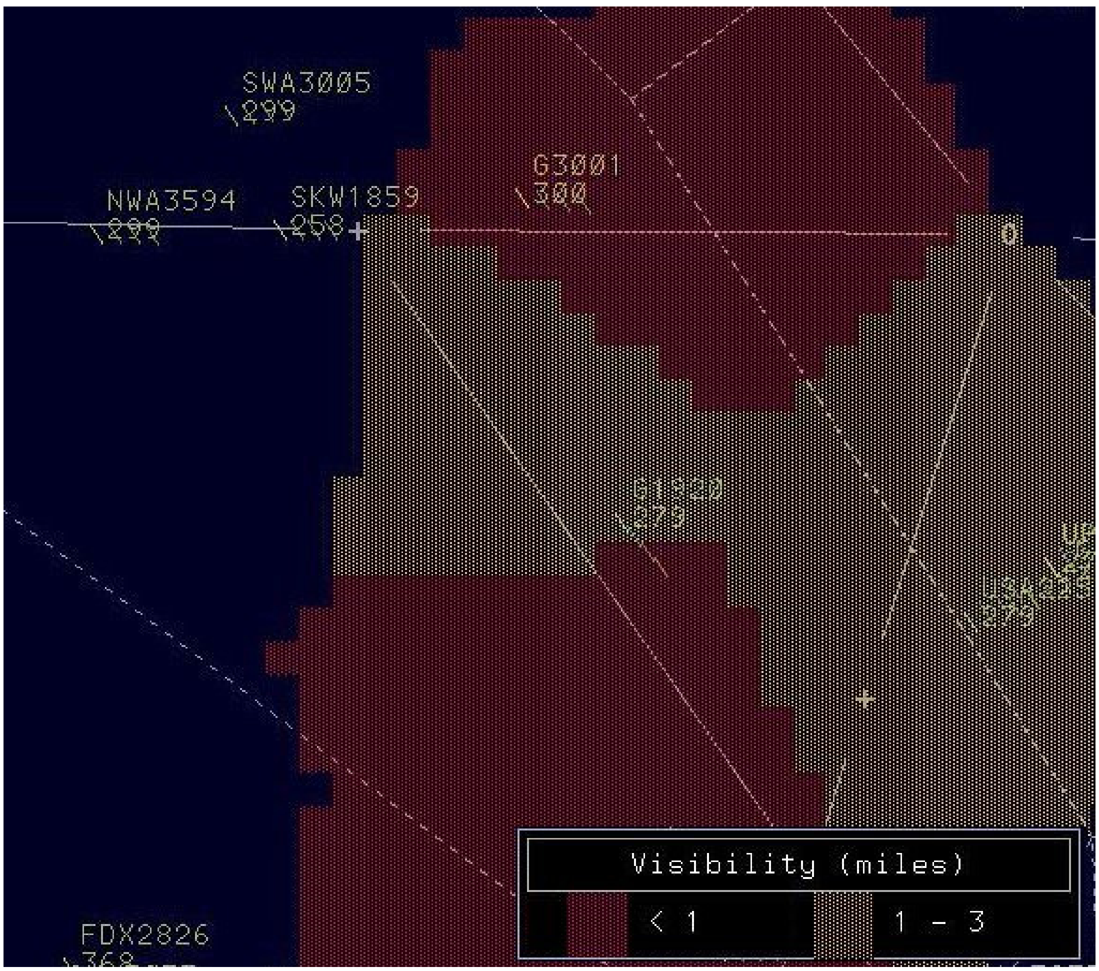

Figure 3. Visibility Display.

3.4.1 Phraseology Example

To communicate visibility information to pilots, en route controllers can use the following phraseology: *N123, visibility less than 1 mile between ten o'clock and two o'clock, one five miles*.

3.4.2 Research Requirements for the Visibility Display

The Visibility Display, as illustrated in Figure 3, is not available in current ATC operations. Therefore, there is a need to develop a graphical Visibility Display that shows a shaded area where the visibility is less than 1 mile, and a second shaded area where the visibility is between 1-3 miles.

3.5 Flight Category Display

The Flight Category Display example in Figure 4 is derived from the Ceiling and Visibility Displays. The display shows shaded regions for obscurations and IFR conditions. Both of these regions are no-go areas for VFR aircraft. All non-shaded regions on the situation display represent VFR conditions. The spatial resolution and update rate is the same as for the Visibility and Ceiling Displays.

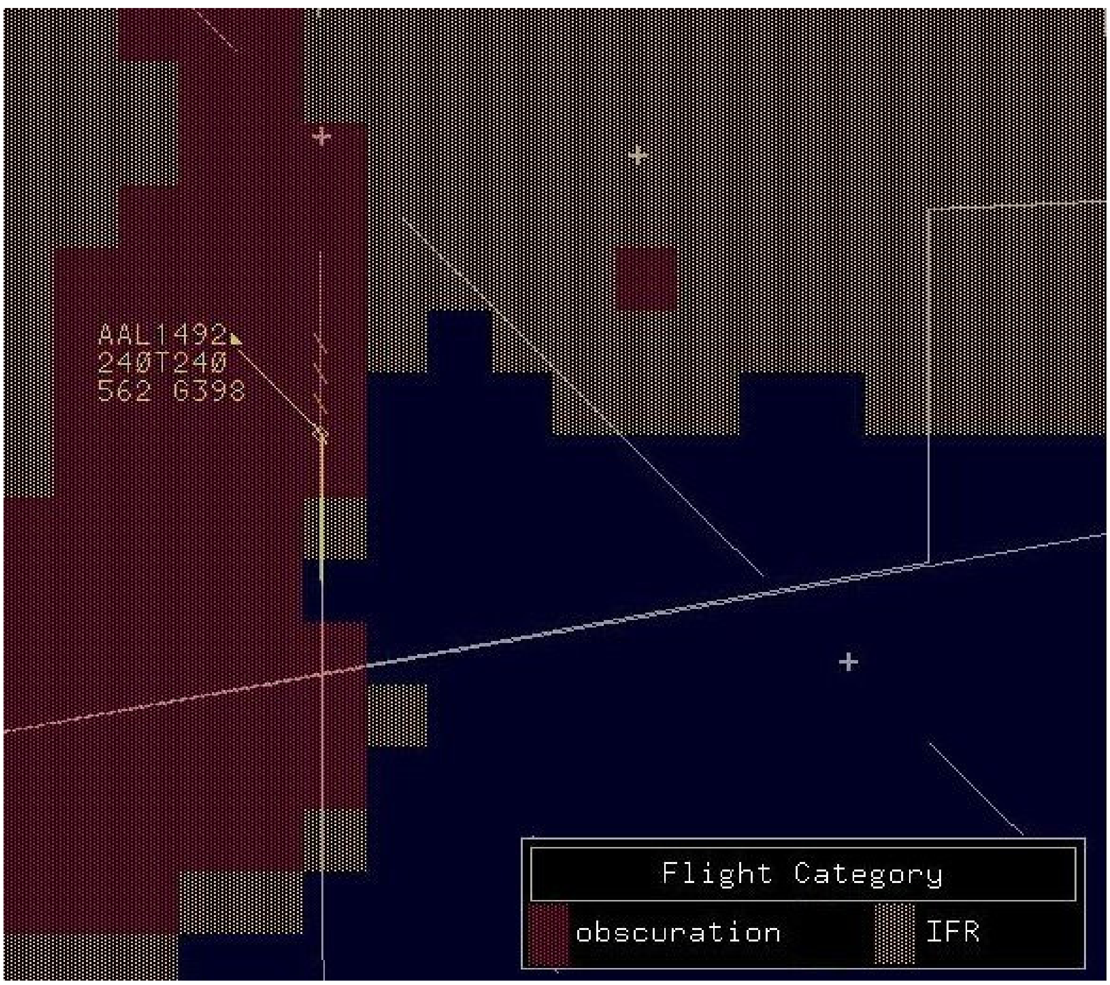

Figure 4. Flight Category Display.

3.5.1 Phraseology Example

The phraseology that en route controllers can use to communicate flight category information to pilots is as follows: *N123, VFR flight not recommended between ten o'clock and two o'clock, one five miles.*

3.5.2 Research Requirements for the Flight Category Display

The Flight Category Display in Figure 4 is not available in current ATC operations. Therefore, there is a need to develop a Flight Category Display that shows shaded areas for obscurations and IFR conditions.

3.6 Icing Probability Display

The Icing Probability Display in Figure 5 shows shaded areas where the probability of icing is 25-50%, 50-75%, or above 75%. The controller can select and display the icing probability for one of eight different pre-defined altitudes. The need for specific altitude strata are determined by the Air Route Traffic Control Center's (ARTCC's) geographical region, weather patterns, and traffic patterns, which are not likely to be the same across the CONUS. The grid resolution for the Icing Probability Display is 20 x 20 kilometers. The display updates once every hour.

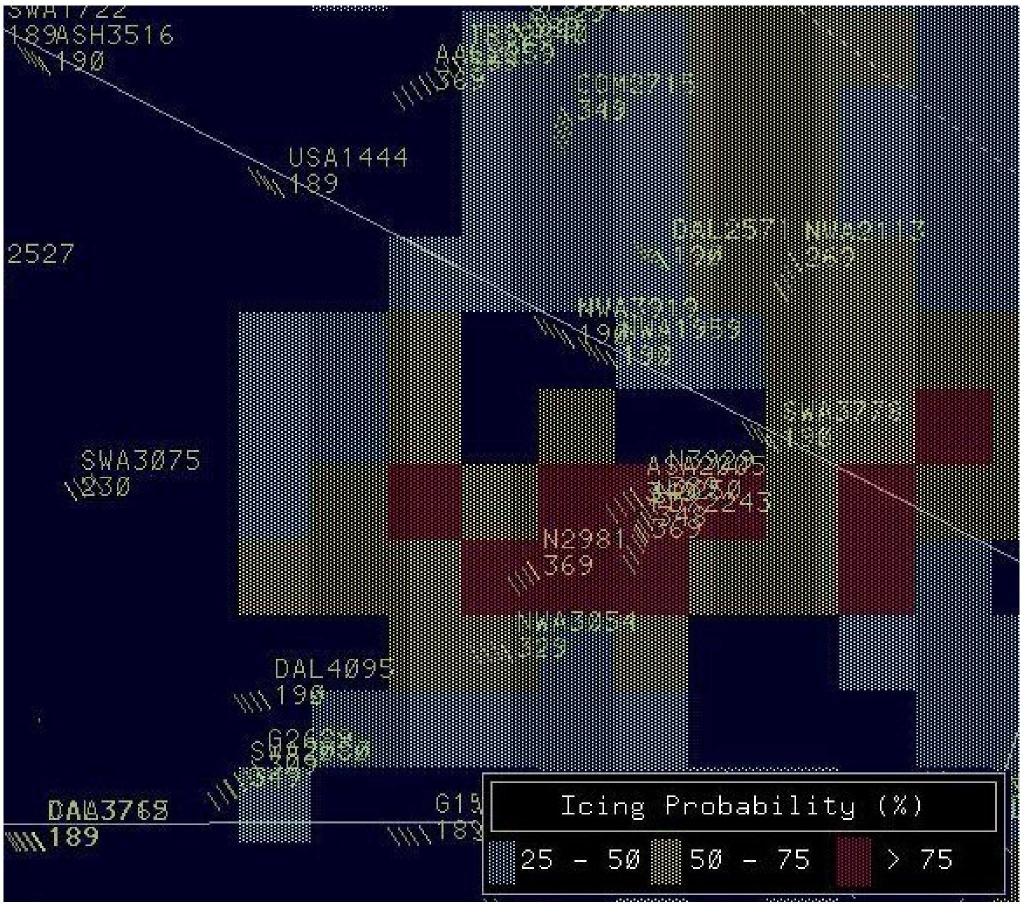

Figure 5. Icing Probability Display.

3.6.1 Phraseology Example

To communicate icing probability information to pilots, en route controllers can use the following phraseology: *N123, icing probability between ten o'clock and two o'clock, one five miles, icing probability is greater than 50% at one two thousand.*

3.6.2 Research Requirements for the Icing Probability Display

The graphical Icing Probability Display is not available at the controller workstation in current operations. Therefore, there is a need to develop an Icing Probability Display that meets the following requirements:

- The capability to show shaded areas where the probability of icing is 25-50%, 50-75%, and above 75%.
- The capability to select one of eight pre-defined altitude strata for the display of icing probability.

3.7 Icing Severity Display

The Icing Severity Display in Figure 6 depicts shaded areas for expected light, moderate, and heavy icing. The controller can select and display the icing severity for one of eight different pre-defined altitudes. As for the Icing Probability Display, the specific altitude strata are determined by the ARTCC's geographical region, weather patterns, traffic patterns, and are not likely to be the same across ARTCCs in the CONUS. The grid resolution for the Icing Severity Display is 20 x 20 kilometers with an hourly update rate.

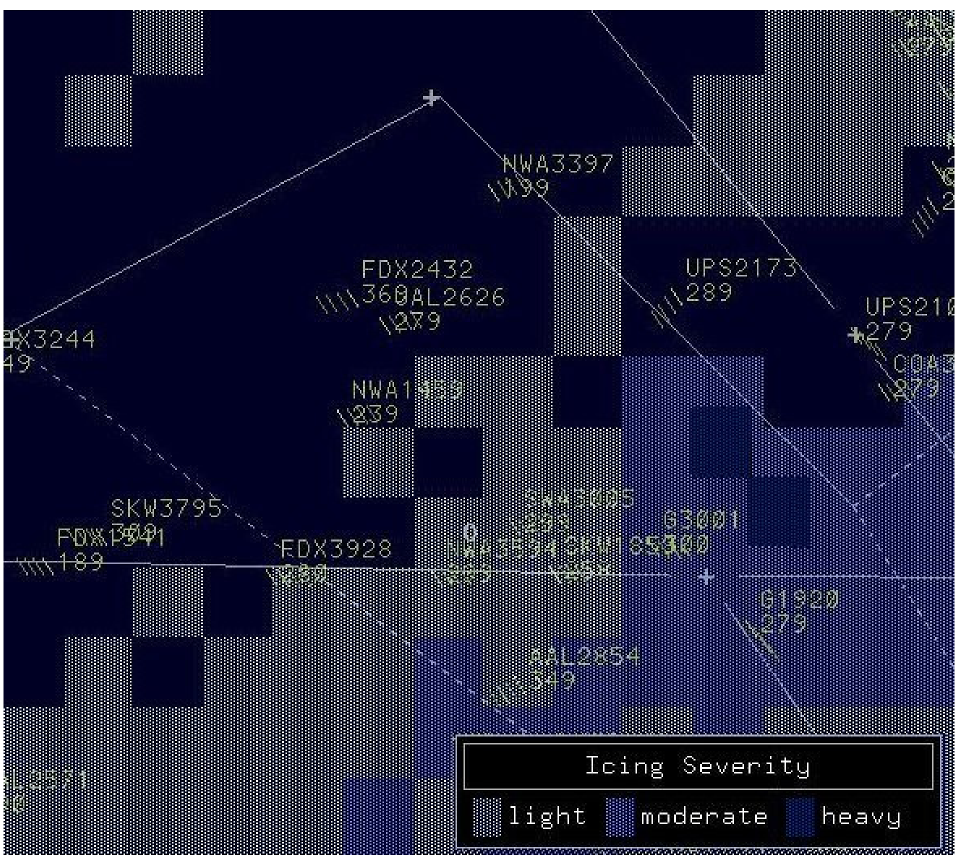

Figure 6. Icing Severity Display.

3.7.1 Phraseology Example

To communicate icing severity information to pilots, en route controllers can use the following phraseology: *N123, icing severity between ten o'clock and two o'clock, one five miles, icing severity is heavy at one two thousand.*

3.7.2 Research Requirements for the Icing Severity Display

The graphical Icing Severity Display is not available in current ATC operations. Therefore, there is a need to develop an Icing Severity Display that meets the following requirements:

- The capability to show shaded areas for expected light, moderate, and heavy icing.
- The capability to select one of eight pre-defined altitude strata for the display of icing severity.

4. DISCUSSION

One of the Federal Aviation Administration's goals is to increase the safety of flight by reducing the number of weather-related accidents. As part of this effort, research and development have provided many new weather products that pilots can use pre-flight and in the air. Although pilots have seen an increase in weather products and weather services, en route controllers still depend on legacy products, such as Precipitation Displays and text-based weather descriptions. En route controllers are at a disadvantage when providing weather-related services to pilots because of the limitations in display accuracy, information specificity, and presentation format of these legacy weather products. This limitation reduces the ability of controllers to take a more pronounced role in keeping aircraft away from hazardous weather areas and limits the usefulness of information that controllers relay to pilots. Researchers need to develop controller weather products that meet controller requirements for severe weather avoidance and enhance the collaboration with pilots. Once developed, these weather products will provide information that enhances cockpit decision making and work towards a reduction in weather-related GA accidents.

In this report, we propose weather displays for use by en route controllers during severe weather avoidance. Primarily, these displays focus on information that allows controllers to support GA pilots to avoid hazards caused by reductions in ceiling/visibility, icing, and convective activity. Furthermore, the weather displays provide pertinent information that controllers can relay to pilots, thereby enhancing cockpit decision making. We also propose an automated support tool that (a) tracks GA aircraft and hazardous weather areas and (b) alerts the controller about impending conflicts to further support the controller during these operations. Once alerted, the controller can either inform the pilot about the location and extent of the hazard or execute necessary weather avoidance actions.

Although we illustrate our display concepts as part of the controller's main situation display in this report, the presentation of these weather displays are not limited to the controller's display. For example, Ahlstrom and Friedman-Berg (2006) showed that Terminal Radar Approach Control controllers could use advanced weather information equally and effectively on both the main situation display and the auxiliary display (which was located on top of the situation display). Likewise, this means that we can present weather displays on the En Route Information Display System next to the controller workstation and on the ESIS in each area of specialization.

As is true for most display concepts for the future air traffic domain, there are issues to be resolved, such as research and development of new data sources or the integration of separate sources of information. Graphical weather data for controllers is problematic. There has been no prior development and there are no operational requirements that specify what controllers need. However, pertinent and sufficient data sources exist today that could meet controller requirements for severe weather avoidance and, when relayed to pilots, could enhance decision making in the cockpit. In fact, all of the data sources for our weather display concepts exist today and are readily available. What has yet to be developed is the capability to display these data sources graphically at the controller workstation or on auxiliary displays. To initiate this development process, we have included research requirements for each weather display to serve as input to the weather research program for the development of these displays.

Granted, controllers would need training on both the displays and on phraseology for weather avoidance and weather advisories before they could use these displays in the field. Similarly, there is a need to inform pilots on *what* information the controller has available and *how* this information can affect cockpit decision making. As far as controller phraseology is concerned, there is virtually no change in the phraseology needed to use our weather displays compared to the phraseology that en route controllers use in current operations. This fact is important for several reasons. First, it eliminates the introduction of an entirely new phraseology for controllers, and it reduces the time needed for training and operational evaluation. Second, the current weather phraseology is familiar to pilots; therefore, it would have very little impact on pilot training and the use of this information in the cockpit.

However, we do see a need for controller and pilot training that aims at developing a new safety culture where all parties work together to increase weather situation awareness and safety of flight. Today's en route environment is limited with regards to what weather information is available to the controller (Ahlstrom & Dury, 2007). Furthermore, there are indications that controllers do not trust their information and that they are uncertain about the value it brings to pilots via advisories (Ahlstrom & Dury). This limits the usefulness of weather information and works against a cultural climate where controllers perceive weather information and weather-related communication between controllers and pilots as important. With our proposed displays, controllers can provide both the big and the small weather picture within the airspace. Pilots, on the other hand, are often restricted to the small weather picture even when equipped with weather radar. By providing controllers with more adequate information that is readily available, displayed in a proper format, and easily transmitted to pilots, we lay the foundation for making a change in the current climate and work towards greater communication and collaboration.

Finally, we envision the use of radio communication for the transfer of weather information between controllers and GA pilots. With our proposed displays and controller phraseology, there is no requirement that necessitates other means for the transfer of this information. Research and development are working on data-linked weather capabilities that will change the way we transfer weather information in the future. Our weather information concepts are compatible with both the present radio-based and future data-linked-based capabilities. However, at present, there is no infrastructure in place that allows the seamless transfer of either text-based or graphical weather data between en route controllers and GA pilots. Once we develop these data-link capabilities, controllers could transfer pertinent weather information and aircraft positions directly to the cockpit. This could be an important step to enhance shared weather situation awareness between controllers and pilots. It could also be an important step to reduce the number of weather-related GA accidents and increase the safety of flight.

5. SUMMARY OF RESEARCH REQUIREMENTS

In the following section, we provide research requirements for the development of our proposed weather avoidance displays. For the Ceiling, Visibility, Flight Category, and Icing Display requirements, we provide one generic example of how the available data can be adapted to display a certain combination of hazard areas or altitude levels. However, operational versions of these Display Systems must be very flexible and allow tailoring of incoming data. There is no single display that will fulfill all sector needs and controller requirements, as this will depend on each sector's geographical location and traffic pattern. Therefore, each display requirement implicitly assumes full control of tailoring the data display at the sector level.

- Automated Weather Avoidance Support Tool
  - Develop a tool that automatically tracks GA aircraft, based on the aircraft type (filed on the flight plan), and correlates this information with the 3D weather database to detect future conflicts between aircraft and weather hazards. The tool alerts the controller by blinking the aircraft data block 20 minutes ahead of a predicted aircraft and hazard conflict. During the alert, the controller receives specific information about the weather hazard on the situation display; the information is presented in the moveable read-out window. The controller also has the option to display the specific weather hazard on the situation display (e.g., the Icing Probability Display for the altitude of 8,000 feet).
- Precipitation Display
  - Develop a Precipitation Display that allows user-defined altitude strata that limit the display of precipitation intensities to the volume within the sector altitudes.
  - Develop a capability to use wind information and previous precipitation updates to extrapolate a best estimate of current intensity locations. The display of the precipitation intensities updates once a minute.
  - Develop a capability to display echo top information in association with the Precipitation Display.
  - Develop a capability to show symbols for cloud-to-ground lightning strikes on the Precipitation Display. Each symbol indicates that there has been a lightning strike at that location within the past 15 minutes. Each symbol times out after 15 minutes.
- Ceiling Display
  - Develop a Ceiling Display that shows shaded areas where ceilings are less than 500 feet and between 500-1,000 feet.

- Visibility Display
  - Develop a Visibility Display that shows a shaded area where the visibility is less than 1 mile, and a second shaded area where the visibility is between 1-3 miles.
- Flight Category Display
  - Develop a Flight Category Display that shows shaded areas for obscurations and IFR conditions.
- Icing Probability Display
  - Develop an Icing Probability Display that shows shaded areas where the probability of icing is 25-50%, 50-75%, and above 75%.
  - Develop the capability to select one of eight pre-defined altitude strata for the display of icing probability.
- Icing Severity Display
  - Develop an Icing Severity Display that shows shaded areas for expected light, moderate, and heavy icing.
  - Develop the capability to select one of eight pre-defined altitude strata for the display of icing severity.

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Acronyms

AOPA	Aircraft Owners and Pilots Association
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
CONUS	Continental United States
ESIS	Enhanced Status Information System
GA	General Aviation
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
LIFR	Low Instrument Flight Rules
MVFR	Marginal Visual Flight Rules
NEXRAD	Next-Generation Weather Radar
NTSB	National Transportation Safety Board
PIREP	Pilot Report
SME	Subject Matter Expert
UCAR	University Center for Atmospheric Research
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions