Federal Aviation Administration

R&D Review

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The Weather Forecast

in this issue

Achieving the Impossible

Aviation Weather Research Program

Mission: To provide accurate and accessible weather products to users of the national airspace system, to reduce weather-related accidents and incidents, and to improve system capacity and efficiency.

The FAA Aviation Weather Research Program accomplishes what many consider impossible — understanding weather science and using that knowledge to develop new aviation weather forecasting tools that enhance aviation safety and capacity.

In partnership with a number of federal agencies and laboratories, such as the National Weather Service, National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), the U.S. Air Force, Navy, and Army, Massachusetts Institute of Technology (MIT) Lincoln Laboratory, and the National Center for Atmospheric Research (NCAR), the research team produces new tools for observations, warnings, and forecasts of weather phenomena such as fog, icing, marine stratus, oceanic weather, snow, thunderstorms, turbulence, and volcanic ash.

This partnership of Federal Agencies and research labs, although somewhat unique for a federal research program, has been in existence since the 1940s," explains Joan Bauerlein, FAA Director of Research and Development. A 1946 amendment to the Civil Aeronautics Act gave the Weather Bureau, which began operations in 1943, responsibility for acting as a clearinghouse for research in aeronautical engineering. In 1959, the newly created Federal Aviation Agency, announced plans to coordinate government research and development in aviation weather forecasting and reporting. The announcement followed a general agreement between the FAA and the Departments of Commerce and Defense for such a joint program.

"The research team, lead by the FAA's Gloria Kulesa and comprised of meteorologists, engineers, computer specialists, and weather modelers from academic and government labs from across the country, represents some of the best weather scientists in the nation. Researchers at these labs have earned over 20 scientific patents, presented over 500 papers at scientific conferences and workshops, and published over 300 technical papers and articles. And, the program has received the Department of Commerce Silver Medal, Federal Aviation Administration Excellence in Aviation Award Government Technology Leadership Awards, and National Weather Association Aviation Meteorology Award."

Better forecasting of weather phenomena provides critical improvements to aviation safety and capacity. Gloria Kulesa describes the program as having "sizeable research efforts in forecasting meteorological phenomena that pose problems for aviation, including: convective weather; aircraft icing (both in-flight and on ground); low ceiling and visibility; and turbulence. Recognizing that data quality can also be affected by the nature and quality of the meteorological sensors, the FAA also invests in new sensor development and radar technology."

The aviation weather research team, however, does not conduct research solely to advance scientific knowledge. They develop tools that help the aviation community and increase public safety. The team ensures its research is operationally available and uses several government platforms to deliver products to the aviation community, through experimental prototypes or formal government technology transfer efforts. Some of those platforms include: ▶

- FAA Integrated Terminal Weather System (ITWS), which operates four prototypes demonstrating aviation weather research products and 11 operational systems at key terminals around the country (air traffic control towers, terminal radar approach control facilities, air route traffic control centers, and the FAA Air Traffic Control System Command Center). Only the FAA and airlines have web access to ITWS.

- FAA Enroute Weather and Radar Processor (WARP) system, which is present in all air route air traffic control facilities, also provides weather products for en route controllers.

- Aviation Digital Data Service (ADDS), specifically developed by the aviation weather research team and operated by the National Weather Service, provides public access to aviation weather data and products. It also serves as an approved site for general aviation pilot weather briefings. ADDS web access is unlimited.

The aviation community now uses a number of forecasting tools developed by the program. This issue of *R&D Review* focuses on the people, technologies, and accomplishments of the FAA Aviation Weather Research Program. "This is an extremely productive program. Our researchers are accomplishing what many have thought impossible," states Ms. Bauerlein. "They are focused on discovering the unknown and remain dedicated to answering the question, 'Are we making a measurable difference?' These researchers are making a difference every day. In fact, independent benefit analyses show that the tools developed by the Aviation Weather Research Program are providing significant safety, capacity, and efficiency benefits that will exceed more than $700 million per year when fully deployed in the national airspace system." R&D Review

For additional information on the FAA weather research program, please see http://www.research.faa.gov.

It ADDS Up

Aviation Digital Data Service

Many within the aviation community know of the Aviation Digital Data Services' (ADDS) reputation for providing aviation weather data and products in user-friendly formats. For years, private and commercial pilots, military and airline dispatchers, airport ground crews, and aviation meteorologists have benefited from increased weather awareness and are flying safer because of the comprehensive, yet comprehensible, weather information available on the operational ADDS site, http://adds.aviationweather.gov/. Further, aviation decision-makers may view the latest aviation research products on the experimental ADDS website at http://weather.aero.

ADDS, a product of the FAA Aviation Weather Research Program, provides pilots, meteorologists, dispatchers, and airport ground crews the latest weather analyses, observations, and forecasts in texts, graphs, and gridded depictions. Some of these tools include:

- Current Icing Potential and Forecast Icing Potential together provide current in-flight icing conditions as well as a forecast 3,6, 9, and 12 hours into the future;
- Graphical Turbulence Guidance predicts the location and intensity of clear air turbulence over the continental United States, currently for altitudes of 20,000 feet and above; and
- National Convective Weather Forecast displays current thunderstorm activity and predicts its location one hour into the future.

A popular feature of ADDS is the Flight Path Tool. Very easy to use, the Flight Path Tool enables users to view graphical weather information along their selected route of flight by graphically selecting departing and arriving airports and preferred altitudes. The resulting display shows the chosen altitude, the color-coded weather for all altitudes, and plots the terrain. The users may then assess the weather's impact on their flights and plan accordingly. The tool not only provides a suggested safe passage away from hazards, it also provides system efficiencies by designating airspace that is free of weather, and by reducing ground holds and delays.

A new version of the Flight Path Tool is the latest addition to the ADDS website. The original Flight Path Tool required a web browser to download code from the ADDS server to a personal computer every time a user accessed the tool. Leaving the tool and returning later, the user had to wait through another full download of the code. Now, based on user feedback, the Flight Path Tool enables users to download the application to their computers. JavaWebStart™ simply launches the tool from a desktop icon, and even detects and downloads any revisions that have been made to the application. Because the application is installed on a user's computer and not downloaded within a web browser, the tool can save user's preferences. It can also export images and/or send them to a printer.

There are many other features of the Flight Path Tool. If the user wants to overlay pilot reports, AIRMETs, and SIGMETs,[1] the Flight Path Tool allows them to chose specified altitudes and time periods for the final display. Available map overlays include counties, highways, and air route traffic control boundaries. For TAFs,[2] ADDS parses information, enabling users to view to view successive snapshots taken in hourly increments.

[1] Pilot reports (PIREPs) offer weather conditions reported by pilots who have just flown through an area. AIRMET, an acronym for "AIRman's METeorological information, provides valuable information about the following conditions: moderate icing; moderate turbulence; sustained surface winds 30 knots or greater; and a wide ceiling of less than 1,000 feet and/or visibility less than 3 miles, and extensive obscurement of mountains. SIGMET stands for SIGnificant METeorological information, which is broadcast for hazardous weather considered extremely important to all aircraft. SIGMETs warn of the following hazards: severe icing; severe and extreme turbulence; dust storms; sandstorms; or volcanic ash lowering visibility to less than 3 miles.

[2] TAF is the international standard code format for terminal forecasts issued for airports.

For METARs,[3] the Flight Path Tool enables users to specify which variables (temperature, dew point, wind, altimeter setting, sky cover, color-coded flight category, ceiling, weather, visibility, and station identifier) are displayed. For national convective weather forecasts, the tool allows users to toggle the height and speed of the forecasted thunderstorm, as well as the one-hour forecast from the previous hour to help users understand how well the forecast is performing. In addition, the user can overlay counties, highways, and air route traffic control boundaries.

ADDS is a joint development effort of the FAA, the National Oceanic and Atmospheric Administration, and the National Center for Atmospheric Research. The funding is provided by the FAA, and operational ADDS system is maintained by the National Weather Service. Currently, the icing, turbulence, and convective products are only authorized for operational use by meteorologists and airline dispatchers. Others may use these products to supplement information contained in AIRMETs and SIGMETs. R&D Review

[3] METAR is the international standard code format for hourly surface weather observations.

Modeling Aviation Weather

Atmospheric Modeling

Computer atmospheric modeling is the foundation of all weather forecasts. Throughout the day, scientists collect weather data using a vast array of observing systems which include the network of weather balloons launched twice a day, sensors on airplanes, Doppler weather radars, automated surface observing systems, and advanced satellites. The data is processed through powerful computer models to calculate the evolution of key features like weather fronts and large-scale storms, and to generate predictions for forecasters.

The cornerstone of modern weather forecasts is numerical weather prediction. Numerical modeling is the process of solving a set of equations that describe the evolution of variables (temperature, wind speed, humidity, pressure, etc.) that define the state of the atmosphere at every point on a regularly spaced three-dimensional grid (e.g., latitude, longitude, altitude) over a geographic area such as the United States. These equations are solved at each 3-D point to produce a prediction of several tens of seconds, and this process is repeated over a number of these time intervals out to 12 hours for aviation purposes. These models incorporate detailed physics-based laws about clouds, radiation, turbulence, and even soil and vegetation processes. Scientists continually work to improve the accuracy of these detailed, high resolution weather models. They also work on improved data assimilation techniques, using new observations from satellites, aircraft, and weather radars, to make the model sees an accurate 3-D depiction of current weather conditions in its starting point updated each hour.

Weather forecasting, modeling, and research are advancing rapidly with the advent of high performance computing. With better high resolution models that are fed at a rapid refresh rate by newer and faster computers, weather researchers can improve upon the traditional mesoscale projections and can zero in on smaller and smaller weather areas that might present hazards to aviation.

FAA-funded researchers are expanding the limits of modeling to meet aviation's real-time operational requirements for weather forecasting. A weather forecast model developed by the research team and run operationally by NOAA is now improving the accuracy and timeliness of short-range weather forecasts. The model, the Rapid Update Cycle (RUC), is helping meteorologists forecast aviation hazards, such as clear air turbulence, icing, clouds and winds. It is also aiding forecasters with short-term significant weather events such as severe thunderstorms, tornadoes, and winter storms.

The model, developed at NOAA's Earth System Research Laboratory (ESRL) and funded by the FAA, combines a number of features, such as hourly updates and precise and accurate information that make it very useful to forecasters. The model covers the continental United States and is run on a 13 kilometer grid.

The RUC model provides accurate numerical forecasts for those needing current storm information during the next 1 to 12 hours. It runs hourly, the highest frequency of any forecast model, assimilating the most recent observations taken from commercial aircraft, radar, satellite, and at the surface, to provide high frequency updates of current conditions and short-range forecasts. "The model," explains Stan Benjamin, a scientist at NOAA/ESRL, "makes 800 trillion calculations for a 12-hour forecast, all within a 17-minute period, to get RUC forecasts out quickly to users."

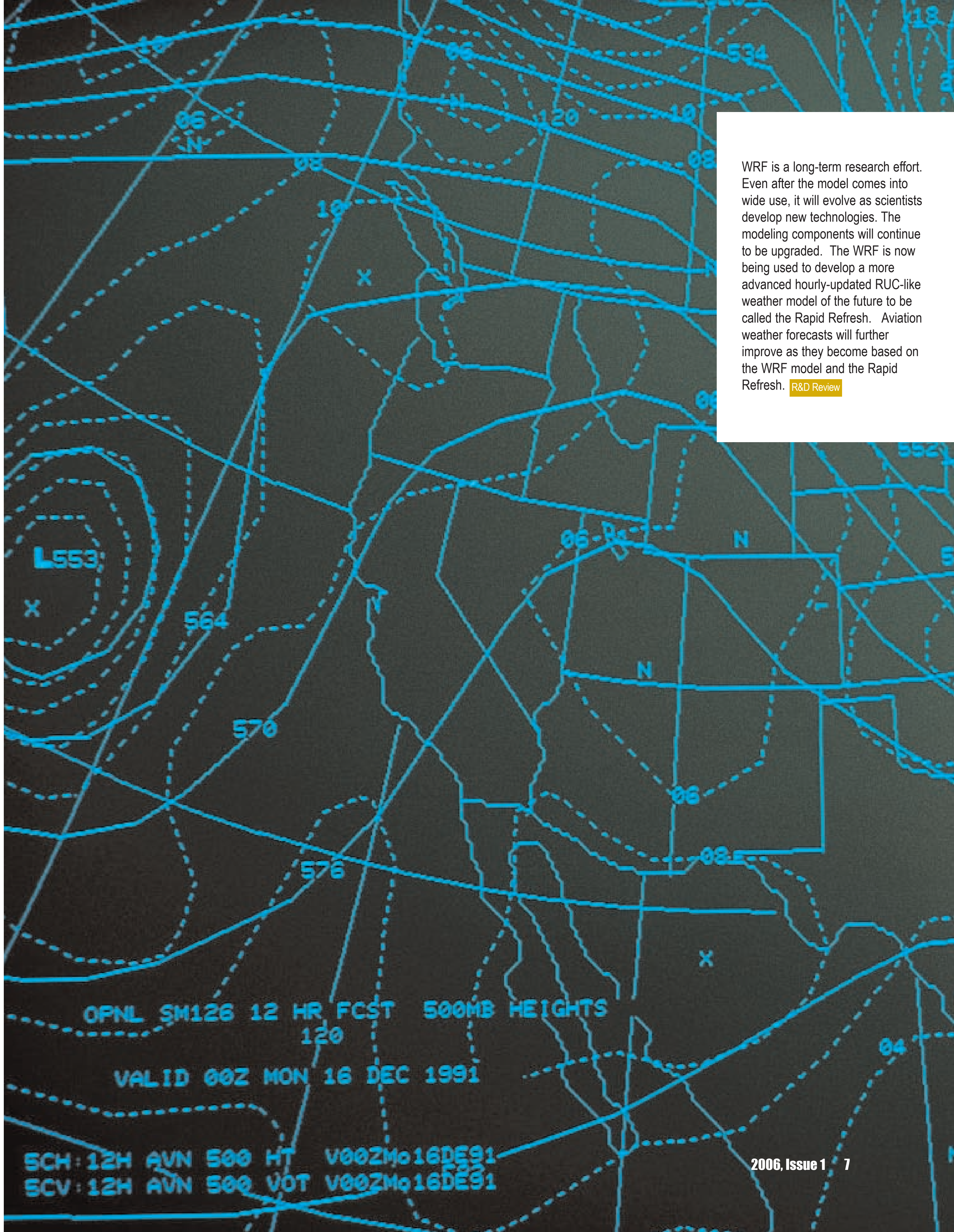
Researchers at the NOAA Earth System Research Laboratory and the National Center for Atmospheric Research have now updated the model to provide higher resolution graphics and assimilation of additional weather information, including improved moisture analysis, and improved cloud/precipitation physics, to increase forecast accuracy. Called RUC 13 because of its 13-kilometer resolution, the model provides improved and surface forecasts of interest to aviation users as well as the general public. The RUC-13's output is used as input for FAA-developed aviation-weather applications that produce weather forecasts.

The FAA is also helping fund the Weather Research and Forecasting (WRF) Model, a next generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers.

The effort to develop WRF is a collaborative partnership, principally among the FAA, National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration (including ESRL), the Air Force Weather Agency, the Naval Research Laboratory, and the University of Oklahoma. WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. It also provides operational forecasting a model that is flexible and efficient computationally, while offering the advances in physics, numerics, and data assimilation contributed by the research community.

WRF has a rapidly growing community of users, and is currently in operational use at the NOAA National Centers for Environmental Prediction. With its advanced cloud microphysics and powerful computational procedures, WRF is expected eventually to generate forecasts so detailed that they will resemble radar images. It will feature a fine-scale horizontal grid of 1 to 10 kilometers (0.6 to 6 miles), compared with horizontal grids in existing operational models that are at least 12 kilometers (7.5 miles). The finer resolution will enable researchers to simulate individual thunderstorms, along with such hard-to-capture features as gust fronts.

Researchers can also link WRF to other specialized computer models to gain more insights into the atmosphere. For example, a scientist will be able to couple WRF with an ocean model for more accurate hurricane analysis, or with a chemistry model to track the formation and movement of chemicals such as ozone. These capabilities will form the basis for future operational forecast models of hurricanes and air quality. ▶



WRF is a long-term research effort. Even after the model comes into wide use, it will evolve as scientists develop new technologies. The modeling components will continue to be upgraded. The WRF is now being used to develop a more advanced hourly-updated RUC-like weather model of the future to be called the Rapid Refresh. Aviation weather forecasts will further improve as they become based on the WRF model and the Rapid Refresh. R&D Review

The NEXRAD

Advanced Radar Technology

Radar is a major tool for observing weather. Radar works by sending out pulses of microwave energy, and then measuring how much of that energy is reflected back and how long it takes to return. The radar essentially listens for echoes. When there is rain, for example, the microwave pulses reflect off the raindrops, returning some of the energy to the radar. The location of the rain is determined from the orientation of the radar antenna and the time taken for the pulses to return to the radar receiver. The intensity of the rainfall is calculated from the power of the returned pulse, which depends on the size of the raindrops and their concentration, from fine light drizzle to huge hailstones.

All weather radars, including Doppler, electronically convert the reflected radio waves into pictures showing the location and intensity of precipitation. If the echo is strong, the object is said to have a high reflectivity and is indicated by a bright color on the radar map. Weak echoes have a low reflectivity and are indicated by darker colors.

Doppler radars also measure the frequency change in returning radio waves. A computer within a Doppler radar uses the frequency changes of echoes to determine how fast objects are approaching or receding from the radar. Scientists and forecasters have learned how to use these pictures of wind motions in storms, or even in clear air, to understand more clearly what is happening now and what is likely to happen in the next hour or two.

The FAA primarily uses WSR-88D (Weather Surveillance Radar - 88 Doppler) radars for weather information. The radars are a product of the NEXRAD program, a joint effort between the Departments of Commerce, Defense, and Transportation. There are 158 operational NEXRAD radar systems deployed throughout the United States and at selected overseas locations, each with a maximum range of 250 nautical miles. The NEXRAD network provides significant improvements in weather warning and preparedness for air traffic safety, flow control for air traffic, resource protection at military bases, and management of water, agriculture, forest, and snow removal.

The FAA-funded Advanced Weather Radar Techniques Product Development Team is working to make the NEXRAD radar network and other weather radar systems more useful for the aviation community. As part of this effort, the research team is developing new radar software that improves nationwide detection and prediction of hazardous weather and is helping to get new radar capabilities integrated into the FAA and National Weather Service NEXRAD network.

The team has already implemented an enhanced national three-dimensional radar mosaic. The system takes base level data from all available radars at any given time, performs quality control, and then combines reflectivity observations from the individual radars onto a unified 3-D Cartesian grid that covers the contiguous United States. The mosaic grid has a 1-kilometer horizontal resolution over 21 vertical levels with a 5-minute update cycle. The reflectivity grid is used for a number of weather analysis and forecast products, including aviation weather applications. Development of the 3-D grid is important because it can depict complete storm systems on a regional scale, and it is easily combined with additional sources (e.g., satellite and models), increasing the radar data's value in the overall forecast process.

In addition to the 3-D mosaic grid, the Advanced Weather Radar Techniques research team has developed, tested, and successfully transferred to the NEXRAD network a number of improvements, including:

- Storm Cell Identification and Tracking Algorithm;
- Hail Detection Algorithm; and
- Tornado Detection Algorithm.

The team's next improvement is likely to be polarimetric radar. This new technology will add vertical polarization to ▶

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Using this "dual polar operation," the radar will be able to distinguish between rain, hail, and snow - a capability that will significantly improve the forecasting of winter storms, severe thunderstorms, and even improve airport safety.

The NEXRAD

the currently used horizontally polarized radar waves, and help to detect exactly what is reflecting the signal back. Using this "dual polar operation," the radar will be able to distinguish between rain, hail, and snow - a capability that will significantly improve the forecasting of winter storms, severe thunderstorms, and even improve airport safety. The team is also considering developing a means to integrate radar (conventional and polarimetric) input into numerical models. All of these tasks are the result of the team's response to the needs of the Aviation Weather Research researchers who continue to improve aviation weather forecasts. R&D Review

A Critical Safety Tool

Preparing for Convective Weather

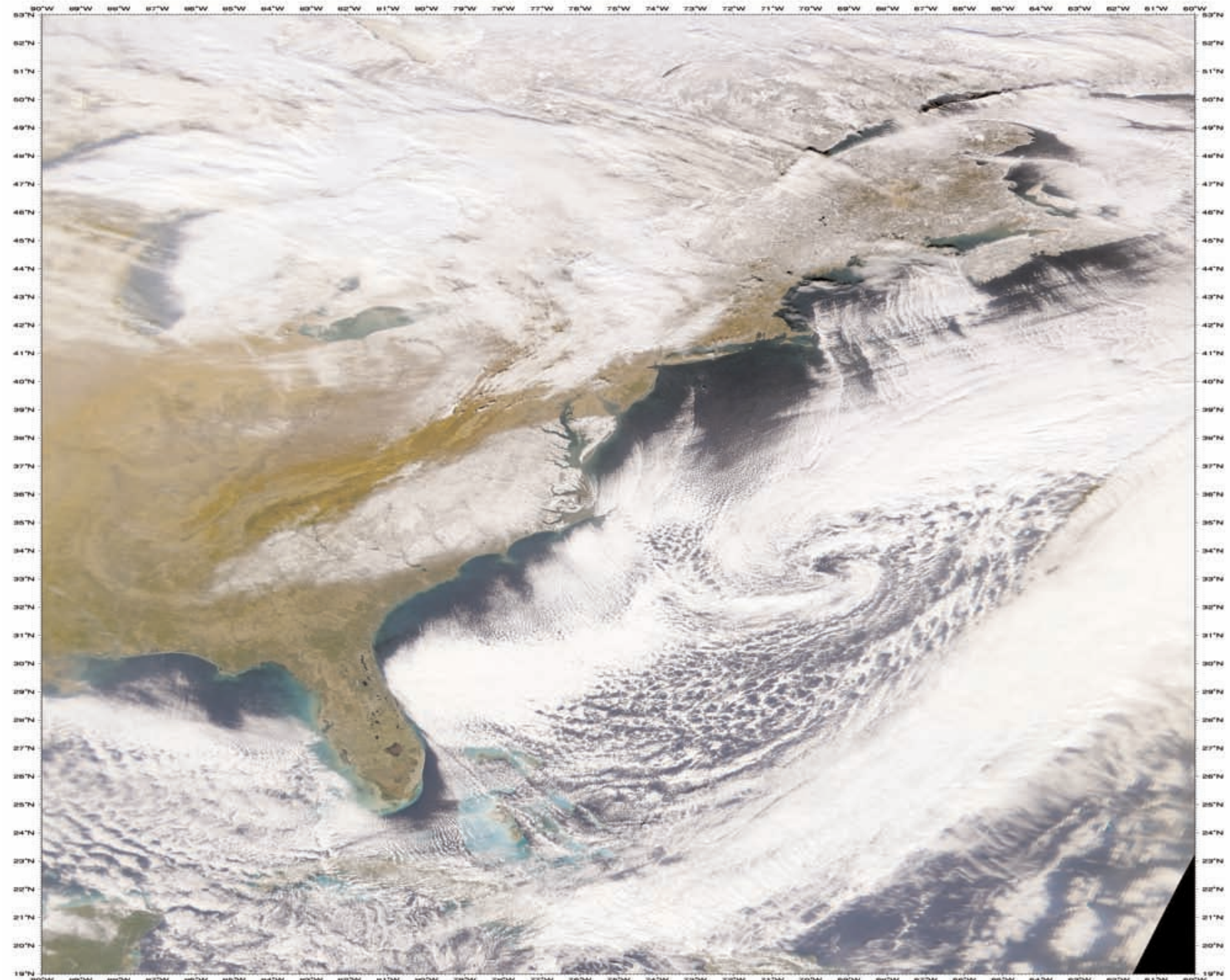
Weather hazards exert an enormous impact on the aviation system. On a typical day the U.S. aviation system operates near maximum throughput. With landing slots, gate slots, and aircraft spacing constraints all highly subscribed, the system has relatively little elasticity to deal with unplanned events, such as taking an aircraft out of service, closing a runway for emergency repairs, or weather events. Even small local disruptions can have a ripple effect that triggers disproportionately large systemwide delays.

Adverse weather, particularly thunderstorms (known to forecasters as convective weather), is the most frequent and pervasive unplanned disruptive event facing aviation. In fact, thunderstorms account for most of the U.S. air traffic delays. Because summer thunderstorms, in particular, are notorious for wreaking havoc on flight schedules, advanced notice of impending storms makes it easier to prepare the aviation system for any ripple effect.

But, thunderstorms are not very predictable hours ahead. For strategic decisions, dispatchers need an accurate look at the current and forecasted situation. Part of the challenge in forecasting convective weather is to be able to predict the initiation and location of new thunderstorms, 30 minutes to two-hours in advance. The other challenge is to anticipate the merger of thunderstorm cells and predict when a thunderstorm will dissipate.

Over the past few years, FAA research efforts have focused on developing automated thunderstorm nowcasting systems that combine information from observations, models, and human forecaster input. Features or forecast parameters relevant to thunderstorm evolution include boundary-layer convergence zones, boundary-storm interactions, cumulus cloud detection and growth, boundary-relative shear profile, boundary-relative updraft strength, and storm trends and tracks. The output from algorithms used to identify these features are combined using fuzzy logic in the form of user-defined functions, interest fields, and weighting schemes to produce forecasts of thunderstorm initiation, growth, and decay.

FAA-funded researchers have developed and deployed three operational systems: a Regional Convective Weather Forecast product; a Terminal Convective Weather Forecast Product; and a National Convective Weather Forecast Product. The Regional product provides detection and a two-hour forecast of convective weather, including growth and decay, across the northeast corridor. The terminal product provides a one-hour forecast of convection weather, including initiation, growth, movement, and decay. The FAA will implement this product into the Integrated Terminal Weather System (ITWS) in Fiscal Year 2006. If deployed at all ITWS airports, the FAA estimates an annual benefit of $524 million.



The National Convective Weather product is a supplement (not a substitute) to convective SIGMETs. Used in conjunction with other weather products, this tool provides additional information for convective weather avoidance and flight planning. Its one-hour national thunderstorm forecast automatically updates every five minutes to help commercial airlines, general aviation and the FAA keep planes safe and on time. The tool provides a better picture of where the thunderstorms will be over the next several hours, which is a critical element in the safe and efficient execution of flight schedules. Among the major airlines using the National Convective Weather Forecast are American, Northwest, and Southwest. Anyone may access the tool on the Internet at the Aviation Digital Data Service website.

The National Convective Weather Forecast product is used with the recently developed Collaborative Collective Forecast Product, a probabilistic forecast tool. The collaborative forecast provides airline meteorologists with the best first guess of thunderstorm activity over the next two to six hours. Every few hours Aviation Weather Center meteorologists, FAA flow control managers, and airline meteorologists adjust this initial forecast during a conference call and then plan accordingly.

The FAA Convective Weather Product Development Team continues to work on new applications of technology, such as using satellite cloud and convergence line detection data, radar characteristic analysis to predict storm lifetimes, boundary layer wind retrieval techniques, and computer weather models. "We are working to provide the most accurate, current, and useful thunderstorm information available with today's technology," says project manager and MIT Lincoln Lab scientist Marilyn Wolfson. "With the products we have already developed, and with new technologies on the horizon, we are making aviation safer and more efficient." R&D Review

Ceiling & Visibility

The Challenges of Cloud Ceiling and Visibility

Before a flight, a pilot checks the ceiling and visibility at the departure point, along the route, and at the destination. Ceiling and visibility conditions, however, can change quickly to create safety hazards for all types of aviation. Predicting cloud ceiling and visibility, presents researchers with a formidable challenge.

The ceiling is the distance between the ground and the lowest cloud layer that covers more than half the sky. The phrase unlimited ceiling means that there are no clouds to interfere with flying. A limited ceiling is low enough to affect flight. Visibility is the farthest distance at which an observer can distinguish objects.

Improved national-scale analyses and forecasts of ceiling and visibility, and new tools to present this information to pilots, weather briefing staff, and others are key to improving the ceiling and visibility safety record. FAA-funded researchers from the National Center for Atmospheric Research, Massachusetts Institute of Technology (MIT) Lincoln Laboratory, the Naval Research Laboratory at Monterey, and the National Oceanic and Atmospheric Administration's (NOAA) Earth Systems Research Laboratory are working to integrate data from pilot reports, radar, satellite, surface observations, and numerical models to develop accurate and timely forecasts of cloud ceiling and visibility conditions.

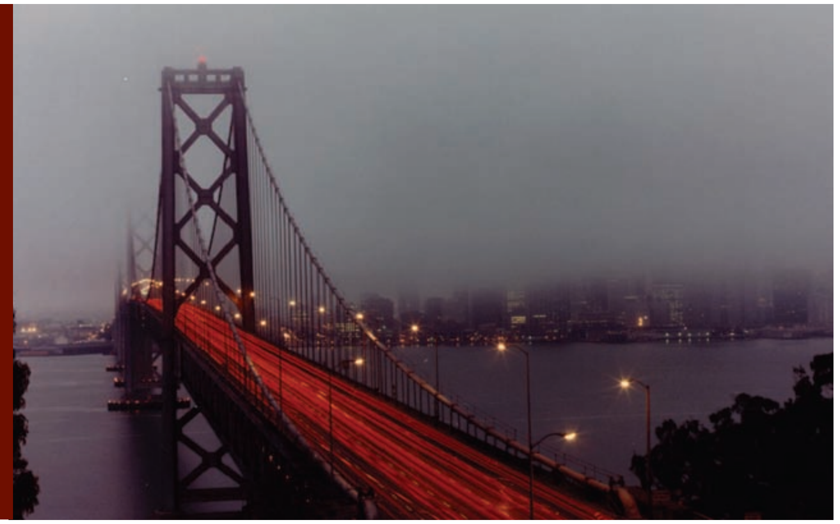
Their work has resulted in an automated analysis and forecast products that predict ceiling and visibility conditions over the continental United States. The National Ceiling and Visibility Analysis product incorporates observational data from Automated Surface Observing Systems and the Geostationary Operational Environmental Satellite (GOES). The satellite data are used to outline the extent of clear and cloudy conditions, while the automated surface observing system data is used to determine cloud ceiling height and visibility. This system forecasts the current ceiling, surface visibility, and flight category information every fifteen minutes. The color-contoured display shows current conditions and allows users to select from national to local scales. The tool is currently in the test stage and is accessible for non-operational evaluation through use of the Java application on the FAA's experimental website at http://weather.aero.

Ceiling and visibility conditions are also a major concern in Alaska. Building on experience gained developing the analysis system for the continental U.S., researchers have developed the first version of an exploratory prototype, the National Ceiling and Visibility Alaska Forecast product. This web-based display uses hourly METAR observations across the region to produce forecasts from 1 to 12 hours of ceiling, visibility, and flight category. This product has also entered the test phase of research, so a controlled set of users may see the product and provide input into the development process.

Together, low ceiling and poor visibility are not just a safety issue. Reduced ceiling and/or visibility can severely reduce the capacity of an airport and lead to airborne or ground delays that result in diversions, cancellations, missed connections, and extra operational costs. Airborne and ground delays that restrict traffic flow into and out of major airports across the country affect the capacity and efficiency of the U.S. air traffic system as a whole. Recent studies suggest that adverse ceiling and visibility conditions account for slightly less than one-third of all U.S. air traffic delays and slightly more than one-third of U.S. weather-related delays.

Ceiling and visibility forecasts for the air terminal area are critical to timely airport decisions on the opening and closing of individual runways and air traffic control decisions on traffic routing and spacing in the terminal area. Researchers in the FAA Aviation Weather Research Program are responsible for developing operational products specifically designed for high volume airports whose runway limitations during low ceiling and visibility conditions result in a substantial loss of operating capacity. ▶

Through coordination with aviation weather forecasters and traffic managers, researchers developed a system to provide automated forecast guidance of approach marine stratus clearing time, as well as a suite of relevant weather observations and operational information.



Ceiling & Visibility

Since the implementation and cancellation of ground delay programs are highly dependent upon anticipation of changes to available operating capacity, an accurate prediction of the onset and cessation of these conditions allows air traffic managers an opportunity to regulate traffic to use available capacity and minimize delay. For example, the failure to forecast accurately the times of onset and of the marine stratus at San Francisco International Airport results in significant system delays. Marine stratus is the trapped cool and humid air from sea breezes. In the San Francisco Bay area, marine stratus causes frequent low ceilings at the airport. During these events, the airport cannot use independent parallel approaches and it must impose delay programs to regulate arrivals.

Through coordination with aviation weather forecasters and traffic managers, researchers developed a system to provide automated forecast guidance of approach marine stratus clearing time, as well as a suite of relevant weather observations and operational information. The forecast system relies on a network of sensors in the San Francisco Bay area installed at locations along the approach zone at the San Francisco and San Carlos airports. In particular, acoustic sonic detection and ranging systems (SODARs) at these two sites provide measurements of the height of the marine inversion, which tracks the vertical growth of the clouds and provides an indication of the stratus cloud layer top. Data from the sensor network are collected and processed at the system base station computer, which prepares a display as input to four forecast models. The four model forecasts are weighted and combined to yield a single "consensus" forecast of approach clearing time.

The new Marine Stratus Forecast system provides daily guidance to aviation weather forecasters and air traffic managers for anticipating the precise time of cloud dissipation, allowing for efficient implementation and cancellation of delay programs to minimize air traffic delays. The new tool has become an important shared resource amongst forecasters and air traffic managers in the collaborative decision process for efficient management of these programs to reduce avoidable delay.

The FAA funded MIT Lincoln Laboratory to develop this decision support system. Research team members included San Jose State University, the University of Quebec at Montreal, and the Center Weather Service Unit at the Oakland Air Route Traffic Control Center. The FAA has transitioned this technology to the National Weather Service for continued operation and maintenance of the system as part of its mission to provide accurate and timely forecasts for the aviation community in the San Francisco Bay area.

Researchers are currently working to develop more accurate forecasts of operationally significant changes in ceiling and visibility near major airports in the northeastern United States. Unlike San Francisco, where low stratus ceiling forms and dissipates on a daily cycle throughout the summer, the exposure to poor ceiling and visibility conditions at these northeastern airports is more typically associated with the clouds, fog, and precipitation that accompany large scale transient weather systems that affect the northeast United States from November through April. Researchers have chosen the New York City terminal radar approach control facility as a test bed site for development of tools to help traffic managers anticipate changes in operating capacity associated with these types of weather systems. Product development for the New York City area airports may lead to applications for the other major airports affected by similar winter season ceiling and visibility conditions. R&D Review

Turbulence

Examining the Bumps

Anyone who flies has felt the airplane bumped by turbulence. Experts define turbulence as rapid air movement. Normally, pilots cannot see this air movement, and often they cannot anticipate it. Many different conditions create turbulence, including surface-heating jet-streams, air flow over mountains, cold or warm weather fronts, or thunderstorms. It can happen at any time during the flight.

The number of pilot-reported encounters with turbulence is substantial: pilot reports (PIREPS) of moderate-or-greater turbulence average about 65,000 per year; and pireps of severe-or-greater turbulence average about 5,500 per year year. While turbulence is normal and happens often, it can also be dangerous. The result can be anything from spilled food trays to broken bones for flight attendants and passengers not buckled in their seats. The cost to the airlines is estimated in the $150-$500 million per year range because of passenger and crew injuries, flight delays, rerouting of aircraft, and aircraft damage. An aircraft that experiences severe turbulence must be removed from service and inspected prior to its next scheduled flight per FAA regulation. This lost time to inspection and maintenance is an additional cost to the airlines. Further, more often than not, pilots will try to avoid or exit turbulent air, so turbulence significantly impacts airspace system efficiency and controller workload.

Turbulence considered light for a heavy commercial aircraft may be severe for a general aviation aircraft. People in small planes encountering turbulence can experience more than an unpleasant ride – if turbulence is significant enough, their aircraft may crash.

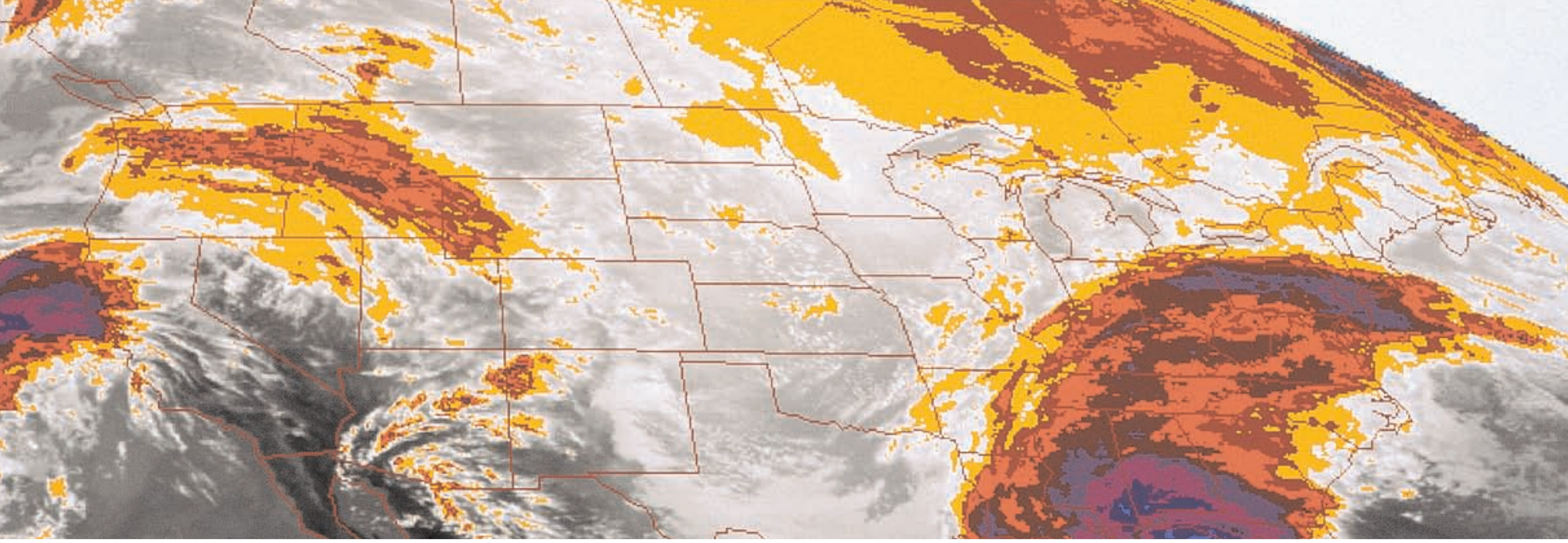
Turbulence is perhaps the most difficult aviation weather hazard to combat. The phenomenon has perplexed some of the greatest minds in science, with Nobel-Prize winning physicist Richard Feynman calling it "the most important unsolved problem of classical physics."

"Encounters with turbulence for commercial and general aviation aircraft pose significant safety, efficiency, and workload issues," explains Dr. Robert Sharman. He is a scientist at the National Center for Atmospheric Research and the leader of the FAA-funded Aviation Weather Research Turbulence Program Product Development Team. "Up to 60 percent of aircraft encounters with this phenomenon are due to turbulence associated with thunderstorms," Sharman adds. "Often pilots can avoid thunderstorm-induced turbulence because they can see bad weather on their onboard weather radars. However, turbulence is not always related to what the pilot sees on the onboard radar." When a sudden change in wind velocity, for example, occurs in the absence of clouds, it is invisible to radar. Such clear air turbulence can buffet a plane without warning. Clear air turbulence often occurs at high altitudes, frequently in thin pancake-shaped bands. It is often associated with a rapid change in wind with height (wind shear) that causes disturbances, or eddies, near the edge of the otherwise smooth flow, especially in the vicinity of the jet stream.

Although turbulence accounts for the majority of all weather-related injuries, not all turbulence conditions can be forecasted. A large percentage of turbulence encounters might be avoided if air traffic controllers, airline flight dispatchers, and flight crews had better forecast products. Studies have shown that, at least for commercial air carriers, strategic planning for turbulence avoidance could reduce cabin injuries and reduce costs.

Because observations and forecasts are not accurate enough to pinpoint the location, time, and intensity of turbulence, FAA-funded researchers are working to gain a better understanding of clear air turbulence, finding better ways to predict it, and providing operationally useful products directly to the users. One such tool is the Graphical Turbulence Guidance (GTG) product. Airline meteorologists and dispatchers are now using this forecasting product to make decisions regarding flight planning and routing to avoid hazardous turbulence at upper flight levels (20,000 feet and above).

The first generation Graphical Turbulence Guidance became operational at the National Weather Service Aviation Weather Center in March 2003 as an aid to forecasting upper level turbulence areas over the continental U.S. The tool, now used as a supplement to turbulence AIRMETs and SIGMETs, refines turbulence assessments by comparing several turbulence diagnostic models with current pilot turbulence reports and providing a graphical depiction of turbulence intensity at forecast intervals of 0, 3, 6, 9 and 12 hours. The results are shown as a contour map of predicted clear air turbulence intensity at altitudes of 20,000 to 45,000 feet. The graphical turbulence guidance product is available via the Aviation Digital Data Service web site at http://adds.aviationweather.gov. ▶



Turbulence

Since the original release, researchers have refined and added new functions to the tool. This next generation extends the turbulence analyses and forecasts down to 10,000 feet. The band between 10,000 and 20,000 feet is especially significant for air taxi providers since they fly in this range. In addition, some new turbulence diagnostics are included that reflect the results of continued research. The Aviation Weather Technology Transfer Board approved the updated product for experimental use in November 2004. It is scheduled to become operational in fiscal year 2006. This is one more step toward a fully automated, advanced technology tool that will provide forecasts for all altitudes and will also have the capability to forecast mountain wave and convectively-induced turbulence.

"The development of automated turbulence forecasting techniques is just one goal of the turbulence research team," explains Dr. Sharman. "Members of this team are also developing and implementing an *in situ*, or onboard measuring system. It augments and/or replaces subjective turbulence pilot reports with automated, objective, and precise turbulence measurements. These turbulence measurements are produced by a software package that uses existing on board sensors, avionics and communication systems. The turbulence intensities are provided in the form of the ICAO standard metric, the eddy dissipation rate (EDR), which is a direct measure of the atmospheric turbulence intensity level. In this way, the turbulence information that is communicated is independent of the aircraft that provide the measurements. On the other hand, the EDR values can be directly related to a given aircraft's response to the turbulence. Hence, the EDR measured by one aircraft can be communicated to another aircraft, and then displayed in terms of the expected response to the receiving aircraft."

These measurements will serve multiple purposes:

- Provide many more turbulence observations than are available with pilot reports thereby, giving meteorologists, dispatchers, air traffic controllers and pilots a much more complete picture of location and intensity of turbulence so that better tactical and strategic decisions can be made;
- Validate turbulence forecasts; and
- Feed valuable data into the forecast product.

This will help researchers further refine turbulence detection and forecasting tools. In fact, they are now testing on-board software that automatically records and computes turbulence intensities (median and peak), and then periodically downloads the data during the flight. The International Civil Aviation Organization (ICAO) adopted this method as an international standard for turbulence data reporting. Currently 200 aircraft from United Airlines have deployed the *in situ* turbulence software, which alone is generating approximately 1.3 million turbulence reports per month as compared to the approximately 55,000 turbulence reports filed by all pilots every month. These EDR reports are available in real time to United Airlines meteorologists and dispatchers via a password-protected website. Researchers are now working with Southwest Airlines to equip their fleet of Boeing 737 aircraft over the next year.

It is very important to alert the flight crew and passengers to prepare for a turbulence encounter (stow moving carts, sit down, buckle up). To do this, the pilot must obtain sufficient warning of turbulence ahead. FAA researchers conducted a real-time regional demonstration last summer that combined the outputs of 16 NEXRAD radars located in the upper Midwest region. Researchers created a three-dimensional image (mosaic) of detected turbulent conditions from the combined sets of data. During the test, a commercial vendor sent the image, including a customized map of the flight region, via an uplink to the cockpit of the demonstration partner's aircraft. The detection product also reports turbulence intensities as EDR. The product provides a 15-minute look ahead of in-cloud aviation hazards, emphasizing convectively induced turbulence.

Once the new tool is fully developed and approved for operational use, it could be incorporated into existing aviation decision support systems to provide nowcasts of convectively induced turbulence to the aviation community. R&D Review

According to the Bureau of Transportation Statistics, a part of DOT's Research and Innovative Technology Administration, air carriers reported 46,127 flight delays due to extreme weather in December 2005.

A flight is counted as "on time" if it operated less than 15 minutes later than the scheduled time shown in the carriers' Computerized Reservations Systems (CRS). Arrival performance is based on arrival at the gate. Departure performance is based on departure from the gate.

Winter Weather

Weather Support to Decision Making

Icing is one of the most feared and respected weather hazards known to pilots – from those who fly single-engine Cessnas to those who pilot jumbo jets for the airlines. All commercial airline passengers who have experienced long delays while their aircraft was being deiced know that airlines take the deicing process even more seriously than the expense of late takeoffs and revised schedules. For the operators have learned that even a very thin layer of ice on a wing surface can increase drag and reduce airplane lift by 25 percent.

To make deicing decisions, airlines generally rely on human observations of visibility and National Weather Service estimates of snow intensity. FAA-funded research shows, however, that large dry snowflakes hampering visibility are less of a threat than small wet flakes. This important finding further shows that reports based solely on visibility can mislead aircraft deicing decision makers. Researchers also have found that the liquid equivalent snowfall rate is one of the most important factors in determining the holdover times (time until a fluid fails to protect against ice buildup) for deicing fluids.

To help airports and airlines make critical deicing decisions, the FAA Aviation Weather Research Program developed the Weather Support to Decision Making (WSDM) system. This innovative system integrates weather data from Doppler radar, surface weather stations, and snow gauges located near the airport to accurately measure the amount of water in the snow. The system then provides graphical displays of real-time weather conditions (including winds, temperature, and precipitation type/rate) as well as one-hour forecasts of liquid equivalent snowfall. The forecasts are updated every five minutes.

WSDM serves as a decisional aide for the airline and airport operator, providing them with critical winter weather information to support ground deicing, runway plowing, and airport traffic management operations. The system's new "checktime" feature provides deicing operators with a digital display of holdover time status for all deiced aircraft awaiting takeoff. It also alerts deicing operators to transition from a one-step deicing procedure (Type I fluid only) to a two-step procedure (Type I followed by Type IV) based on increasing snowfall rates. Use of the improved technology has already decreased hold times.

WSDM-related research has been incorporated into winter training manuals for commercial pilots. Additionally, WSDM's accuracy is enhanced by current and site specific weather information that results in more accurate decision making at serviced airports. The system requires little meteorological knowledge and minimal training to operate, and it provides decision makers with valuable information in seconds.

The FAA transferred the WSDM technology to a commercial vendor in 1999. Denver International Airport now uses the system. In December 2005, WSDM became operational at its newest locations, the Minneapolis airport and two nearby regional airports. Purchased by the Minnesota Department of Transportation Bureau of Aeronautics, WSDM displays are located at the Northwest Airlines systems operations center, as well as the deicing facility and at the Metropolitan Airports Commission operations center.

Now that it is eligible for FAA Airport Improvement Program funds, the system is expected to be acquired by additional airports. Because its displays show "windows of opportunity" when weather conditions abate or lessen, WSDM will increase the deicing, runway plowing and traffic management efficiency, and will reduce the environmental impacts of deicing fluid consumption, at any airport it services. Most importantly, however, it will significantly increase aircraft safety. R&D Review

Shifting Gears

Transitioning Research to Operations

The aviation weather products and tools developed by the Aviation Weather Research Program undergo scientific and programmatic rigor before moving into the operational national airspace system. In fact, no product can enter operational use until it receives the approval of the FAA and National Weather Service (NWS).

In 1999, the FAA established a process to guide the orderly transfer of weather capabilities and products from research and development into operations. The management team that oversees this process has grown in membership throughout the years. Now called the Technology Transfer Working Group, members from the various FAA air traffic organizations and aviation safety offices meet together with staff from NWS on a bi-weekly basis.

The technology transition process guides the development, testing, and transition of new aviation weather hazards detection and forecast products. It also addresses policy, training, certification, regulation, and life cycle funding cost considerations. The Working Group prepares product documents (e.g. concept of use, implementation plans, roadmaps), assesses the technical merit of emerging products, and interfaces with industry users in preparation for executive decision making. The Group also:

- facilitates user needs analyses;
- compiles requirements;
- recommends research priorities;
- recommends product graduations from experimental to operational use; and
- plans and monitors the conversion to operations (e.g. rule/guidance changes, training, software platforms, communications).

The decision portion of the technology transfer process contains four stages:

- D1 - initial product concept
- D2 - test, the product is released into a controlled test group
- D3 - experiment, the product is released for all users to evaluate. This stage requires:
  - Product technical descriptions
  - Quality assessment reports
  - Concept of Use and Implementation Plan documentation
- D4 - operations, the product is ready for operational use (either as supplementary or primary). This step requires a revision to the D3 documentation, as well as a complete/in-depth evaluation of the operational product following their implementation.

The Group has proposed a charter for the executive decision-making bodies, now called the Aviation Weather Steering (AWSG) and Aviation Weather Advisory (AWAG) Groups. A newly identified group with its details still under formation, the AWSG has thus far considered more than a dozen aviation weather products, and approved all to its next stage of release.

The AWSG includes the FAA's Air Traffic Organization Vice Presidents and the Associate Administrator of Safety, as well as directors from Air Traffic and the Safety organizations. Non-FAA participants include NWS executives, representatives from the NWS Joint Program Development Organization Weather Integrated Product Team and the Offices of Climate, Water and Weather Services, Science and Technology, and representatives from the National Center for Environmental Predictions.

Together, these inter-agency officials strive to align the current national airspace system and the next generation air traffic system research and development and move the research products into operations. The AWSG meets semi-annually, or as needed, to determine the readiness of weather research products for experimental or full operational use, basing their decisions on technical and operational readiness, cost and benefits, user needs, and budget considerations. In their meetings, they review research progress at the appropriate decision stages (D2-D4) and determine whether the product should advance to the next step, or if more work is needed, thereby deferring consideration for some future date. R&D Review

Quality Assessment

Improving Weather Forecasts

The FAA Aviation Weather Research Program's applied research is improving weather forecasts for the aviation community. Much of this research, in the form of automated tools to predict aviation weather phenomena such as icing and turbulence, is transferred from research laboratories to FAA air traffic control platforms and the National Weather Service through the Aviation Weather Technology Transfer process. Before these automated tools, or algorithms, are transfered into the operational environment, the Quality Assessment Product Development Team objectively evaluates their performance to ensure that the tools provide improved forecasting capabilities.

Over the past decade the program has developed and deployed a number of forecast tools for use by the aviation community. "These tools integrate observations, models, and other data to make a scientific guess about the weather," explains Jennifer Mahoney, FAA Quality Assessment Product Team lead and a meteorologist at NOAA's Earth System Research Laboratory. "Basically, a weather forecast can be defined as an experiment. Given a set of conditions or data, we develop a hypothesis about what will happen. Like all scientific experiments, the results must be verified."

But, how can forecasters verify weather predictions? "Since a forecast is a prediction of a future weather state, verification is the process of assessing the quality of that forecast, i.e., how well did the forecast represent the actual weather conditions," says Mahoney. "Hence, the forecast is verified against an observation of the actual event. This verification or quality assessment process provides information on how well the forecasts are working."

The Quality Assessment team provides the following services to the Aviation Weather Research Program:

- Gives feedback to the scientists during the research process regarding research product performance;
- Maintains the Real Time Verification System (RTVS) publicly available website, providing a measurement of research product performance;
- Performs an independent review for each new weather product, details the product's performance and reports to the FAA-National Weather Service Aviation Weather Technology Transfer Board for consideration when evaluating the product's graduation from research into operations; and
- Develops advanced verification methods to evaluate newly developed, high-resolution aviation weather forecasts.

The research team conducts an intensive, independent assessment of every new forecast product. Each algorithm transitioning through the technology transition process is evaluated for a three-month period, with its performance compared to an operational standard. The team establishes objective procedures for evaluating forecast quality and accuracy, using and applying advanced weather observations and measurements from remote-sensing instruments. These observations form the basis for the verification methodologies and estimates of forecast accuracy. Often, the available observational datasets do not directly represent the forecast attributes, so the researchers use inferences and comparisons among a variety of observational datasets to establish forecast quality. The statistical verification methodologies are designed to represent the operational use of the forecasts. ▶

Quality Assessment

"To evaluate the aviation weather forecasts and algorithms, the researchers often must develop new advanced verification tools and methodologies that provide a better measure of forecast accuracy than standard approaches." Mahoney explains, "One important tool is the RTVS that provides long-term assessment of National Weather Service forecasts. This technology allows users to compare various forecasts through short-term evaluations, and provides interactive data verification for forecasters and model developers."

The RTVS interpolates forecasts to observation locations in near real time. The interpolated pairs are stored in a relational database management system and are accessed by users through an interactive web-based graphical user interface. The RTVS provides verification statistics and displays of icing, turbulence, convection, ceiling and visibility, and precipitation forecasts from both human and automated forecasts. Users can compare various forecast lengths and issue times, over a user-defined time period and geographical area, for a variety of forecast models and algorithms.

The RTVS provides a mechanism for monitoring and tracking improvements in FAA's forecast products. RTVS provides displays and statistical information to forecasters and managers at the Aviation Weather Center, Air Traffic Systems Control Command Center, and to researchers. The RTVS is available online at http://www.ad.fsl.noaa.gov/fvb/rtsvs/index.html. R&D Review

Hot off the Press!

FAA's Latest Technical Reports

Sherri Magyarits FEASIBILITY OF MALSR AND RUNWAY LIGHTING FOR ILS APPROACHES FOR HELICOPTERS (DOT/FAA/AR-TN05/55)

The FAA Office of Aviation Research and Development Airport and Aircraft Safety R&D Division (ATO-P), William J. Hughes Technical Center Flight Program Group (ACB-870), Simulation and Analysis Group (ACB-330), and support contractors performed a human-in-the-loop Copter Instrument Landing System (ILS) study in a Level D Sikorsky 76 simulator at Flight Safety International, West Palm Beach, FL, March 27-April 1, 2004. For the Copter ILS study, researchers evaluated the adequacy of airport lighting to support helicopter approaches with reduced minima. Specifically, the study investigated whether a helicopter could successfully land only using a Medium Intensity Approach Lighting System with Runway Alignment Indicator Lights, runway markings, and runway edge lights. The majority of participant feedback and performance data, based on a sample of 14 pilots, supported the feasibility of the Copter ILS procedure in terms of lighting and visual cue adequacy and the two-person crew landing technique. They all agreed a two-person crew would be essential to the safety of the procedure. In most cases, pilots visually acquired the airport environment, before the 100-foot decision height. Due to the small sample size in the study, the collection of more data is desirable to augment and validate the results of this simulation.

Yann-Hang Lee, Elliott Rachlin, and Philip A. Scandura, Jr. SAFETY AND CERTIFICATION APPROACHES FOR ETHERNET-BASED AVIATION DATABUSES (DOT/FAA/AR-05/52)

With the advent of higher-performance computing and communication systems, aircraft will have the capability to process an unprecedented amount of information pertaining to performance, safety, and efficiency. Flight instruments will be integrated to share information and to cooperate with each other. It is inevitable that a high-speed and versatile network infrastructure will be required in the next generation of aircraft. One commercial off-the-shelf technology, Ethernet, is seen as potentially attractive in avionics systems due to its high bandwidth, low wire count, and low cost. Ethernet has been used in the Boeing 777 to transmit non-flight-critical data and in the Boeing 767ER within a flight-critical display system. There are many safety concerns, however, when Ethernet is applied to flight-critical systems. The inherent nature of the Ethernet protocols can easily result in nondeterministic behavior and interference. These are significant technical hurdles that must be overcome before Ethernet will be a viable candidate as an aviation databus technology. In this report, safety and certification issues of Ethernet-based aviation databuses are summarized. Initially, it focuses on the issues of deterministic operations of Ethernet controller, device drivers, and communication stack, and possible solutions to avoid any adverse effects. In the latter part of the report, the discussion is centered on the evaluation criteria for the certifiability of Ethernet-based databuses. A prototype communication subsystem to support deterministic data delivery in Ethernet is also illustrated. Using this proposed design as an example, the report explains how the specific avionics requirements can be satisfied. Finally, it describes the implementation of the design on a test bed and analysis of the final results.

Steven J. Lundin and Richard B. Mueller ADVANCED AIRCRAFT MATERIALS, ENGINE DEBRIS PENETRATION TESTING (DOT/FAA/AR-03/37)

This report documents the results of testing conducted in July and August 2001 at the Naval Air Warfare Center-Weapons Division, China Lake, CA, as part of the continued effort to characterize uncontained engine events. Researchers conducted these tests in support of the FAA Aircraft Catastrophic Failure Prevention Program. Data generated from this test will support the penetration equation development for the Uncontained Engine Debris Damage Analysis Model (UEDDAM), a developmental design tool for conducting aircraft safety analysis for engine rotor burst events. This testing investigated composite materials and metals for use in component shielding applications. Previous testing had focused on aircraft skins and structural components. Four materials were investigated during this series of testing: 2024-T351 aluminum; Ti-6Al-4V titanium; Inconel® 625 low-cycle fatigue; and a generalized composite. Impact data from these materials was used to characterize the ballistic response via a material constant within the penetration equations. This material property was previously denoted as the dynamic shear modulus (Gd). Examination of the ballistic limit equation used within the UEDDAM has determined that the material constant is more appropriately a shear constant (Cs).

AIA Rotor Manufacturing Project Team GUIDELINES TO MINIMIZE MANUFACTURING INDUCED ANOMALIES IN CRITICAL ROTATING PARTS (DOT/FAA/AR-06/3)

The Aerospace Industries Association (AIA) Rotor Manufacturing Project Team (RoMan) and the Federal Aviation Administration prepared these guidelines in response to accidents and incidents caused by manufacturing induced anomalies in critical rotating parts. According to a 1997 summary from the AIA Rotor Integrity Sub-Committee, post-forging manufacturing induced anomalies cause about 25 percent of recent rotor cracks/events. The guidelines represent an industry consensus on the currently available best practices to minimize manufacturing induced anomalies in critical rotating parts consistent with the AIA RoMan team charter and vision. Recommendations for nominal rotor manufacturing process development and control, including process validation, quality assurance, disposition of suspect parts, process monitoring, human factors and training, and non-destructive evaluation, are included to provide an overall framework for a highly reliable manufacturing process. Because critical rotating part reliability has demonstrated particular sensitivity to hole machining practices, specific recommendations for hole making are included. In addition, a section containing industry lessons learned is included to provide guidance on issues common in the industry. The term lessons learned generally refers to useful pieces of practical wisdom acquired by experience or study. Appendices are attached which include the team charter and vision and detailed information concerning process monitoring of holes and non-destructive evaluation.

Paul M. Hergenrother, Craig M. Thompson, Joseph G. Smith Jr., John W. Connell, Jeffrey A. Hinkley, Richard E. Lyon, and Richard Moulton FLAMMABILITY OF EPOXY RESINS CONTAINING PHOSPHORUS (DOT/FAA/AR-TN05/44)

As part of a program to develop fire-resistant exterior composite structures for future subsonic commercial and general aviation aircraft, flame-retardant epoxy resins are under investigation. Epoxies and their curing agents (aromatic diamines) containing phosphorus were synthesized and used to prepare epoxy formulations. Phosphorus was incorporated within the backbone of the epoxy resin and not used as an additive. The resulting cured neat epoxy formulations were characterized by thermogravimetric analysis, propane torch test, elemental analysis, microscale combustion calorimetry, and fire calorimetry. Several formulations showed excellent flame retardation with phosphorous contents as low as 1.5 percent by weight. The fracture toughness and compressive strength of several cured formulations showed no detrimental effect due to phosphorus content. The chemistry and properties of these new epoxy formulations are discussed.

Stanislav I. Stoliarov, Qaadir Williams, Richard N. Walters, Sean Crowley, and Richard E. Lyon HEATS OF COMBUSTION OF BROMINATED EPOXIES (DOT/FAA/AR-TN05/45)

The widespread use of brominated flame retardants and fire extinguishing agents in aircraft cabins and recent concerns about their combustion toxicity and environmental impact prompted a study to understand the mechanism by which bromine inhibits the flaming combustion of plastics as a first step towards identifying alternative chemicals or compounds. The heats of combustion of bromine-containing epoxies were calculated from the known atomic composition and compared to measured values in flaming and nonflaming combustion. The heat of flaming combustion was measured in a fire/cone calorimeter (CC) and by burning pyrolysis products in a methane laminar diffusion flame (pyrolysis-flaming combustion calorimetry (PFCC)). Heats of nonflaming combustion were measured by pyrolysis-combustion flow calorimetry (PCFC). The results of these tests indicate that the combustion heat released by these materials decreases with increasing amounts of brominated components as a result of incomplete combustion, char formation, and dilution of the materials with noncombustible bromine. Gas-phase combustion efficiency in the various test methods decreased as: PCFC > PFCC > CC. R&D Review

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