Benefits of Sharing Information from Commercial Airborne Forward-Looking Sensors in the Next Generation Air Transportation System

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The air transportation system of the future will need to support much greater traffic densities than are currently possible, while preserving or improving upon current levels of safety. Concepts are under development to support a Next Generation Air Transportation System (NextGen) that by some estimates will need to support up to three times current capacity by the year 2025. Weather and other atmospheric phenomena, such as wake vortices and volcanic ash, constitute major constraints on airspace system capacity and can present hazards to aircraft if encountered. To support safe operations in the NextGen environment advanced systems for collection and dissemination of aviation weather and environmental information will be required. The envisioned NextGen Network Enabled Weather (NNEW) infrastructure will be a critical component of the aviation weather support services, providing access to a common weather picture for all system users. By taking advantage of Network Enabled Operations (NEO) capabilities, a virtual 4-D Weather Data Cube with aviation weather information from many sources will be developed. One new source of weather observations may be airborne forward-looking sensors, such as the X-band weather radar. Future sensor systems that are the subject of current research include advanced multi-frequency and polarimetric radar, a variety of Lidar technologies, and infrared imaging spectrometers.

I. Introduction

IN order to support the next generation air transportation (NextGen) system of 2025 and beyond, an integrated nationally and internationally consistent common weather and operational picture for observational and forecast data should be available to all system users. This JPDO concept includes the use of a "single authoritative source" of weather observations and forecasts for air traffic management (ATM) decision-making for safe and efficient operations[1]. In the future system it is envisioned that communications channels will provide increased bandwidth and that aircraft will increasingly be sources as well as consumers of weather information. This improved communications capability will reduce data latency and enable refresh in seconds rather than minutes. This NextGen Network Enabled Weather (NNEW) system will provide the basis for cooperative decision-making, with all parties to the decision process having access to the same weather information. Network Enabled Operations (NEO) capabilities will include a virtual four-dimensional (4D) Weather Data Cube, with aviation weather information from many sources[2]. An FAA sponsored study found that based upon analysis of several 2005-2006 convective events, as much as two-thirds of the weather related delay was potentially avoidable[3]. The NextGen system will proactively adjust traffic flow on multiple, strategic and tactical time scales, based on probabilistic weather information, with Weather-influenced 4D trajectory updates "on the fly" to adapt to changing weather constraints with minimum disruptions and delays. Operational decision making will be highly automated, and will accommodate uncertainty-based weather and other types of information, and areas (volumes) of weather constrained airspace will be reduced. This integrated approach to weather information will make standalone legacy weather systems obsolete for use as sources of weather information in the cockpit.

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Proper integration of information into the modern flight deck must be of paramount consideration. Information implies more than raw data, and intelligent onboard systems will be required to collect and process data from onboard and off-board sources. These automated decision support systems will assist the pilot in utilizing the data in cooperative decision-making processes for safe and efficient operations, as well as, generating warnings and alerts about potential hazards. Recent advancements in airborne weather radar capabilities and research into new airborne hazard sensors and decision support systems present opportunities that were not previously available. The same systems that support the pilot can be the source of information for use by NNEW users (including flight crews, dispatchers, airline operations centers, and air traffic controllers) through NEO systems with enhanced bandwidth over current capabilities. While airborne weather radar is proposed as the first source of new data, the system design should accommodate future sensor systems as they are developed and deployed. Similarly cockpit systems and procedures to utilize and present NEO information should be designed with sufficient adaptability to make use of new data sources as they become available, without requiring major changes. It should also be noted that while the emphasis of current work in the NASA Aviation Safety Program elements supporting this research is on weather and atmospheric hazards, the same systems should be able to provide and use other sensor-derived information such as radar detection of airborne and ground moving obstacles (particularly non-cooperative targets without transponders or with equipment failures), validation of terrain and obstacle databases, confirmation of GPS position based on identification of known targets, and other types of surveillance data. The technical and system architecture challenges required to make use of this rich new source of aircraft-based observations, and the benefits for both for aviation safety and capacity, and for general users of weather information, will be discussed later.

II. Shared Weather Data Concepts

In order to fully realize the benefits of these integrated NextGen weather systems, weather data needs to be of high quality and available everywhere. In data sparse areas such as oceanic, international, or at small airports without weather infrastructure, timely and complete data are not currently available. Current generation airborne weather radar systems (Figure 1) can provide pilots with weather out to about 300 nautical miles by employing adaptive scanning techniques to automatically mitigate ground/sea clutter effects and optimize the collection of weather data[4,5]. These radar systems also include algorithms for detection of weather hazards including wind shear and turbulence; however, this information currently does not leave the aircraft, except possibly in a subjective pilot report (PiRep), and even then only in the traditional verbal manner which limits its utility. In a NEO environment airborne radar information could be exploited in many ways. Integration of airborne sensor data into the 4D weather cube would provide a rich source of weather observations including real-time hazard detections and characteristics and also prediction and tracking of dynamic hazards and resulting flight path constraints.

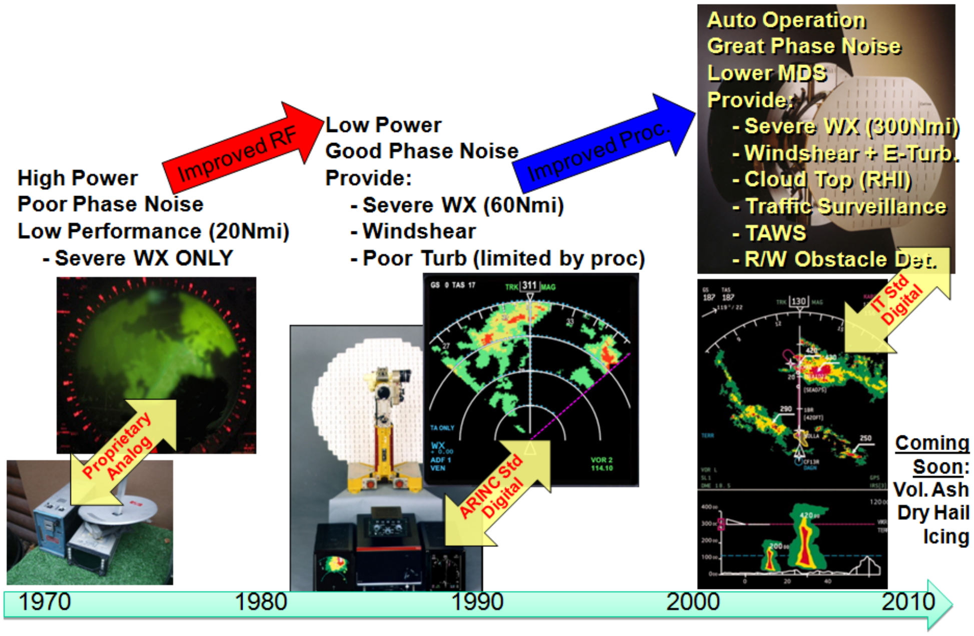


Figure 1. Current generation airborne radar system capabilities

Recent evolution of commercial airborne weather radar including their capabilities

Increased coverage through network-enabled sharing of fused airborne weather sensor data products supports NextGen Global Harmonization. Automatic two-way weather data sharing would allow an airborne weather information system to exploit ground information, and ground systems to exploit airborne sensor capabilities, in any location globally. An example of this concept is already in use; weather nowcast and forecast models incorporate *in situ* data from aircraft sensors. This data is transmitted through an automated meteorological report[6], and is provided to pilots as real-time advisory information through flight service centers. The addition of observations from forward-looking sensors is a natural extension that will provide added benefit and increased coverage.

A key concept of the shared use of weather data is information integration for improved tactical and strategic weather prediction and for more robust detection and estimation of the severity of potential weather hazards. Advanced processing techniques can be applied to multiple sensors and data sources to produce more reliable information than can be derived from single sensors, or from smaller subsets of the data. Data communications; automated decision support systems to collect, process, and track information to anticipate and avoid conflicts[7]; and advanced display systems are all required to make effective use of additional information from diverse sources. Integrated airborne weather systems providing improved detection, resolution, and update rates for rapidly developing hazards will support cooperative decision-making based upon common situational awareness, and could dramatically shorten the detection to decision-making (trajectory update) cycle for rapidly changing weather. Aircraft in the NEO environment should be fully participatory nodes in the networked environment, providing higher-level weather products as well as raw observations and real-time hazard alerts.

III. Application Examples

There are numerous potential applications in which information derived from airborne forward-looking sensors (currently the airborne weather radar) could help to enable safe implementation of NextGen by mitigating or eliminating the risk of aircraft encountering dynamic atmospheric hazards. Examples include transmission of warnings for growing convection, turbulence, or wind shear; air-air or air-ground transmission of radar reflectivity and velocity data (particularly valuable in data-sparse oceanic or international environments), rapid updates for evolving terminal-area weather phenomena (convection, reduced visibility, wake vortices, orographic turbulence, etc.), or automated responses by the radar system to off-board requests from weather infrastructure systems to adaptively scan areas of interest. This last item could provide coverage within areas of ground-based radar shadows due to terrain or severe weather, or within the cone of silence or umbrella of silence[8].

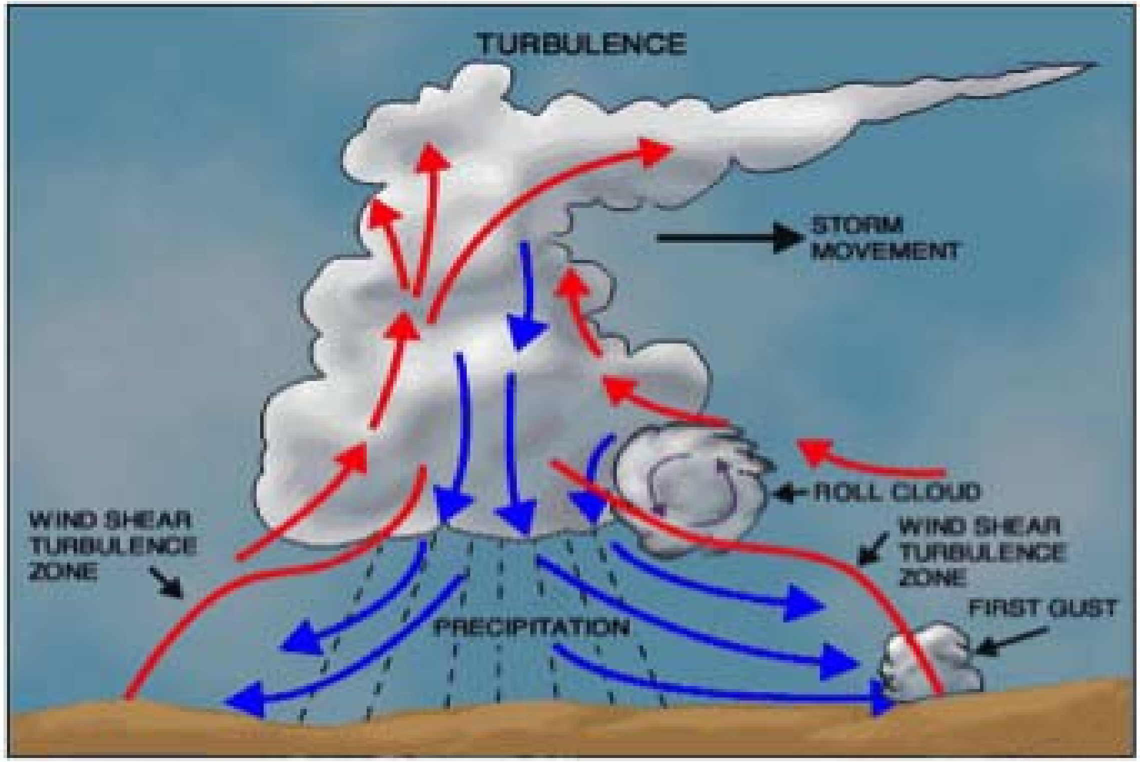


Figure 2 Cross-Section of a thunderstorm

Trailing aircraft can benefit from information available on those ahead of them, or on a nearby flight track. Short-term trending of airborne radar detected weather cells could be used for nowcasts of rapidly growing convective areas and associated hazards. Combination of airborne weather radar with satellite images and lightning data can enable better estimates of hazards due to convection. Satellites provide a strategic picture of rapidly developing convection, over-shooting cloud tops, glaciation, and their concomitant wind shear, lightning, heavy precipitation, high ice water content, gravity waves and turbulence hazard (Figure 2). Airborne radar can augment the picture with real-time reflectivity, short-term trending, and accurate storm top data. The combined data could be processed using algorithms similar to those used for prediction of convective transport, growth, and decay employed by ground-based forecast systems to generate a short-term forecast or nowcast product suitable for sharing with other aircraft in the vicinity, or incorporation into the 4D weather cube.

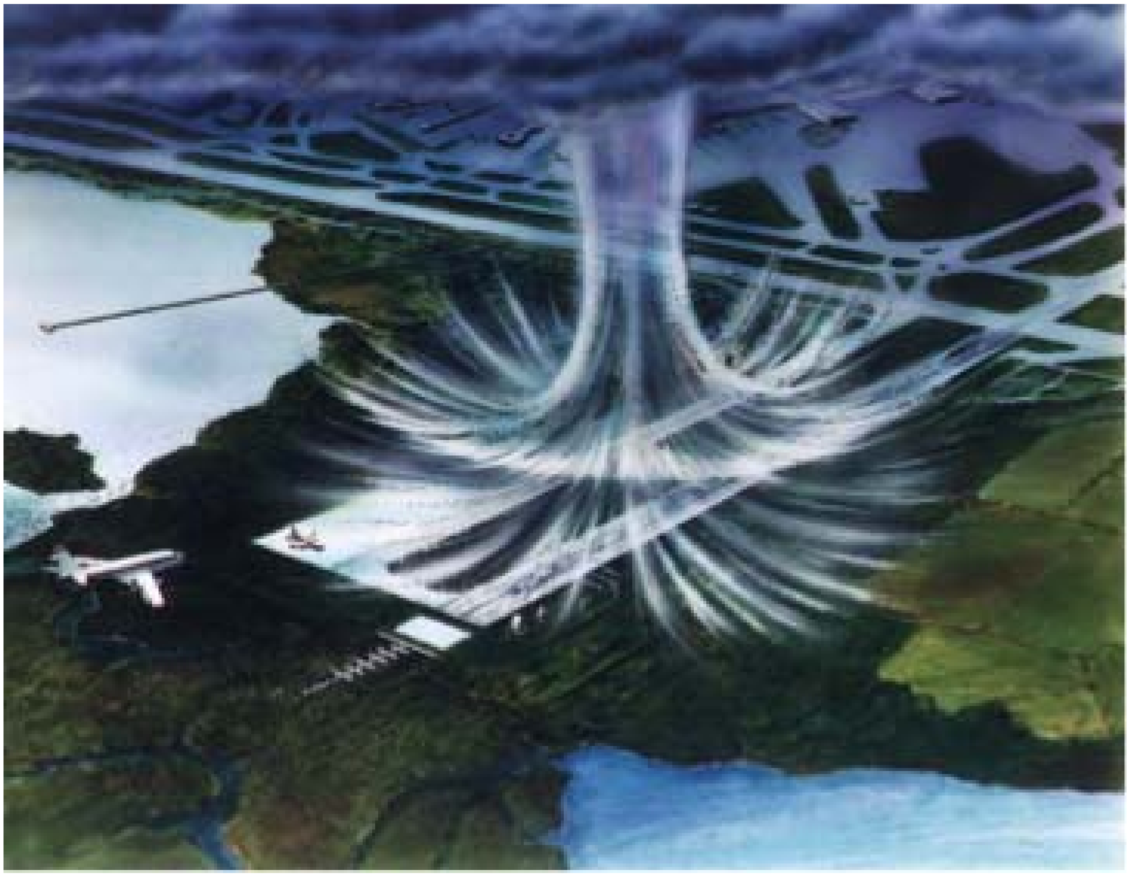
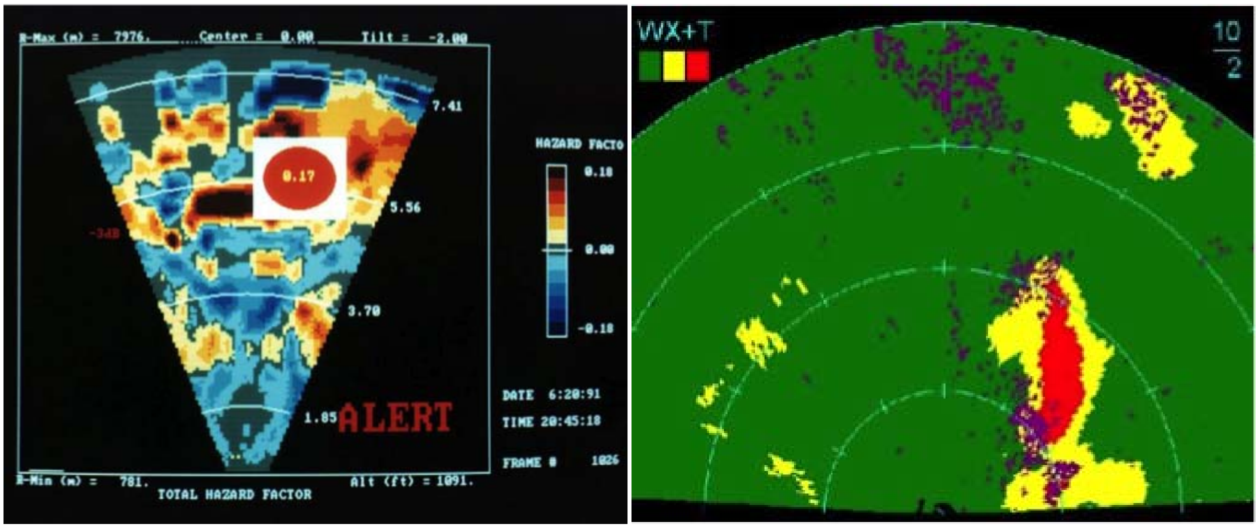


Figure 3 Wind shear hazard

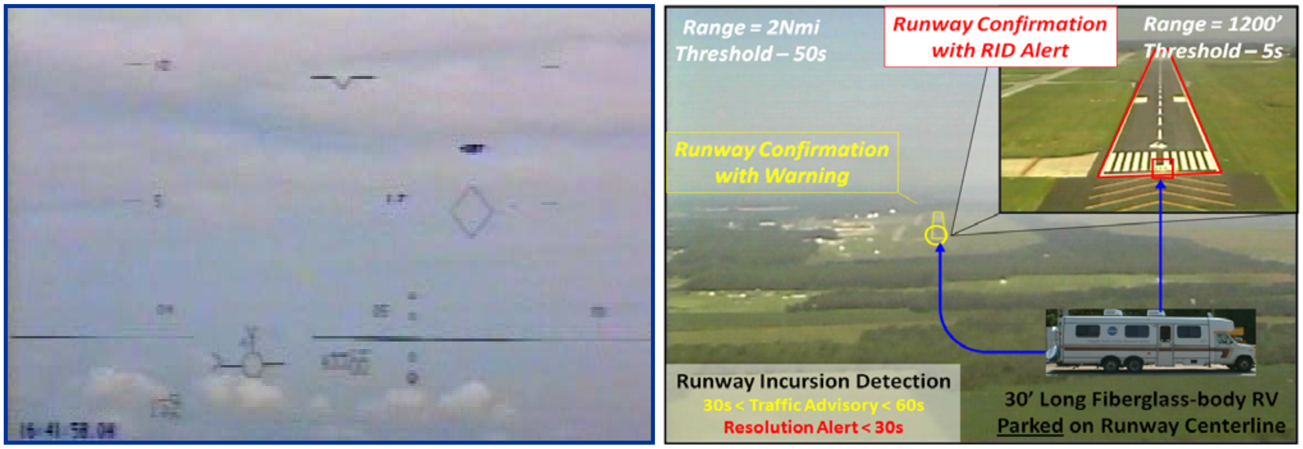
Specific hazard alerts from on-board sensors can be shared to improve safety. Wind shear (Figure 3) alerts generated to warn the flight crew could be broadcast to warn those behind them in the landing pattern of the divergent wind fields in the outflow region. The bandwidth requirements for such an alert could be quite low, for instance, the 3D location and divergence associated with the wind shear alert icon as shown in Figure 4a would be sufficient for a trailing aircraft to estimate the hazard for its airframe and flight conditions, and take appropriate actions to avoid or mitigate the hazard. Similarly, modern radar systems have substantial capabilities for estimation of turbulence severity in conditions where sufficient reflectivity is present to enable detection, such as often exists for convectively induced turbulence (Figure 4b). The development of an enhanced turbulence detection mode for airborne radar, termed “better magenta” after the color used to represent turbulence on the radar display, resulted from a cooperative research effort including NASA, industry, and the FAA[9]. The research efforts resulted in algorithms to go beyond turbulence detection and calculate predicted root mean square (RMS) accelerations for a specific aircraft type[10]. The same radar measurements can be used to derive an estimate of eddy dissipation rate (EDR), the *de facto* and International Civil Aviation Organization (ICAO) standard for airborne turbulence reporting[11], for off-board use. These radar-derived EDR values, provided via air-to-air datalink or through the 4D weather cube, could in turn be used on other aircraft to derive predicted RMS accelerations.



(a) **(b)**

Figure 4 NASA research radar displays (a) wind shear and (b) turbulence

In addition to weather related hazards, some commercial weather radars are now capable of providing terrain and traffic information to flight crews. Flight tests, during the NASA High Speed Research Program (1994-1999), demonstrated (see Figure 5a) traffic surveillance by a commercial weather radar offered similar or superior performance to TCAS for traffic within the forward octant centered on the ownship longitudinal axis. Similarly in a series of flight tests during the NASA Synthetic Vision Project (2000-2005), an airborne weather radar was used to detect runway incursions by ground traffic and discriminate these events from traffic properly situated at a hold-line. These capabilities are not just research results; the major avionics manufacturers have subsequently incorporated these applications into their own product lines, providing enhanced situational awareness for pilots. Given these additional capabilities, future pilots' "tactical" situational awareness may exceed that of the air traffic controller. By sharing this information, both groups benefit from a superior, common view of ground/airborne traffic and other aviation hazards thereby enabling a wider range of safe operations for ATM.



(a) **(b)**

Figure 5 NASA research HUD display showing radar-based:
(a) traffic surveillance and (b) runway incursion detection

IV. Barriers to Implementation

Implementation barriers fall into three broad categories: technical, programmatic, and regulatory, but many problems span multiple categories. One prerequisite for data sharing is the availability of communication channels to carry the information. Current and near-term developmental systems are relatively low bandwidth and could only accommodate compact representations of these data such as a hazard type, location, and strength; however, even these would require changes to the standards to accommodate the new data types. Similarly, current avionics displays could accommodate such information, but would require modifications to do so, and would require certification of these new functions. A robust and flexible design is needed to avoid a mosaic of patches and add-ons or small incremental solutions. Modification of current rules and procedures would also be required if the use of this new information led to generation of alerts and requisite flight crew actions. These changes would have to be supported by new concept of operations (ConOps), which itself requires research into the human factors and presentation issues related to introduction of new products into the cockpit. But for such research to proceed, funded programs must support both the system development and the flight operations and ATM research required to make use of the new information sources.

V. Research on Enabling Technologies and Future Airborne Systems

A number of developments are required to fully implement data sharing with aircraft in a manner consistent with NextGen concepts. In general it is necessary that changes to aircraft and the airspace system be incremental. Thus early development focusing on sharing weather data from existing onboard systems is a necessary step along the path to full development. The weather radar provides an excellent starting point due to the value of the data and the processing capability available in modern systems. Bandwidth to pass some compressed radar data is also available in existing systems, so an early implementation of data sharing can be developed for radar data, using the radar processor and display plus communications via an existing system. The advantage of doing this is that the utility and value of the concept will be demonstrated and a better understanding of the requirements for full implementation and utilization will result.

A full implementation of data sharing will require significant changes in aircraft equipage and the airspace system, but many of the required changes are necessary for other NextGen concepts and not solely for the purpose of sharing weather data. For example, greater communication bandwidth for data is needed as a general requirement for NextGen. The message is that as the airspace system evolves toward NextGen, the capability and the requirement to share weather and other hazard data, or operational data, will grow. In addition, a parallel evolution in airspace operations is needed to exploit emerging NextGen capabilities so that greater safety and efficiency will result. It is important to understand that initial changes may be incremental and based on relatively small changes utilizing existing systems, but if the full potential of NextGen is to be realized, significant changes will be required and these changes may only be implemented in newer aircraft.

The initial development of data sharing capabilities can begin with weather radar and in relatively small, incremental steps, and it will evolve with significant improvements in communications, information processing, and sensing capabilities. While communications is a research area outside the scope of the Aviation Safety Program, the development of sensing capabilities for hazards and information processing in the cockpit are both subjects of Aviation Safety Program research.

Additional research is required to make the best use of shared sensor data from currently available systems, and to develop more consistent airborne and ground based weather hazard criteria. Consistent standards need to be developed to enable integration of airborne measurements with those from ground-based systems. Current displays for airborne and ground radar use different color schemes, and those may be modified based on pilot settings and adaptive algorithms in the radar that adjust the display based on known weather characteristics for different geographic locations[4]. In order to combine data from airborne and ground-based radar systems into products for the 4D weather cube, new techniques would have to be developed to accommodate the airborne data with its different spatial resolution, different frequency of operation, and asynchronous availability. If new data is to be incorporated into forecast models then studies need to be done to demonstrate the feasibility and to do cost/benefit analyses. If available bandwidth is sufficiently high, then detailed 3D storm models, based on multiple accumulated radar scans at different tilts and across time, can be shared. For lower bandwidth communication channels, data compression techniques, such as representation of radar data by polygons[12] bounding areas of reflectivity, could be used. While data compression will be employed to reduce bandwidth requirements, how much data compression can be used and what salient weather features need to be retained are also fertile ground for future research.

Advanced and fused airborne sensors for detection and mitigation of aviation hazards are being developed in the current NASA Aviation Safety program. These include advanced radar systems employing polarimetric and multi-frequency techniques, airworthy Lidar systems, and imaging infrared hyperspectral radiometers using Fourier Transform Spectrometry (FTS) techniques. They target hazards such as icing conditions (Figure 6), hail, runway incursions, non-cooperative aircraft, clear air and wake turbulence, volcanic ash, reduced visibility, runway contamination, and dry wind shear. Additional research is planned to investigate combining airborne sensor data with ground and satellite information to produce more accurate and reliable estimates of potential hazard levels.

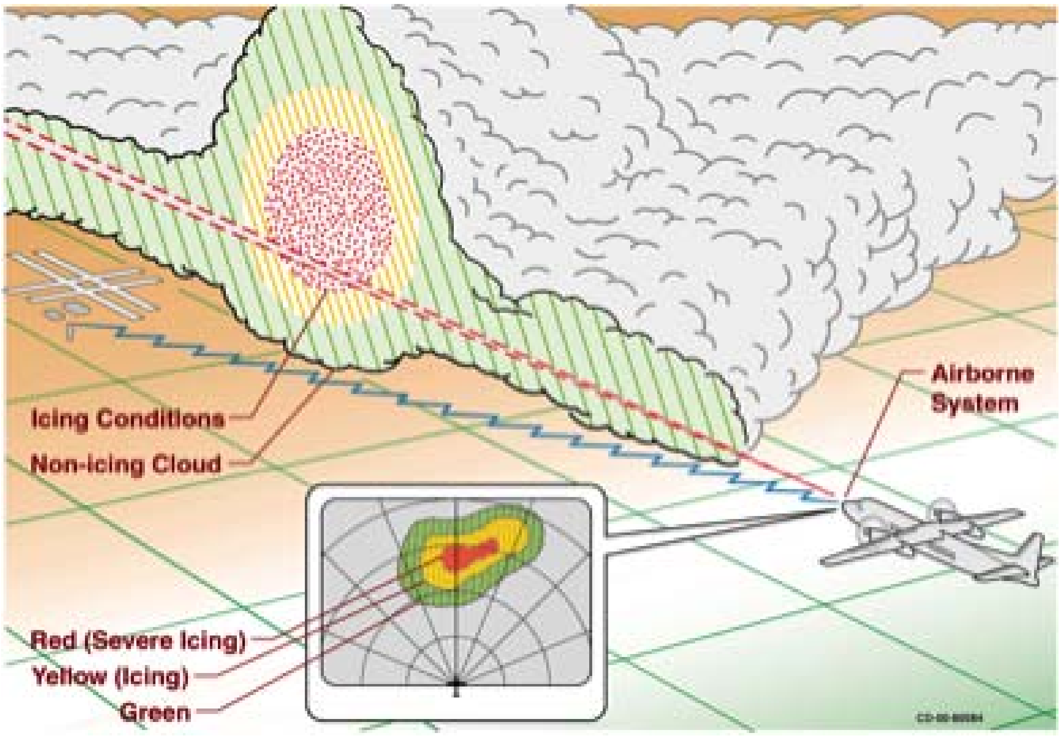


Figure 6 In-flight icing hazard detection

Any or all of these new sensor technologies and techniques can be employed as sources for new data to be shared to enhance NNEW weather products to the benefit of operational safety and efficiency. The framework developed to support data from current systems such as the airborne weather radar should be designed to accommodate new data sources as they are developed and deployed.

Little has been said thus far regarding information processing requirements to implement data sharing on a large scale. In fact there is an identifiable need for an information processing system in the cockpit that performs central functions associated with the collection, interpretation, integration, and distribution of information. From a safety perspective, the concept has been investigated as the Integrated Alerting and Notification (IAN) Function[13, 14, 15], and research on this function continues in the Vehicle Systems Safety Technology (VSST) project[16]. The IAN system, while being investigated from a safety perspective at this time, would not be a system solely for safety but would be a central cockpit system supporting the pilot through all phases of flight and routine operations as well as hazardous situations.

The IAN system would perform several related functions in the cockpit. The system would gather information from sensors and subsystems to monitor the vehicle's status and health. It would have information about what the aircraft is doing operationally via interfaces to the flight management system, so that information can be considered in the context of the planned flight path. Gathering information and understanding the aircraft status will allow the system to perform other functions. Information from various sources can be comparatively analyzed to validate or enhance results and/or detect faults. Finally, the IAN can generate alerts and provide information for cockpit displays. Decision aids and intelligent functions like trajectory negotiation can be provided. Relative to data sharing, the IAN can be seen as a central point for data collection, integration, and verification as well as the source for data telemetry. It is also the system that could determine how information, such as alerts, are communicated or included in displays. Current research on the IAN is focused on modeling basic IAN functions in a piloted simulation – processing and communicating weather hazard information derived from the weather radar and off board sources. Hazardous regions ahead of the aircraft are identified and the pilot is provided information to avoid these hazards through displays. As radar data sharing concepts are developed, the IAN simulation studies will be able to incorporate and exploit the additional weather information. In the future new sensing capabilities, such as Lidar, will be modeled and added in the simulation studies to investigate utilization of new information sources. In addition to providing the means for investigating methods for data utilization and sharing, the simulation provides the potential for investigating operational changes to exploit the new capabilities to realize better operational efficiency and safety.

VI. Conclusion

NASA and other participants in NextGen development including NOAA, FAA, and Industry are working to improve weather sensing and hazard avoidance. Data from airborne forward-looking sensor systems represents a rich, new, data source that can be utilized towards these goals in a NextGen network-enabled environment, but research toward use of this data is at an early stage and opportunities to contribute abound. Benefits from use of such data appear to be substantial but additional work is required to develop products suitable for NEO data sharing, to investigate how these products could be incorporated into operational systems, and to quantify the value of the new information.

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