NASA/TM—2014-218417

A Terminal Area Icing Remote Sensing System

Andrew L. Reehorst
Glenn Research Center, Cleveland, Ohio

David J. Serke
National Center for Atmospheric Research, Boulder, Colorado

November 2014

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to *help@sti.nasa.gov*

- Fax your question to the NASA STI Information Desk at 443–757–5803

- Phone the NASA STI Information Desk at 443–757–5802

- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2014-218417

A Terminal Area Icing Remote Sensing System

Andrew L. Reehorst
Glenn Research Center, Cleveland, Ohio

David J. Serke
National Center for Atmospheric Research, Boulder, Colorado

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

November 2014

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://www.sti.nasa.gov

A Terminal Area Icing Remote Sensing System

Andrew L. Reehorst
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

David J. Serke
National Center for Atmospheric Research
Boulder, Colorado 80301

Abstract

NASA and the National Center for Atmospheric Research (NCAR) have developed an icing remote sensing technology that has demonstrated skill at detecting and classifying icing hazards in a vertical column above an instrumented ground station. This technology is now being extended to provide volumetric coverage surrounding an airport. With volumetric airport terminal area coverage, the resulting icing hazard information will be usable by aircrews, traffic control, and airline dispatch to make strategic and tactical decisions regarding routing when conditions are conducive to airframe icing.

Building on the existing vertical pointing system, the new method for providing volumetric coverage will utilize cloud radar, microwave radiometry, and NEXRAD radar. This terminal area icing remote sensing system will use the data streams from these instruments to provide icing hazard classification along the defined approach paths into an airport.

Strategies for comparison to in-situ instruments on aircraft and weather balloons for a planned NASA field test are discussed, as are possible future applications into the NextGen airspace system.

Introduction

Aircraft icing continues to be a major issue for the aircraft community. Despite advances in all aspects of icing related technologies, icing accidents still occur and aircraft winter operations are negatively impacted. Part of the challenge of dealing with icing conditions is the significant spatial and temporal variability of icing severity. It is not unusual for a series of aircraft on a landing approach to experience different levels of icing severity over a relatively short period of time. This variability makes the accurate prediction of icing conditions very difficult. While weather models and their predictions of icing have improved dramatically, the need for the direct detection and measurement of hazardous icing conditions aloft is still great.

Ideally all aircraft would have onboard systems to indicate icing conditions in their flight path, analogous to thunderstorm detection with airborne radar. However, even if these systems were developed, and became practical and affordable, the likelihood of all aircraft being adequately equipped is low. Therefore a better approach is to provide coverage to indicate icing conditions in areas of greatest traffic volume and flight risk: the terminal area.

Development of a ground-based hazard detection algorithm test bed, the NASA icing Remote Sensing System (NIRSS), began in 1997 (Ref. 1). NIRSS consists of three vertically pointed instruments: a Metek Ka-band cloud radar, a Radiometrics Corporation multi-frequency microwave radiometer, and a Vaisala laser ceilometer. The radar provides cloud base and tops and particle density distribution information, the radiometer provides temperature profiles and integrated liquid (water path) measurements, and the ceilometer provides refined cloud base measurements. The NIRSS algorithm combines these measurements to determine the presence of icing conditions aloft and assigns a severity based on the calculated local liquid water content (LWC) intensity. NIRSS is shown notionally in Figure 1 and its components are shown in Figure 2.

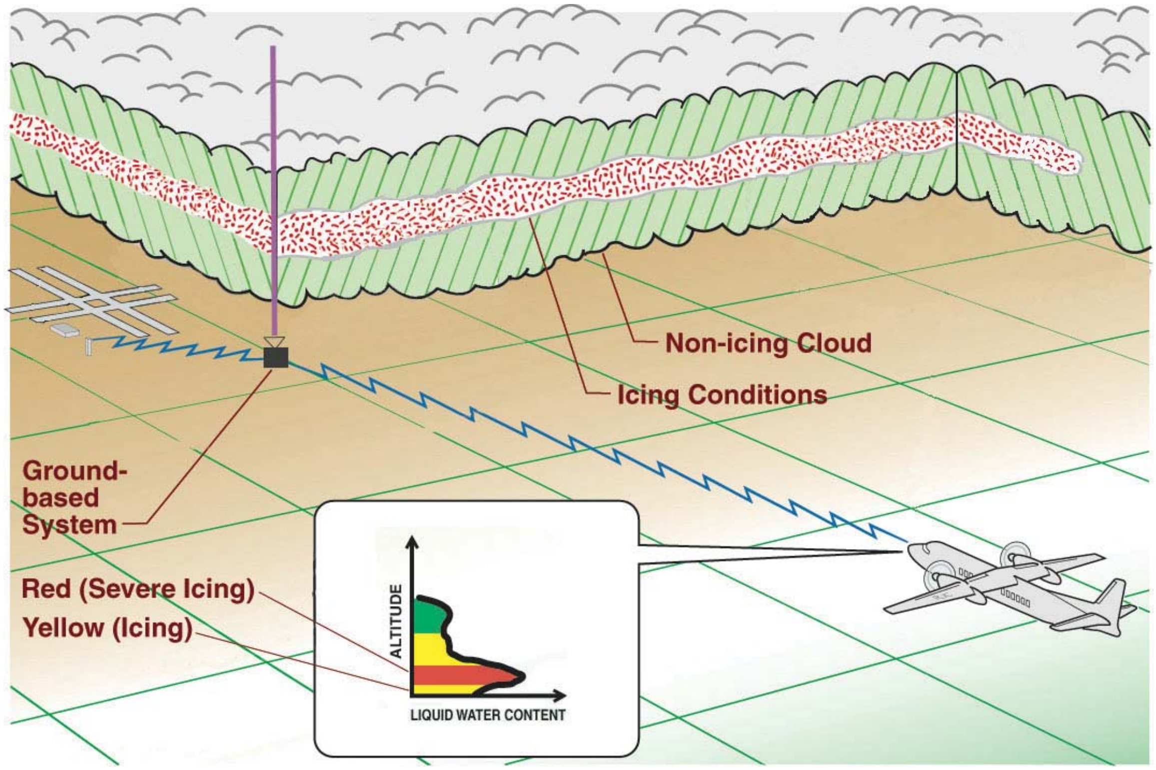

Figure 1.—NIRSS concept.

Figure 2.—NIRSS hardware. METEK Ka-band radar in foreground, Vaisala ceilometer in middle left, and Radiometrics MP3000 in back left.

A statistical analysis examining the agreement of NIRSS and the Current Icing Product (CIP) with pilot Reports (PIREPs) found that NIRSS performed well with an 80 percent positive PIREP agreement and a 70 percent negative PIREP agreement (Ref. 2).

An acknowledged shortcoming of the NIRSS technology has been that it only provides a vertical profile of icing condition severity. To help fully protect a terminal area and provide information that accounts for the temporal and spatial variability of icing conditions, a volumetric remote measurement capability is required.

To provide the most utility to the widest range of aircraft, an icing remote sensing system with airport terminal volume coverage is envisioned and is shown notionally in Figure 3.

A terminal icing remote sensing system needs to provide reliable and timely information to operators and traffic managers. The volume of coverage needs to be of a reasonable range and altitude, allowing for routing flexibility to avoid hazardous conditions for both arriving and departing traffic.

This paper describes such a terminal area remote sensing system that can practically determine icing severity aloft with coverage over an entire airport terminal area. This capability is being developed by NASA and NCAR and has reached a level of maturity that warrants prototype testing. An initial prototype testing of this system at NASA Glenn Research Center is discussed along with a strategy to compare remotely sensed data with in-situ flight data within a terminal area.

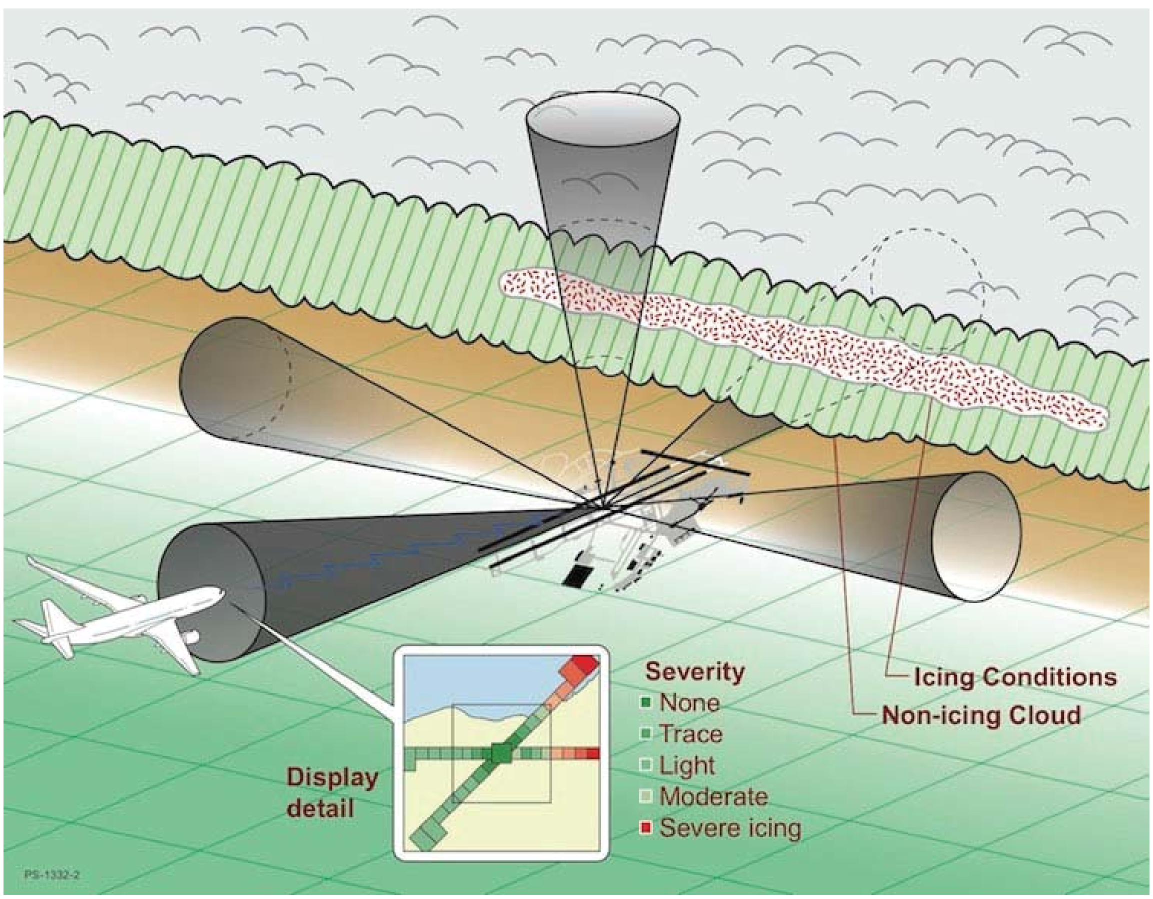

Figure 3.—A terminal area icing remote sensing concept.

Hardware Systems

An early concept for a terminal area icing remote sensing capability made use of the current vertical pointing NIRSS algorithms with the addition of a scanning radar and a scanning radiometer to provide the required 3-D measurements. However, there are physical constraints with both radar and radiometer technologies that prevent this extension.

Meteorological radar systems primarily span a frequency range from S-band (2 to 4 GHz or 15 to 7.5 cm) to W-band (75 to 110 GHz or 4 to 2.7 mm). S-band radars such as NEXRAD (around 10 cm wavelength) have large antennas and powerful transmitters to allow them to observe precipitation and severe weather at long ranges (hundreds of kilometers). However they are generally unable to accurately quantify the macro- and micro-physical details of non-precipitating cloud particles because of their insensitivity to small hydrometeors, relatively coarse spatial resolution, and ground clutter issues. Ka- and W-band meteorological radars (3 to 9 mm wavelengths) are designed specifically to monitor clouds and have excellent sensitivity and spatial resolution, but suffer from significant attenuation in the presence of liquid water that limits their range to 30 km or less (Ref. 3). Thus, both the NEXRAD and Ka-band have potential drawbacks, but as will be discussed shortly, the availability of both provides complimentary parts of the answer toward the problem of in-flight icing detection within a terminal-area sized volume.

One shortcoming of current microwave radiometer technology is the requirement of a dwell time for each measurement. Scanning a volume of space with even a limited number of microwave frequencies would require approximately an hour. The icing environment may vary appreciably during this time, making a volume scanning radiometer, with the current required dwell times, unacceptable for use in a terminal area icing remote sensing system.

At first glance these constraints of radar and radiometer technologies appear to indicate that a remote sensing system that can provide volumetric coverage for a terminal area is impractical. However, utilizing the strengths of these sensing technologies along with an additional processing step allowing the movement of features with time, a useful remote sensing capability is possible. The icing remote sensing system described here will make use of a vertical pointing Ka-band radar, a multi-frequency microwave radiometer with limited azimuth and slant elevation positioning, and NEXRAD feature extraction and tracking. The instruments that are specifically planned for use in the terminal area icing remote sensing system are as follows: (1) the cloud radar is a Metek MIRA-36 vertical pointing Ka-band Doppler radar (Ref. 4), (2) the microwave radiometer is a Radiometrics Corporation MP-3000A, a multi-frequency, microwave radiometer (Ref. 5), and (3) the NEXRAD radar is referenced as KCLE and is located adjacent to NASA Glenn Research Center and Cleveland Hopkins Airport and operated by the National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS).

Terminal Area Algorithms

The algorithms to determine icing hazard within an airport terminal area have their foundation in the algorithms used in NIRSS. The primary data used by the NIRSS are the temperature profile and integrated liquid water (ILW) from the microwave radiometer, and the cloud layering information from the cloud radar. The radiometer derived temperature profile is used to identify altitudes in the atmosphere where liquid water could be present. The ILW from the radiometer is then distributed within the potential liquid cloud heights using the cloud layering information from the cloud radar to determine a liquid water content (LWC) profile. Liquid water that has been identified at sub-freezing altitudes is then identified as an icing layer. Finally, the icing layer LWC values are mapped into qualitative in-flight icing hazards values.

The development of a terminal area icing remote sensing capability requires the coverage of critical terminal airspace while living within the hardware technology constraints discussed in the previous section. Thus, a scanning cloud radar is not sought. Rather, the vertical cloud profile is assumed to apply to the entire terminal volume. This is a reasonable assumption since most weather events do not vary significantly within 50 horizontal kilometers, when dealing with 1 to 5 min time resolution. One notable exception to this assumption is strong cold-frontal passages.

Since the radiometer can be azimuthally positioned to allow measurements at multiple discrete headings within 5 min, slant-angle radiometer ILW and temperature profile can be practically collected along all of the airport approach azimuths. Having a radiometer that can scan along each respective approach runway at multiple elevations can provide individualized runway approach vector hazard warning values. Previous research also shows that slant angle products from the radiometer have improved vertical resolution in the lowest few kilometers and thus higher overall accuracy compared to vertically profiled values (Ref. 6).

The domain of concern for the software is the total volume of airspace within 25 horizontal kilometers of an airport. The software needs to ingest slant elevation ILW fields at various azimuths along with all of the vertically pointing NIRSS fields (temperature, ILW, LWC, droplet size, cloud base, cloud top, number of layers, etc.), package these profiled fields into data 'packets', and use one of two methods to advect the data packets into the 3-D airport terminal environment. This needs to be done every 5 min, so that several packets of various ages are located within the terminal domain at any given time—each containing all of the relevant meteorological fields for in-flight icing diagnosis.

The first advection method will ingest NEXRAD reflectivity data and run it through previously existing pattern recognition and tracking software (Ref. 7). This code is setup to output East-West and North-South vector components of the horizontal advection as it follows the 0 dBZ reflectivity contour in time at the 1 km AGL height level. The second advection method relies on surface wind speed and direction values from the NWS Automated Surface Observing System ground station for use in cases when NEXRAD data is not available. In this manner, patterns in NEXRAD reflectivity or surface winds speed/direction are used to advect packets of profiled input and derived output fields within the airport domain.

Aircraft are most vulnerable to in-flight icing during approach, flying at lower speeds at near-constant altitudes for a prolonged period of time. Each airport has predetermined approach routes for aircraft, with rules that define the aircraft altitude at given distances for each different runway heading. The software needs to model these approach vectors by inflating the 2-D centerline, as defined by FAA approach plates, into a 3-D volume to represent the air volume that an aircraft could be affected by during approach. This volume is defined by centering a box of 0.25 km (~1000 ft) vertical by 2 km (~6500 ft) horizontal on the vector (the lateral size of the boxes are doubled at the outer portions of the approach path to accommodate defined holding areas). The resulting approach volumes are then sectioned horizontally into 9 zones based on runway heading and radial distance from the tarmac: Zone (1) contains all of the approach volume within a 5×5 km box centered over the airport is defined in one volume zone; Zones (2) through (5) contain 4 volume zones along the runway headings outside the center box and inside a 25×25 km box and; Zones (6) through (9) contain four more volume zones extending from the middle box out to the outer 50×50 km box (Figs. 4 and 5). Figure 4 is a top-view, 2-D representation of all the approach zones for the prototype system at Cleveland Hopkins Airport and Figure 5 shows an isometric view with more details of zones 1 through 9 for one approach path. The most recent hazard output profile that is determined by the software to be located within a given volume zone is applied to that zone at 5 min intervals. The highest hazard level designation (on a scale from 'none', 'trace', 'light', 'moderate' to 'severe') that exists within the defined vertical bounds of the given volume zone is assigned as that zone's in-flight hazard value at a given time.

Takeoffs are typically at higher energy levels and gain airspeed and altitude rapidly thus spending minimal time in icing conditions that tend to be stratified. While considered a lower priority than the approach coverage, a separate warning output for departure quadrants will need to be added in the future to achieve full terminal area coverage.

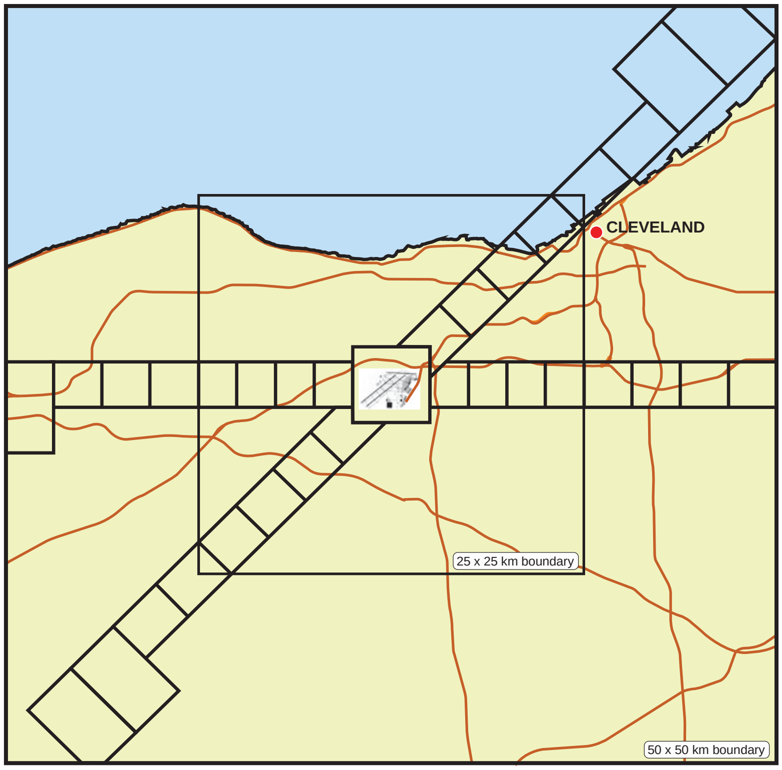

Figure 4.—Terminal area approach zones for Cleveland Hopkins Airport.

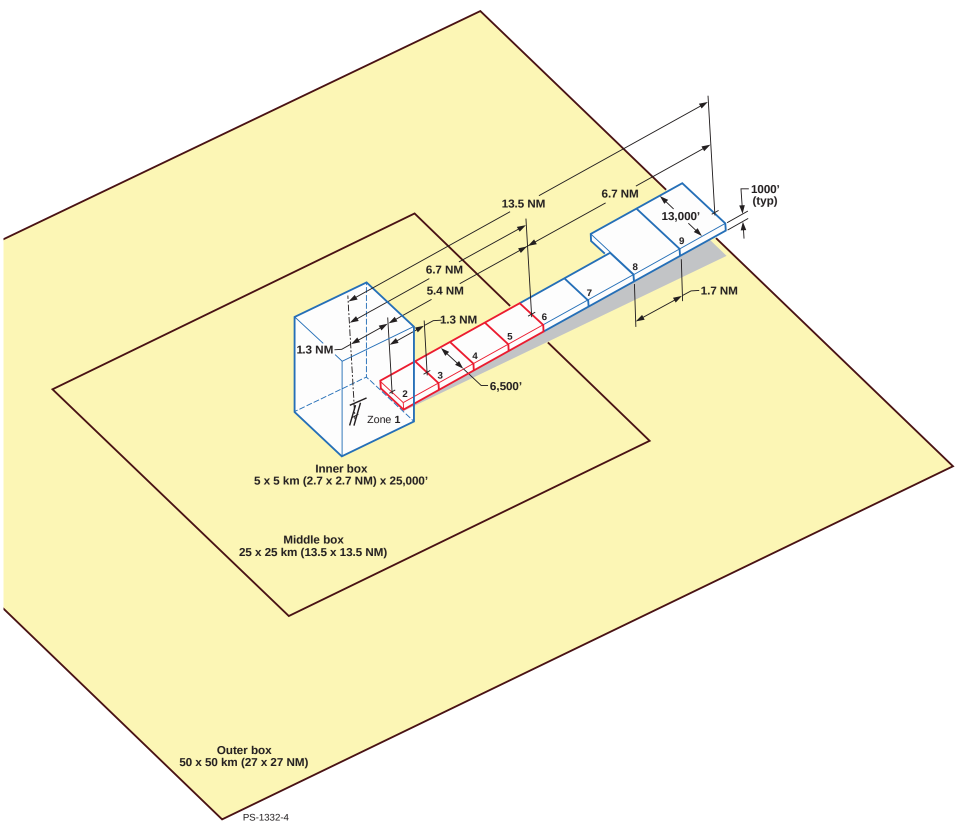

Figure 5.—Terminal area approach zones detail.

Comparison Strategy

To test the accuracy and feasibility of the system described, a field test including ground remote sensing operations and a series of in-situ measurements aloft are planned. Since the terminal area icing remote sensing system must first calculate temperature, LWC and cloud droplet size before determining icing severity, it is most desirable to have comparable in-situ measurements of these quantitative fields and not the potentially subjective icing severity. This is best accomplished with a research aircraft equipped to measure and record air temperature, LWC, cloud particle size distribution, aircraft position and altitude, and time. The planned field test will include flights with the NASA Twin Otter aircraft (Fig. 6). The in-situ measurements are primarily desired along the airport approach paths, but also elsewhere in the terminal area volume. A combination of approaches, constant heading and altitude transects, and climbing or descending spirals are desired to maximize the breadth of the comparison database. A record of the evolving meteorological synoptic conditions during test periods should also be obtained. If discrepancies are identified during the post-test analysis, a good understanding of the surrounding weather conditions will be enormously valuable.

Additionally, it is desirable to also use weather balloons (Fig. 7) to supplement the data provided by research aircraft. Weather balloons are capable of operations at times and conditions that would preclude aircraft operations. While the data gathered from instrumented balloons is typically more limited than aircraft data (spatially and temporally and by instrument type) balloons are relatively inexpensive. Weather balloons can be used for a “quick look” at atmospheric conditions before committing the resources for an aircraft launch and can fill data gaps between aircraft flights. Through the Small Business Innovation Research (SBIR) Program, NASA sponsored Anasphere, Inc. for the development of a supercooled liquid water content sensor for use with weather balloons (Ref. 8). This sensor, along with the traditional weather balloon sensors, will be a valuable part of the icing in-situ validation activity by providing valuable data for direct comparison to the remote sensing measurements and for weather assessment before a research flight.

The post analysis of all the comparison data will likely be a significant effort. Due to the size of the sample dataset of both in-situ and remote measurements, some form of statistical assessment will be necessary. It is very likely that the terminal area algorithms will evolve during the process, and a statistical score method will be necessary to categorize the strengths, and compare between different versions.

Figure 6.—NASA Twin Otter aircraft.

Figure 7.—Weather balloon just after launch.

Concluding Remarks

NASA has been developing icing remote sensing technologies since 1997. This research and development activity is now on the verge of a major milestone, prototype testing, of providing a remote sensing capability to determine icing severity with coverage over an entire airport terminal area.

Since this capability will be completely new, for maximum operational value it will very likely require further development after the initial prototype testing. The field test will, to some extent, require looking into the future and predicting potential areas of system improvement. For example: will the proposed approach-path oriented scheme provide sufficient icing information for departing aircraft? During the field test, it may be necessary to provide more remotely sensed and in-situ sampling than just the approach paths to allow future development. Also the optimal methods for relaying the remotely sensed information to aircrews, air traffic control, and airline dispatch will need to be thoroughly examined so that it blends well with the rest of the data being utilized for flight under the FAA’s Next Generation Air Transportation System (NextGen).

The development and eventual fielding of this kind of new capability should have significant impact to the flying community in the future. With this kind of icing severity information feeding into the NextGen airspace system, flight crews, air traffic control, and airline dispatch will have solid information of the current icing situation in an airport terminal area, removing the need for a flight crew to first “dip their wings” into potentially hazardous conditions. This technology also has the potential of feeding into decision support tools (DSTs) (Ref. 9) that would enable the airspace system to assess a specific aircraft’s unique, current safety margins based upon its capability, phase of flight, past exposure, and (now) known future icing condition exposure.

References

1. Reehorst, Andrew; Brinker, David; Politovich, Marcia; Serke, David; Ryerson, Charles; Pazmany, Andrew; Solheim, Frederick, “Progress Towards the Remote Sensing of Aircraft Icing Hazards,” NASA/TM—2009-215828, November 2009.
2. Johnston, Christopher J.; Serke, David J.; Adriaansen, Daniel R.; Reehorst, Andrew L.; Politovich, Marcia K.; Wolff, Cory A.; and McDonough, Frank, “Comparison of In-Situ, Model and Ground Based In-Flight Icing Severity,” NASA/TM—2011-217141, December, 2011.
3. Kenneth P. Moran, Brooks E. Martner, M.J. Post, Robert A Kropfli, David C. Welsh, and Kevin B. Widener, “An Unattended Cloud-Profiling Radar for Use in Climate Research,” Bulletin of the American Meteorological Society, Vol. 79, No 3, pgs. 443-455, March 1998.
4. “Meteorologische Messtechnik GmbH, Doppler Radar 35 GHz,” METEK GmbH, Elmshorn, Germany, viewed March 26, 2014 <http://www.metek.de/product-variants/doppler-radar-35-ghz.html>.
5. “MP-Series Profilers,” Radiometrics Corporation, Boulder, CO, viewed March 26, 2014 <http://radiometrics.com/products-services/product/mp-series/>.
6. Guirong Xu, Randolph Ware, Wengang Zhang, Guangliu Feng, Kewen Liao, and Yibing Liu, “Effect of off-zenith observations on reducing the impact of precipitation on ground-based microwave radiometer measurement accuracy,” Atmospheric Research, Volumes 140-141, pgs 85-94, April-May 2014.
7. Tuttle, John D., and Foote, G. Brant, “Determination of the Boundary Layer Airflow from a Single Doppler Radar,” Journal of Atmospheric and Oceanic Technology, Volume 7, pgs 218-232, 1990.
8. David Serke, Emrys Hall, John Bognar, Allen Jordan, Spencer Abdo, Kirstin Baker, Tom Seitel, Marta Nelson, Andrew Reehorst, Randolph Ware, Frank McDonough, and Marcia Politovich, “Supercooled liquid water content profiles with a new vibrating wire sonde compared to ground-based microwave radiometry,” American Meteorological Society, 16th Conference on Aviation, Range, and Aerospace Meteorology, pres. 5.3, January, 2013.
9. “Weather – Air Traffic Management Integration,” Massachusetts Institute of Technology, Lincoln Laboratory, viewed April 18, 2014 <http://www.ll.mit.edu/mission/aviation/wxatmintegration/usedecisionsupport.html>