Atmospheric Research 185 (2017) 84–91

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

A new narrow-beam, multi-frequency, scanning radiometer and its application to in-flight icing detection

David J. Serke[a,*], Kimberly A. Reed[b,a], James Negus[b], Levi Blanchette[b], Randolph Ware[b,a], Patrick C. Kennedy[c]

[a]National Center for Atmospheric Research, Research Applications Laboratory, PO Box 3000, Boulder, CO 80307,USA
[b]Radiometrics Corporation, 4909 Nautilus Ct N, Suite #110, Boulder, CO 80301,USA
[c]CSU-CHILL Radar, 30750 Weld County Road 45, Greeley, CO 80631,USA

ARTICLE INFO

Article history:
Received 15 August 2016
Received in revised form 20 October 2016
Accepted 24 October 2016
Available online 26 October 2016

Keywords:
In-flight icing
Supercooled liquid water
Aviation hazard
Icing detection and avoidance
Microwave radiometer
Terrain mapping

ABSTRACT

A one degree beamwidth, multi-frequency (20 to 30 and 89GHz), dual-polarization radiometer with full azimuth and elevation scanning capabilities was built with the purpose of improving the detection of in-flight icing hazards to aircraft in the near airport environment. This goal was achieved by collocating the radiometer with Colorado State University's CHILL polarized Doppler radar and leveraging the similar beamwidth and volume scan regiments of the two instruments. The collocated instruments allowed for the liquid water path and water vapor measurements derived from the radiometer to be merged with the radar moment fields to determine microphysical and water phase characteristics aloft. The radiometer was field tested at Colorado State University's CHILL radar site near Greeley, Colorado during the summer of 2009. Instrument design, calibration, and initial field testing results are discussed in this paper.

1. Introduction

Aircraft accrete ice in flight when the cold surface of the aircraft comes into direct contact with supercooled liquid water. Accretion often occurs on engine intakes or propellers, leading edges of the wings, and tail fin structures. This in-flight icing can result in significant loss of aerodynamic performance due to increased drag, changes in the effective wing shape, and added weight. Loss of performance can lead to dangerous aircraft responses that are outside the realm of normal flight operations. Supercooled large drops, which are defined as those with a diameter greater than 50 µm, can freeze on aircraft structures unprotected or inadequately protected by anti-icing systems (Lynch and Khodadoust, 2001). Several episodes of aircraft icing have been related to the existence of supercooled large drops (Fernández-González et al., 2014a). As a result, the aviation safety community is dedicated to understanding aircraft icing detection with an overarching goal of accurately quantifying the presence of in-flight icing hazards on both a temporal and spatial scale (Barbagallo, 2015). Due to the need for an aircraft to be present in order to physically generate in-flight icing, the phenomena cannot be directly observed or measured with a remote sensing system. Ideally, all aircraft would be equipped with in-flight icing remote detection instrumentation that would provide detailed route-specific icing information, however budgetary constraints and technology shortfalls limit the practicality of this option. Therefore, a ground-based system with the capability to provide icing information to all aircraft entering and departing a terminal area is a key element in facilitating icing detection and avoidance.

Current techniques for remote detection and measurement of icing conditions generally rely on the identification of liquid water and the measurement or inference of the surrounding air temperature. Quasi-vertical profiles of supercooled liquid water content have been collected with vibrating wire sondes attached to standard meteorological radiosondes (Serke et al., 2014). These sondes have shown promise in accurately detecting supercooled water contents when compared to radiometers and research flight data, but are relatively expensive and provide only temporal snapshots of the atmospheric profile. The National Weather Service's network of polarized WSR-88D Doppler Radars operate at a wavelength of 10.7 cm. This wavelength is good at detecting precipitation-sized particles, but not cloud-sized particles such as small homogeneous

* Corresponding author.
E-mail addresses: serke@ncar.edu (D. Serke), k.reed@radiometrics.com (K. Reed), james.negus@radiometrics.com (J. Negus), l.blanchette@radiometrics.com (L. Blanchette), randolph.ware@radiometrics.com (R. Ware), pat@chill.colostate.edu (P. Kennedy).

http://dx.doi.org/10.1016/j.atmosres.2016.10.016

Fig. 1. Image of the NNMSR located at the CSU CHILL radar site during the summer of 2009.

supercooled liquid drops. These radars send pulses of energy radially outward and some fraction of the original power is returned to the radar receiver based on the sixth power of the diameter of the particles in the targeted sampled volume. This means that even large numbers of relatively smaller supercooled drops that coexist with small numbers of typically larger ice-phase crystals can be very difficult to detect (Ikeda et al., 2009). The Current Icing Product (CIP), developed by the National Center for Atmospheric Research (Bernstein et al., 2005) and currently in operational use by the FAA, ingests near real-time Rapid Update Cycle model output of atmospheric and microphysical conditions along with visible and infrared satellite data, surface weather observations, PIlot REPorts (PIREPs), and lightning network data to infer the presence of liquid along with subfreezing temperatures aloft. Another numerical weather prediction model approach for the forecasting of in-flight icing was detailed in Lamraoui et al. (2015). The NASA Icing Remote Sensing System (NIRSS) (Reehorst et al., 2006) makes use of the aviation hazard detection capabilities of several pieces of ground-based instrumentation. NIRSS consists of a vertically pointing Metek K-band radar used to define cloud top and base heights as well as determine cloud layer structure. In addition, there is a Radiometrics Corporation multi-frequency microwave radiometer (Solheim et al., 1998), that utilizes multiple channels to derive integrated liquid water and atmospheric temperature profiles. A laser ceilometer is also incorporated to further assist in cloud base detection. Software integrates the data streams in real-time, and the derived liquid is distributed within the detected cloud layer(s) based on internal logic in order to arrive at an in-flight icing hazard categorized risk assessment. This testbed system is an effort to provide in-flight icing hazard warnings with existing, cost-effective technologies. The system is currently positioned near John Hopkins Airport at the NASA Glenn Research Center in Cleveland, Ohio. Campos et al. (2014) utilized a method to detect the water phase dynamics of mixed-phase winter storms and applied the method to several winter cases. These results were

Table 1
NASA Narrow-beam Multi-channel Scanning Radiometer (NNMSR) specifications.

Parameter	NASA Narrow-beam Multi-channel Scanning Radiometer (NNMSR)
Frequency channels [GHz]	22.000, 22.234, 22.500, 23.000, 23.034, 23.500,
	23.834, 24.000, 24.500, 25.000, 25.500, 26.000, 26.234, 26.500, 27.000, 27.500, 28.000, 28.500, 29.000, 29.500, 30.000, 89.0V, 89.0H
Antenna beamwidth	1°
Calibration	Microwave Ambient Target, Microwave LN2 Target, Terrain Mapping
Mass	Scanhead ~ 90 kg, Tripod ~ 16 kg
Dimensions	Scanhead 1 m × 1 m × 1.5 m, Tripod 3 m × 3 m × 2 m
Power consumption	110 V

compared to output from a ground-based instrumentation platform similar to NIRSS.

Combining ground-based microwave radiometer data with radar retrievals has shown great promise, however deficiencies with the current generation of radiometers have somewhat limited their capabilities. Among these shortcomings is an observation discontinuity problem resulting from the wide 6° beamwidth associated with the radiometer, which limits the spatial resolution and possibility of direct comparisons with the 1° beamwidth data available from weather surveillance radars.

Through previous efforts, solutions have been determined to resolve several technical challenges, including those mentioned above, with the design of a new instrument. The new instrument, referred to as the NASA Narrow-beam Multi-waveband Scanning Radiometer (NNMSR), is designed to operate in conjunction with and complementary to weather surveillance radars. This paper will detail the design (Section 2.1), calibration (Section 2.2), and overview of NNMSR data interpretation (Section 3), as well as field testing results of the NNMSR at Colorado State University's polarized CHILL S-band radar facility (Fig. 1) for the application of improving in-flight icing hazard detection and avoidance. This new instrument has the ability to provide the necessary information to fulfill the need for airport terminal area icing hazard warnings, when integrated into the existing NIRSS system and positioned in close proximity to the dual-polarization NEXRAD radars near each large national terminal.

The system also presents the possibility for additional applications beyond the scope of terminal area in-flight icing hazard detection and avoidance. One potential application includes the use of the system for decision support assistance in determining the need for deicing treatment in advance of aircraft departure via nowcasting. The inclusion of high-resolution icing information in the decision

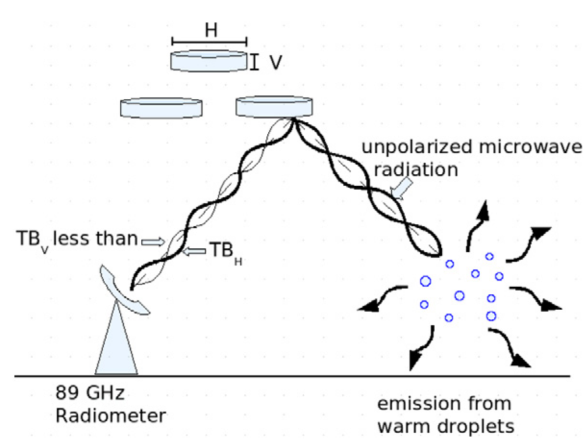

Fig. 2. Schematic of unpolarized microwave radiation becoming polarized and the resultant dual-polarization brightness temperature differences.