12.4 INFLIGHT ICING DETECTION WITH ONBOARD MICROWAVE RADIOMETRY

Charles C. Ryerson* and George G. Koenig
ERDC-CRREL, Hanover, New Hampshire

Andrew L. Reehorst
NASA Glenn Research Center, Cleveland, Ohio

Forrest R. Scott
SCA Inc., Phoenix, Maryland

1. INTRODUCTION

The risks of encountering inflight icing conditions, even with onboard ice protection systems, are well-understood. Since aircraft have crashed due to icing with ice protection systems operating, experience shows that certified ice protection systems are not adequate for all conditions, especially supercooled large drops for which there are currently no certification standards (NTSB, 1996). The most effective protection from icing is still avoidance; either fly in areas with no liquid water, or fly where temperatures are sufficiently warm to prevent icing.

Icing analysis and forecast tools, such as the Current Icing Potential (CIP) and Forecast Icing Potential (FIP) models, are effective for helping pilots avoid icing conditions (Moran and Singer, 2005). However, pilots can still encounter dangerous icing conditions because of spatial and temporal resolution issues and because knowledge of the atmosphere is not perfect. In addition, these models are most effective where weather information is spatially dense and of uniformly high quality. Information is generally not as reliable over the oceans and over significant portions of the earth's land masses.

Icing analysis and forecast tools are also not as useful in areas of complex terrain, especially at low altitudes. Most helicopters and turboprops and many business aircraft fly at low altitudes, with helicopters flying almost exclusively less than about 3,000-m above ground level (agl). And, because of their flying qualities and generally limited on-board ice protection systems, these aircraft are more vulnerable to icing. Unlike most jets, which encounter icing primarily during departure and approach, turboprops and helicopters can also be immersed in icing conditions during cruise. Since these aircraft fly more slowly than jets, they tend to be immersed in the icing conditions for longer periods.

Remote sensing may provide additional assistance in avoiding icing. Similar in concept to the use of X-band radar to avoid thunderstorms by detecting raindrops and hail, icing remote sensing systems operate by detecting the conditions that cause aircraft icing, temperature and cloud liquid water content. Icing does not occur until supercooled droplets collide with and freeze upon aircraft surfaces. Therefore, icing remote sensing systems only sense icing potential ahead of aircraft.

The magnitude of icing severity on an aircraft is a function of meteorological conditions and the susceptibility of specific aircraft aerodynamics to icing contamination. Since icing remote sensing systems can only sense meteorological conditions, they cannot predict the effects that the sensed conditions might have on aircraft flying qualities except through simulations or measurements of actual aircraft performance in icing.

There are a variety of approaches that can be used to remotely sense icing conditions ahead of aircraft. Sensing systems can be ground-based or airborne (Figures 1 and 2). They can also be of a variety of fused sensor modalities including radar, lidar, and passive microwave radiometry. Our approach is to use passive microwave radiometry because of this technology's potential for lower cost and smaller size, most useful for smaller aircraft that frequently encounter icing conditions during cruise flight.

This paper describes the evolution of airborne passive microwave radiometer system development by ERDC-CRREL and the multi-agency Flight in Icing Remote Sensing Team (FIRST), a consortium of agencies (National

* *Corresponding author address:* Charles C. Ryerson, ERDC-CRREL, 72 Lyme Road, Hanover, NH 03755-1290; email: charles.c.ryerson@erdc.usace.army.mil

Aeronautics and Space Administration, Federal Aviation Administration, National Center for Atmospheric Research, Army Corps of Engineers) working to develop icing remote sensing technologies.

2. CONCEPT OF OPERATION

Microwave radiometers operate by receiving thermal energy emitted and scattered by the earth's atmospheric constituents (Grody, 1997). They are passive instruments, receiving radiation and actively emitting none of their own. Radiative energy is emitted, scattered, and absorbed by the atmosphere, and radiometers typically measure a narrow spectral portion of this energy. Passive microwave radiometers are used to measure many atmospheric and terrestrial characteristics, but their ability to measure atmospheric temperature, cloud liquid-water content, and attributes of cloud and precipitation constituents is needed for estimating icing hazards. Since microwave measurement is based on the brightness temperature of atmospheric constituents, the radiation intensity observed by a radiometer is a function of the temperature, reflectivity, transmissivity, and emissivity of the emitter and attenuation by constituents between the emitter and the radiometer at the waveband of interest (Ryerson, 2000).

Each atmospheric constituent, gas, liquid, and solid, has a unique absorption spectrum. As a result, the atmosphere absorbs in several narrow wavelength bands and allows radiation to be transmitted through several broad windows due to the atmosphere's gaseous composition. The primary absorbers are oxygen and water vapor. Oxygen absorbs and re-emits in the 50 to 60-GHz region and at 118 GHz and is used for temperature profiling. Water vapor has peak absorption and re-emission at 22, 37, and 183 GHz (Grody, 1997). Liquid-water peak absorption and emission occurs near 37 GHz and 89 GHz. The dielectric strength of ice is approximately 10% of that of water in the millimeter wave spectrum. Therefore, the brightness temperature of water clouds will tend to be greater than the brightness temperature of ice clouds. However, ice clouds are more transparent and therefore the background is important. When looking down an ice cloud may appear brighter than a water cloud, while looking up the water cloud may be brighter.

Since we are interested in observing the radiative characteristics of cloud droplets and drizzle drops, this gaseous absorption is noise in an environmental sense. Because water vapor is potentially distributed non-uniformly in the clear atmosphere outside the cloud, the behavior of the sensor will also vary within and between flight levels (Savage et al., 1999).

Passive microwave detection of cloud water and precipitation is commonly achieved using ground-based sensors that look to zenith and observe the brightness difference between clouds that exhibit high brightness temperatures, and space that exhibits a low brightness temperature. This has been demonstrated in numerous field studies, including the Mt. Washington Icing Sensors Project (MWISP) and the Alliance Icing Research Study programs I and II (Reehorst et al., 2006; Ryerson et al., 2002; Ryerson, 2000) (Figure 1). Conversely, satellite-borne radiometers looking nadir can detect cloud water and rainfall rates over water bodies because like space they also provide a low brightness temperature background.

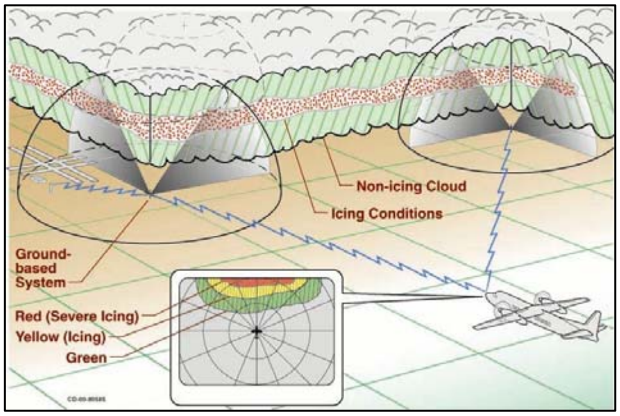

Figure 1. Ground-based icing remote sensing systems detect icing conditions around airports and protect aircraft during departure and approach.

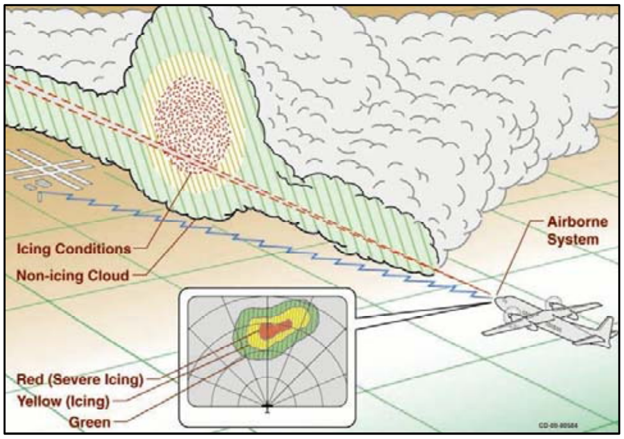

Figure 2. Airborne icing remote sensing systems detect icing conditions using aircraft-mounted sensors scanning along the flight path.

Aircraft mounted radiometers must scan nearly-horizontally along the aircraft flight path (Figure 2). In addition, aircraft-mounted microwave radiometers may be looking toward space during departure, or toward the earth's surface during approach, which can be land-or water-covered, making the detection of cloud supercooled water more challenging.

Because of these difficulties, Savage et al. (1999) developed a technique for locating and estimating icing conditions using two frequencies sensitive to liquid water content, 37 and 89 GHz, and three viewing angles. A radiometer placed on the nose of an aircraft would scan ahead of the aircraft horizontally, and 2° above and below the horizontal. In a clear-sky condition, the +2° beam detects colder temperatures by viewing cold space than does the –2° beam looking toward the warmer surface of the Earth. Since the atmosphere is more transmissive at 37 GHz, the brightness temperature of the +2^o beam will be less than (colder) than the +2^o 89 GHz beam. For the downward looking geometry, the brightness temperature difference between 37 and 89 GHz depends on the surface and the atmospheric conditions.

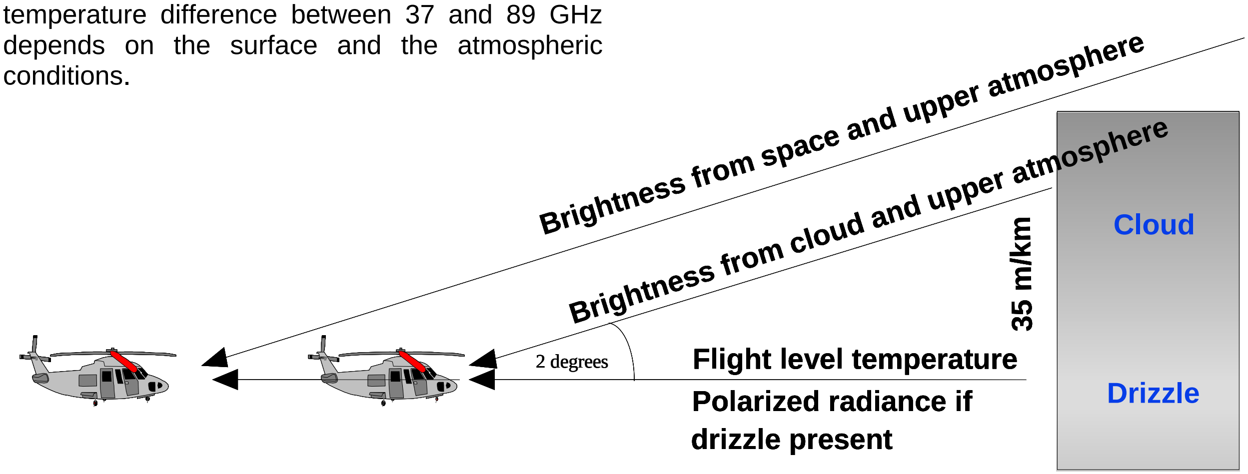

Figure 3. ERDC radiometer sensing scheme modified from Savage et al. (1999).

As the aircraft approaches a cloud, the +2^o beam and the -2^o beam converge in brightness temperature toward that of the horizontal beam. The rate of convergence to the temperature of the horizontal viewing beam depends on the distance from the cloud, the cloud height above and below the flight altitude, the decrease of air temperature with altitude, and the cloud LWC. As the aircraft approaches the cloud, the +2^0 and -2^0 viewing sensors start to intercept the cloud. As the aircraft gets closer to the cloud the in-cloud path length intercepted by the +2^0 and -2^0 increases and the brightness temperature approaches the brightness temperature of the horizontal looking sensor. An estimate of liquid-water content magnitude is obtained by comparing the brightness temperatures of the 37- and 89-GHz beams in the +2° orientation. Since the 37-GHz beam penetrates farther into cloud than the 89-GHz beam, it will be colder than the 89-GHz beam if there is little liquid water because it can detect the cold of space through the water. As liquid water content increases, the +2° 89- and 37-GHz brightness temperatures converge as the cloud transmissivity decreases. Savage et al. (1999) also speculated that the presence of drizzle-size drops can be detected by sensing polarized radiation scattered by large drops. He hypothesized that polarization resulted from drizzle drop scattering of polarized radiation from Earth surfaces, and shape distortion of the largest drops.

Since the upward-looking radiometer concept may provide the most useful information with regard to locating supercooled water, a variation of the Savage et al. (1999) technique, without the downward staring radiometers, is being evaluated by ERDC-CRREL and the FIRST team (Figure 3).

3. Simulation

RADTRAN was developed by the Air Force Geophysics Laboratory, now the Air Force Research Laboratory (AFRL), in the late seventies to model the attenuation, scattering and brightness temperatures associated with natural atmospheres for the frequency range from 1 to 1000 GHz (Falcone et al., 1979). It was developed in the spirit of the well-known atmospheric transmission model LOWTRAN (now called MODTRAN). The original RADTRAN used a horizontally stratified (plane parallel) atmosphere and considers the absorption of naturally occurring atmospheric gases and scattering by hydrometeors. In the late eighties RADTRAN was upgraded to include multiple scattering and emission and scattering by a number of natural surfaces (grasses, ocean, etc).

RADTRAN, as originally configured, predicts brightness temperature and attenuation for ground based and space-based microwave radiometers for vertical and slant paths. The model did not effectively handle the scenario of a radiometer placed in the nose of an aircraft to detect potential icing conditions ahead of the aircraft. ERDC/CRREL and NASA, in conjunction with AFRL, sponsored the modification of RADTRAN to handle the aircraft scenario by using a concentric layered atmosphere and providing a ‘fly through’ capability (Koenig et al., 2004).

RADTRAN calculates the attenuation, transmittance, and brightness temperatures based on the radiative transfer equation for thermal emission of microwave frequencies. The brightness temperature for a downward looking microwave sensor depends on the surface emitted radiance, the surface reflected downwelling atmospheric radiance both attenuated by the atmosphere between the ground and the sensor, and the atmosphere emitted radiance between the surface and the sensor. For an upward looking sensor the radiance associated with the ground is replaced by a constant brightness temperature representing cold space attenuated by the atmosphere between the sensor and space.

RADTRAN has six predefined atmospheric profiles; tropical, mid-latitude summer and winter, sub-artic summer and winter, and U.S 1962 standard atmosphere. In RADTRAN, clear sky atmosphere absorption is due primarily to water vapor and oxygen (Falcone et al., 1979). In addition, a capability to enter a user defined atmospheric profile is provided. In the microwave region the Rayleigh approximation can be used to compute the attenuation due to clouds. A capability to model partial or fully glaciated clouds is not available in RADTRAN. Though precipitation can be either in a liquid or solid state, invoking the above assumptions for clouds allows the volume extinction cross-section to be defined in terms of the mass of the cloud-condensed water. Also, a Graphic User Interface (GUI) now makes it considerably easier to generate the input information required by the model.

RADTRAN was originally a plane parallel model and therefore it was not possible to model a horizontally looking millimeter wave (MMW) sensor. An onionskin or concentric shell model that accounts for the curvature of the Earth’s atmosphere was added to RADTRAN that accommodates horizontally viewing sensors. For a sensor that is not viewing directly upward or downward the concentric shell approach more faithfully approximates the path through each layer. Since a multi-frequency, multi-view MMW radiometer can potentially provide information that can be used to define an icing potential metric, it is now possible to simulate an aircraft-mounted multi-frequency, multi-view sensor.

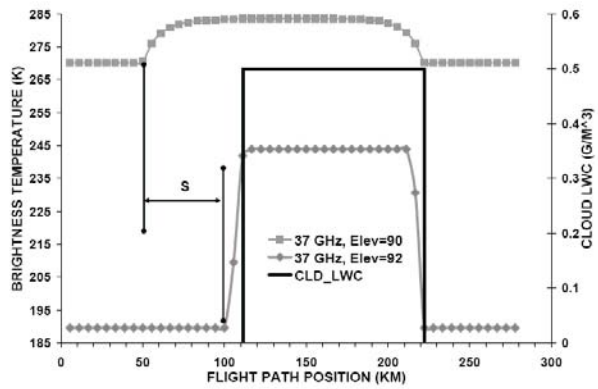

Figure 4. 35 GHz brightness temperatures associated with 90° and 92° view directions for a radiometer on an aircraft approaching a single cloud.

The virtual fly-through capability in RADTRAN operates as follows. The user specifies the cloud and atmospheric conditions, the frequencies and view directions, the start and end point of the flight path, the number of points along the flight, and the altitude of the flight path. At each designated point along the flight path the cloud atmospheric conditions along the view direction are determined at a spatial resolution of 250 meters. RADTRAN then computes the brightness temperatures, attenuation, and transmission for each frequency and view direction at the flight path location before moving on to the next point.

Figure 4 presents an example of a 37 GHz radiometer with 90 and 92 degree viewing directions used to compute both the distance to a cloud ahead of the aircraft and the cloud top altitude. A single cloud with a Cloud Liquid Water Content (CLD_LWC) of 0.5 g/m3 and a cloud base and top altitude of 0.3 km, and 1.0 km, respectively extends along the flight path from 111 km to 222 km. The aircraft flight altitude is constant at 0.7 km. Initially, the cloud is below the horizon even for the 90 degree viewing direction. When the aircraft is approximately 50 km from the leading edge of the cloud, the 37 GHz brightness temperature for the 90 degree view direction jumps almost 55 degrees Kelvin, indicating the radiometer is 'seeing' the cloud. At approximately 10 km from the cloud, the 37 GHz brightness temperature for the 92 degree viewing direction jumps 16 degrees Kelvin. From the aircraft altitude h' and the arc distance S between when the 90 degree viewing sensor first 'sees' the cloud and the 92 degree viewing sensor 'sees' the cloud it is possible to compute the cloud top altitude h'' and the distance S2 to the cloud from the position when the 92 degree viewing sensor 'sees' the cloud. The calculated cloud top is 0.96 km and the distance to the cloud is 9.2 km, while the actual values are 1.0 and 10 km, respectively.

To explore the use of RADTRAN for modeling multi-frequency, multi-view radiometer systems that could be used to derive cloud liquid water content from the MMW brightness temperatures, a variety of cloud scenarios have been explored, including cloud masses with multiple liquid water contents (Koenig et al., 2004). Figure 5 shows, conceptually, how multiple cloud liquid water contents were organized in RADTRAN for modeling.

4. CLOUD LIQUID WATER CONTENT INVERSION

If the horizontal distribution of water vapor, LWC, and temperature is specified, RADTRAN provides brightness temperatures from known cloud conditions. However, a successful MMW radiometer–based system must provide liquid water content from cloud brightness temperature – a considerably more difficult, problem. There is no analytical inversion technique that can be used to obtain the parameters critical to predicting icing potential from brightness temperature measurements from a horizontally pointing MMW radiometer. It is fairly simple to solve the forward problem of predicting the MMW brightness temperature; it is the inversion of the brightness temperature to obtain the cloud microphysical parameters critical to predicting icing that is difficult. Therefore, it is necessary to consider an alternative approach for inverting the MMW brightness information to obtain the desired atmospheric and cloud parameters.

Neural Network (NN) models are well suited for situations where the forward problem is relatively easy to solve but the inverse problem is fairly difficult (Massie et al., 2003). While it appears neural nets may be the solution to the radiometer liquid water inversion problem, there is an art to training neural nets. If over trained, the net will memorize the path through the net, if under trained the net may key on a local solution rather than the global solution. Despite these problems, the use of neural net models to invert MMW brightness temperature information to obtain cloud microphysical parameters is promising.

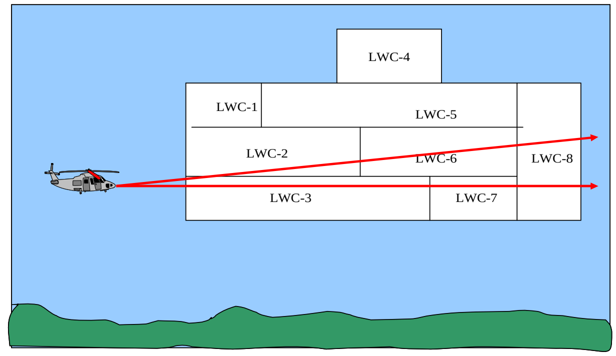

Figure 5. Use of modified Savage et al. (1999) concepts and fly-through RADTRAN to simulate brightness temperatures from cloud masses of varying distance, height, and liquid water content.

Massie et al. (2003) developed a NN model to predict liquid water content for the ERDC-CRREL system. Before the neural net could be used to predict cloud microphysical properties, it was trained by providing the net with appropriate input and output vectors. The input vectors were the integrated cloud liquid water content (ILWC) for specified spatial distributions of cloud LWC, water vapor, and temperature as a function of MMW frequency and sensor view direction. The output vectors are the MMW brightness temperatures for each frequency and view direction. The spatial distribution of cloud LWC was specified using aircraft data collected by NASA in supercooled (icing) clouds over the Great Lakes and Ohio. The aircraft measurements included the LWC, drop size distribution and outside air temperature along the flight path at a sampling resolution of approximately 90 meters.

Five independent data collection periods were used to define the envelope of atmospheric conditions conducive to icing and to develop the input and output vectors for training the neural net. For each aircraft data set, the average vertical LWC profile and LWC variations as a function of the height above the cloud base were determined. The horizontal distribution of cloud LWC was specified by defining regions (clusters) where the variations in the cloud LWC obeyed Poisson statistics. The coherence lengths associated with the clusters were obtained using a two-point correlation function. The Air Force Geophysics Laboratory standard mid-latitude winter atmospheric profile was used to specify the distribution of water vapor and temperature.

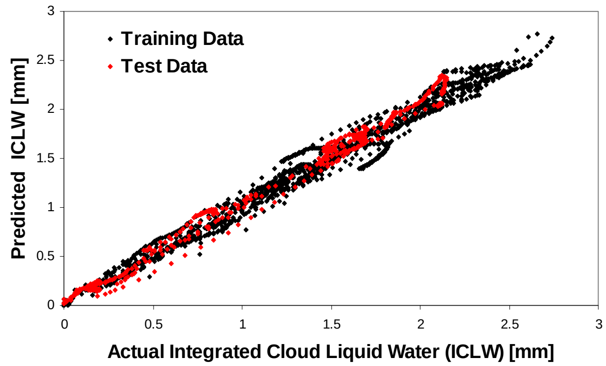

Figure 6. Actual integrated liquid water content versus integrated cloud liquid water content predicted using two frequencies (37 and 89 GHz) along the slant path and one frequency along the horizontal path as the input vector.

The modified Savage et al. (1999) model was used to predict the ILWC and MMW brightness temperatures by solving the MMW brightness temperature equation based on the MMW frequency and the spatial distribution of LWC, water vapor and temperature. The model output consists of the ILWC and brightness temperature as a function of frequency and view direction. Initially, 1000 cases were used to train the neural net, while approximately 1000 cloud scenarios were used to evaluate the net.

Results indicated that the neural net has considerable skill in predicting the ILWC using multi-frequency, multi-view MMW brightness temperature information (Figure 6). To enhance the effectiveness of the neural net, the net was re-trained using approximately 10,000 cases and evaluated using independent cloud scenarios. The most effective approach, also the least expensive in terms of radiometer costs, to further enhance the effectiveness of the net is to increase the number of view angles rather than increasing the number of operating frequencies.

5. HARDWARE DEVELOPMENT

Aircraft icing hazard is caused by the weight and the shape of ice accumulation on airfoils. Though increased weight impacts flying qualities, it is not as significant as ice shape which directly alters aerodynamics increasing drag and reducing control authority. A factor significantly altering ice shape is drop size, which often drives the freezing process from dry growth, creating rime ice, to wet growth creating clear ice with drag-inducing horns on airfoil leading edges when drop sizes increase into the drizzle size range.

The MMW brightness temperature of most earth materials is typically different in the vertical and the horizontal, with the vertical brightness temperature often warmer than the horizontal. Therefore, Savage et al. (1999) hypothesized that surface emitted MMW energy scattered by drizzle and rain drops will also be polarized and the apparent cloud temperatures for the horizontal and vertical polarization will differ if the cloud contains large drops. This is because the volume scattering efficiency for large drops is several orders of magnitude greater than for cloud drops. In addition, large rain drops that are non-spherical will emit or scatter MMW radiation differently than spherical drops resulting, again, in different horizontal and vertical brightness temperatures. These differences in brightness temperature and polarization are clues that large drops are present.

Hardware development for flight testing was intended to satisfy many of the requirements identified by Savage et al. (1999). Radiometers must operate at 36.0 - 37.0 and 86.0 to 92.0 GHz, the internationally-designated “quiet bands” reserved for remote sensing. The sensors must measure the Stokes parameters to detect Supercooled Large Drops (SLD), and have multifunctionality. The sensor much be small enough and light enough to fit on small aircraft.

The only previous widely applied radiometer providing Stokes parameters in these frequencies is the Polarized Scanning Radiometer (PSR) developed by the Georgia Institute of Technology and the U.S. National Oceanographic and Atmospheric Administration (NOAA). The PSR allows measurement of all four Stokes' parameters at 10- and 18-GHz, and the first three Stokes' parameters at 37- and 89-GHz (Piepmeier and Gasiewski, 1996). However, the PSR is large and heavy (approximately 500 kg), and requires a transport aircraft such as a Lockheed Electra to fly. We required instruments that could be flown on small aircraft, so weight and size were critical factors.

Through the Small Business Innovation Research (SBIR) program, ERDC-CRREL sponsored development of two polarimeters, one operating at 35 GHz, and the second at 94 GHz. Waveband, Inc. (now owned by Sierra Nevada Corporation), the polarimeter developer, created small, lightweight (less than 20 kg each) units capable of measuring the four Stokes parameters using a single antenna and a single amplifier for each frequency. Called Direct Detection Polarimetric Radiometers (D2PR), they employ a

Spinning Phase Retarder (SPR). During each rotation of the SPR, the output signal of the SPR varies in amplitude and phase. All polarimetric information is gathered from the processing of the rapidly varying signal making it possible to suppress flicker noise and, thereby, increase the sensitivity of the polarimeters. The polarimeters directly measure the second, third and fourth Stokes parameters and derive the first Stokes parameter from the other three. Since the algorithm used to derive the first parameter is only valid for a fully polarized signal, the system also provides a DC output that may be used to obtain the brightness temperature (the first Stokes parameter) when a fully polarized signal is not available.

The polarimeters were delivered to ERDC-CRREL in early 2007, and initial flight testing was conducted in December, 2006 (Figure 7). Flight tests were conducted with an aircraft that was not ice protected, thus it was not possible to collect information in clouds that could potentially produce icing. Therefore, clouds that were warm, supercooled and largely water, and glaciated were located for the flight tests through skilled weather forecasting. The polarimeters were mounted to view out the right side of the aircraft. Cloud scans were executed by flying below clouds and looking upward at about 10° above the horizon, or by flying alongside clouds. During turns, the radiometer pointed toward the ground. Preliminary analysis of the radiometer information indicates that the second Stokes parameter responded most strongly when the radiometer viewed the terrain (Figure 8). Analyses are planned to assess the response of the polarimeters to the test flight cloud conditions.

The polarimeters are mounted in flight-ready canisters designed for "hard points" on aircraft designed to fly common in situ cloud microphysics equipment (Figure 7). We anticipate flying the radiometers on the NASA-Glenn Research Center S-3 research aircraft in a few years for a comprehensive proof-of-concept on an aircraft equipped with in-situ cloud microphysics measurement equipment.

6. CONCLUSIONS

All of the fundamental elements to assess the capability of microwave radiometers for detecting icing conditions from aircraft in-flight have been developed in this program; concept of operation, simulation of operational configuration and atmospheric environments, inversion of cloud integrated liquid water content from brightness temperature, and instrumentation for in-flight proof of concept. Simulation with the updated fly-through RADTRAN model demonstrates that multiple frequencies and multiple fields of view do provide unique brightness temperatures that can be used to detect icing conditions. RADTRAN provides the brightness temperatures for each location in flight, and allows sensing concepts to be fully evaluated for their ability to discriminate integrated liquid water content in multiple cloud geometry and aircraft traverse geometries.

The neural-network-based inversion technique demonstrates that integrated cloud water can be retrieved from multiple frequency brightness temperatures at multiple angles of view. Though cloud parameters are specified with explicit cloud liquid water contents for RADTRAN, microwave radiometry provides only the integrated liquid water over a path length limited by the transmissivity of the cloud. Integrated values are useful, however, because ice formation on airfoils is an integration of the variable supercooled water content intercepted by the aircraft. Though it is theoretically possible to detect the presence of large drops using our MMW polarimeters, this concept has not been modeled or fully assessed through measurements.

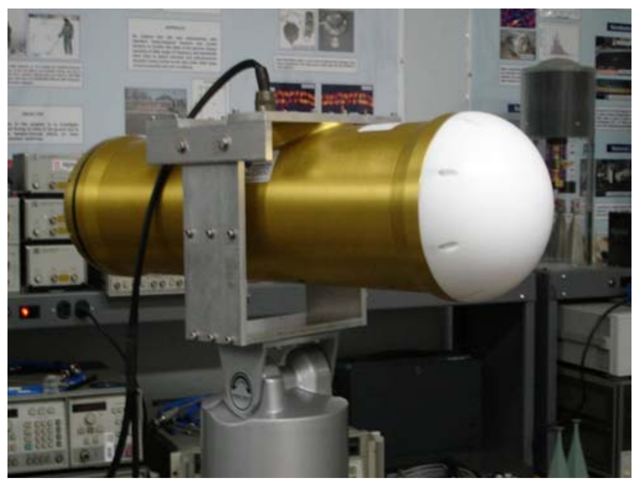

Figure 7. 35 GHz polarimeter in flight-ready canister.

The prototype polarimeters provide the capability of testing in actual supercooled clouds. Though the D2PR polarimeters provide the magnitude of three of the four Stokes parameters, Q, U, and V, they do not provide a direct brightness temperature measurement. However, we believe it is possible to use the DC component to obtain the desired brightness temperature information.

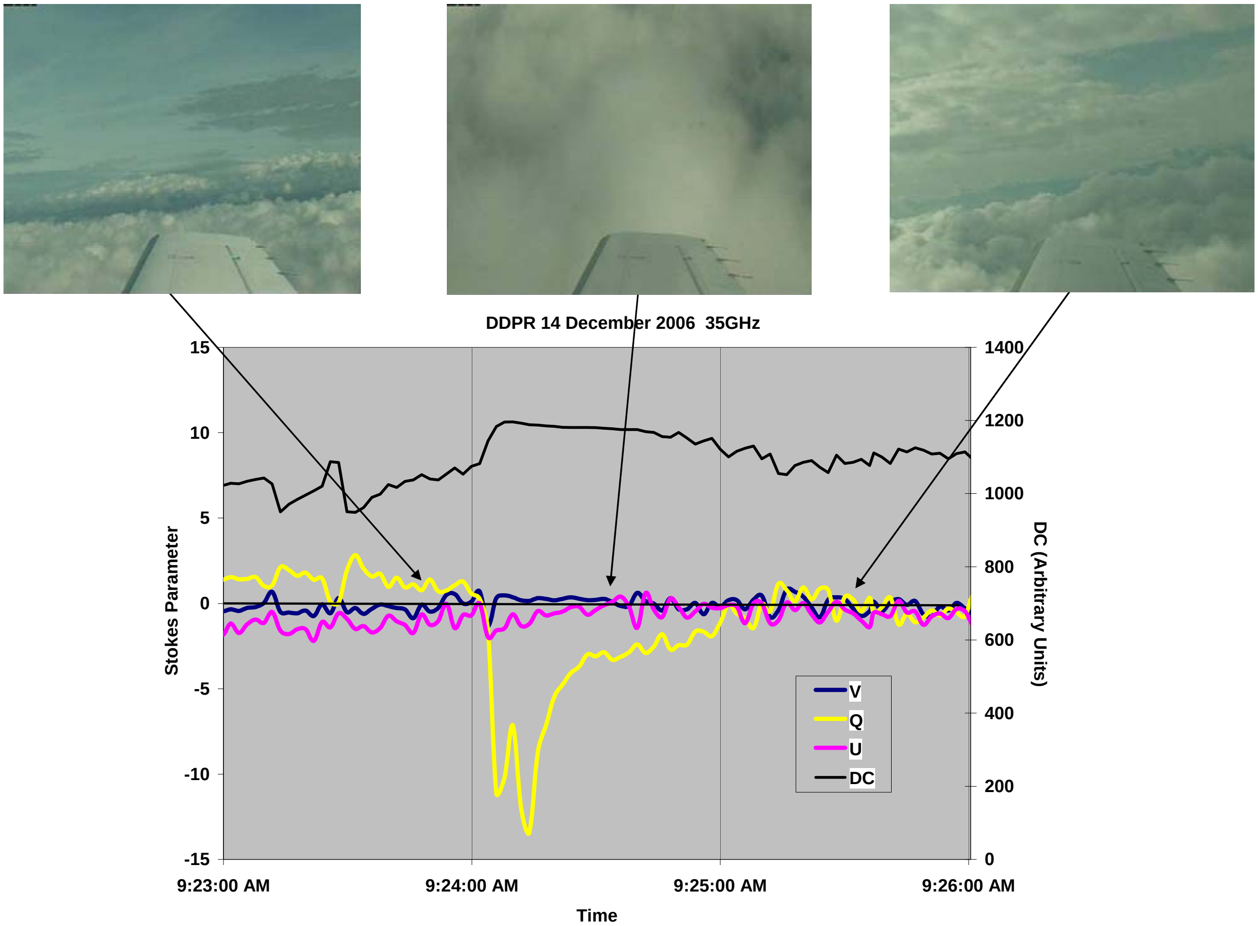

Figure 8. Sequence showing Stokes parameter responses with polarimeters viewing distant clouds with wings level, left and right photos, and polarimeter dipped through clouds to ground. When viewing ground, Q goes sharply negative.

All elements of a test program are in place. An operational concept has been developed, modeling and simulations have occurred, and prototype instruments are constructed. Though issues such as integrated brightness temperature retrieval need to be resolved, the prototype system is ready for proof of concept flights.

6. ACKNOWLEDGMENTS

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