

The NASA Icing Remote Sensing System

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Abstract

NASA and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) have an ongoing activity to develop remote sensing technologies for the detection and measurement of icing conditions aloft. A multiple instrument approach is the current emphasis of this activity. Utilizing radar, radiometry, and lidar, a region of supercooled liquid is identified. If the liquid water content (LWC) is sufficiently high, then the region of supercooled liquid cloud is flagged as being an aviation hazard. The instruments utilized for the current effort are an X-band vertical staring radar, a radiometer that measures twelve frequencies between 22 and 59 GHz, and a lidar ceilometer.

The radar data determine cloud boundaries, the radiometer determines the sub-freezing temperature heights and total liquid water content, and the ceilometer refines the lower cloud boundary. Data are post-processed with a LabVIEW program with a resultant supercooled LWC profile and aircraft hazard identification. Remotely sensed measurements gathered during the 2003-2004 Alliance Icing Research Study (AIRS II) were compared to aircraft in-situ measurements. Although the comparison data set is quite small, the cases examined indicate that the remote sensing technique appears to be an acceptable approach.

Background

The NASA Icing Remote Sensing activity started with the findings of the 1997 White House Commission on Aviation Safety and Security, which directed the FAA and NASA to significantly increase the level of safety for aircraft, including all-weather operations. NASA then initiated the Aviation Safety Investment Strategy Team (ASIST), which prioritized aviation safety activities required to meet the White House goals. The ASIST Weather team identified Inflight Icing as one of its top three priorities to improve flight safety. Simultaneous to this activity, the NASA Advanced General Aviation Transport Experiment

(AGATE) was defining technologies required to enhance General Aviation aircraft safety and operation. Within AGATE, the Ice Protection Systems Workpackage was defining the *Avoid and Exit* strategy as the key to improving flight safety in the icing environment. Key to success of the *Avoid and Exit* strategy was the ability to remotely measure the icing environment.

In 1997, NASA Glenn Research Center (then Lewis Research Center), the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), and the FAA sponsored the Inflight Remote Sensing Icing Avoidance Workshop. The outcome of this workshop was the formulation of the NASA Icing Remote Sensing activity.

The primary thrust of the NASA Icing Remote Sensing activity is to develop the required sensing technologies and test them in the real-world aviation environment. The technologies considered for the NASA activity were examined by Ryerson (2000) and Reehorst and Koenig (2001).

Besides the NASA and CRREL development activity, the National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration (NOAA) are also pursuing the development of icing remote sensing capability. The NCAR and NOAA systems are described by Reehorst and Koenig (2003), and rely on somewhat different sensing concepts than the NASA system.

Description of Sensors

The NASA development activity was designed with several assumptions in mind:

1. The information generated by an icing remote sensing system will be used not only by flight crews, but by the entire aviation community, including also air traffic controllers, airline dispatchers, and aviation weather forecasters.
2. The development of ground-based systems will likely be less costly and technically more achievable than for airborne systems due to relaxed size,

power, and weight restrictions. Therefore, ground-based system development should occur before airborne system development.

3. It is likely that no one sensing technology will be able to satisfy the requirements of the remote measurement of icing conditions.
4. The detection of icing needs to be conservative so that the presence of hazardous icing conditions without detection is rare.

With these developmental assumptions in mind, the NASA Icing Remote Sensing System is made up of three sensor components, a radar, a microwave radiometer, and a ceilometer.

The radar unit used for the NASA Icing Remote Sensing System for the winter of 2003-2004 was a slightly modified Honeywell WU-870 airborne X-band

radar. This radar system is described by Reehorst and Koenig (2004). The radar provides reflectivity measurements that are used to define cloud boundaries.

The microwave radiometer is a Radiometrics, Inc. WVP/TP 3000 Temperature and Water Vapor Profiler. The WVP/TP 3000 radiometer is described by Solheim (1998). Among other measurements, this microwave radiometer provides temperature profile and integrated liquid water measurements.

Finally, the ceilometer being used is a standard Vaisala CT25K Laser Ceilometer. The ceilometer is used to refine the definition of the lower cloud boundary since it is less susceptible to precipitation for this than is radar.

Figure 1 shows these three instruments installed for operations at the 2003-2004 Alliance Icing Research Study (AIRS II) field test program.



Figure 1.—NASA Icing Remote Sensing hardware as installed for the AIRS II field test program.

Description of Software

The measurements from the three instruments are fused by post-processing to produce a single indication of aircraft icing hazard. For this report, the fusion technique is quite simple. The radar reflectivity data is used to define the boundaries of cloud layers. The lower boundary of the lowest cloud layer is refined with the ceilometer data to correct for precipitation effects or for the close-range radar blind spot. Once the cloud boundaries have been defined, the temperature profile is used to determine the portion of the clouds that are likely to be supercooled. The test for supercooled cloud is that the temperature must be below 0 °C and above -40 °C. Another test is conducted for liquid cloud (temperatures greater than -40 °C). The integrated liquid water measured by the radiometer is then evenly distributed over the liquid cloud region to determine the cloud liquid water content (LWC). The LWC cloud boundaries are then further limited by the range of supercooled cloud. If the resultant supercooled liquid

cloud has an LWC greater than 0.1 gm⁻³, then it is defined as being an aircraft icing hazard.

These various measurements and calculated values are shown for 12/10/03 from 1500UTC to 1759UTC at the AIRS II Mirabel site in Figure 2. The top left plot is the temperature distribution over the test period. A temperature inversion is evident over this test period. The center left plot shows the radar reflectivity measurements for the same period. It should be noted that the reflectivity below 5000 ft (1500 m) includes elevated values caused by side-lobe and receiver noise. The top right plot shows the integrated liquid measured during this same period by the microwave radiometer. The bottom right plot shows the cloud base as measured by the ceilometer. Finally, the bottom left plot shows the regions of calculated icing hazard. From the ceiling plot, it is seen that the lower cloud boundary dropped to around 3500 ft (1000 m) for the last 2/3 of the displayed period. However, the region of icing hazard does not drop this low. The lower boundary of the icing hazard is determined by the remotely-sensed freezing level, thus it is closer to 7000 ft (2100 m).

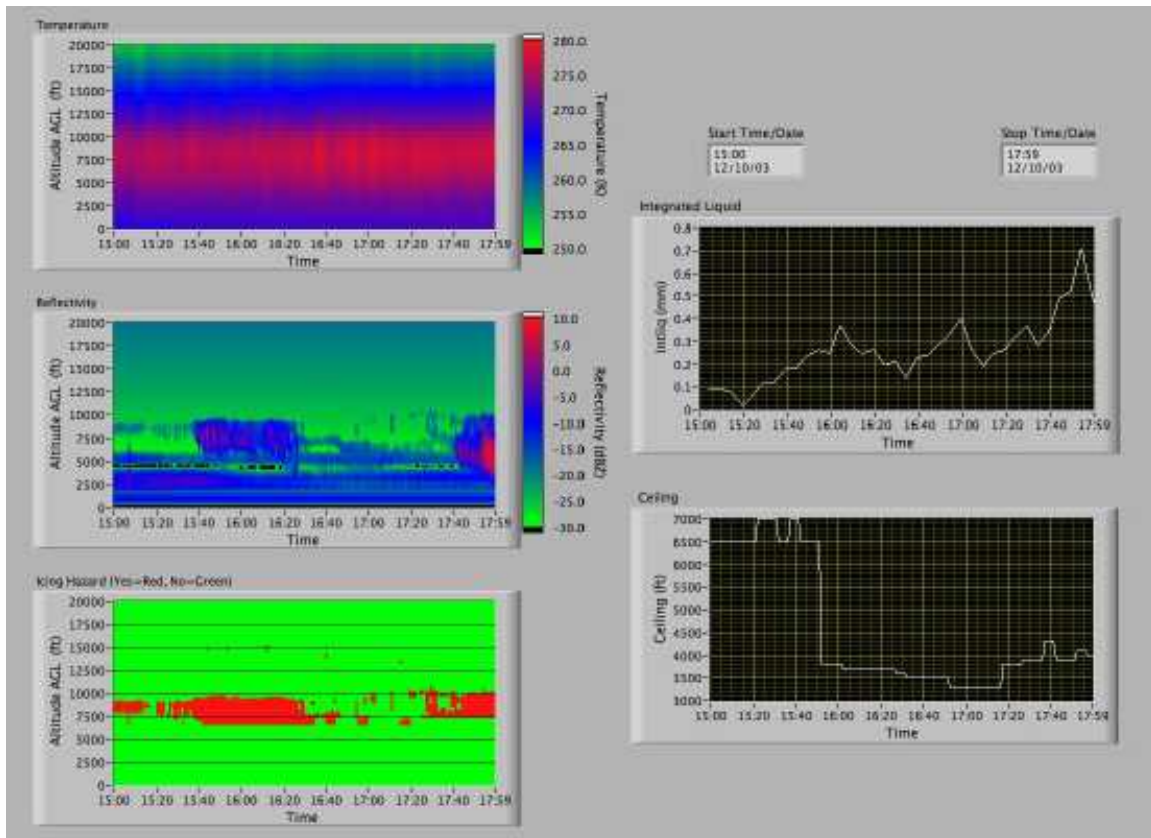


Figure 2.—LabVIEW program screen for 12/10/03 from 1500Z to 1759Z.

Field Test Program

The NASA Icing Remote Sensing System was operated as part of the Second Alliance Icing Research Study (AIRS II), which was conducted between November 2003 and February 2004. AIRS II was a collaborative scientific project involving numerous research organizations from Canada, the United States and Europe. The central research theme of AIRS II was aircraft icing, with operational objectives to test and evaluate remote sensing technologies, improving icing forecast technologies, further characterize the icing environment, and further characterize the aerodynamic effects of ice accretions (Strapp, 2003).

Several research aircraft operated out of Ottawa, Ontario, Cleveland, Ohio, and Bangor, Maine, and a large array of instrumentation was located at Mirabel Airport, Montreal, Quebec. The NASA Twin Otter

Icing Research Aircraft operated out of Ottawa during the test period. Besides other research activities, the Twin Otter performed spiral descents and missed approaches to obtain atmospheric soundings to compare to ground instrumentation.

Data from the sensors listed in Table 1 were acquired by the NASA aircraft using a Science Engineering Associates (SEA) M300 data acquisition system. The M300 system applied calibration data to convert raw signals to engineering units for real-time display. For each flight, the data was post-processed using the SEA M300 play back utility to output ASCII files containing flight and cloud parameters in engineering units at 1-second intervals. These files were imported to Microsoft (Microsoft Corporation, Redmond, WA) Excel workbooks to develop time history and sounding plots for each flight. The Excel data was used to compare to the output of the NASA Icing Remote Sensing System's post-processing described above.

TABLE 1.—INSTRUMENTATION ON THE NASA TWIN OTTER AIRCRAFT DURING THE AIRS II FIELD TEST

Parameter	Instrument	Range	Placement
Cloud Droplets	Particle Measuring Systems Forward Scattering Spectrometry Probe (FSSP-100 extended)	3-47 μm	Under left wing
Hydrometeors	Particle Measuring Systems Optical Array Probe (OAP-2DC-Gray)	15-960 μm	Under right wing
Liquid Water Content	CSIRO-King LWC: model KLWC-5	0-2 gm^{-3}	Nose
Liquid Water Content	Attex Nevzorov Liquid Water Content (NTWC), model IVO-2	0.003-3.000 gm^{-3}	Nose
Total Water Content	Attex Nevzorov Total Water Content (NLWC), model IVO-2	0.003-3.000 gm^{-3}	Nose
Ice Detection	Rosemount Ice Detector, Model 871FA211	0-5 Volts	Nose
Air Temperature	Rosemount OAT, model 102AU1P	-20 to 30 F	Nose
Dewpoint Temperature	General Eastern Dewpoint Hygrometer,	-20 to 30 F	Nose
Velocity	Rosemount 542K	0 to 190 knot	Nose boom
Altitude	Rosemount 542K	0 to 15 k.ft	Nose boom
Angle of attack & sideslip	Rosemount 858 probe	± 15 deg	Nose boom
Linear Accelerations	Systron-Donner BEI MotionPak	± 3 g	Inertial Box (cabin)
Angular Rates	Systron-Donner BEI MotionPak	± 60 deg/s	Inertial Box (cabin)
Attitude angles	Humphrey VG24-0636-1	± 90 deg	Inertial Box (cabin)
Aircraft Heading	Twin Otter's heading gyro	0-360 deg	Cockpit
Geographic Location	Trimbull TNL-2000 Global Positioning System (longitude, latitude)		Cockpit
Control Positions	Space Age Control	specific to control device	near control

Results

Comparisons were made for all cases when the NASA Twin Otter performed descending spirals over the Mirabel site, thus providing a sounding over the ground equipment test site. Flight data over Mirabel was obtained on November 11, 2003 between 1630UTC and 1657UTC, November 18, 2003 between 1233UTC and 1246UTC, November 25, 2003 between 1809UTC and 1830UTC, December 10, 2003 between 1617UTC and 1637UTC, and on December 10 between 1720UTC and 1732UTC.

For the purposes of the comparisons shown here, the Above Ground Level (AGL) altitude that the Remote Sensing System would normally output was converted to Pressure Altitude. During the test, the surface-level pressure altitude was monitored and recorded using a standard aircraft altimeter fixed to the research ground site. This altimeter was set to 29.92 in. of mercury (1013.2 mb), which is the standard setting for the research pressure system in the NASA aircraft. During post-processing, the ground site altimeter reading was added to the AGL values, thus providing a comparable altitude for the aircraft data.

Three figures are shown for each comparison between flight and remotely sensed data. These figures are numbered X.1, X.2, and X.3, where X equals the figure-set number. For each of these charts the aircraft measured parameter is compared to a remotely sensed (R-S) value from the beginning of the maneuver (value 1) and the end of the maneuver (value 2). Each Figure X.1 shows the comparison between flight

measured LWC and the value derived from the remote sensed (R-S) measurements, as described above. On this figure, the aircraft term, labeled KLWC, is the zero-corrected output of the CSIRO-King LWC probe. Each Figure X.2 shows the comparison between aircraft measured static outside air temperature (T_s) and the air temperature profile calculated from the TP/WVP 3000 radiometer measurements. Each Figure X.3 shows the comparison between aircraft measured ice detection and the icing hazard term derived from the remotely sensed measurements, as described above. The aircraft term is the voltage (divided by ten) output of the Rosemount Ice Detector.

It should be noted that the output of the remote sensing system contains a mixture of imperial and SI units. This mixture of units is caused by the desire to conform to the standard units of the United States aviation community.

November 11, 2003 between 1630UTC and 1657UTC

Flight records noted that there was no ice accretion during this spiral maneuver, with only ice crystals present above the freezing level.

The comparison between aircraft-measured values and remotely-sensed and derived values is shown in Figures 3.1, 3.2, and 3.3. Both flight and remotely-sensed values of LWC are negligible. The air temperature measurements agree within 3 °C.

This case demonstrates that the remote sensing system can distinguish between liquid and ice content, and that it correctly determined that there was no icing hazard present.

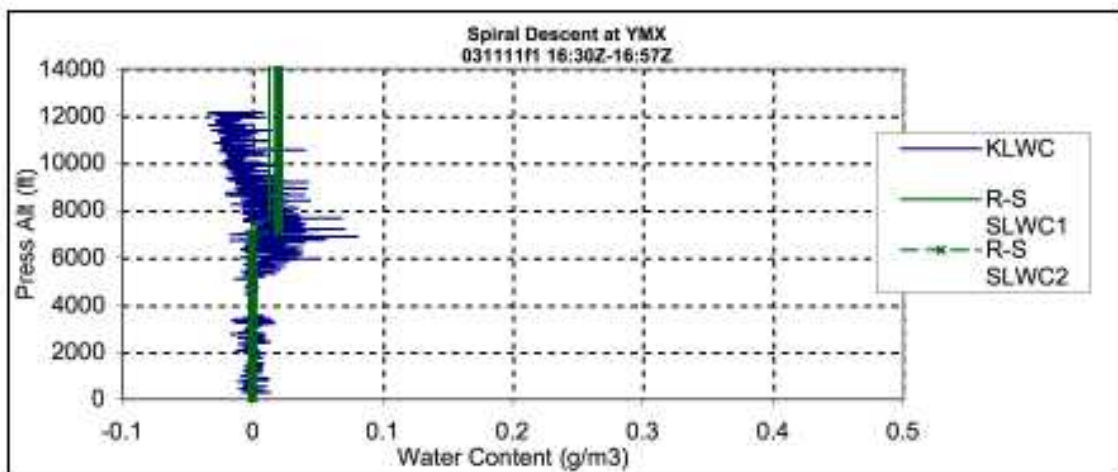


Figure 3.1.—LWC plot for Nov. 11, 2003 between 1630 and 1657UTC.

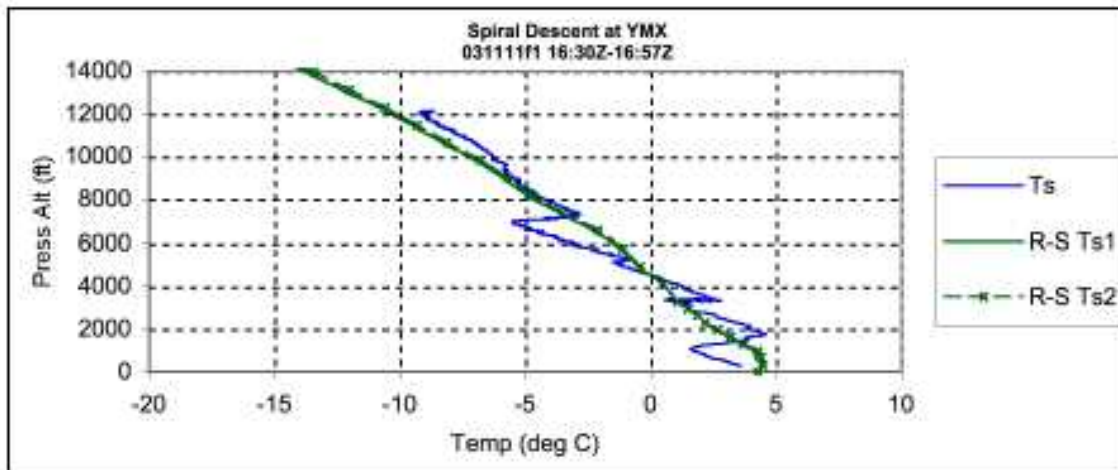


Figure 3.2.—Temperature plot for Nov. 11, 2003 between 1630 and 1657UTC.

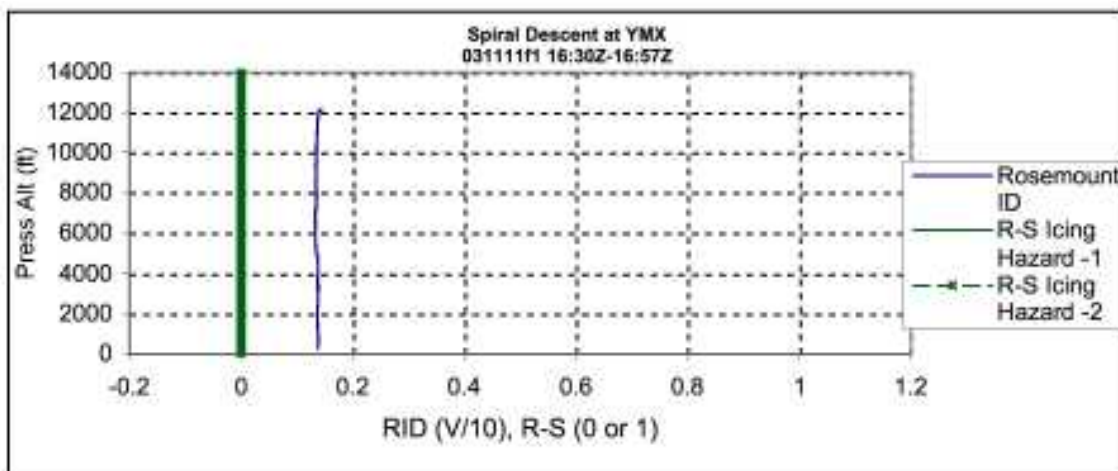


Figure 3.3.—Icing hazard plot for Nov. 11, 2003 between 1630 and 1657UT.

November 18, 2003 between 1233UTC and 1246UTC

The flight records noted that there was no ice accretion during this spiral maneuver, with a single cloud layer and clear sky above. In this case there was liquid water present, but the temperatures were above freezing throughout the cloud layer.

Comparison between aircraft-measured values and remotely-sensed and derived values is shown in Figures 4.1, 4.2, and 4.3. Likely because of the temperature inversions present, the temperature agreement was not as good for this case compared to the one shown in Figure 3.2. In this case the temperature varied by up to 5 °C. But the remote sensing system correctly determined that the liquid water was not supercooled, and that there was no icing hazard present.

November 25, 2003 between 1809UTC and 1830UTC

Flight records noted that there was light rime icing during this spiral maneuver with ice crystals precipitating from the cloud and clear sky above the single cloud layer.

Comparison between aircraft-measured values and remotely-sensed and derived values is shown in Figures 5.1, 5.2, and 5.3. Again, the remotely measured temperature profile is smoothed through the temperature inversion, so that disagreement as great as 6 °C existed. However, despite the temperature errors, the remote sensing system correctly bounded the region of supercooled liquid water content leading to a conservative flagging of the altitudes with icing hazard present.

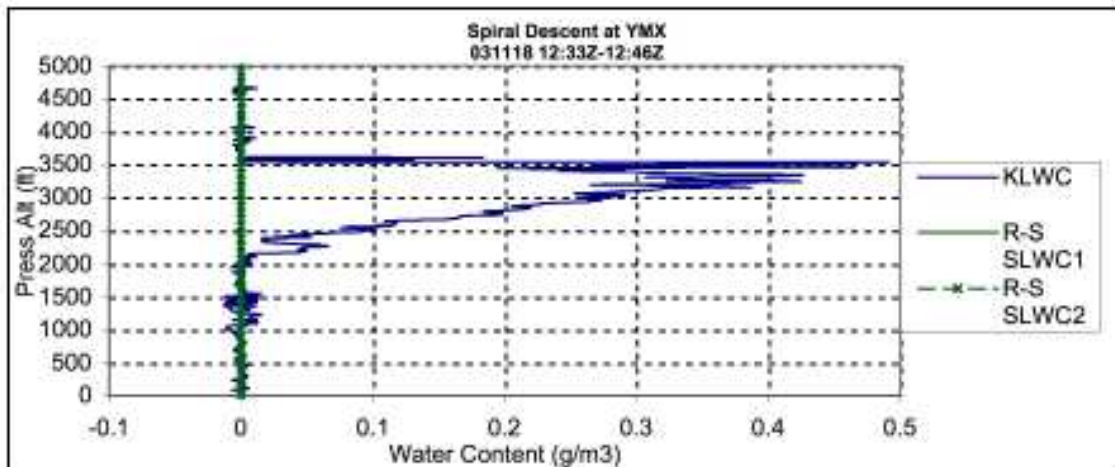


Figure 4.1.—LWC plot for Nov. 18, 2003 between 1233 and 1246UTC.

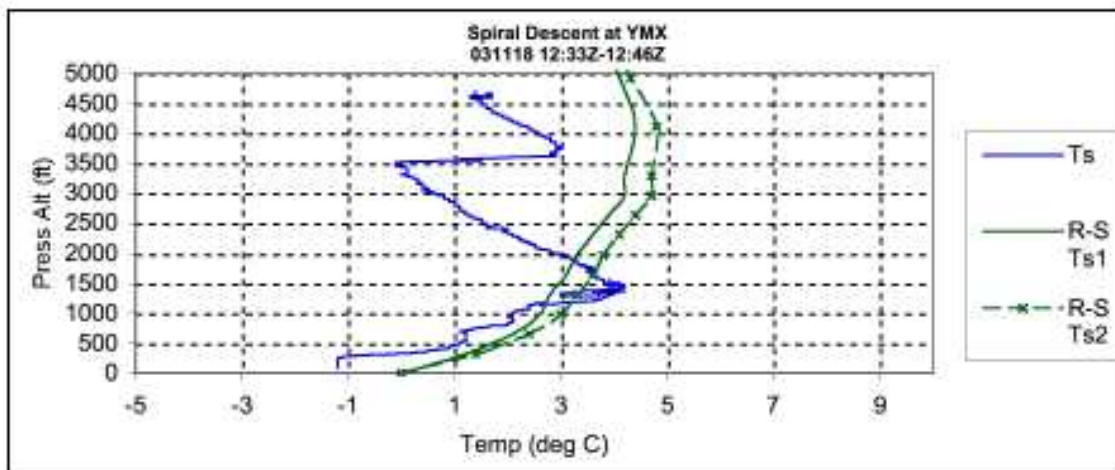


Figure 4.2.—Temperature plot for Nov. 18, 2003 between 1233 and 1246UTC.

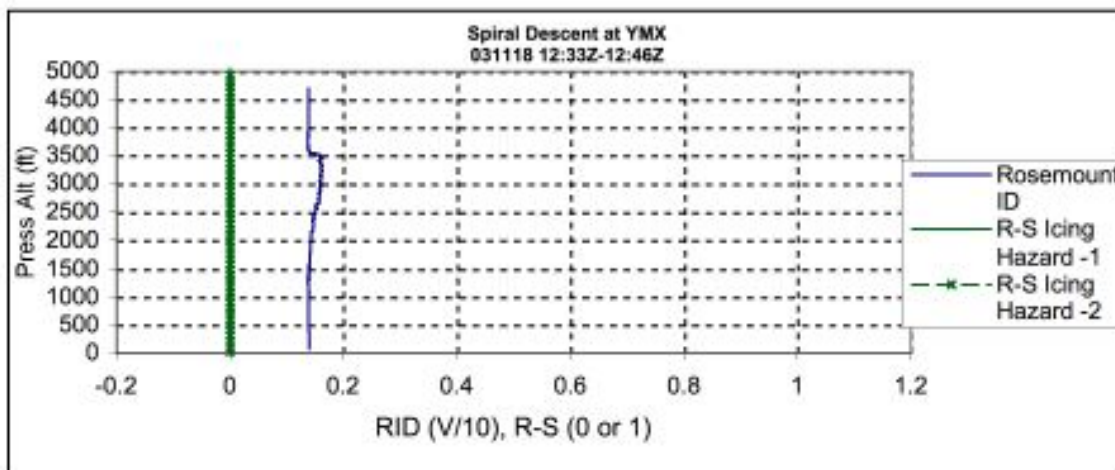


Figure 4.3.—Icing Hazard plot for Nov. 18, 2003 between 1233 and 1246UTC.

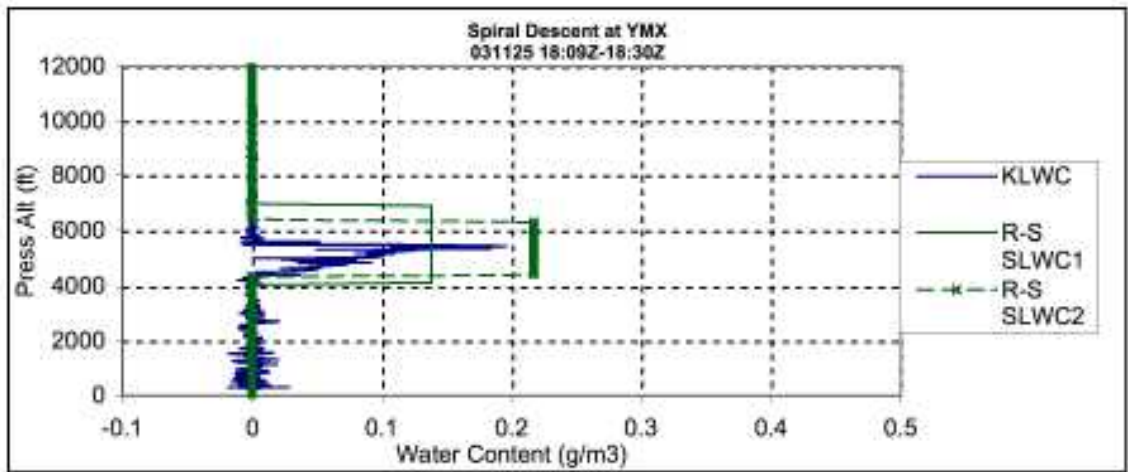


Figure 5.1.—LWC plot for Nov. 25, 2003 between 1809 and 1830UTC.

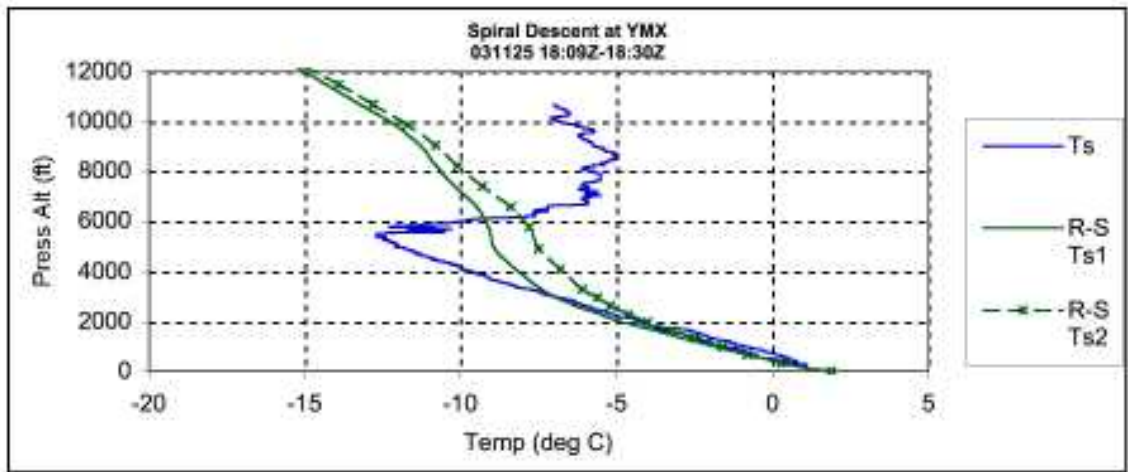


Figure 5.2.—Temperature plot for Nov. 25, 2003 between 1809 and 1830UTC.

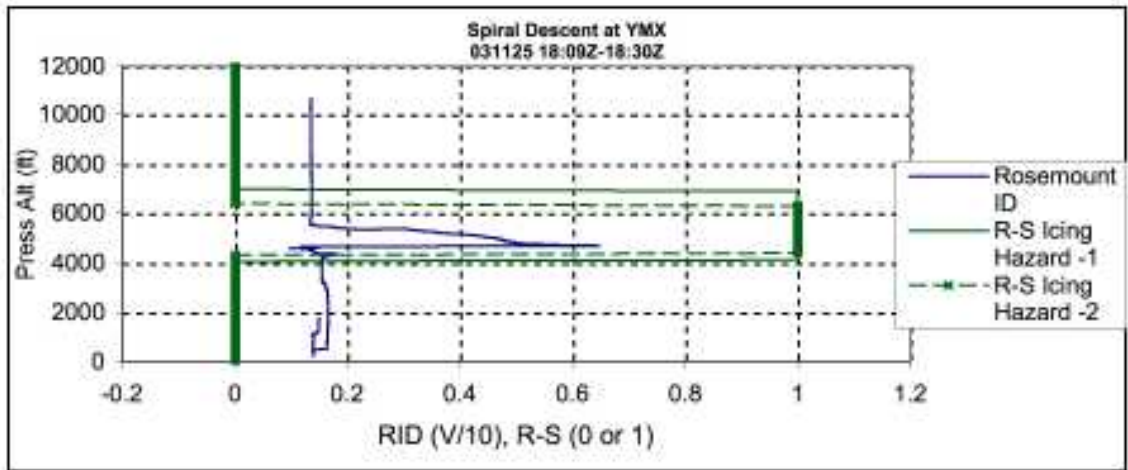


Figure 5.3.—Icing Hazard plot for Nov. 25, 2003 between 1809 and 1830UTC.

December 10, 2003 between 1617UTC and 1637UTC

Flight records noted three liquid cloud layers, with the upper one below 0 °C and producing a light clear ice accretion; the sky was clear above these three layers and clear below the layers with no precipitation.

Comparison between aircraft-measured values and remotely-sensed and derived values is shown in Figures 6.1, 6.2, and 6.3. Because of the sharp temperature inversion near 2,000 ft (610 m) the disagreement in temperature peaked at that point at 5 °C. The determination of supercooled liquid water content and the corresponding identification of hazardous icing conditions agrees well with the flight measurements and flight log.

December 10, 2003 between 1720UTC and 1732UTC

Occurring roughly an hour after the previous case, flight records again noted three liquid cloud layers, with the upper one colder than 0 °C and producing a light clear ice accretion; the sky was clear above these three layers and clear below the layers with no precipitation.

Comparison between aircraft-measured values and remotely-sensed and derived values is shown in Figures 7.1, 7.2, and 7.3. Because of the 8 °C temperature inversion near the surface, the remotely measured temperature again varies from the aircraft measured values, this time by less than 4 °C. However, since the temperature measurements were accurate in the area of icing conditions, the remote sensing system properly bounded the region of supercooled liquid water and identified it as an aircraft hazard.

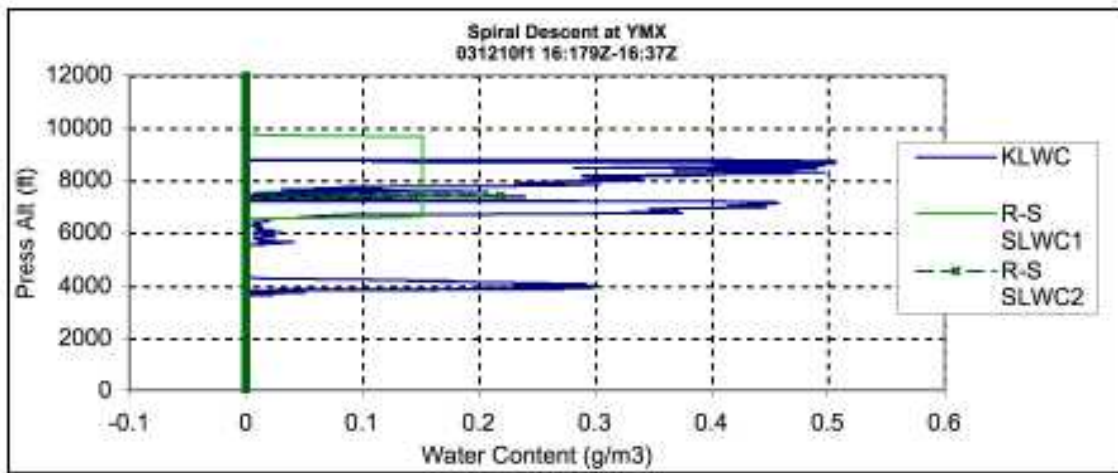


Figure 6.1.—LWC plot for December 10, 2003 between 1617 and 1637UTC.

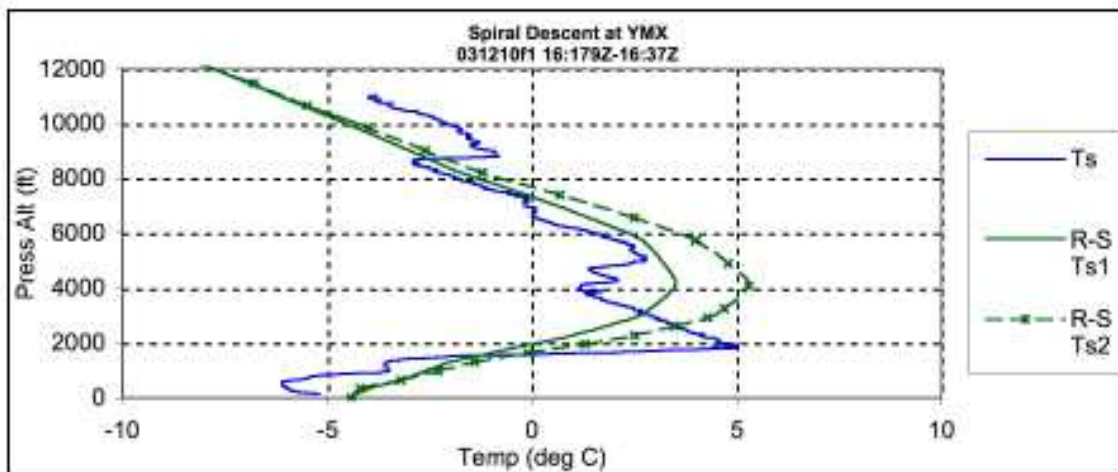


Figure 6.2.—Temperature plot for December 10, 2003 between 1617 and 1637UTC.

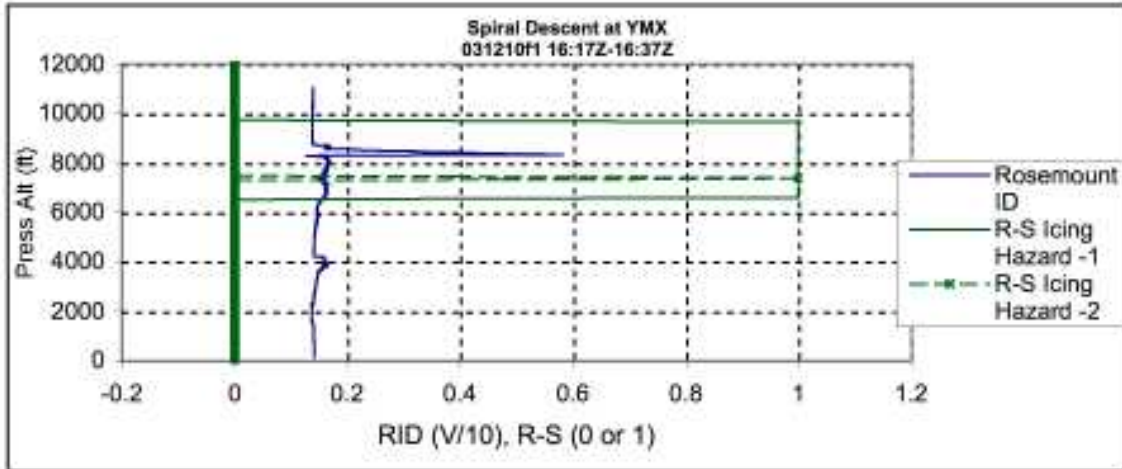


Figure 6.3.—Icing Hazard plot for December 10, 2003 between 1617 and 1637UTC.

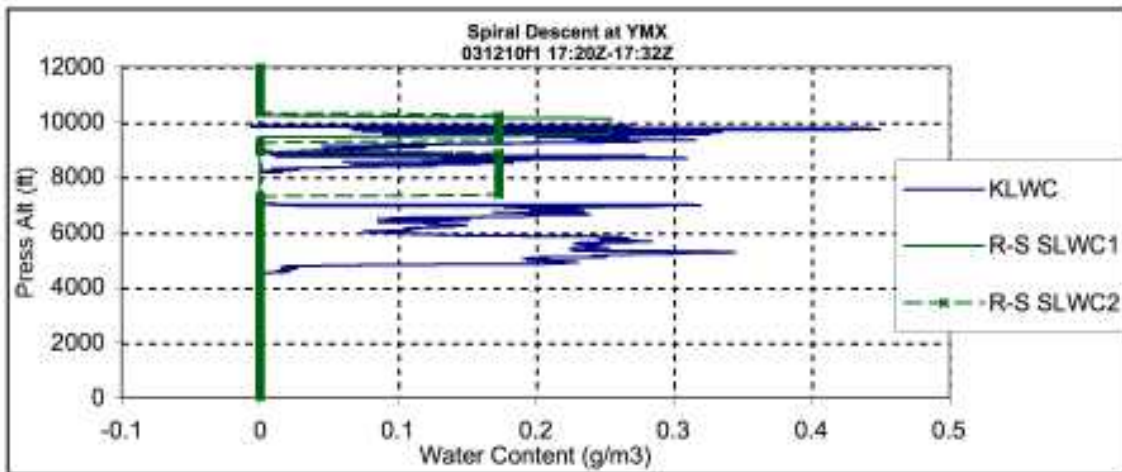


Figure 7.1.—LWC plot for December 10, 2003 between 1720 and 1732UTC.

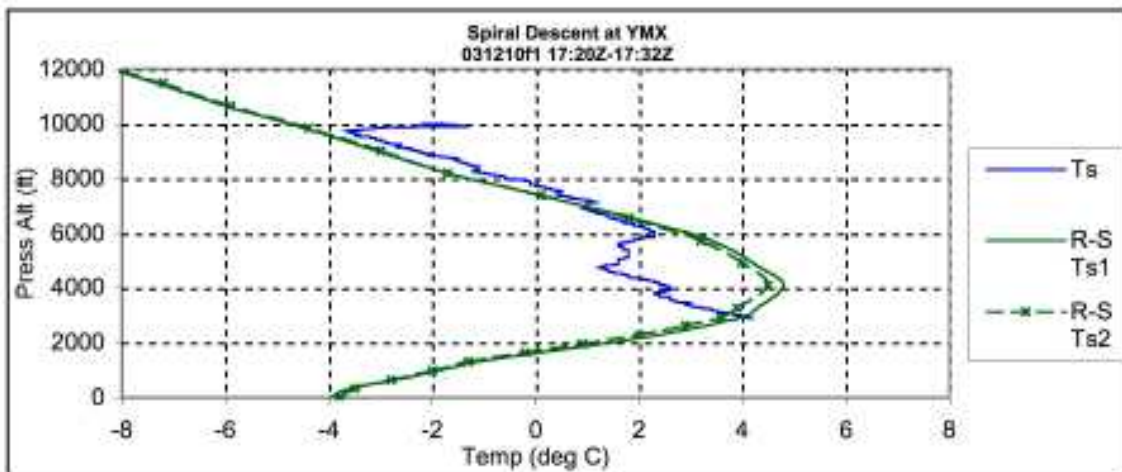


Figure 7.2.—Temperature plot for December 10, 2003 between 1720 and 1732UTC.

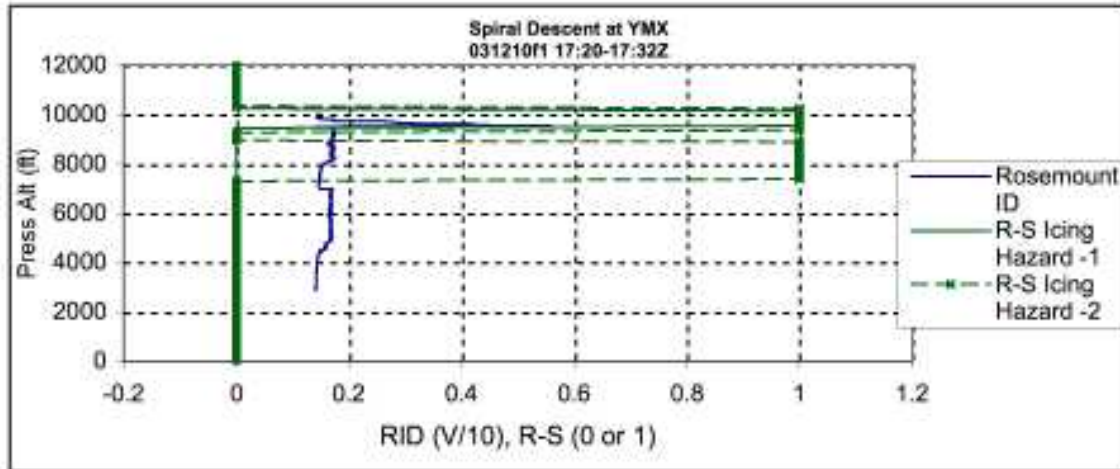


Figure 7.3.—Icing Hazard plot for December 10, 2003 between 1720 and 1732UTC.

Conclusion

Based upon a review of the data from AIRS II, several issues become apparent.

First, the LWC calculation used by the remote sensing system is obviously too simplistic to accurately measure icing clouds. The primitive liquid parsing scheme should be improved to take into account more knowledge of the cloud structure either from the cloud reflectivity or basic cloud physics.

Second, the difference between aircraft measured and remotely sensed temperature profile must be addressed. Either a safety margin must be added to the determination of the cloud freezing level, or the temperature profile must be further refined, or both.

Third, the comparison dataset is quite small. The conclusions of the comparisons made here should not yet be assumed to be valid for a larger sample size. Additional measurements are required to determine the validity of the first two shortcomings. It is particularly interesting that despite the apparent inaccuracy of temperature measurements that the identification of icing hazards was so good. Perhaps the temperature sensing technique is valid in regions of icing conditions. Or perhaps the small sample size just happened to not include a case where this became a factor.

Despite these apparent shortcomings, for the comparisons presented here from the AIRS II field project between flight measurements and those of the NASA Icing Remote Sensing System, the remote sensing system identified all cases where aircraft icing was present and conservatively bounded the altitude ranges where the icing occurred. Therefore, the basic methodology utilized by the NASA Icing Remote Sensing System is deemed to be acceptable for further evaluation and development.

The next major steps in the development of useful icing condition remote sensing technology, as currently envisioned, are to (1) convert the current software to near real-time processing to allow a system output of current icing hazard, (2) refine the physics models used for defining the boundaries of clouds, distributing the liquid water, and producing the temperature profile, and (3) begin developing the dissemination methodology.

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