7B.3

USING KA-BAND DOPPLER FALL VELOCITY SPECTRA TO ENHANCE NASA'S ICING REMOTE SENSING ALGORITHM

David J. Serke [a*], Andrew L. Reehorst [b] and Marcia K. Politovich [a]

[a] NCAR- National Center for Atmospheric Research
Research Applications Laboratory
Boulder, Colorado

[b] NASA Glenn Research Center
Cleveland, Ohio

1. INTRODUCTION

In-flight icing is a significant hazard to the aviation industry. In-flight icing occurs when supercooled liquid water (SLW) comes in contact with and freezes to the leading surfaces of an aircraft, which can significantly alter the aircraft's aerodynamic properties. In-flight icing increases the amount of weight and drag on the aircraft, which reduces the lift. Airborne detection hardware have significant technical hurdles related to forward looking radiative transfer that have yet to be addressed. A ground-based detection system that can provide information to all aircraft entering and departing a terminal area (Fig. 1) will be a key element in facilitating icing avoidance in the future.

The NASA Icing Remote Sensing System (NIRSS) (Reehorst et al., 2006) is a prototype hazard detection platform that integrates three vertically pointing sensors. Integrated liquid water (ILW) and atmospheric

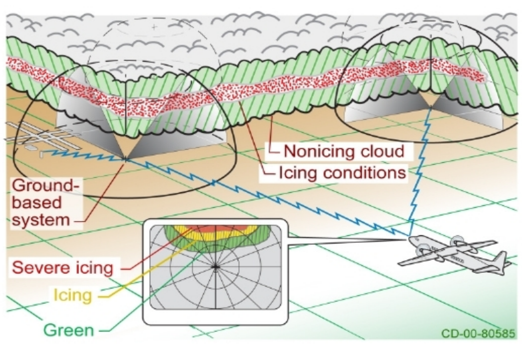

***Figure 1**. NIRSS in-flight icing detection concept.*

**Corresponding author address: David J. Serke, National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307, serke@ucar.edu*

temperature profiles are derived using the microwave absorption and emission characteristics collected from a Radiometrics Corporation multi-channel microwave radiometer (Solheim et al., 1998). A Vaisala laser ceilometer, is used to define cloud base heights, while a Metek K_a-band radar is used to delineate cloud top and base heights. NIRSS's internal logic distributes ILW within cloud layers that are between 0 and -20°C using combinations of temperature and reflectivity dependant liquid profiles and wedge shaped liquid profiles. These combinations are based on previous experience with liquid profiles collected with icing research aircraft (Politovich et al., 1995).

The overall goal of NIRSS is the development of a in-flight icing warning system for the airport environment that utilizes existing, relatively inexpensive, off-the-shelf technologies. For the past several years, the development of NIRSS has focused on upgrading the software infrastructure, field testing and development of system capabilities. Some of these system developments have included comparison of the characteristics of radar profiles at icing and non-icing times as determined by icing research flights (Serke et al. 2009), field testing a new 1° beamwidth scanning radiometer (Serke et al., 2010) and the discrimination of supercooled large drops by combining radiometer and radar data (Serke et al., 2010). A study comparing NIRSS icing severity to the National Center for Atmospheric Research's 'Current Icing Product' and pilot reports of icing severity (Johnston et al., 2010) was also conducted. Several other studies have used NIRSS output as verification for their own icing development studies (Spangenberg et al., 2010, Smith et al., 2010, Smith et al., 2011, and Ellis et al., 2011). All of these developments have significantly advanced the utility of NIRSS towards the project's goal of optimal cost-effective detection of in-flight icing hazard.

Recent research (Luke et al., 2010 and Kollias et al., 2011) has shown that certain morphological features in profiles of Doppler spectra from millimeter wavelength radars correspond to supercooled drizzle drops in the presence of cloud-sized particles and/or larger ice crystals. The ability to detect the presence and range from ground-based remote sensors of mixed-phase conditions is crucial to our ability to accurately warn on in-flight icing hazard. The goal of this study is to test the utility of ingesting realtime Ka-band Doppler spectra into NIRSS for detecting SLW. Combining reflectivity and velocity moment analysis within NIRSS should allow for refined SLW ranging through improved hydrometeor classification.

In the next section (Section 2), the collection and realtime ingest of spectral data from NIRSS is discussed. Section 3 highlights a spectral processing and statistical analysis package developed by Department of Energy researchers for detection of bimodal fall velocity detection of SLW. The next section (Section 4) shows how layers of SLW mixed within ice clouds can be detected by the NIRSS testbed through a case study example from the 2010 field campaign. A summary of the authors' findings is presented in Section 5.

2. NIRSS DATA COLLECTION AND INGEST

During the winter of 2010, the mobile NIRSS platform (Fig. 2) was positioned at Platteville, CO to collect icing cases alongside polarized research S-band radars (Serke et al., 2011). At the very end of the field campaign period, the authors began collecting full K_a-band spectral data for select cases. Spectral data volumes are on the order of 3.5 gigabytes per day. This large data volume created problems in terms of ingesting and processing spectra, especially for a system designed to operate in realtime such as NIRSS. For this reason, spectral data was not previously collected. With the development of the processing utilities described briefly in the introduction and in more detail in Section 3, the authors have developed an ingest scheme which reads in binary format time-stamped raw spectral fields once per minute. The code keeps track of the position of the last scan read so that it can effectiviely 'fast forward' to new data as it becomes available. Once a new data block is ingested, the reflectivity profile is scanned for altitudes where values are below the minimum detectable. These times and heights get no spectral processing. Spectral processing is currently run in Interactive Data Langauge, and that code would have to be transcribed to C++ in order to be merged into a realtime NIRSS environment. For current archival mode proof-of-concept purposes, the spectral processing routines described in Section 3 are run in the Interactive Data Language environment.

Figure 2. *Image of the NIRSS hardware located at the Platteville, CO field location in 2010.*

3. SPECTRAL PROCESSING

The power that is returned to a radar is the sum of the combined signal from all distributed targets within the radar volume. These returned powers have associated velocities, otherwise known as the Doppler spectrum. Millimeter wavelength radars such as NIRSS's K_a-band are highly sensitive to small cloud drops and small ice due to superior clutter performance, narrow beamwidth and high peak power. Any spectral processer needs to work off a microphysical model (particle

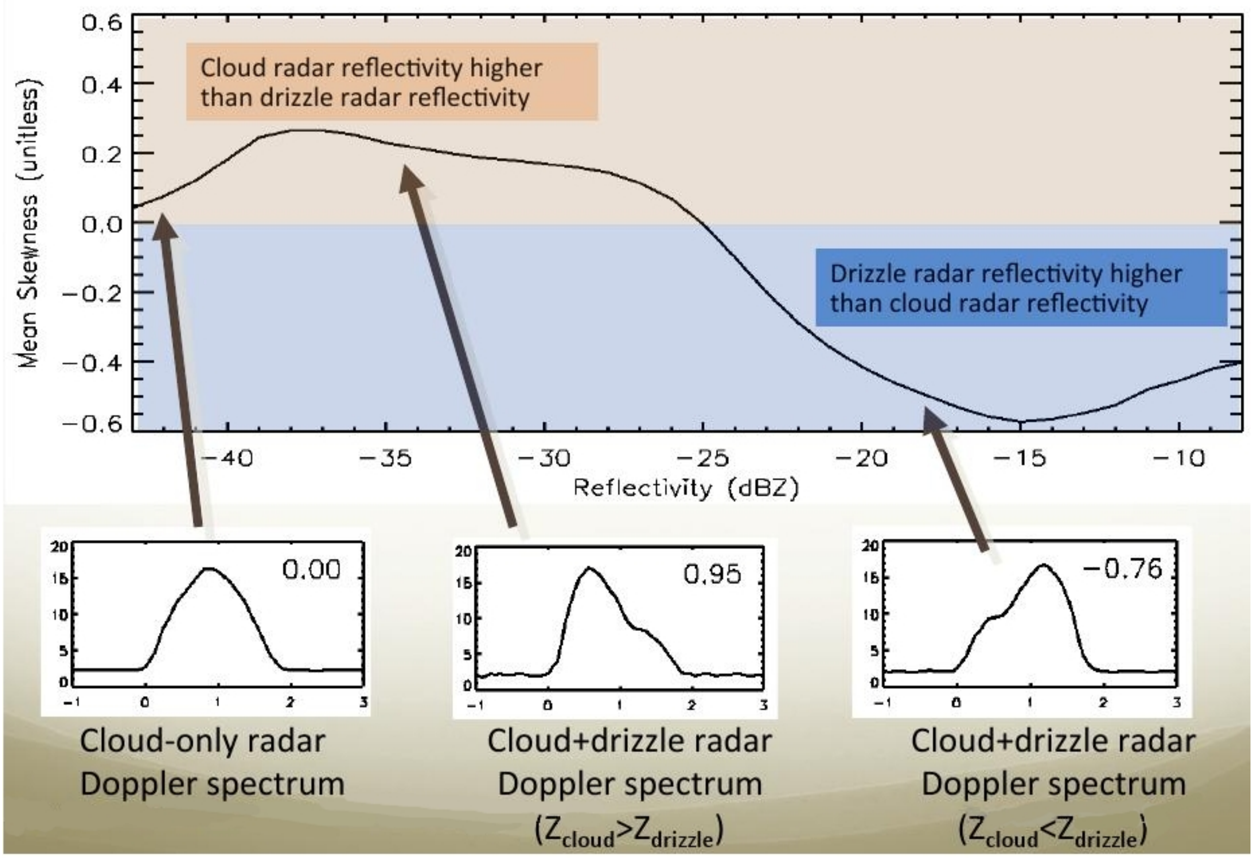

Figure 3*. Doppler velocity spectra skewness versus reflectivity for K_a-band radar .*

size, phase, density and velocity), an electrmagnetic forward model (wavelength dependent scattering, absorption and dielectric properties), and information specific to the instrument (transmit and receive parameters, pulse and antenna patterns and signal filters used). For this study, the authors chose to work with a spectral processer outlined by Kollias et al. 2011, parts 1 and 2. For millimeter wavelength radars, spectra are somewhat related to particle size, but vertical motions on all size scales keep this relation from being directly correlated. Synoptic scale mean vertical motions act to shift spectral distributions from the zero velocity line. Turbulence broadens or smears a sampled volume and makes the velocities look Gaussian, when in fact that shape is not necessarily due to the properties of the particle distribution.

The processer searches for and utilizes clear air scattering spectra to provide knowledge on wind speed and the strength of turbulence (May and Rajopadyaya, 1996), while hydrometeor spectra are used to detemine the distribution of particle sizes and their fall velocities. Luke et al. 2010 found that any deviation from a unitless Gaussian skewness of 0.0 gives important information on the presence of small (< 50 µm) or large (> 50 µm) droplets (Fig. 3). This information, combined with radiometer temperature profiles from NIRSS can help refine the range of SLW within the NIRSS algorithm. A sample case study which utilizes this technique is discussed further in the following sections.

4. CASE STUDY: MAY 18th, 2011

An icing case study is presented to illustrate how the spectral velocity data could be used in NIRSS to enhance in-flight icing detection. Weakly convective spring-like conditions existed through the afternoon on this day, as evidenced by reports of thunder in the area of DIA from 20:00 to 23:00 UTC, 38 km distance from NIRSS's location. Temperature profiles from the radiometer at 19:59 UTC and from balloon sondes four hours later at Denver International Airport (DIA) showed the freezing height at roughly 1.5 km AGL altitude. No measurable precipitation was recorded during the day at DIA's automated reporting station or from the distrometer located at the NIRSS site. At 19:59 UTC, the vertically pointing NIRSS radiometer was indicating 0.25 gm^{-2} of integrated liquid above the instrument.

The full velocity spectral profile from 19:59 UTC is shown in Figure 4, left column. Fall velocity spectra (right column, labeled A, B and C) are horizontal slices at a given height of the full velocity spectral profile shown at the left. The strongest uncalibrated powers, shown in red, are located within the 'all ice' conditions above the melting level from 1.5 km to 5.5 km AGL. A typical 'all ice' spectrum is shown in Fig. 4A, with a higher mean maximum noise floor (horizontal magenta line) at 19 dB and a significantly downward (positive, right of green dashed neutral velocity vertical line) velocity. At 6.1 km AGL (Fig. 4B), the spectral power is nearly Gaussian and centered near zero ms^{-1}, indicating all cloud particles. The noise floor is much lower due to a lack of scattered power from larger ice particles. From 6.5 to 7.5 km AGL (Fig. 4C), the spectra evolve into a more complex bi-modal distribution, with the primary peak at +1 ms^{-1} and the secondary peak at -2.5 ms^{-1} (indicated as mean vertical velocity at this altitude, w). The secondary peak are cloud particles, smeared into a somewhat Gaussian shaped distribution by microscale turbulent diffusion. The cloud population is shifted toward rising motion by larger scale dynamic forcing. This forcing at cloudtop level is also responsible for supercooled drizzle particle production, which is evident as the primary spectral peak. Right and left-hand mean spectral slopes are calculated from the noise floor to the maximum value of the primary peak, and the skewness is calculated from these respective slopes. The negative skewness shown in Fig. 4C is very similar to the spectral signature is shown in Fig. 3C, and can be found within a realtime version of NIRSS by employing the spectral ingest, processing and statistical approaches highlighted in this research.

It has been shown through the spectral processing research described in Section 3 and from the case study discussed in this section with NIRSS data that K_a-band spectra can be used to detect and flag heights with bimodal fall spectra associated with SLW. The current version of NIRSS algorithm (Fig. 5, top) checks for ILW from the radiometer then checks if there is radar return above the minimum detectable at heights where the radiometer temperature profile is between 0 and -20^o C. If both of these conditions are met, the ILW is distributed in the vertical based on fuzzy logic weighted combinations of four different profiles. These profiles are a wedge-shaped, temperature-dependant, reflectivity dependant and uniform with height profiles, with weights shown in the figure. With the addition of bimodal fall velocity detection described in previous sections (Fig. 5 bottom), the wedge-shaped profile weighting is distributed only through the flagged heights. The rest of the liquid is distributed in the same manner as was described previously. Liquid tends to exist in wedge-shaped profiles in nature (Politovich et al., 1995), so confining the majority of radiometer detected liquid to wedge profiles based on bimodal spectral flagging should logically lead to more realistic SLW profiles, and thus more realistic NIRSS in-flight icing hazard quantities.

In finding heights with the spectral processor for the May 18th case study at 19:59 UTC that exhibited significant skewness due to overlapping bimodal spectral power, a flag is set (Figure 6, left) to the value of one. The current NIRSS LWC profile at this time, as described at the top of Fig. 5, is shown in blue on the right side of Fig. 6. A model of the prototype NIRSS LWC profile, as described at the bottom of Fig. 5, is shown in red on the right side of Fig. 6. The integrated liquid is the same under both curves, but the spectral LWC distributes 50% of the liquid within a more confined area as determined by the heights at which the spectral flag equals unity.

Another improvement to NIRSS that arises out of this spectral processing work is reducing the algorithm's reliance on a hardcoded temperature minimum for bounding the presence of in-flight icing. Currently, icing is defined when liquid is detected between 0 and -20^0 C. In this case, -20^0 C is detected by the radiometer at about 6.5 km AGL, so the LWC profile is capped at that height.

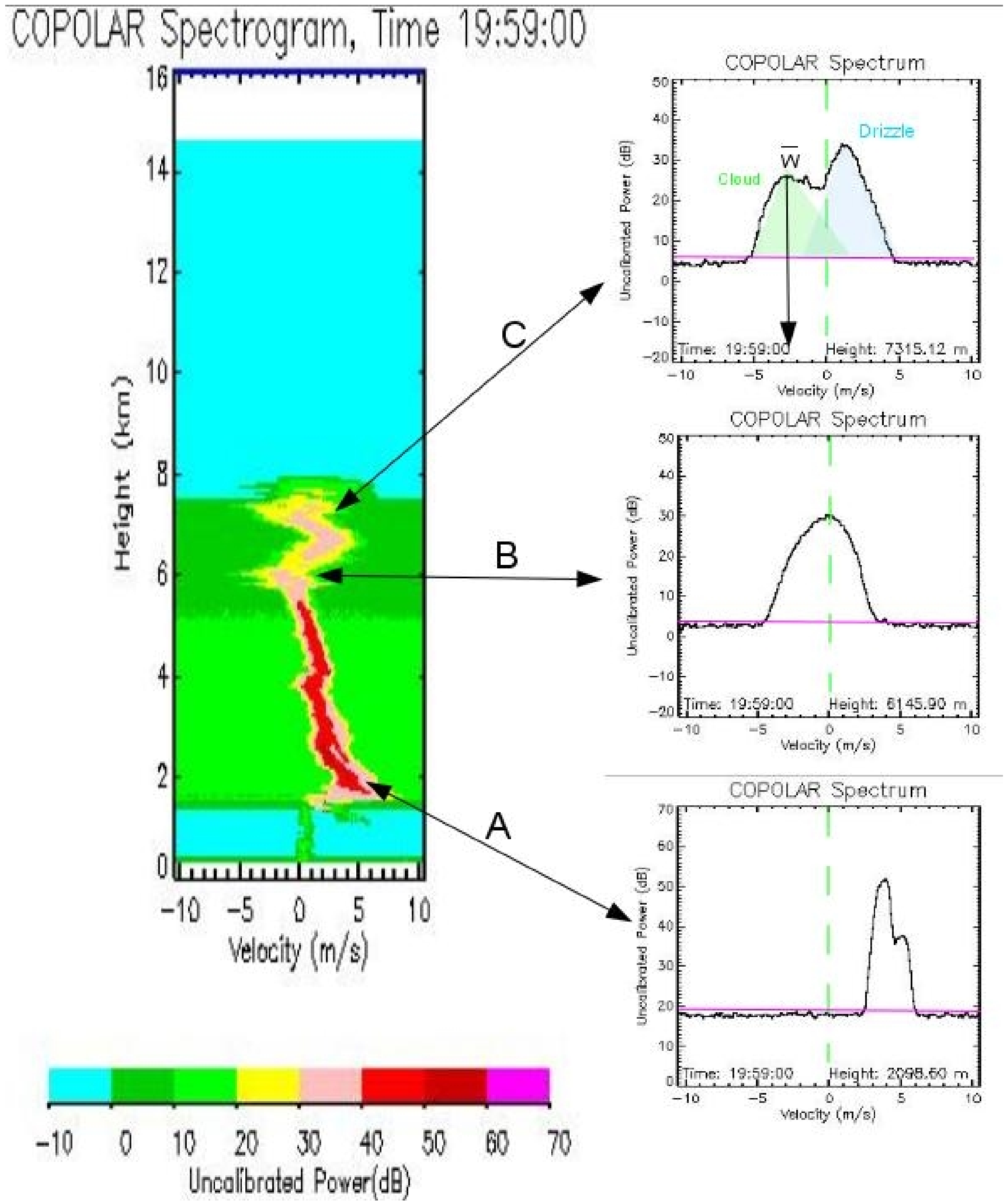

Figure 4. *Doppler velocity spectral profile from K_a-band at 19:59 UTC (left) on May 18th, 2011. Snow spectra above the melting level (A) at 2.1 km altitude AGL, gaussian cloud particle spectra (B) at 6.1 km AGL and a drizzle (C, blue triangle) mixed with cloud particle (C, green triangle) spectra at 7.3 km AGL. Maximum mean noise floor shown with horizontal magenta line. Neutral velocity shown as vertical green dashed line.*

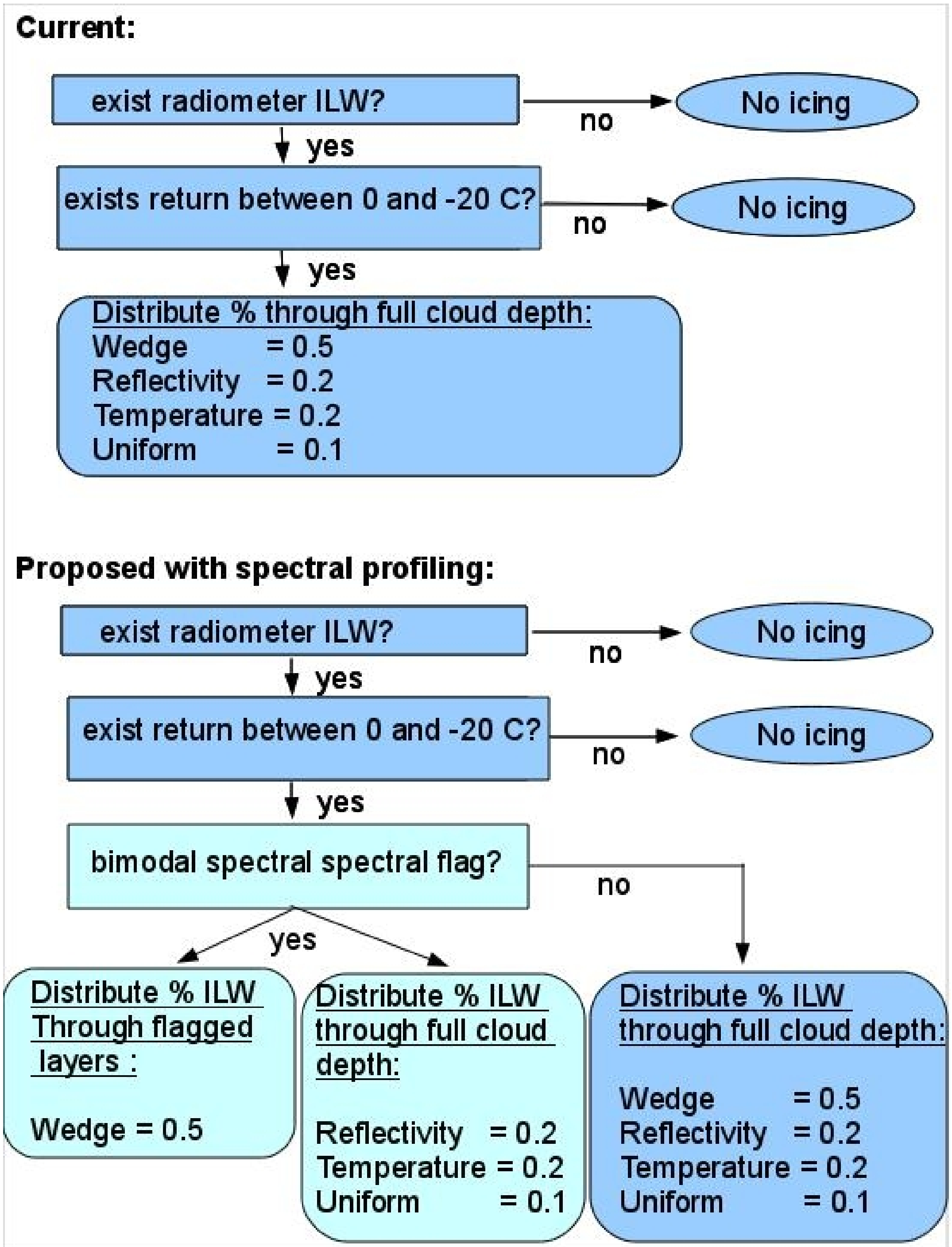

***Figure 5**. Simplified version of relevant NIRSS internal logic for current algorithm (top) and the proposed algorithm upgrade with doppler fall velocity processing and bimodal flagging (bottom, additions shown in green boxes).*

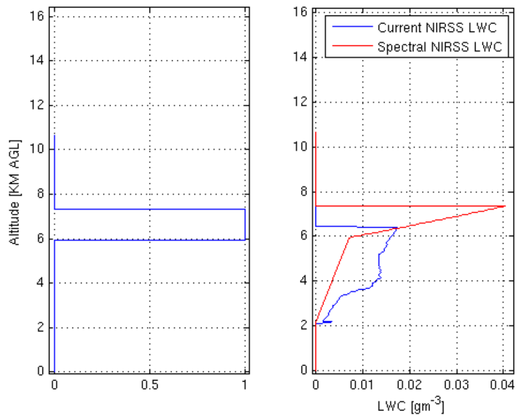

Figure 6. *Bimodal spectral flag value versus altitude (left) and current NIRSS LWC profile (right, blue) with proposed spectral-based NIRSS LWC profile (red) at 19:59 UTC on May 18th, 2011.*

The spectral processing indicates the height of significant skewness and thus bimodality extends up to 7.3 km AGL. In this way, the presence of supercooled liquid should be defined in the NIRSS logic by the microphysical information captured by the fall velocity spectra and not a rigid, somewhat arbitrary temperature threshold.

5. SUMMARY

In-flight icing detection is a top priority for the aviation safety community. NASA's ground-based Icing Remote Sensing System combines the strengths of several off-the-shelf, existing instrumentation to detect, range and quantify in-flight icing hazards. Many software and hazard detection logic upgrades have been incorporated into the system in the last few years to enhance the system's flexibility, reliability and skill in detecting icing and non-icing conditions above the system. This work gives a case study example of how further upgrades to the ranging of detected supercooled liquid can be enhanced through utilization of the K_a-band radar's voluminous Doppler velocity spectra. By creatively ingesting the huge files and carefully processing out known spectral artifacts, detection of overlapping bimodalities in the processed Doppler spectra is possible. This is done by searching particle distribution skewness at each height and at roughly every minute, to detect supercooled drizzle layers within and above 'all ice' cloud layers.

Future work on this path includes further data collection and archival case study mode testing. A significant engineering effort to code this processing and analysis scheme into NIRSS for realtime operations would be required. A flight campaign involving a research aircraft outfitted with a full compliment of calibrated particle sensors flying over NIRSS is needed to test the validity of functionality discussed in this work, as well as the functionality that has been added recently as discussed in the introduction section.

6. ACKNOWLEDGEMENTS

This research is supported by the NASA Aviation Safety Program under the Atmospheric Environment Safety Technologies (AEST) project. The views expressed are those of the authors and do not necessarily represent the official policy or position of the NASA. The authors would like to thank Matthias Bauer-Pfundstein for his help with the K_a-band radar processing and Karen Johnson for her help with the radar spectral processor.

7. REFERENCES

Ellis, S., Serke, D. J., Hubbert, J.., Kennedy, P., and Albo, D., 2011: In-flight icing detection using S-band dual-polarimetric weather radar data, AMS Radar Conference Preprint, Sept. 26-30, Pittsburgh, PA.

Johnston, C., Serke, D. J., Adriaansen, D., Reehorst, A., Politovich, M. K., Wolff, C. and McDonough, F., 2011: Comparison of in-situ, model and ground based in-flight icing severity, AMS Preprint, Jan. 24-27, Seattle, WA.

Kollias, P., Rémillard, J., Luke, E., and Szyrmer, W., 2011: Cloud radar Doppler spectra in drizzling stratiform clouds:1. Forward modeling and remote sensing applications, J. Geophys. Res., 116, D13201, [DOI:10.1029/2010JD015237].

Kollias, P., Szyrmer, W., Rémillard, J., and Luke, E., 2011: Cloud radar Doppler spectra in drizzling stratiform clouds:2. Observations and microphysical modeling of drizzle evolution, J.

Geophys. Res., 116, D13203, [DOI:10.1029/2010JD015238].

Luke, E., Kollias, P. and Shupe, M., 2010: Detection of supercooled liquid in mixed-phase clouds using radar Doppler spectra, J. Geophys. Res.,115, D19201, [DOI: 10.1029/2009JD012884].

May, P., and Rajopadhyaya, D., 1996: Wind profiler observations of vertical motion and precipitation microphysics of a tropical squall line, Mon. Wea. Rev., 124, pp. 621-633.

Politovich, M., Stankov, B., and Martner, B., 1995: Determination of liquid water altitudes using combined remote sensors, J. Appl. Meteor., 34, pp. 2060-2075.

Reehorst, A., Politovich, M. K., Zednik, S., Isaac, G. A., & Cober, S., 2006: Progress in the Development of Practical Remote Detection of Icing Conditions (NASA/TM 2006-214242). NASA.

Rogers, R. R., M. K. Floyd, 1989: A short course in cloud physics. Pergamon Press, Oxford England.

Serke, D., J., Reehorst, A., and Politovich, M. K., 2010: Supercooled large drop detection with NASA's Icing Remote Sensing System, SPIE Remote Sensing Preprint, Sept. 19-22, Toulouse, FR.

Serke D. J., M. K. Politovich, A. Reehorst and A. Gaydos, 2009: Use of X-band radar to support the detection of in-flight icing hazards during AIRS- II, J. Atmos. Remote Sensing, January 1st [DOI: 10.1117/12.837080].

Serke D. J., F. Solheim, R. Ware, M. K. Politovich, A. Reehorst Kennedy and Bowie, 2010: A new Narrowbeam, Scanning Radiometer and its application to the detection of in-flight icing hazards, ARAM Preprint, Atlanta, GA, Jan. 18-21.

Smith, W., Minnis, P., Fleeger, C., Spangenberg, D., Serke, D. and Reehorst, A., 2011: New methods to infer aircraft icing conditions using satellite data, SAE Preprint, June 13-17, Chicago, IL.

Smith, W., Fleeger, C., Minnis, P., Spangenberg, D., Palikonda, R., Serke, D. and Reehorst, A., 2010: Evaluation of cloud parameters and in-flight icing estimates derived from satellite using the NASA Glenn Icing Remote Sensing System, 13th Conference on Cloud Physics, June 28th, Tacoma, WA.

Solheim, F., Godwin, J., Westwater, E., Han, Y., Keihm, S., Marsh, K., and Ware, R., 1998: Radiometric profiling of temperature, water vapor and cloud liquid water using various inversion methods, Radio Sci., 33, pp. 393-404.

Spangenberg, D., Fleeger, C., Smith, W., Palikonda, R., Chang, F., Serke, D. and Reehorst, A., 2010: Determining the effects of ice crystals on a satellite-based in-flight icing threat product in single-layer and multi-layer cloud conditions, 13th Conference on Cloud Physics, June 28th, Tacoma, WA.