2B.6 IN-SITU VERIFICATION OF REMOTE AIRCRAFT ICING DETECTION USING S-BAND POLARIZATION RADAR MEASUREMENTS

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1. Introduction

The presence of supercooled large drops (SLD) at temperatures below 0^o C poses a significant threat to aviation safety. SLD are subject to contact freezing or riming when they come into direct contact with an aircraft. The result is the formation of ice, disrupting the airflow around aircraft. SLD typically occur at temperatures of 0 to -20^o C, with droplets between tens of microns to over one millimeter in diameter (Vivekanandan et al. 2000).

A comprehensive icing detection system should be sensitive to both pure liquid and mixed phase conditions. In order to avoid aircraft icing encounters, ground-based remote detection of SLD over the range of the airport approach patterns is desirable.

Effective ground-based remote icing detection techniques have been proposed using highly sensitive cloud radars (Vivekanandan et al. 2000; Reinking et al. 2000). However, the maximum range coverage of cloud (millimeter wavelength) radars is smaller than a typical S-band radar. Cloud radars also suffer from of Mie scattering effects and attenuation in the presence of precipitation sized hydrometeors.

Recent studies have shown the utility of polarimetric radar measurements to distinguish between different hydrometeor types (Doviak and Zrnic 1993; Straka et al. 2000; Vivekanandan et al. 1999; Ellis et al. 2000). Preliminary studies to verify hydrometeor identification algorithms using in-situ aircraft measurements have shown encouraging results (Ellis et al. 1999; Goeke et al. 2000).

In this paper we evaluate the potential of remotely detecting icing conditions with a polarimetric S-band radar. To accomplish this, radar data and fuzzy logic particle classifications (Vivekanandan et al. 1999) are compared to in-situ aircraft microphysical data. Once the radar characteristics of icing conditions are more fully understood, the fuzzy logic algorithm is easily optimized. Aircraft/radar comparisons are performed using in-house software that objectively matches aircraft location to the closest radar measurement in time and space. Using the objective matching algorithm allows larger quantities of data to be compared much more easily and reliably than manual methods.

The NCAR S-Pol radar has recently been deployed in the Mesoscale Alpine Precipitation (MAP) study in northern Italy in coordination with instrumented aircraft. On September 20, 1999 NCAR's Electra aircraft flew a mission through stratiform precipitation and measured numerous icing events using the Rosemont icing probe. In this paper we present preliminary results of the objective radar/aircraft comparison.

This study is part of a continuing effort to verify the polarimetric radar signature of icing conditions and the particle classification algorithm performance. This technique is unlikely to replace cloud radars for detecting aircraft icing due to the higher sensitivity of cloud radars. However, S-band polarimetric radars are well suited for discriminating the precipitation sized particles that produce serious problems for cloud radars due to Mie scattering and signal attenuation. Also, the WSR-88D radar network covers numerous airports and is due to be upgraded with dual-polarimetric capabilities. The current C-band Terminal Doppler Weather Radar (TDWR) network could be similarly converted in the future. It may be feasible to combine the data from cloud radars and weather radars to obtain more complete remote aircraft icing detection.

2. Polarimetric signature of icing conditions

The S-Pol radar alternately transmits horizontal and vertical polarized radiation, while simultaneously receiving both. In addition to the standard reflectivity factor (Z_{HH}), the radar measures differential reflectivity (Z_{DR}), linear depolarization ratio (LDR), correlation coefficient (ρ_{HV}), and specific differential phase (K_{DP}). The measurements depend on: particle size, shape, and orientation, phase (liquid or solid) and bulk density.

Differential reflectivity is the ratio of the horizontal co-polar (horizontal transmit, horizontal receive) received power to the vertical co-polar return and can be viewed as the power-weighted mean axis

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ratio of the particles in the observed volume. Liquid drops falling at equilibrium are deformed by aerodynamic forces into an oblate shape, and their oblateness is directly proportional to size. Small drizzle and cloud drops remain spherical resulting in near zero Z_{DR} and small Z_{HH}, while larger drops have larger Z_{HH} and Z_{DR} values (0.3 - 2.0 dB).

Correlation coefficient (ρ_{HV}) is the correlation between horizontal and vertical co-polar received signals. Decorrelation occurs in wet or tumbling particles and mixed phase conditions resulting in ρ_{HV} values < 0.96. Pure rain and pure ice both result in ρ_{HV} values > 0.98.

For automated icing detection we use the full suite of observations, as well as a temperature profile, in a fuzzy logic framework (Vivekanandan et al. 1999). Clearly, Z_{DR}, ρ_{HV} and LDR play prominent roles in identifying icing conditions. Unfortunately, low density snow and ice crystals may not have measurable polarization signatures due to the signals' sensitivity to particle density (refractive index). In that case, the polarimetric signature of snow/ice will be very similar to that of small drizzle and cloud drops.

In real time, the temperature profile is typically obtained using a proximity sounding. Often the time and space separation of sounding to the region of interest limits the validity of the temperature profile. In order to alleviate this discrepancy an automated melting layer detection algorithm has been developed. The height of the 0^{o} C isotherm can then be inferred from the computed brightband level.

3. Results and aircraft-radar comparisons

Ellis et al. (2000) showed two examples from the PRECIP98 field experiment conducted on the east coast of Florida in late summer 1998. The University of North Dakota's Citation aircraft penetrated a small convective turret at a temperature near -10^{o} C. During the cloud penetrations the aircraft encountered supercooled large drops (SLD) and mixed phase icing conditions. The multi-parameter signatures from the S-Pol observations were consistent with the aircraft data. Further, the fuzzy logic hydrometeor classification algorithm successfully identified both the pure SLD and mixed phase conditions. In those cases the particles were relatively large, resulting in reflectivity (Z_{HH}) values of approximately 25 to 30 dBZ. For this range of Z_{HH}, low density ice was unlikely to be the dominant species and did not confound the polarimetric signatures.

The Electra research aircraft, equipped with particle imaging instruments (PMS), Rosemont icing probe and standard measurements (temperature, altitude, wind, etc.), flew numerous missions during the 1999 MAP field program. On the September 20 flight, several mild icing episodes occurred within the S-Pol radar's volume scans at temperatures near -15^{o} C. Figures 1 and 2 show results of the radar/aircraft data matching software for segments of the flight when icing occurred. Plotted are aircraft icing rate (mm/s) computed from the Rosemont probe, Z_{HH} (dBZ), Z_{DR} (dB) and ρ_{HV} versus time (in sec.). Following Liu et al. (1994), ρ_{HV} was corrected for the effects of low signal-to-noise ratio. The cross-polar power was mostly in the noise, meaning the LDR measurements were not available.

The icing rate was computed from the airborne in-situ Rosemont probe observations. The probe detects the presence of super-cooled liquid using a vibrating rod. Only super-cooled liquid accretes to the rod whereas the ice particles bounce off the sensor. As the liquid water freezes onto the sensor, its vibration frequency is reduced. The change in frequency is proportional to icing rate. When accretion reaches the maximum limit, the probe is heated to remove the ice before the next measurement cycle.

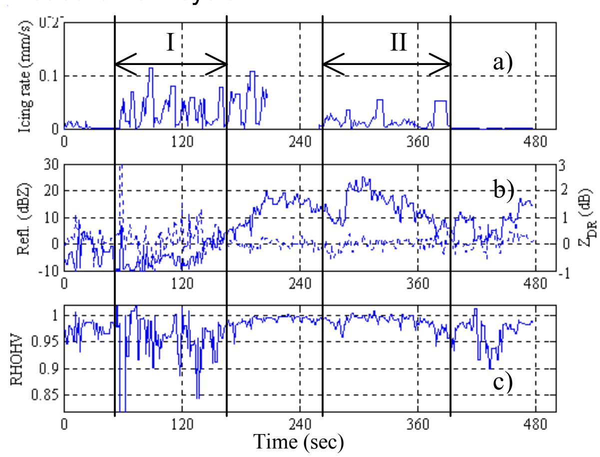

Figure 1. Coincident time series plots of radar and aircraft observations. a) aircraft icing (mm/s), b) Z (dBZ, solid line) and Z_{DR} (dB, dashed line) and c) ρ_{HV}.

The data shown were matched within 3 minutes, 0.5 km in the vertical and 2.5 km in the horizontal. Air parcel trajectories were estimated using the aircraft winds to account for advection. Data are only plotted if a match was found and the signal-to-noise ratio was more than 7 dB above the noise, resulting in the time plotted in not being equal to the elapsed time. The aircraft was 20 to 100 km from the radar.

Figure 1a depicts two icing regions labelled I and II based on the icing rate derived from the Rosemont probe measurements. In region I Z_{HH} is < 0 dBZ and Z_{DR} varies between 0 and 1dB. Lower values of reflectivity suggest the mean particle size is small. The combination of low Z_{HH} and Z_{DR} > 0 dB is in good agreement with PMS probe observation of small non-spherical ice crystals. Correlation coefficient is significantly lower than unity in region I, possibly due to comparable ice and liquid reflectivity components in the radar sampling volume. Typically, the cloud liquid reflectivity is lower than 0 dBZ. Thus Z_{HH} < 0 dBZ and ρ_{HV} < 1 indicate mixed phase, or riming, icing. Reflectivity in region II is greater than 10 dBZ, Z_{DR} is near 0 dB and the corresponding ρ_{HV} is near unity. In contrast to region I, polarimetric measurements can only infer the region is dominated by irregular ice particles. The PMS data confirm the existence of larger ice crystals in region II.

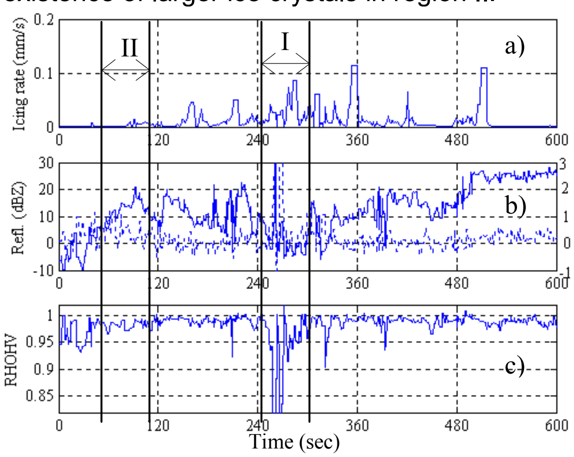

Figure 2. As in Figure 1, for a different time period.

Figure 2 is similar to Figure 1 for a different icing event. Again, region I contains Z_{HH} values near 0 dBZ, Z_{DR} between 0 and 1 dB and ρ_{HV} below unity. Ground clutter contamination is evident by the high fluctuations in Z_{HH}, Z_{DR} and ρ_{HV}. Ground clutter contamination can reduce ρ_{HV} . It is unclear if the reduction in ρ_{HV} within region I is due to the mixed phase signal or ground clutter contamination. In this case, region II contains no icing. However, the Z_{HH}, Z_{DR} and ρ_{HV} values are similar to region II in Figure 1, which contained icing. Again, the PMS data confirms the existence of larger ice crystals in region II of Figure 2.

In both cases the reflectivity values are higher (10 – 20 dBZ) in region II than in region I with mixed phase ρ_{HV} signatures. The higher Z_{HH} values and the PMS probes indicate the presence of large ice crystals (> 1.5 mm), which dominate Z_{HH} and ρ_{HV}. In this case ρ_{HV} will not be able to detect the presence of small cloud drops mixed with the larger ice particles.

4. Discussion

Preliminary analysis of the MAP and PRECIP98 data sets show that polarimetric radar has the potential to remotely detect varying aircraft icing conditions. Some of the limitations of S-band polarimetric radar for this purpose have been pointed out, but need to be more fully understood. Correlation coefficient may only be able to detect mixed phase icing conditions when the reflectivity contribution from the liquid and solid particles is comparable.

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