OBSERVATIONS OF SUPERCOOLED CLOUDS USING AIRBORNE G-BAND RADIOMETER AND W-BAND RADAR

M. Wolde[1], A. L., Pazmany[2], D. Hudak[3], J. W. Strapp[3], A. Korelev[3] and H. Barker[3]

[1]Institute for Aerospace Research, NRC, Ottawa, Canada
[2]ProSensing Inc., Amherst, MA, USA
[3]Environment Canada, Toronto, Canada

1. INTRODUCTION

There are numerous research publications focused on the development of remote sensing systems and methodologies for retrievals of cloud properties. Ground and space-based remote sensing systems now routinely provide quantitative estimation of precipitation amount and types for operational and research applications. However, there is still a need to develop or improve existing retrieval techniques by combining new systems such as CloudSat and CALIPSO satellites. Often, validation of ground and space based remote sensing systems and model-based retrieval techniques require measurements of cloud microphysical properties and remote sensing data that are matched both spatially and temporally. Instrumented research aircraft equipped with highly sensitive radars and radiometers can provide these datasets. Aircraft measurements also have the advantage of targeting weak cloud systems that might be undetectable from ground or space based systems. For example, cloud microphysical properties such as effective radius, r_{eff} and concentration, N, of supercooled clouds are very important parameters necessary for characterizing liquid cloud properties. These parameters are needed to estimate the energy feedback mechanism between liquid clouds and the boundary layer or the severity of aircraft icing potential in supercooled liquid clouds, as few relevant examples. This paper highlights the use of aircraft based systems in the study of cloud structure by comparing airborne in-situ cloud microphysical data collected in a layered winter cloud system with retrieved cloud properties from a 94 GHz (W-band) cloud radar and a 183 GHz water vapour radiometer (G-band) installed on the National Research Council (NRC) of Canada Convair-580 research aircraft.

2. INSTRUMENTATION

The data used in this paper were collected during one of the flights of the Canadian CloudSat and CALPSO satellite Validation Project (C3VP) conducted between October 31, 2006 and March 01, 2007 over Ontario, Canada using the NRC Convair-580 research aircraft. The main objective of the C3VP campaign was to validate the CloudSat and CALIPSO satellite measurements using ground based as well as airborne systems. In addition, a number of weather related flights, similar to the case presented in this paper, were also conducted around Environment Canada's (EC) Center for Atmospheric Research Experiment (CARE) site located in Egbert, Ontario. This paper presents data collected using the airborne in-situ and remote sensing instruments, described below. Detailed descriptions of the C3VP campaign can be found in Hudak et al. (2006) and also on the project web site (www.c3vp.org).

Corresponding author address: Dr. Mengistu Wolde, Flight Research Laboratory, Institute for Aerospace Research, National Research Council, Ottawa, Ontario, K1A 0R6; email: mengistu.wolde@nrc-cnrc.gc.ca.

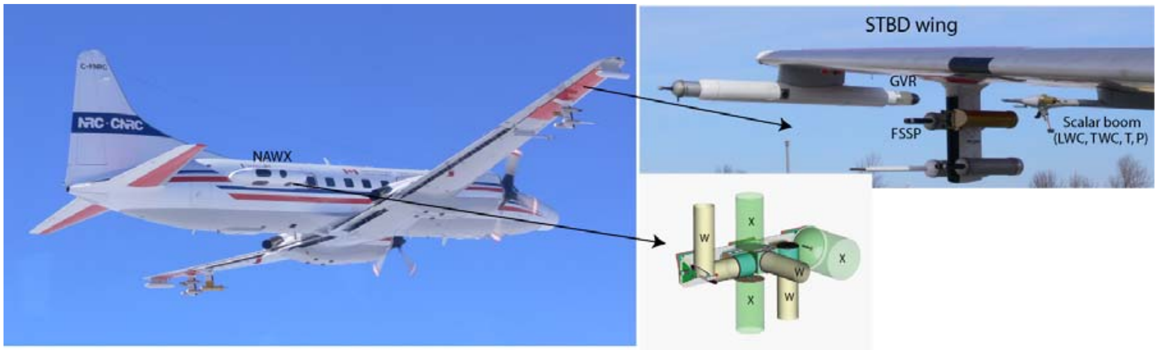

Fig. 1. During the C3VP field project, the NRC Convair-580 aircraft was equipped with an array of in-situ Cloud Physics instruments mounted in under-wing and wing-tip pylons. Schematics of the NAWX antenna configurations in the blister radome and the in-situ probes mounted on the starboard side of the aircraft including the GVR installation on the wingtip are shown in the picture.

During the C3VP field campaign, NRC and EC jointly instrumented the NRC Convair-580 with its standard suites of in-situ and remote sensing probes for atmospheric research (Fig.1). In addition, the NRC Airborne W and X-band radar system (NAWX) and a 183 GHz G-band water Vapor Radiometer (GVR), developed by ProSensing Inc. (Pazmany, 2007) were integrated on the aircraft for the first time.

The NAWX radar system (Wolde and Pazmany, 2005; www.nawx.nrc.gc.ca) has polarimetric and Doppler capabilities at both frequencies and can switch electronically between zenith, nadir and side looking antennas. Using a motorized reflector plate, the zenith W-band antenna is also capable of scanning -5° aft to +45° forward in the horizontal and vertical directions, to provide a dual-Doppler capability. The compact airborne GVR was installed on the NRC Convair-580 in a PMS-type wing-tip pod (Fig. 2). The key system parameters of the airborne GVR are summarized in Table 1. The Liquid Water Path (LWP) and Perceptible Water Vapour (PWV) were estimated from the up-looking GVR brightness temperature measurements using a neural network technique described by Pazmany (2007) and Cadeddu et al. (2007).

Fig. 2. Airborne GVR installed on the NRC Convair-580 aircraft (upper left), in a standard PMS probe canister (middle) and with the radome head removed, showing the fixed 90 degree metal mirror and the solenoid

The Convair in-situ cloud physics measurements were used when evaluating the radar and radiometer retrieval results. These include, liquid cloud particle concentrations and size measured by one of the Forward Scattering Spectrometer Probe

TABLE I
AIRBORNE GVR KEY PARAMETRERS

Frequency:	183.31 ±1, ±3, ±7 and ±14 GHz
Bandwidth:	0.5 (1), 1.0 (3), 1.4 (7) and 2.0 (14) GHz
Receiver Noise T:	1750 K (1), 1610 K (3), 1600 K (7) and 2170 K (14)
ΔT:	0.2 K @ 200 ms integration (5 Hz data rate)
Allan Deviation:	0.05 K @ 500 sec.
Measurement Rate:	up to 20 Hz with a 0.25 sec calibration gap once every 3 seconds
Antenna:	10 cm (4") Aperture, 90 deg Parabolic Metal Mirror, 1.7° BW
Radome:	Matched TPX (Polymethylpentene) Window
Weight (Probe)	10 kg (22 lb) without Canister
Power	28 W @ 115 VAC, 126 W @ 28 VDC
Data	RS422 Serial Data Stream, Notebook PC Recorder

(FSSP), Liquid Water Content (LWC) measured by King Probe, particle images measured by a PMS 2D-C Probe. For a detailed description of the NRC Convair-580 in-situ cloud physics measuring probes refer to Isaac et al. (2001).

3. RADAR/RADIOMETER RETRIEVAL TECHNIQUE

The effective radius, r_{eff} is defined in terms of the cloud drop size distribution, *n(r)* at some height, *h* as (Szczodrak et al., 2001):

$N(h) = \int_0^\infty n(r,h)dr$ and

$$r_{eff} = \int_0^\infty n(r,h) r^3 dr \Big/ \int_0^\infty n(r,h) r^2 dr .$$

The zenith pointed GVR measured LWP which is the height integrated Liquid Water Content (*LWC*), given by

$$LWC(h) = \frac{4\pi}{3} \int_0^\infty n(r,h) r^3 dr$$ and

$$LWP = \int_0^\infty LWC(h) dh .$$

In stratoform clouds, LWC may be estimated from the GVR retrieved LWP by flying the aircraft in a porpoise pattern or stepped ascent/descent through a liquid cloud depth. The zenith beam of the W-band radar samples a very similar cloud volume and for small cloud droplets, Z from the W-band can be approximated using Rayleigh scattering as the sixth moment of the drop size distribution:

$$Z(h) = 2^6 \int_0^\infty n(r,h) r^6 dr$$

From the third and sixth moment of the drop size distribution, a new, *Z*-based estimate of the characteristic cloud drop radius, r_Z may then be obtained according to:

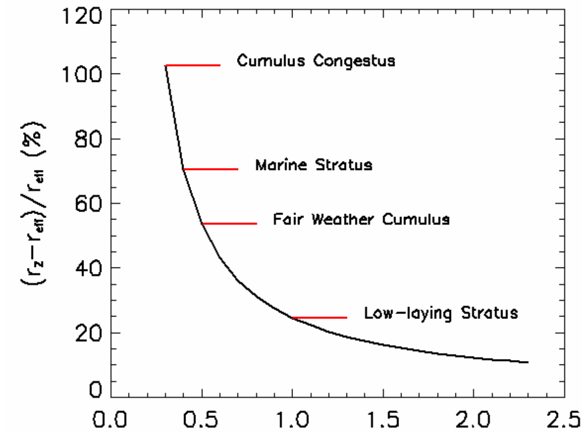

Fig. 3. Percent error between effective radius, r_{eff}, and the radar reflectivity based estimate of cloud drop size, r_Z, calculated based on the modified gamma drop-size distribution and cloud parameters tabulated in Ulaby et al. (1981) and the marine stratus distribution shape observed by Vali (1998).

$$r_Z = \sqrt[3]{\frac{\pi}{48} \frac{Z(h)}{w}} = \sqrt[3]{\int_0^\infty n(r,h) r^6 dr \Big/ \int_0^\infty n(r,h) r^3 dr}$$

The difference between r_{eff} and r_Z is primarily a function of the width of the drop size distribution and often can be estimated based on cloud type. This difference, expressed in terms of percent error in r_Z relative to r_{eff} is illustrated in Fig. 3, assuming a modified Gamma cloud drop-size distribution for a number of common cloud types. This figure can be used to estimate r_{eff} from r_Z and then to obtain the effective number density according to: $N_{eff}(h) = \frac{3}{4\pi} \frac{LWC(h)}{r_{eff}^3}$.

4. DATA

On January 26, 2007 the NRC Convair 580 made repeated measurements in two different locations over Southeastern Ontario (Fig. 4). The Convair first sampled a deep cloud system around the EC CARE site and then headed north to near Georgian Bay to sample a lake-effect storm system detected by ground radars. The aircraft made the transit from the CARE

Fig. 4. The NRC Convair-580 flight track on Jan 26, 2007. The data used in this presentation were collected between 22:29 and 24:16 UTC around Midland, Ontario, highlighted by the blue arrow.

facility to the targeted region at an altitude of 2.5 km and then made a spiral ascent (23:29-23:39 UTC) when it reached the targeted cloud system. The vertical profiles of temperature and LWC and the W-band radar equivalent reflectivity (Z) obtained from the NAWX radar are shown in Fig 5. The figures show a marked inversion layer extending from the lowest level of the aircraft height to about 3 km with regions of supercooled cloud with LWC of up to 0.6 g m^{-3} at the top of the inversion layer. The LWP estimated from the GVR show a maximum value of 0.1 mm (Fig. 6) just before the aircraft was ascending through the supercooled cloud top with low reflectivity values of less than -20 dBZ (~23:30 UTC). As indicated from the in-situ data, the base of the upper cloud layer consisted mainly of irregular ice crystals with no liquid (Fig. 6). The GVR also show very low LWP (< 0.02 mm - close to the baseline) in the upper ice clouds layer suggesting that there was no liquid above the aircraft. As can be seen from the zenith looking W-band measurements as well as the in-situ data, the upper cloud layer extended from 4 km to 8 km and was fairly uniform during the spiral ascent. In contrast, the low cloud cell started to dissipate with significant intrusion of clear air separating the upper and lower cloud systems.

After the spiral, the aircraft made five transects along a south-north line. Each of these legs were 6-8 minutes long with the aircraft mainly porposing between 2.5-5 km. Figure 7 shows the vertical Z profiles along this S-N track. The radar as well as the in-situ data presented in Fig. 6 show a change in cloud composition and thickness during the 45 minutes of sampling. In the first S-N leg, the aircraft stayed in the glaciated system, so no temperature inversion was measured during the descent. The W-band vertical Z profile clearly shows the layered clouds, with clear air at around 3 km, extended from the southern edge to mid-way of the track. At the northern edge of the track (top Panel in Fig. 7), the cloud deck extended from the surface to 8 km. In the reverse N-S track (Leg-2 - Panel 2 of Fig. 7), the cloud structure remained similar, but the aircraft sampled the clear air and went through a temperature inversion and a supercooled cloud layer. Similar to the measurements during the spiral ascent, the GVR measurements of LWP in the

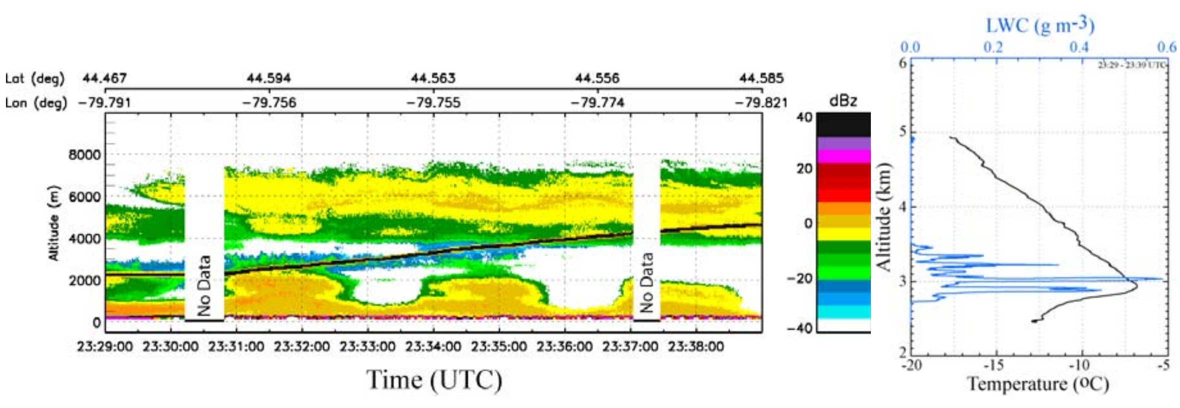

Fig. 5 Left: Vertical Profile of W-band Z measured by the NAWX zenith and nadir-looking antennas during the spiral ascent in a multi-layer cloud system. The aircraft altitude is shown by the black line. Right: vertical profiles of T (black) and LWC (blue) measured during the spiral ascent.

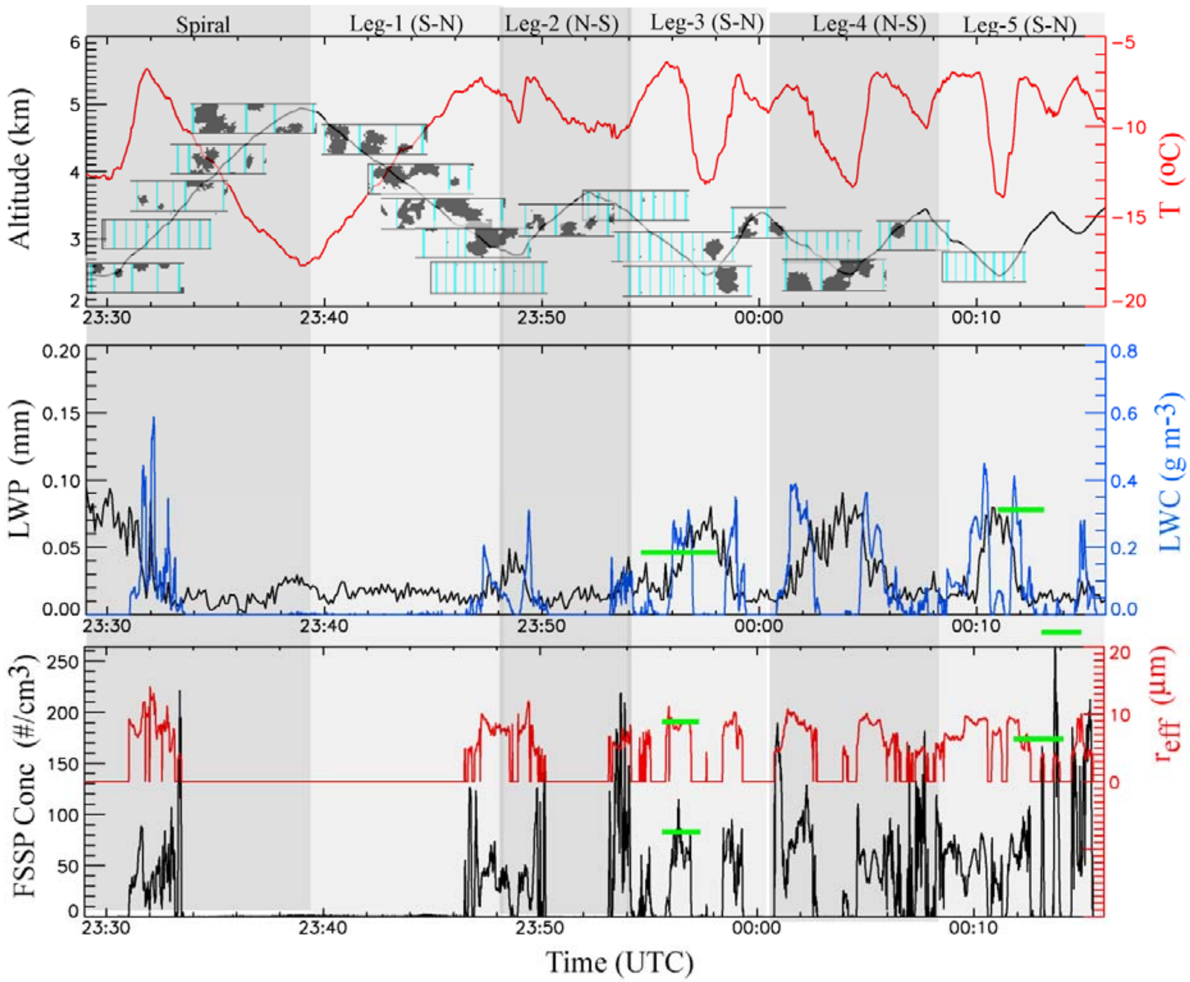

Fig. 6. Time series of in-situ and GVR measurements of the study area. Top panel: aircraft altitude (black), T (red) and examples of particle images measured by the PMS 2D-C probes (vertical scale ~ 800 μm). Middle panel: LWP estimated from GVR (black) and LWC (blue) measured by the King probe. Bottom panel: Liquid particle concentrations (black) and effective radius (red) measured by one of the FSSP probes (red). The green lines in the bottom and middle panels show retrieved values from GVR and NAWX radar data.

supercooled layer agrees very well with the in-situ data measurements (Fig. 6). The next three legs (23:50-00:16 in Fig. 6 and Panels 3-5 in Fig. 7) captured the progression of a formation/movement of a solid supercooled cloud deck at the top of the low cloud layer (~700 m thick) with LWC of up to 0.4 g m^{-3}. The GVR show a LWP of 0.08 mm at the base of the supercooled layer. The GVR LWP measurements during the porpoise maneuver in and out of the liquid layer also tells a consistent story with that of the in-situ LWC.

5. SUMMARY DISCUSSION

Examples of the cloud microphysical properties (LWC, r_{eff} and N) estimated from the GVR and NAWX radar as described in Section 3 are shown by the green horizontal line in Fig. 6 (23:57 UTC descent and 00:12 UTC ascent). The LWC values estimated from the GVR data (0.16 g/m3 in Leg-3 and 0.30 g/m^3 in Leg-5) compare well with the in situ probe measured values of 0.25 g m^{-3} and 0.4 g m^{-3}. Both the low Z values (<-20 dBZ) and the in-situ particle size data suggests the supercooled layer was dominated by small liquid drops (<100 μm in size), so the Rayleigh scattering approximation and the retrieval of particle size information and concentration outlined in Section 3 should be valid. The characteristic cloud drop radius, r_Z was

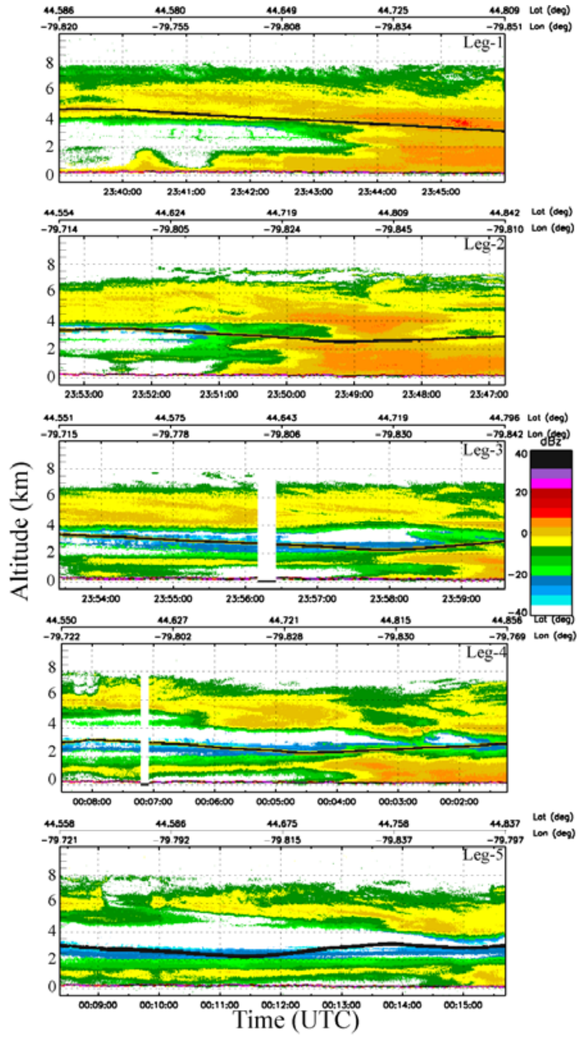

Fig. 7. Sequences of vertical profiles of Z measured by the zenith and nadir-looking W-band radar along a S-N track, while doing porpoise maneuver between 2.5 km and 4 km. The back line shows the aircraft altitude.

estimated using the measured LWC and Z values measured by the zenith-looking W-band radar data. After estimating r_Z, a 40% difference was applied to obtain r_{eff} by assuming a continental stratus cloud type, with a size distribution width between cumulus and low-lying stratus. The GVR derived r_{eff} values of 7.6 μm and 6.2 μm are within the 5-10 μm range measured by the FSSP. Finally, the effective number concentration was calculated from LWC and r_{eff}. The total particle concentrations estimate of 87 cm^{-3} in Leg-3 compares very well with the FSSP measured concentration of 80-100 cm^{-3}, while the concentration estimate of 300 cm^{-3} at Leg-5 is higher than the 100-250 cm^{-3} measured by the FSSP.

The airborne G-band radiometer and NAWX radar data presented in this paper are preliminary and more analysis will be done using a larger dataset to quantify the performance of the two instruments and to thoroughly test the retrieval algorithms described in this paper. However, the limited GVR and airborne W-band data presented in this paper are consistent with the in-situ measurements and also show promise for retrieval of liquid cloud microphysical properties from combined airborne G-band radiometer and W-band radar measurements.

Acknowledgments

The Canadian Space Agency, NRC and EC funded the C3VP field project. Many technicians, engineers and scientists from the NRC, EC and ProSensing Inc. worked tirelessly during the instrument integration on the aircraft as well as the C3VP field project flights. We would like to acknowledge NRC for providing funding for the development of the NAWX radar system as well as the integration of GVR on the NRC Convair-580. Special thanks to Yizhe Shen from Carleton University, who processed the radar data that are used in this paper.

References

Cadeddu, M. P., J. C. Liljegren and A. L. Pazmany: “Measurements and retrievals from a new 183-GHz water-vapor radiometer in the Arctic”. Trans. Geosci. and Remote Sensing, 45, 7, 2207-2215, 2007.

Hudak, D., H. Barker, P. Rodriguez, and D. Donovan: “The Canadian CloudSat Validation Project", paper presented at 4th European Conf. on Radar in Hydrology and Meteorology, Barcelona, Spain, 18-22 September, 2006.

Isaac, G.A, S. G. Cober, J. W. Strapp, A. V Korolev, A. Trembly, and D.L. Marcotte:, “Recent Canadian research on aircraft in-flight icing”. Canadian Aeronautics and Space Journal, Vol. 47, 213-221, 2001.

Pazmany, A. L. :“A compact 183-GHz radiometer for water vapor and liquid water sensing”. IEEE Trans. Geosci.. Remote Sens. Vol. 45, No. 7, pp. 2202-2206, July 2007.

Szczodrak, M., P. H. Austin, P. B. Krummel, “Variability of optical depth and effective radius in marine stratocumulus clouds” J. Atmos. Sci., Vol 58, pp. 2912-2926, 2001.

Ulaby, F. T., R. K. More and A. K. Fung: "Microwave Remote Sensing", Vol. 1, *Addision-Wesley Publishing Co.,* 1981.

Wolde and Pazmany: "NRC Dual-frequency airborne radar for atmospheric research", paper presented at the *32nd Conference Radar Meteorology, Albuquerque, NM, 24-29 October, 2005.*

Vali, G., R. D. Kelly, J. French, S. Haimov, D. Leon, R. E. McIntosh and A. L. Pazmany: "Finescale structure and microphysics of coastal stratus", Vol. 55, No. 24, pp. 3540-3564, Dec. 1998.