4A.8 CALIBRATION OF A 94 GHZ AIRBORNE CLOUD RADAR USING MEASUREMENTS FROM THE OCEAN SURFACE

Lihua Li [1], Gerald M. Heymsfield [2], Paul E. Racette [2], Lin Tian [1]

1. Goddard Earth Sciences and Technology Center
University of Maryland, Baltimore County
Baltimore, MD 21250
2. NASA Goddard Space Flight Center
Greenbelt, MD 20771

1. Introduction

In atmospheric research, especially for cloud studies, millimeter-wave cloud radars have gained favor because of their high scattering efficiency, low power consumption and compact size. A number of airborne millimeter-wave cloud radars have been developed (Pazmany et al. 1994; Sadowy et al. 1997) while a 94 GHz spaceborne cloud radar is in preparation for the NASA CloudSat (Stephens et al. 2002). One challenging issue of using millimeter-wave radars for retrieving cloud parameters is the system calibration. The delicate nature of millimeter-wave components and harsh environment in which they operate may cause undetected performance changes unless regular system calibration is performed. The ocean surface has been widely used as a calibration target for airborne and spaceborne microwave radars and radiometers and numerous works have been done microwave frequencies (Jones et al. 1976, Valenzuela 1978, Masuko et al. 1986). In order to maintain calibration accuracy, it is essential to perform system calibration checks periodically for these airborne and spaceborne radars. The ocean surface is an ideal calibration target since there are many opportunities under clear conditions. However, at millimeter-wave frequencies, the ocean surface backscattering mechanism is still not well understood due to the lack of experimental measurements. Meanwhile, attenuation caused by water vapor and oxygen absorption in the lower troposphere is significant at millimeter-wave frequencies. It is therefore necessary to correct this attenuation to improve the accuracy of the calibration using ocean surface as a reference.

The Cloud Radar System (CRS) is a new 94 GHz (W-band) Doppler polarimetric radar developed by NASA Goddard Space Flight Center for autonomous operation on the NASA ER-2 high-altitude aircraft. It is capable of providing high-resolution profiles of reflectivity and Doppler velocity in clouds. The details about CRS hardware, installation on ER-2, system calibration and preliminary cloud measurements is described by Racette *et al* (2003). During July 2002, the CRS was operated on the NASA ER-2 in support of the NASA CRYSTAL-FACE program. Although CRS was configured in a nadir looking mode during the experiment, scattering from the ocean surface at different incidence angles was measured when the aircraft made routine flight track maneuvers. This paper discusses the ocean-surface backscatter signature as a calibration reference in the context of these measurements.

2. Ocean surface backscatter models

In general, the normalized ocean surface scattering cross section σ_o is a function of radar frequency, radar beam incidence angle, ocean surface wind speed as well as wind direction and polarization. For incidence angle θ smaller than 15°, σ_o is dominated by large scale surface waves and quasi-specular scattering theory works well in this region. When θ is larger than 15°, Bragg scattering produced by small scale waves becomes more significant. For CRS during the CRYSTAL-FACE program and for the CloudSat radar, the main goal is to obtain the vertical profile of cloud and precipitation layers. Therefore, the radars operate at low incidence angle and quasi-specular scattering theory is valid. Under this theory, σ_o is approximately given as (Valenzuela 1978)

$$\sigma_o(\theta, v) = \frac{|\Gamma_e(0)|^2}{s(v)^2 \cos^4(\theta)} \exp(-\frac{\tan^2(\theta)}{s(v)^2}), \qquad (1)$$

where v is surface wind speed in ms^{-1} and $s(v)^2$ is the total mean-square surface slope given as $s(v)^2=s_x(v)^2+s_y(v)^2$. The mean-square surface slope in x and y plane is given by the empirical relationships $s_x(v)^2=0.003+1.92\text{x}10^{-3}v$, $s_y(v)^2=3.16\text{x}10^{-3}v$ (Cox and

Munk 1954). $\Gamma_e(0) = C_e(n-1.0)/(n+1.0)$ is the effective ocean surface Fresnel reflection coefficient at normal incidence, $n=7.56-j13.6$, is the refractive index of 20^o C sea water at 94 GHz (Ulaby et al. 1981) and C_e=0.89, is the correction factor due to the ocean surface roughness (Freilich, 2003).

3. Radar Equation of Ocean Surface Scattering

Figure 1 illustrates the measurement geometry of CRS during the CRYSTAL FACE experiment. Although CRS was configured as fixed nadir pointing mode, incidence angle scanning in the cross direction was achieved when the ER-2 made turns during its flight. When the aircraft changed its flight direction, it kept same altitude, but rolled its body to one side and gradually changed its heading direction, then rolled back to a leveled position after the turn. The incidence angle of the radar beam, θ, is therefore derived using aircraft pitch and roll angles.

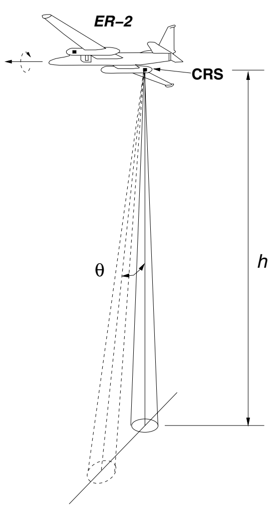

Figure 1: Geometry of CRS measurements from NASA ER-2 during the CRYSTAL-FACE experiment.

To examine the effect of incidence angle on σ_o, we use the received signal from the ocean surface scattering given by (Kozu 1995)

$$P_r(h) = \frac{10^6 P_t G_a{}^2 \lambda^2 \beta\varphi \cos(\theta)}{512 \ln 2\pi^3 l_r l_{tx} l_{atm}{}^2 h^2} \sigma_o , \qquad (2)$$

where P_t is the peak transmit power (kW), G_a is the antenna gain, λ is the radar signal wavelength (m), β, φ are the antenna 3 dB beamwidth in horizontal and vertical (radians), l_r is the loss between the antenna and receiver port, l_{tx} is the loss between the transmitter and the antenna port, l_{atm} is the one way path attenuation due to atmospheric absorption. θ is the radar beam incidence angle (radians), σ_o is normalized ocean surface radar cross section, h *is the* altitude of the aircraft (m).

The factor of $\frac{P_t G_a{}^2 \lambda^2 \beta\varphi}{l_r l_{tx}}$ only depends on the radar system parameters. It is related to the radar constant such as used by Sekelsky (2002). If the ocean surface conditions and σ_o are known, the radar constant can be derived from P_r.

4. CRS Measurements from CRYSTAL-FACE

a. Overview of CRS Setup and CRYSTAL-FACE experiment

CRYSTAL-FACE is field campaign designed to investigate tropical cirrus cloud physical properties and formation processes. It was conducted over the southern Florida peninsula and the adjacent ocean areas during July 2002. During CRYSTAL-FACE, ancillary measurements from ground sites, aircraft, and satellites were made. A number of important remote sensors were operated on ER-2 to measure cloud and precipitation systems. CRS was installed in the tail cone of ER-2 right wing superpod. In a normal flight, ER-2 flew at approximately 20 km altitude above the surface, the 3 dB surface foot print of CRS antenna in the cross track direction was about 210 m for the 0.6^o beamwidth. The CRS RF pulsewidth was 1.0 µs (150 m in range). With this pulsewidth, the surface foot print is beam-filled up to a 32^o incidence angle. The return signal was over sampled at 0.25 µs thus providing better resolution of the surface return. During the CRYSTAL-FACE flights, the maximum radar beam incidence angle was less than 30^o when the aircraft made turns. Therefore, all radar measurements from this experiment were valid for the beam-filled condition. Data were averaged over 0.5 s before it was saved on the storage disk.

Navigation data is provided by the aircraft navigation system at 8 Hz rate and simultaneously recorded along with the 2 Hz radar data. On board dropsondes were launched from the ER-2 to obtain the profile of meteorological data including temperature, relative humidity, pressure, wind speed and direction from the aircraft altitude down to the ocean surface along the aircraft flight path.

b. Water Vapor and Oxygen Absorption Correction

Water vapor and oxygen does not produce significant backscatter even at 94 GHz. However, water vapor and oxygen absorption at millimeter-wave frequencies is much stronger than at microwave frequencies. Because water vapor and oxygen is highly concentrated in the lower troposphere, the ocean surface measurements from an airborne or spaceborne radar are attenuated by their presence. With the meteorological data collected by dropsondes launched from ER-2 and the radiosondes launched from the surface, the attenuation due to water vapor and oxygen absorption was estimated using the Liebe (1985) millimeter-wave propagation model.

During the CRYSTAL-FACE, the typical ER-2 flight duration was about 5 hours. Typically, 4-8 dropsondes were launched during each flight. The ER-2 made 11 flights during the experiment and about 50 dropsondes were launched. The results show that the averaged two-way integrated water vapor and oxygen absorption is about 5.8 dB while the standard deviation is 0.65 dB. The high absorption indicates the importance of the correction of ocean surface measurements for atmospheric attenuation.

c. σ_o Versus Incidence Angle

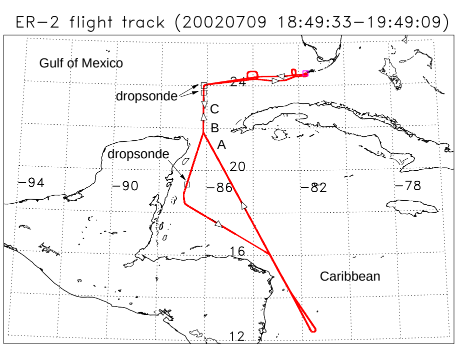

Figure 2. ER-2 flight track on July 9, 2002.

On 9 July 2002, ER-2 flew a tropical cirrus mission. Its flight track crossed the southwest of the aircraft base at Key West, FL, through the Yucatan Channel, then south-southeast into the Caribbean (Fig. 2). On the return trip, the ER-2 made a turn through point B (19:35 UTC, N21.72°, W86.11°) in Fig 2 in a clear region. Figure 3 shows σ_o versus the incidence angle during that turn. It is difficult to obtain the exact wind condition at the turn point B, but measurements were made by dropsondes launched at 16:01 UTC (N23.75°, W86.16°), at 16:44 UTC (N19.01°, W86.91°) on the outbound trip, and at 19:54 UTC (N23.83°, W86.16°) on the return (see locations in Fig 2). The surface wind speeds measured by these dropsondes were 2.6 ms^{-1}, 3.1 ms^{-1} and 6.8 ms^{-1}, respectively. Results using the quasi-specular model with wind speeds of 2.5 ms^{-1}, 4.0 ms^{-1} and 6.5 ms^{-1} are plotted as comparison. For incidence angles smaller than 12°, radar measurements agree very well with the model with a 4.0 ms^{-1} wind speed. For incidence angles larger than 12°, Bragg scattering produced by small scale waves becomes more significant, and thus a two-scale models has to be used (Gary 1978).

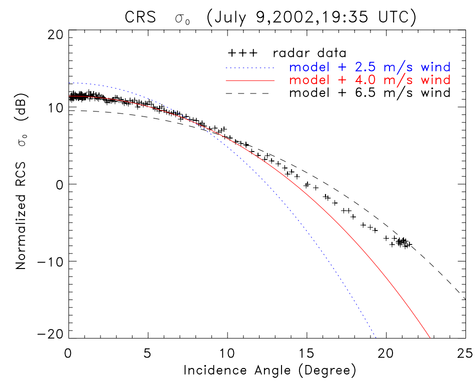

Figure3. σ_o versus incidence angle

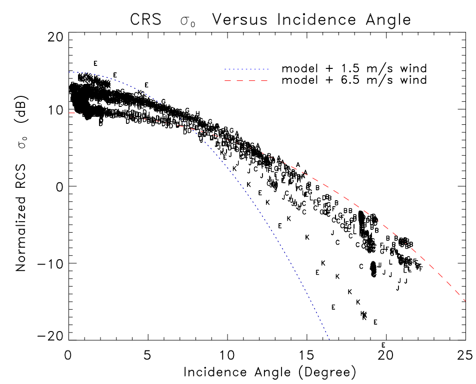

Figure 4: σ_o measured by CRS versus incidence angle from different days. Twelve turns from clear weather are shown.

The normalized backscatter cross section, σ_o , was also derived from other turn events on different days during the experiment. Figure 4 shows σ_o versus incidence angle from 12 clear weather cases. The different shape of the curves are attributed to the different wind conditions for each case. Results from the quasi-specular model assuming a 1.5 ms^{-1} and 6.5 ms^{-1} wind speed are plotted for comparison. It is noteworthy that at 9° incidence angle, σ_o measurements are less sensitive to wind speed, which also agrees with the quasi-specular model and measurements obtained at lower microwave frequencies (Jones et al. 1976, Masuko et al. 1986).

5. Conclusion

Ocean surface scattering measurements were obtained using a 94 GHz airborne cloud radar. The analysis results show very good agreement between the theoretical models and the measurements. It confirms that even at 94 GHz, the quasi-specular ocean surface scattering models work well for low radar beam incidence angles. The measurements also confirm that the σ_o is insensitive to surface wind conditions at a 9^o incidence angle. At 94 GHz, the use of the ocean surface as a calibration target is greatly affected by attenuation due to water vapor and oxygen absorption. Our calculations demonstrate the importance to correct for this attenuation using vertical humidity profiles. The analyses provide a valuable reference for the development of future airborne and spaceborne millimeter-wave cloud radars.

Acknowledgments

We thank Dr. Jeffrey Halverson for providing ER-2 dropsonde data and Dr. Robert Meneghini for instructive discussions.

References

Cox, C. and W. Munk, 1954: Measurements of the roughness of the sea surface from photographs of the sun's glitter. *Journal of Optical Society of America* 144, 838-850.

Gary, S. B., 1978: Backscattering from a Gaussian-distributed perfectly conducting rough surface. *IEEE Transactions on Antennas and Propagation,* 26, 472-482.

Freilich, M. H. and B. A. Vanhoff, 2003: The Relationship between Winds, Surface Roughness, and Radar Backscatter at Low Incidence Angles from TRMM Precipitation Radar Measurements. *Journal of Atmospheric and Oceanic Technology*, 20, 549-562.

Jones, W. L., L. C. Schroeder, and J. L. Michell, 1976: Aircraft measurements of the microwave scattering signature of the ocean. *IEEE Transactions on Antennas and Propagation*, 25, 52-61.

Kozu, T., 1995: A generalized surface echo radar equation for down-looking pencil beam radar. *IEICE Transactions on Communications,* E78-B, 1245-1248.

Racette P. E., L. Li, G. M. Heymsfield, L. Tian, and E. Zinker, 2003: The Cloud Radar. 31st *International Conference on Radar Meteorology,* Seattle, WA.

Liebe, H., 1985: An updated model for millimeter-wave propagation in moist air. *Radio Science* 20 (5), 1069-1089.

Masuko, H., K. Okamoto, M. Shimada, and S. Niwa, 1986: Measurements of microwave backscattering signatures of the ocean surface using X-band and ka band airborne scatterometers. *Journal of Geophysical Research,* 91, 13065-13083.

Pazmany, A. L., R. E. McIntosh, R. Kelly, and G. Vali, 1994: An Airborne 95 GHz Dual Polarization Radar for Cloud Studies. *IEEE Transactions on Geoscience and Remote Sensing*, 731-739.

Sadowy, G., R. McIntosh, S. Dinardo, S. Durden, W. Edelstein, F. Li, A. Tanner, W. Wilson, T. Schneider, and G. Stephens, 1997: The NASA DC-8 airborne cloud radar: Design and preliminary results. *International Geoscience and Remote Sensing Symposium*, Singapore.

Sekelsky, S., 2002: Near field reflectivity and antenna boresight gain corrections for millimeter-wave atmospheric radars. *Journal of Atmospheric and Oceanic Technology, 19, 468-477.*

Stephens, G. L., D. G. Vane, G. G. Boian, R. J. and Mace, K. Sassen, Z. Wang, A. J. Illingworth, E. J. O'Connor, W. B. Rossow, S. L. Durden, S. D. Miller, R. T. Austin, A. Benedetti, C. Mitrescu, and the CloudSat Science Team, 2002: The CloudSat mission and the A-train. *Bulletin of the American Meteorological Society*, *1771-1789.*

Ulaby, F., R. Moore, and A. Fung, 1981: *Microwave Remote Sensing*; *Active and Passive* vol. 1. Artech House.

Valenzuela, G. R., 1978: Theories for the interaction of electromagnetic and oceanic waves – a Review. *Boundary-Layer Meteorology, 13, 61-85.*