A POTENTIAL OF CLOUD PROFILING RADAR FOR MEASUREMENTS OF CLOUD AND PRECIPITATION

Takahisa Kobayashi*, Ahoro Adachi and Kazuhiko Masuda
Meteorological Research Institute, Tsukuba, Ibaraki, Japan

1. INTRODUCTION

A cloud profiling radar (CPR) is a millimeter wavelength radar (Ka-band : 35 GHz or W-band : 94 GHz) and has been primarily developed for measurements of cloud properties. For measurements of precipitation, a 14 GHz radar is currently operated in the Tropical Rain Measuring Mission (TRMM). Although, CPR uses a shorter wavelength band than that for the radar used in the TRMM, CPR is thought to be useful for measurements of a rainfall as well as of clouds.

The attenuation coefficient of rain is about 4 dB/km at a frequency of 94 GHz for rain intensity of 10 mm/h (Lhermitte, 1990). Even for high rain intensity of 50 mm/h, the attenuation coefficient is about 20 dB/km. These suggest that the radar signal is detectable for a penetration depth of a few kilometer in rain. CPR is thought to have a considerable potential for measuring light or moderate precipitation.

In deriving liquid water content from CPR measurements, the radar reflectivity is converted to liquid water content by assuming some appropriate models of drop size distribution (Sassen and Liao, 1996). An accurate estimate of the size distribution (*N(D)*) is critical for the retrieval of liquid water content. One of the methods to estimate the size distribution is to use a dual-frequency cloud profiling radar system (e.g. Firda et al., 1999). Another method to estimate *N(D)* is to use a Doppler cloud profiling radar. Ice crystals in cirrus cloud are usually large in size and are detectable with the radar. Raindrops, needless to say, fall much faster. The size of falling particles will be measured by the use of a Doppler radar assuming an appropriate relationship between the drop size and the fall velocity (Lhermitte, 1987, Gossard et al., 1997).

This paper describes the use of cloud profiling Doppler radar for measuring precipitation. The computations of the radar reflectivity and the Doppler spectra for precipitation are carried out to assess the potential of a cloud profiling radar for determining the rainwater content.

2. MONTE CARLO MODEL

In order to examine the potential of a cloud profiling radar, we performed Monte Carlo simulations. The Monte Carlo model used in this study is similar to the model described by Kobayashi (1988). Photon trajectories are calculated in a conventional manner. The distance the photon travels until it interacts with a particle and the scattering angle are determined by the volume scattering coefficient and the phase function. Reflected signals detected by a satellite sensor are calculated

---

*Corresponding author address: Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan; e-mail: kobay@mri-jma.go.jp stochastically to improve computational efficiency (Kunkel and Weinman, 1976, Kobayashi et. al., 1998). If a collision site of a photon is within the satellite field of view, the probability (Pr) that the photon will return directly to the satellite-borne sensor is calculated at each scattering event, given by

$$P_r = P(\theta_D)\exp(-\tau/\cos\theta_V)\ \triangle\Omega/4\pi, \qquad (1)$$

where P is the phase function, θ_D the angle between the direction of photon propagation and the direction of the sensor, θ_V the zenith angle of the sensor viewed from the scattering position, τ the optical thickness between the scattering site and sensor, and $\triangle\Omega$ the angle subtended by sensor.

3. PRECIPITATION MODEL

The atmospheric model applied for the present simulations contains only precipitation. The precipitation model assumes the Marshall-Palmer drop size distribution, given by

$$N(\mathrm{D}) = N_0 \exp(-aD). \qquad (2)$$

The parameters N_0 and a vary from one case to another. The values of N_0 given by Marshall and Palmer (1948) is 8000 $\mathrm{m}^{-3}\ \mathrm{mm}^{-1}$ and the parameter a is related to rain fall rate as

$$a = 4.1\,R^{-0.21}\ . \qquad (3)$$

The rainfall rate R is in millimeters per hour.

Atmospheric humidity was not included in the simulations. The attention due to the atmospheric humidity is small, i. e. 1~2 dB/km. Therefore, the neglect of the atmospheric humidity does not lead to serious error in examining the potential of CPR in rain measurements. The simulations were made for space-borne 94 GHz CPR. The CPR is located 500 km above the rain top and the beam width in this case is taken to be 0.1 mrad. The CPR measures in nadir direction.

4. ATTENUATION

Because a 94 GHz CPR uses a relatively short wavelength of 3 mm which is almost equal to rain drop diameters, significant attenuation will occur for heavy rain.

Figure 1 shows CPR signals scattered from rain as a function of range in rain. The range in rain is a photon path length in a rain layer and is two times of a penetration length in a rain layer. The rain top and bottom boundary corresponds to a range in rain of 0 and 6 km, respectively. The geometrical depth of the rain layer is assumed to be 3 km. The CPR signals from rain top are about 30 ~ 40 dBZ. If the minimum detectable level of CPR is –35 dBZ,

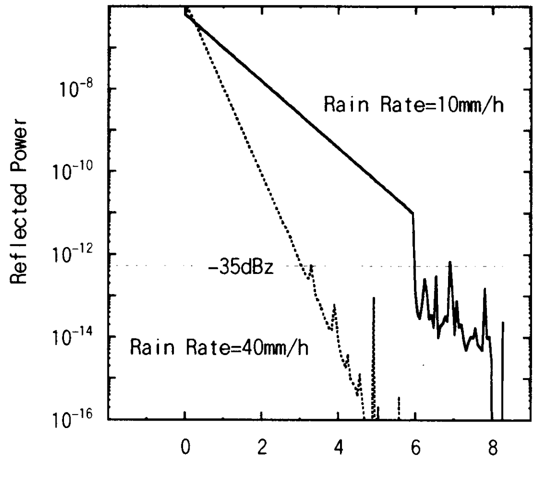

Fig.1 CPR signals scattered from rain for a rain rate of 10 and 40 mm/h as a function of range in rain.

the rain bottom boundary is clearly detected by CPR for a rain rate of 10 mm/h. For a rain rate of 40 mm/h, however, only a penetration depth of 2 km from the rain top is detectable.

Figure 2 shows the ratio of total scattered signals to single scattered signals for a rain rate of 40 mm/h. The multiple scattering contribution increases with range in rain. At a range in rain of 2 km, almost one fourth of the CPR signal is due to the multiple scattering contribution.

5. RETRIEVAL OF RAIN WATER CONTENT

Estimate of liquid water content (LWC) is one of the important objects of a space-borne CPR mission. LWC is usually derived from CPR signals assuming some appropriate relationship between the radar reflectivity and LWC relationship. A number of studies have been made deducing this relationship. Scattered power, however, depends on *N(D)* as well as LWC, significantly. In addition, *N(D)* varies in space to space and in time to time. Therefore, the accuracy of the method of assuming the relationship is very limited.

Figure 3 shows CPR signals as a function of LWC for various values of *a*, assuming the M-P drop size distribution. The CPR signal for a = 4.1 and LWC = 0.85 gm^{-3}, almost coincides to that for a = 2.2 and LWC = 1.8 gm^{-3}. In this case, uncertainty of *N(D)* leads to error in the derived LWC by 100 %. Estimate of realistic *N(D)* is, therefore, needed for accurate retrieval of LWC.

One of the method to determine *N(D)* is to use a Doppler Spectrum assuming a relationship between the fall velocity and the drop diameter. A Doppler spectrum measured with a vertically pointing beam was used to derive the drop size. The Doppler spectrum *S(D)*

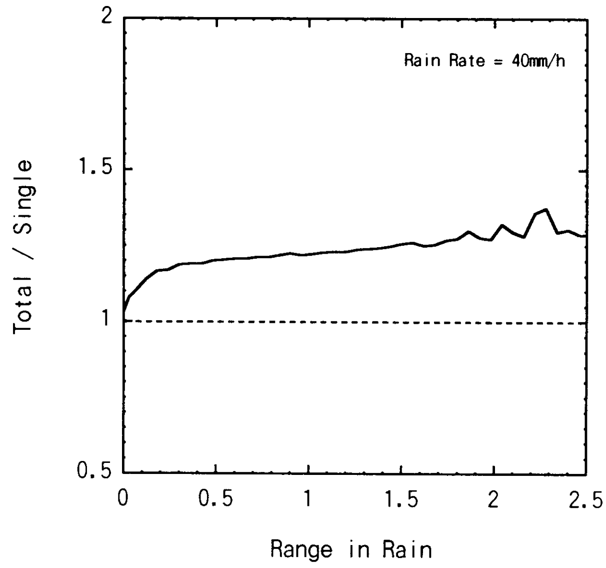

Fig. 2 Calculated ratio of the total signal to the single scattered signal for a rain rate of 40 mm/h.

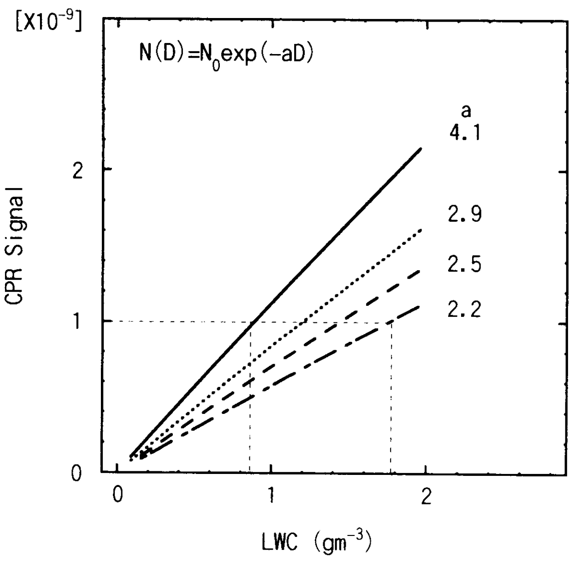

Fig. 3 CPR signals as a function of LWC for various values of *a*, assuming M-P drop size distribution.

scattered by spherical particles is given by

$$S(D) = \sigma\ N(D)\ \frac{dD}{dV}\ , \qquad (4)$$

where N is the size distribution, D the particle diameter, V the falling velocity, and σ the back scattering cross section. The terminal velocity of the particle is assumed to be related to the diameter as

$$V(z) = [\ 9.65 - 10.3 \exp(-0.6D)\ ]\ (\ \frac{\rho}{\rho_0}\ )^{-0.4}, \qquad (5)$$

(Gunn & Kinzer, 1949), where ρ and ρ_0 are atmospheric density at an altitude z and reference level, respectively.

Assuming the drop size distribution by a M-P distribution, a theoretical Doppler spectrum can be obtained by using (4) and (5). The parameter N_0 and a in the M-P distribution is determined by fitting the theoretical Doppler spectrum to the observed one.

This technique is well known in the retrieval of *N(D)* from measurements of an UHF wind profiler which can measure the clear-air motion as well as the falling velocity of rain drops. The Doppler spectrum obtained from CPR, however, has complicated shape (Figure 4). There are four peaks in the Doppler spectrum. In addition, the Doppler spectrum due to raindrop scattering is smeared by atmospheric turbulence, which can not be measured by CPR. We, therefore, use a mean diameter instead.

Mean diameter ($<D>$) is defined as

$$<D> = -1.667\ \log\ [\ (9.56 - <V>)\ /\ 10.3\ ]\ , \qquad (6)$$

where

$$<V> = \frac{\int v\, s(v)\, dV}{\int s(v)\, dV}\ .$$

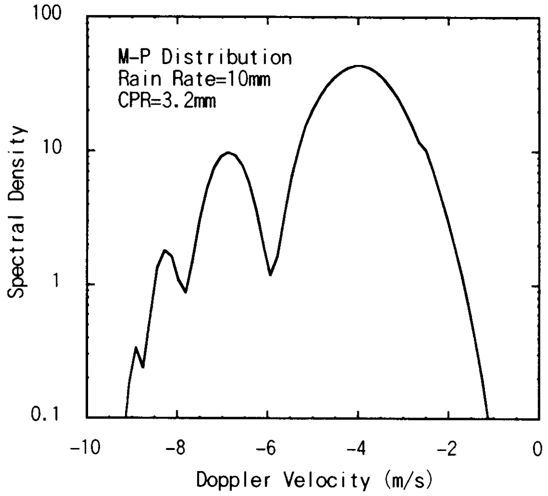

Fig.4 Calculated Doppler spectrum for rain at a frequency of 94 GHz.

Figure 5 shows a flowchart of the algorithms to derive liquid water content. An inappropriate model of *N(D)* leads to erroneous estimate of LWC. But more accurate value of the LWC can be obtained by the use of $<D>$. Figure 6 shows diagram to determine LWC from CPR signals and the mean diameter. For small value of LWC, 0.09 gm^{-3}, the CPR signal is almost insensitive to the mean diameter, in which $<D>$ is not needed for the retrieval of the LWC. For large values of LWC, however, a significant decrease in the CPR signal with $<D>$ appears in which $<D>$ is useful for accurate estimate of LWC.

A serious problem in determining $<D>$ from a measured Doppler spectrum, is the effect of clear-air velocity. A measured falling velocity of raindrops is a sum of the terminal velocity of drop and the clear-air vertical motion. Neglect

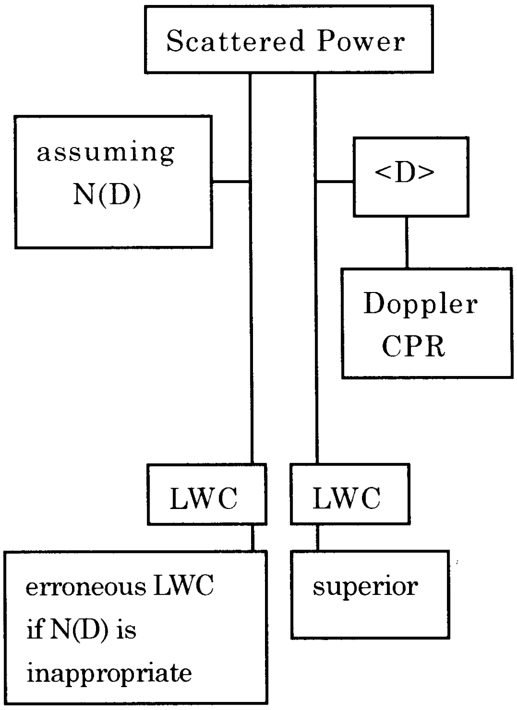

Fig.5 Flowchart of liquid water content retrieval algorithm.

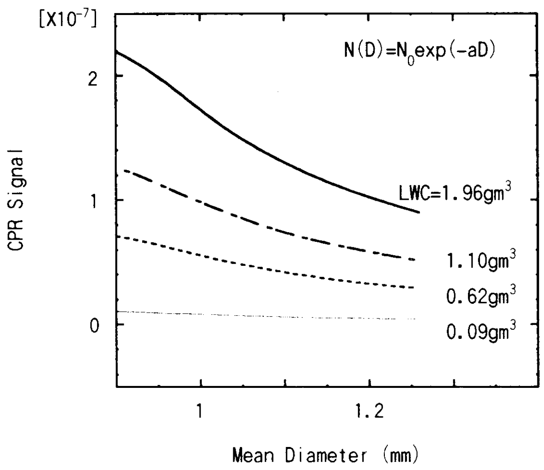

Fig. 6 Diagram to determine LWC from CPR signals and the mean diameter.

of the clear-air motion give rise to bias in the retrieved *<D>* . To retrieve clear-air motion is not so easy task for CPR, but a dual-frequency cloud profiling radar system operated at 95 and 34 GHz can be applied to derive the vertical air velocity (Firda et al., 1999).

6. CONCLUSIONS

The potential of a cloud profiling radar for rainfall measurements was examined by using Monte Carlo technique. The results of the simulations show that

- A cloud profiling radar is a very useful tool for measurements of light, moderate and heavy rainfall.
- An accuracy of the measurement of LWC is significantly improved by the use of a Doppler CPR.

Space borne cloud profiling radar, which is planned in Japan, the United State and Europe will give us an useful data of cloud and precipitation statistics.

REFERECCES

Firda, J. M., S. M. Sekelsky and R. E. McIntosh, Application of dual-frequency millimeter-wave Doppler spectra for the retrieval of drop size distributions and vertical air motion in rain. *J. Atmos. Oceanic Technol.*, **16**, 216-236, 1999.

Gossard, E. E., J. B. Snider, E. E. Clothiaux, B. Martner, J. S. Gibson, R. A. Kropfli, and A. S .Frisch, The potential of 8-mm radars for remotely sensing cloud drop size distribution. *J. Atmos. Oceanic Technol.*, **14**, 76-87, 1997.

Gunn, R., and G. D. Kinzer, The terminal velocity of fall for water droplets in stagnant air. *J. Meteor.*, **6**, 243-248, 1949.

Kobayashi, T., Parameterization of reflectivity for broken cloud fields. *J. Atmos. Sci.*, **45**, 3034-3045, 1988.

Kobayashi, T., Y. Sasano, K. Masuda, and Y. Muraji, Multiple scattering effects on the space-borne lidar signals. *J. Remote Sense. Soc. Japan*, **18**, 2-11, 1998.

Kunkel, K. E., and J. A. Weinman, Monte Carlo analysis of multiply scattered lidar returns. *J. Atmos. Sci.*, **33**, 1772-1781, 1976.

Lhermitte, R., A 94-GHz Doppler radar for cloud observation. *J. Atmos. Oceanic Technol.*, **4**, 36-48, 1987.

Lhermitte, R, Attenuation and scattering of millimeter wavelength radiation by clouds and precipitation. *J. Atmos. Oceanic Technol*, **7**, 464-479, 1990.

Marshall, J. S., and W. McK. Palmer, The distribution of rain drops with size. *J. Meteor.*, **5**, 165-166, 1948.

Sassen, K., and L. Liao, Estimation of cloud content by W-band radar. *J. Appl. Meteor.*, **35**, 932-938, 1996.