NOTES AND CORRESPONDENCE

Simulation-Based Error Analysis of Doppler Velocity Measured by a Spaceborne Cloud-Profiling Radar in the W-band

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Abstract

The Communications Research Laboratory is studying spaceborne cloud-profiling radar with Doppler measurement capability. This study uses pulse-pair operation, based on the polarization-diversity technique, to measure Doppler velocity. The error in the measured Doppler velocity was analyzed using simulation technique as a parameter of pulse-pair intervals at several signal to noise ratios. The optimal pulse-pair interval (T_S) is investigated in this paper because it is a key parameter in determining the dynamic range of the Doppler velocity and its accuracy. Moreover, it was found that the terminal fall velocity of cloud drops in still air could be measured.

Two T_S 's (10 μ sec and 60 μ sec) were used as the optimal values. The dynamic range of Doppler velocity for $T_S = 60 \mu$ sec is 13.3 m/sec. If this dynamic range for Doppler velocity is enough to avoid the aliasing of Doppler velocity, $T_S = 60 \mu$ sec will be suitable for spaceborne cloud-profiling radar because it effectively reduces the error of mean Doppler velocity ($\langle v \rangle$). If the accuracy of the beam-alignment of the antenna is not within 0.1 degrees as a general requirement, a wider dynamic range of Doppler velocity is required to avoid the aliasing of Doppler velocity. It was found that T_S of 10 μ sec gives a wide dynamic range of Doppler velocity. It is thus expected that use of $T_S = 10 \mu$ sec is an optional way for spaceborne cloud-profiling radar, though it does not give good accuracy. Selecting T_S ranging from 10 to 60 μ sec is also a possible way of optimizing the expansion of the dynamic range of Doppler velocity and reducing the error of $\langle v \rangle$.

1. Introduction

Satellite observation of clouds can provide information on their global distribution. Such information is essential for evaluating the global climate. Because clouds have a large effect on the earth's radiation budget, even small changes in their abundance or distribution could alter the climate more than the changes anticipated as a result of greenhouse gases,

anthropogenic aerosols, or other factors associated with global change.

A spaceborne cloud-profiling radar (CPR) is now being proceeded (Li et al. 2000). However, this radar is designed to measure only back-scattering reflectivity from clouds in the nadir direction. The Communications Research Laboratory is studying a next-generation spaceborne W-band CPR that can measure not only reflectivity but also Doppler velocity. For instance, information on Doppler velocity can be used to distinguish between drizzles and cloud particles in liquid water clouds, which is difficult task using only reflectivity. The frequency (f) used in CPR is 94.05 GHz.

Figure 1 shows a schematic configuration of

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Fig. 1. Schematic configuration of Doppler observation with spaceborne CPR.

Doppler observation by spaceborne CPR. In the present study, the satellite orbit is set at an altitude of 450 km, and then the satellite velocity (V_{sat}) is 7.6 km/sec. Doppler observation will be done using the nadir direction to measure vertical motion of cloud drops. The vertical motion of cloud drops is composed of the vertical motion of air and the terminal fall velocity of cloud drops in still air (Orr and Kropfli 1999). W-band Doppler radar can not separately estimate the vertical motion of air, and the terminal fall velocity of cloud drops from the measurements of the vertical motion of cloud drop. A very-high-frequency (VHF) wind profiler with vertical pointing can measure the vertical motion of air, which in the convective cloud (less than about 2 m/s) is larger than that in the stratiform cloud (about ± 0.5 m/s) (Cifelli and Rutledge 1994). The vertical motion of air is often measured as zero in stratiform cloud (Yoe et al. 1992). In this situation, W-band Doppler radar measures the terminal fall velocity of cloud drops in still air. This velocity is very small, so measuring the terminal fall velocity of cloud drops in still air at high accuracy is very difficult. The present study focuses on this situation, so a condition of still air is assumed in the measurement of the terminal fall velocity of cloud drops in still air.

When the antenna direction differs from the nadir direction due to, for instance, a satellite navigation error, the measurement of the vertical motion of cloud drops is disturbed by satellite motion. In this case, the Doppler velocity can be corrected by referring to satellite navigation data, or to Doppler velocity at the earth's surface if the aliasing of Doppler velocity does not occur. A wide dynamic range of Doppler velocity is required to avoid the aliasing. Kobayashi et al. (2002) proposed a pulse pattern for pulse-pair operation with a wide dynamic range of Doppler velocity. The dynamic range of Doppler velocity with pulse-pair processing can be calculated from $\pm \frac{\lambda}{4T_c}$, where λ is the wavelength of radar, and T_c is the time interval between pulses with a constant pulse-repetition frequency (PRF) (Doviak and Zrnic 1993). Unambiguously measured range of radar can be calculated from $\frac{cT_c}{2}$, where c is the velocity of light.

Wavelength of λ can be calculated from $\frac{c}{f}$. Doppler radar requires a short T_c to increase the dynamic range of Doppler velocity. However, a short T_c makes the unambiguously measured range of radar narrow. The dynamic range of Doppler velocity and unambiguously measured range can not be simultaneously increased using constant PRF. To simultaneously increase these two values, Doviak and Sirmans (1973) used a polarization-diversity technique. Figure 2 shows a pulse pattern for pulse-pair operation with polarization diversity. In this pattern, orthogonally polarized components are transmitted in pairs of pulses with an interval T_s smaller than the pulse repetition interval T . Horizontal (H) and vertical (V) polarization have no meaning in the nadir direction; however, for convenience, H and V polarizations are used as orthogonally polarized components. The polarization-diversity technique requires less cross coupling between H and V polarizations. A spherical cloud drop, is assumed which does not produce cross coupling. Cross coupling, is assumed between H and V polarizations in the transmitter and receiver is negligible. And we employ the pulse pattern proposed by Kobayashi et al. (2002). They used $T = 222 \mu\text{sec}$. Unambiguously measured range of radar, with polarization diversity, can be calculated from $\frac{cT}{2}$, which is about 33 km. This unambiguously measured range of radar will be enough for

Fig. 2. Pulse pattern of pulse-pair operation with polarization diversity. Here orthogonally polarized components (horizontal and vertical) are transmitted in pairs of pulses with an interval T_s smaller than the pulse repetition interval T .

measurements from the earth's surface to a cloud top. T_s is a key parameter that determines the dynamic range of Doppler velocity, and its accuracy as discussed in Section 2.4.

Even when the antenna direction is well controlled in relation to the nadir, Doppler observation of vertical cloud motion is affected by the high velocity of the satellite through the antenna beam width. This is a serious problem for Doppler observation with spaceborne CPR. The effect of the high velocity of the satellite through the antenna beam width is evaluated in Section 2.4.

Kobayashi et al. (2002) have already studied the accuracy of Doppler velocity measured by spaceborne CPR using perturbation theory. They expressed doubt that perturbation theory could be adjusted to fit a case with a low signal-to-noise ratio (SNR). Simulation is a powerful method used in statistics for handling theoretically intractable problems. The simulation method can be adjusted to fit cases with various SNR. Comparison between theory and simulation is discussed in Section 2.4. It can also evaluate the effects of non-linear input-output characteristics, and analog-to-digital conversion in the receiver (Ohsaki et al. 1993; Ohsaki and Kozu 1997). It is difficult to consider these effects theoretically. However, concrete hardware specification has not been proposed yet. Those effects will be considered in a future study. The present study investigates the possibility of measuring Doppler velocity of cloud drops by a spaceborne CPR under still air.

2. Error analysis of Doppler velocity

2.1 Basic concept of simulation

Mean Doppler velocity ($\langle v \rangle$) can be estimated from pulse-pair processing (Doviak and Zrnic

1993) as

$$\langle v \rangle = -\left(\frac{\lambda}{4\pi T_s}\right) \arg\left(\frac{1}{N_a} \sum_{i=1}^{N_a} H_i^* \cdot V_i\right), \quad (1)$$

where λ is the wavelength of CPR, N_a is the number of pulse pairs for averaging, H^* is the complex conjugation of H , H_i is the i th number of the H polarization received signal at a fixed range, and V_i is the i th number of the V polarization received signal at the same fixed range. If N_a is infinite, $\langle v \rangle$ can be measured without error. In fact, N_a is finite, so experimentally measured $\langle v \rangle$ always has some errors. The main aim of this study is to establish the relationship between the number of pulse pairs for averaging and the relative error of measured Doppler velocity. This relationship is derived from simulated spaceborne CPR signals. This simulation approach is based on a previous study by Ohsaki (1994).

The basic concept of the simulation method is as follows. A number N_a of H, and V polarization pulse pairs are generated. From these signals, $\langle v \rangle_{N_a}$ is calculated from Eq. (1). Subscript N_a in $\langle v \rangle_{N_a}$ means that $\langle v \rangle_{N_a}$ is calculated from the number N_a of H, and V polarization pulse pairs by averaging. $\langle v \rangle_{N_a}$ always has some errors because it is experimentally measured by averaging. Errors of $\langle v \rangle_{N_a}$ are evaluated from a large number (N_s) of $\langle v \rangle_{N_a}$. This is explained as follows. The number of $N_s \langle v \rangle_{N_a}$ is calculated from additional H and V polarization pulse pairs. The standard deviation of the mean Doppler velocity is directly calculated from the number of $N_s \langle v \rangle_{N_a}$. The relative error can be calculated from the standard deviation. The relationship between the number of pulse pairs to be averaged, and the relative

error of measured Doppler velocity, is obtained by changing the number N_a .

If there is no correlation between the pulse pairs, Doppler velocity can not be calculated from pulse-pair processing. Spaceborne CPR signals, composed from successive H and V polarizations pulse pairs that correlate to each other, can be generated by using a computer simulation based on the following model of a physical cloud drop. The H_i signal can be calculated by summing the vectors of the back-scattered signals from cloud drops. The V_i signal can be simulated by shifting the phase of each cloud drop as would be caused by the cloud-drop motion during T_s . H_i and V_i correlate to each other because T_s is fairly small compared with T . On the other hand, H_i and V_i almost do not correlate to H_{i+1} and V_{i+1} , because T is fairly large compared with T_s (Amayeng et al. 1993).

2.2 Formulation of cloud-drop size distribution

A physical cloud-drop model needs the formulation of cloud-drop size distribution to generate its size distribution using random numbers. A lognormal distribution is often used to formulate cloud-drop size distribution (Frisch et al. 1995; Pruppacher and Klett 1997). Lognormal distribution of cloud-drop size ($N(X)$) is given as

$$N(X) = \frac{N_t}{\sigma_X \sqrt{2\pi}} \exp - \frac{(X - X_0)^2}{2\sigma_X^2}, \quad (2)$$

where X is the logarithm of cloud-drop diameter D in μm , X_0 is the mean value of X , σ_X is the standard deviation of X , and N_t is the

total number of cloud drops per unit volume (cm^{-3}). To formulate cloud-drop size by lognormal distribution, X_0 , σ_X , and N_t should be determined by actual experiment. Heymsfield et al. (1991) measured N_t , mean cloud-drop diameter (MDD), and liquid-water content (LWC) as a function of height ranging from 7300 to 7420 m. Pruppacher and Klett (1997) give an example of Heymsfield's measurement. This example is used to formulate cloud-drop size distribution. Heymsfield et al. (1991) did not show σ_X , but σ_X can be calculated from LWC . LWC in g/m^3 is given as

$$LWC = 10^6 \left(\frac{4\pi}{3} \rho_w \right) \times \int_{\log D_{\min}}^{\log D_{\max}} \left(\frac{1}{2} \cdot 10^{-4} \cdot 10^X \right)^3 N(X) dX, \quad (3)$$

where $D_{\min}$ and $D_{\max}$ are the minimum and maximum diameters of the cloud drop, which are assumed to be 0.1 and 100.0 μm ; ρ_w is the density of water, which is fixed at 0.99984 in g/cm^3 . The term $\frac{1}{2} \cdot 10^{-4} \cdot 10^X$ represents the cloud-drop radius in cm. When LWC , N_t , and MDD are given, σ_X can be calculated by solving the non-linear equation, Eq. (3). In this study, Newton's method was used to solve Eq. (3). LWC , N_t , and MDD were obtained from a figure given by Pruppacher and Klett (1997) for several heights. Table 1 lists LWC , N_t , and MDD and calculated σ_X . Figure 3 shows the cloud-drop size distributions formulated by a lognormal distribution.

When cloud drops are small with respect to wavelength, Rayleigh scattering can be assumed (Doviak and Zrnic 1993). The radar re-

Table 1. Parameters of clouds at several heights. N_t , MDD , LWC , σ_X , Z , V_m , and V_{DOP} mean the total number of cloud drops per unit volume, mean cloud-drop diameter, liquid water content, standard deviation of lognormal distributed cloud-drop size, radar reflectivity factor, mean terminal fall velocity of the cloud drop in quiet air, and Doppler velocity, respectively.

Height (m)	N_t (cm^{-3})	MDD (μm)	LWC (g/m^3)	σ_X	Z (dBZ)	V_m (cm/s)	V_{DOP} (cm/s)
7400	96	5.8	0.015	0.414	-13.8	0.27	19.8
7380	136	6.0	0.018	0.406	-12.7	0.27	19.6
7360	136	6.3	0.019	0.401	-12.4	0.28	19.5
7340	69	5.7	0.011	0.417	-15.2	0.26	19.8
7320	40	4.2	0.002	0.418	-22.1	0.15	19.3

Fig. 3. Cloud-drop size distributions formulated by lognormal distribution. Full, long dashes, dash-dot-dash-dot, dotted, and dash-dot-dot-dot lines show cloud-drop size distributions at heights of 7320 m, 7340 m, 7360 m, 7380 m, and 7400 m. $N(X)$ is the distribution for cloud-drop size, and 10^X is cloud-drop diameter.

flectivity factor Z (mm^6/m^3) is then expressed in terms of cloud-drop size distribution by

$$Z = \int_{\log D_{\min}}^{\log D_{\max}} (10^{-3} \cdot 10^X)^6 10^6 \cdot N(X) dX, \quad (4)$$

where term $10^{-3} \cdot 10^X$ means the cloud-drop diameter in mm. Table 1 also lists Z in dBZ calculated from Eq. (4).

Gossard et al. (1997) show that the terminal fall velocity of a cloud drop in quiet air V_t (cm/sec) can be described as a function of cloud-drop diameter D (μm) as

$$V_t(D) = 100 \cdot a_1 \cdot D \cdot (1.0 - \exp(-a_2 \cdot D)), \quad (5)$$

where a_1 and a_2 are constants, namely, $4.0 \cdot 10^3$ and $1.2 \cdot 10^4$, respectively. Figure 4 shows the relationship between the cloud-drop diameter, and the terminal fall velocity of a cloud drop. The mean terminal fall velocity of a cloud drop in quiet air (V_m) can be calculated from

$$V_m = \frac{\int_{\log D_{\min}}^{\log D_{\max}} V_t(10^X) \cdot N(X) dX}{\int_{\log D_{\min}}^{\log D_{\max}} N(X) dX}. \quad (6)$$

Table 1 also lists V_m calculated from Eq. (6).

Doppler radar with pulse-pair operation can not measure V_m , because radar signals are weighted by Rayleigh scattering. Instead, Dop-

Fig. 4. Relationship between cloud-drop diameter and terminal fall velocity of a cloud drop.

pler radar measures Doppler velocity (V_{DOP}), which can be calculated from

$$V_{DOP} = \frac{\int_{\log D_{\min}}^{\log D_{\max}} V_t(10^X) \cdot (10^X)^6 \cdot N(X) dX}{\int_{\log D_{\min}}^{\log D_{\max}} (10^X)^6 \cdot N(X) dX}. \quad (7)$$

Table 1 also lists V_{DOP} calculated from Eq. (7). Note that V_{DOP} is different from V_m as shown in Table 1. To estimate V_m from Doppler observation, the spectrum of Doppler velocity is required. It is impossible to estimate V_m from pulse-pair operation. This requirement makes the hardware of a satellite more complicated. A pulse-pair operation is used to simplify the hardware of the satellite. This study concentrates on error analysis of V_{DOP} .

2.3 Simulation of spaceborne CPR signals

Figure 5 shows a schematic illustration of measurement of cloud using spaceborne CPR in the nadir direction. The antenna beam width is 2θ ($\theta = 0.05$ degrees). The range resolution is 250 m. The measurement height corresponds to the altitude of the center of the resolution volume. The number of 10^{10} lognormally distributed cloud drops randomly arrayed in the resolution volume is generated. This number of cloud drops is fairly small compared with the actual number of cloud drops in a resolution volume. However, this is not a problem in the simulation, because 10^{10} cloud drops is statistically adequate (Ohsaki 1994). A random array means that each generated cloud drop has a random initial phase ranging from 0 to 360 de-

Fig. 5. Schematic illustration of measurement of cloud using spaceborne CPR in the nadir direction.

grees. The H_i signal can be calculated by summing the vectors of the backscattered signals from cloud drops. The V_i signal can be simulated by shifting the phase of each cloud drop as would be caused by cloud-drop motion and satellite motion during T_s . This study does not deal with the vertical motion of air. The phase shift of j th number of cloud drop ($\Delta\phi_j$) is calculated from the following equation,

$$\Delta\phi_j = \frac{4\pi(V_{tj} + 10^6 V_{sat} \sin \alpha_j \cos \beta_j)}{\lambda} T_s, \quad (8)$$

where V_{tj} is the terminal fall velocity of the j th number of cloud drop, α_j is the angle from the nadir of the j th number of cloud drops ranging from $-\theta$ to θ , and β_j is the angle from the flight direction of j th number of cloud drop ranging from 0 to 360 degree as shown in Fig. 5. λ is radar wavelength in cm. The vector summing of backscattered signals from cloud drops is executed in a phaser diagram. Thus, it is not necessary to consider the effect that the some cloud drops entering and/or leaving the resolution volume. The number of cloud drops used in the simulation is always constant. In summing the vectors of backscattered signals from

cloud drops, the antenna pattern approximated by the Gaussian expression (Skolnik 1984) $\left(\exp\left(\frac{-2.78\theta_j^2}{\theta^2}\right)\right)$ is considered. The noise effect is considered to add a noise signal to the vector summing. The effect of SNR can be investigated by changing the power of the noise level.

Kobayashi et al. (2002) propose that $T = 222 \mu\text{sec}$ is suitable for Doppler observation of spaceborne CPR. When the phase shift of cloud drops during T_s is small, H_i and V_i correlate to each other. However, the phase shift of cloud drops during T is fairly large. Thus, H_i and V_i almost do not correlate to H_{i+1} and V_{i+1} (Amayeng et al. 1993). $T = 222 \mu\text{sec}$ is employed. After generating the H_i and V_i signals, randomly arrayed cloud drops in the resolution volume are re-generated by using different random numbers for calculating the H_{i+1} and V_{i+1} signals. This makes the H_i and V_i signals, and H_{i+1} and V_{i+1} signals, independent of each other. The use of T_s to match Doppler observation of spaceborne CPR is discussed in the section 2.4.

The total number of the vector summing is defined as the number of cloud drops $\times N_a \times N_s \times 2$. Unfortunately, our computer's capability limited the total number of vector summing to less than about 2×10^{20} . Since the number of cloud drops is 10^{10} , 10^{10} H and V signal pairs is the maximum number that can be generated using our computer. Therefore, as N_a increases, N_s decreases. In calculating Doppler-velocity error, the sample size N_s is not constant.

2.4 Optimal T_s

Kobayashi et al. (2002) investigated optimal T_s . Optimal T_s is also investigated because Kobayashi et al. doubt that perturbation theory can be adjusted to the case of low SNR. The simulation that has been developed can be adjusted to the case of low SNR. For instance, in this investigation, MDD and σ_X at a height 7360 m, given in Table 1, are used to simulate spaceborne CPR signals. It is assumed that a resolution volume ranging from 7360 – 125 m to 7360 + 125 m in height is uniformly filled by cloud drops, which are characterized by MDD and σ_X at a height of 7360 m. It is also assumed that the target resolution volume exists at the top of the cloud. Therefore, it is not necessary to consider the attenuation of radio waves.

Fig. 6. Relationship between T_s (pulse interval), and the relative error of $\langle v \rangle$, at $N_a = 6000$ as a parameter of noise level. Full, long dashes, dash-dot-dash-dot, dotted, and dash-dot-dot-dot lines correspond to equivalent noise levels of -37.4 , -27.4 , -17.4 , -7.4 , and 2.6 dBZ respectively, which correspond to SNR of 25.0 , 15.0 , 5.0 , -5.0 , and -15.0 dB, respectively. The red and blue lines obtained from simulation and theory, respectively.

Figure 6 shows the relationship between T_s (pulse interval) and the relative error of $\langle v \rangle$ at $N_a = 6000$ as a parameter of noise level. As shown in Table 1, Z at a height of 7360 m is -12.4 dBZ. Five different Z 's (-37.4 , -27.4 , -17.4 , -7.4 , and 2.6 dBZ) are added after vector summing as equivalent noise signal. Thus, the corresponding SNR's are 25.0 , 15.0 , 5.0 , -5.0 , and -15.0 dB. The red and blue lines obtained from simulation and theory (Kobayashi et al. 2002), respectively. The relative error is defined by the standard deviation divided by its mean value. As shown in Fig. 6, blue lines correspond well to red lines when SNR is high. When SNR is low, the blue and red lines are widely separated. This separation is caused by the limitation of perturbation theory. In spaceborne radars, hardware limitations, such as power supply, antenna size, and transmitting power, make the SNR low. Thus, error analysis at low SNR is important.

Figure 7 shows the relationship between T_s and the relative error of $\langle v \rangle$ at $N_a = 600$ as a parameter of noise level. As shown in Table 1,

Fig. 7. Relationship T_s (pulse interval) and relative error of $\langle v \rangle$ at $N_a = 600$ as a parameter of noise level. Full, long dashes, dash-dot-dash-dot, dotted, and dash-dot-dot-dot lines correspond to equivalent noise levels of -30.0 , -25.0 , -20.0 , -15.0 , and -10.0 dBZ, respectively, which correspond to SNR of 17.6 , 12.6 , 7.6 , 2.6 , and -2.4 dB, respectively. The effect of the high velocity of the satellite through the antenna beam width is taken into account in the red line, but not in the blue line.

Z at a height of 7360 m is -12.4 dBZ. Five different Z 's (-30.0 , -25.0 , -20.0 , -15.0 , and -10.0 dBZ) are added after vector summing as equivalent noise signal. Thus, the corresponding SNR's are 17.6 , 12.6 , 7.6 , 2.6 , and -2.4 dB. Both the red and blue lines were obtained from simulation. The effect of the high velocity of the satellite through the antenna beam width is taken into account in the red line, but not in the blue line. Each red line is higher than the corresponding blue line for each SNR. This is because of the effect of the high velocity of the satellite through the antenna beam.

As mentioned in Kobayashi et al. (2002), the error of $\langle v \rangle$ is determined by two competing effects: one is the decrease in the resolution of Doppler-phase-shift detection with small T_s , and the other is the deterioration in the correlation between pulse pairs with large T_s . Since Doppler phase shift at small T_s is very small, it is difficult to accurately measure small Doppler phase shift from noise-added signals. Therefore, relative error of $\langle v \rangle$ is large at small T_s .

When T_s becomes large, correlation between pulse pairs becomes poor. Therefore, relative error of $\langle v \rangle$ is large at large T_s . According to the above explanation, the relative error of $\langle v \rangle$ for each red curve in Fig. 7 is minimized at around $T_s = 60 \mu\text{sec}$ by two competing effects. The shape of the red lines for each SNR is determined by these two competing effects.

Relative error of $\langle v \rangle$, shown by the blue lines in Fig. 7, monotonously decreases. When T_s becomes large, Doppler phase shift also becomes large, so when T_s becomes large, the measurement of Doppler phase shift from noise-added signals becomes more accurate. Monotonously decreasing relative error of $\langle v \rangle$ shown by the blue lines in Fig. 7, is due to the improved accuracy of Doppler phase shift when T_s becomes large. When T_s becomes large (more than $150 \mu\text{sec}$), the correlation between pulse pairs should become poor. The deterioration in the correlation between pulse pairs with large T_s (more than $150 \mu\text{sec}$), should make the relative error of $\langle v \rangle$ shown by the blue lines in Fig. 7 large. According to the above explanation, it can be supposed that the relative error of $\langle v \rangle$ for each blue curve in Fig. 7, is also minimized at large T_s (more than $150 \mu\text{sec}$). Consequently, the shape of the blue lines for each SNR is also affected by the above mentioned two competing effects. When the effect of the high velocity of the satellite through the antenna beam is considered, the deterioration in the correlation between pulse pairs is rapid when T_s increases. On the other hand, when the effect of the high velocity of the satellite through the antenna beam is not considered, the deterioration in the correlation between pulse pairs is low when T_s increases. The difference between the red and blue lines in Fig. 7 is caused by consideration of the effect of the high velocity of the satellite through the antenna beam.

When the antenna direction differs from the nadir direction, the measurement of the vertical motion of cloud drops is disturbed by satellite motion. In this case, the Doppler velocity can be corrected by referring to satellite navigation data or to Doppler velocity at the earth's surface if the aliasing of Doppler velocity does not occur. A wide dynamic range of Doppler velocity is required to avoid the aliasing of Doppler velocity. The accuracy of the beam-alignment of the antenna as a general require-

ment is 0.1 degrees (Kobayashi et al. 2002). Kobayashi et al. (2002) shown that when the accuracy of the beam-alignment of the antenna is kept below 0.1 degrees, the dynamic range of velocity should be over 10 m/sec to avoid the aliasing of Doppler velocity. The supposed equivalent noise level is about -20.0 dBZ (Kobayashi et al. 2002). This corresponds with the dash-dot-dash-dot line in Fig. 7. This line is minimized at about $T_s = 60 \mu\text{sec}$ as shown in Fig. 7. The equivalent noise signal of -17.4 dBZ closes to the supposed equivalent noise level of -20.0 dBZ , so this minimum point is also confirmed in Fig. 6 as shown by the blue dash-dot-dash-dot line, which is obtained from simulation for an equivalent noise signal of -17.4 dBZ . The dynamic range of Doppler velocity used in pulse-pair processing using the polarization diversity can be calculated from $\pm \frac{\lambda}{4T_s}$. Figure 8 shows the relationship between measurable Doppler velocity (positive value only) and T_s . The dynamic range of Doppler velocity for $T_s = 60 \mu\text{sec}$ is 13.3 m/sec, which meets Kobayashi's requirement.

If the accuracy of the beam-alignment of the antenna, i.e., 0.1 degrees, is not satisfied, a wider dynamic range of Doppler velocity is required to avoid the aliasing of Doppler velocity. Dynamic range of Doppler velocity for $T_s = 10 \mu\text{sec}$ is expanded to 79.7 m/sec as shown in Fig. 8. Two T_s 's (10 and $60 \mu\text{sec}$) are used; T_s of $10 \mu\text{sec}$ can expand the dynamic range of Doppler velocity; T_s of $60 \mu\text{sec}$ can effectively re-

Fig. 8. Relationship between measurable Doppler velocity (positive value only) and T_s (pulse interval).

Fig. 9. Relationship between N_a (number of pulse pairs) and relative error of $\langle v \rangle$ as a parameter of noise level. Full, long dashes, dash-dot-dash-dot, dotted, and dash-dot-dot-dot lines correspond to equivalent noise levels of -30.0 , -25.0 , -20.0 , -15.0 , and -10.0 dBZ, respectively, which correspond to SNR of 17.6, 12.6, 7.6, 2.6, and -2.4 dB, respectively. The red line corresponds to the case of $T_S = 10$ μ sec, and the blue line corresponds to the case of $T_S = 60$ μ sec.

Fig. 10. Relationship between N_a (number of pulse pairs) and the relative error of $\langle v \rangle$ as a parameter of noise level. Full, long dashes, dash-dot-dash-dot, dotted, and dash-dot-dot-dot lines correspond to equivalent noise levels of -30.0 , -25.0 , -20.0 , -15.0 , and -10.0 dBZ, respectively, which correspond to SNR of 17.6, 12.6, 7.6, 2.6, and -2.4 dB, respectively. The red line corresponds to the case of $T_S = 10$ μ sec, and the blue line corresponds to the case of $T_S = 60$ μ sec.

duce the relative error of $\langle v \rangle$. In Section 2.5, the error in Doppler velocity for $T_S = 10$ μ sec and $T_S = 60$ μ sec is analyzed as a parameter of N_a (number of pulse pairs).

2.5 Error analysis of Doppler velocity

Figure 9 shows the relationship between N_a (number of pulse pairs) and the relative error of $\langle v \rangle$ as a parameter of the same noise levels as in Fig. 7. The red lines correspond to the case of $T_S = 10$ μ sec, and the blue lines correspond to the case of $T_S = 60$ μ sec. The results in Fig. 9 are based on simulated spaceborne CPR signals characterized by MDD , and σ_X at a height of 7360 m as shown in Table 1 (Case 1). As shown in Table 1, Z at a height of 7320 m is fairly small compared with other heights. This small value of Z makes the SNR low. We investigated the relationship between N_a , and the relative error of $\langle v \rangle$ at a low SNR. This is an investigation on the possibility of measuring the Doppler velocity in feathery clouds. Figure 10 is the same as Fig. 9, except it is based on simulated spaceborne CPR signals characterized by MDD

and σ_X at a height of 7320 m as shown in Table 1 (Case 2). To simulate these spaceborne CPR signals, it is assumed that a resolution volume ranging from $7320 - 125$ m to $7320 + 125$ m in height is uniformly filled by cloud drops, which are characterized by MDD and σ_X at a height of 7320 m. It is also assumed that the target resolution volume exists at the top of the cloud.

As already mentioned in the Section 2.4, since Doppler phase shift at small T_s is very small, it is difficult to accurately measure this small Doppler phase shift from noise-added signals. For this reason, the relative error of $\langle v \rangle$ is large at small T_s . This can be confirmed in Figs. 9 and 10. Relative error of $\langle v \rangle$ for $T_S = 10$ μ sec (red lines) is always larger than that for $T_S = 60$ μ sec (blue lines) at the same noise level.

The supposed equivalent noise level is about -20.0 dBZ (Kobayashi et al. 2002), which corresponds with the dash-dot-dash-dot lines in Figs. 9 and 10. The relative error of $\langle v \rangle$ is minimized at $N_a = 10000$ in Figs. 9 and 10. The

satellite flight distance for averaging (L) is given by

$$L = N_a \cdot V_{sat} \cdot T. \quad (9)$$

When $N_a = 10000$, L of about 16.8 km is required. The clouds are uniform for averaging in the distance of L is assumed. The horizontal spatial resolution at the earth's surface determined by antenna beam width is about 1.5 km. When $N_a = 10000$, the horizontal spatial resolution is 1.5×16.8 km. If N_a increases to more than 10000, the accuracy of $\langle v \rangle$ becomes better, but the horizontal spatial resolution becomes poor. And clouds may be horizontally non-uniform in the distance of 16.8 km, thus, N_a must not be more than 10000. The effect of horizontally non-uniform distribution of cloud in the distance of L will be investigated in a future study.

An acceptable relative error in Doppler velocity is assumed at least less than 50% as our target, for instance. Then, we can measure V_{DOP} within $19.5 \pm 19.5/2.0$ cm/s for Case 1, and we can measure V_{DOP} within $19.3 \pm 19.3/2.0$ cm/s for Case 2. The relative errors of $\langle v \rangle$, indicated by the dash-dot-dash-dot lines at $N_a = 10000$ for $T_S = 10$ μ sec, and $T_S = 60$ μ sec in Fig. 9 are about 70% and 20%, respectively. The relative errors of $\langle v \rangle$ indicated by the dash-dot-dash-dot lines at $N_a = 10000$ for $T_S = 10$ μ sec and $T_S = 60$ μ sec in Fig. 10, are about 160% and 40%, respectively. 20% and 40% of relative errors of $\langle v \rangle$ for $T_S = 60$ μ sec is less than target error. On the other hand, 70% and 160% of relative errors of $\langle v \rangle$ for $T_S = 10$ μ sec is larger than target error. From this explanation, it will be concluded that the measurement of the terminal fall velocity of cloud drops in still air for $T_S = 60$ μ sec is possible, but that for $T_S = 10$ μ sec is difficult. But, the results depend on SNR, which is determined by the value of Z for clouds. The global distribution of Z for clouds is not still well known. If the values of Z used in this study are included in the region of small value of Z in the distribution of Z , the measurement of the terminal fall velocity of cloud drops in still air for $T_S = 10$ μ sec may be possible in the remaining region of larger value of Z in the distribution of Z . The author expects that use of $T_S = 10$ μ sec is an optional way for spaceborne cloud-profiling radar when a wide dynamic range of Doppler velocity is required

to avoid the aliasing of Doppler velocity. Selecting T_S , ranging from 10 to 60 μ sec, is another way of optimizing the expansion of the dynamic range of Doppler velocity and reducing the error of $\langle v \rangle$.

3. Concluding remarks

The error in measured $\langle v \rangle$ at various T_S and SNR is analyzed. Two T_S 's (10 μ sec and 60 μ sec) were used as the optimal values. The dynamic range of Doppler velocity for $T_S = 60$ μ sec is 13.3 m/sec. If 13.3 m/sec of dynamic range for Doppler velocity is enough to avoid the aliasing of Doppler velocity, $T_S = 60$ μ sec will be suitable because it effectively reduces the error in measured $\langle v \rangle$. If the accuracy of the beam-alignment of the antenna is not within 0.1 degrees, a wider dynamic range of Doppler velocity is required to avoid the aliasing of Doppler velocity. Namely, T_S of 10 μ sec gives a wide dynamic range of Doppler velocity. The author expects that use of $T_S = 10$ μ sec is an optional way, though it does not give good accuracy in measured $\langle v \rangle$. Selecting T_S ranging from 10 to 60 μ sec is another way of optimizing the expansion of the dynamic range of Doppler velocity and reducing the error in measured $\langle v \rangle$.

References

- Amayeng, P., J. Testud, and M. Marzoung, 1993: Proposal for a spaceborne dual-beam rain radar with Doppler capability, *J. Atmos. Oceanic Technol.*, **10**, 262–276.
- Cifelli, R. and S.T. Rutledge, 1994: Vertical motion structure in maritime continent mesoscale convective system: Results from a 50-MHz profiler, *J. Atmos. Sci.*, **51**, 2631–2652.
- Doviak, R.K. and D. Sirmans, 1973: Doppler radar with polarization diversity, *J. Atmos. Sci.*, **30**, 737–738.
- Doviak, R.J. and D.S. Zrnic, 1993: *Doppler Radar and Weather Observations*, Second edition, Academic Press Inc., 562 pp.
- Frisch, A.S., C.W. Fairall, and J.B. Snoder, 1995: Measurement of stratus cloud and drizzle parameter in ASTEX with a Ka-band Doppler radar and a microwave radiometer, *J. Atmos. Sci.*, **52**, 2788–2799.
- Gossard, E.E., J.B. Snider, E.E. Clothiaux, B. Martner, J.S. Gibson, R.A. Kropfli, and A.S. Frisch, 1997: The potential of 8-mm radars for remotely sensing cloud drop size distributions, *J. Atmos. Oceanic Technol.*, **14**, 76–87.

- Heymsfield, A.J., L.M. Miloshevich, and A. Slingo, 1991: An observational and theoretical study of highly supercooled altocumulus, *J. Atmos. Sci.*, **48**, 923–945.
- Kobayashi, S., H. Kumagai, and H. Kuroiwa, 2002: A proposal of pulse-pair Doppler operation on a spaceborne cloud-profiling radar in the W-band, *J. Atmos. Oceanic Technol.*, **19**, 1294–1306.
- Li, F.K., E. Im, S.L. Durden, and R. Girard, 2000: Cloud profiling radar (CPR) for the CloudSat mission, *Proc. 2000 Int. Geosci. Remote Sensing Symp.*, 2821–2823.
- Ohsaki, Y., T. Ihara, and T. Kozu, 1993: Error analysis of rain echo power of spaceborne radar measurements, *J. Commun. Res. Lab.*, **40**, 153–169.
- , 1994: Computer error analysis of rainfall rates measured by a C-band dual-polarization radar, *IEICE Trans. Commun.*, **E77-B**, 1162–1170.
- and T. Kozu, 1997: A software-based dynamic range expansion of the TRMM radar receiving system, *J. Remote Sensing Soc. Japan*, **17**, 65–69.
- Orr, W.B. and R.A. Kropfli, 1999: A method for estimating particle fall velocities from vertically pointing Doppler radar, *J. Atmos. Oceanic Technol.*, **16**, 29–37.
- Pruppacher, H.R. and J.D. Klett, 1997: *Microphysics of clouds and precipitation*, Kluwer academic publishers, 954 pp.
- Skolnik, M.I., 1984: *Introduction to radar systems*, Second edition, McGraw-hill international book company, 581 pp.
- Yoe, J.G., M.F. Larsen, and E.J. Zipser, 1992: VHF wind-profiler data quality and comparison of methods for deducing horizontal and vertical air motions in a mesoscale convective storm, *J. Atmos. Oceanic Technol.*, **9**, 713–727.