Report of the National Research Center for Disaster Prevention, No. 44, October, 1989

551.501.8

Effect of Rapid Scan of the Doppler Radar on the Estimation of Spectrum Moments

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Abstract

To investigate the effect of antenna scan rate on the estimation of Doppler spectrum moments (reflectivity factor and Doppler velocity), Doppler radar observations were carried out at five speeds of antenna rotation. Stratiform precipitation during the Baiu season was chosen as the phenomenon of investigation because it can be regarded as being in a quasi-steady state during the data acquisition period of a few minutes.

Comparing the images of the reflectivity factor and Doppler velocities observed at the scan rates of 1, 2, 3, 6, and 15 rpm, it was found that though substantial differences among the images could not be recognized, a smooth image tends to be scattered especially on the echo boundary according to the scan rate. Based on the estimation of error due to the increase in the scan rate, it was found that a bias is generated in the estimation of the mean reflectivity factor when the scan rate is over about 6 rpm, and a normalized mean error rate due to a rapid scan becomes about 3 % when the scan rate is 15 rpm. The rapid scan does not generate any bias in the case of the estimation of the mean Doppler velocity. Standard deviations of the estimated reflectivity factor and Doppler velocity increase with the scan rate.

Several weather phenomena for which a rapid scan Doppler radar could serve as a valuable tool are discussed briefly. It must be stressed that error due to rapid scan can be acceptable when rapid observations of short-lived atmospheric phenomena are required.

Key word: Doppler rader, rapid scan, signal processing, Doppler spectrum, rader reflectivity factor

1. Introduction

There are three important spectrum moments which are provided by the pulse Doppler radar observation. Zero moment of the Doppler spectrum, or the echo power is an indicator of the precipitation rate in the resolution volume which is defined by the

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pulse-width and the beam-width. The first moment of the normalized spectrum, or the mean Doppler velocity is a measure of the scatterers' mean motion in the resolution volume toward or away from the radar. The square root of the second moment of the normalized spectrum, or the Doppler spectrum width is a measure of radial velocity shear or turbulence within the resolution volume.

Most conventional Doppler weather radars are operated at two speeds of the antenna rotation to obtain these spectrum moments. The antenna rotation speed is usually 6 rpm in measuring the echo power and 1 rpm in measuring the mean Doppler velocity and the Doppler spectrum width. However, when one carries out three-dimensional observations of weather phenomena such as convective storms at a slow antenna scan rate, the steady state assumption on the investigating phenomena becomes questionable. This is due to the fact that phenomena such as convective storms evolve rapidly with time. In addition to this, there are some cases where the phenomena in themselves cannot be detected because of their short lifetime.

To conduct a close investigation of these phenomena and to improve a detecting and warning method of them, the Doppler radar of NRCDP was designed and completed in March, 1988. It can be said that the Doppler radar of NRCDP is a further developed version of the Doppler radar of the Institute of Low Temperature Science (ILTS) of Hokkaido University (Fujiyoshi *et al.*, 1986) with several new performances. One of them is the antenna rapid scan rate. ILTS's radar rotetes its antenna at a maximum speed of 30 rpm in measuring the reflectivity factor. In addition to measuring the reflectivity factor, NRCDP's Doppler radar scans rapidly in measuring the Doppler velocity and Doppler spectrum width. This is one of the unique performances of NRCDP's Doppler radar and is required for the detection of short-lived phenomena and for close investigation which satisfies the steady-state assumption of the phenomena.

However, the rapid scan may affect radar signal processing. An increase in the scan speed causes a reduction of the number of samples for averaging, which implies the generation of biases and the increase in uncertainty in estimating Doppler spectrum moments. Rogers (1971) showed that the calculation of the zero moment of the Doppler spectrum, i. e. reflectivity factor, using outputs of logarithmic receivers would yield biased results. Zrnić (1975) showed from his theoretical study that this bias would be a function of the number of independent samples. On the other hand, the variance of the mean Doppler spectrum estimates is inversely proportional to the number of independent samples (Doviak and Zrnić, 1984).

The purpose of this study is to estimate the error arising from the rapid scan and to examine the effectiveness of the rapid scan Doppler radar for the atmospheric science.

2. Principal performance of the Doppler radar of the National Research Center for Disaster Prevention (NRCDP)

In this paper, only the principal performance of NRCDP's Doppler radar is described. Detailed specifications of the radar including data analysis procedures and some examples of the observations the radar are shown in Maki *et al.* (1989). Main specifications of the radar are as follows:

Antenna aspect	
Reflector	2 m aperture
Gain	42 dB
Beam-width	1.2°
Scan speed	1, 2, 3, 6, 15 rpm
Transmitter aspect	
Radar frequency	9,415 MHz
Transmitted peak power	40 kW
Transmitted pulse-width	0.5 μsec
Pulse repetition frequency	2,000 Hz
Receiver aspect	
Noise figure	$\leqq$5 dB
Minimum detectable signal	$\leqq -110$ dBm
Band-width	2 MHz
Signal processor aspect	
Maximum range	64 km
Reflectivity	0.1 dBZ
Velocity	16 m/s (0.125 m/s)
Spectrum width	16 m/s (0.125 m/s)
Other	
Location	portable

The beam-width and range resolution described above allows the radar to measure the phenomena with sufficient spatial resolutions of the order of 1 km within the detectable range. Five speeds of the antenna scan were provided to investigate the effect of the scan speed on the estimation of the spectrum moments.

3. Estimation of error caused by rapid scan

3.1 Number of samples for averaging

As the precipitation particles, which are scatterers of electromagnetic waves, distribute randomly and move with respect to one another, returned echo signal samples also show rapid fluctuations. To make a meaningful interpretation of Doppler radar data, echo signal samples need to be averaged in the resolution volume defined by the pulse length $c\tau/2$ and the beam-width θ (Fig. 1). The number of pulses, M, which hit the

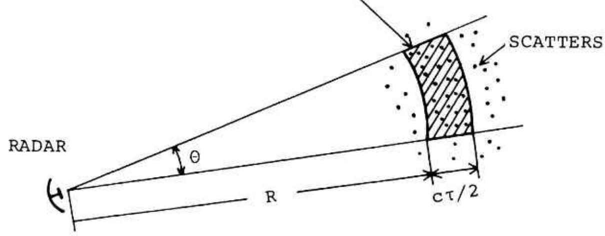

Fig. 1 Definition of the resolution volume; c is the speed of light, γ the pulse-width, θ the beam-width, and R the range from the radar.

Table 1 Scan rates and number of samples.

α (rpm)	1	2	3	6	15
M	256	128	64	32	16

resolution volume, is given by

$$M=\frac{PRF}{6\alpha}\cdot\theta, \tag{1}$$

where PRF is the pulse repetition frequency, θ the beam-width, and α the antenna scan rate. The number of samples which were used for averaging is shown in Table 1.

3.2 Method of error estimation

For a quantitative estimation of errors due to the rapid scan, the following method was applied.

Three kinds of image data which are shown in Fig. 2 are considered ; both 'IMAGE 0' and 'IMAGE 2' are obtained at a scan rate of 1 rpm and 'IMAGE 1' is obtained at a scan rate of n rpm (n=2, 3, 6, 15). Then, the difference $\Delta D(i, j)$ between 'IMAGE 1' and 'IMAGE 0' are calculated,

$$\Delta D(i, j)=D_1(i, j)-D_0(i, j), \tag{2}$$

where $D_1(i, j)$ is a value of the pixel at the grid point (i, j) of 'IMAGE 1', and $D_0(i, j)$ is that of 'IMAGE 0'. $\Delta D(i, j)$ can be regarded as a sum of the difference $\Delta D_S(i, j)$ caused by the difference in the scan speed and the difference $\Delta D_T(i, j)$ caused by the time lag between observations of 'IMAGE 0' and 'IMAGE 1',

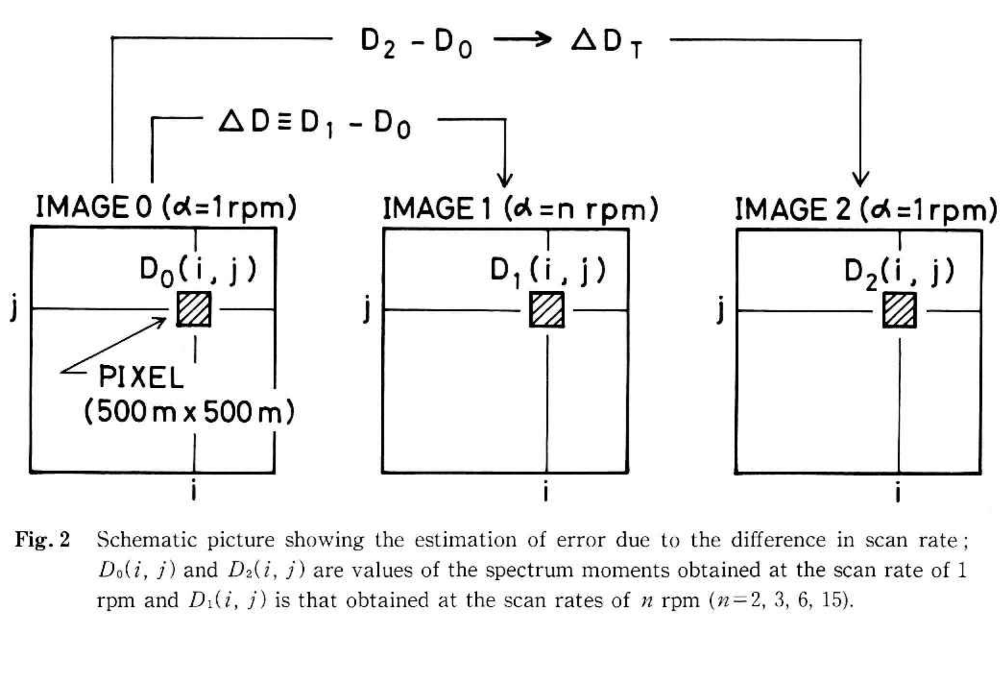

Fig. 2 Schematic picture showing the estimation of error due to the difference in scan rate ; $D_0(i, j)$ and $D_2(i, j)$ are values of the spectrum moments obtained at the scan rate of 1 rpm and $D_1(i, j)$ is that obtained at the scan rates of n rpm (n=2, 3, 6, 15).

$$\Delta D(i,\ j)=\Delta D_S(i,\ j)+\Delta D_T(i,\ j). \tag{3}$$

Using 'IMAGE 0' and 'IMAGE 2' data, $\Delta D_T(i,\ j)$ can be calculated by

$$\Delta D_T(i,\ j)=(D_2(i,\ j)-D_0(i,\ j))\frac{\Delta t_{1,0}}{\Delta t_{2,0}}, \tag{4}$$

where $D_2(i,\ j)$ is a value of the pixel at the grid point $(i,\ j)$ of 'IMAGE 2', $\Delta t_{1,0}$ is the time lag between the observations of 'IMAGE 1' and 'IMAGE 0', and $\Delta t_{2,0}$ is that of 'IMAGE 2' and 'IMAGE 0'. Substituting (2) and (4) to (3), $\Delta D_T(i,\ j)$ can be eliminated, and $\Delta D_S(i,\ j)$ can be calculated by

$$\Delta D_S(i,\ j)=D_1(i,\ j)-D_0(i,\ j)-(D_2(i,\ j)-D_0(i,\ j))\frac{\Delta t_{1,0}}{\Delta t_{2,0}}, \tag{5}$$

where $\Delta t_{1,0}$ is about 70 seconds and $\Delta t_{2,0}$ is about 80 to 110 seconds. Hereafter, $\Delta D_S/D_0$ is called a normalized error due to rapid scan.

3.3 Data

To investigate the effect of decrease in the number of pulses on the estimation of spectrum moments, observations of the stratiform precipitation during the Baiu season were carried out at different speeds of the antenna scan rate (1, 2, 3, 6, 15 rpm). The reason why the stratiform precipitation was investigated is that it can be regarded as being in a quasi-steady state during the data acquisition period of a few minutes, thus, we can examine the effect of the antenna scan rate on the estimation of spectrum moments.

For the error estimation of the reflectivity factor, the data of 10 dBZ or more are selected. For the error estimation of Doppler velocity, the data, the absolute values of which are less than an unambiguous velocity (16 m/s) and more than the resolution velocity (0.2 m/s) are selected.

4. Results

PPI images of reflectivity factors obtained at the scan rate of 1, 3, 6, and 15 rpm, respectively, are shown in Fig. 3. The no echo areas radiating in the direction of the azimuth angles of 120 degrees and 200 degrees are shadows of the radar observation due to structures near the radar site. By comparing each image, it can be seen that the echo shapes, especially on their boundaries, tend to be scattered according to the increase in the scan rate. This is recognized more clearly in the case of Doppler velocities (Fig. 4).

The scattering characteristic of the PPI image observed at a high scan rate may be due to the reduction of the number of samples for signal processing, or averaging. To investigate this more quantitatively, subtraction images for a reflectivity factor and Doppler velocities were calculated by Eq. (5) and shown in Fig. 5 and Fig. 6, respectively. In the figures the marks, $-$, $+$, and $*$ represent the grid points where the ratio $\Delta D_S/D_0$ is more than or equal to 5, 10, and 20 %, respectively. It can be noted that the faster the scan rate is, the larger the area of errors is. This means statistically that the variance of error increases with the scan rate.

Assuming that the distribution of the normalized error due to a rapid scan was Gaussian distribution, the mean and standard deviation of the error was calculated and

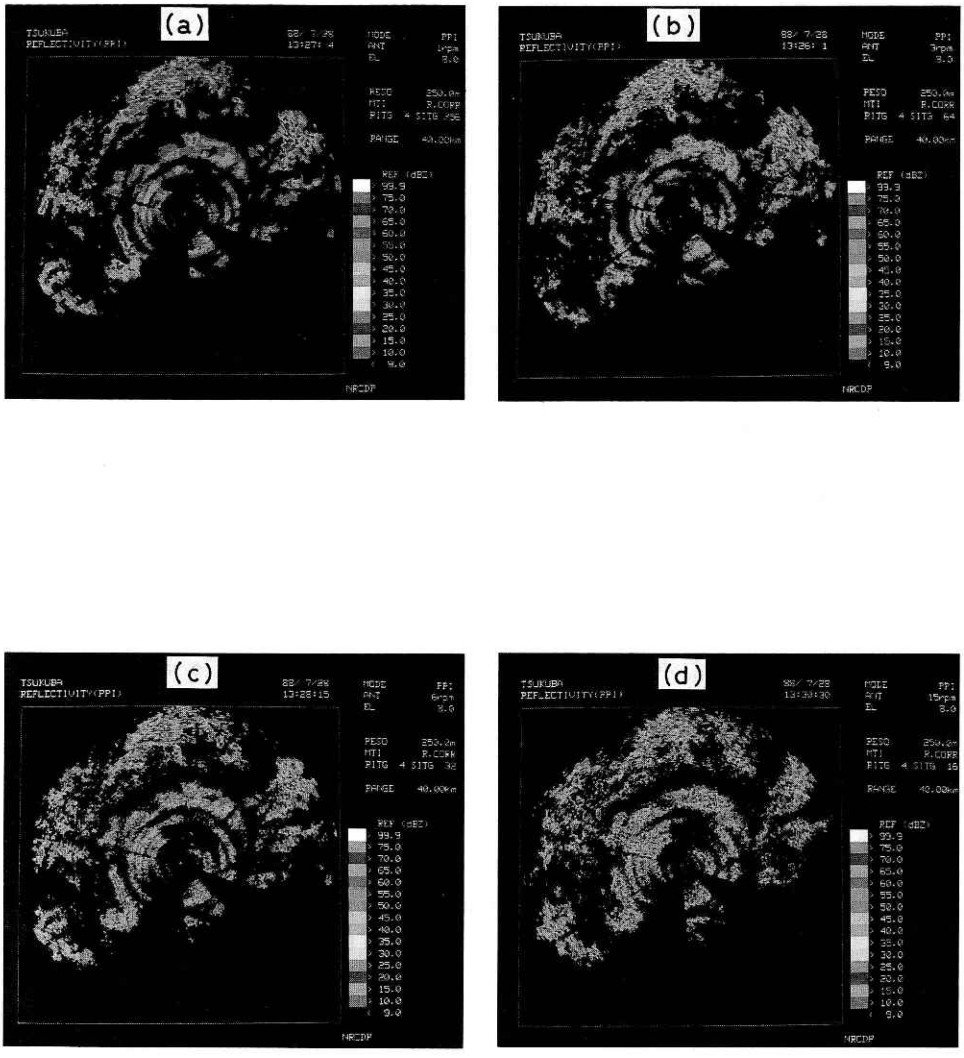

Fig. 3 PPI display of the reflectivity factor for the stratiform precipitation of July 28, 1988. Each photograph was obtained at the scan rate of (a) 1 rpm, (b) 3 rpm, (c) 6 rpm, and (d) 15 rpm, respectively. The elevation angle is 8.0 degrees.

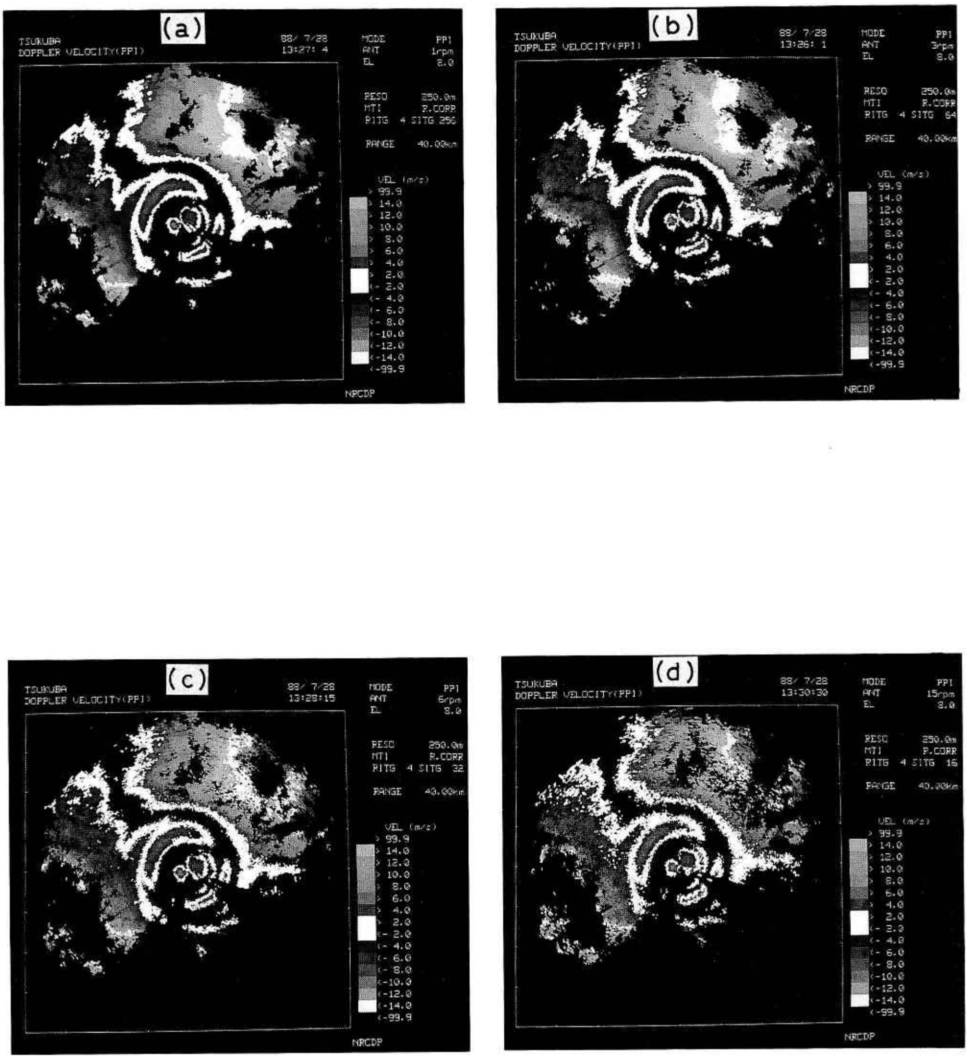

Fig. 4 As in Fig. 3 except for the Doppler velocities.

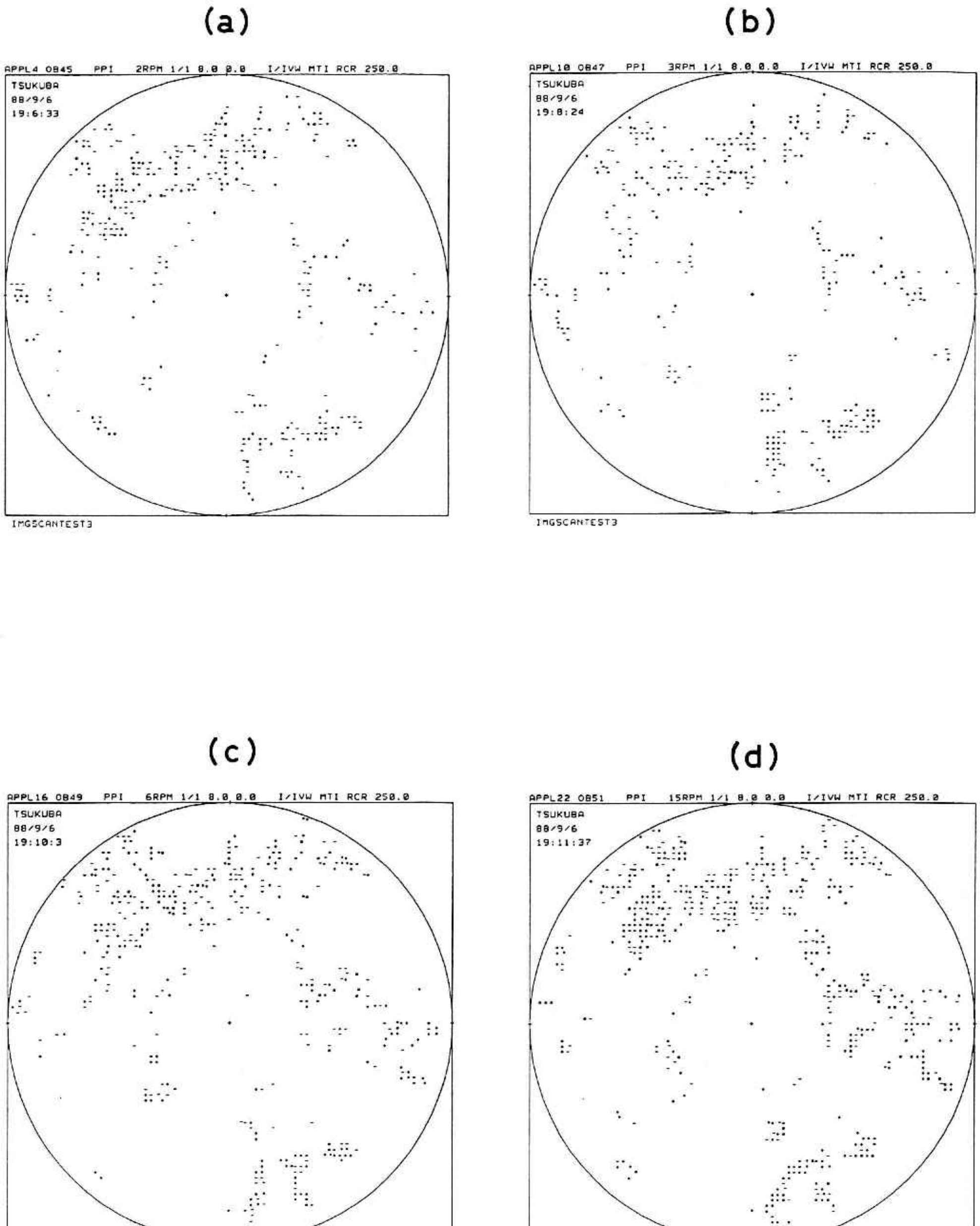

Fig. 5 Subtraction images of the reflectivity factor for the scan rate of (a) 2 rpm, (b) 3 rpm, (c) 6 rpm, and (d) 15 rpm.

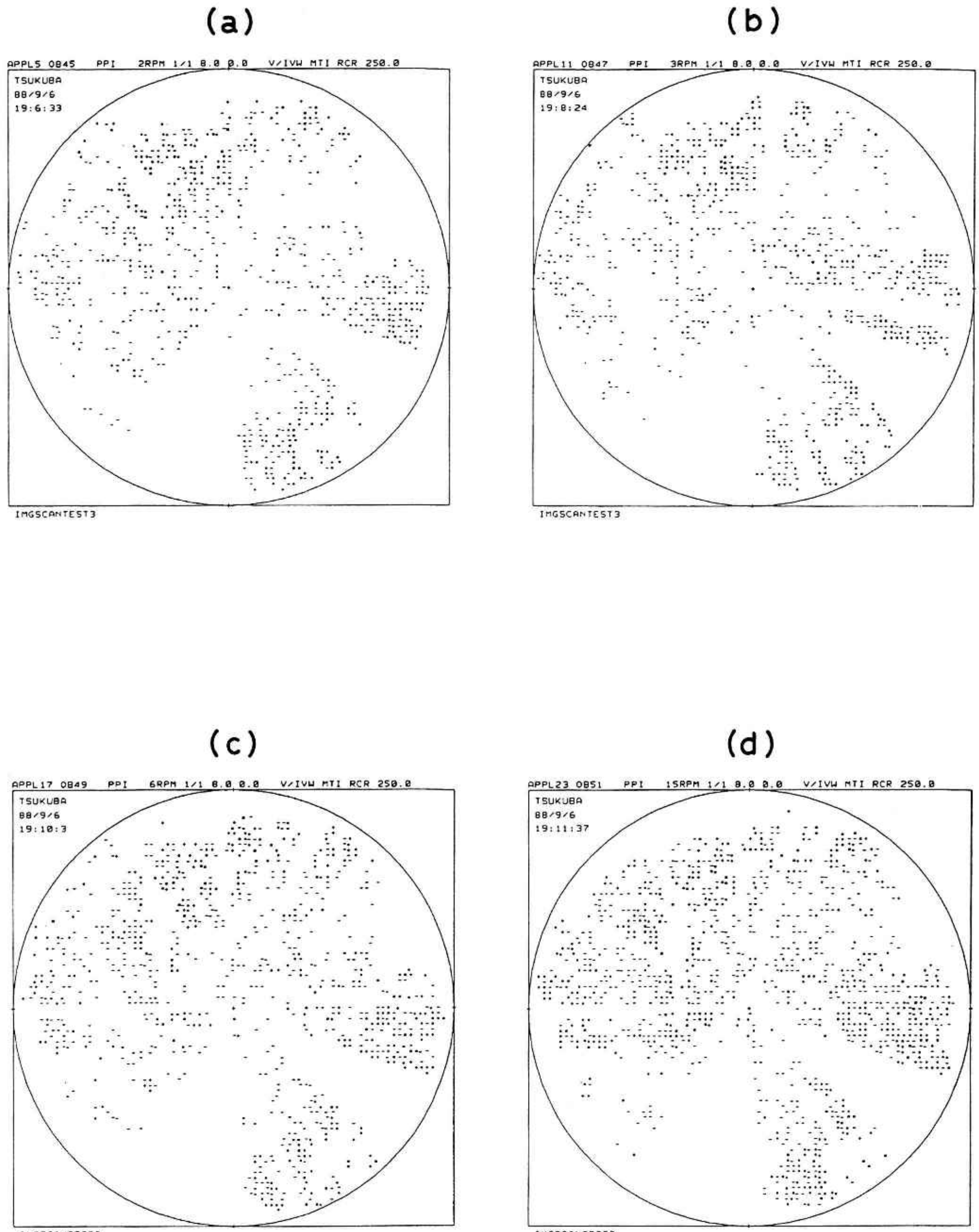

Fig. 6 As in Fig. 5 except for the Doppler velocities.

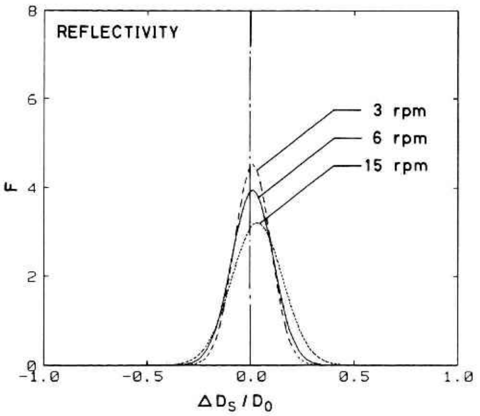

Fig. 7 Distributions of the normalized error $\Delta D_S/D_0$ for the reflectivity factor which is generated by rapid scan. Gaussian distribution function is assumed and F is the probability density.

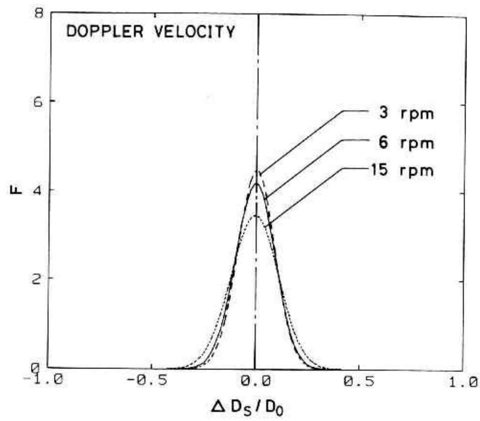

Fig. 8 As in Fig. 7 except for the Doppler velocities.

shown in Fig. 7 for a reflectivity factor and in Fig. 8 for Doppler velocities. As suggested by Fig. 5, the error distribution curves in Fig. 7 broaden with the increase in the scan rate, i.e., the standard deviation of error increases with the scan rate. As for the mean of $\Delta D_S/D_0$, the position of the axis of the error distribution curve shifted slightly to the right, i.e., bias in the estimation of the reflectivity factor was generated when the scan rate was 15 rpm while it was not generated when the scan rate was 3 and 6 rpm. This is explained theoretically by the fact that a back scattering cross section of precipitation particles satisfies the "Rayleigh approximation" and a returned echo can be expressed by the Rayleigh probability density (Marshall and Hitschfeld, 1953 ; Wallace, 1953). The error distribution curves in the case of Doppler velocities also broaden with the scan rate (Fig. 8). However, in this case, the error distribution curves does not shift.

For a more quantitative estimation of the change of the mean and standard deviation of error due to rapid scan, observations at different kinds of scan rates were carried out five times. The results are shown in Fig. 9 and Fig. 10. The vertical bars in the figures represent the degree of scatters in five time measurements. Each number M in the figures, 128, 64, 32, and 16, corresponds to the number of samples for averaging when the scan rate was 2, 3, 6, and 15 rpm, respectively. It is evident from the data in Fig. 9 that the mean of the error of the reflectiviity factor increases rapidly when M is less than about 30. In other words, if the scan rate is over about 6 rpm, the bias in the estimated mean reflectivity factor increases with the scan rate. These results conform well to the theoretical results (Zrnić, 1975 ; Zrnić, 1979). However, it must be stressed that the bias in the mean reflectivity factor at the scan rate of 15 rpm is only 3 %. The standard deviation of $\Delta D_S/D_0$, which may be used as a measure of the accuracy of the estimation, increases with a decrease in the number of samples.

The standard deviations of $\Delta D_S/D_0$ in the case of Doppler velocities also increase

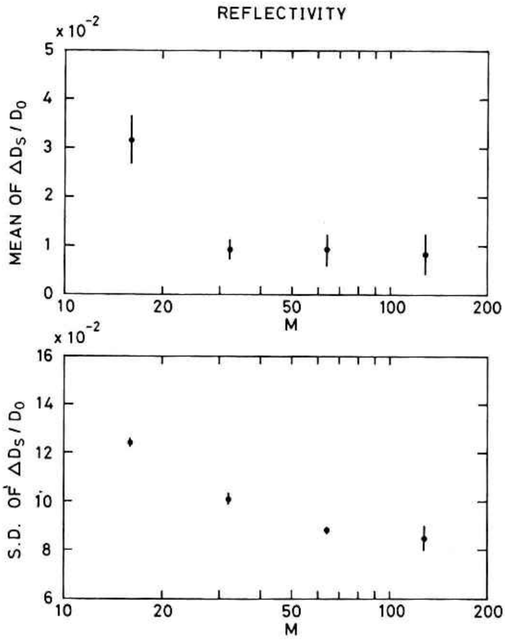

Fig. 9 Relationship between the mean of $\Delta D_S/D_0$ and M (upper), and the standard deviation of $\Delta D_S/D_0$ and M. M is the number of samples used to calculate the mean reflectivity factor.

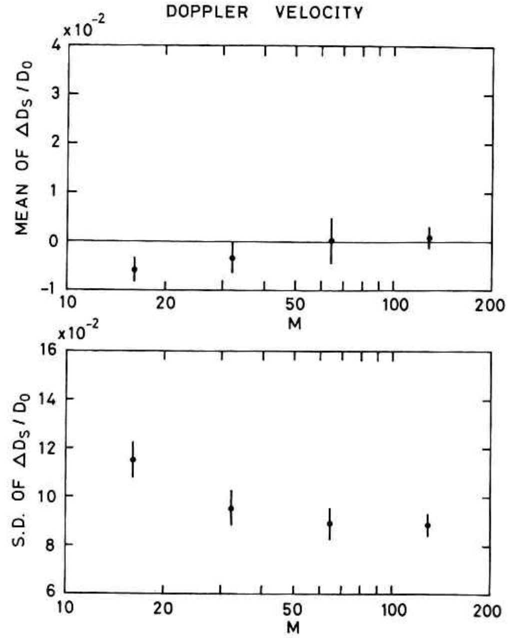

Fig. 10 As in Fig. 9 except for the Doppler velocities.

with a decrease in the number of samples as shown in Fig. 10, but the bias in the estimation of the mean Doppler velocity is not generated by a rapid scan.

5. Discussion

We stated in a previous paper (Maki *et al.*, 1989) that the Doppler radar of the National Research Center for Disaster Prevention (NRCDP) was designed to study meso-scale weather phenomena which often cause serious damage in daily life and public property, and the rapid scan is one of the performances required for observations of short-lived weather phenomena.

Here, a short discussion will follow regarding the characteristics of the phenomena for which NRCDP's rapid scanning Doppler radar can be used effectively.

As pointed out by Carbone and Carpenter (1983), a convective storm is one of the typical phenomena for which rapid scan Doppler radar can serve as a valuable observing tool. According to Battan (1973), the mean duration of individual convective echoes is about 20 minutes and the average time required for each echo to attain a mature stage is about 10 minutes. Battan (1980) also showed the highly turbulent and unsteady nature of the radar reflectivity factors and updrafts in relatively small thunderstorms, which were observed by a zenith-pointing Doppler radar. Vasiloff *et al.* (1985) investigated reflectivity and updraft growth rates of a thunderstorm that evolved from a group of small cells into a supercell storm and showed that reflectivity factor growth rates ranged from 4 to 7 dBZ per minute and that the updraft growth rate ranged from 3 to 7 m/s per minute.

Another example which requires the rapid scan observation is a hazardous wind which is known as a downburst. According to Fujita (1985) a downburst (macroburst and microburst), which is small in size (from less than one kilometer to tens of kilometers) and a short lifetime (from a few minutes to 30 minutes), is a strong downdraft which induces an outburst of strong wind on the ground.

The rapid scan is one tool required for the study of short-lived and rapidly evolving phenomena, some examples of which were mentioned above. Though technological developments of the radar system including antenna design, waveform design, and signal processing are needed for the rapid scan radar (Keeler and Frush, 1983), observation with rapid scan combined with antenna scanning strategies (Vasiloff *et al.*, 1985) will certainly bring significant developments in the study of short-lived weather phenomena. NRCDP's rapid scanning Doppler radar is used for the research project of orographically enhanced snowfall in basins and for the snowstorm observations in the Tohoku area (Maki *et al.*, 1989). These projects have just started and analyses of the observation data are in progress.

6. Conclusions

To investigate the effect of antenna rapid scan on the estimation of Doppler spectrum moments, Doppler radar observations were carried out at five different antenna rotation speeds (1, 2, 3, 6, 15 rpm). Stratiform precipitation during the Baiu season was chosen as the phenomenon of investigation because it tends to be in a quasi-steady state during an observation period of a few minutes. The following results were obtained.

When comparing images of the reflectivity factor and Doppler velocities observed at the scan rates of 1, 2, 3, 6, and 15 rpm,

(1) although substantial differences among the images could not be recognized, a smooth image tended to be scattered especially on the echo boundary in relation to the scan rate.

According to the estimation of error due to the increase in the scan rate,

(2) a bias is generated in the estimation of the mean reflectivity factor when the scan rate is over about 6 rpm, and the normalized error due to a rapid scan, $\Delta D_S/D_0$, becomes about 3 % when the scan rate is 15 rpm.

(3) The rapid scan does not generate any bias in the case of the estimation of Doppler velocity.

(4) Standard deviations of the estimated mean reflectivity factor and Doppler velocity increase with the scan rate, i.e., they increase with a decrease in the number of samples taken for averaging.

In addition to the results mentioned above, it must be stressed that an error due to a rapid scan can be acceptable when rapid observations of short-lived atmospheric phenomena are required. The observations at the scan rate of 15 rpm will increase our knowledge about those phenomena.

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(Manuscript received July 24, 1989)

Report of the National Research Center for Disaster Prevention, No. 44, October. 1989

ドップラースペクトルモーメントの推定に及ぼす空中線高速スキャンの影響

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要　旨

ドップラースペクトルモーメント（レーダー反射強度，ドップラー速度）の推定に及ぼすドップラーレーダー空中線速度の影響を調べるために，データ取得時間（約2分）の間は準定常状態にあるとみなせる梅雨期の層状性の降水現象について空中線スキャン速度を変えてドップラーレーダー観測を行なった．

スキャン速度を変えて観測したレーダー反射強度およびドップラー速度の画像の比較からスキャン速度による本質的な違いは見られないものの，スキャン速度が遅くなると滑らかな画像が特にエコーの境界付近でこわれる傾向が認められた．この空中線スキャンの高速化に伴う誤差の定量的な推定を行なった結果，レーダー反射強度について，スキャン速度が6 rpmまでは影響がないが15 rpmになると約3％ではあるがレーダー反射強度が大きく見積られることがわかった．これは高速化により信号処理に用いられるサンプル数が減少するためである．ドップラー速度についてはこのようなバイアスは生じなかった．また，推定された高速スキャンによる誤差の標準偏差はサンプル数の減少に応じて増加する事がわかった．

最後に空中線の高速スキャンが要求される大気現象についていくつかの例を挙げて議論した．

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