Assessment of radar reflectivity and Doppler velocity measured by *Ka*-band FMCW Doppler weather radar

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Abstract. This study proves the measurement capability of a *Ka*-band frequency modulated continuous wave (FMCW) Doppler weather radar (KaDR) developed for the Japanese cloud seeding experiments for precipitation augmentation (JCSEA) research project. To continuously monitor precipitation and clouds with reduced maintenance costs, KaDR uses a traveling wave tube (TWT) transmitter which is originally designed for satellite communication. The TWT produces signals with a frequency of 35.25 GHz (8-mm wavelength) and a peak power of 100 W. Because the peak power of the TWT was small compared with conventional *Ka*-band weather radars which use transmission tubes, KaDR transmits FMCW in order to attain enough sensitivity and range resolution.

Using the dataset collected from 1700 JST 25 October to 0300 JST 26 October 2009 at Shigaraki MU Observatory (34°51′N, 136°06′E, 385 m above the sea level), the equivalent radar reflectivity factor (*Z*<sub>e</sub>) and Doppler velocity (*V*<sub>d</sub>) measured by KaDR were compared with micro rain radar (MRR). To evaluate *Z*<sub>e</sub> (*V*<sub>d</sub>) measured by KaDR, a correlation coefficient and regression line were computed using a scatter plot between the two *Z*<sub>e</sub>s (*V*<sub>d</sub>s). High correlation coefficient of 0.904 (0.912) and regression slope of 1.023 (1.038) between the two *Z*<sub>e</sub>s (*V*<sub>d</sub>s) demonstrate the capability of KaDR to measure *Z*<sub>e</sub> and *V*<sub>d</sub> quantitatively.

Keywords: weather radar, Doppler radar, millimeter wave, frequency modulated continuous wave (FMCW), micro rain radar

1. Introduction

Nationwide C-band weather radar network in Japan is an indispensable mean for monitoring rainfall intensity (Makihara, 2007; Makihara et al., 1996). In Japan, X-band weather radars also have been widely used for studying severe storms and for monitoring regional rainfall intensity (Inoue et al., 2011; Kato and Maki, 2009; Maki et al., 2005). Though weather radars operated at or below X-band frequency are useful to detect raindrops with negligible or small radio wave attenuation, they cannot detect a small-sized hydrometeor such as drizzle and cloud particle. On the other hand, though weather radars operated at 35 GHz or 94 GHz frequency (i.e., 8-mm or 3-mm wavelength; hereafter millimeter-wave radars) suffer larger attenuation by atmospheric gases and raindrops than radars operated at or below X-band frequency, they have sufficient sensitivity to detect the small-sized hydrometeors due to their short wavelengths. Therefore millimeter-wave radars have been used for applications ranging from detailed cloud and precipitation process studies to long-term monitoring activities.
that strive to improve our understanding of cloud processes over a wide range of spatial and temporal scales (Kollia et al., 2007). Currently, for cloud and precipitation researches, millimeter-wave radars were developed and are operated by Japanese research institutes (e.g., Hamazu et al., 2003; Horie et al., 2000; Iwanami et al., 2001; Takano et al., 2010).

Transmission tubes (e.g., magnetron, klystron, traveling wave tube (TWT)) can produce a peak output power of several ten kW or greater, and hence have been widely used for millimeter-wave radars. However, purchase and maintenance costs of large-power transmission tubes were not suitable for research usages with limited budget and networked and/or long-term monitoring of cloud and precipitation. Though range aliasing causes a spurious radar echo in the presence of strong hydrometeor scattering, pulse compression techniques using phase coding (e.g., Moran et al., 1998) or frequency modulated continuous wave (FMCW) chirping (e.g., Takano et al., 2010; Yoshikawa et al., 2010) enable weather radars to attain all of high sensitivity, reduced operation costs, and long-term observations. In order to continuously monitor cloud and precipitation with minimum maintenance time and cost, a Ka-band Doppler weather radar using TWT with small peak power of 100 W and FMCW chirping (hereafter KaDR) were developed under the Japanese cloud seeding experiments for precipitation augmentation (JCSEPA) research project (Ohigashi et al., to be submitted). In order to quantitatively evaluate a measurement capability of KaDR, equivalent radar reflectivity factor \( Z_e \) and Doppler velocity \( V_d \) measurements by collocated KaDR and Micro Rain Radar (Meteorologische Messtechnik GmbH, 2005; hereafter MRR) were carried out at Shigaraki MU Observatory, Japan (34°51’N, 136°06’E, 385 m above the sea level) from 25 to 26 October 2009. In this study, \( Z_e \) and \( V_d \) measured by KaDR (hereafter \( Z_{e,KaDR} \) and \( V_{d,KaDR} \), respectively) were compared with those measured by MRR (hereafter \( Z_{e,MRR} \) and \( V_{d,MRR} \), respectively) in order to prove the measurement capability of KaDR.

### Table 1: Specifications of KaDR

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Antenna</td>
<td>Two antennas each for transmission and reception, 46 dB gain, 0.55° beam width, and 1.2 m diameter</td>
</tr>
<tr>
<td>Center frequency</td>
<td>35.25 GHz</td>
</tr>
<tr>
<td>Transmitter</td>
<td>TWT with a peak power of 100 W</td>
</tr>
<tr>
<td>Sweep rate of carrier frequency</td>
<td>3.0 MHz / 40.96 ( \mu )s</td>
</tr>
<tr>
<td>Range resolution</td>
<td>50 m</td>
</tr>
<tr>
<td>Maximum data sampling height</td>
<td>15 km</td>
</tr>
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</table>

2. Signal processing

2.1. KaDR

Table 1 lists principal specifications of KaDR. Two antennas, one for transmission (hereafter TX) and the other for reception, were covered by slanted radomes (Fig. 1a) and separated by radio wave absorbent material in order to protect the antennas from radio wave interferences between them. A distance between the two antennas was 1.8 m. The beam direction of KaDR was fixed to the vertical incidence. In order to attain continuous long-term observation over several months or longer without regular maintenance, KaDR uses a 100-W TWT originally designed for spaceborne broadcast transmitter. The center carrier frequency is 35.25 GHz, and 3-MHz frequency sweep is done during a sampling time of 40.96 \( \mu \)s. Therefore improvement of range resolution down to 50 m and transmission gain of 20.9 dB (i.e., equivalent peak output power up to 12.3 kW) can be attained. Frequency conversion for detecting beat signals and phase
and $Q$ signals are consecutively digitized with a sampling frequency of 100 MHz. Ranging was executed by applying Fast Fourier Transform (FFT) to the digitized $I$ and $Q$ signals. The number of data sampling (4096) is selected so that the frequency resolution of FFT (24.4 kHz; hereafter $\Delta f$) matches the range resolution of 50 m; the 24.4-kHz band width is the same as the frequency sweep within a duration of 0.33 $\mu$s ($= \frac{1}{3\text{MHz}}$), which corresponds to the 50 m range resolution.

![Fig. 1: Outside view of the (a) outdoor and (b) indoor unit of KaDR.](image)

$Z_{e_{\text{KaDR}}}$ and $V_{d_{\text{KaDR}}}$ were computed using Doppler spectra measured at each range gate. In order to secure time necessary for storing Doppler spectrum data to the hard disk drive, data sampling of KaDR was not continuous. During the experiment described in this study, 256-point consecutive time series of received signal were sampled every 20 s. Inter pulse period was 200 $\mu$s. Using a 256-point time series measured at an identical range gate, a Doppler spectrum is computed. Using the Doppler spectra, spectral moments were calculated in order to produce $Z_{e_{\text{KaDR}}}$ and $V_{d_{\text{KaDR}}}$ data. Fig. 2 is an example of Doppler spectrum measured by KaDR. For details of $Z_e$ and $V_d$ computation from Doppler spectra, see Doviak and Zrnić (1993).

$Z_{e_{\text{KaDR}}}$ was computed using the zeroth-order moment of Doppler spectrum and radar system parameters measured or designed in the factory. Because KaDR uses two antennas, $Z_{e_{\text{KaDR}}}$ was computed using a radar equation based on a bistatic configuration. The most significant factor that affected the $Z_e$ computation was a range dependency of two-way antenna beam pattern (Yamaguchi et al., 2009). A value of two-way antenna gain was computed by numerical calculation. TX and RX antennas were assumed to be parallel to one another and point vertically. Far-field approximation was applied to compute the antenna beam pattern. Fig. 3 shows a range dependency of a loss of the two-way antenna gain compared with monostatic radar configuration, in which it is assumed that only one antenna was used for TX and RX. Because the lowest distance at which far-field approximation can be applied in the antenna beam pattern of KaDR is 340 m, the value of two-way antenna gain above 340 m was plotted. The loss in antenna gain was 2.0 dB at 400 m above the ground level (AGL), 0.9 dB at 600 m AGL, and reduced to less than 0.3 dB above 1.0 km AGL. In order to interpret $Z_{e_{\text{KaDR}}}$ signals without corrections, corrections of radio wave attenuation by raindrops and non-Rayleigh scattering effect were not done.
The expected sensitivity of KaDR is roughly estimated. Minimum detectable $Z_{e_{\text{KaDR}}}$ was computed using the radar equation based on the bistatic configuration. To simplify the calculation, attenuation by hydrometeors is not considered. Because gaseous attenuation is small (typically $\sim 0.1$ dB km$^{-1}$ or less), it is not taken into account. Because FMCW radars transmit and receive signals simultaneously, leakage of transmitted signals to the receiver is a factor that deteriorates the sensitivity of KaDR. However, only effect of receiver noise is considered to compute the sensitivity under the optimum condition. A noise figure (NF) of the low-noise amplifier (LNA) is 3.5 dB, and the loss between the receive antenna and LNA (L) is 1.3 dB. Therefore, for the ambient temperature ($T_a$) value of 300 K, the receiver noise temperature ($T_r$) is $T_r = (L - 1) + L(NF - 1))T_a = 606$ K. Using the value of Boltzmann constant $k_B = 1.38 \times 10^{23}$ JK$^{-1}$, the receiver noise level ($P_n$) becomes $P_n = k_BT_r\Delta f = -127$ dBm. When we assume that the minimum detectable signal-to-noise ratio (SNR) is 3 dB (i.e., minimum detectable signal level of $-124$ dBm), the minimum detectable $Z_{e_{\text{KaDR}}}$ is estimated to be $-50$ dBZ$_e$ at 1.0 km AGL and $-36$ dBZ$_e$ at 5.0 km AGL.

$V_{d_{\text{KaDR}}}$ was computed from the first-order moment of Doppler spectrum. The use of two antennas can cause misestimation of $V_{d_{\text{KaDR}}}$ because the center of beam direction determined by the two-way beam direction was not pointed to the vertical incidence exactly. Therefore, possible errors in $V_{d_{\text{KaDR}}}$ measurements were estimated by numerical computation. A range dependency of two-way beam pattern as described by Yamaguchi et al. (2009) and Doppler velocity computation for bistatic radars as described by Protat and Zawadzki (1999) were taken into account in the numerical computation. Fig. 4 shows a range dependency of estimated error in $V_{d_{\text{KaDR}}}$ caused by contamination of horizontal wind velocity to $V_{d_{\text{KaDR}}}$. In order to investigate the worst case, the direction of horizontal wind was set to be parallel to the direction of antenna alignment. See Yamamoto et al. (2003) for details of the mechanism how the horizontal wind velocity affects vertical velocity measurement when a radar beam was not pointed to the vertical incidence exactly. In the case of horizontal wind velocity of 30 m s$^{-1}$, contamination of horizontal wind velocity to $V_{d_{\text{KaDR}}}$ was 0.03 m s$^{-1}$ at 0.4 km AGL and less than 0.01 m s$^{-1}$ above 1.3 km AGL. Measurement error by vertical velocity itself caused by the tilt of beam direction is another factor that affects the $V_{d_{\text{KaDR}}}$ measurement. However, the measurement error by vertical velocity itself was less than
0.001% above 0.4 km AGL (not shown as a figure). Therefore, effects of the two-way antenna beam pattern on $V_{\text{dkaDR}}$ measurement were concluded to be negligible.

Fig. 3: Range dependency of the loss of the two-way antenna gain compared with the assumed monostatic radar configuration.

2.2. MRR

During 25-26 October 2009, KaDR and MRR were operated at Shigarakai MU Observatory. MRR is a small-sized Doppler weather radar operated at 24-GHz center frequency. MRR transmits FMCW for improving sensitivity and range resolution, and its beam direction is fixed to the vertical incidence. MRR observation software processed $Z_{\text{eMRR}}$ and $V_{\text{dmMRR}}$ with 1-min and 150-m intervals in real time. To confirm the correctness of $Z_{\text{eMRR}}$ measurement, rainfall amount measured by MRR was compared with that measured by a surface rain gauge installed at Shigarakai MU Observatory. Total rainfall amount measured by the surface rain gauge was 46.3 mm during 25-26 October 2009, and that measured by MRR at the lowest observation height (150 m AGL) and 300 m AGL were 38.9 mm and 46.5 mm, respectively. Though there are sensitivity and measurement method differences between the surface rain gauge and MRR, the difference between the two rainfall amounts was less than 16% (i.e., 0.78 dB) within the 300 m height range from the ground and hence indicates that $Z_{\text{eMRR}}$ was useful to be used as the standard value for assessing $Z_{\text{eKadr}}$. Though raindrops cause significant radio wave attenuation and do not exactly follow the Rayleigh scattering approximation at the MRR wavelength (~1.25 cm), these effects on $Z_{\text{eMRR}}$ computation were corrected in the MRR observation software (Meteorologische Messtechnik GmbH, 2005). The non-Rayleigh scattering effect on $V_{\text{dmMRR}}$ computation was not corrected.

2.3. LQ-7

To assess the $V_{\text{dkaDR}}$ measurement, a Doppler radar referred to as LQ-7 (Imai et al., 2007; Yamanaka et al., 2008) was also used. Using radio wave scattering from clear-air turbulence, LQ-7 operating in a center frequency of 1.3575-GHz measures height profiles of vertical and horizontal winds in clear skies. However, because LQ-7 preferentially detects hydrometeor echoes in precipitating conditions, LQ-7 can measure $V_d$ using hydrometeor echoes (Tabata et al., 2011). LQ-7 has a phased array antenna which can point the radar beam to the vertical direction and north, east, south and west directions with a zenith angle of 14°. However, during the field experiment,
the radar beam of LQ-7 was pointed only to the vertical direction in order to match the beam direction of KaDR. 512-point Doppler Spectra were processed every 6.14 s, and Nyquist velocity and spectral resolution were 23 m s$^{-1}$ and 0.09 m s$^{-1}$, respectively. Sampling interval of 150 m in the range direction matches the range resolution determined by the transmitted pulse width of 1 µs. The procedure to compute $V_d$ measured by LQ-7 ($V_{dLQ-7}$) was the same as $V_{dKaDR}$. In order to compare the observational results of KaDR with those of LQ-7 accurately, $V_{dLQ-7}$ data which were misestimated due to contamination of clear-air echoes were carefully removed.

![Horizontal wind velocity contamination](image)

**Fig. 4:** Range dependency on the measurement error of $V_{dKaDR}$ caused by contamination of horizontal wind velocity.

3. **Comparison results between KaDR and MRR**

3.1. $Z_e$

Scatter plots are presented to quantitatively evaluate relations between $Z_{eKaDR}$ and $Z_{eMRR}$ and those between $V_{dKaDR}$ and $V_{dMRR}$. Because radio wave attenuation by water coated on the antenna radome of KaDR causes significant errors in $Z_{eKaDR}$ evaluation, the period from 1700 JST 25 October to 0300 JST 26 October 2009, when surface rainfall was almost absent, was used for producing the scatter plots. $Z_{eKaDR}$, $Z_{eMRR}$, $V_{dKaDR}$, and $V_{dMRR}$ were averaged over 1-min period in order to reduce their fluctuations. $Z_{eKaDR}$, $Z_{eMRR}$, $V_{dKaDR}$, and $V_{dMRR}$ data in a height range of 0.6-1.9 km AGL were used in order to produce the scatter plots. The lowest height used for producing the scatter plots (0.6 km AGL) was selected to remove possible clutter contamination in Doppler spectra measured by KaDR. Note that the lowest distance at which far-field approximation can be applied in the antenna beam pattern of KaDR is 340 m, and hence the far-field approximation was able to be applied in the height range used for producing the scatter plots. The highest height used for producing the scatter plots (1.9 km above AGL) was selected because the correction of radio wave attenuation and non-Rayleigh scattering effects for $Z_{eMRR}$ are effective only for raindrops, and a melting layer in which a hydrometeor can have both ice and liquid phases was observed above 1.9 km AGL. $Z_{eKaDR}$ and $V_{dKaDR}$ were averaged in height in order to match the 150-m range resolution of MRR. The range dependency of the loss of the two-way antenna gain, which is shown in Fig. 3, was corrected in the $Z_{eKaDR}$ computation.

Fig. 5a shows the scatter plot of $Z_{eMRR}$ and $Z_{eKaDR}$. There are factors that cause errors both in the $Z_{eMRR}$ and $Z_{eKaDR}$ measurements. The receiver noise of MRR (KaDR)
causes errors in the sampled $Z_{\text{eMRR}}$ ($Z_{\text{eKaDR}}$) values. Further, the radar configuration differences between MRR and KaDR (e.g., the sampling volume and sampling time) cause differences between the $Z_{\text{eMRR}}$ and $Z_{\text{eKaDR}}$ values. However, because differences between the $Z_{\text{eMRR}}$ and $Z_{\text{eKaDR}}$ values caused by the above-mentioned factors are independent from sample to sample, their effects can be reduced by using the indices which are computed statistically. Therefore, the correlation coefficient (hereafter $r$) and regression line, both of which were computed statistically, were used to assess the relation between $Z_{\text{eMRR}}$ and $Z_{\text{eKaDR}}$ quantitatively. $Z_{\text{eKaDR}}$ tended to be smaller than $Z_{\text{eMRR}}$ where $Z_{\text{eMRR}}$ was greater than $\sim 25$ dBZ$_{e}$, probably due to greater non-Rayleigh scattering effects for large-sized raindrops. However, the data points with $Z_{\text{eMRR}}$ greater than $25$ dBZ$_{e}$ were not so significant for values of $r$ and regression line. Though there were possible effects that caused misestimation of $Z_{\text{eKaDR}}$ (radio wave attenuation by raindrops, non-Rayleigh scattering, and differences in sampling volume and time), high $r$ of 0.904 and regression slope close to 1.0 (1.023) computed between the two $Z_{e}$s indicate that $Z_{\text{eKaDR}}$ agrees well with $Z_{\text{eMRR}}$. Further, the difference between $Z_{\text{eMRR}}$ and $Z_{\text{eKaDR}}$ estimated by the regression line ranged from 0.38 to 0.84 dB for $Z_{\text{eMRR}}$ range of 10-30 dBZ$_{e}$. The small difference between the two $Z_{e}$s indicates that KaDR worked with expected system performance as designed and produced in the factory.

Fig. 5: (a) Scatter plot of $Z_{\text{eMRR}}$ and $Z_{\text{eKaDR}}$ in the period from 1700 JST 25 October to 0300 JST 26 October 2009 and the height range of 0.6-1.9 km AGL. Gray lines present the regression line. (b) Same as (a) except for $V_{d\text{MRR}}$ and $V_{d\text{KaDR}}$.

3.2. $V_d$

Fig. 5b shows the scatter plot of $V_{d\text{MRR}}$ and $V_{d\text{KaDR}}$. $V_{d\text{KaDR}}$ tended to be smaller than $V_{d\text{MRR}}$ where $V_{d\text{MRR}}$ was greater than $\sim 7$ m s$^{-1}$, probably due to greater non-Rayleigh scattering effect for large-sized raindrops. However, the data points with $V_{d\text{MRR}}$ greater than $\sim 7$ m s$^{-1}$ were not so significant for values of $r$ and regression line. The difference between $V_{d\text{MRR}}$ and $V_{d\text{KaDR}}$ estimated by the regression line ranged from 0.002 to 0.135 m s$^{-1}$ for $V_{d\text{MRR}}$ range of 3.0-6.5 m s$^{-1}$. The small difference and high $r$ (0.912) between the two $V_d$s indicate that $V_{d\text{KaDR}}$ agrees well with $V_{d\text{MRR}}$. The comparison results between $V_{d\text{MRR}}$ and $V_{d\text{KaDR}}$ clearly prove the capability of $V_d$ measurement of KaDR.

It is noted that the non-Rayleigh scattering effect existing both for MRR and KaDR contribute to the agreement between $V_{d\text{MRR}}$ and $V_{d\text{KaDR}}$. To confirm the non-Rayleigh
scattering effect on the $V_{dMRR}$ and $V_{dKaDR}$ measurements, LQ-7 was used additionally. Because LQ-7 was operated with a much lower frequency (1.3575 GHz) than MRR and KaDR (i.e., 24 GHz and 35.25 GHz), the non-Rayleigh scattering effect is negligible for the LQ-7 measurement. $V_{dKaDR}$ and $V_{dLQ-7}$ data in a height range of 1.0-4.0 km AGL were used in order to produce the scatter plots. The lowest height used for producing the scatter plot (1.0 km AGL) was selected to remove possible clutter contamination in Doppler spectra measured by LQ-7. The highest height used for producing the scatter plot (4.0 km AGL) was selected to remove a possible effect of range aliasing in Doppler spectra measured by KaDR. $V_{dKaDR}$ was averaged over 150 m in height in order to match the 150-m range resolution of LQ-7. The period from 1700 JST 25 October to 0300 JST 26 October 2009 was used for the data analysis. $V_{dKaDR}$ and $V_{dLQ-7}$ were averaged over 1-min period in order to reduce their fluctuations. Fig. 6 shows a scatter plot of $V_{dLQ-7}$ and $V_{dKaDR}$. $V_{dKaDR}$ tended to be smaller than $V_{dLQ-7}$ as shown by the regression intercept ($-0.280$). This discrepancy can be explained by the non-Rayleigh scattering effect which was significant only for KaDR. However, it should be noted that high $r$ (0.990), regression slope close to 1.0 (1.030) computed between the two $V_d$s indicate that except the existence of non-Rayleigh scattering effect on the $V_{dKaDR}$, $V_{dKaDR}$ agrees well with $V_{dLQ-7}$.

Fig. 6: Scatter plot of $V_{dLQ-7}$ and $V_{dKaDR}$ in the period from 1700 JST 25 October to 0300 JST 26 October 2009 and the height range of 1.0-4.0 km AGL. Gray line presents the regression line.

4. Conclusions

KaDR is a Ka-band Doppler radar which attains low purchase and maintenance costs. To attain high cost performance, KaDR uses a TWT with a small peak output power of 100 W and FMCW transmission. By comparing $Z_{eKaDR}$ ($V_{dKaDR}$) with $Z_{eMRR}$ ($V_{dMRR}$) collected in the field experiment at Shigaraki MU Observatory during 25-26 October 2009, measurement capability of KaDR was demonstrated (Fig. 5). The authors believe that the results presented in this study are useful for current and future users of KaDR. The results showing the usefulness of a combination of commercial-based TWT and FMCW transmission would contribute to future development of millimeter-wave Doppler weather radar, because high cost performance is strongly required for research usages with limited budget and networked and/or long-term monitoring of cloud and precipitation. Further observational results of KaDR at Shigaraki MU observatory will be reported in subsequent studies.
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