A 35-GHz Scanning Doppler Radar for Fog Observations

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ABSTRACT

To observe fog, a 35-GHz scanning Doppler radar was designed, assembled, and tested. The radar, mounted on a flatbed vehicle for portability, transmits peak powers of 100 kW in a pulse of 0.5-μs width and a beamwidth of 0.38°. Thus, a reflectivity factor $Z$ of $-20$ dBZ at a range of 10 km generates a signal-to-noise ratio of 0 dB. Doppler velocity measurements are made by sampling the radio frequency phase within each pulse transmitted by a magnetron oscillator and referencing the phases of the received echoes to the transmitted phase. A Nyquist velocity of approximately 9.7 m s$^{-1}$ is obtained in real time using the spaced pulse-pair method, and aliases of radial velocities are corrected using software. The three-dimensional structure of sea fog and its advection are depicted with the radar.

1. Introduction

Fog is, in simple terms, a cloud near the ground. The minute water drops floating in the air that compose the fog have sizes of approximately several tens of micrometers (i.e., approximately two orders of magnitude smaller than that of raindrops). Although there are optical remote sensing techniques (e.g., lidar, ceilometer, etc.) to measure fog properties, optical signals cannot penetrate into thick fog to observe the fog’s horizontal and vertical dimensions and its internal structure. On the other hand, radar signals can penetrate fog to measure its three-dimensional reflectivity and velocity structure.

Since the backscatter cross section of tiny drops (i.e., several tens of micrometers in diameter) increases in proportion to $\lambda^{-4}$, where $\lambda$ is the radar wavelength, fog and cloud drops are more easily detected by radars of millimeter rather than centimeter wavelengths. On the other hand, attenuation of millimeter waves is much stronger, and the $\lambda^{-4}$ advantage gained using millimeter waves is offset by the strong attenuation these waves experience. For example, the 10-cm-wavelength Weather Surveillance Radar-1988 Doppler (WSR-88D) (e.g., Heiss et al. 1990), used principally for storm warnings by the U.S. National Weather Service, can detect a reflectivity factor of about $-28$ dBZ at a range of 5 km, about equal to that of the 8.6-mm-wavelength radar described in this paper. Although the two radars’ detection capabilities are equivalent, the angular resolution of the millimeter radar is a factor of 3 better (i.e., 0.3° vs 1.0°). Because there are several strong absorption bands at millimeter wavelengths, observations are practical at few spectral windows (i.e., $\lambda = 8.6, 3.2, 2.14, \text{and } 1.36 \text{ mm}$). But, high-power millimeter-wave radars are only affordable at $\lambda = 8.6$ and 3.2 mm (i.e., 35 and 95 GHz).

Several 35-GHz research radars have been developed for the purpose of cloud observation in the vertical direction (e.g., Pasqualucci 1984; Pasqualucci et al. 1983; Hobb et al. 1985). Sekelsky and McIntosh (1996) and Mead et al. (1994) describe multiparameter 33- and 95-GHz radars for profiling clouds; the 33-GHz radar has a peak power of 120 kW. Nakamura and Inomata (1992) used 3-cm- and 8-mm-wavelength radars to observe precipitation. Yanagisawa et al. (1986) observed sea fog with a 35-GHz non-Doppler radar. An important instrument for the Atmospheric Radiation Measurement (ARM) experiment, recently conducted in the western part of the Pacific Ocean, is a 35-GHz Doppler radar (Moran et al. 1998). The ARM radar was developed for the use of cloud physics research. The main purpose is to determine cloud boundaries, for example, cloud bottoms and tops. The ARM radars are operating continuously in Oklahoma and Alaska, in addition to three
locations in the Pacific Ocean area. Several 94- and 95-GHz radars have also been developed for cloud physics research (Lhermitte 1987; Pazmany et al. 1994). The main purpose of the radar described in this paper is to map the reflectivity and velocity structure of fog; this requires relatively high transmitted powers, an antenna that scans, and a coherent receiver. There are few reports of high-power scanning millimeter-wavelength Doppler radars (e.g., Kropfl et al. 1984, 1995; Sekelsky and McIntosh 1996). These radars are essential for the observation of the three-dimensional structure of fogs and clouds.

The system configuration and operation of the radar are discussed in section 2. Section 3 describes the Doppler velocity estimation and the method to resolve velocity ambiguities. Section 4 discusses the radar performance for the observations of fog. In section 5, we present the results of the first observations of sea fog. Section 6 concludes with comments about the system and its potential for the observation of fog and clouds.

2. System configuration of the radar

The primary functions of this radar are to determine the spatial distribution of nonprecipitating water particles, such as those found in fog, and to obtain the movement of them in real time. The design concept for the radar is that it be reliable and easy to relocate. Also the cost of the transmitting tube, the most expensive part of the equipment, is to be kept low.

a. Selection of the transmitting frequency and tube

There are two frequencies suitable for the observation of fogs and clouds by radar, 35 and 94 GHz. At 94 GHz, a drop’s backscatter cross section is larger, by about 17 dB, than that at 35 GHz. However, a peak transmitting power of about 100 kW is available at 35 GHz, whereas the peak power is only a few kilowatts at 94 GHz. This difference of more than 18 dB cancels the larger cross section at 94 GHz. In addition, a 94-GHz radar has other disadvantages: larger attenuation by the atmosphere, larger loss in the waveguide components, and a relatively high noise figure for the receiver, when compared with a 35-GHz radar. In a vertically pointing mode, the attenuation by the atmosphere is relatively small compared to that on longer horizontal paths near the ground. Therefore, a 94-GHz radar is best suited for vertical observation in airborne or satellite-borne applications, wherein it is important to decrease size and weight. On the other hand, a 35-GHz radar is best suited for ground-based observations.

Besides the magnetron, the klystron and the traveling wave tube (TWT) are generally used as transmitters. However, there is no klystron at 35 GHz that operates at a power of several tens of kilowatts in a high duty cycle. Therefore, the choice is limited to two tubes, the magnetron, which has random phase from pulse to pulse, and the fully coherent TWT. The maximum peak output of the tubes at 35 GHz is about 150 kW for the magnetron and about 50 kW for the TWT. Higher peak power is desirable for horizontal observation in the scanning mode, and, in terms of production and operating costs, the magnetron is more cost effective at nearly half the cost of the TWT. Therefore, we selected the magnetron as the transmitting tube. But, because the phases of the magnetron’s transmissions are random, from pulse to pulse, it becomes necessary to measure and record the transmitted phases so that the phase of echoes can be referenced to it. Doppler measurement can be made if the transmitted phase is measured at an appropriate point within the transmitted pulse. For example, Hobbs et al. (1985) describe the sampling, digitization, and recording of the phases of transmissions from a 35-GHz magnetron used in their radar.

b. Other radar components

For portability, the radar is mounted on a flatbed vehicle. The data acquisition and display system, antenna controller, transmitter, receiver, and signal processor, are contained in the cube enclosure on the front flatbed portion of the vehicle. In Fig. 1, a radar block diagram shows (a) the transmitter and the antenna, and (b) the receivers, signal processor, and other components. Table 1 summarizes the radar characteristics.

The radar operates at a frequency of 34.75 GHz and is equipped with a 2-m-diameter parabolic antenna with an antenna gain of 54 dB and a 3-dB beamwidth of 0.3° (Table 1). Observations of fog require the use of low-elevation-angle measurements. Although the radar is equipped with a ground clutter canceller, we do not use it routinely, and all the observations in this paper were made without the ground clutter canceller so as not to lose data from fog moving at slow velocities. To further mitigate low-elevation data from being compromised by ground clutter, the parabolic reflector was designed to achieve a narrow beamwidth with low sidelobes. The antenna radiation patterns in the E and H planes are shown in Figs. 2a and 2b, respectively. The Cassegrain feed causes the sidelobes to be higher, but we were able to keep the sidelobes below −24 dB in the H plane (Fig. 2b). The antenna scans according to a programmable sequence over 360° for full azimuthal coverage, or over azimuthal sectors, with elevation angles ranging from −2° to +92°. The maximum azimuth and elevation rotation rates are 36° s⁻¹ and 6° s⁻¹ for azimuth and elevation directions, respectively.

The radar trigger is generated by the radar controller in the signal processor shown in Fig. 1b and is applied to the transmitter as shown in Fig. 1a. The transmitter amplifies the trigger signal and applies it to the modulator to produce the magnetron-switching signal. The magnetron generates transmitted pulses with a peak power of 100 kW and a width of 0.5 μs. The frequency is controlled with mechanical tuning of the cavity. The
The breakdown power of a 35-GHz waveguide with a safety factor of 2 is approximately 30 kW. Hence, the waveguide is filled with SF$_6$ gas pressurized to 0.2 MPa to prevent breakdown.

A part of the transmitted pulse is sampled for the use of automatic frequency control (AFC) referencing of the magnetron and for the phase referencing in the Doppler processor (radiation monitor to receiver 1 in Fig. 1a). The radiation monitor signal and return echoes are passed through the low-noise amplifier (LNA) in receiver 1, converted to the first intermediate frequency (IF) of 176 MHz, and applied to receiver 2. The AFC
Various sampling times and fixed it to a point 0.25 echo phases. The radar is equipped with the capability to transmit start and used as a reference for the transmitted RF signal could be sampled at a fixed time after the transmission interval, and digitally recorded in the signal processor every sampling interval, 0.83 and velocity spectrum width are estimated by the signal processor every sampling interval, 0.222 ms/2.22 ms (spaced-pair mode).

Another part of the radiation monitor signal is applied to the receiver, digitized with 12-bit resolution every transmission interval, and digitally recorded in the signal processor for phase referencing in the Doppler processor. Although the starting phase of each radio frequency (RF) pulse from a magnetron changes randomly, the pattern of the phase change within the pulse is virtually constant. This means that the phase of the transmitted RF signal could be sampled at a fixed time after the transmission start and used as a reference for the echo phases. The radar is equipped with the capability to change the sampling point of the transmitted signal in steps of 25 ns. We evaluated the phase stability for various sampling times and fixed it to a point 0.25 μs delayed from the pulse rise point of the transmitted signal.

The received echo phase is then referenced to the recorded transmitted phase. The Doppler data are calculated with the autocovariance processing method after digital phase referencing and then sent to the engineering workstation (EWS) that operates with UNIX via a small computer system interface (SCSI) bus. A quick-look display and data storage for applicable analysis are available in the EWS.

c. Digital phase referencing performance

The performance of the digital phase referencing technique was tested using ground clutter and analyzing its Doppler spectra. Frequency spectra were obtained by fast Fourier transform (FFT) processing. The measurement took place at the Shigaraki MU Observatory of Kyoto University in Japan (34.85°N, 136.10°E, and 385 m above sea level) on 14 and 15 July 1997. The radar beam was pointed at slopes of a hill, approximately 2.4 km from the radar. The ground clutter was sampled at the PRF rate of 900 pps. Figures 3a and 3b show the spectral data obtained in this experiment. The target of Fig. 3a was a wooded slope, while the target of Fig. 3b was a rocky slope. The dashed lines in each panel show the spectral data before the digital phase referencing was applied. Because there is no coherence between each of the transmitted signals and the echoes, the spectrum appears as white noise. The solid lines show the frequency spectra after digital phase referencing has been performed; the Doppler spectral power now concentrates about the zero Doppler line. The phase noise of the magnetron oscillator produces a spectral noise floor that is about 40 dB below the spectral peak. [Note that the fully coherent klystron oscillators used in the WSR-88D radars have a noise floor 70 dB below the spectral peak.]

3. Doppler velocity estimation

a. Nyquist velocity estimation and resolving ambiguous velocities

The interpulse period \( T_s \) for an unambiguous range \( r_u \) is determined from \( T_s = 2r_u/c \), where \( c \) is the speed of light. Choosing an unambiguous range \( r_u = 30 \text{ km} \) to cover observations of fogs, clouds, and other localized weather phenomena, \( T_s = 2 \times 10^{-4} \text{ s} \). However, the upper limit of the magnetron’s duty cycle \( \eta = \tau_p/T_s \) is about \( 0.0005 \), where \( \tau_p \) is the pulse width. Thus, with \( \tau_p = 0.5 \mu\text{s}, T_s \) must be larger than \( 1 \times 10^{-3} \text{ s} \). Leaving a 10% margin, the minimum \( T_s \) allowed is 1.1 ms. In this case, the Nyquist velocity is approximately 2 m s\(^{-1}\). This value is too small to measure unambiguously the Doppler speed of fog particles. To estimate Doppler velocity, however, a uniformly spaced pulse sequence (Fig. 4a) is not needed. Pulses can be transmitted in

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<th>Table 1. Performance characteristics of the radar.</th>
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pairs such that the spacing $T_s$ between the pairs is much larger than $T_s$, the intrapair period (i.e., the spaced pulse-pair mode; Doviak and Zrnic 1993, section 7.4.2). We applied the spaced-pair technique by interlacing short intrapair periods $T_s = 0.222$ ms with long interpair periods $T_{s2} = 2.22$ ms, as shown in Fig. 4b. Adopting this mode of operation (i.e., the spaced-pulse-pair mode), the magnetron’s duty cycle was not exceeded, and a higher Nyquist velocity ($V_N = 9.7 \text{ m s}^{-1}$) was attained.

Nevertheless, this Nyquist velocity value is not high enough for common meteorological conditions, and the observed Doppler velocity may be aliased. An effective way to correct the aliased velocity is to use spatial continuity of the velocity field. Figure 5a shows a Doppler velocity field when velocity ambiguities were not corrected, and Fig. 5b shows the same field but with the velocity correction algorithm applied.

b. Comparison with the 50-MHz MU radar

To verify the method of correcting Doppler velocity estimates, and to estimate its accuracy, we simultaneously operated our 35-GHz radar and the 50-MHz middle- and upper-atmospheric (MU) radar (Fukao et al. 1985a,b) at the same place and then compared horizontal wind data obtained with the two. The 35-GHz radar utilizes the velocity azimuth display (VAD) method, assuming uniform wind over the scanned circle at an elevation angle of 80°. The VAD is applied to de-aliased Doppler velocities at each range to obtain a height profile of horizontal wind. The terminal velocities of the hydrometeors can be ignored because the measurements were made in a nonprecipitating cloud, and thus the Doppler velocities are the radial components of the wind. The 50-MHz MU radar utilizes the Doppler beam swinging (DBS) method, a variant of the VAD using data at a few selected azimuths (four in this case: north, south, east, and west). Figure 6 shows height profiles of the meridional and zonal winds obtained with the 35-GHz (thin curves) and 50-MHz radars (thick curves) on 15 September 1997. Wind data obtained with the 50-MHz MU radar are not reliable below 1.5 km due to the limitation of the transmitter/receiver switching circuits. Missing horizontal winds obtained by the
FIG. 3. Doppler spectra of ground clutter approximately 2.4 km from the radar. The dashed and solid lines, respectively, show the spectra before and after digital phase referencing is applied. (a) A wooded slope on 15 Jul 1997; (b) a rocky slope on 14 Jul 1997.

FIG. 4. The transmitted signals for (a) the continuous-pulse mode and (b) the spaced-pulse-pair mode.

35-GHz radar from heights above 6.5 km are due to lack of data. These two profiles are consistent above 1.5 km.

For the horizontal velocities at heights of between 1.5 and 6.5 km, the rms differences between the 35-GHz and 50-MHz radars were 1.7 and 1.2 m s\(^{-1}\) for meridional and zonal winds, respectively. Assuming that the rms differences are equally divided between the 50-MHz and 35-GHz radars and are caused by Doppler measurement errors, the corresponding errors in the radial winds are approximately 0.2 and 0.15 m s\(^{-1}\), respectively. Because the 35-GHz radar data were obtained in high signal-to-noise ratio (SNR) conditions, the theoretical standard deviation of radial velocity is calculated, using the formulas of Doviak and Zrnic (1993, section 6.4), to be about 0.2 m s\(^{-1}\). This agreement confirms that the Doppler velocity aliasing correction scheme is operating effectively, and, moreover, that the estimate accuracy is in agreement with
theory. This agreement verifies that the spatial and temporal sampling differences between the two radars do not contribute significantly to the observed rms differences.

4. Radar performance for the observations of fog
a. The reflectivity factor of fog
Fog is composed of droplets of various sizes (all much
smaller than the radar wavelength), and the radar reflectivity factor is defined as the sixth power of the spherical drop's diameter summed over all the drop sizes per unit volume. The relation between the diameter of the drops and the radar reflectivity factor is expressed as (e.g., Doviak and Zrnic 1993, section 8.3.2)

\[ Z = \int_0^\infty N(D)D^6 \, dD, \]  

where \( Z \) is the reflectivity factor, \( N(D) \) is the drop size distribution, and \( D \) is the sphere diameter.

To determine the capability of radar to detect fog, we compute the \( Z \) expected for fog by relating \( Z \) to liquid water contents \( W \) and drop diameters \( D \) typically found for fog. For sea fog, \( D \) is mainly between 10 and 50 \( \mu m \), and \( N(D) \) is exponential (Yanagisawa et al. 1986), although we assume, for simplicity, a monodispersed distribution. In this case, the number of drops per unit volume \( n(D) \) is related to \( W (g \, m^{-3}) \) and \( D (m) \) as

\[ n(D) = \frac{6W}{\pi \rho_w D^3}, \]  

where \( \rho_w = 10^6 \, g \, m^{-3} \) is the density of liquid water. Reflectivity \( Z \) (in \( mm^6 \, m^{-3} \)) is, from Eqs. (1) and (2),

\[ Z = \frac{6 \times 10^{12} \pi WD^3}{\pi}. \]  

Figure 7 shows \( Z \) (dBZ) = 10 \times \log_{10} Z \) (\( mm^6 \, m^{-3} \)) for \( W \) and \( D \) found in fog (Yanagisawa et al. 1986).

b. System performance

Assuming that the radar’s resolution volume at range \( r \) is uniformly filled with fog, the sampled echo power \( S \), in watts, is (Doviak and Zrnic 1993, section 4.4.5)
where \( P_\text{r} \) is the peak transmitted power in watts; \( g \) is the power gain (a dimensionless parameter including the antenna’s directive gain and loss from the calibration port to the atmosphere); \( \tau \) is the transmitted pulse width in seconds; \( \theta_\text{w} \) is the one-way beamwidth between half-power points in degrees; \( |K_w|^2 = 0.91 \) is the dielectric factor (dimensionless) of liquid water at 35 GHz; \( r \) is the range in meters; \( \lambda \) is the wavelength in meters; \( l(r) \) is the one-way propagation loss factor (dimensionless) due to scatter and absorption by molecules and fog particles; and \( l_\text{s} \), the finite bandwidth loss (dimensionless), is 1.58 (i.e., 2 dB for our receiver). The dielectric factor depends on the drop temperature and wavelength (Gunn and East 1954), but the dependence is weak. The reflectivity factor \( Z \) is calculated from \( S \) in (4) and the radar parameter values listed in Table 1.

The value of \( l(r) \) for fog was estimated as follows. The attenuation by fog is estimated by using the empirical formula of Benoit (Ulaby et al. 1981, 259–314), and the attenuation by the atmosphere (without fog) is estimated using the Millimeter-wave Propagation Model (MPM) of Liebe (1985). Assume that uniform fog has a depth of 600 m, a constant relative humidity (100%), and water content \( W = 0.15 \text{ g m}^{-3} \) as shown in Fig. 8a, and that the vertical profile of temperature is that of the U.S. Standard Atmosphere, 1976. The two-way attenuation calculated by the above procedure is shown in Fig. 8b. The attenuations at ranges of 5 and 10 km are less than 4 and 8 dB, respectively.

The noise power \( N \), in watts, at the receiver input is expressed by (e.g., Doviak and Zrnic 1993, section 3.5.1)

\[
N = k T_\nu B_\nu, \tag{5}
\]

where \( k = 1.38 \times 10^{-23} \text{ J K}^{-1} \) is the Boltzmann constant, \( T_\nu \) (K) the system noise temperature, and \( B_\nu \) (Hz) the noise bandwidth of the receiver. Noise power \( N \) is calculated using \( T_\nu \) and \( B_\nu \) values listed in Table 1.

Figure 8c shows the reflectivity factor required to produce a signal-to-noise ratio, \( \text{SNR} = 10 \log(S/N) \), equal to 0 dB, where \( S \) and \( N \) are calculated using Eqs. (4) and (5). The \( Z \) values for \( \text{SNR} = 0 \text{ dB} \) at ranges of 2.5, 5, and 10 km are approximately –38, –30, and –20 dBZ, respectively, for a height of less than 1000 m. Using model parameters in Figs. 7 and 8c, we roughly expect that the radar can detect fogs with particle sizes greater than approximately 10, 20, and 40 \( \mu \text{m} \) for ranges of 2.5, 5, and 10 km, respectively.

5. First observations of fog

First observations of sea fog were carried out to evaluate the radar performance and to prepare for future observation programs. Sea fogs generally contain larger droplets because of the large maritime condensation nuclei. Hence, sea fogs are easier to detect than continental fogs. Annually, especially in summer, there are many foggy days along the eastern Pacific coast of Hokkaido in Japan. Sometimes, certain areas are covered with fog all day long. During the July to August 1999 sea fog data acquisition program, reflectivity and Doppler velocity data were obtained simultaneously with the radar at Kushiro Airport (43.02°N, 144.12°E, 90 m above sea level) on the eastern Pacific coast of Hokkaido. The radar was installed on the east side of the airport runway. The site location is shown in Fig. 9. The radar vehicle and trees behind the radar blocked observations to the north through east (N–E). However, a satisfactory perspective of the runway and the SSE–W–NNW sector, in the direction of the ocean was obtained. Three kinds of fog often appear in this area: radiation fog in the morning, advective fog moving from the ocean, and upslope fog (Sawai 1988). During the program, radiation fogs were observed between 22–27 July and advective fogs during 5–7 August.

On 5 August 1999, fogs were detected during the observation from 0200 to 1000 LT. Examples of the reflectivity structure of the fog in a volume is presented in Fig. 10. This display was constructed offline by a three-dimensional volume-rendering graphic display program that shows the integrated \( Z \) along the line of view. The left-hand panels in Fig. 10 are views from above the fog, whereas the right-hand panels are views from the side. Data were obtained between 0540 and 0630 LT in the constant altitude plan position indicator (CAPPI) mode at an antenna rotation rate of 1 rpm. Reflectivity factors above the minimum detectable ones (Fig. 8c) are shown in the display volume of 20 km (E–W) \( \times 20 \text{ km (S–N)} \times 1.5 \text{ km (height)} \). The lack of data east of the radar is due to blockage of the beam by the radar vehicle and trees. The displays (Fig. 10) show the reflectivity data at (a) the start, (b) 10 min after (a), and (c) 20 min after the start; the brighter the fog image, the larger the reflectivity is. A series of observations in the same mode showed a repetition of the increase and decrease of fog intensity and its advection from the ocean (i.e., from south to north). Continuous observations of the top view showed the appearance of the sea fog landing on the coast and proceeding inland.

Range profiles of reflectivity in the direction of the ocean were extracted from the continuous PPI observation at low elevation angles. Figure 11 shows the time–range reflectivity obtained in 1-min intervals for the south direction (azimuth = 180°, elevation = 0.3°–1.1°) between 0205 and 0900 LT. From this figure, it is apparent that the fog moved from south to north, with a repeated increase and decrease of echo intensity during the observation period. The speed of the advection was nearly constant, and the time required to move 10 km was approximately 50 min; therefore, the advection speed is about 3.3 m s\(^{-1}\). Also apparent from an examination of Fig. 11 is that the temporal scale of fog...
intensity, at any one range, varied considerably over the 7-h observational period.

The appearance and movement of the fog was also determined by vertically scanning the beam [range–height indicator (RHI) mode] at the azimuth angle of 180° during the period from 0231 to 0232 LT (Fig. 12). The fog top is almost constant at an altitude of approximately 550 m. Because the elevation angle for the observations at the height of 500 m or lower, and for ranges of 2 km or more, do not exceed approximately 15°, and because the terminal velocity of fog droplets is less than several centimeters per second (Kunkel 1984), it is reasonable to take the radial velocity to be equal to the projection of the horizontal wind onto the radial. The Doppler velocities (Fig. 12a) of the upper portion of the fog are more negative than −3 m s⁻¹ (toward the radar). Below 250 m, the Doppler velocities are relatively uniform between 0 and +2 m s⁻¹ (away from the radar). There is a relatively strong shear layer between 250 and about 320 m where the radial wind changes from about +1 to about −5 m s⁻¹, a vertical shear of radial velocity equal to about 10⁻¹ s⁻¹. The movement of fog masses shown in Fig. 11 was obtained at altitudes below 200 m, where fog-drop Doppler velocities are positive. Figure 11 does not show the movement of the fog particles but projects the movement of the reflectivity structure.
The velocities in the fog layer above 320 m (Fig. 12a) roughly coincide with the movement of the fog’s reflectivity structure shown in Fig. 11, but those in the lower layer do not. We suppose that fog particles are first generated in the upper layer and then move toward the radar as they fall into the lower layer. In the lower layer, the fog particles continue to fall but now move away from the radar, while the reflectivity structure formed in the upper layer advects toward the radar. Figure 12b shows the RHI display of the reflectivity field obtained simultaneously with the Doppler observation, where the decrease of echo power due to range ($1/r^2$, $r$ range) is corrected, but the attenuation of power due to the fog and humid atmosphere is not corrected. The reflectivity factor at the same range generally increases with the decrease in altitude, suggesting the growth of fog particles as they fall. Fog cells appear to tilt to the north. This suggests that the wind speed at the upper altitudes of the fog layer is more northward than that at the lower altitudes, in agreement with the Doppler velocity data.

The reflectivity fields (Figs. 13a,b) show the distribution of fog cells near the ground. These data were taken with the antenna scanning in PPI mode at elevation angles of 0.4°–1.0°, and with $Z$ corrected for decrease of power due to range. Figure 13a shows the first stage of the observation period obtained at 0230 LT. Fog cells were aligned in rows or streets roughly parallel to the coastline, and the rows moved from south to north before 0500 LT. The fog streets disintegrated gradually around 0500 LT, and the fog began to form three-dimensional convective structures. Finally, the distributions of convective cells at 0700 LT are shown in Fig. 13b. The sizes of the cells varied from a few hundred meters to more than 2 km. We suspect that the 3D convective cells that appeared after 0500 LT were due to solar radiation heating the ground, which causes strong 3D convection, and the fog streets seen earlier in Fig. 13a were due to dynamic instabilities, as reported by Doviak and Berger (1980) in their analysis of radar observations of reflectivity streets.

In Fig. 13, the minimum reflectivity at about 10 km is around −24 to −22 dBZ. At ranges of about 5 km, $Z$ less than −26 dBZ is observed. (Data having $S/N < 0.5$ is censored in hardware.) Comparing the reflectivity field required to obtain $S/N = 1$ (Fig. 8c) and those values obtained from the observed data, we see reasonable agreement.

6. Conclusions

The three-dimensional structure of reflectivity and velocity in fog was observed for the first time with a scanning millimeter Doppler radar. This paper describes the characteristics and performance of an 8.6-mm-wavelength Doppler radar and its use in observing sea fog. The radar has the following properties.

1) Reliable and accurate Doppler velocity measurement is achieved with a magnetron transmitter by recording the initial phase of the transmitted RF signal and implementing a phase referencing method.

2) The Nyquist velocity is extended to approximately 9.7 m s$^{-1}$ by transmitting closely spaced pairs of pulses in a widely spaced uniform sequence. This approach satisfies the duty cycle constraints of the
Fig. 10. Examples of volume images of a fog: top view (left) and side view (right), obtained between 0540 and 0630 LT in the CAPPI mode at an antenna rotation rate of 1 rpm. The echo volumes of radar reflectivity factor of more than $-40$ dBZ are integrated in height and range. The radar is at the point of (0 km, 10 km) and at the altitude of 0 m. The brighter the echo, the larger the reflectivity. The displays show data at (a) the start, (b) 10 min after (a), and (c) 20 min after (a).
magnetron but attains a relatively large Nyquist velocity. Radial velocities in excess of 9.7 m s\(^{-1}\) are dealiased off-line using a software technique.

3) The reflectivity factors required to produce \(S/N = 1\) in uniform fog with a water content of 0.15 g m\(^{-1}\) at ranges of 2.5, 5, and 10 km are around \(-38\), \(-30\), and \(-20\) dBZ, respectively.

The first observations of sea fog, carried out for the purpose of evaluating the radar also show the following properties of sea fog.

1) Sea fog reflectivity factor is far from being horizontally homogeneous.

2) Early in the day, before surface heating becomes strong, the reflectivity factor field of fogs has roll structures (i.e., fog streets), and at later times, when...
surface heating is stronger, fog is composed of three-dimensional convective cells.

3) Strong wind shear tilts the vertical structure of the fog streets and/or 3D convection cells.

Fog, a cloud with its base on the ground, is hazardous especially for aviation. One potential application of this radar is fog observations for airport operations as well as potential for observations of other kind of clouds, such as stratus and cumulus.

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