Cloud Radar Network in Tokyo Metropolitan Area for Early Detection of Cumulonimbus Generation

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Introduction

Recently municipal engineers point out that urban city is vulnerable for localized heavy rainfall, and that rainfall monitoring and forecasting are important for water management. A weather radar is a powerful tool for that purpose; however it is only precipitation particles (hydrometeors excluding cloud particles) that current operational radars (S-, C- and X-band) can detect. This means that when the radar catches the echo, the rainfall may have already started. Meanwhile, the heavy rainfall is caused by a mature cumulonimbus which develops from a cumulus. So the detection of the cumulous is expected to make the lead time of heavy rainfall forecasting longer. But the current operational radar cannot observe the cumulus which consists of the cloud particles. For an early warning of heavy rainfall, we developed the cloud radar network around Tokyo metropolitan area.

Specifications

Our main target is a monitoring of a cloud development from cumulus into sever cumulonimbus. For this purpose, the sensitivity is most important specification of our radar. According to Kessler's warm rain parameterization, rain water is generated from cloud water when the mixing ratio of cloud water exceeds some threshold (about 1 g kg^{-1}). This mixing ratio corresponds to the radar reflectivity of -13 dBZ (M=4.5Z0.5 by Atlas 1945). So our radar sensitivity is determined as ...

-17 dBZ @ r=20 km
where pulse integration is not considered,
and detectable level is 3 dB higher than noise

To realize the sensitivity, we selected the pulse compression radar with Ka-band 3 kW EIK. And dual-polarimetric capability is also needed to detect an ice-phase process in the cloud, because the process may change the cloud development and its precipitation efficiency. Our cloud radar network consists of 5 Ka-band radars. The two of them are single polarization radar, because elimination of H/V divider (magic T) makes the sensitivity higher.

Table 1. Specifications of cloud radar.

Features	Specifications
Frequency	34.815 GHz - 34.905 Ghz (Ka-band)
Occupied bandwidth	13 MHz
Microwave amplifier	Extended Interaction Klystron (EIK)
Transmit power	3 kW
Pulse compression	Linear frequency modulation (2 MHz)
Pulse width (short)	0.5 μs and 1.0 μs
Pulse width (long)	30 μs, 45 μs, 55 μs, 80 μs and 100 μs
Pulse repetition frequency	Max. 2500 Hz @ τ=30 μs
IF digitizer	16 bit, 36 MHZ
Antenna	Cassegrain antenna (⌀=2.2 m)
Antenna gain	54 dB (Typ.)
Beam width	0.3 deg (Typ.)
Antenna Sidelobe level	-23 dB (Typ.)
Polarization	H/V simultaneous or single H or V
Observation range	30 km
Output data resolution	75 m or 150 m
Nyquist Velocity	5.38 ms^{-1} @ PRF=2500 Hz
Dual PRF	3:2, 4:3 and 5:4 for velocity de-aliasing
Clutter Filters	IIR or spectrum interpolation
Output Data	Pr, Z, V, W, SQI, SNR and I/Q
Output Data (Simul. dual-pol.)	Z_{DR}, ρ_{HV}, Φ_{DP} and K_{DP}
Output Data (Single, dual-receive)	$LDR_{H\ or\ V}$, $\rho_{H\ or\ V}$, $\Phi_{H\ or\ V}$

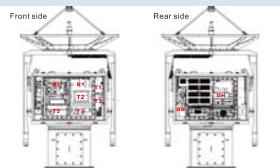

Figure 4. Antenna overview and module layout of the cloud radar. Red notations indicate the modules in Fig. 2.

Figure 1. Photos of five Ka-band cloud radars and their distributions on a map around Tokyo (upper right). Blue circles indicate the observation ranges (r=30 km)of each radar. Colored areas indicate a densely inhabited districts. Some radars are planed to move to near Tokyo.

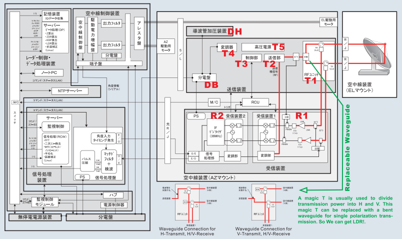

Figure 2. Block diagram of cloud radar. Vertical polarization receivers are omitted in the single polarization radar (2 of 5 radars). I am very sorry for the diagram denoted in Japanese. But you may understand what this diagram means. Red notations indicate the modules in Fig. 4.

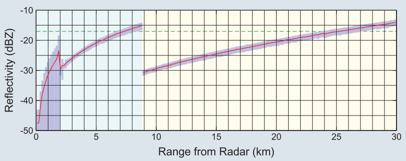

Figure 3. Reflectivity profile of noise observation (vertical-pointing data under no cloud environment). Red line and violet shadow indicate the average and standard deviation of the reflectivity profiles (1600 rays), respectively. The number of samples per one ray data is 64. Green dashed lines indicate the sensitivity specification (dual-pol. type). Light cyan and yellow backgrounds show the processing ranges of showrt and long pulses, respectively.

Summary

- Five Ka-band cloud radars were installed around Tokyo Metropolitan area to investigate the initiations of cumulus and cumulonimbus cloud.
- The sensitivity specification was determined from the threshold of Kessler's warm rain parameterization to observe the development from a cloud droplet into a rain drop.
- Preliminary observation showed the high sensitivity of the cloud radar to capture the stratus and cumulus clouds. Dual-polarimetric capability was also checked.
- The observation also showed the initiation stage of the cumulonimbus, in which the isolated cumulus clouds were organizing.
- We attempted to detect the range sidelobe, and it seemed to work well.
- Mikumon: A mascot character of NIED's cloud radar. The pronunciation of "Mikumon" vaguely recalls "cloud watcher" in Japanese. "Miru" = watch, "kumo" = cloud, and "mon" is something like Pokémon!

Observed Parameters

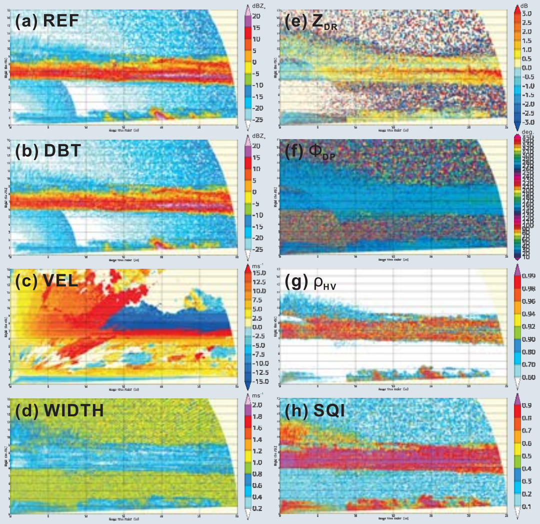

Figure 5. RHIs of observed parameters by Ka1 at 1921 JST 7 September 2015, when altostratus, shallow stratus and nimbostratus (drizzle) remained just after a frontal rainfall decaying. Pulse widths are 1.0 μs and 55 μs, PRFs are 1900 Hz and 1520 Hz (5:4), Nyquist velocities are 4.08 ms^{-1} and 3.27 ms^{-1}, and their lowest common multiple is 16.33 ms^{-1}. a) Reflectivity width clutter filter, b) Reflectivity without clutter filter, c) Doppler velocity, e) Spectrum width, f) Differential reflectivity, g) Differential phase shift, g) Co-polar correlation coefficient, and h) Signal quality index.

Detection of Range Sidelobe

Range sidelobe echo sometimes appears around heavy precipitation because of high sensitivity and wide dynamic range of the cloud radar. The heavy precipitation is not our scope of the cloud radar; however it may sometimes make us misunderstood the cloud generation. So we attempted to detect the range sidelobe.

At first, simulated and observed range sidelobes were compared. The observed one was acquired by air plane (Fig. 7), and was not matched with simulated one around the near range (Fig. 8). The observed pattern was used to retrieve the original reflectivity pattern. By the comparison between observed and retrieved reflectivity pattern, the range sidelobe was detected as shown in Fig. 10b.

Range Sidelobe Pattern Matrix (see Fig. 9)

$$P=\begin{pmatrix}
p_0 & p_1 & p_2 & p_3 & \cdots & p_{n/2-2} & p_{n/2-1} & p_{n/2} & p_{n/2+1} & p_{n/2+2} & \cdots & p_{n-3} & p_{n-2} & p_{n-1} & p_n \\
p_{-1} & p_0 & p_1 & p_2 & \cdots & p_{n/2-3} & p_{n/2-2} & p_{n/2-1} & p_{n/2} & p_{n/2+1} & \cdots & p_{n-4} & p_{n-3} & p_{n-2} & p_{n-1} \\
p_{-2} & p_{-1} & p_0 & p_1 & \cdots & p_{n/2-4} & p_{n/2-3} & p_{n/2-2} & p_{n/2-1} & p_{n/2} & \cdots & p_{n-5} & p_{n-4} & p_{n-3} & p_{n-2} \\
p_{-3} & p_{-2} & p_{-1} & p_0 & \cdots & p_{n/2-5} & p_{n/2-4} & p_{n/2-3} & p_{n/2-2} & p_{n/2-1} & \cdots & p_{n-6} & p_{n-5} & p_{n-4} & p_{n-3} \\
\vdots & & & & & & & & & & & & & & \vdots \\
p_{-n/2+2} & p_{-n/2+3} & p_{-n/2+4} & p_{-n/2+5} & \cdots & p_0 & p_1 & p_2 & p_3 & p_4 & \cdots & p_{n/2-1} & p_{n/2} & p_{n/2+1} & p_{n/2+2} \\
p_{-n/2+1} & p_{-n/2+2} & p_{-n/2+3} & p_{-n/2+4} & \cdots & p_{-1} & p_0 & p_1 & p_2 & p_3 & \cdots & p_{n/2-2} & p_{n/2-1} & p_{n/2} & p_{n/2+1} \\
p_{-n/2} & p_{-n/2+1} & p_{-n/2+2} & p_{-n/2+3} & \cdots & p_{-2} & p_{-1} & p_0 & p_1 & p_2 & \cdots & p_{n/2-3} & p_{n/2-2} & p_{n/2-1} & p_{n/2} \\
p_{-n/2-1} & p_{-n/2} & p_{-n/2+1} & p_{-n/2+2} & \cdots & p_{-3} & p_{-2} & p_{-1} & p_0 & p_1 & \cdots & p_{n/2-4} & p_{n/2-3} & p_{n/2-2} & p_{n/2-1} \\
p_{-n/2-2} & p_{-n/2-1} & p_{-n/2} & p_{-n/2+1} & \cdots & p_{-4} & p_{-3} & p_{-2} & p_{-1} & p_0 & \cdots & p_{n/2-5} & p_{n/2-4} & p_{n/2-3} & p_{n/2-2} \\
\vdots & & & & & & & & & & & & & & \vdots \\
p_{-n+3} & p_{-n+4} & p_{-n+5} & p_{-n+6} & \cdots & p_{-n/2+1} & p_{-n/2+2} & p_{-n/2+3} & p_{-n/2+4} & p_{-n/2+5} & \cdots & p_0 & p_1 & p_2 & p_3 \\
p_{-n+2} & p_{-n+3} & p_{-n+4} & p_{-n+5} & \cdots & p_{-n/2} & p_{-n/2+1} & p_{-n/2+2} & p_{-n/2+3} & p_{-n/2+4} & \cdots & p_{-1} & p_0 & p_1 & p_2 \\
p_{-n+1} & p_{-n+2} & p_{-n+3} & p_{-n+4} & \cdots & p_{-n/2-1} & p_{-n/2} & p_{-n/2+1} & p_{-n/2+2} & p_{-n/2+3} & \cdots & p_{-2} & p_{-1} & p_0 & p_1 \\
p_{-n} & p_{-n+1} & p_{-n+2} & p_{-n+3} & \cdots & p_{-n/2-2} & p_{-n/2-1} & p_{-n/2} & p_{-n/2+1} & p_{-n/2+2} & \cdots & p_{-3} & p_{-2} & p_{-1} & p_0
\end{pmatrix}$$

Original Range Profile of Received Power (unknown)

$$\vec{X}=\begin{pmatrix} x_0 \\ x_1 \\ \vdots \\ x_n \end{pmatrix}$$

Observed Range Profile of Received Power

$$\vec{Y}=\begin{pmatrix} y_0 \\ y_1 \\ \vdots \\ y_n \end{pmatrix}$$

The observed reflectivity is considered as the original reflectivity filtered by range sidelobe pattern. So the following equation can be described.

$$P\vec{X}=\vec{Y}$$

By solving the inverse of the pattern matrix, we get the original range profile.

$$\vec{X}=P^{-1}\vec{Y}$$

If the difference between observed and original reflectivities is larger than some threshold (e.g. 6 dB), the observed reflectivity is contaminated by the range sidelobe.

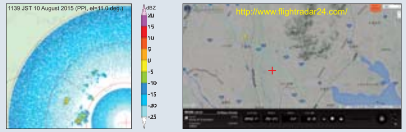

Figure 7. Reflectivity without clutter filter of the cloud radar Ka1. Airplane is used as a point target to investigate the range sidelobe. Right) A location and a flight path of the airplane which is used as the point target.

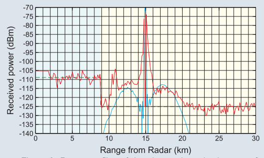

Figure 8. Range profiles of the observed received power of the range sidelobe (red line) and the simulated sidelobe pattern (blue line). Green line indicates the noise level.

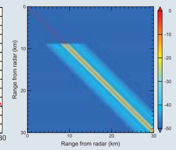

Figure 9. Range Sidelobe pattern matrix.

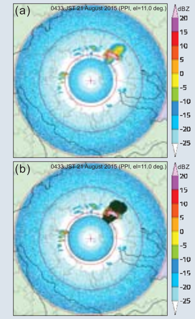

Figure 10. a) Reflectivity PPI including the obvious range sidelobe. b) The same as (a), but with the detected sidelobe colord by dark green.

Development from Cumulus into Cumlonimbus

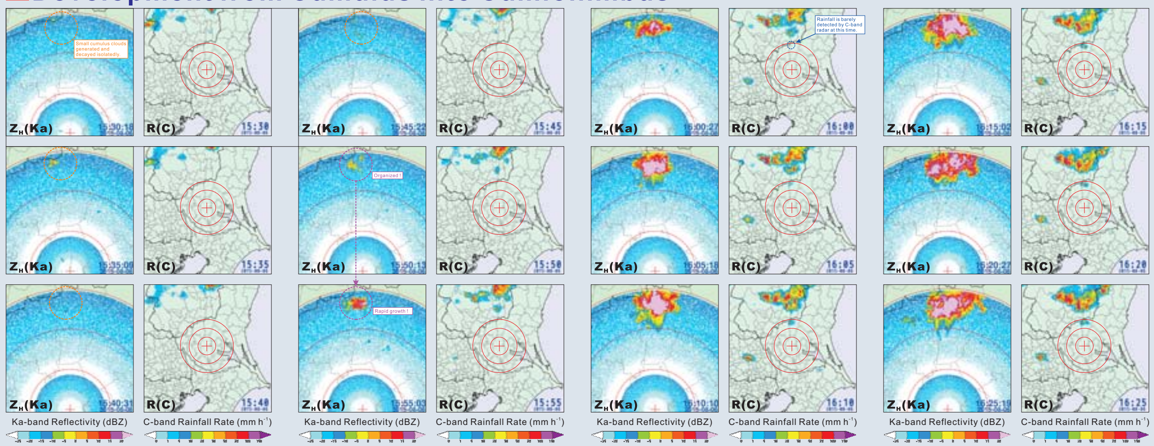

Figure 6. Comparisons between Ka-band reflectivity (PPI el=11.0 deg.; left) and C-band rainfall mosaic (Japan Meteorological Agency; right) are shown every 5 minutes from 1530 JST to 1625 JST on 6 August 2015. Red cross indicates the location of Ka-band cloud radar (Ka1), and ranges from the radar (red circles) are drawn every 10 km.