Poster #63 (Emerging Technology and Phased Arrays)
40th Conference on Radar Meteorology
27. Aug.- 01 Sep., 2023, Minneapolis, MN, USA

Dual-Frequency Terahertz Weather Radar Observing Cloud and Water Vapor

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Background

Cloud Radar

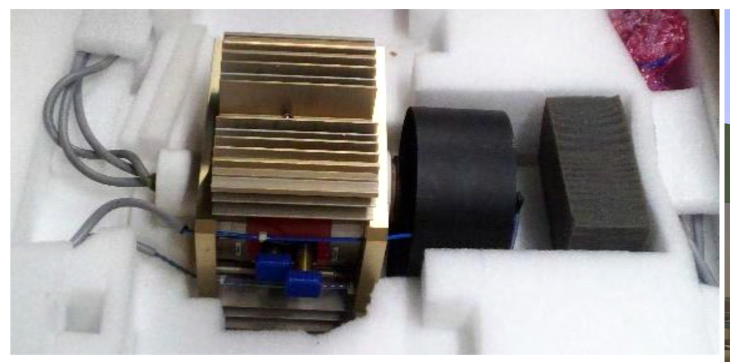
A microwave weather radar is used to observe a distribution of precipitation. However, non-precipitating clouds cannot be observed with the sensitivity of ordinary weather radars, because cloud droplets are much smaller than precipitation particles. Therefore, a cloud radar was developed with higher sensitivity using a shorter wavelength. National Research Institute for Earth Science and Disaster Resilience (NIED) developed a Ka-band cloud radar to observe cumulus cloud developing into cumulonimbus. To realize the detectability of such a cloud, 3 kW Extended Interaction Klystron (EIK) and pulse compression technology are used. NIED developed the detection system of developed cumuli which will generate rain by the Ka-band cloud radar network in Tokyo metropolitan area.

Problems

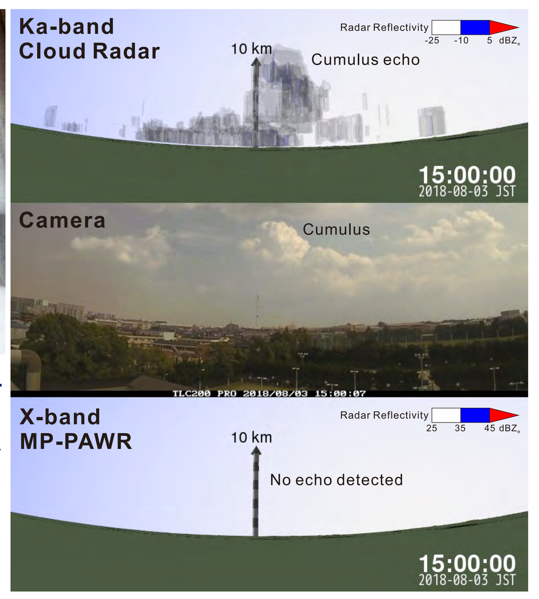
Extended Interaction Klystron (EIK): Recently, the EIK price is increasing and its delivery period is also getting longer. Solid State Power Amplifier (SPPA) may be an alternative device for EIK, but a transmit power of SPPA is smaller than that of EIK. Higher radio-frequency is needed to compensate the sensitivity of cloud radar. However, it is difficult to use higher frequency radar reflectivity, because such radio wave is easily attenuated by cloud and water vapor.

Quantitative Estimation of Cloud water: The current Ka-band cloud radar system uses radar reflectivity to detect the cloud, but the reflectivity is not well correlated with the cloud water content. The Dual-Wavelength Ratio (DWR) of the reflectivity is sometime used to estimate the difference of the attenuation between two frequencies, which is well correlated with the cloud water content. Ka- and W-bands are used for this purpose.

Distributions of five Ka-band cloud radars (left) and their photos (right). Blue circles indicate the observation ranges (r=30 km) of each radar. The radars indicated by open circles are dual-polarization radars, while open squares indicate single polarization radars.

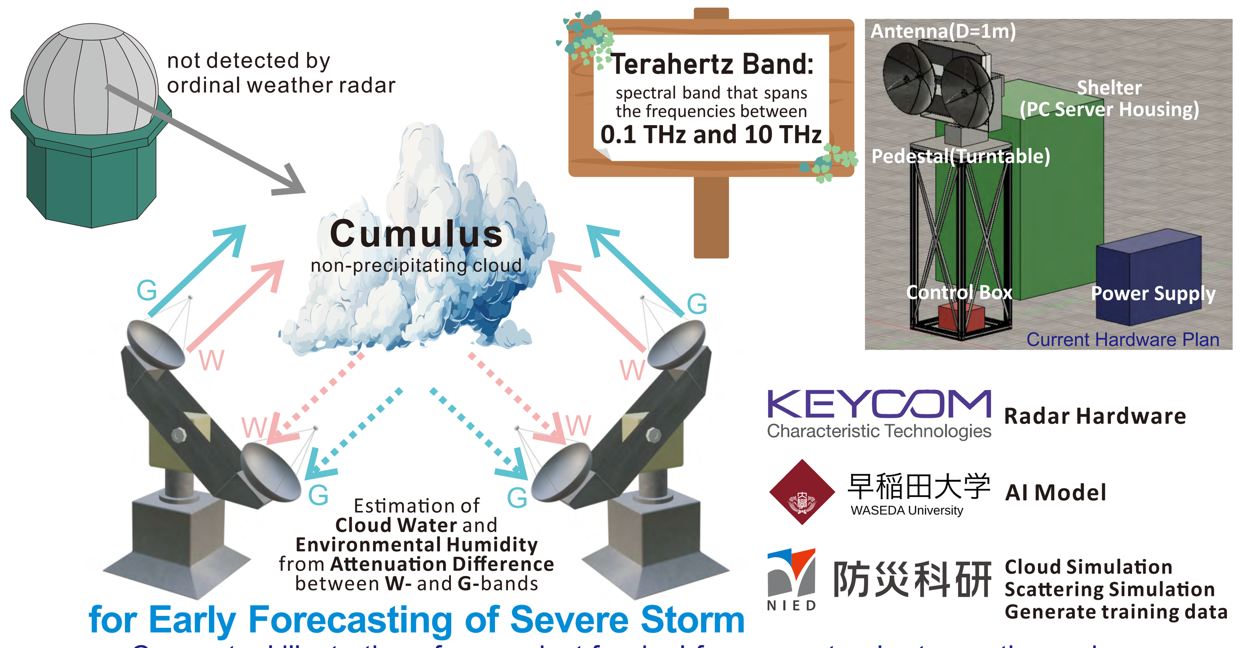


Extended Interaction Klystron (EIK) used in NIED's Ka-band cloud radar.



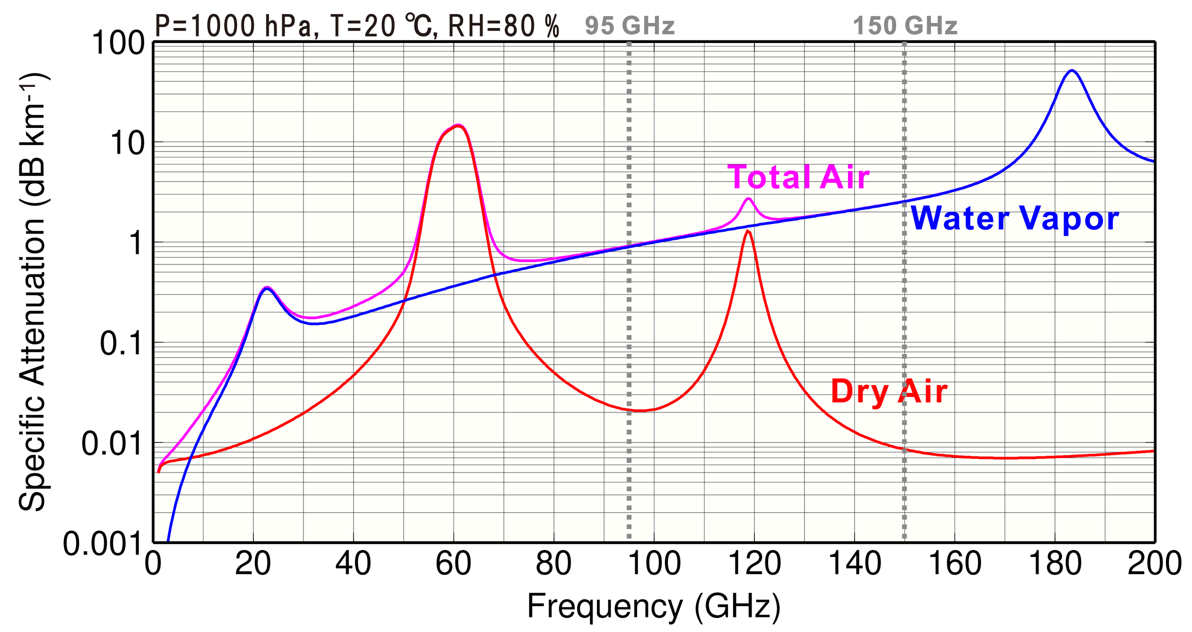
3D distribution of radar reflectivity observed by Ka- and X- band radars (top and bottom, respectively). Middle panel is a photography of cumulus in Tokyo, taken at X-band MP-PAWR site.

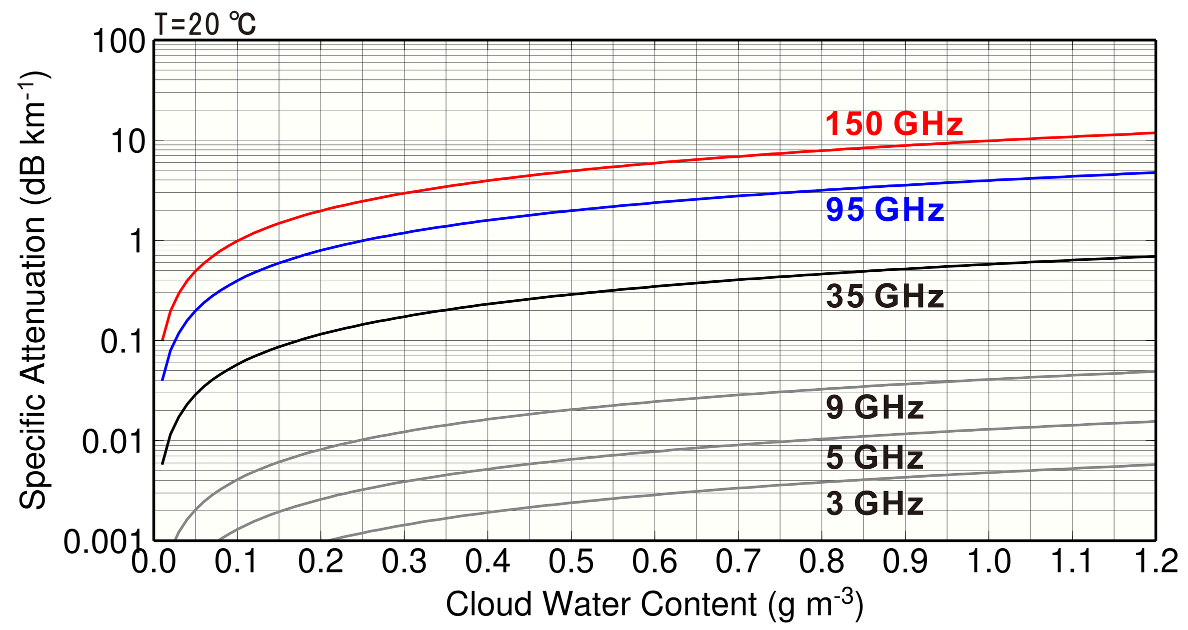
Dual-Freq. Terahertz Weather Radar



Conceptual illustration of our project for dual-frequency terahertz weather radar.

We propose a dual-frequency terahertz (95 GHz/W-band and 150 GHz/G-band) weather radar with SPPA to solve these problems. DWR of radar reflectivity is used to estimate the attenuation information by both cloud and water vapor. The cloud and water vapor effects in the DWR are separated by an artificial intelligence (AI) model, which learns the relationship between meteorological parameters and radar reflectivity simulated by meteorological model using the spectral-bin microphysics. The development of the proposed radar has just been started under the Beyond 5G R&D Promotion Project funded by National Institute of Information and Communications Technology (NICT), Japan.





Specific attenuations by air (top panel, vs. frequency), and cloud water (bottom panel, vs. cloud water content).

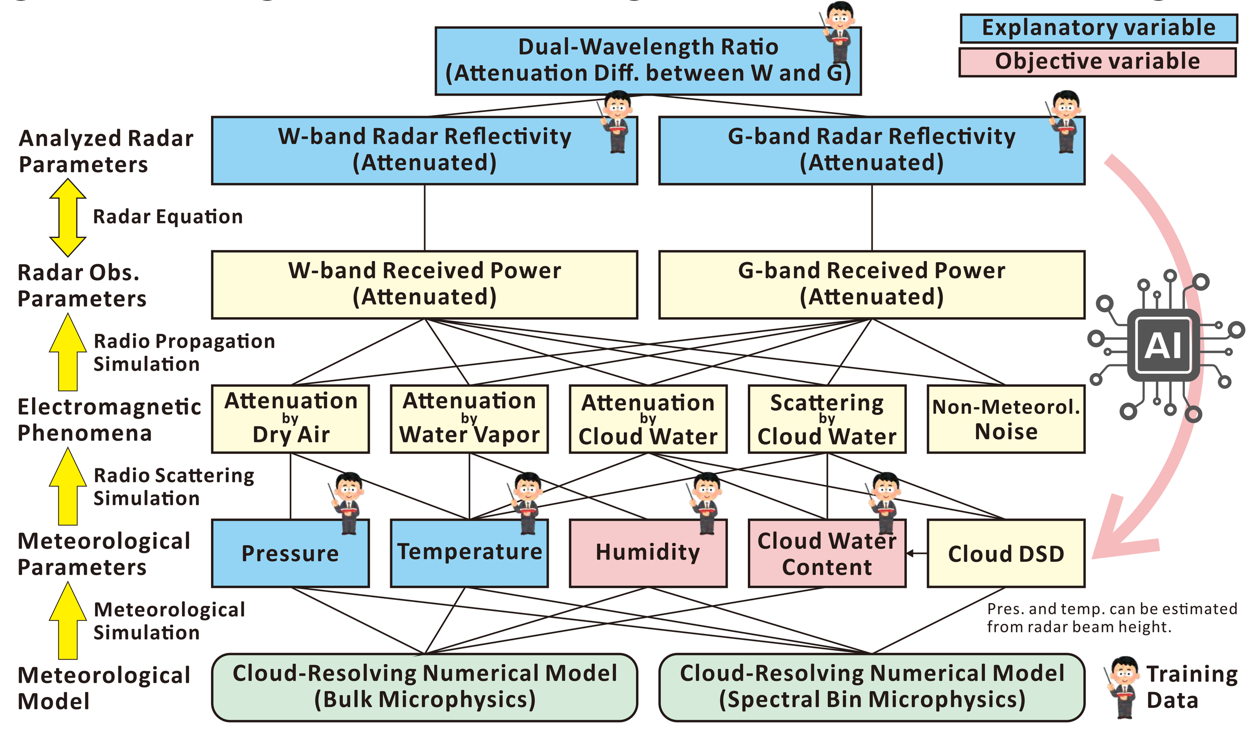
Radar Specifications

(Tentative values)

Specifications	W-band	G-band
Frequency	94 GHz	148 GHz
Band width	15 MHz	15 MHz
Transmit power	4 W or more	0.8 W or more
Transmit pulse width	40 µsec (High PRF) / 130 µsec (Normal PRF) / 260 µsec (low PRF)	
Receive pulse width	0.5 µsec (High resolution) / 1 µsec (Normal resolution)	
Antenna	Dual-band Cassegrain parabolic antenna, separated Tx/Rx	
aperture diameter	1 m	
Antenna gain	55 dBi or more	61 dBi or more
Beam width	~ 0.26 °	~ 0.18 °
Polarization	H	H
Antenna sidelobe	-15 dB or less	-15 dB or less
Cross-polarization isolation	30 dB or more	30 dB or more
Pulse repetition frequency	2048 - 8192 Hz (T.B.D.)	
Dynamic range	80 dB or more	80 dB or more
IF for A/D converter	4 MHz	2 MHz
A/D converter resolution	16 bits	16 bits
A/D converter sampling	20 MHz	20 MHz
Noise figure	7.5 dB or less	8.1 dB or less
Minimum detectable reflectivity @ 5 km	-45.8 dBZ / -40.6 dBZ (Lair=4.8 dB)	-42.0 dBZ / -30.8 dBZ (Lair=12.8 dB)
Processing range	6 km (High PRF) / 19 km (Normal PRF) / 38 km (low PRF)	
Moment data	Reflectivity, Doppler velocity, Spectral width (each frequency)	
Dual-frequency processing	Dual-wavelength ratio, Nyquist velocity extending	
Antenna scanning mode	Sector-PPI(finite rotation), Sector-RHI, POSITION	
Antenna rotation speed (max.)	Azimuth: 55 sec/rotation or more, Elevaton: 13 sec/90 deg. or more	

AI-Based Estimation of Cloud/Water Vapor

Radar reflectivity can be calculated from meteorological parameters, such as P, T, Qv and DSD of cloud drops (or Qc), by scattering simulation and radar equation; however, the reverse calculation is quite difficult. AI-based model learned with the relationship between meteorological parameters and W-/G-bands reflectivity is used to estimate the Qc and Qv. Output of cloud-resolving numerical model, especially using spectral-bin microphysics, are used to generate a large amount of training dataset for machine learning.



Relationship diagram between meteorological parameters and radar parameters. (Maesaka, T., Y. Aoyama, H. Fujii and W. Kameyama, 2023: Cloud and Water Vapor Observing Radar for Early Forecasting of Extreme Weather. *IEICE Technical Report*, 122(48), 76-80)

Simulation to Generate Training Data

Step 1: Execute cloud-resolving numerical model.

Step 2: Interpolate the model outputs into radar coordinates.

Step 3: Calculate radar reflectivity, W-/G-band attenuation due to moist air and hydrometeors.

Step 4: Calculate attenuated reflectivity and dual-wavelength ratio.

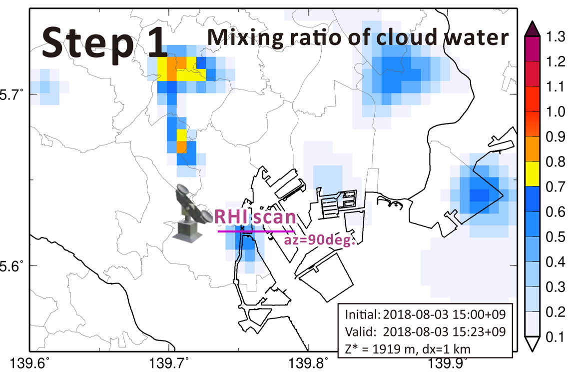
Model: Cloud Resolving Storm Simulator (CReSS, Tsuboki and Sakakibara 2002) using bulk microphysics.

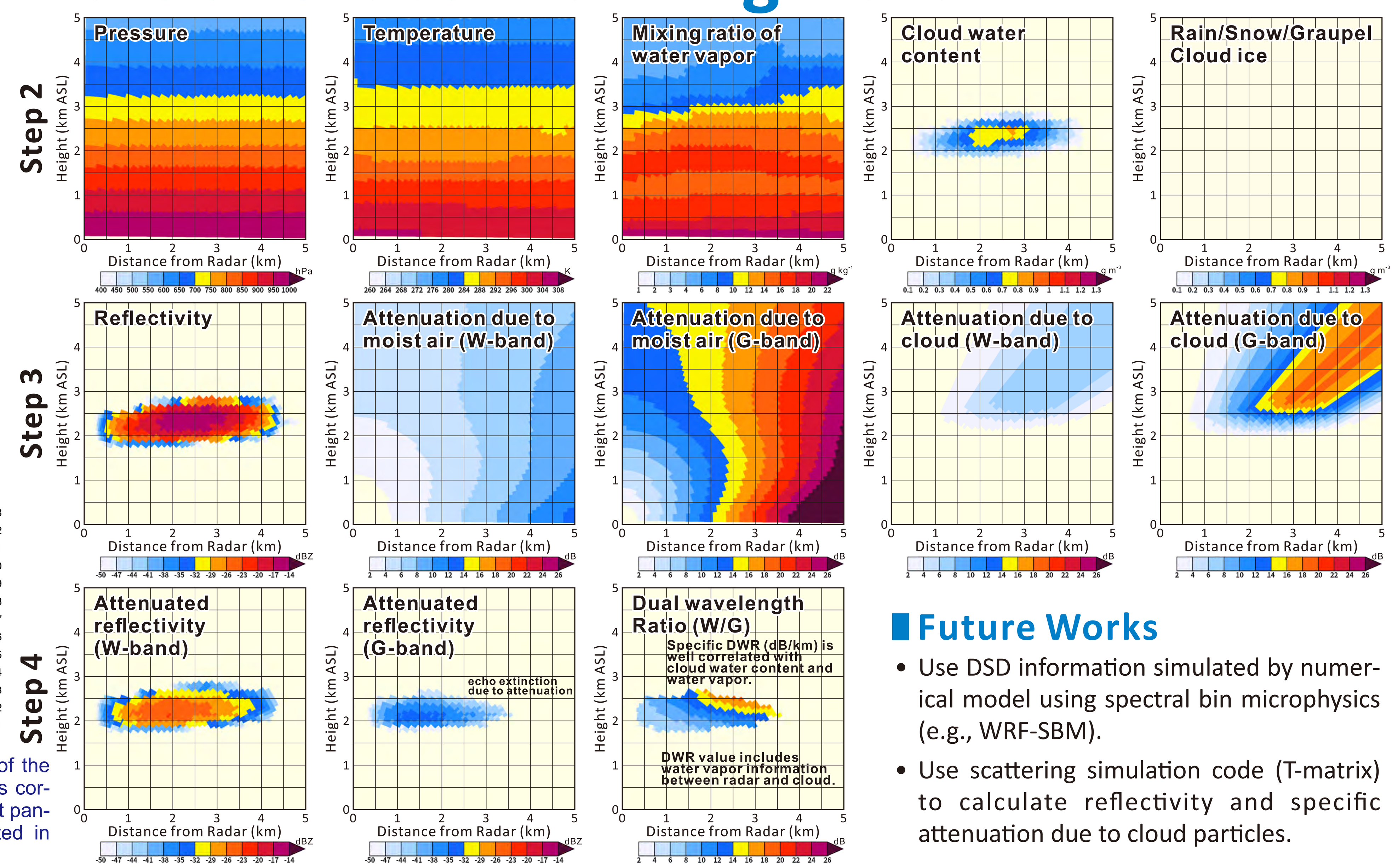
Model Configuration: Kato et al. 2022: Prediction of meso-γ-scale local heavy rain by ground-based cloud radar assimilation with water vapor nudging. *Wea. Forecasting*, 37, 1553-1556.

Radar Reflectivity: Atlas 1954: The estimation of cloud parameters by radar. *J. Meteorol.*, 11, pp309-317.

Gas Attenuation: ITU-R P.676-12

Cloud Attenuation: Benoit 1968: Signal attenuation due to neutral oxygen and water vapor, rain and clouds, *Microwave J.*, 11, 73-80.





Qc simulated by CReSS (Step 1). Outputs of the model are interpolated into radar coordinates corresponding to RHI scan above (Step 2). Right panels show RHI-scanned parameters calculated in Steps 2, 3 and 4.

Future Works

- Use DSD information simulated by numerical model using spectral bin microphysics (e.g., WRF-SBM).
- Use scattering simulation code (T-matrix) to calculate reflectivity and specific attenuation due to cloud particles.

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Acknowledgements: The development of the dual-frequency terahertz radar is supported by the commissioned research (B5G R&D Promotion Project, No. 06901) by National Institute of Information and Communications Technology (NICT), Japan.