Continuing Evolution of Weather Radar Technology

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1. Introduction

Occurrence of damage due to typhoons, linear-precipitation zones and localized heavy rain has increased recently, and become a new social issue. Weather radar can be effective for observing these sorts of precipitation, spatially and temporally over wide areas, both quantitatively and at fine intervals. Weather radar is operated by various agencies including the Meteorological Agency, the Water and Disaster Management Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and local governments, and is used for purposes such as managing rivers, drainage and other social infrastructure, for weather forecasts, and to provide information to residents. Japan's weather radar technology is advanced, leading the industry with features such as solid-state transmitters and high-speed observations through electronic scanning. This article gives an overview of weather radar concepts and the development of weather radar technology.

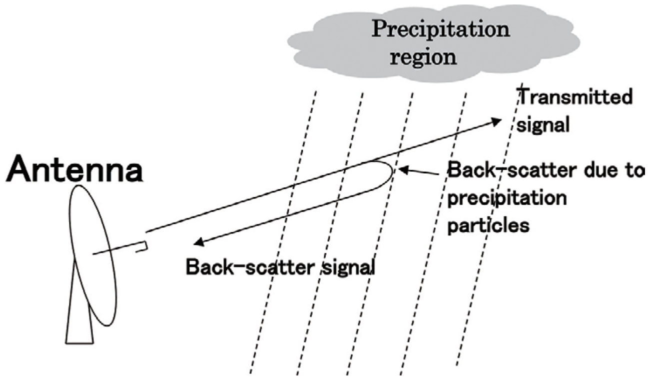
2. Precipitation observations using weather radar

Rain gauges have long been used to understand precipitation, and the Automated Meteorological Data Acquisition System (AMeDAS) operated by the Meteorological Agency takes precipitation measurements, at approximately 840 locations throughout Japan at roughly 21 km intervals, using tipping-bucket rain gauges. Tipping-bucket rain gauges collect and directly measure precipitation so they are very reliable, but they have issues including: (1) they are only able to measure precipitation at the device location, (2) accuracy of instantaneous measurements such as volume/minute is poor, and (3) precipitation amounts can be underestimated if there is cross wind.

In contrast, weather radar observations have advantages including (1) wide area observations ranging from tens to hundreds of km in radius, (2) instantaneous estimates of rainfall, minute-to-minute, and (3) ability to make observations at altitude, and not just at the ground level. In the past, precipitation estimations were not always adequate due to lack of precision and poor maintainability, but these limitations are being removed through new technologies such as dual-polarization observations and solid-state transmitters.

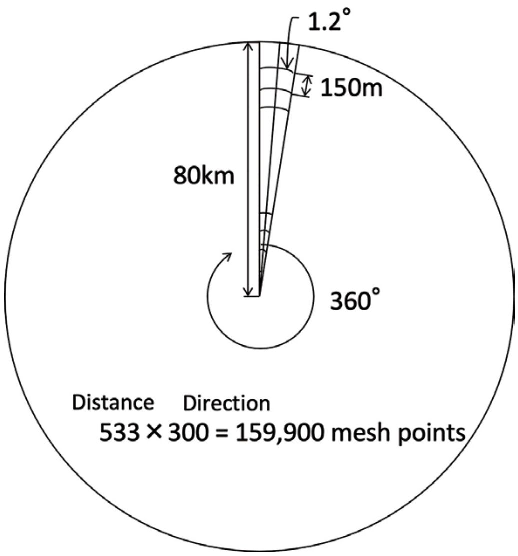
As shown in Figure 1, weather radar transmits radio signals into the air and then the antenna receives the back-scatter signal that occurs when the transmitted signal hits various precipitation particles (rain, snow, hail, etc.) suspended in the air, enabling estimation of the state of precipitation in the air (quantity, movement, particle type, etc.).

Figure 1: Weather radar observation principles



Here we use Figure 2 to describe a feature of weather radar: the mesh used for wide-area observations. Typically, the observation range for X-band weather radar is a radius of approximately 80 km, usually operating with resolution of 150 m radially, yielding data from 533 partitions for distance. Direction is divided into 1.2° intervals, yielding 300 partitions over the full 360°. As such, typical X-band weather radar provides measurements at approximately 160,000 points in real time. Characteristics of the data are somewhat different, but in simple terms, a single weather radar installation gives effectively the same results as 160,000 rain gauges deployed over the area.

Figure 2: Typical observation mesh for X-band weather radar



3. Development of weather radar technology

3.1 History of weather radar technology

When weather radar was first introduced, large amounts of quantitative observations were not immediately available. The history of the development of weather radar technology is shown in Figure 3.

Initial weather radar sets were analog devices that used a self-excited oscillating electron tube called a magnetron as the transmitter, projected the output signal from the receiver on a black-and-white afterglow display, and indicated rain intensity by brightness. A sketch of this was then made in a darkened room. Later, with the development of digital technology, systems became more stable, high-speed processing became possible, and weather radar capable of quantitative precipitation observations was developed.

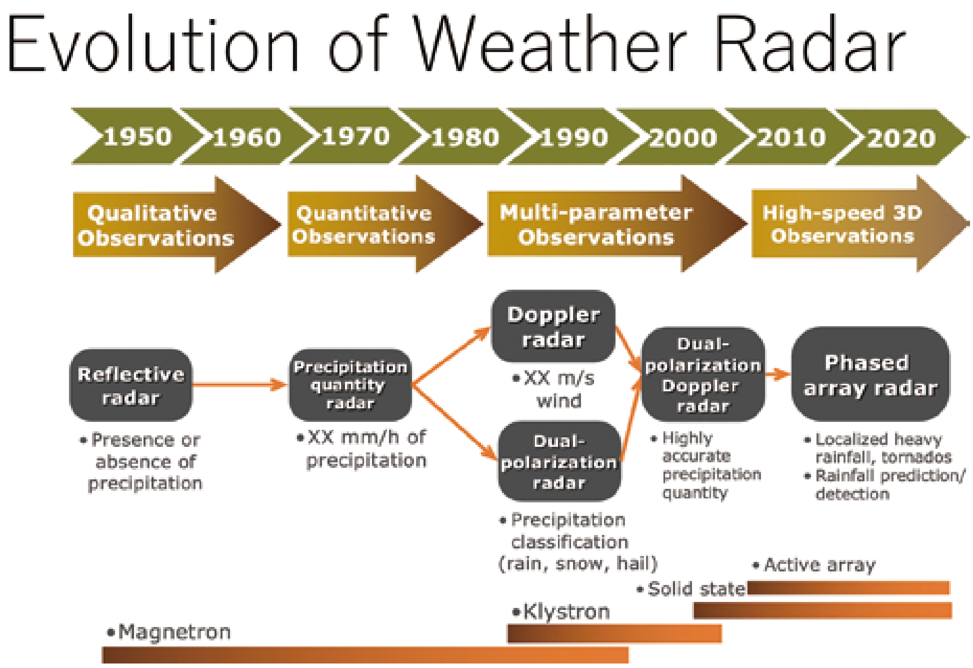
In the 1990s, Doppler radar was developed, capable of observing both precipitation intensity and air flow (estimating wind from phase of the reflected signals). From this time, an amplifying device called klystrons came into mainstream use, enabling stable handling of phase information.

Most types of radar to this point used radio transceivers of only one polarization (generally horizontal), but at almost the same time as Doppler radar was developed, dual-polarization radar, with both horizontal and vertical polarizations, was also implemented. This enabled collection of more information regarding precipitation particles. Observations made using both Doppler and dual-polarization are called multi-parameter observations. Entering the 2000s, radar integrating both Doppler radar and dual-polarizing radar, or true multi-parameter (MP) radar, became practical.

Around this time Japan took the lead in weather radar technology around the world. One factor contributing to this was the development of solid-state transmitters. This was achieved by integrating multiple stages of high-output microwave semiconductors to achieve the transmission power needed for weather radar, successfully transitioning away from the magnetron and klystron electron tube devices (Figure 4). In 2012, phased-array weather radar (horizontal polarization type) was developed, capable of high-speed 3D observations in multiple directions at the same time, and in 2017, multi-parameter phased array weather radar with a dual polarization signal function was developed.

Figure 4: C-band solid-state multi-parameter weather radar

Figure 3: History of weather radar technology



3.2 Multi-parameter observations

Weather radar with a multi-parameter observation function transmits and receives two linear-polarization signals (horizontal and vertical) (Figure 5). As the precipitation particles become larger, they flatten in the horizontal direction due to air resistance (Figure 5). With earlier, non-multi-parameter radar, precipitation volume was estimated from the received intensity of the horizontally polarized signal only, so for the same amount of rain, the volume was over-estimated if the drops were large, and under-estimated if the drops were small, as with light rain.

With multi-parameter radar, both intensity and phase for both horizontally and vertically polarized signals can be measured, and these can be combined to derive various parameters.

The “Specific Differential Phase” (KDP) parameter in particular, has come into broad use to increase the accuracy of quantitative precipitation observations. Radio waves propagating through water travel slower than they do in air. As raindrops get larger, they tend to flatten horizontally, so when radio waves travel through rain, the phase of horizontally polarized signals tend to be delayed relative to vertically polarized signals. Taking the ratio of this phase delay to the rain quantity, regardless of raindrop size, is the principle behind estimation of rain volume using KDP.

Other parameters can also be derived at the same time, including polarization parameters: inter-polarization correlation coefficient (ρHV) and differential radar reflectivity (ZDR); and parameters similar to regular Doppler weather radar: the radar reflectivity factor (Zh), Doppler velocity (V), and Doppler velocity width (W). These parameters help increase the accuracy of precipitation quantity, but are also used in analysis such as particle classification (whether particles are rain, snow, hail, etc.) and determining cloud type (stratification, convectional).

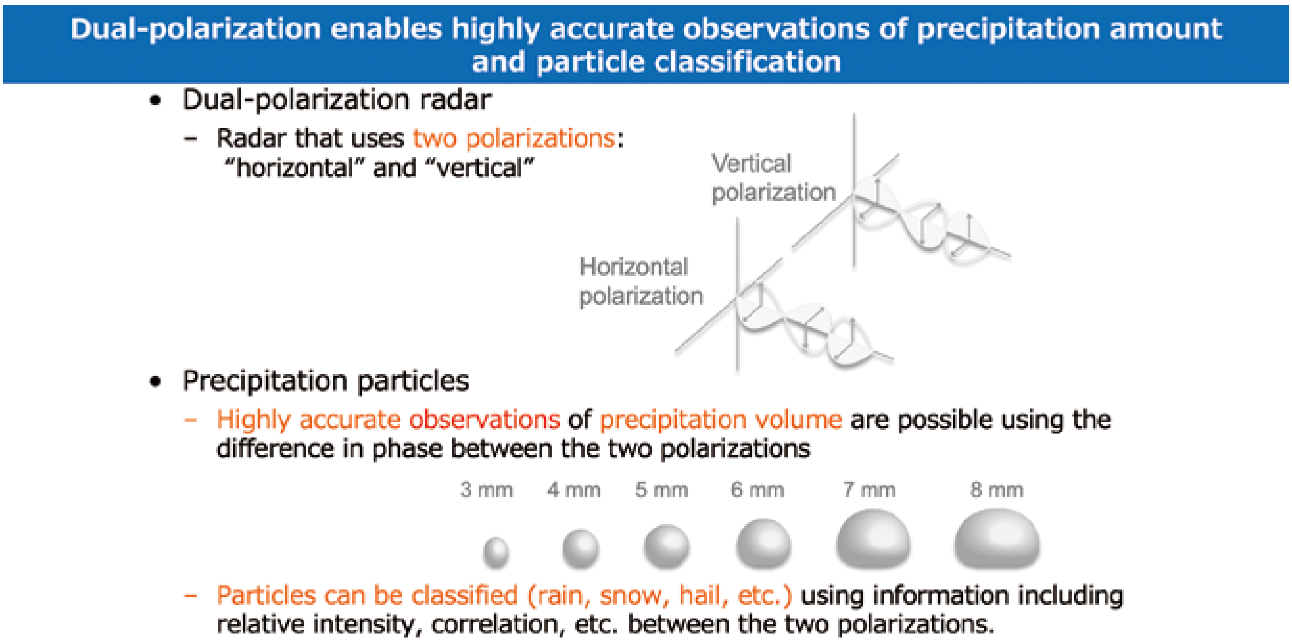
4. Multi-parameter phased array weather radar

Under the direction of a Cabinet Office SIP*1, Multi-Parameter Phased Array Weather Radar (MP-PAWR*2) has been developed (Figure 6), realizing high-density, highly-accurate, and high speed observations. This radar is installed at Saitama University, and is currently undergoing verification tests for real operation.

■ **Figure 6: Multi-parameter phased array weather radar equipment (left) and observation range (right)**

We now describe the features of MP-PAWR, touching on the differences between MP-PAWR and conventional parabolic-antenna radar. For 3D observations with conventional radar, plan position indicator (PPI) scans are performed, gradually changing the angle of elevation for radar observations. This can take from five to ten minutes to complete. There are also areas spatially between consecutive scans where observations cannot be made. On the other hand, with MP-PAWR, the scan of antenna direction is driven mechanically as with conventional radar, but

■ **Figure 5: Dual-polarization radar observation mechanisms**



*1 SIP: Cross-ministerial strategic innovation promotion program
*2 MP-PAWR: Multi-Parameter Phased-Array Weather Radar

scanning in the vertical direction (altitude) is done electronically. This enables rapid and dense observations of 3D space up to an altitude of approximately 15 km, and requires only 30 seconds to one minute to complete (Figure 7).

Figure 8 shows the results from observations over a 30 s interval, a radius of 60 km and at altitudes up to 15 km. With MP-PAWR, this sort of 3D observation of rainfall distribution can be made every 30 seconds to one minute.

Figure 9 shows how features of MP-PAWR can be used. Various stages of the rapid increase in river water levels after a sudden heavy downpour are represented conceptually as "Raincloud appearance," "Rapid raincloud growth," "Rainfall," and "Water level rise." MP-PAWR is able to observe rainfall amounts in the air at high speed, so during the "rapid raincloud growth" stage before the rain reaches the ground, rainfall can be detected at dense spacing, before it reaches the ground. By computing rainfall in the air based on MP-PAWR observation data detected at this stage, using it as input to predict rainfall amounts, and then to predict water levels, it should be possible in principle to provide this information earlier than with conventional methods.

This approach is comparable to that of emergency earthquake bulletins. For emergency earthquake bulletins, earthquakes are detected, having already occurred at the epicenter, and bulletins are distributed to areas predicted to receive tremors several seconds before they arrive. This information is used to control a range of infrastructure automatically, such as pushing notifications to mobile phones, reducing speed on bullet trains to prevent derailments, and stopping elevators at the nearest floor to prevent people getting trapped.

Figure 7: Comparison of conventional radar and MP-PAWR antenna scanning methods

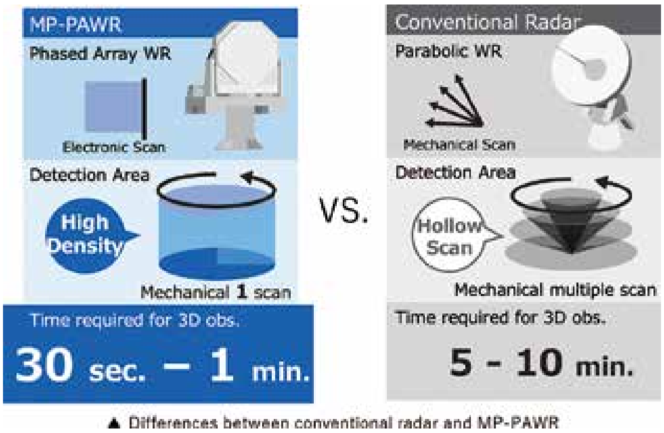


Figure 8: Precipitation observations from MP-PAWR (Aug. 27, 2018)

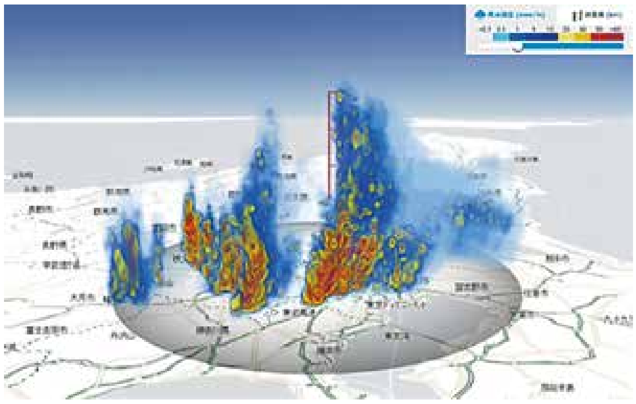
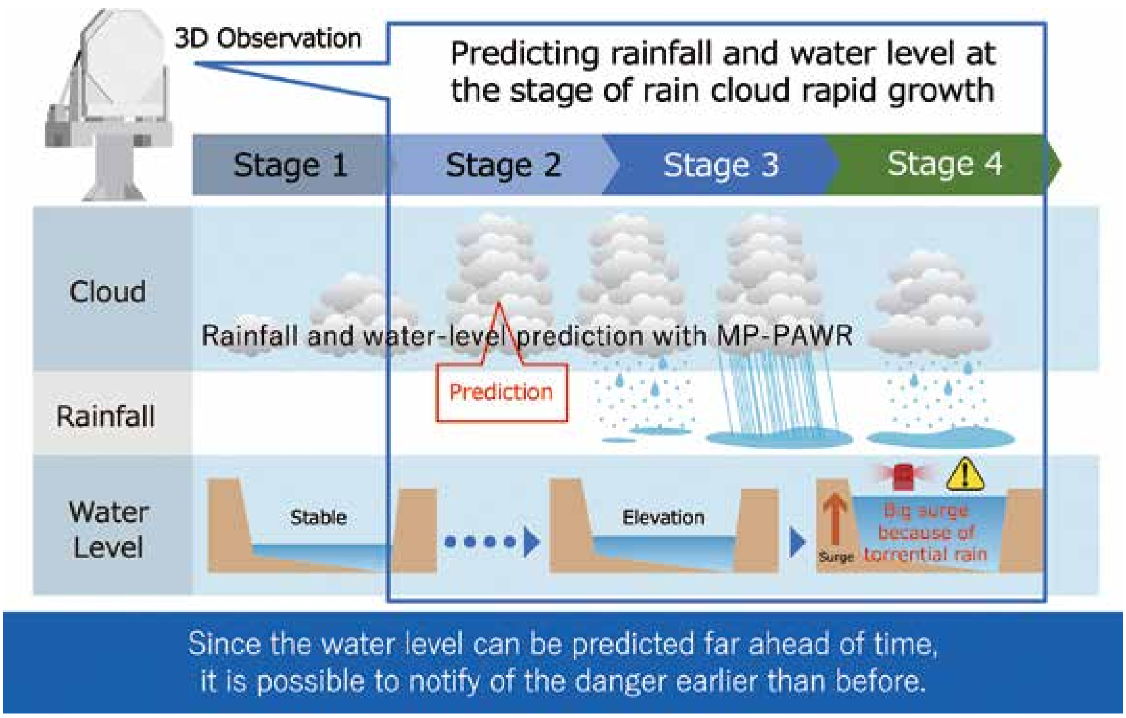
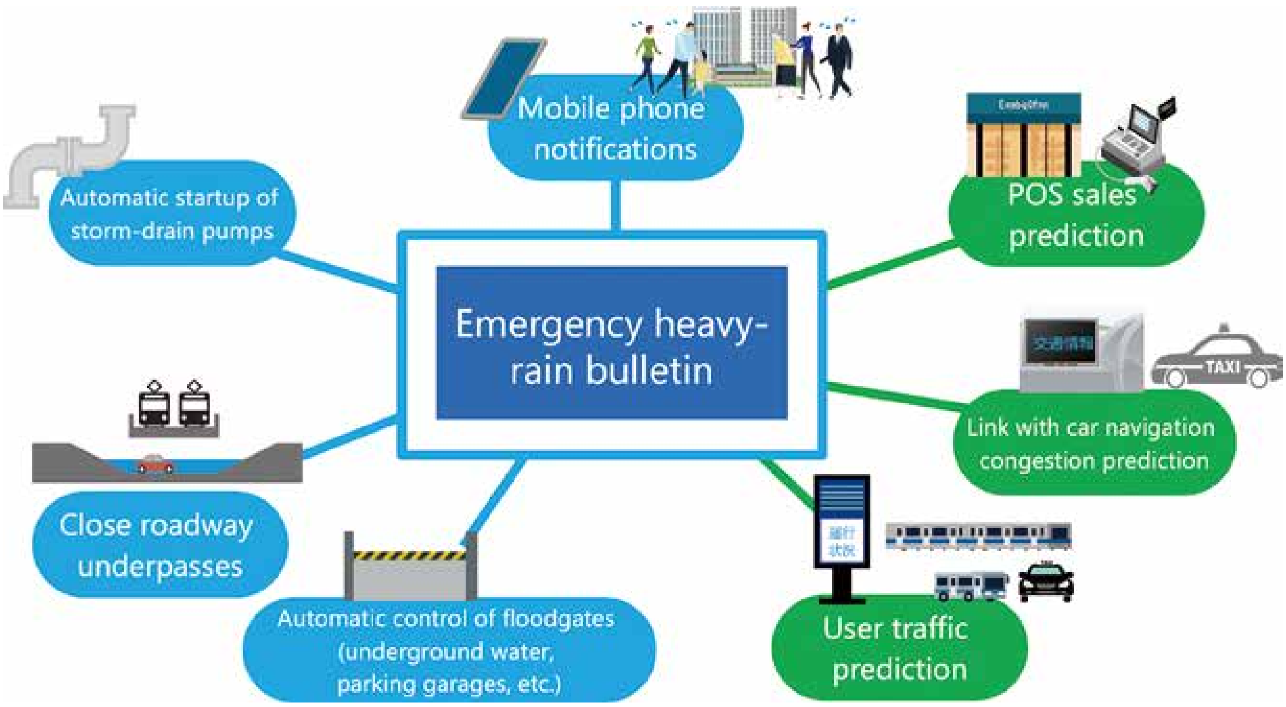


Figure 9: Rainfall and water-level prediction with MP-PAWR



■ **Figure 10: Utilization of MP-PAWR for emergency heavy-rainfall bulletins**



Similarly, emergency heavy-rain bulletins through MP-PAWR could be used to detect and notify of heavy rain that has already occurred in the air, minutes before it reaches the ground. Specific examples are shown in Figure 10, including disaster prevention measures such as automatically starting drainage pumps and stopping entry to roadway underpasses, but also convenience measures such as predicting congestion for car navigation systems.

5. Conclusion

Japan experiences many damage-causing natural disasters including earthquakes, volcanoes, heavy rain and gusty wind, and sudden heavy rain is one such phenomenon that causes damage in society. Reports of conditions made using weather radar and distributed nationally have long been helpful in reducing damage from sudden heavy rain storms.

In the future, we hope to contribute to realizing a safer, more secure society with automatically controlled infrastructure by combining MP-PAWR 3D observations of precipitation before it even reaches the ground, with other technologies such as AI and IoT.

Cover Art

Evening at Takanawa (Takanawa no yukei)

Utagawa Hiroshige (1797~1858)

Collection of the Art Research Center (ARC)
Ritsumeikan University
Object number: BN03828992-1-05