# Development of High-Resolution Meteorological Radar

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Rainfall observation using weather radars has a major advantage that it is possible to observe precipitation over a wide area in a short time. However, the precipitation data observed by weather radars often do not correspond to those obtained by ground-based rain gauges. One of the causes of this disagreement is the non-uniformity of rainfall distribution in a radar scattering volume. Another cause is that most types of radar cannot receive radar echo at low altitude, because the earth's curvature causes radar beam to overshoot several kilometers above the ground surface, or because the receiver in a vertical pointing mode is turned off during pulse transmission. For the purpose of identifying how the reflectivity profile changes near the ground and estimating precisely the causes of reflectivity measurement errors, the authors developed a high-resolution meteorological radar that is capable of observing radar echo near the ground with a high temporal and spatial resolution and a high accuracy.

## 1. Introduction

In recent years, weather observation instruments are being developed and installed for early detection of abnormal weather. There are already more than 20 units of real-time weather radars for rainfall observation in Japan, and more number of high-performance weather radars with Doppler detection or dual polarization capability are being installed each year. The observation area of this kind of weather radar covers 100 to 300 km in radius of the radar. Therefore, it may seem as if there already exists in Japan a weather radar network covering the whole country. However, rainfall data observed by a weather radar does not necessarily correspond to that measured by an instrument such as a ground-based rain gauge. There are often cases where it is shown on the web that a radar echo is received when no actual rainfall is observed. Such incidents occur because the earth has a curved surface. Due to the earth's curvature, a radar that emits radio waves horizontally observes far up in the sky at a point 100 to 200 km from its installation location. Thus, this brings about a problem known by the name of "sensing gap," which is the existence of many unobservable areas around the boundary layer with the existing weather radar network. Also, for example, even when an azimuth resolution is about 0.1 degree, the spatial extent at a point 200 km ahead is more than 300 m, so a weather radar can observe only the average field of the space. Moreover, a range resolution needs to be more than several tens of meters due to a limited occupied bandwidth, and therefore the nonuniformity of rainfall density is theoretically unobservable. This is the reason for data discrepancy. For early prediction and detection of regional extreme weather such as tornadoes and torrential rains, the cells of the existing weather radar network should be further subdivided, and it is indispensable to install many medium-range radars that can provide high temporal and spatial resolution data. Based on this idea, the authors successfully developed a high-resolution meteorological radar (hereafter referred to as HRMR) in cooperation with Osaka University's Graduate School of Engineering. In this paper, the authors report on the technological aspect of this HRMR (**Photo 1**) and the initial observation results. The evaluation of actual observation of the developed radar system was carried out at the Tanegashima site of the Japan Aerospace Exploration Agency (JAXA).

**Photo 1.** HRMR (at JAXA's HRMR site)

## 2. System outline

**Table 1** and **Fig. 1** show the specifications and configuration of the developed HRMR system, respectively. This HRMR system is composed of antenna units, a transmitter/receiver unit, a signal processing unit, and a data processing unit (a PC). The basic design concepts of these constituent units will be described in the following sections.

### 2-1 Frequency

For observing the nonuniformity of rainfall distribution and for analyzing the structure of tornadoes, a

**Table 1.** HRMR system specifications

| Items | | Specifications | Remarks |
|---|---|---|---|
| System | Operational Frequenc | 15.75GHz | |
| | Operational Mode | Spiral , Conical , Fix | |
| | Band Width | 80MHz (max) | 15.71GHz - 15.79GHz |
| | Modulation | FM charp | |
| | Coverage | Az : 360˚ / El : 90˚ | |
| | Resolution (Az/El) | 3˚(min) | |
| | Resolution (Range) | 5m (min) | variable |
| | Resolution (Time) | 1min./scan | |
| Antenna | Antenna Gain | 36dBi | |
| | Beam Width | 3˚ | |
| | Polarization | Linear | |
| | Cross Polarization | 25dB (min) | |
| | Antenna Noise Temp. | 75K (typ.) | |
| Transmitter Receiver | Transmitted Power | 10W (max) | |
| | Duty Ratio | 0%~100% | |
| | Noise Figure | 2dB (max) | |
| Signal Processing | D/A | 170MHz - 14bit | IQ 2ch |
| | A/D | 170MHz - 14bit | IQ 2ch |
| | Range Gate | 32k (max) | |
| | IPP | variable | |
| Data Processing | OS | Windows XP | *1 |

*1 Windows and Windows XP are either trademarks or registered trademarks of Microsoft Corporation in the United States and/or other countries.

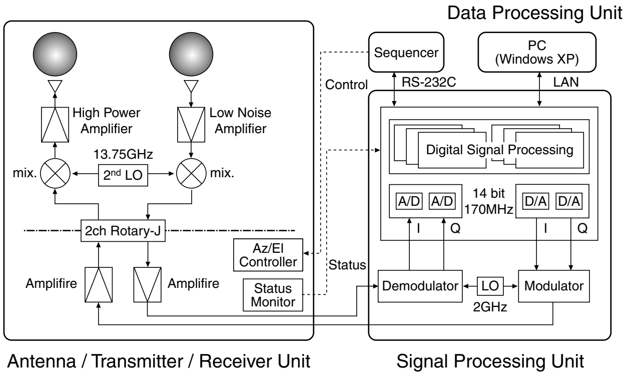

**Fig. 1.** HRMR system configuration

range resolution of at least 2 m is required. With common pulse modulation and/or frequency modulation taken into consideration, the frequency bandwidth necessary for this 2-m range resolution is 80MHz and higher. Therefore, either of Ku-band and Ka-band, which are relatively easy to obtain certification among the frequency bands assigned to radar systems, is suitable for this HRMR. Moreover, considering the scale of cumulonimbus clouds, mutual interference among radars, and the cost for further radar network expansion, it is desirable that the current weather radar network is complement by installing medium-range radars having a range coverage around 20 km. In this development, Ku-band (15.75 GHz) was selected as the center frequency, because the output power of semiconductor power devices is not high enough with Ka-band although they are recently becoming increasingly higher in output.

### 2-2 Antenna and beam scanning method

A mechanical azimuth/elevation (Az/El) drive system typically used in parabolic antennas is presently common among most weather radars. Recently, the use of a mechanical drive system for Az rotation only and a phased array antenna for El scanning is being proposed. However, in order to compensate the earlier described problem of surface gap, full-volume scanning including the zenith direction is necessary, so it is technically difficult for a phased array antenna whose practical scanning range is ±45 degrees, and it is also difficult in terms of costs. Regarding temporal resolution, it is desirable that full-volume scanning takes less than one minute, so the speed of rotation in the Az direction needs to be 20 to 40rpm. Although this is not a rotation speed that is technically difficult to achieve, it must withstand continuous running for 24 hours, 365 days, and small and light antennas are required. In consideration of these requirements, the authors adopted Luneberg lens antenna that is used in Sumitomo Electric's conventional weather observation radar (wind profiler radar) and whose performance is proven. With the use of Luneberg lens, the authors realized a method of high-speed beam scanning using a compact primary radiator.

The principle of Luneberg lens is shown in **Fig. 2**. A Luneberg lens is a type of dielectric lens proposed by R. K. Luneberg in 1944. The permittivity changes depending on the distance from the center of the lens, and the incident plane wave is concentrated into one focal point on the surface symmetrical to the lens. Because the lens is of spherical shape, each of the radio waves coming from every direction has its own focal point, and therefore all points on the lens surface can become focal points, and radio waves from arbitrary directions can be received independently. Conversely, a radio wave from a focal point is radiated as a plane wave after passing

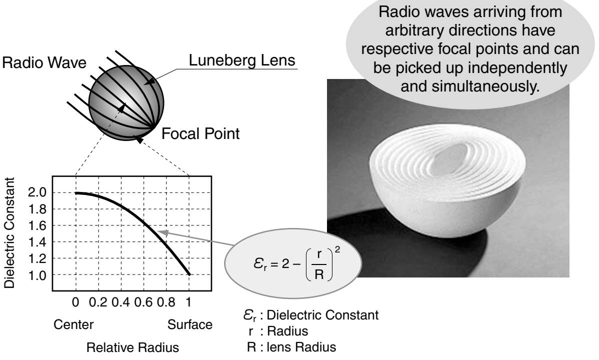

**Fig. 2.** Principle of Luneberg lens

through this lens. These characteristics suggest that the Luneberg lens functions as a multi-beam transmission/reception antenna. In the HRMR development, the authors used this Luneberg lens as a high-speed beam scanning antenna. In the developed system, a pair of Luneberg lenses (diameter: 450 mm, antenna gain: 36 dBi) are being used, respectively, as a transmitter and a receiver. **Figure 3** shows the antenna pattern of a Luneberg lens at a frequency of 15.75 GHz.

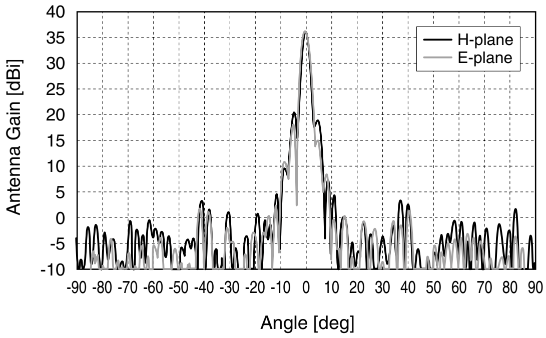

**Fig. 3.** Antenna pattern of 450 mm dia. Luneberg lens antenna

### 2-3 Radome

Because of its structure, a standard parabolic antenna radar can be used without a cover. However, in the case of a weather radar to which absolute received signal strength is important, a radome is indispensable because the antenna gain is greatly affected by raindrops flowing on the reflector.

The problems of a polyhedral radome made of a flat panel are that it tends to be large in size, and that its performance may be insufficient for use with dual polarization that demands a cross polarization of more than 25 dB. Therefore, the radome adopted in the developed radar system is of an integrated-type honeycomb sandwich structure that features excellent strength and transmission/reflection characteristics.

### 2-4 Transmitter

Although klystrons and other types of vacuum tubes are used in existing weather radars and other equipment, solid-state components are seen as indispensable to the transmitters of future radars from the viewpoints of lifetime and handling ease. Because a range coverage of 20 km (at 20 dBZ) is the design value in this development, an output of 10 W was realized by the parallel composition of GaAs power devices that deliver several watts each. In frequencies beyond Ku-band, the maximum output power of a GaAs power device is several W. Therefore, instead of GaAs power devices, which are the mainstream so far, GaN power devices are recently getting a lot of attention. GaN power devices have already been put to practical use in applications such as cellular phone base stations. GaN devices of several watts for X-band applications are already on the market, and what is anticipated for the future is the model change to GaN transmitter for Ku-band radars.

For a radar system to obtain enough observation range (observation coverage), the loss in feed systems (from transmitter to antenna and from antenna to receiver) need to be restrained. Therefore, in this development the authors divided a receiver-transmitter into two parts, and installed a second local oscillator (13.75 GHz) at the top of the rotary joint. By this it has become possible to keep the loss in feed systems at less than 0.5 dB because a signal is transmitted at 2 GHz to the rotary joint and the frequency is up-converted to 15.75 GHz just under the lens antenna and then amplified by a high-power amplifier.

Because the system is assumed to be used for continuous observation, each device's status monitoring signals (DC power fail, internal temperature anomaly, transmitting frequency, transmitter output power, etc.) are sent to the indoor device through the slip ring, and then warning messages are displayed on the PC screen.

### 2-5 Signal Processing Unit

In order to cover an observation range of 20 km with a range resolution of 2 m, an inter-pulse period (IPP: 1/PRF) has to be composed of 10K or more sampling points. When pulse compression is done by FFT techniques such as matched filtering, the required processing ability is 16K or 32K FFTs per IPP. In this system, parallel processing is performed by using 32 units of DSPs. A configuration where general-purpose DSPs are cascade connected to FPGAs has flexibility, cost advantages, and high versatility. In initial observations, linear frequency chirp signals were used for modulation. For future optimization of range side-lobe and S/N deterioration, the system employs dual-channel (IQ) A/D and D/A converters whose sampling rate is 170 MHz and dynamic range 14 bits.

Because the capacity of data obtained at above range resolution and temporal resolution is about 360 MB in one minute, issues of data quality management and real-time generation/storage of lighter processed data are to be discussed in the future.

## 3. Initial observation results

The initial observation results obtained by this system at the HRMR site of the Japan Aerospace Exploration Agency (JAXA) are shown in the following. All data are rainfall observation results.

**Figure 4** shows a Doppler spectrum in a certain direction. The horizontal axis shows the Doppler velocity of the target. In this figure, positive velocity represents target approaching toward the radar, and negative velocity represents target moving away from the radar. The figure shows that wind velocity varies altitudinally and that this is observed at a very high range resolution.

**Figures 5 and 6** respectively show the radar echo strength and the radial Doppler velocity observed by a radar scanning in the Az direction at a fixed elevation angle of 3 degrees. The horizontal axis shows the distance in the east–west direction and the vertical axis shows the distance in the north–south direction. The outline of Tanegashima Island is also plotted in the background. The developed radar system is located at the center of this figure.

The radar echo strength and the radial Doppler velocity shown respectively in these figures are indicated by the color gradation. Positive velocity represents a direction moving toward the radar, and negative velocity represents a direction moving away from the radar. This means that it can be understood from **Fig. 6** that the wind was from the west in the area concerned during the observation. These data obtained at an unprecedentedly high range resolution show that non-uniformity rainfall distribution was observed.

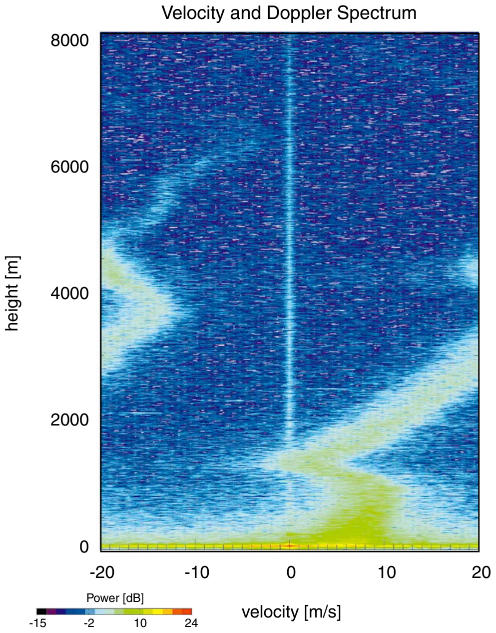

**Fig. 4.** Range profile of the Doppler Spectrum

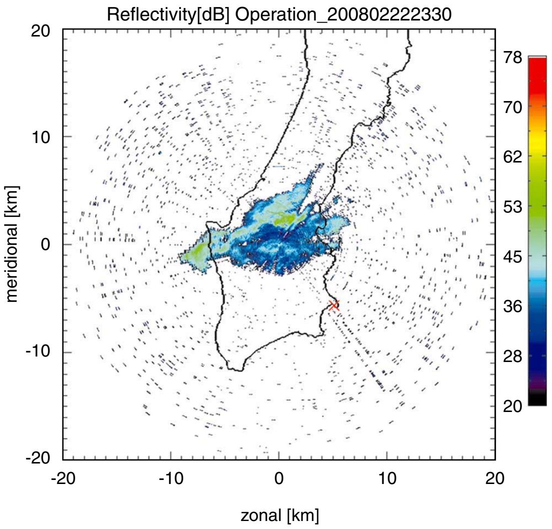

**Fig. 5.** Radar echo strength

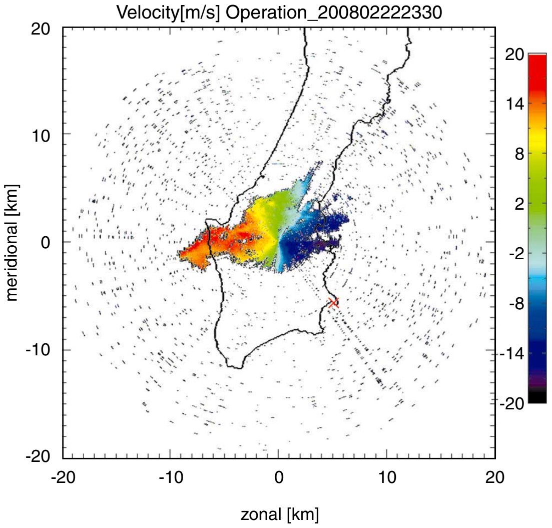

**Fig. 6.** Radial Doppler velocity

## 4. Conclusion

The authors developed a high-resolution meteorological radar (HRMR) and the initial observation was conducted in Tanegashima island. The initial observation shows a fire structure of precipitation which is difficult to be obtained by the conventional weather radar, demonstrating the usefulluess of this radar. As was stated in the Introduction section, the original purpose of this development was to subdivide each cell of the existing weather radar network and increase the network density by installing a large number of the developed radar. Obtaining more detailed initial data is extremely effective not only in improving the accuracy of weather prediction but also in making early detection and prediction of localized extreme weather such as tornadoes and localized torrential downpours. The future development subjects are to develop a method for multilateral observation of tornado occurrence by radar covering the cell concerned and a tracking algorithm for intercell movement of tornadoes.

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