Development of advanced radar technologies for weather application

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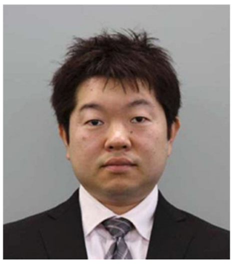

Masakazu Wada

1 Introduction

Recently, the number of unusual extreme weather that causes natural disasters is increasing, and accompanying phenomena such as local heavy rainstorms, tornado, and gust fronts have caused an immediate and often devastating impact on a broad range of human activities. Weather radar has played an important role to survey those meteorological phenomena associated with rainfall and to mitigate most of the damage and loss of life for a long time. The advent of electrical and signal processing technologies has helped for rapid development and improvement of the modern weather radar and provides us opportunities to choose appropriate weather radars based on functions that we need. In this paper, we introduce new type of weather radars; Solid-State Weather Radars (SSWR), Phased-Array Weather Radar (PAWR) and Dual-Polarization Phased-Array Weather Radar (DP-PAWR), along with history and features of the weather radars.

Figure 1 shows history and future of weather radar technology development in Japan. Time frame might be different but a sweeping trend is not very different in many countries. In the first period around the 1950s, it was the age of analog radar that could only tell you the presence or absence of rain fields. At this time, only magnetrons were available for transmitters. In the second period around the 1970s, weather radar became able to estimate the amount of rainfall to some extent. This type of radar enabled us to survey rainfall fields and measure rainfall rates. However, the reliability of the estimated rainfall rate from the measurements with the radar was low, and the radar of this kind provided no information on winds. To overcome this issue, in the third period around the 1990's, the development of technologies was separated into two different directions, the Doppler radar and the dual polarization radar. In addition, the mainstream of transmitter technology began to shift from magnetrons to klystrons in this period. However, by the 2000's, the two different directions have been united, and most of recent users prefer to have radars with dual polarization and Doppler capabilities in Japan. Because of its numerous advantages over conventional radars, the government of Japan has persuaded uses to make a purchase of dual-polarization-Doppler radar equipped with solid-state transmitters. In 2010's, an operational phased-array weather radar was developed to observe convective clouds including cumulonimbus that develop in short time. Currently, we are developing Dual-Polarized Phased-Array (Doppler) Weather Radar (DP-PAWR) to obtain dual-polarized information with high spatial and temporal resolution, which is the next generation radar.

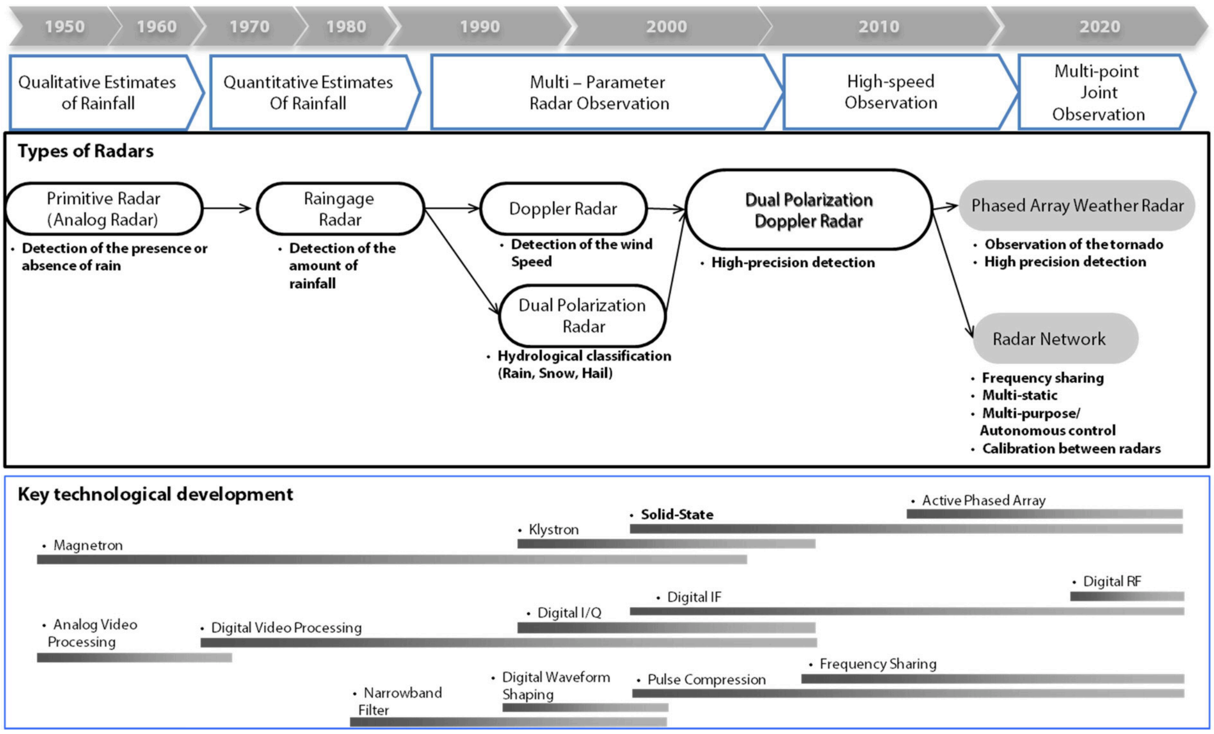

Figure 1: Overview history and future of Weather Radar technologies

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SSWR including DP-PAWR is equipped with semiconductor transmitters that are stable and suitable for precise rain observations by using dual-polarization capability. It is more accurate and robust, lower lifecycle cost, less down time and less spectrum occupation if compared with klystron or magnetron. A number of SSWRs have been already installed as a part of operational radar network in Japan, and currently expanding over the sea. On the other hand, PAWR is an advanced weather radar suitable for observations with high temporal and spatial resolution of convective clouds, which develops rapidly within 15 min. Indeed, this type of radar is capable of performing full volume scanning within 1 min., despite it takes more than 5 min. for conventional radars with parabolic antenna to make. Some PAWR have been already installed and operated in Japan. The DP-PAWR is the most advanced dual-polarized weather radar, developed for rapid and reliable observation of meteorological phenomena, to complement disadvantage of current single-polarized PAWR. In this paper, we show each radar system in detail.

2 Solid-State Weather Radar (SSWR)

SSWR uses Solid-State transmitter, which was originally very low transmission power compared with electron tube radar system and only used for smaller scale system. In late 1990s, power outputs from each microwave semiconductor were increased, which uses GaAs and GaN FET. Even after combining such high power microwave semiconductor as power amplifier components, peak power was not enough for weather observation. To overcome such issues, pulse compression technique was used. However, uses of long transmit waveform and pulse compression remains issue of range sidelobe problems, which need to be reduced. As a result of development, Toshiba overcome these problems (Wada et al. 2009) and SSWR gained popularity because of its capability for pulse shaping, which allows for a precise control of the actual bandwidth usage. Currently, Solid-State transmitters based weather radars are widely used by many users. (Anraku et al, 2013)

Toshiba developed and installed first SSWR in 2007. The SSWR installed in Japan Meteorological Agency - Meteorological Research Institute (MRI) is the first C-band SSWR system used in Japan, which uses Dual-Polarization with solid-state transmitter to achieve highly accurate observation of precipitation. The SSWR installed under management of Ministry of Land, Infrastructure, Transportation and Tourism (MLIT) in 2010 is the first operational SSWR used in Japan. Also, we have drastically reduced its size and life-cycle cost compared with conventional radar. As of July 2014, more than 20 sets of SSWR are manufactured and installed by TOSHIBA Corporation.

In this chapter, we described the characteristic and performance of SSWR to show superior performance by evaluating actual data observed at MRI.

2.1 C-band SSWR

Figure 2 shows the appearance of C-band SSWR in MRI (MRI radar). The size of transmitter was reduced by approximately half (based on Toshiba products) compared with the conventional weather radars. Table 1 show the major specification of MRI radar. It has small and high-performance digital signal processor to enable wide-area and high-precision observation with low transmission power.

Figure 2: C-band SSWR installed in the MRI facility, located in Tsukuba

Table 1: Specification of MRI radar

Item	Description
Observation range	230 km or more in radius
Frequency	5370 MHz
Pulse width	1 us to 350 us
Peak Power	3.5 kW per polarization
Receiver dynamic range	110 dB
Radome diameter	7 m or less
Antenna diameter	4 m or less
Antenna gain	42 dBi or more
Beam width	1 deg or less
Range resolution	150 m or less
Output data	Received signal power (Ph, Pv)
	Doppler velocity V (m/s)
	Spectrum width W (m/s)
	Differential phase ΦDP (eg)
	Correlation coefficient (ρHV)
Manufacture	Toshiba Corporation

Figure 3 shows the distribution of RhoHV for samples collected in stratiform rain with SNR larger than 20dB by the MRI radar. Peak values of RhoHV are 0.998 and 0.992 for long and short pulse observations, respectively. The distribution seems almost independent of sample number N. Figure. 4 shows the distribution of standard deviation of PhiDP calculated using nine gate windows along radial. Peak values of PhiDP are 1.0 deg and 2.0 deg for long and short pulse observations, respectively. As is the case with RhoHV, the distribution seems independent of sample number N.

Adoption of solid-state transmitters brings several advantages. One of the most important advantages is high precision of dual-pol parameters. By virtue of the high precision with small sample number, the radar can observe dual-pol parameters with practical antenna scan speeds of 4 rpm for low elevation angle (EL < 8 deg) and 6 rpm with high PRF for high elevation angle (EL >= 8 deg). This enables us to conduct volume scan with 13 elevations of PPI and 2 azimuths of RHI every 4 minutes. The lowest elevation PPI scan (EL=0.5deg) is conducted every 2 minutes. (Yamauchi et al, 2012)

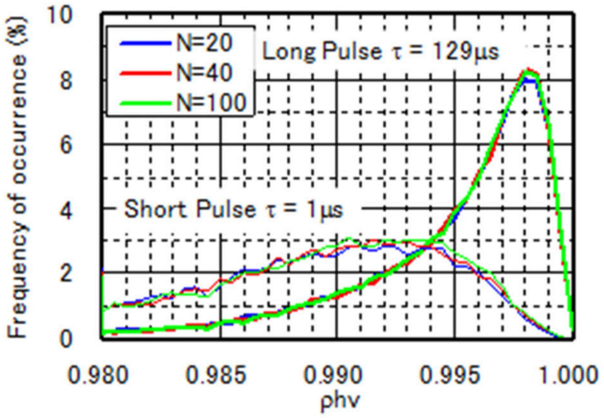

Figure 3. Distribution of RhoHV for samples collected in stratiform rain with SNR larger than 20dB by the MRI radar.

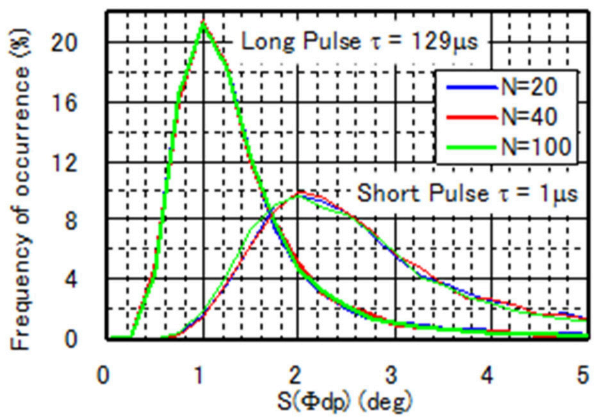

Figure 4. Distribution of the standard deviation of PhiDP for samples collected in stratiform rain with SNR larger than 20dB by the MRI radar

Other than MRI radar, Toshiba also manufactured and delivered number of similar C-band SSWR to MLIT, and JAMSTEC. Figure 5 shows Toshiba's standard C-band SSWR, and Table 2 shows Specification. Transmitter rack was reduced to one rack and has capability to upgrade to high power transmitter (double the number of power amplifiers) without significant change of the system.

Figure 5: Latest model of C-band SSWR which also used by MLIT

Table 2: Specification of Latest C-band SSWR

Item	Description
Observation range	230 km or more in radius
Frequency	5300-5850 MHz
Pulse width	0.5 us to 200 us
Peak Power	3 kW or 6 kW per polarization
Receiver dynamic range	110 dB
Radome diameter	7 m or less
Antenna diameter	4.2 m or less
Antenna gain	45 dBi or more
Beam width	1 deg or less
Range resolution	75 m or less
Output data	Received signal power (Ph, Pv)
	Doppler velocity V (m/s)
	Spectrum width W (m/s)
	Differential phase PhiDP (deg)
	Correlation coefficient (RhoHV)
Manufacture	Toshiba Corporation

2.2 X-band SSWR

Figure 6 shows the first operational X-band Solid-State transmitter based weather radar installed in MLIT site. The major components were accommodated in the radome at the top of a steel tower by making them compact and light weight. Thus, by minimizing the length of waveguide, the attenuation of radio wave was greatly reduced so that it allows sufficient observation performance with small power. The size was reduced by approximately 1/4 (based on Toshiba products) compared with the conventional weather radars and the consumption power was reduced by approximately 1/10 (based on Toshiba products). This radar is used for MLIT XRAIN, X-band operational radar network.

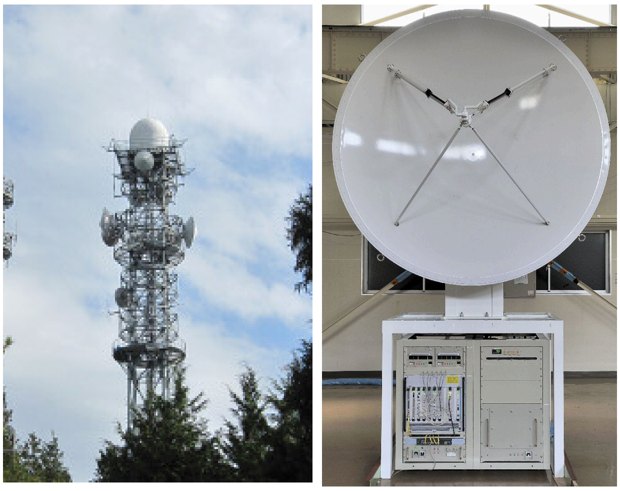

Figure 6: X-band SSWR installed in the MLIT

Table 3:Specification of X-band SSWR installed in MLIT

Item	Description
Observation range	80 km or more in radius
Frequency	9700 to 9800 MHz
Pulse width	1 us to 32 us
Peak Power	200 W per polarization
Receiver dynamic range	110 dB
Radome diameter	4.5 m or less
Antenna diameter	2.2 m or less
Antenna gain	41 dBi or more
Beam width	1.2 deg or less
Range resolution	150 m or less
Output data	Received signal power (Ph, Pv)
	Doppler velocity V (m/s)
	Spectrum width W (m/s)
	Differential phase PhiDP (deg)
	Correlation coefficient (RhoHV)
Manufacture	Toshiba Corporation

3 Phased-Array Weather Radar (PAWR)

Severe weather phenomena such as localized heavy rainfalls, gusts and tornadoes are mainly caused by the rapid growth of cumulonimbus clouds which grows to more than 10 km altitude. Generally, the life-span of a cumulonimbus cloud is as short as 10 to 30 minutes. However, conventional weather radar systems with parabolic antenna requires approximate 5 to 10 minutes for full volume scanning to observe the three dimensional structure of a cumulonimbus cloud, which has an inadequate capability in temporal and spatial resolution for observing the behavior of cumulonimbus clouds. In order to achieve precise three dimensional observations of cumulonimbus clouds for predicting severe weather, weather radar is expected to observe the full volume of meteorological phenomena within 1 minute.

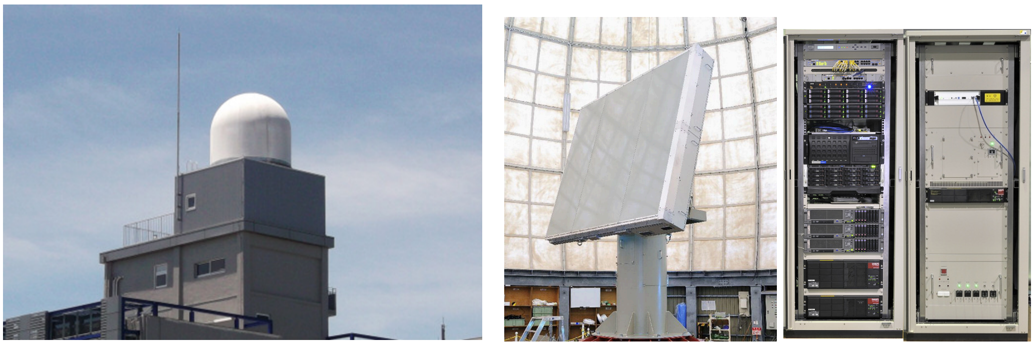

Figure 7: X-band PAWR installed in the Osaka University Campus

Toshiba's newly developed X-band PAWR, shown in Figure 7 has the capability to observe cumulonimbus clouds within 1 minute. PAWR is already installed at Osaka University (Japan) under a grant of NICT, has a 128-slotted array antenna and applied Digital Beam Forming (DBF) technique to simultaneously generate the multiple vertical beams for covering the elevation angle from 0 to 90 degrees. PAWR antenna is mounted with a mechanical drive for azimuth angle and electronic scanning for elevation angle. For the elevation angle, the transmitted beam is formed as a fan beam, and the received beams are formed as multi-beam using DBF technology. Tilt angle of the antenna was set to 30 degrees in elevation, transmitted and receiving by time-division radio wave from -30 degrees to +60 degrees, to observe without a gap from 0 degrees to 90 degrees in elevation. The main feature of PAWR is to perform dense 3-D volume scanning within 10 to 30 seconds without gaps between each beam. (Mizutani et al, 2012)

Table 4: Specification of X-band PAWR

Major Specification		
Tx Power	430 W or higher	
Tx Frequency	9,320 to 9,445 MHz (5MHz step)	
Beam Width (after DBF)	About 1 degree	
Range Resolution	100 m	
Doppler Velocity Measurement	60m/s (max); Dual PRF	
Doppler Velocity Accuracy	0.1 m/s	
Observation Mode	Rapid Mode	Wide Range Mode
Coverage Area (Radius)	20 km	60 km
Full Volume Update Time	10 sec	30 sec
Number of Hits	10 hits	20 hits
Simultaneous Elevations Scanned	100 angles	100 angles

Figure 8: X-band PAWR Antenna

Table 4 describes the major specifications of PAWR. This system has two observation modes. One is “Rapid Mode” which able to update the full volume scanning in 10 seconds with the 20 km radius range. Another is “Wide Range Mode” which observes a 60 km radius range in 30 seconds. Compared with conventional parabolic antenna weather radar, PAWR in “Wide Range Mode” has 100 elevation angles which are 10 times more numerous than conventional radar, and scanning time has been reduced to 30 seconds compared to 5 minutes for conventional radar. In total, performance is 100 times improved by PAWR. Typical observation range for rapid mode is shown in Figure 9. Comparison of PAWR and conventional radar are shown in Figure 10.

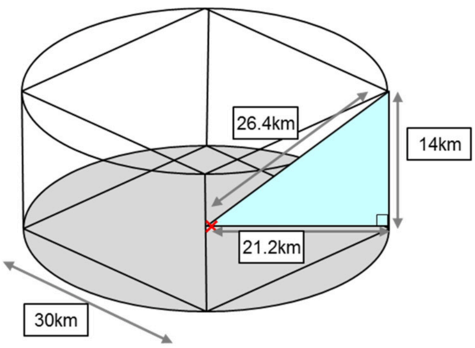

Figure 9: Typical observation range for rapid mode

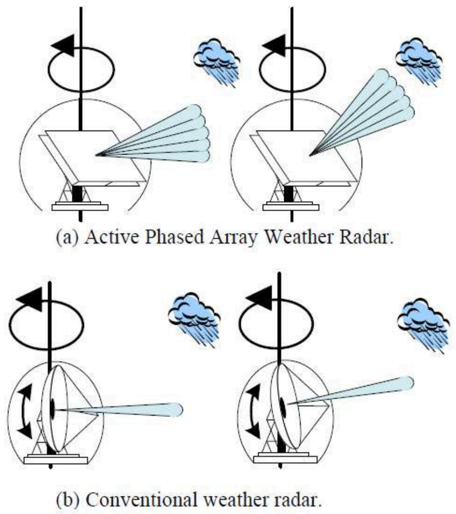

Figure 10: Comparison of conventional parabolic antenna radar and phased-array antenna radar

Figure 8 shows the active phased array antenna used in PAWR which consisted of 128 slot antennas and its aperture length is 2 m by 2 m. This antenna has receiving and transmitting units, DBF units, and those units are located in the rear side of antenna. Each TxRx Unit or Rx Unit has the capability of transmitting or receiving up to 8ch. This radar is able to transmit up to 24ch with 3 TxRx Units, and receive up to 128ch with 13 Rx Units.

The DBF Unit has the capability of processing 128ch synchronized A/D conversion and I/Q detection, and it has at least 60dB of dynamic range. The receiving multi beams at 1 degree from 128ch I/Q signals are formed by DBF technology. DBF Unit is capable of simultaneously handling 16 beams at same time. Azimuth beam width is about 1 degree and side lobe is less than -23 dB. Elevation beam width is about 4 degrees for transmitting by using 24 elements (24 slots), and about 1 to 1.2 degrees for receiving by DBF technique.

For the reception pattern of elevation direction, we have achieved the reduction of the beam width to less than 1.2 degree at 0 degree elevation. Thus, the spatial resolution is about 500 m at 20 km, 1.3 km at 60 km; also able to observe all of the observation space and output 3D data such as radar reflectivity factor (Z) and Doppler velocity (V) within minimum of 10-second intervals.(Mizutani et al, 2012)

Figure 11 shows the three dimensional image of actual observation results observed in July 26, 2012. One cumulonimbus echo was about 3 km vertically and 8 km horizontally. Observation data showed a small indication of heavy rainfall (we call it an "a heavy rainfall in the making") of 4 to 6 km in altitude has exponentially grown and then became localized heavy rainfall within few minutes. By using PAWR, any changes in localized meteorological phenomena can be observed every 30 seconds or less. Our system is expected to use for preventing disasters by forecasting localized heavy rainfalls, gust and tornadoes.

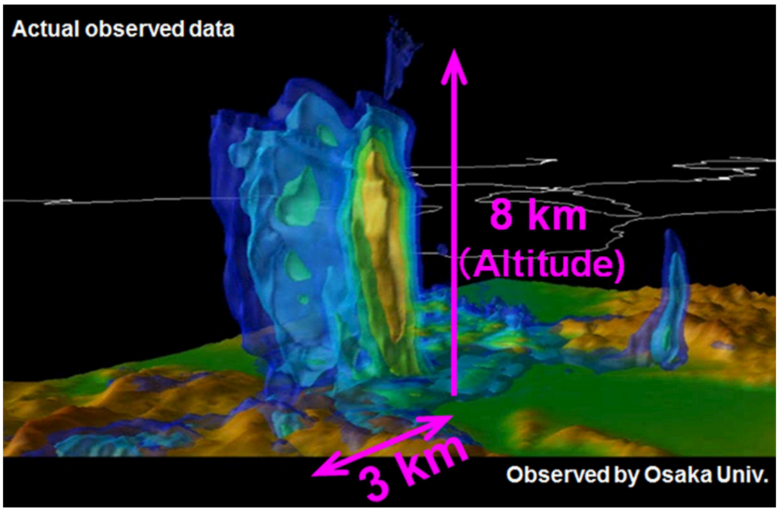

Figure 11: Three dimensional image of actual observation results observed by a phased-array antenna radar in July 26, 2012

4 Dual-Polarization Phased-Array Weather Radar (DP-PAWR)

In recently years, weather radar is more than ever required to have the capability of high precision observation, dual-polarization for hydrometeor classification and phased-array for rapid observation. Toshiba had already developed high precision dual-polarization SSWR and high speed PAWR which described in chapter 3 and 4.

And now, Toshiba started the development of radar which integrates the two functions of dual-polarization and phased-array. This chapter describes the overview of the radar. This research is conducted jointly with NICT and Osaka University: NICT investigates the synchronization technology by using plural radars, while Osaka University develops the signal processing method of digital beam forming and Toshiba is responsible for system design and equipment manufacturing.

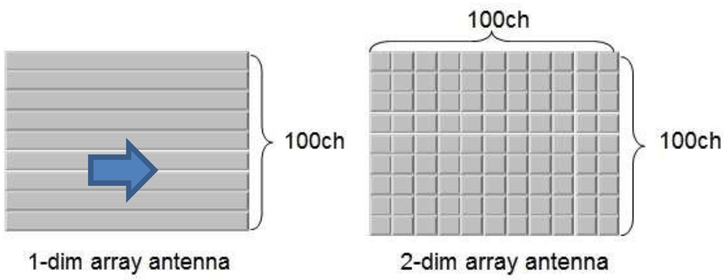

Figure 12: Conversion to 2 dimensional phased array antenna

Toshiba already developed one-dimensional phased-array radars which mechanically drive the system in the azimuth direction and which perform electronic scanning in the vertical direction (elevation angle). Although this radar embodies 24 channels of transmitter system and 128 channels of receiver system in a single unit, Toshiba tried to provide low-cost radar systems by the use of highly integrated circuits. For example, as shown in Figure 12, to produce a two-dimensional phased-array radar, 128×128 channels will be required and this results in a system with 10,000 channels or more. In this case, even if the cost per channel may be reduced by the high integration of conventional boards, the entire radar system may become extremely costly. Therefore, in order to realize the dual-polarization phased-array radar, the cost per channel should be reduced considerably.(Wada et al, 2013)

Compare with PAWR, Technical challenges for this DP-PAWR development is, (1) Dual-pol antenna with good cross polarization characteristics within wide beam scan range. (2) Because of doubled channel density compare with single-pol radar, DP-PAWE needs technology to achieve lower cost, smaller dimension and lower power consumption. We will overcome these challenges before evaluation of proto-type radar within few years.

One of the characteristics which are not in PAWR is flexibility of changing antenna aperture area and form. In PAWR, least antenna unit size was equal to the size of antenna aperture, but least antenna unit size of DP-PAWR is sufficiently smaller than the size of antenna aperture. Because of this characteristics, cost and time for changing radar antenna size are drastically reduced, compare with PAWR. This will be very beneficial for customers who want to have slightly different specification rather than standard user.

Acknowledgement

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