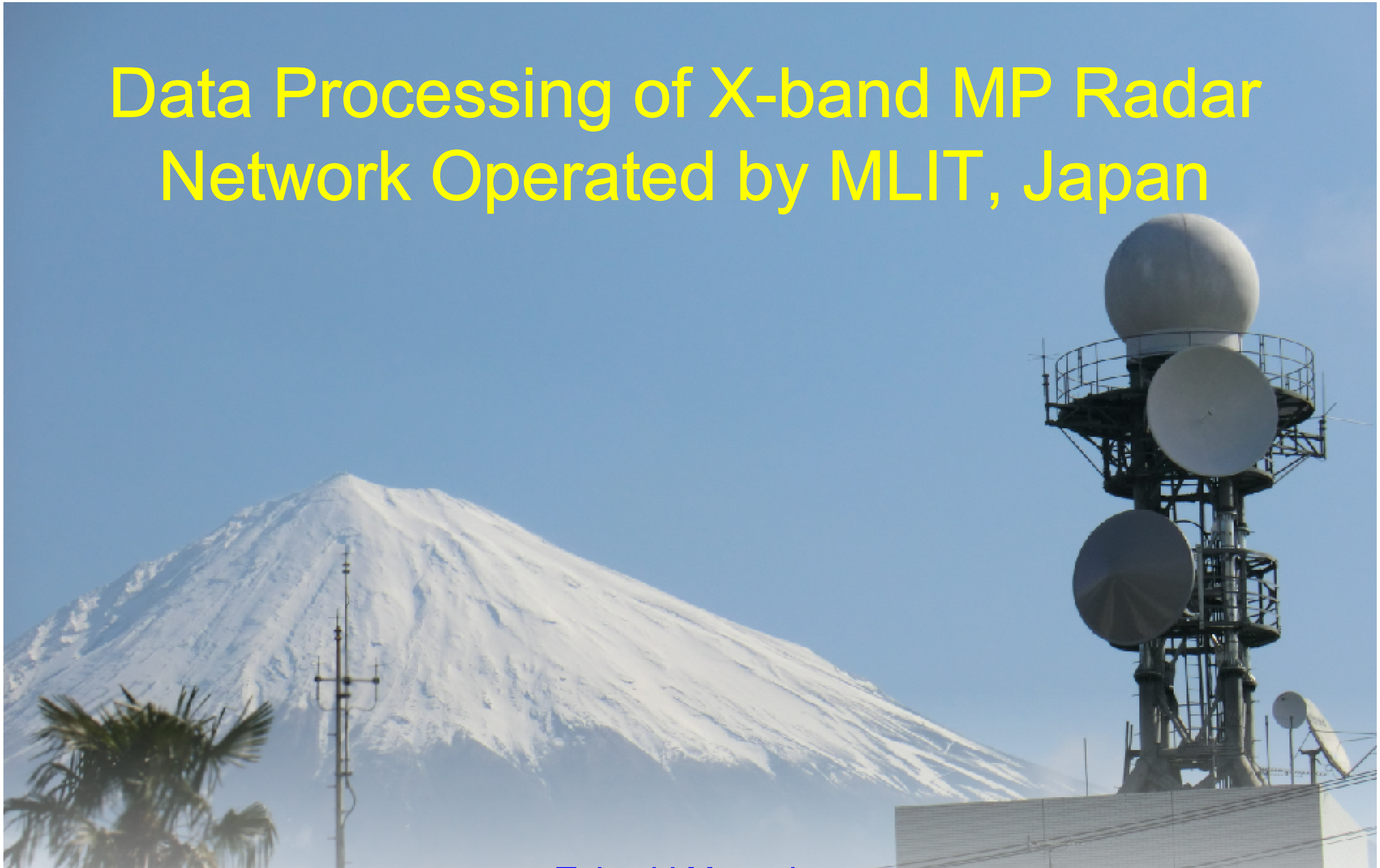
Data Processing of X-band MP Radar Network Operated by MLIT, Japan



Takeshi Maesaka

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Exceptional Seminar at Ecole des Ponts ParisTech on July 2st 2012

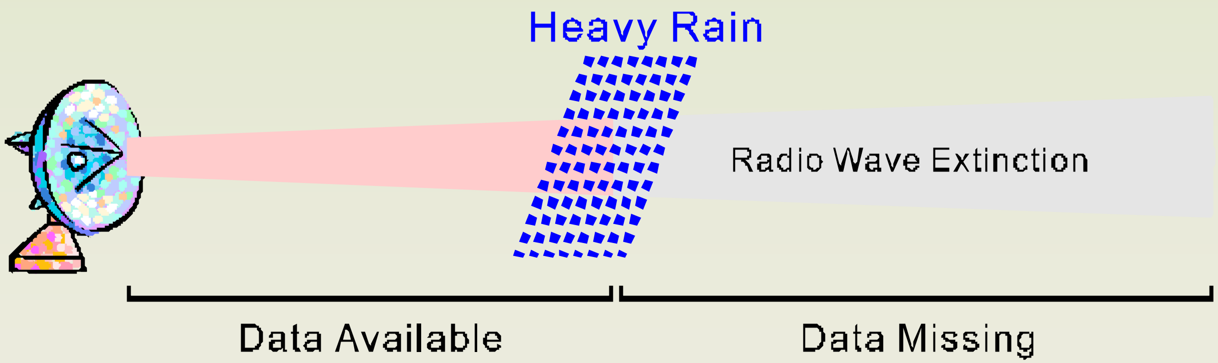
Data Processing of X-band MP Radar Network Operated by MLIT, Japan

- X-band Weather Radar
- Multi-Parameter (MP) Radar
  ≒ Dual Polarimetric Radar
- Polarimetric Parameters
- Z-R versus K_{DP}-R Relationships

Why X-band Weather Radar in Japan ?

- For meteorological research, X-band radar was the only radar we could use in Japan, because of radio wave frequency allocation problem.
- X-band radar has a big disadvantage: rainfall attenuation.

Kingdom of X-band
that we didn't necessary desire…



Band	λ	Rainfall Attenuation
S-band	10 cm	negligible
C-band	5 cm	slightly
X-band	3 cm	significant

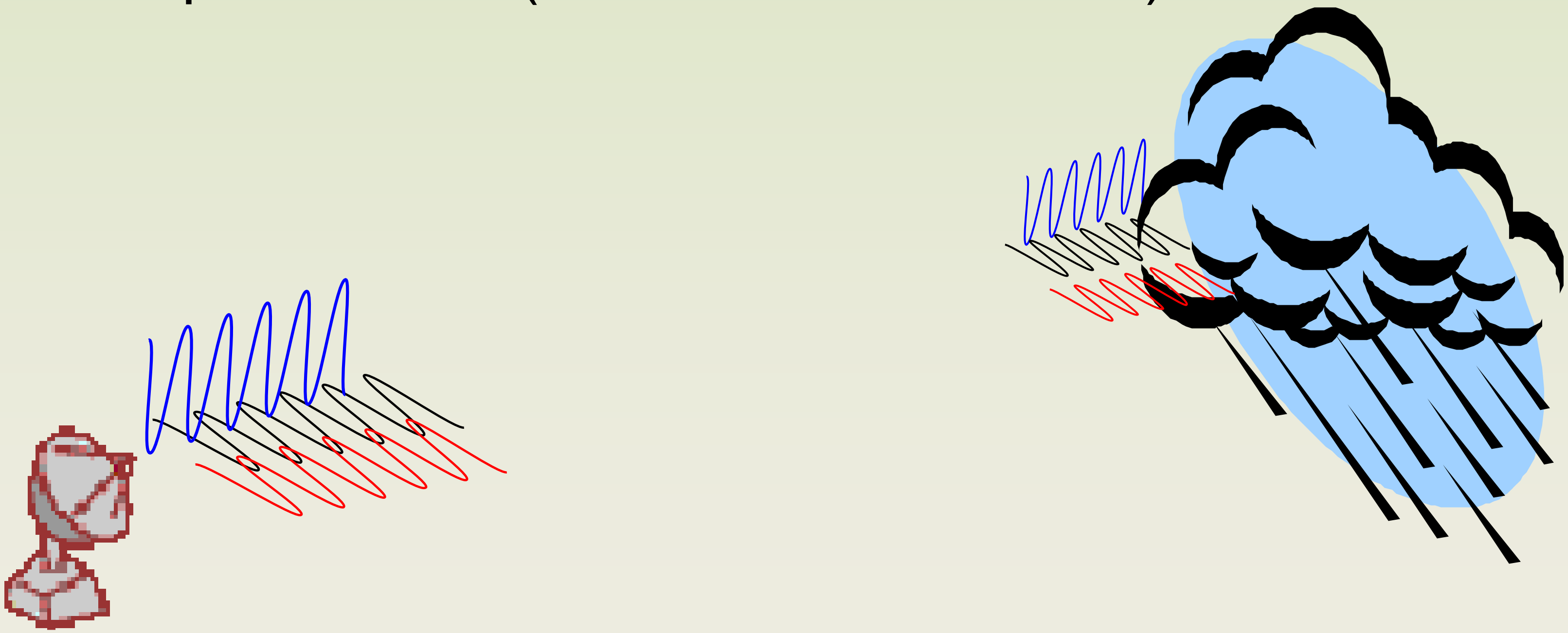
Rainfall attenuation becomes significant with the wavelength shortening.

Everyone thought that X-band radar was not suitable for rainfall estimation. So S- or C-bands radar have been used for operational rainfall estimation.

BACKGROUND (2/6)

Multi-Parameter (MP) Radar

- Conventional Radar
  uses horizontal polarization, and estimates rainfall rate from received power (Reflectivity).
- Multi-Parameter (MP) Radar(≒ Dual-Polarimetric Radar)
  uses two polarization (horizontal and vertical).

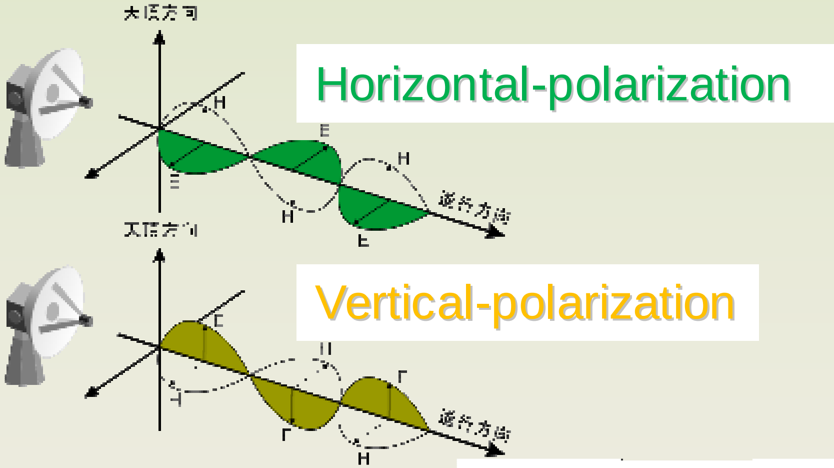


Polarimetric Parameters

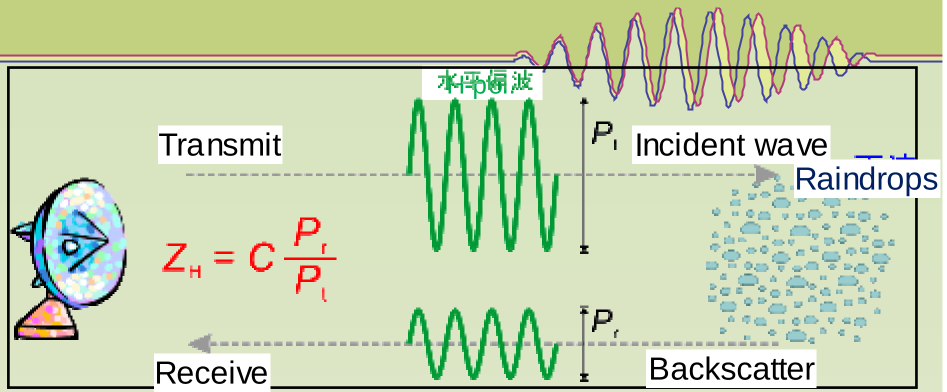
- Z_H: reflectivity factor at H-pol. [dBZ]
- Z_{DR}: differential reflectivity [dB]
- Φ_{DP}: differential propagation phase [°]

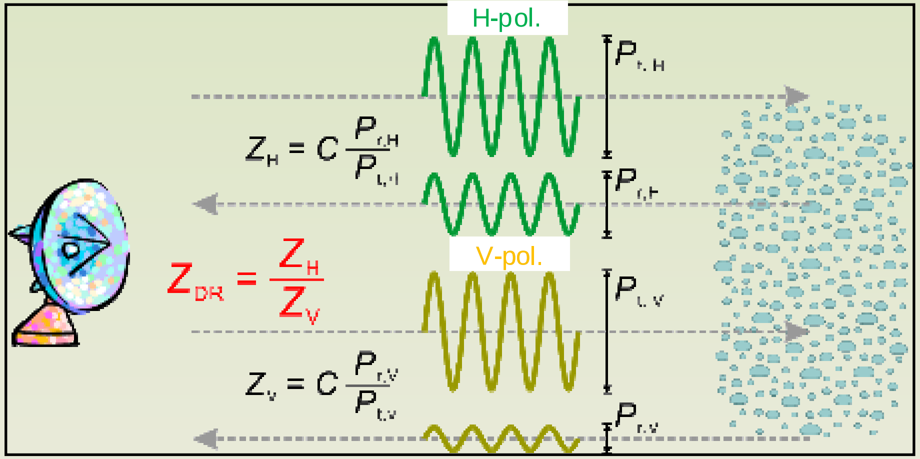
→ K_{DP}: specific differential phase [°/km]

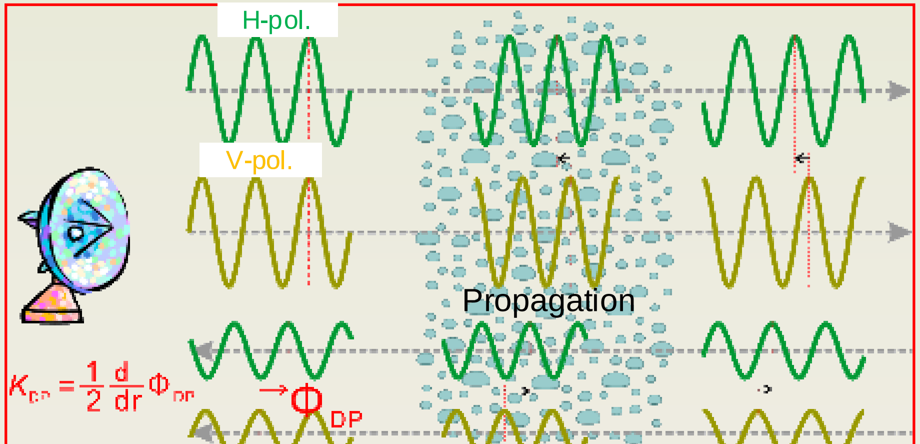
- ρ_{HV}: co-polar correlation coefficient



raindrop







BACKGROUND (4/6)

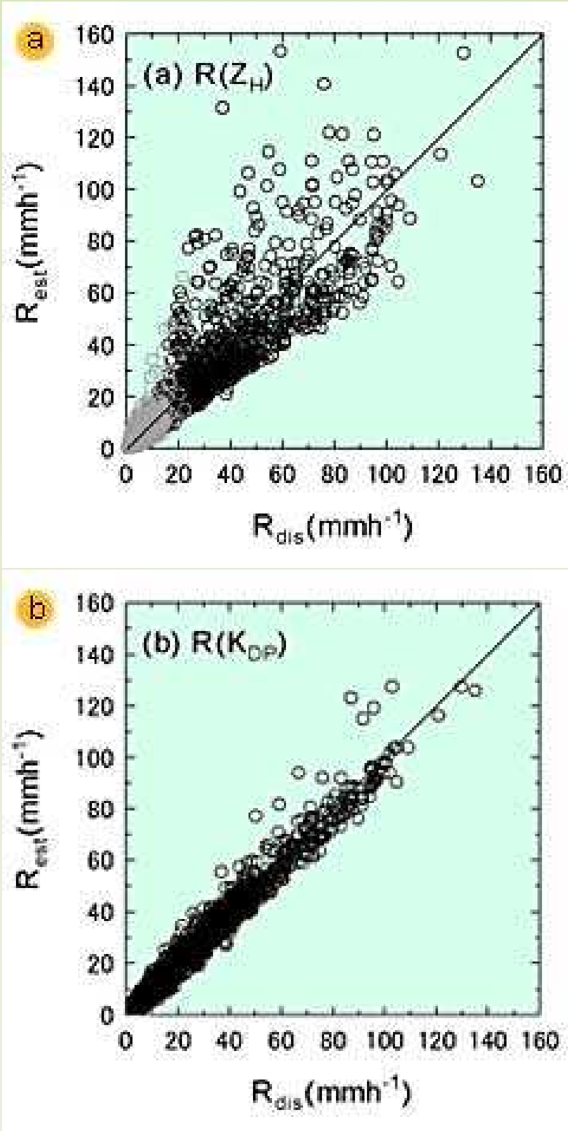
Z-R versus K_{DP}-R Relationships

Estimated *R* vs. Measured *R* [mm/h] from Disdrometer observation

Conventional Radar
Z-R relationship

sensitive to
fluctuations in DSD
not so sensitive to

MP-Radar
K_{DP}-*R* relationship



BACKGROUND (5/6)

Comparisons X-band MP Radar with Other Bands

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	X-Band Radar	S- or C- Band Radar
Quantitative Rainfall Estimation by Differential Phase Shift (Φ_{DP} or K_{DP})	Better	Worse
Observation Range	Shorter	Longer
Influence of Rainfall Attenuation	Significant	Negligible or Slightly
Number of Radars to Cover Same Area.	Larger	Smaller
Typical Antenna Diameter	2 m	8.5 m or 4 m
Cost per One Radar Including Incidental Facilities	Less Expensive	More Expensive
Total Cost to Cover Same Area	**Almost Same ???** It depends on the number of radars, because the unit price becomes cheaper with the number of the production.	

One possible solution is the COMBINATION…
S- or C- bands Radar to cover the all country (where stable observation is needed), and
X-band Radar to cover the important big cities (where high-accurate QPE is needed).

So X-band dual-pol. Becomes Popular!

- Dual-Pol. radar can measure "differential phase shift (Φ_{DP})".
- K_{DP}, which is the differential phase shift per unit distance, is calculated by the derivative of Φ_{DP} with respect to range.
- K_{DP} is a better rainfall estimator than Z_H.
- K_{DP} of X-band is more sensitive than those of S- and C-band.
- So an evaluation to the X-band radar is now completely changed!!! "X-band is now suitable for Quantitative Rainfall Estimation (QPE)."
- Recently, many X-band dual-pol. radars are deployed in the world.

Brief History of X-band Weather Radar in Japan

1980s – 1990s

- Universities and national institutes had mobile X-band Doppler radars to investigate inner structures of rain/snow storms by dual-Doppler wind synthesis. (Some radars were alternative dual-pol. radars.)
- It was very difficult to have C- or S-band radars, because of frequency allocation problem.
- C-/S- band radars were only for operational use.

Kingdom of X-band
But we didn't necessary desire…

2000

- NIED developed "Multi-Parameter (MP) Radar system", which consists of X-band simultaneous dual-pol., Ka-band Doppler, and W-band alternative dual-pol. radars.
- In 2003, the X-band radar was unmounted from the truck, and fixed on the building for QPE research.

MP Radar System

2008

- NIED succeeded in an accurate real-time monitoring of heavy rainfall in Tokyo.
- Ministry of Land, Infrastructure, Transportation and Tourism (MLIT) decided to deploy X-band radar network.

Localized Heavy Rainfall on 5 August 2008

- Six workers were swept away in sewage pipe at Zoshigaya, Tokyo at noon on Aug. 5, 2008.
- They were in process of sewage pipe renewal construction, and 5 workers died.
- Then severe thunderstorm developed suddenly, and brought a heavy rainfall over 100 mm around Zoshigaya.

(Figure: asahi.com)

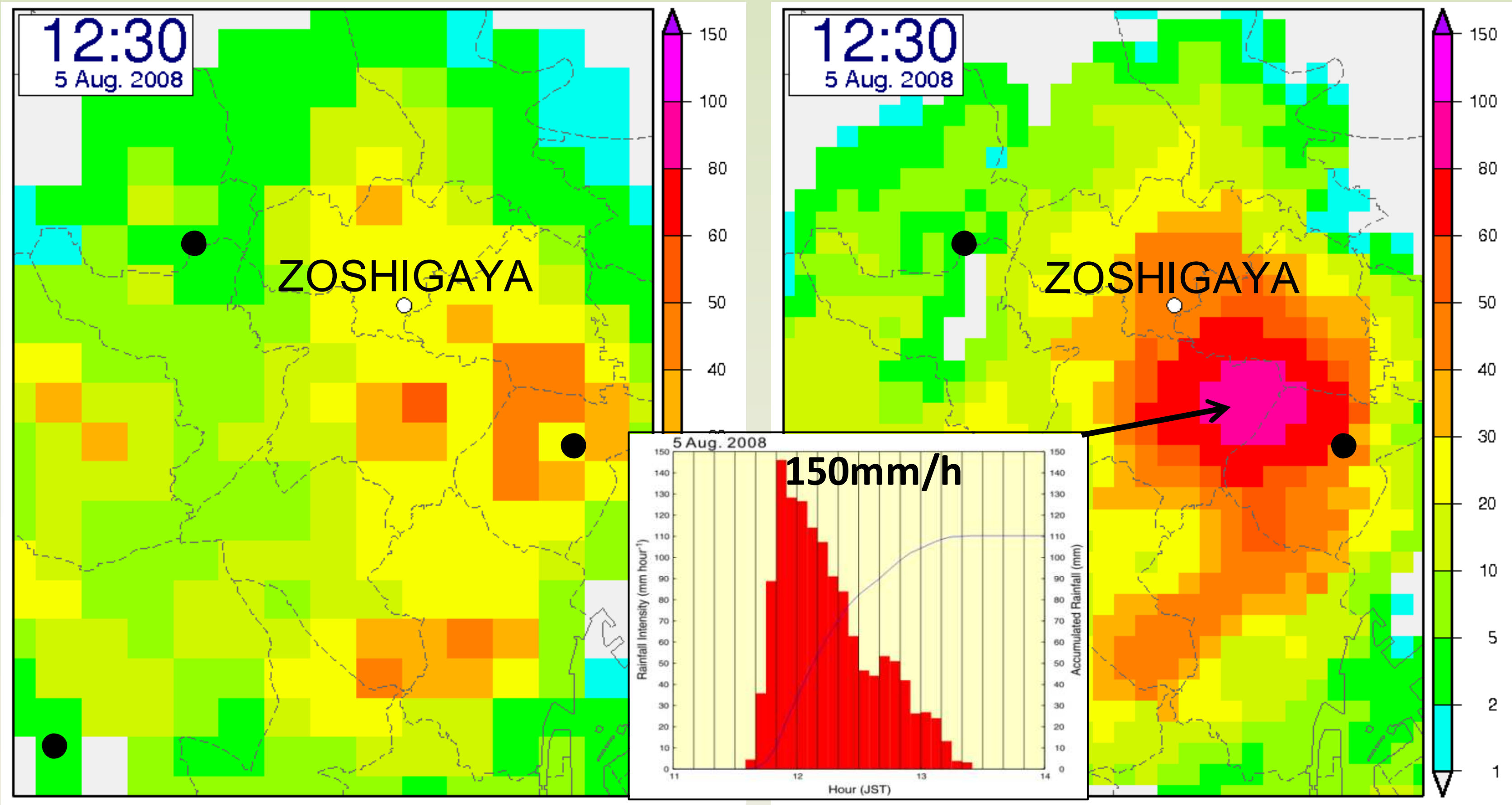
Rescue team, Tokyo Fire Department
(photo: Sankei News)

Epoch-Making QPE Result in Japan

1-hour Accumulated Rainfall Amount

C-band Conventional Radar with Rain Gauge Calibration

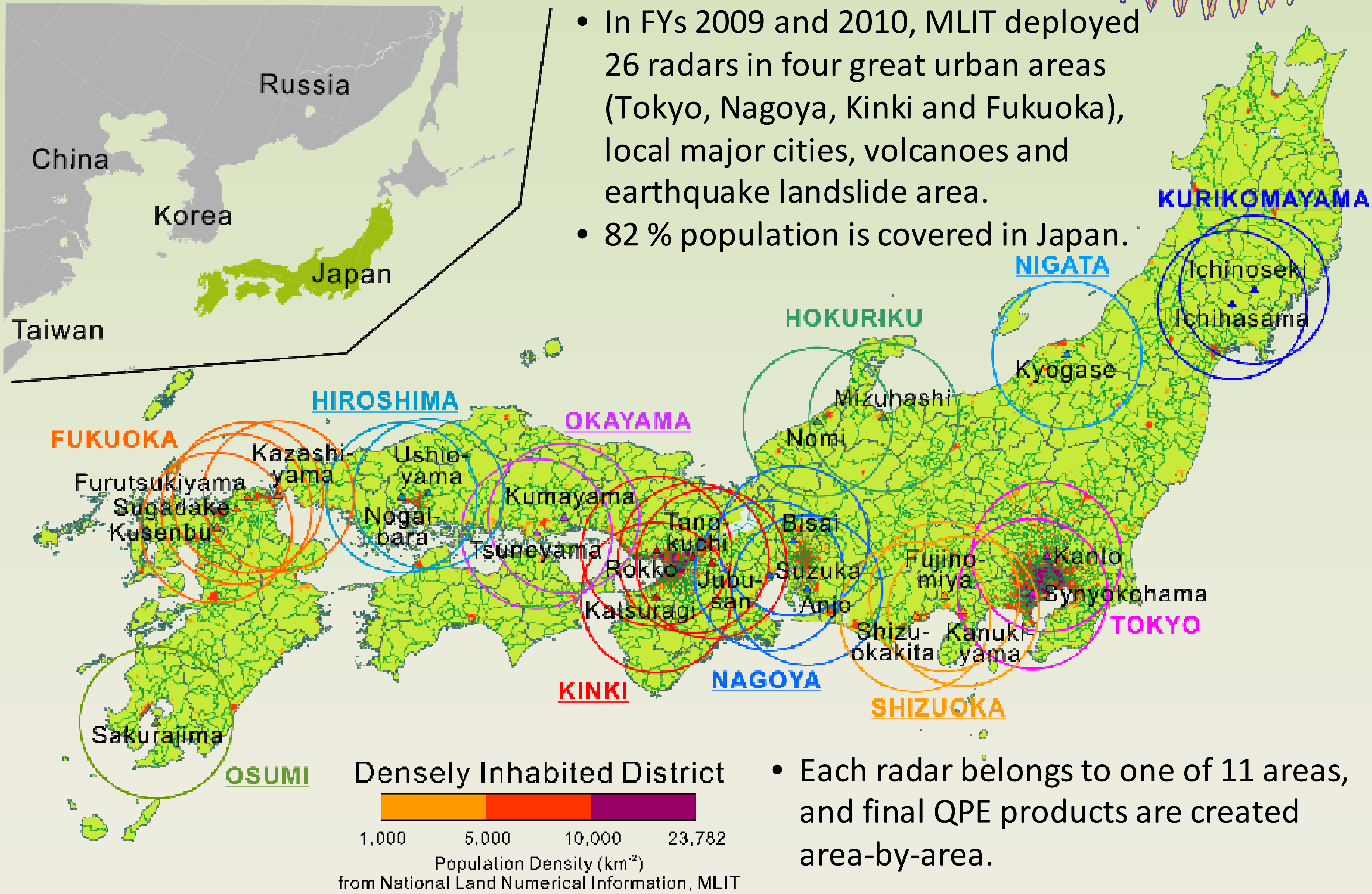
NIED X-band Dual-Pol. Radar Only



Ministry of Land, Infrastructure, Transportation and Tourism (MLIT) decided to deploy X-band radar network.

MLIT X-band MP Radar Network

- In FYs 2009 and 2010, MLIT deployed 26 radars in four great urban areas (Tokyo, Nagoya, Kinki and Fukuoka), local major cities, volcanoes and earthquake landslide area.
- 82 % population is covered in Japan.



- Each radar belongs to one of 11 areas, and final QPE products are created area-by-area.

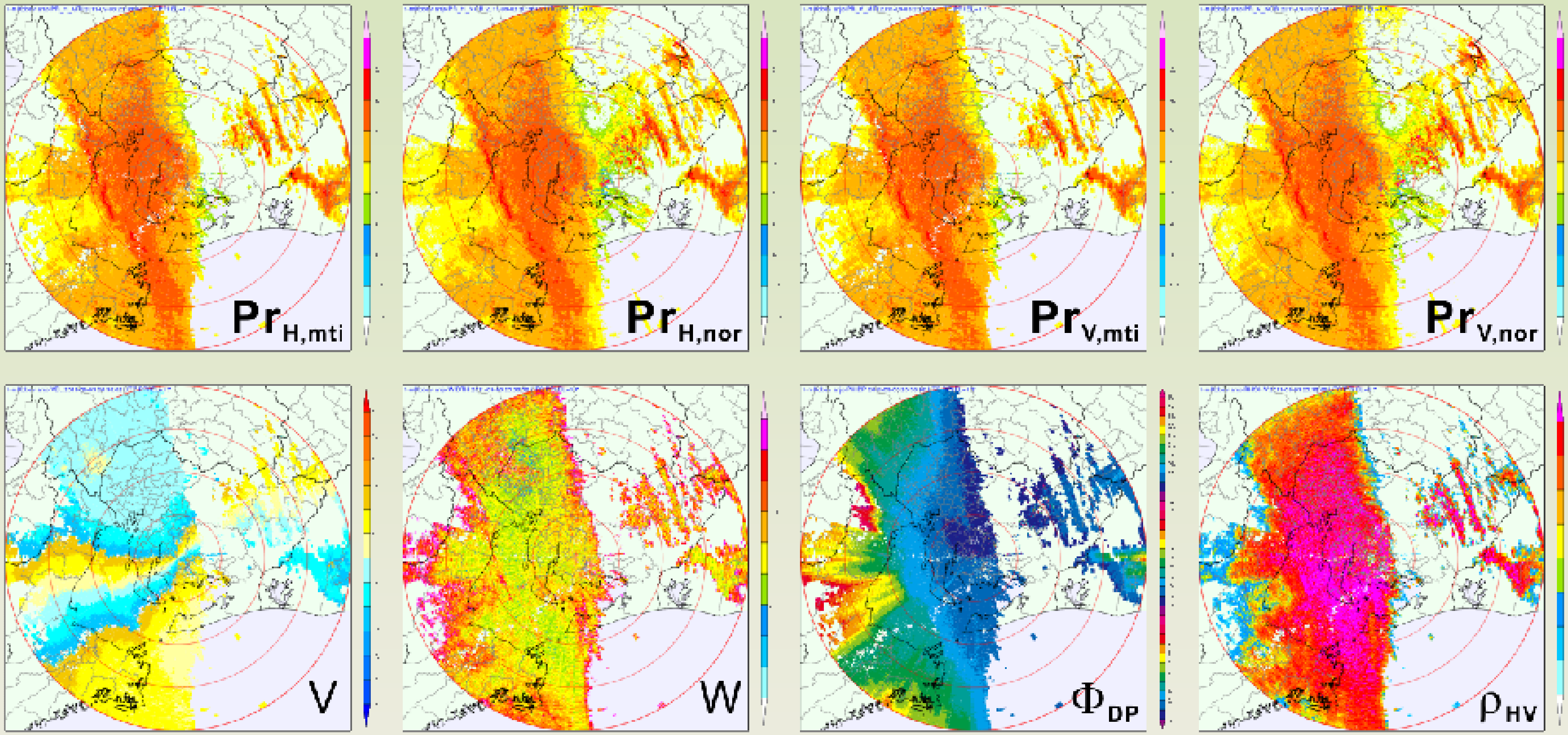
Typical Specifications of MLIT X-band Radar

Features	Specifications
Microwave amplifier	Klystron or solid state device
Frequency	9700 MHz – 9800 MHz
Transmit power	100 kW *1
Pulse width	1.0 μ sec. *2
Occu. bandwidth	$\leq$ 4 MHz
Pulse Repetition Frequency	1200 Hz – 1800 Hz *3
Antenna	Parabola, $\phi \leq$ 2.2 m
Antenna gain	$\geq$ 42 dBi
Beam width	$\leq$ 1.2 °
Polarization	H & V, Simultaneous transmit/receive
Min. Sensitivity	$\leq$ -110 dBm
Observation range	80 km
Data resolution	150 m (range), 1.2 °(azimuth)
Sampling number	100 (approximately, at PRF=1800 Hz)
Output parameters	$Pr_{\mathrm{H,nor}}$, $Pr_{\mathrm{V,nor}}$, $Pr_{\mathrm{H,mti}}$, $Pr_{\mathrm{V,mti}}$, V, W, Φ_{DP}, ρ_{HV} *1

*1. This transmit power is equally divided to H/V. If the solid state device is used, this power includes the pulse compression gain. In Shizuoka area, the transmit power is 50 kW.
*2. If the solid state device is used, this value is pulse-compressed.
*3. Dual-PRF observation is available.
*4. Subscriptions H and V for Pr (received power) indicate the polarizations. Subscriptions mti and nor also indicate that clutter removal by coherent motion target inhibition is applied or not.

Radar Output Parameters

Anjo / 2039 UTC 3 September 2011



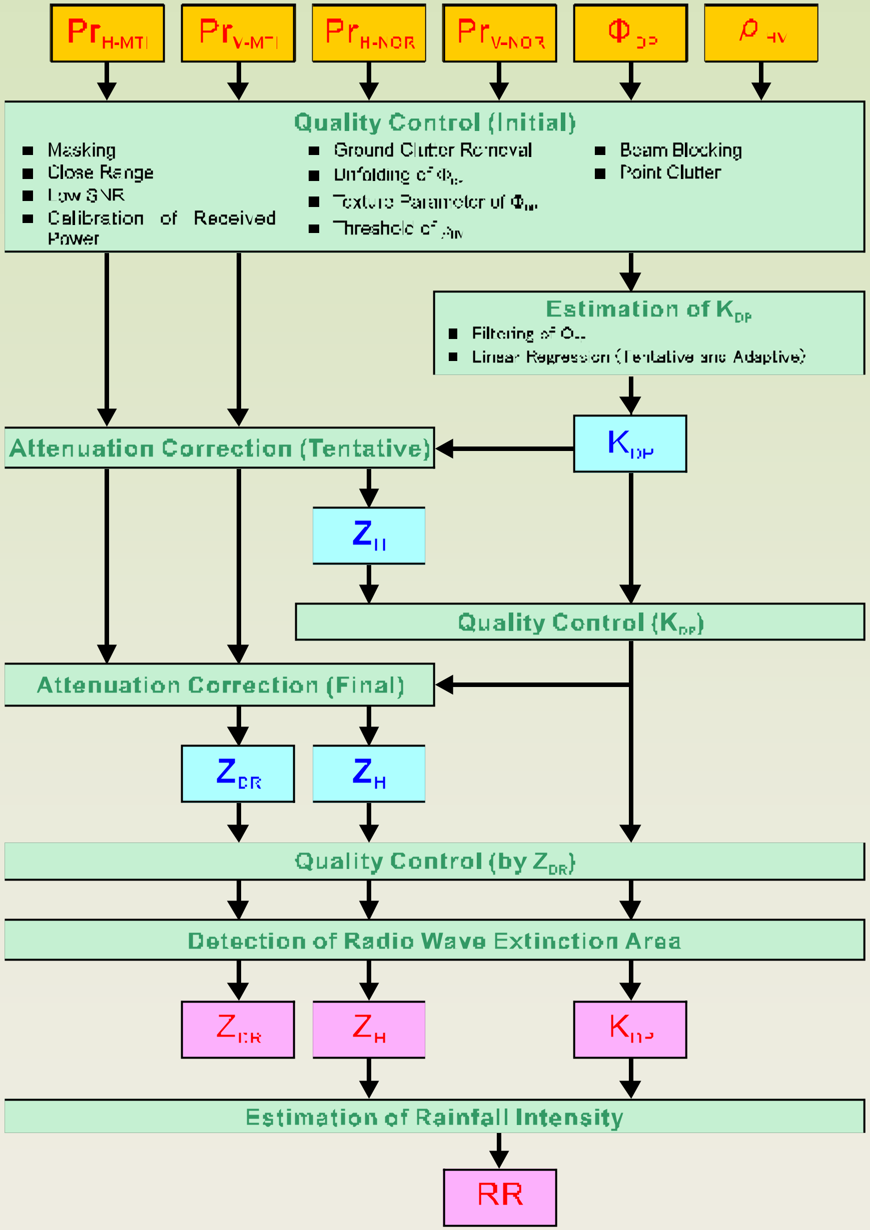
Pr: Received Power (range corrected)

H: Horizontal Polarization, V: Vertical Polarization

mti: Doppler filter is applied, nor: No Doppler filter is applied

Data Flows

Data Flow for Rainfall Estimation



- The observed radar data (tilt-by-tilt) are immediately transferred to two data processing centers in Tokyo and Osaka.
- The same processing is performed for redundancy in these two centers.
- In the data center, K_{DP}, attenuation-corrected Z_H and Z_{DR}, and Rainfall Intensity are calculated after a quality control.
- Finally, polar-coordinate data are interpolated and composited to geographical coordinate.

Final QPE Product

- Composited area by area
- Geographical (Lon./Lat.) coordinate
- Horizontal resolutions of 45/4" and 30/4" (about 250 m)
- Updated every 1 minute

Quality Control

■Masking

The range bin data in blanking zone, shadow zone by building, and known clutter area are eliminated by a masking map (geographical polygons).

■Low SNR

Low SNR data are eliminated.

■Calibration of received power

Pre-determined biases of H/V received powers are subtracted from the powers.

■Ground clutter removal

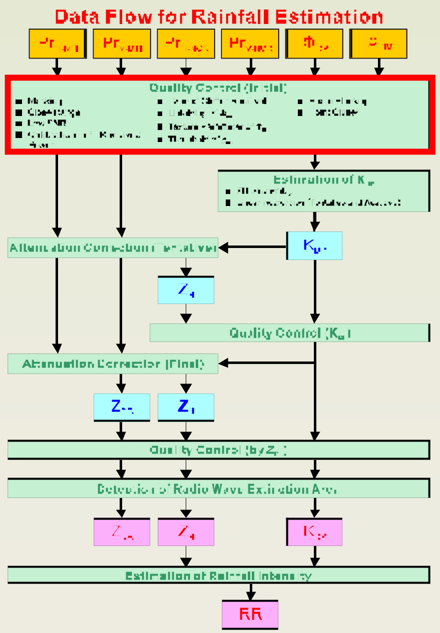
If the difference between $Pr_{H,nor}$ and $Pr_{H,mti}$ is larger than a threshold (5 dB), the range bin data are eliminated.

■Unfolding of Φ_{DP}

In case Φ_{DP} exceeds 360 degrees (folding or aliasing), Φ_{DP} is unfolded with a consideration of the continuity.

■Texture parameter of Φ_{DP}

If texture parameter of Φ_{DP} , which is a difference from the running average, is larger than the threshold (10 degrees), the range bin data are eliminated.



■Threshold by ρ_{HV}

If ρ_{HV} is less than threshold (0.6), the range bin data are eliminated.

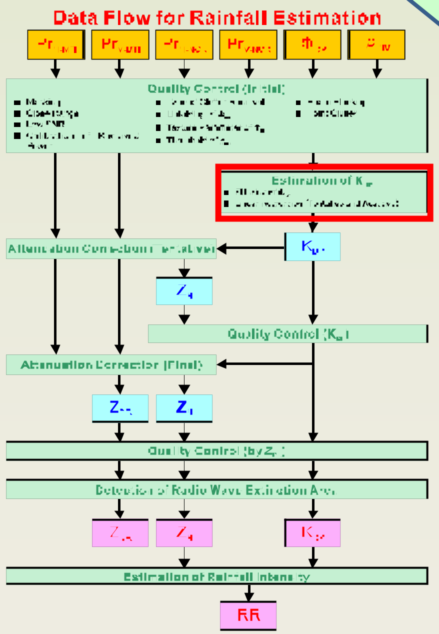
■Beam blocking

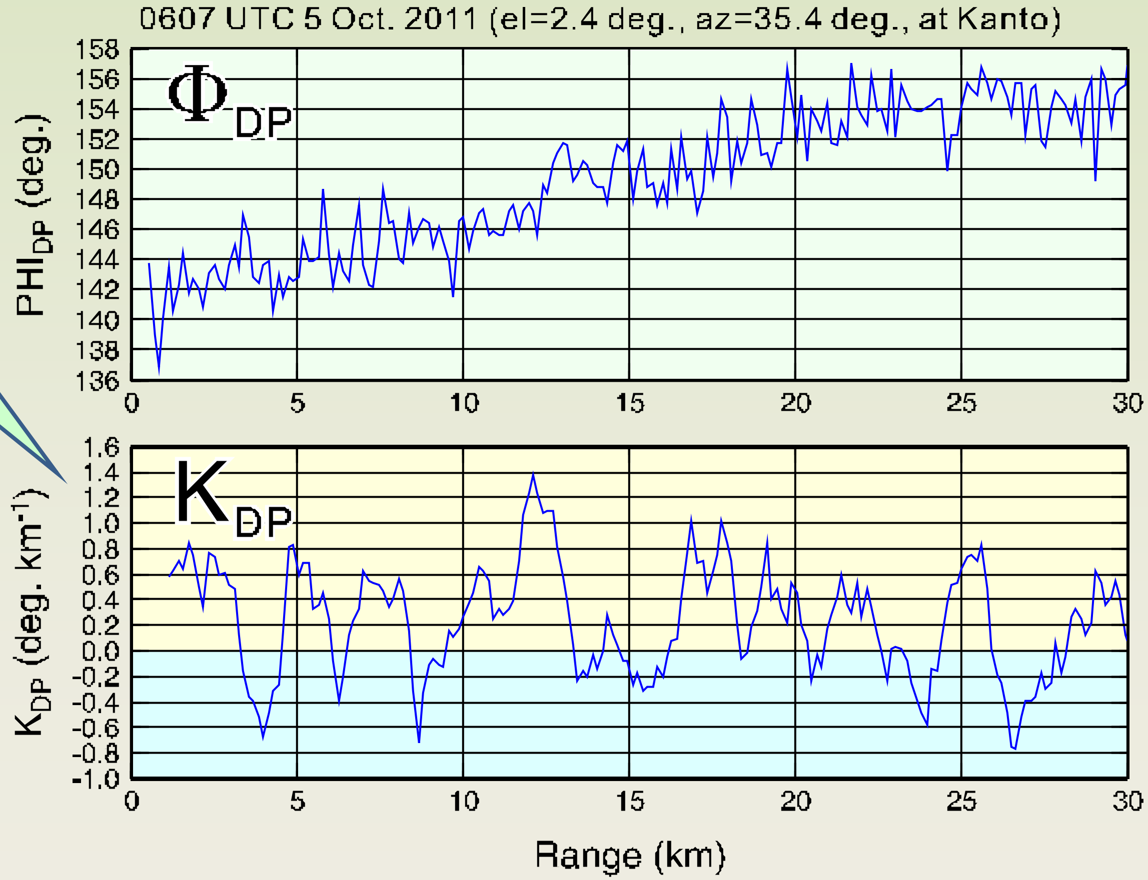
A beam blocking rate data with the coordinates of elevation, azimuth and range have been created for each radar site by using a digital elevation map (DEM) with the horizontal resolution of 50 m. The Pr data are corrected by multiplication of the interpolated blocking rate. If the interpolated blocking rate is larger than 50 %, the range bin data are eliminated.

Estimation of K_{DP} (1)

- K_{DP} is the most important polarimetric parameter for rainfall estimation using X-band dual-pol. radar.
- K_{DP} is calculated by a differentiation of Φ_{DP}; however the observed Φ_{DP} is usually contaminated by noises and differential scattering phase.

Calculated by a simple linear regression of Φ_{DP} with the window width of 2 km.



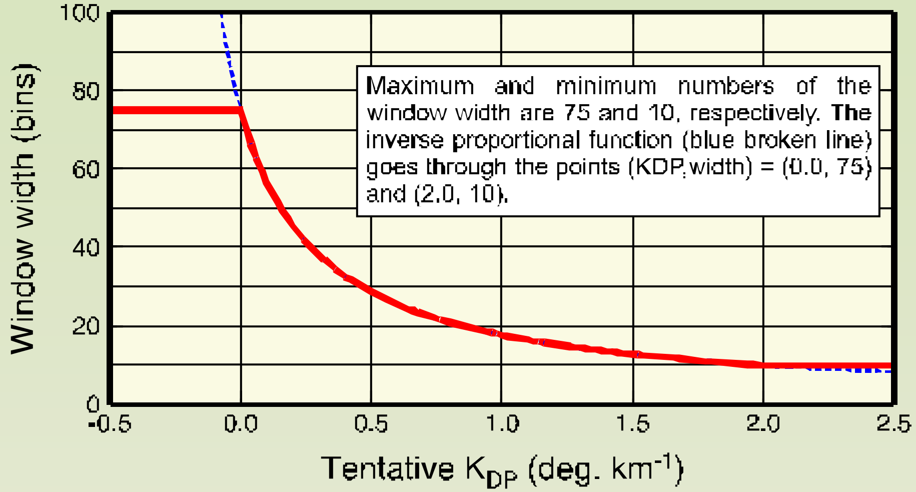


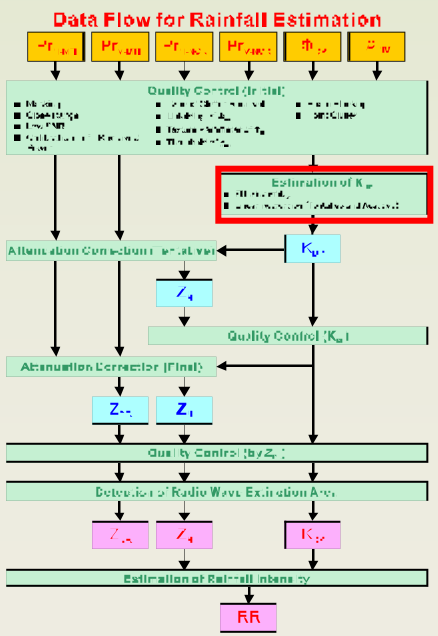
Estimation of K_{DP} (2)

■Filtering of Φ_{DP}

FIR filters with long and short cutoff lengths are applied before the differentiation of Φ_{DP}.

LONG (Cut-off length= 4 km): iterative filter proposed by Hubbert and Bringi (1995), for removing differential scattering phase in strong reflectivity area.
Short (Cut-off=2 km): For smoothing of Φ_{DP}.





■Linear Regression (Tentative)

Tentative K_{DP} is calculated by the linear regression with the window width of 30 range bins.

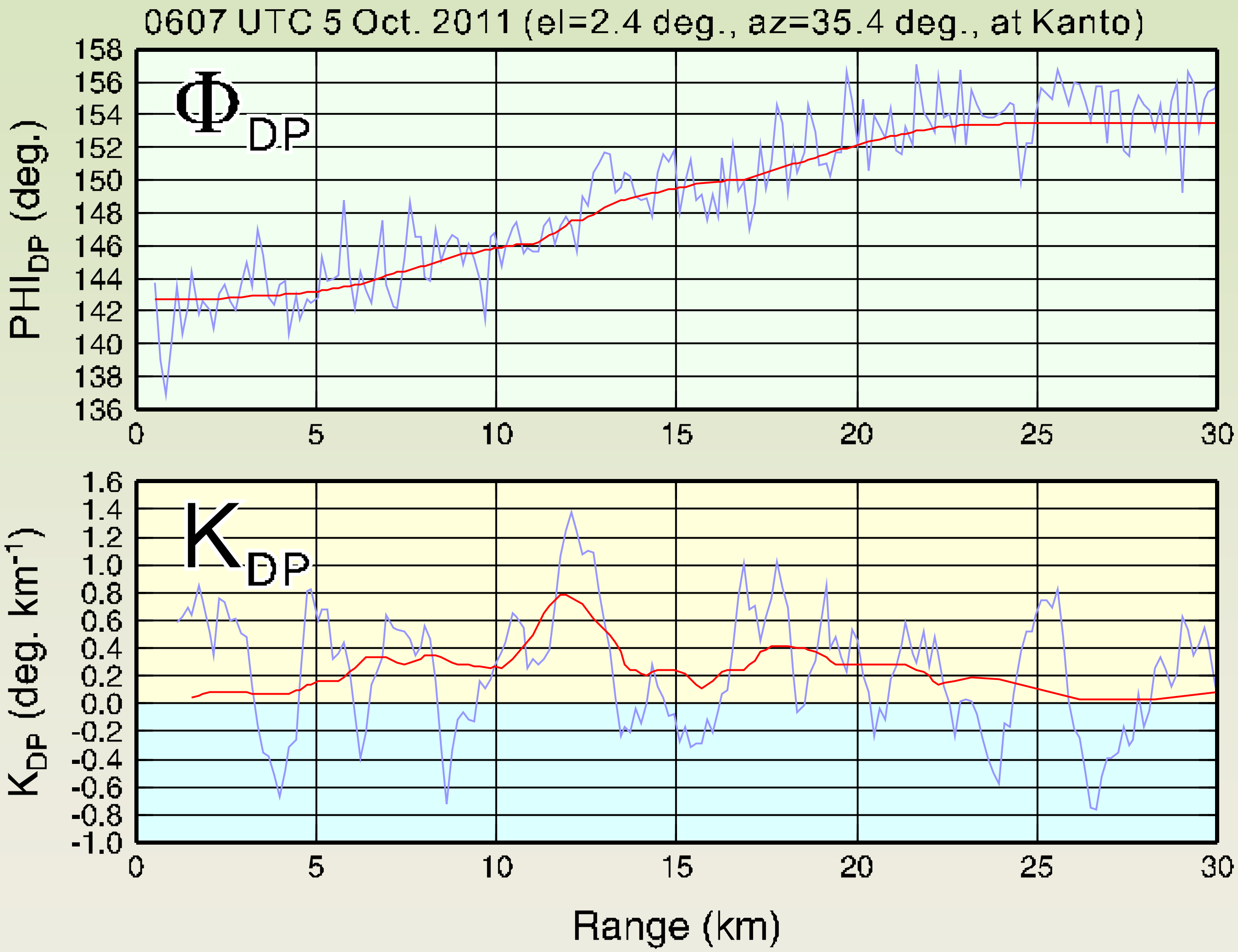
■Linear Regression (Adaptive)

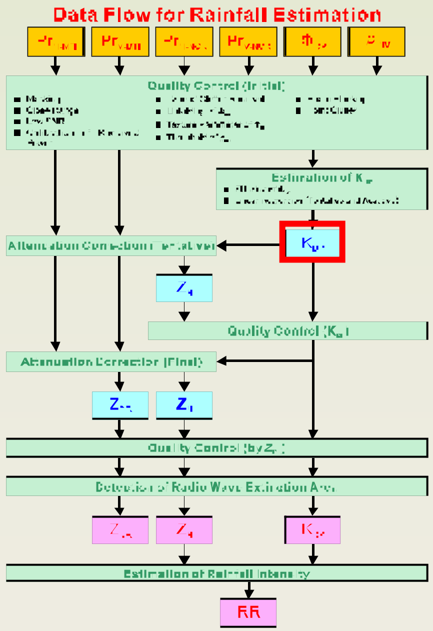
- The needless negative K_{DP} can be suppressed by making the window wider, but this also makes the peak value of K_{DP} smaller.
- Because such Φ_{DP} fluctuations usually occur in weak rain region, the window widths are tuned by the tentative K_{DP}.
- That is to say, narrow (wide) window width is used in heavy rainfall (weak rainfall) region, respectively.

Estimation of K_{DP} (3)

Blue: Observed Φ_{DP} and K_{DP} calculated by linear regression with the window of 2 km (shown previously).

Red: K_{DP} calculated by adaptive method, and Φ_{DP} reconstructed from the adaptive K_{DP}.



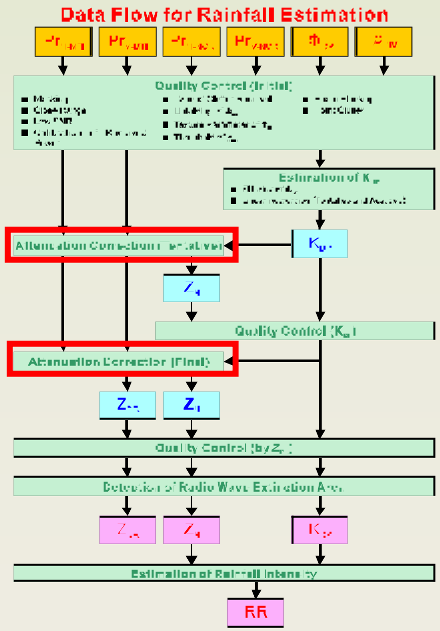


Attenuation Correction of Z_H and Z_{DR}

- Specific attenuation (A_H) and differential attenuation (A_{DR}) are estimated by K_{DP} with following equation.
- These relationships are based on the scattering simulation in Park et al. (2005a), and it is approximated with a consideration of the elevation dependency.

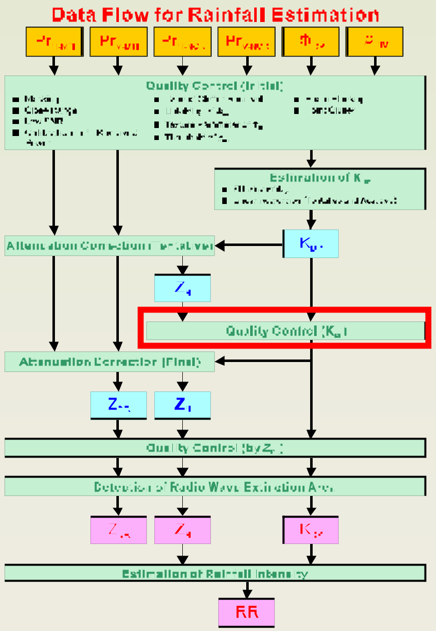
$$\begin{aligned} A_h &= a_1 K_{DP}^{b_1}, \\ a_1 &= 0.2925 + 7 \times 10^{-4} el \\ &\quad +1 \times 10^{-5} el^2 + 3 \times 10^{-6} el^3, \\ b_1 &= 1.1009 - 3 \times 10^{-5} el \\ &\quad -4 \times 10^{-6} el^2, \end{aligned}$$

$$\begin{aligned} A_{DR} &= a_2 K_{DP}^{b_2}, \\ a_2 &= 0.0298 + 5 \times 10^{-6} el \\ &\quad +2 \times 10^{-6} el^2 + 3 \times 10^{-8} el^3, \\ b_2 &= 1.293, \end{aligned}$$



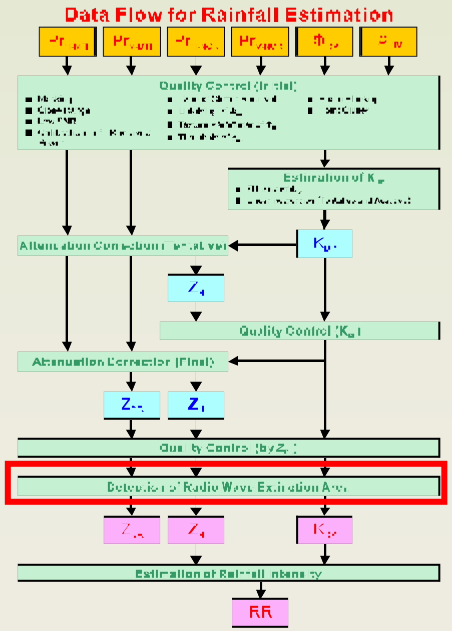
Quality Control (K_{DP})

- In weak rainfall region, it is difficult to estimate the rainfall intensity from the K_{DP}, because the estimation accuracy of the K_{DP} is not enough.
- So when the Z_H is less than 30 dBZ, the K_{DP} is not used.



Radio Wave Extinction Area

- X-band weather radar sometimes misses precipitation echoes behind heavy rainfall by the rain attenuation.
- We cannot know if there is a rainfall or not in this radio wave extinction area.
- When the distribution of rainfall intensity is graphically drawn, this area should be shown not as "no rain" area but as unknown area where it may be rain.
- The radio wave extinction area is where a distance from the radar (r) satisfies the following equation,

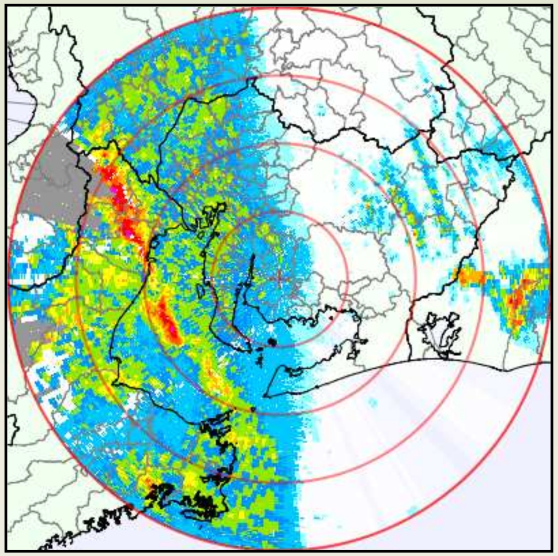


$$PIA(r) = \int_0^r A_h(r)dr.$$

$$2 \times PIA(r) \geq dBZ_{thresh} - dBZ_0(r),$$

$dBZ_0(r)$: Minimum detectable reflectivity at the range.

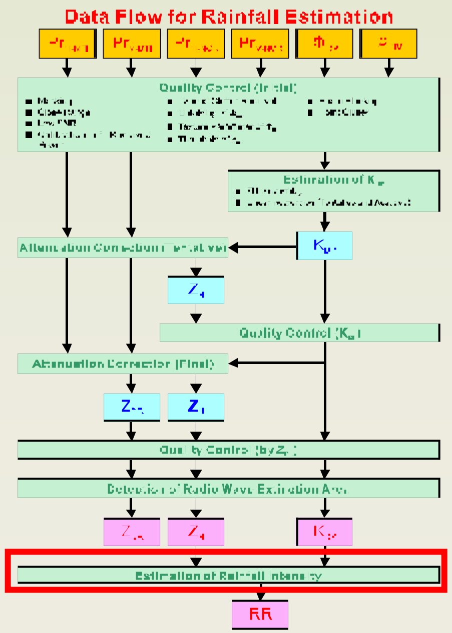
dBZ_{thresh}: threshold reflectivity (corresponding to 3 mm/hour rainfall)



Estimation of Rainfall Intensity

- If K_{DP} is available below melting layer, the rainfall intensity is calculated as following equation. (The melting layer is determined by the 0 degree C level of operational mesoscale simulation by Japan Meteorological Agency, and the thickness of the layer is assumed as 1 km.

$$
\begin{aligned}
R &= c \times a_3 K_{DP}^{b_3}, \\
a_3 &= 19.6 + 2.71 \times 10^{-2} el \\
&\quad + 1.68 \times 10^{-3} el^2 + 1.11 \times 10^{-4} el^3, \\
b_3 &= 0.815,
\end{aligned}
$$



- Then, Z-R relationship is used to estimate the rainfall intensity, if the Z_H is available.
- The calibration factor c, which has been determined by the comparison with the rain gauge observation, is 1.3 at present.
- One of the reasons of this underestimation may be that the regression window width of K_{DP} is too wide.
- But if the window width is made narrower, the needless fluctuations of K_{DP} (Rainfall) become visible. (It is in a dilemma!)

Interpolating and Compositing

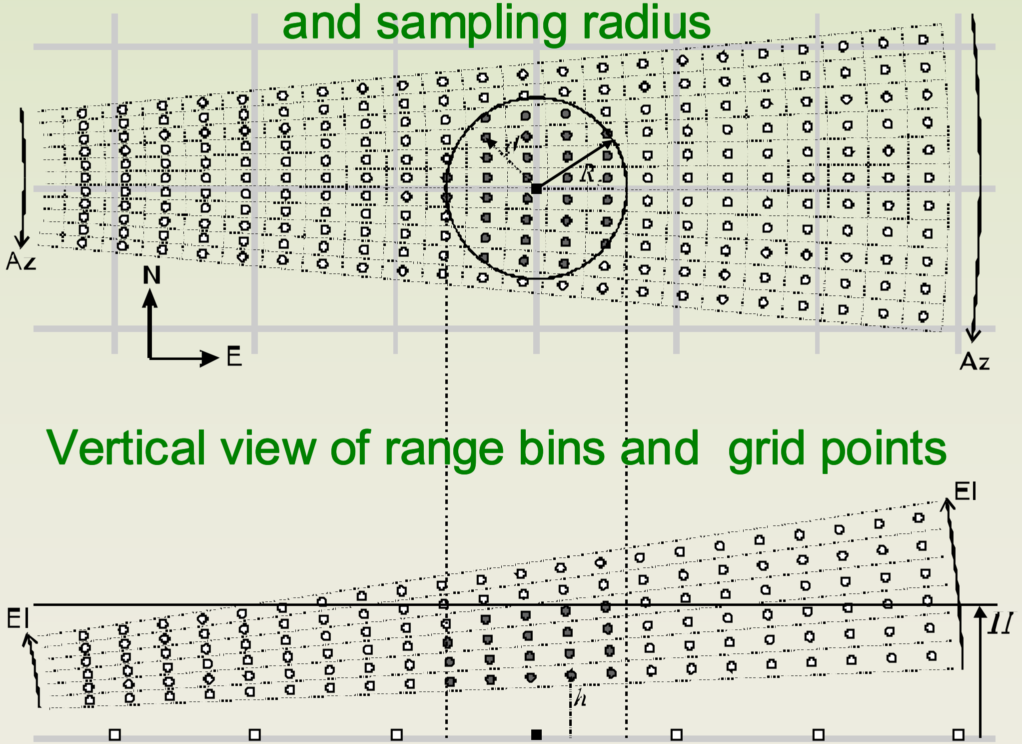
- The estimated rainfall intensities of each radar site are interpolated and composited into the geographical grid mesh (dx = about 250 m).
- The modified Cressman interpolation is used in this process.
- Horizontal sampling radius is proportional to the range from radar for considering the beam width.
- Vertical weighting is introduced because lower altitude observation is more correlative with the ground level rainfall.

$$W = w_h \times w_a,$$

$$w_h = \frac{1}{1 + C_h\left(\frac{d}{R_a}\right)^2}, \quad w_a = \frac{1}{1 + C_a\left(\frac{h}{H}\right)^2}.$$

- In overwrapped area by multiple radars, lower-level observation is averaged with larger weighting.

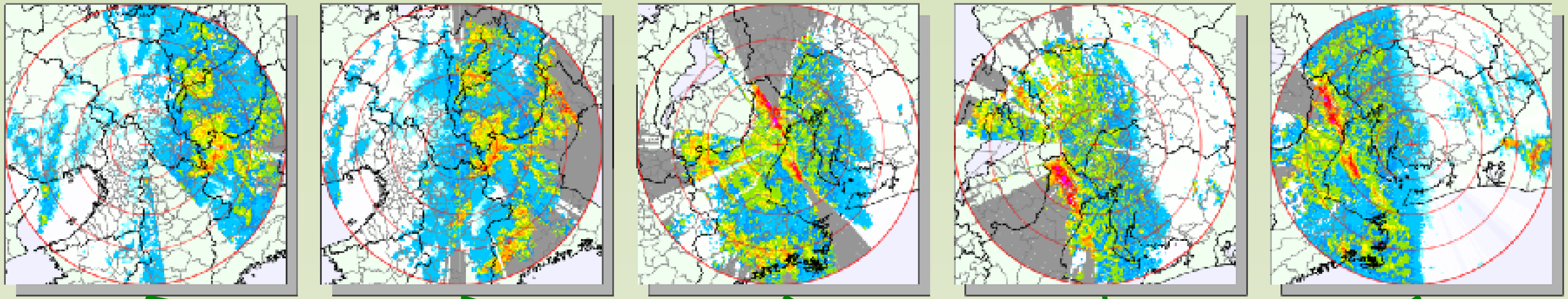
Horizontal view of range bins, grids, and sampling radius

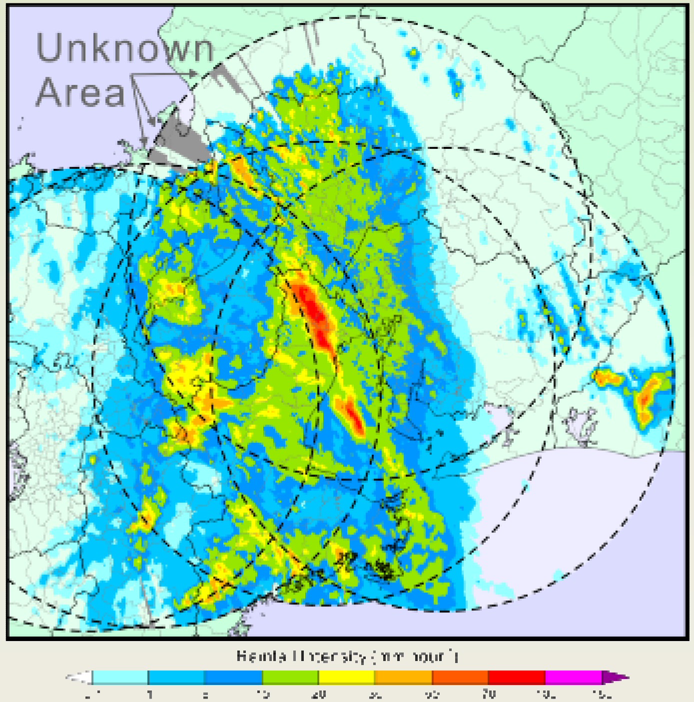


Vertical view of range bins and grid points

Composite Example

2039 UTC 3 September 2011





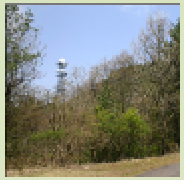
- The radio wave extinction areas, as shown by gray shades, were compensated by other radars in the overlapped observation area, but remained in single observation area.
- This remained area should be indicated not as "no rain" area but as unknown area where it may be rain.

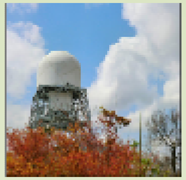
Conclusions







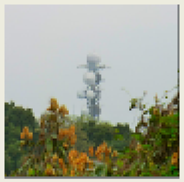




- MLIT deployed 26 radars in Japan, and they are experimentally operated. NIED developed the data processing system for rainfall estimation.


- Now rainfall information with 250 m resolution are updated every 1 minute in 11 areas.

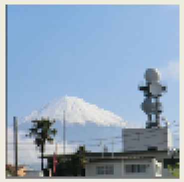

- A validation of the estimated rainfall is in progress by using rain gauge data (to be presented by Dr. Tsuchiya).


- The processing system continues to be improved during the experimental period (lasts to 2013) to solve the dilemmas.



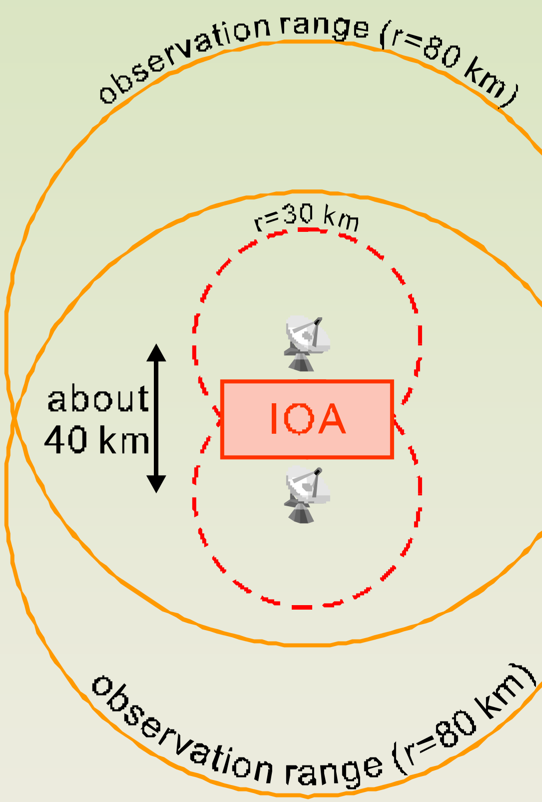





Supplemental Slides

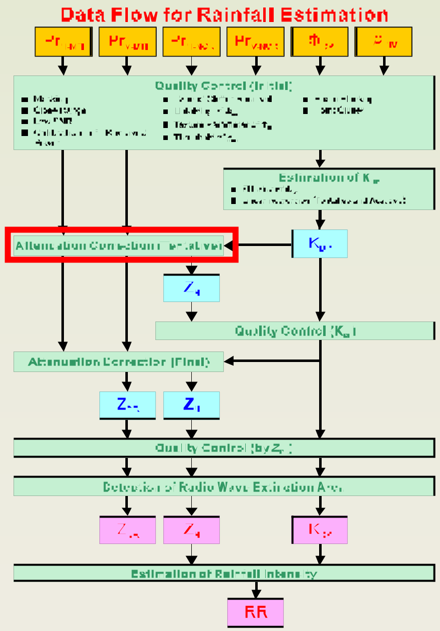
Radar Deployment Policy

- Designating an intensive observation area (IOA), such as densely inhabited districts, landslide areas, and volcanoes.
- Covering the IOA by several radars to compensate the rain attenuation by each other radar.
- The distance between each radar should be about 40 km.
- Each radar should cover the IOA within the range of about 30 km (high space-resolving area with narrow beam width).
- A few beam blocking by terrains or artificial objects.



Attenuation Correction of Z_H (Tentative)

- Specific attenuation (A_H) is estimated by K_{DP} with following equation.
- This relationship is based on the scattering simulation in Park et al. (2005a), and it is approximated with a consideration of the elevation dependency.
- Horizontal reflectivity (Z_H), which is calculated from $Pr_{H,mti}$ according to the radar equation, is corrected by adding the range-integrated A_H.
- This tentative Z_H is used for next quality control of K_{DP}.



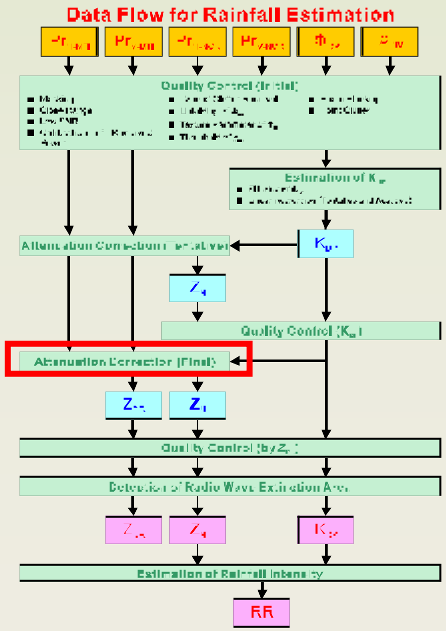
$$
\begin{aligned}
A_h &= a_1 K_{DP}^{b_1}, \\
a_1 &= 0.2925 + 7 \times 10^{-4} el \\
&\quad + 1 \times 10^{-5} el^2 + 3 \times 10^{-6} el^3, \\
b_1 &= 1.1009 - 3 \times 10^{-5} el \\
&\quad - 4 \times 10^{-6} el^2,
\end{aligned}
$$

Attenuation Correction (Final)

NIED

- Using the quality-controlled K_{DP}, the attenuation correction is performed again in the same manner.
- The attenuation correction of Z_{DR} is also performed with the following specific differential attenuation (A_{DR}).

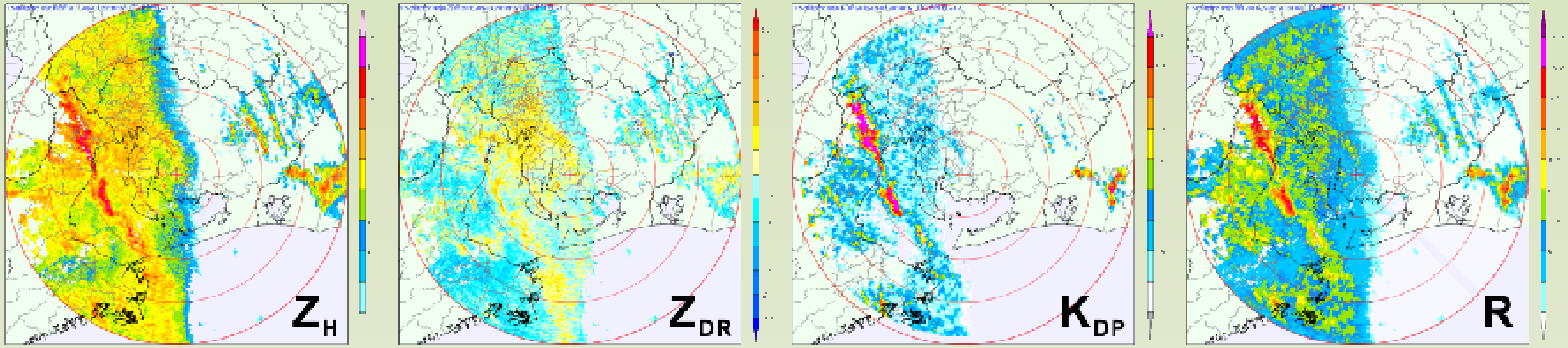
$$
\begin{aligned}
A_{\mathrm{DR}} &= a_2 K_{\mathrm{DP}}^{b_2}, \\
a_2 &= 0.0298 + 5 \times 10^{-6} el \\
&\quad + 2 \times 10^{-6} el^2 + 3 \times 10^{-8} el^3, \\
b_2 &= 1.293,
\end{aligned}
$$

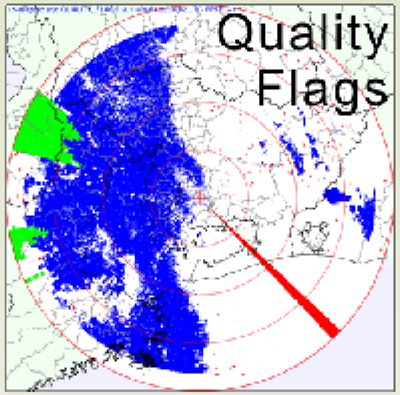


The corrected Z_{DR} should be used for next quality control; but it is not performed because we have no way to determine the Z_{DR} bias in on-line. (Vertical pointing observation is not scheduled in current operation.)

PPI Outputs of the Data processing System

Anjo / 2039 UTC 3 September 2011



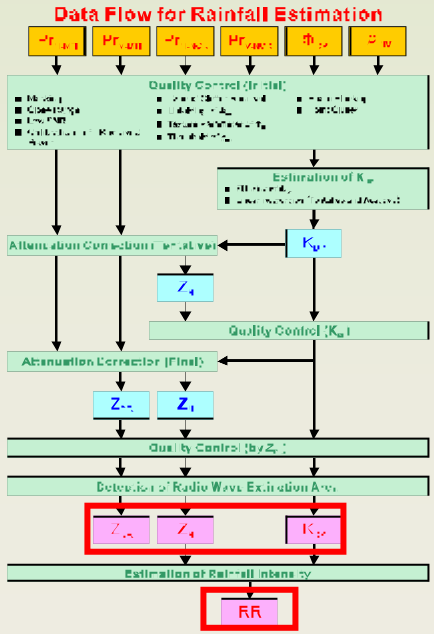


Z_H is used for rainfall estimation.

K_{DP} is used for rainfall estimation.

Radio wave extinction area. Not composited.

Bad quality data (including beam blocking). Not composited.



MP Radar ?

- NIED planned to have dual wavelength and dual polarimetric radar in 1990s, and we named them "Multi-Parameter (MP) Radar System".
- In 2000s, NIED used X-band dual-pol. radar (a part of the system) for QPE research, and achieved QPE around Tokyo.

DOPPLER RADAR AND WEATHER OBSERVATIONS
Second Edition

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So, dual-polarimetric (especially, simultaneous transimit/receive) radar which can observe Φ_{DP} is commonly called "MP Radar" in Japan.

MP Radar ?

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P3.6 DEVELOPMENT OF A MULTIPARAMETER RADAR SYSTEM ON MOBILE PLATFOAM

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1. INTRODUCTION

It is important to observe cloud and precipitation systems during their whole life cycles from the initiation of cloud through formation and development of precipitation to dissipation of cloud and precipitation in order to study mechanisms and develop forecast methods of heavy rainfall and snowfall that causes disasters.

National Research Institute for Earth Science and Disaster Prevention (NIED) has investigated rainfall and snowfall clouds, especially that caused disasters, using X-band Doppler and polarimetric radars. But we could not observe non-precipitating clouds and measure simultaneously Doppler velocity and polarimetric parameters. So we have developed a multiparameter radar system with three frequencies of 9, 35 and 95 GHz on mobile platforms under contract with Mitsubishi Electric Corporation in order to observe cloud and precipitation systems through their whole life cycles. It will be useful for observation researches of not only

auto-driving license in Japan, for field experiments. The antenna is mounted on the rear portion of flatbed and the radar control and data acquisition systems are contained in the container on the front portion of flatbed of each truck. The system can be easily transported to observation sites according to the meteorological situation.

FIG. 1. Photograph of developed multiparameter radar system. X-band (right) and Ka/W-band (left) radar subsystems are mounted on 4-ton trucks. The antenna on the top of