Overview of Phased Array Radar System
- Concept, Design and Future -

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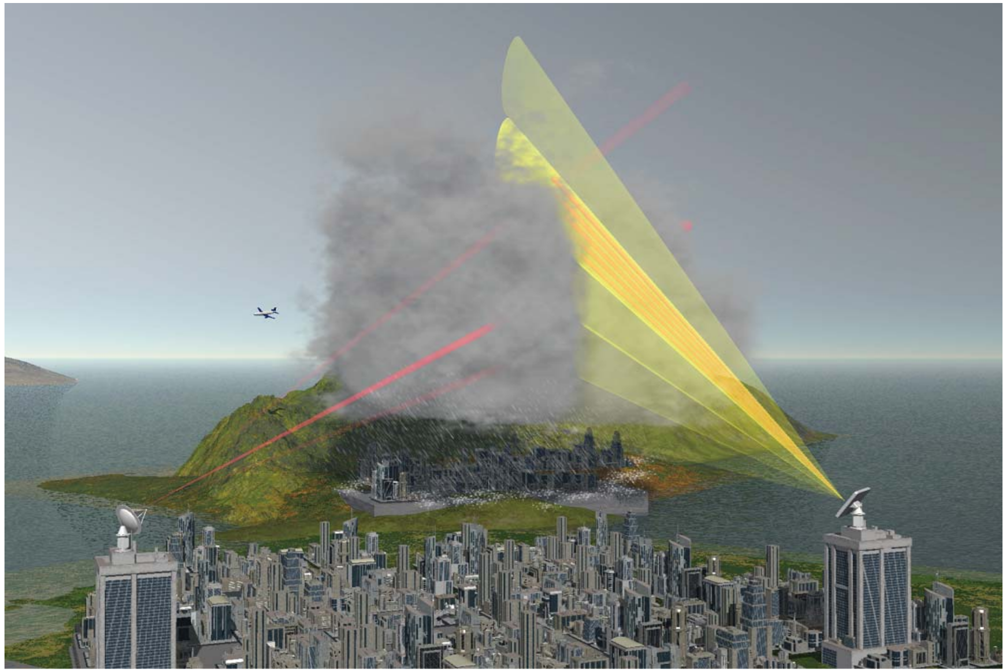
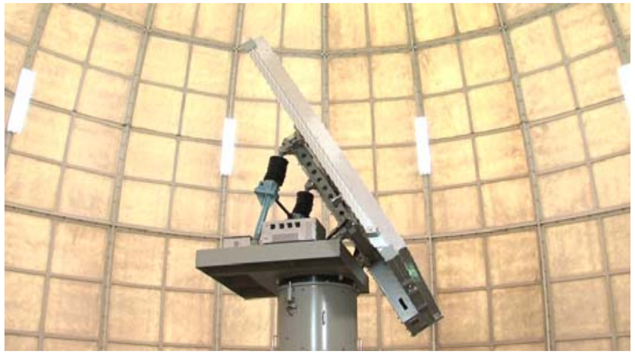
Phased Array RADAR in Osaka University

A new Phased Array Radar (PAR) system for meteorological application has been developed by Toshiba Corporation and Osaka University under a grant of NICT, and installed in Osaka University, Japan 2012. The phased array radar system developed has the unique capability of scanning the whole sky with 100m and 10 to 30 second resolution up to 60 km.

Phased Array RADAR in Osaka University





- **Achieves high speed volume scan of 10 sec** to detect severe storms **instantaneously in urban area**

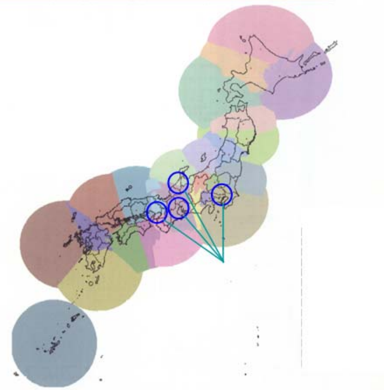
Scan system	**Elevation: Electronic scan** **Azimuth: Mechanical scan**
Coverage	3D scan (100 elevations) / 10 sec (- 1 min)
Parameters	Z_h, v_h, σ_{vh} (single-polarization)

Social Background

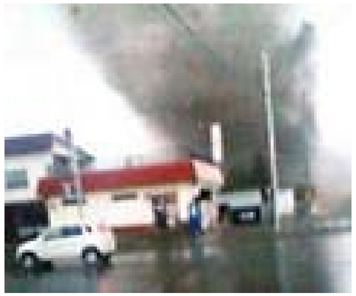
- In Japan, severe weather disasters caused by tornadoes or localized heavy rainfalls have occurred frequently in the last few years.
- There is an increasing number of heavy rainfall events in recent years.

Flash flood in the Toga river, Kobe（28 July 2008）

Fatal accident in the sewerage at Zoshigaya, Tokyo（5 Aug 2008）

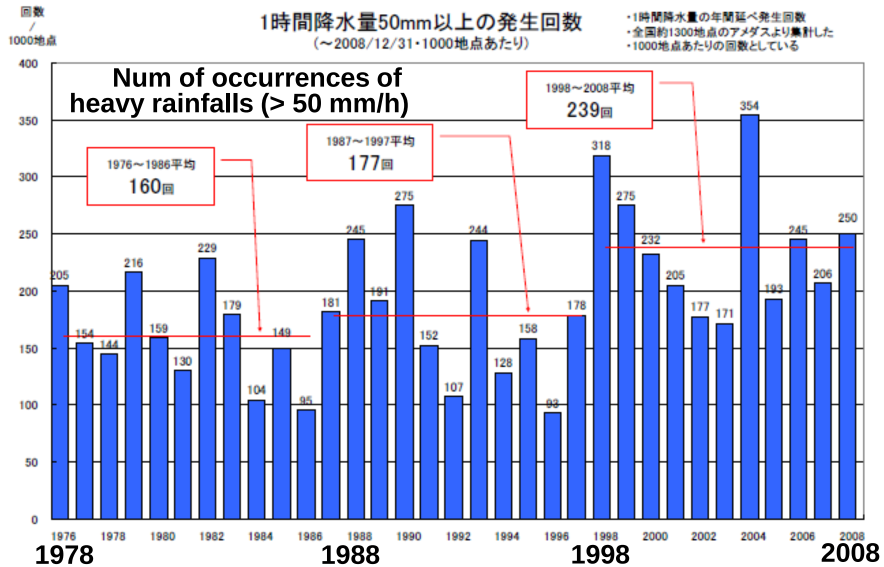


The observation area of MLIT C-band radar, and the installation area of X-band MP radar.

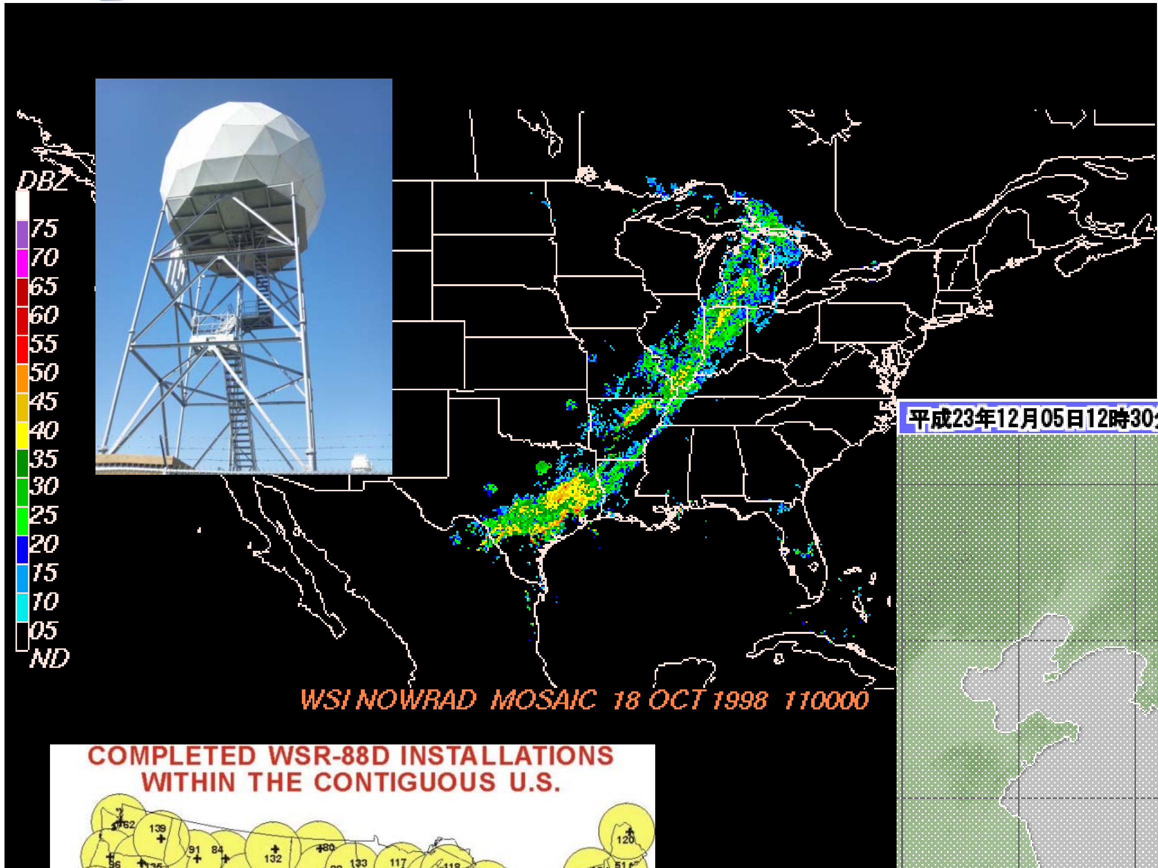


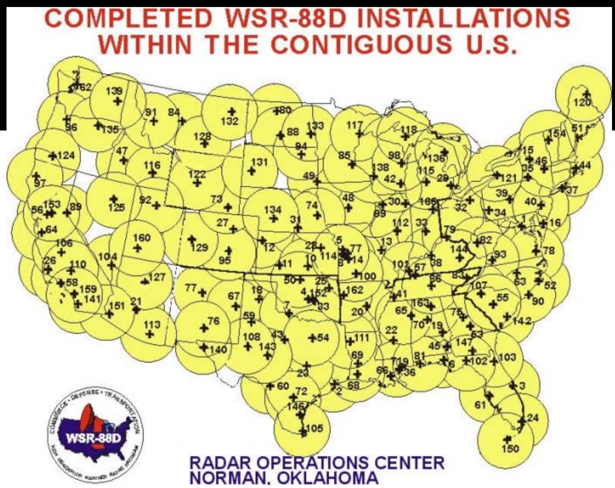
F3 tornado in Saroma, Hokkaido（7 Nov 2006）

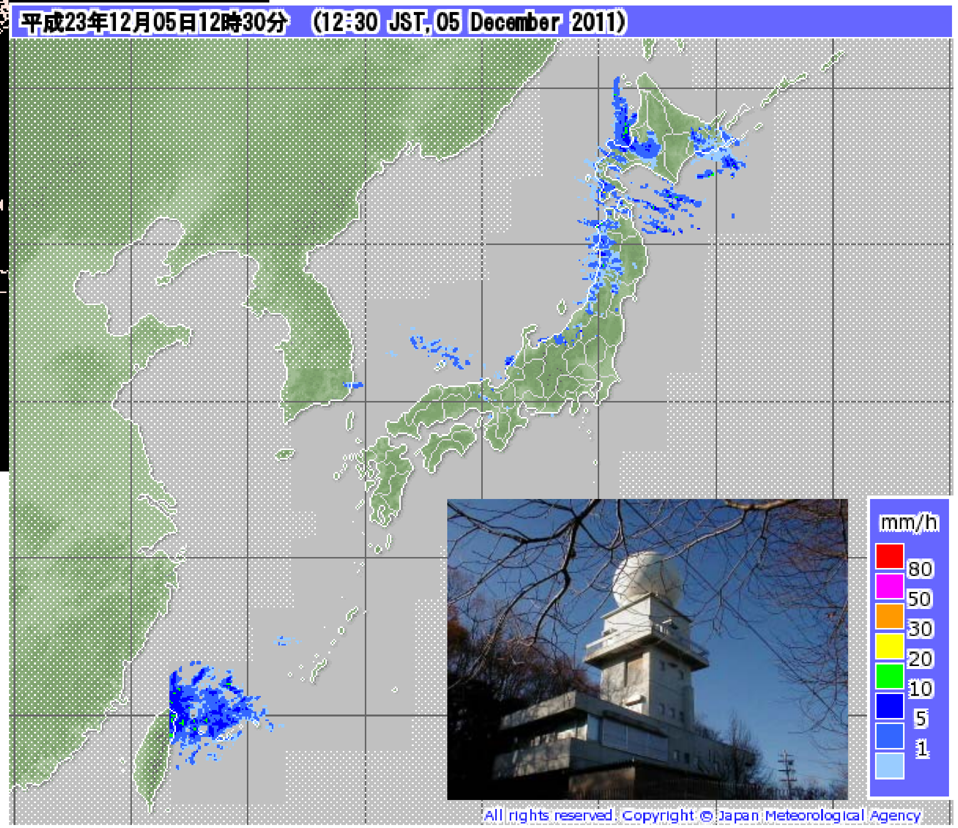
Railcars overturned by tornado in Nobeoka, Miyazaki (17 Sept 2006)



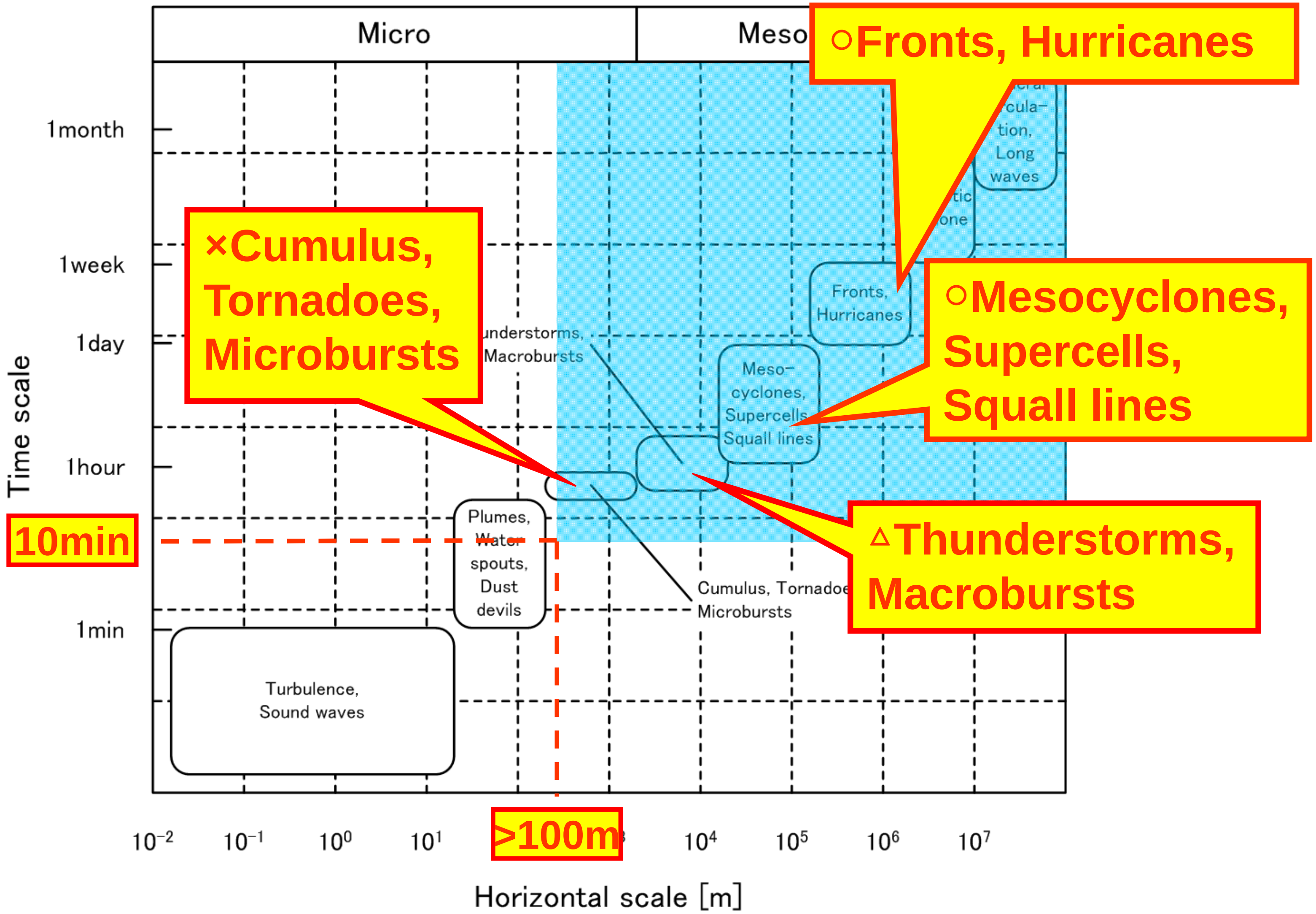
Nationwide Radar Network at S or C band



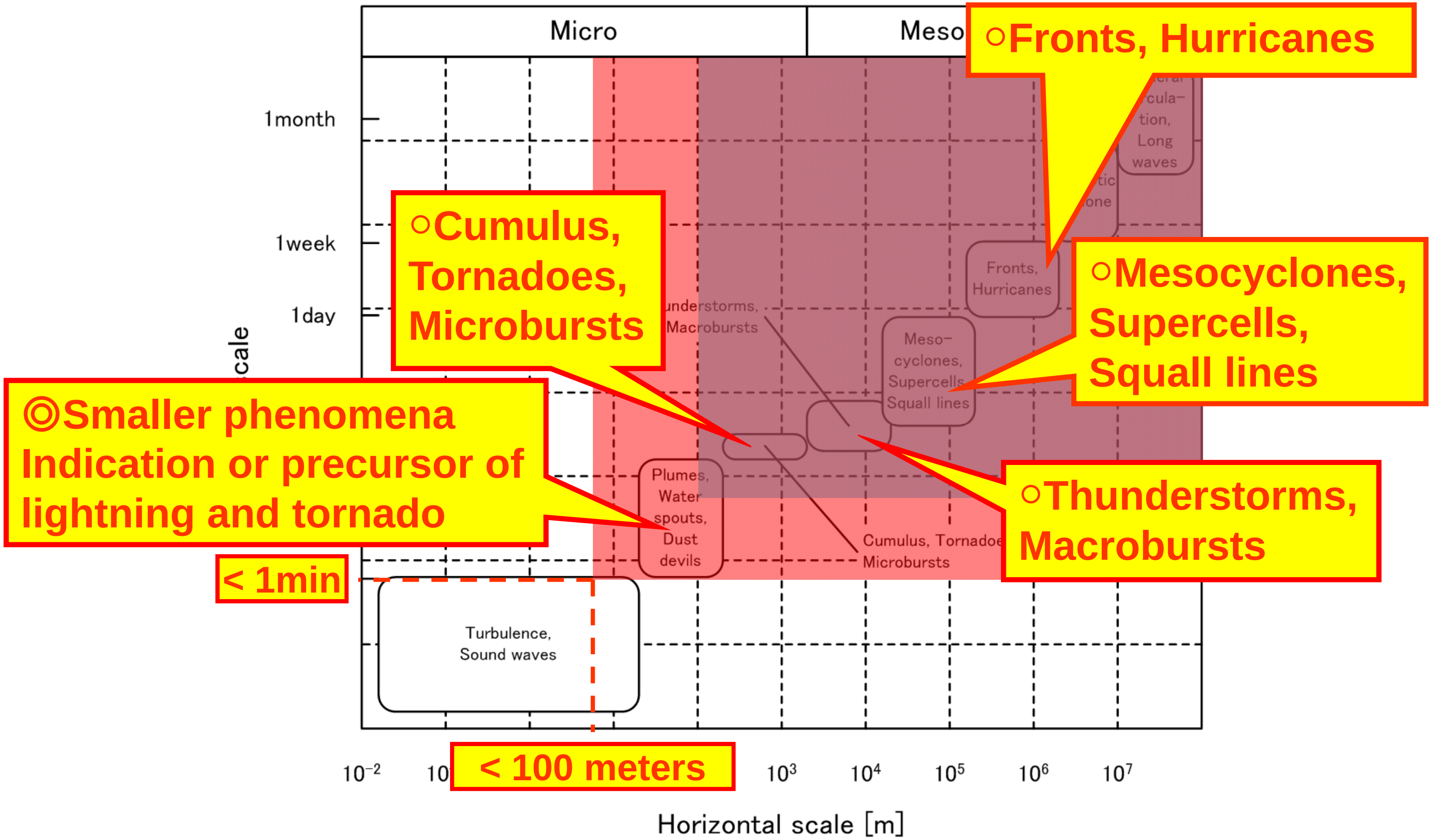




Resolution of Conventional Weather Radar



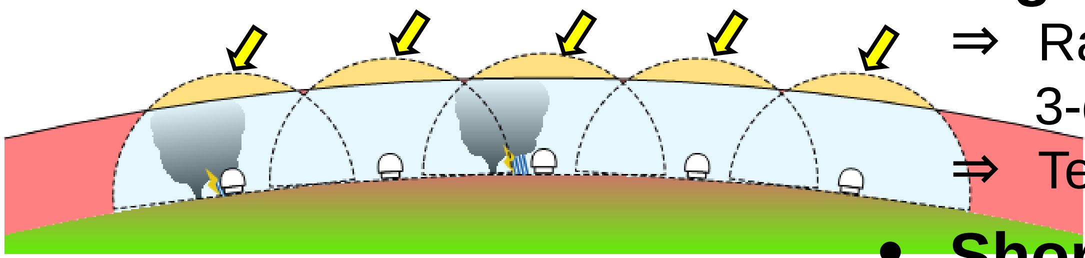
Resolution of the Ku-BBR Network



Network Approach for weather radar

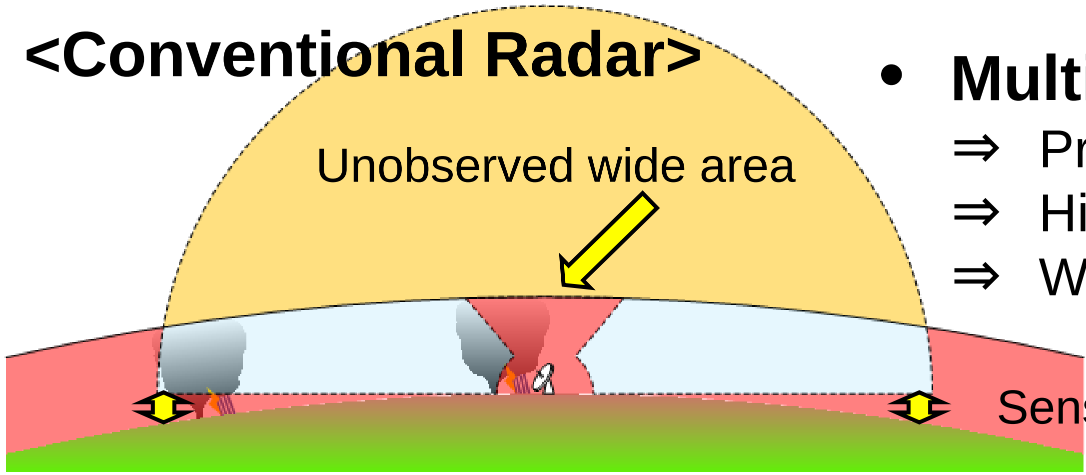
By putting multiple high resolution and short range radars, we can observe the whole thunderstorm with high resolution

<High Resolution Radar>



- **High resolution**
  - ⇒ Range resolution : < 100 meters
    3-dB beam width : < 1 deg
  - ⇒ Temporal resolution : < 1 min/VoS
- **Short range radar**
  - ⇒ Min altitude : near ground
  - ⇒ Efficient for Troposphere
    (8 through 15 km altitude)
- **Multi-Radar Network**
  - ⇒ Precipitation attenuation correction
  - ⇒ High resolution grid retrieval
  - ⇒ Wider area

<Conventional Radar>

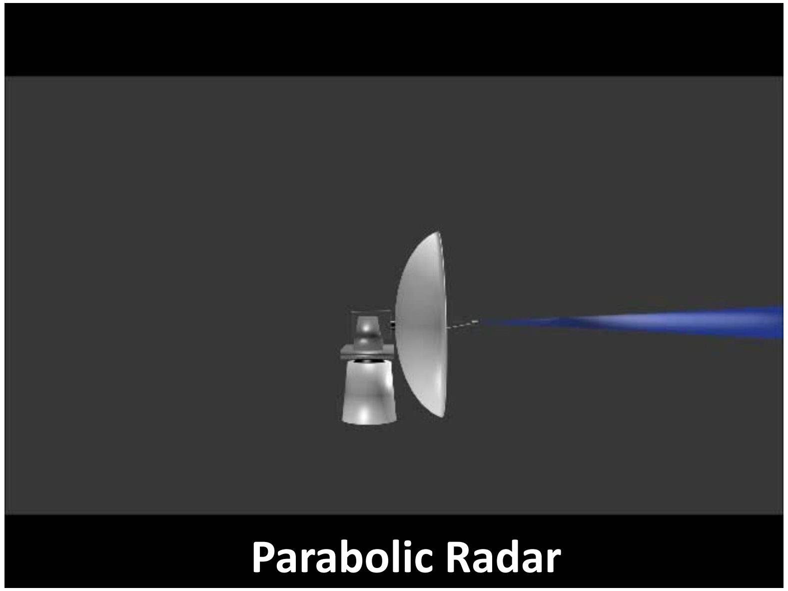


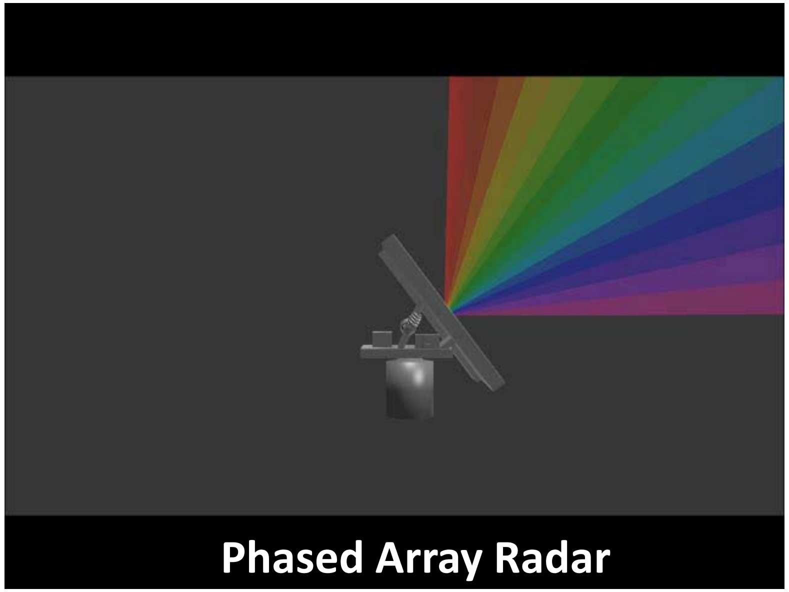
Outline

- High Resolution RADAR System
  - Broad Band Radar Network

  - Development of the Phased Array Radar

Fast Scanning Strategy





PARABOLIC TYPE

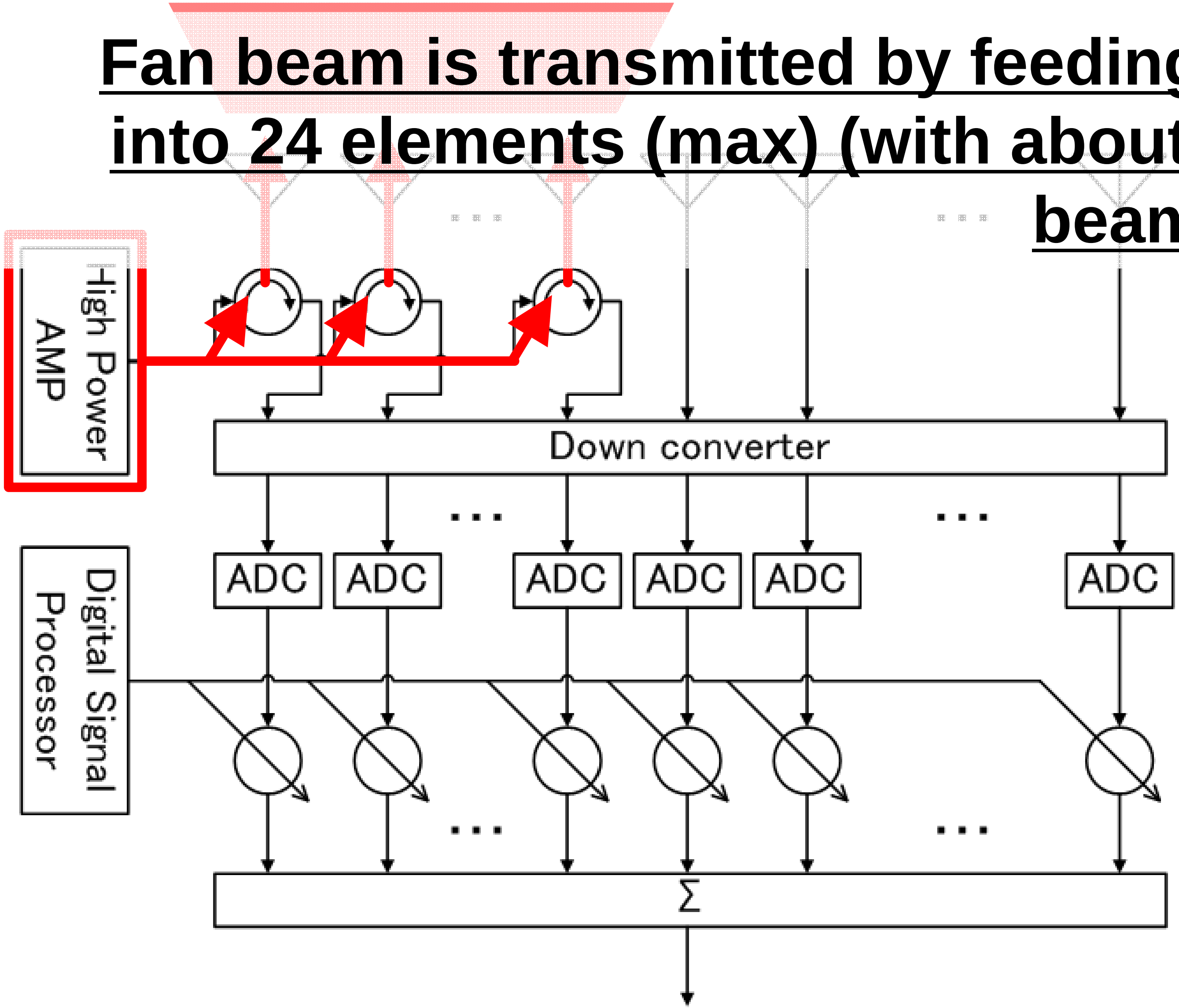
・Pencil beam
→mechanically scanning both in elevation and azimuth

PHASED ARRAY TYPE

・Fan beam
→ electrically scan in elevation

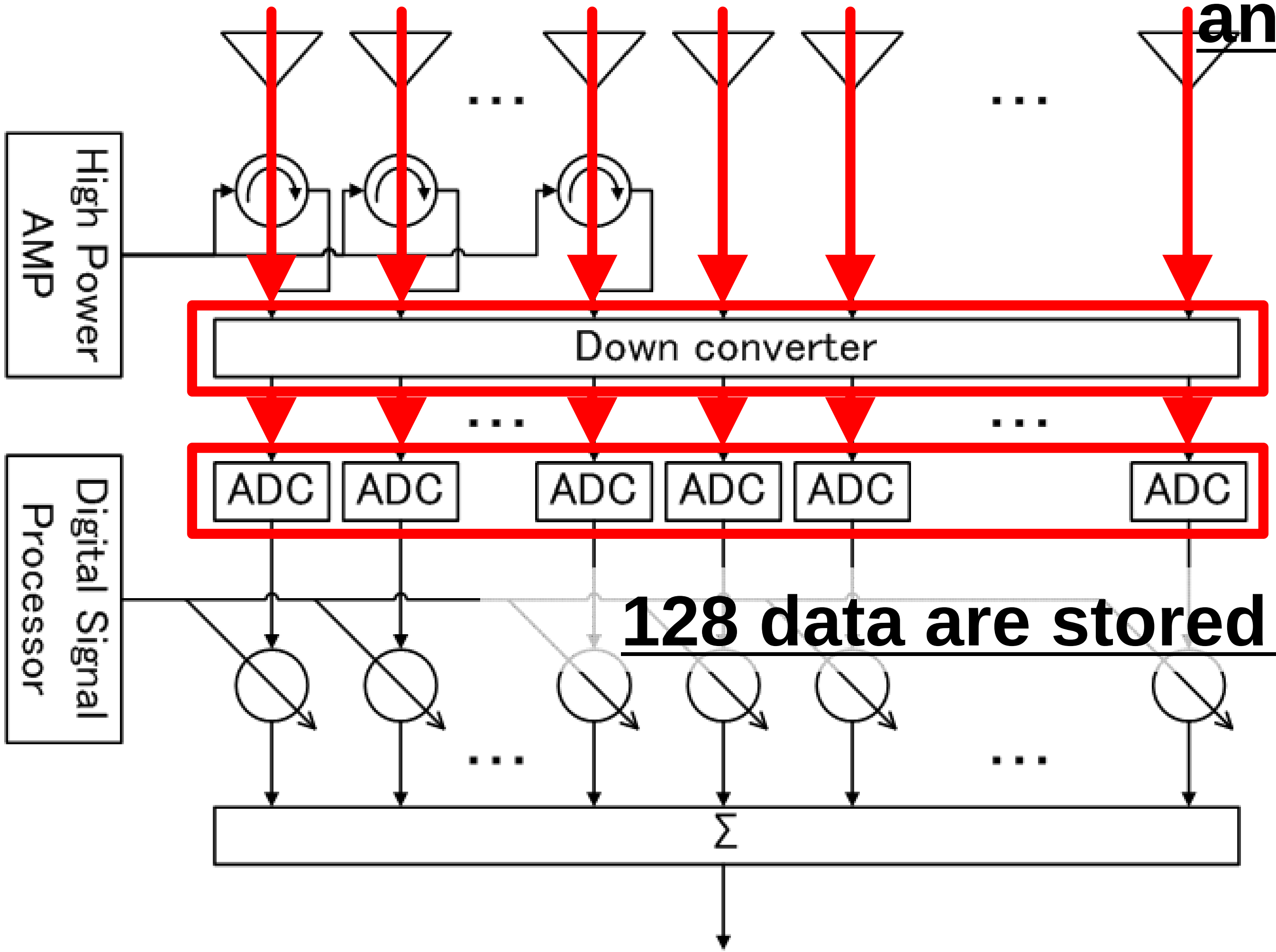
Flow –Transmission

Fan beam is transmitted by feeding power into 24 elements (max) (with about 10 deg beam width)



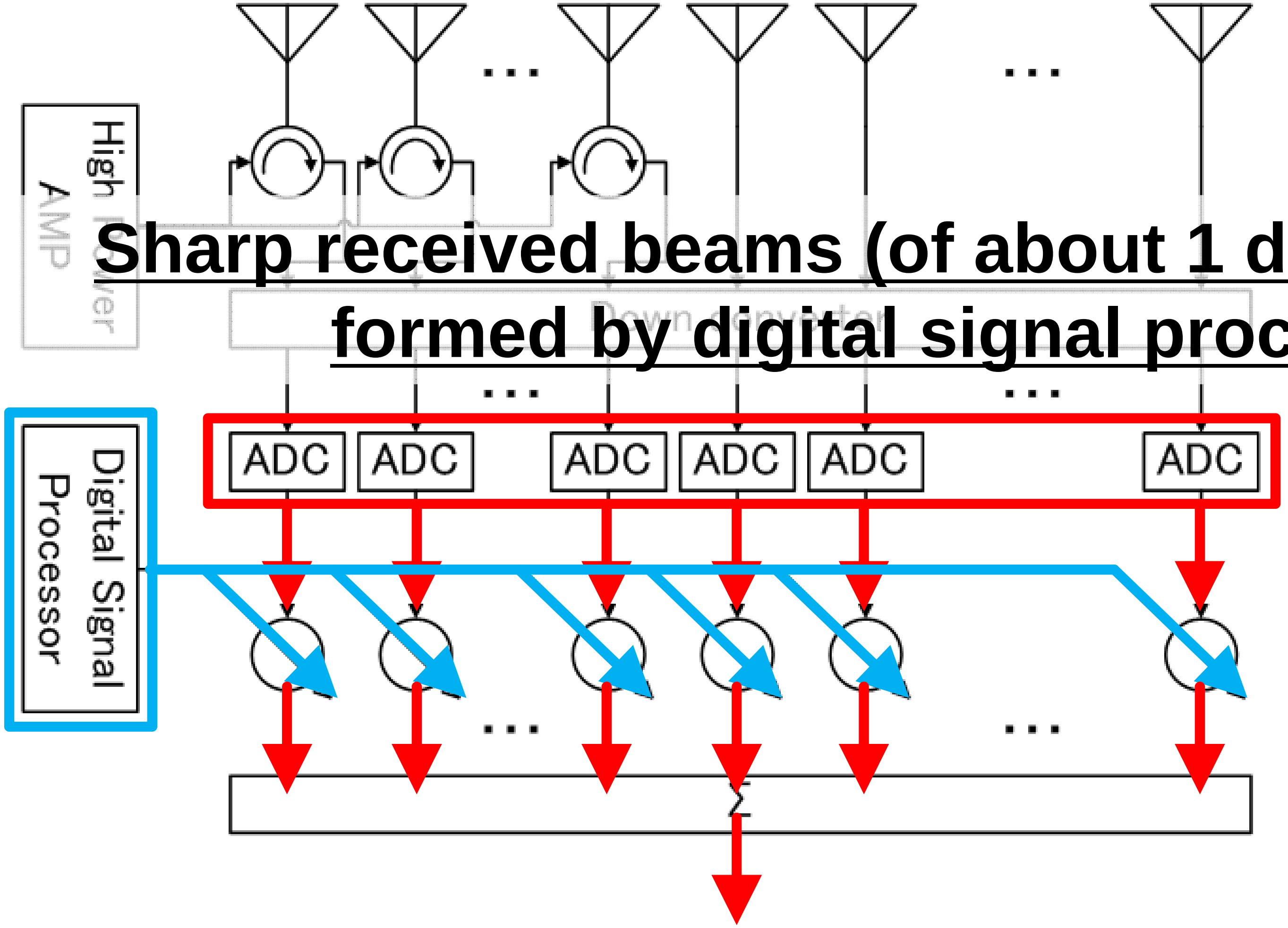
Flow –Reception

Scattered signals are received by all 128 antennas



128 data are stored by 128 ADCs

Flow –Signal Processing



Sharp received beams (of about 1 deg) are formed by digital signal processing

Phased Array RADAR in Osaka University

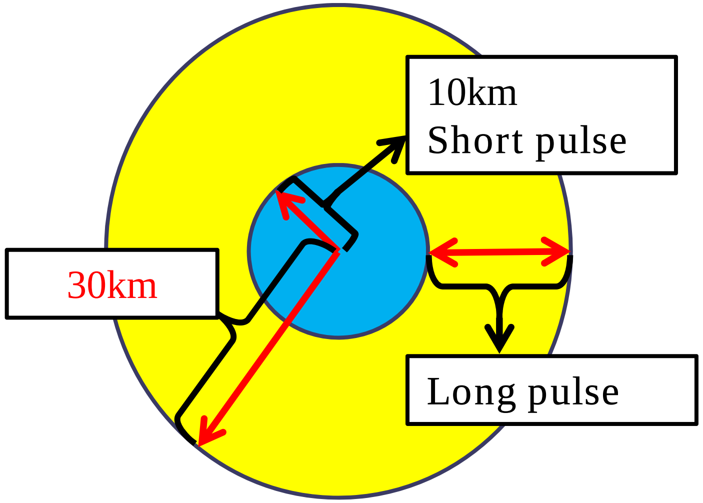
Phased Array Antenna

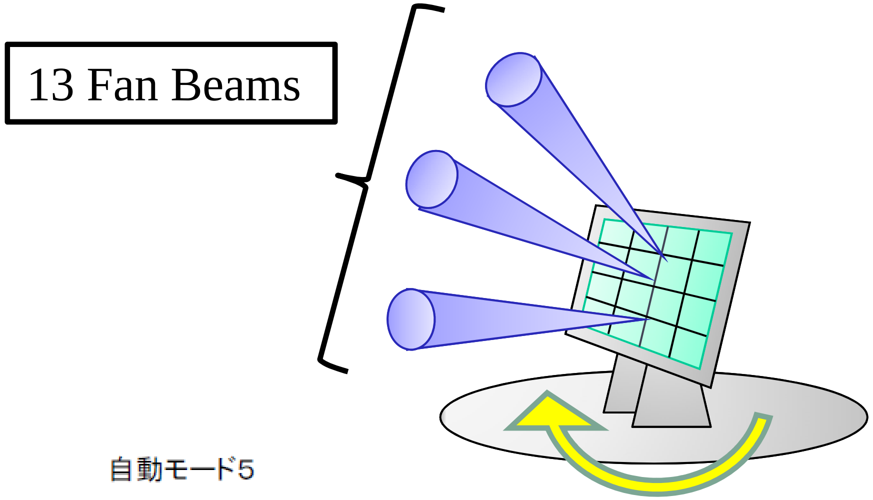
Left: Signal Processing Unit
Right: Controlling Unit.

Installation of the Phased Array RADAR at the top of the building in Osaka University

Phased Array RADAR system at the Electrical Engineering Department building in Osaka University

Observation mode





Mode 1：can observe in 10 sec within 30 km

Frequency: 9430MHz
Long pulse: Linear Chirp (BW: 1MHz)
Short pulse: Rectangular
Sampling Frequency: 1.5MHz
(Range Res. 100m)

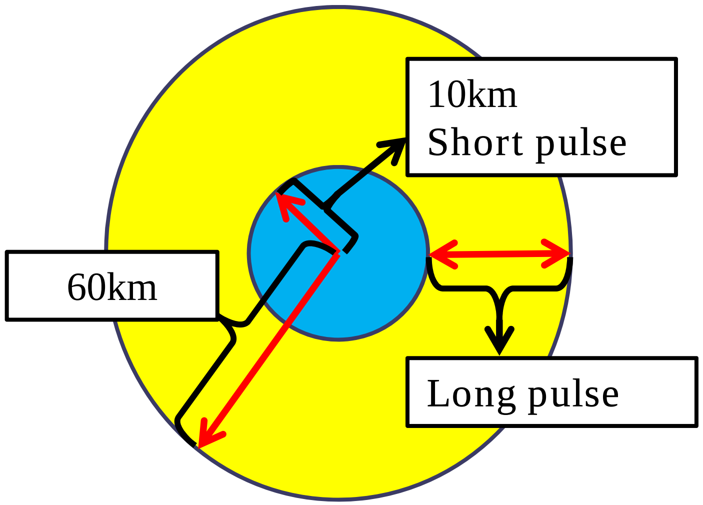
Window Func. : Blackman Harris

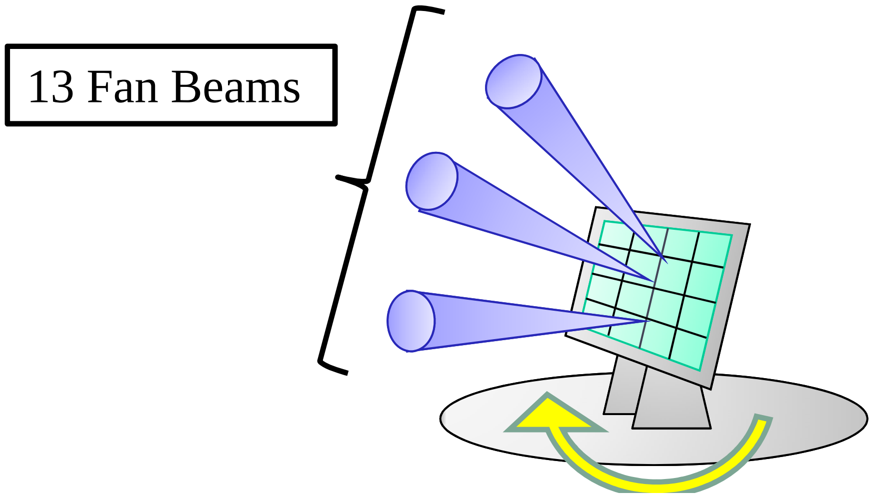
自動モード5

Low → High El.

送信ビーム番号	PRF High	PRF Low	ヒット数 High	ヒット数 Low	長パルス幅 μs	短パルス幅 μs
1	1712	1369	22	17	72.000	1.333
2	1696	1356	22	17	72.000	1.333
3	1681	1344	22	17	72.000	1.333
4	1953	1562	22	17	47.333	1.333
5	2373	1898	22	17	47.333	1.333
6	2819	2255	22	17	47.333	1.333
7	3571	2856	22	17	25.333	1.333
8	4746	3796	22	17	25.333	1.333
9	5208	4166	22	17	25.333	1.333
10	5597	4477	22	17	25.333	1.333
11	5952	4761	22	17	25.333	1.333
12	6147	4917	22	17	25.333	1.333
13	6250	5000	22	17	25.333	1.333

Observation mode





Mode 5：can observe in 30 sec within 60 km

Frequency: 9430MHz
Long pulse: Linear Chirp (BW: 1MHz)
Short pulse: Rectangular
Sampling Frequency: 1.5MHz
(Range Res. 100m)

Window Func. : Blackman Harris

自動モード1

Low → High El.

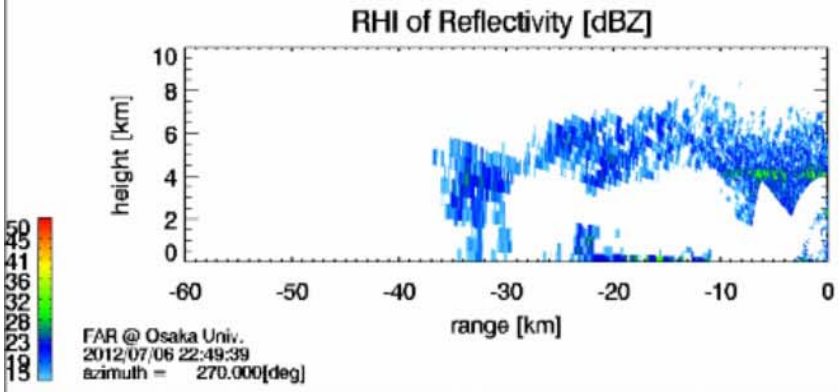
送信ビーム番号	PRF High	PRF Low	ヒット数 High	ヒット数 Low	長パルス幅 μs	短パルス幅 μs
1	4807	3845	10	8	25.333	1.333
2	4746	3796	10	8	25.333	1.333
3	4310	3448	10	8	34.667	1.333
4	4213	3370	10	8	34.667	1.333
5	4076	3260	10	8	34.667	1.333
6	3947	3157	10	8	34.667	1.333
7	3947	3157	10	8	34.667	1.333
8	4573	3658	10	8	28.667	1.333
9	5067	4053	10	8	25.333	1.333
10	5434	4347	10	8	25.333	1.333
11	5514	4411	10	8	28.667	1.333
12	5952	4761	10	8	25.333	1.333
13	6147	4917	10	8	25.333	1.333
14	6250	5000	10	8	25.333	1.333

Higher PRF and lower samples

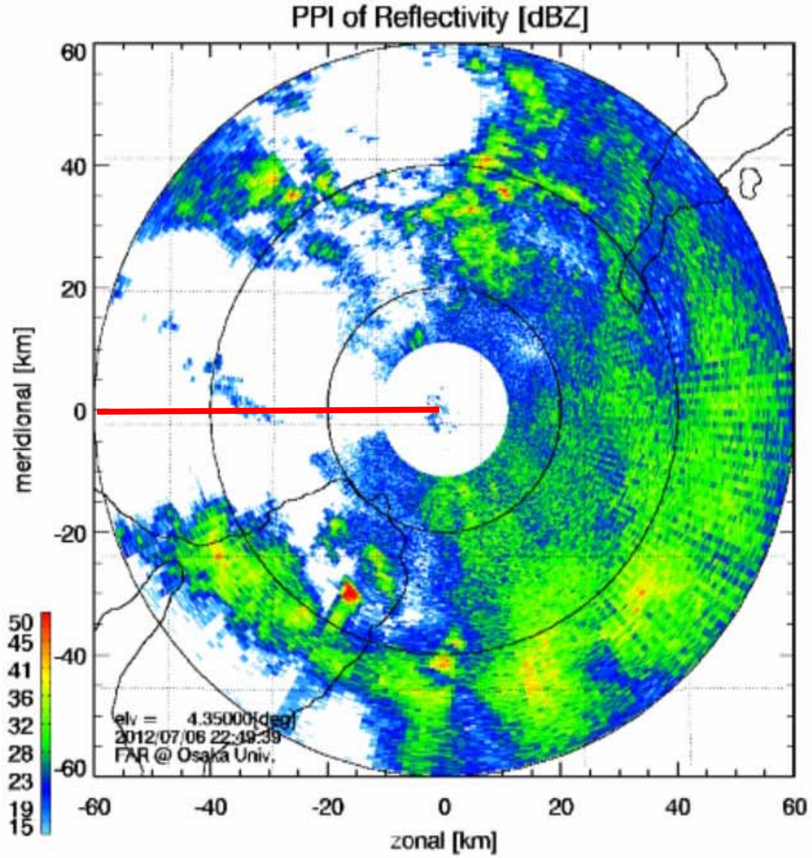
30 Sec. Resolution

2012年July 6th 2012 22:49:39～23:59:39

RHI along the red line



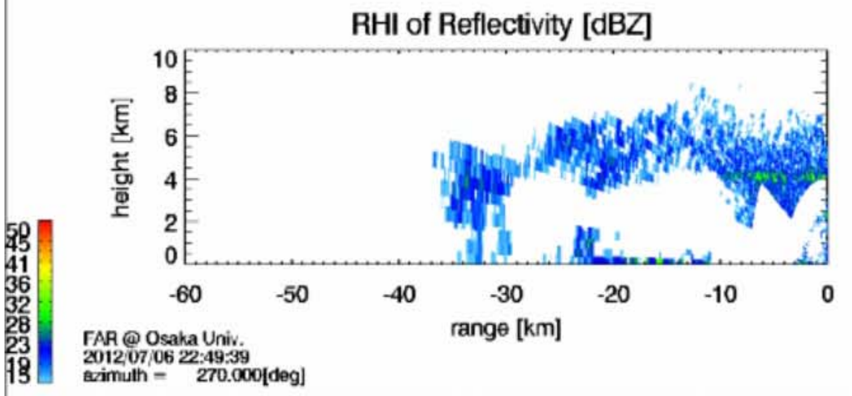
PPI at El. 4.35 deg.



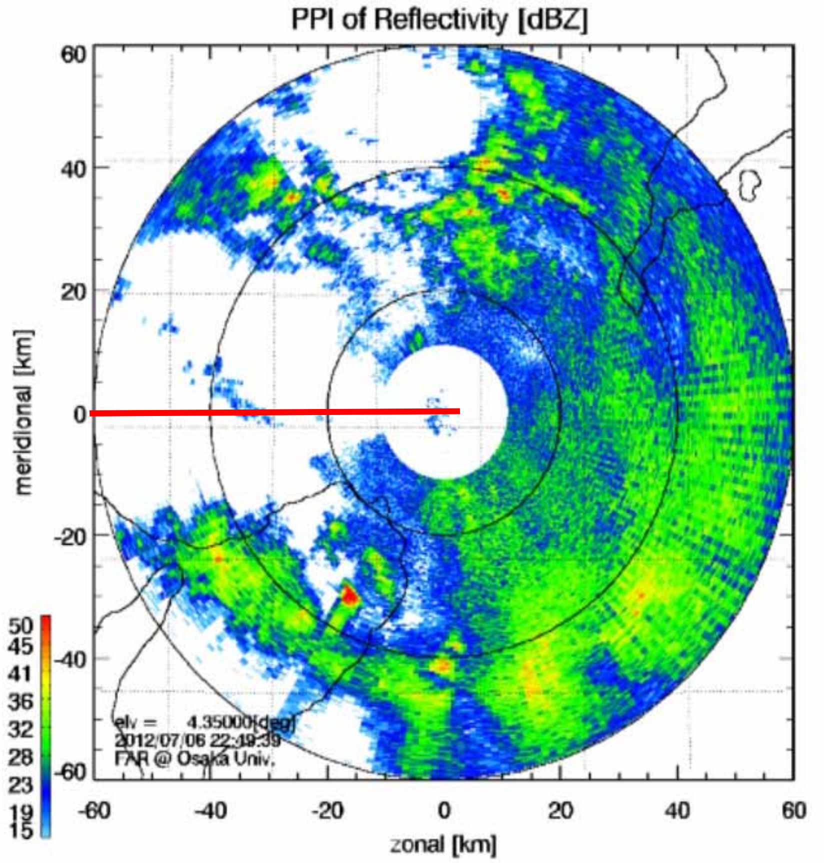
5 min. Res.

7/6 2012 22:49:39～23:59:39

RHI along the Red Line



PPI at 4.35 degree in El.



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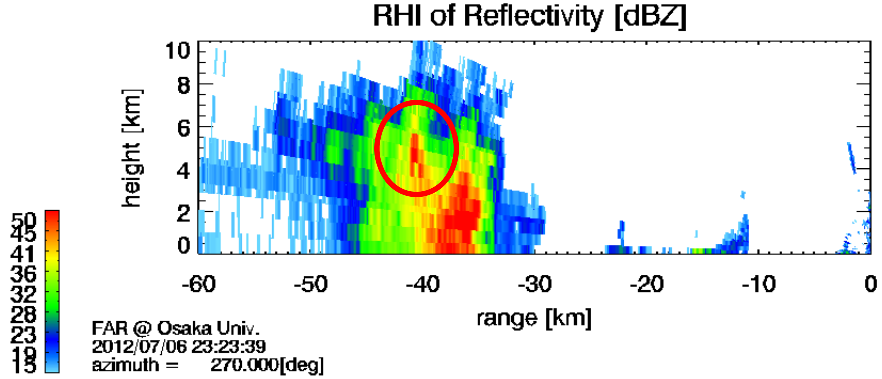
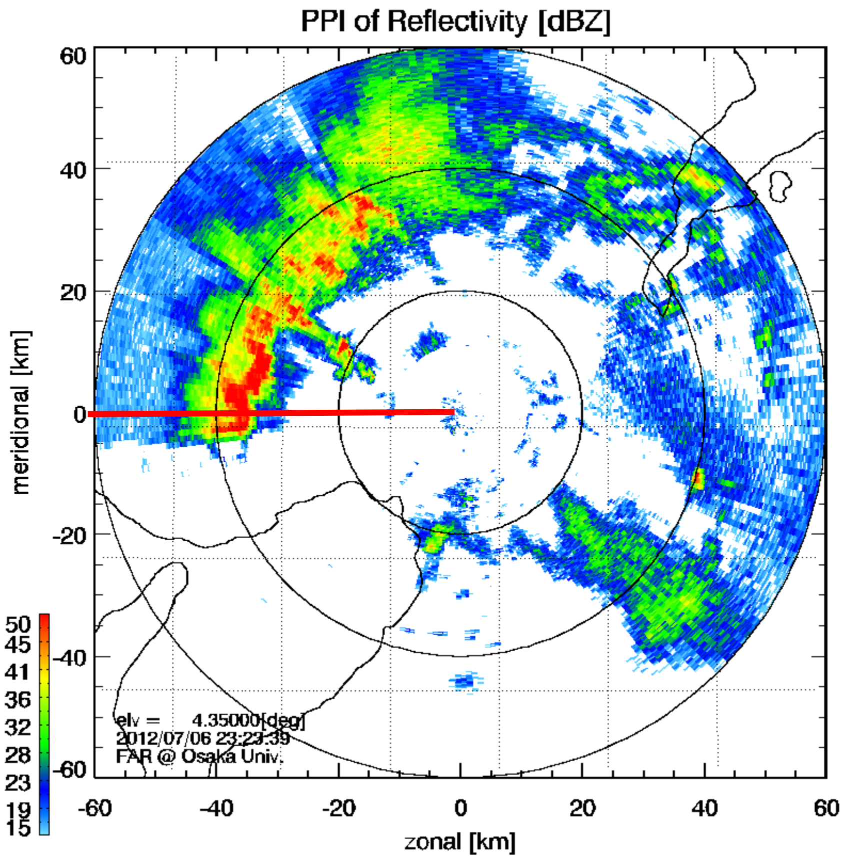


右図の赤い線に沿ったRHI



仰角4.35度におけるPPI

時間進展

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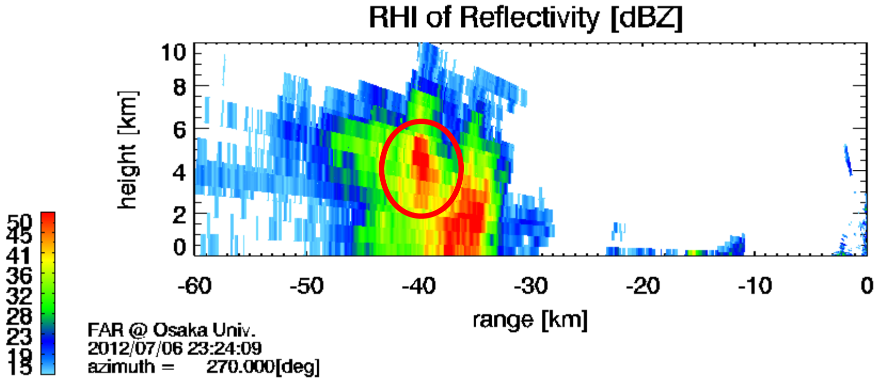

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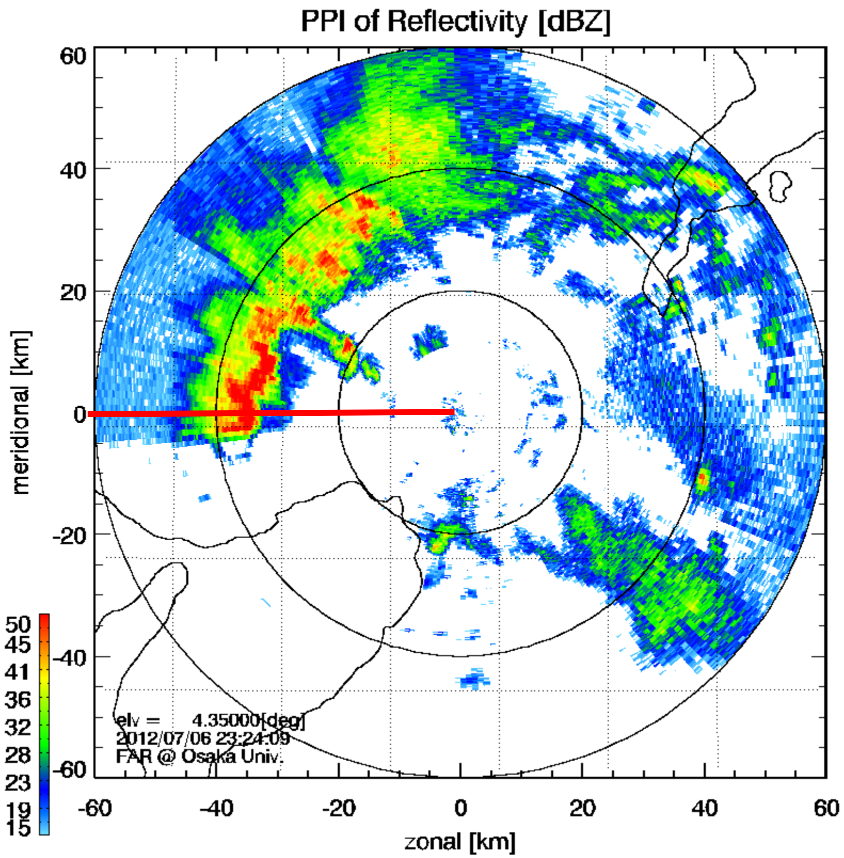

仰角4.35度におけるPPI

時間進展

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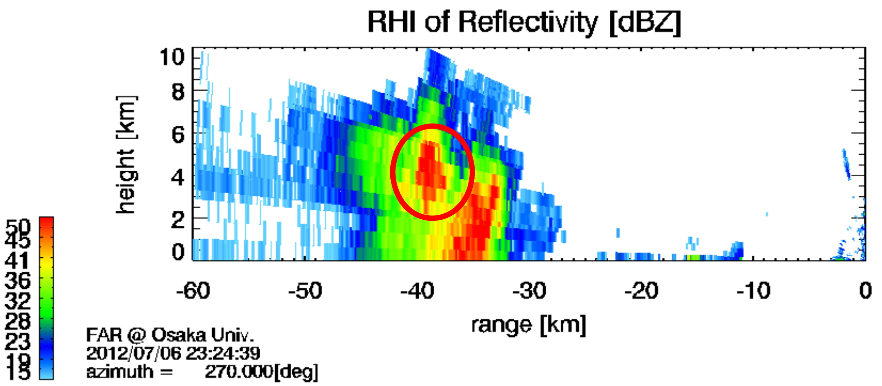

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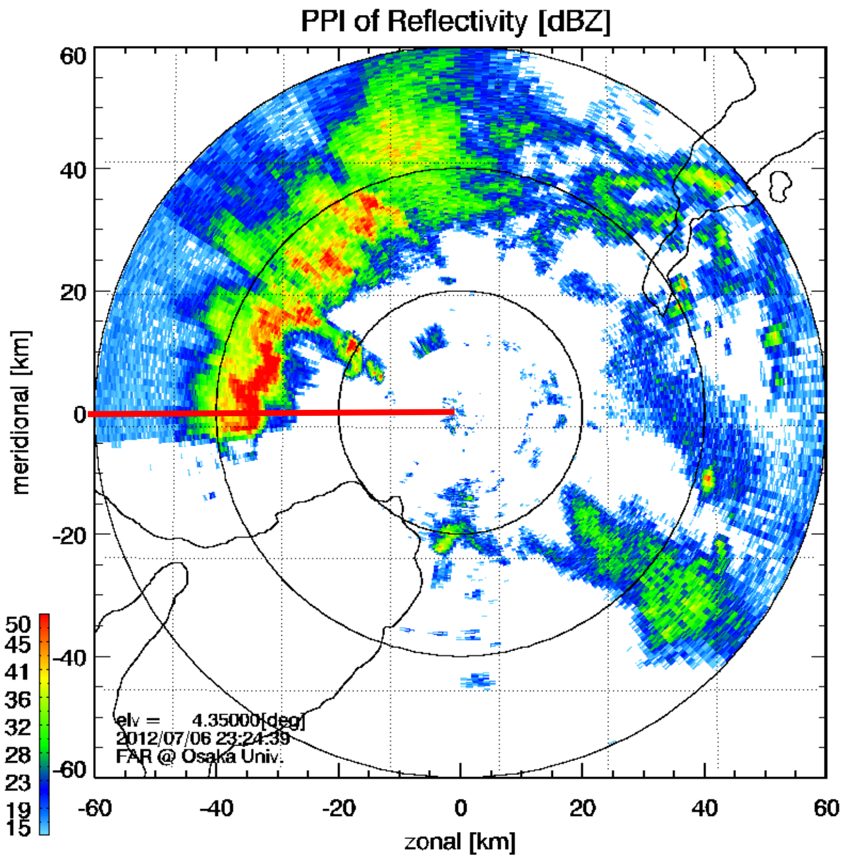

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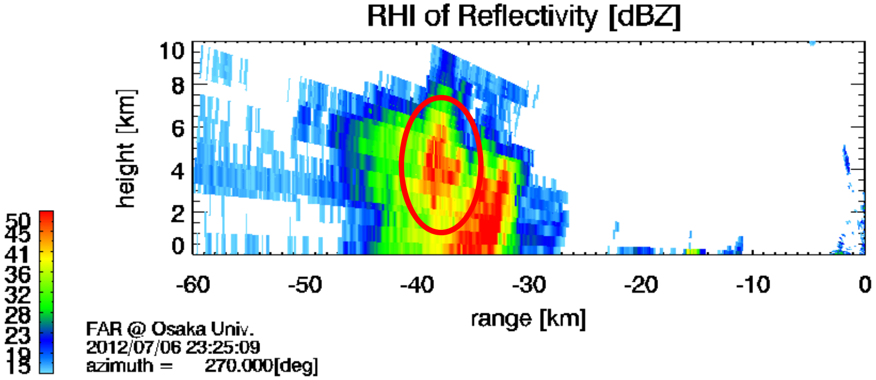

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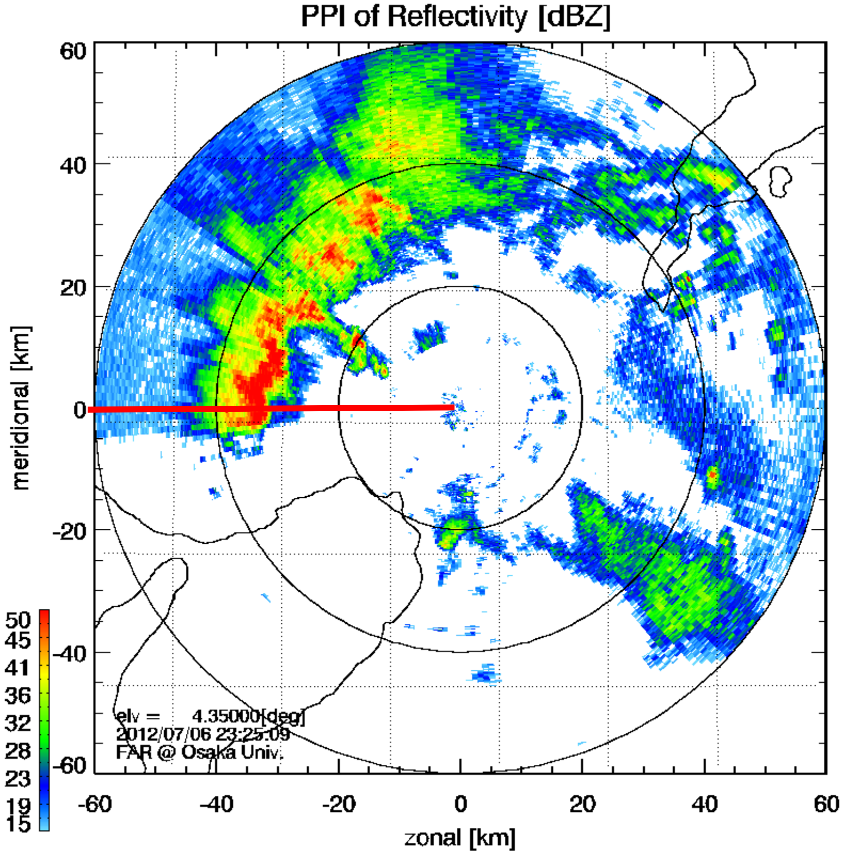

仰角4.35度におけるPPI

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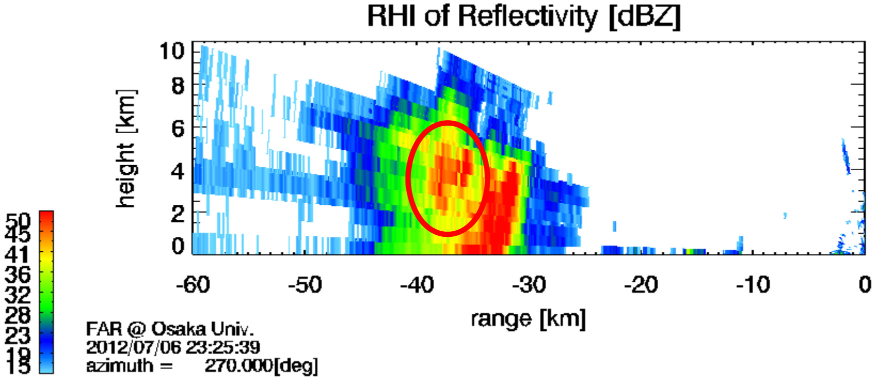

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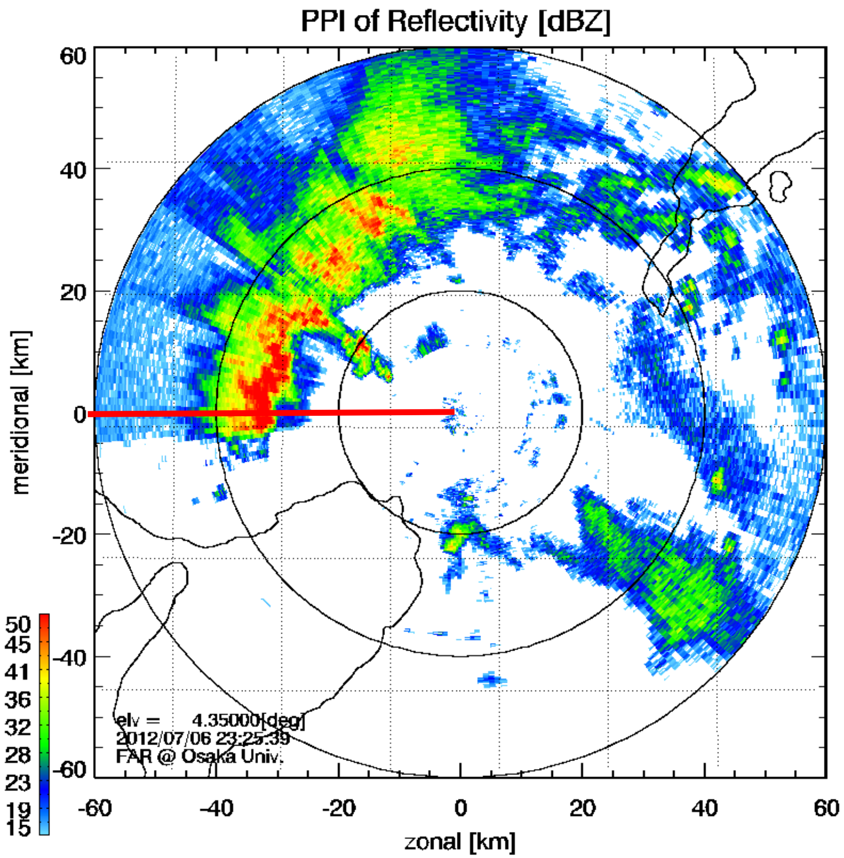

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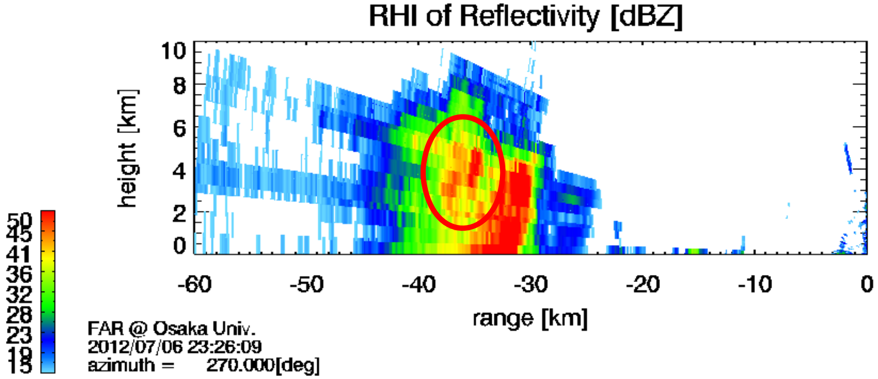

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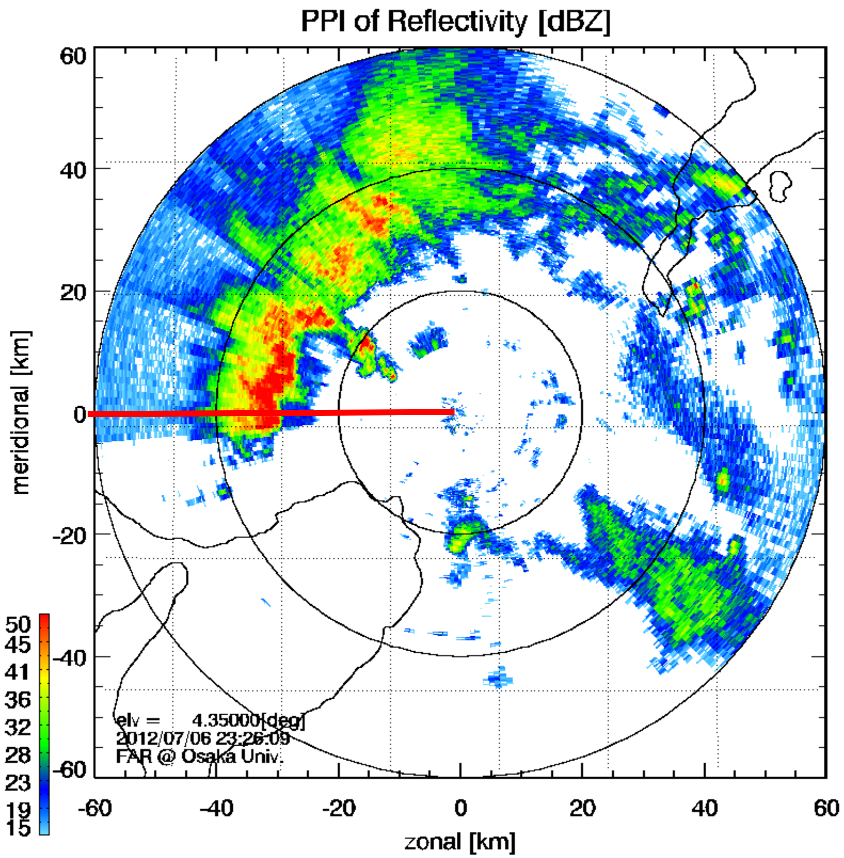

仰角4.35度におけるPPI

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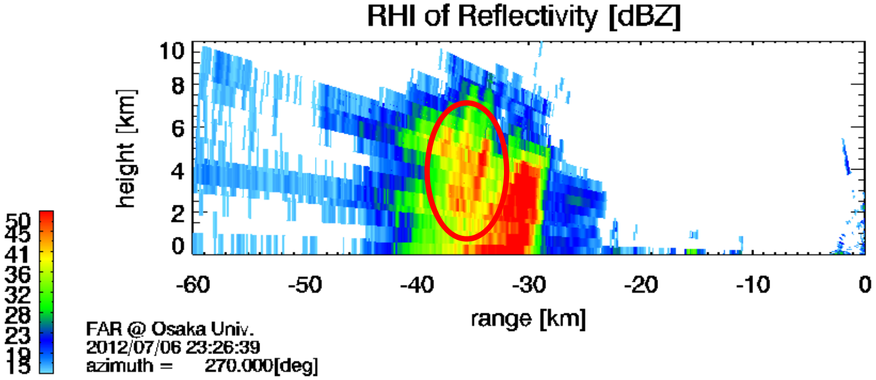

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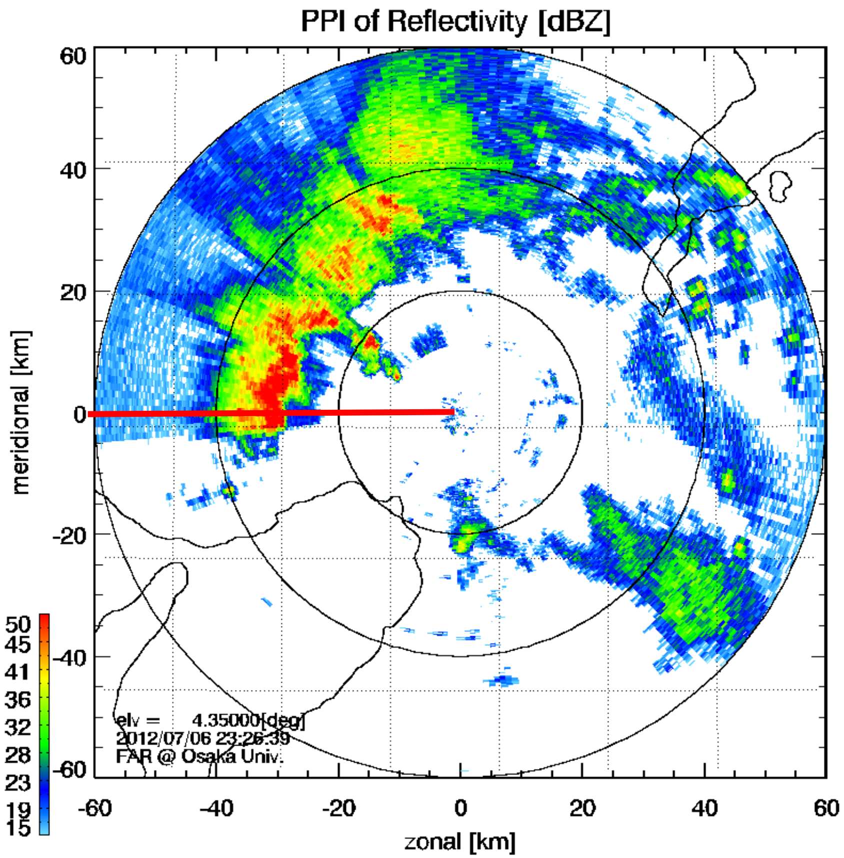

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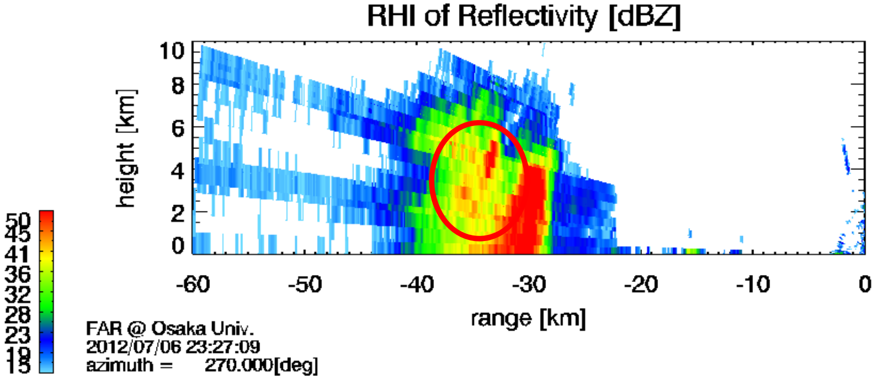

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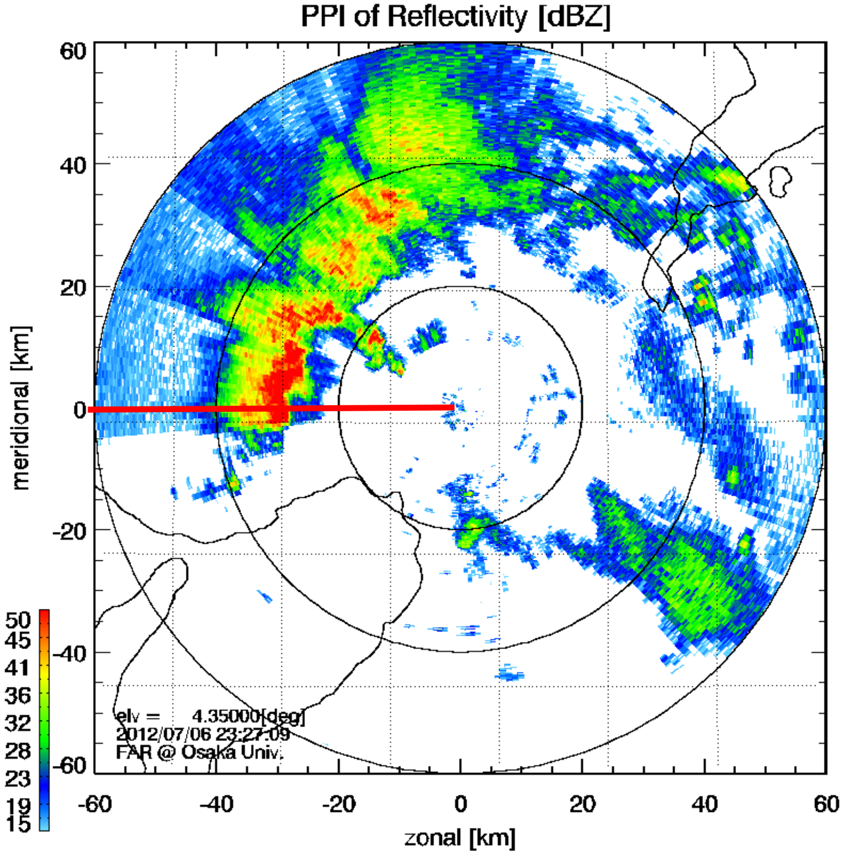

仰角4.35度におけるPPI

時間進展

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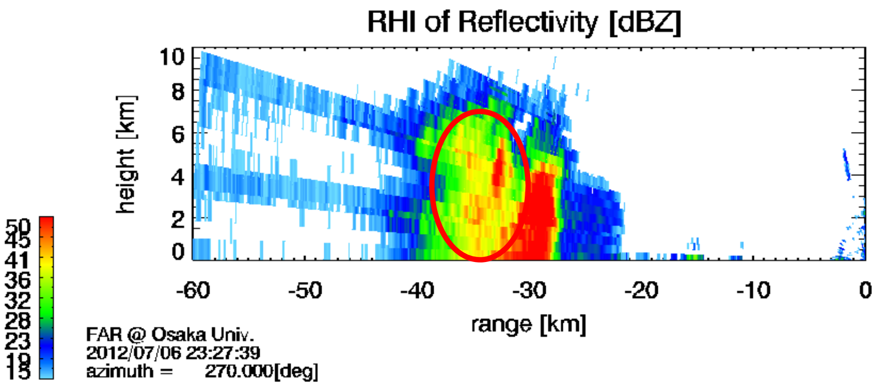

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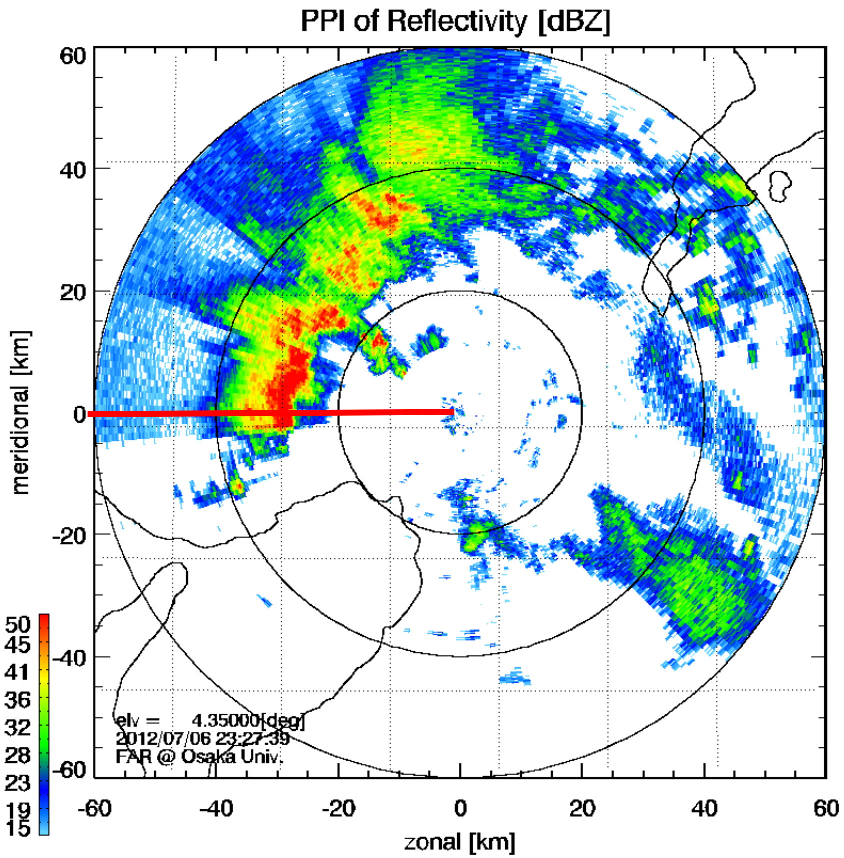

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時間進展

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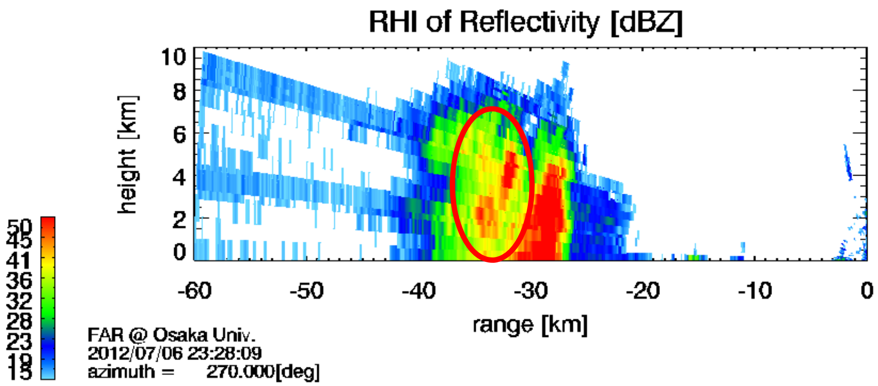

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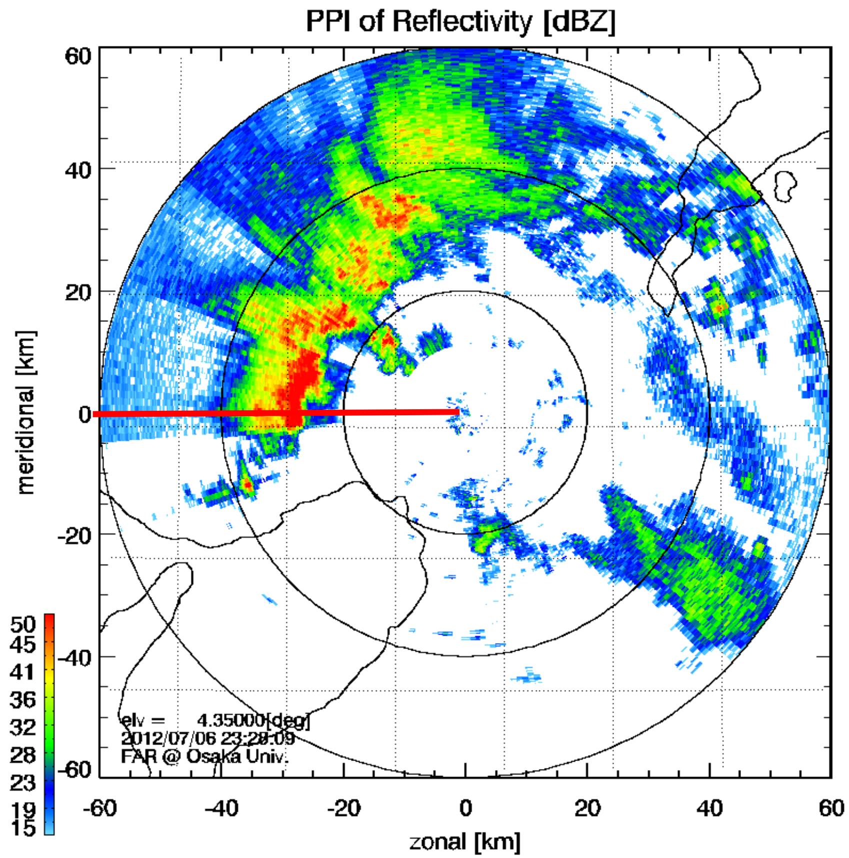

仰角4.35度におけるPPI

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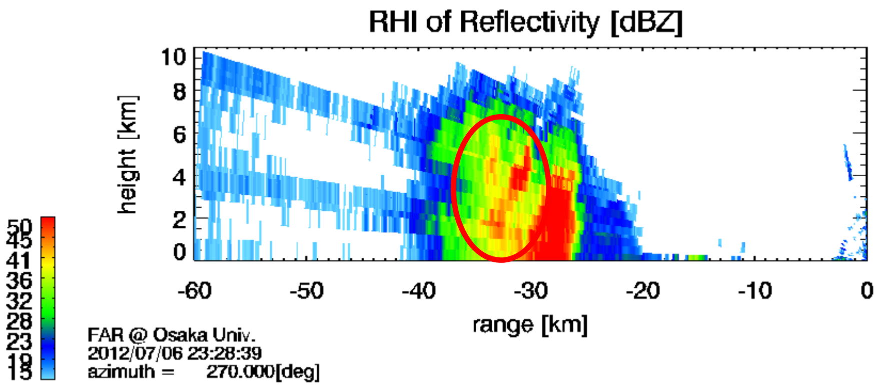

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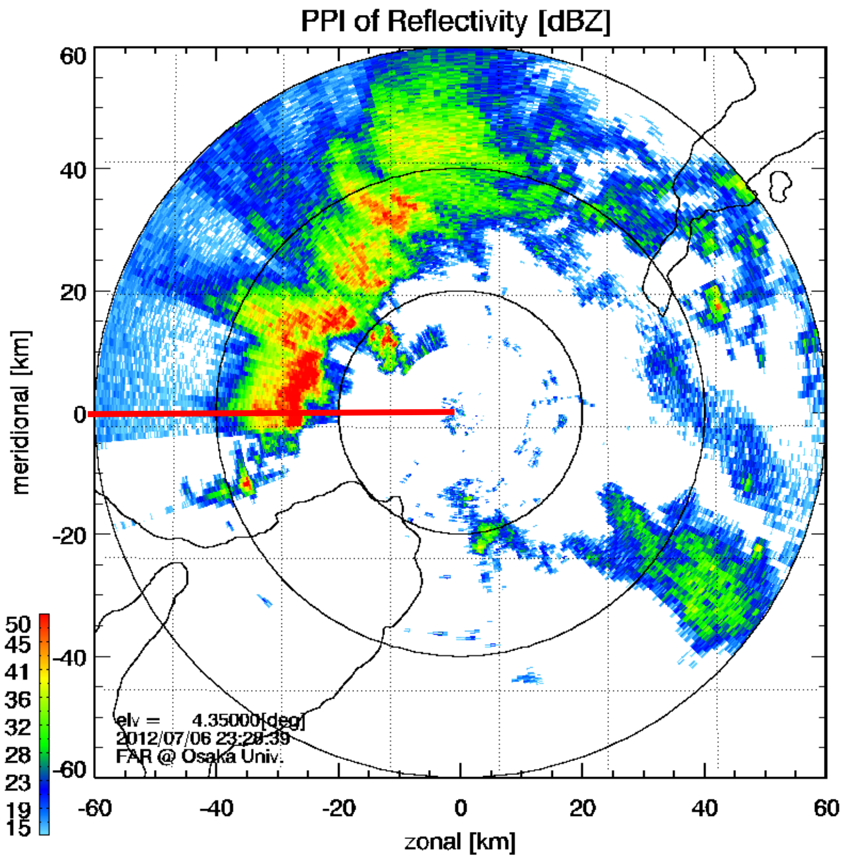

仰角4.35度におけるPPI

時間進展

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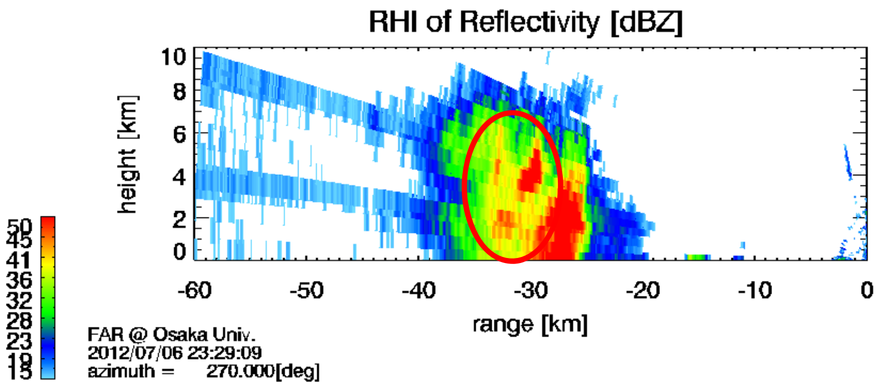

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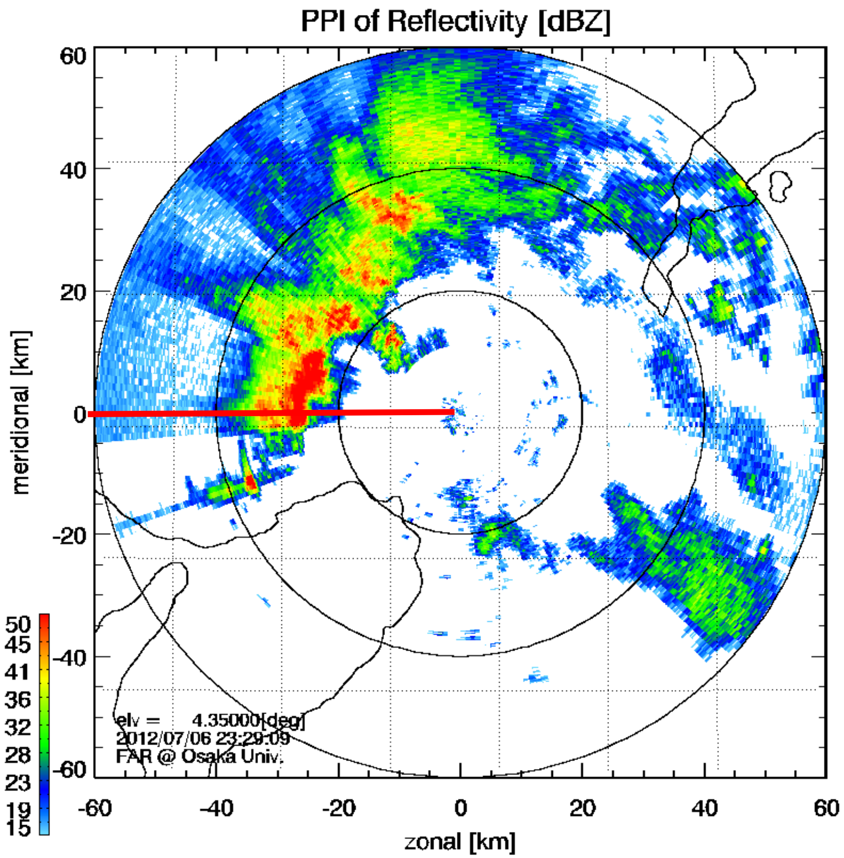

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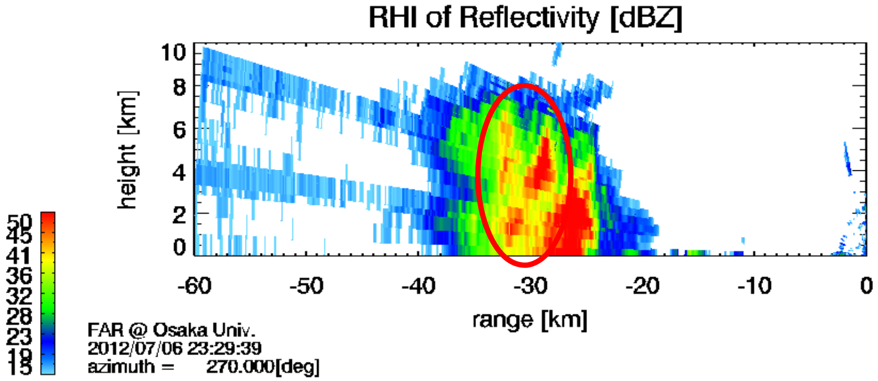

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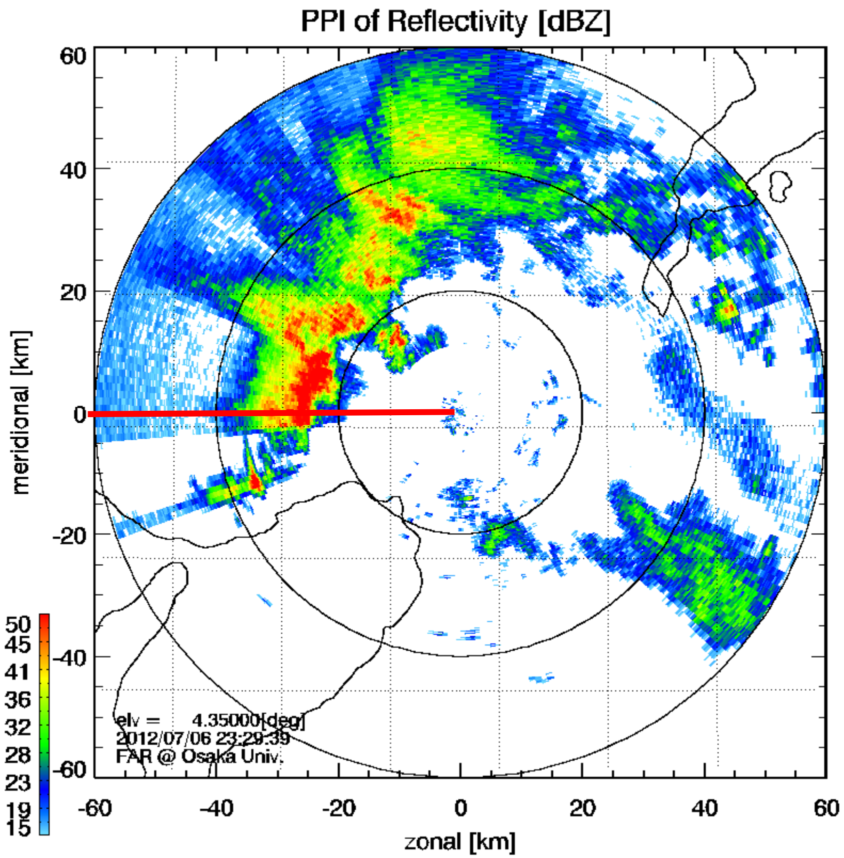

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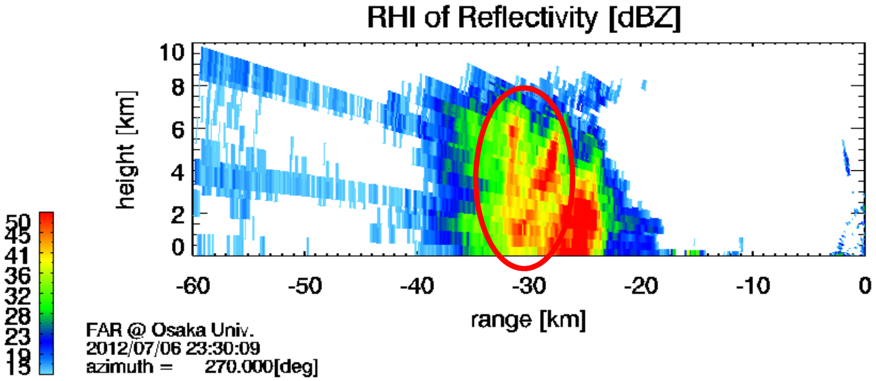
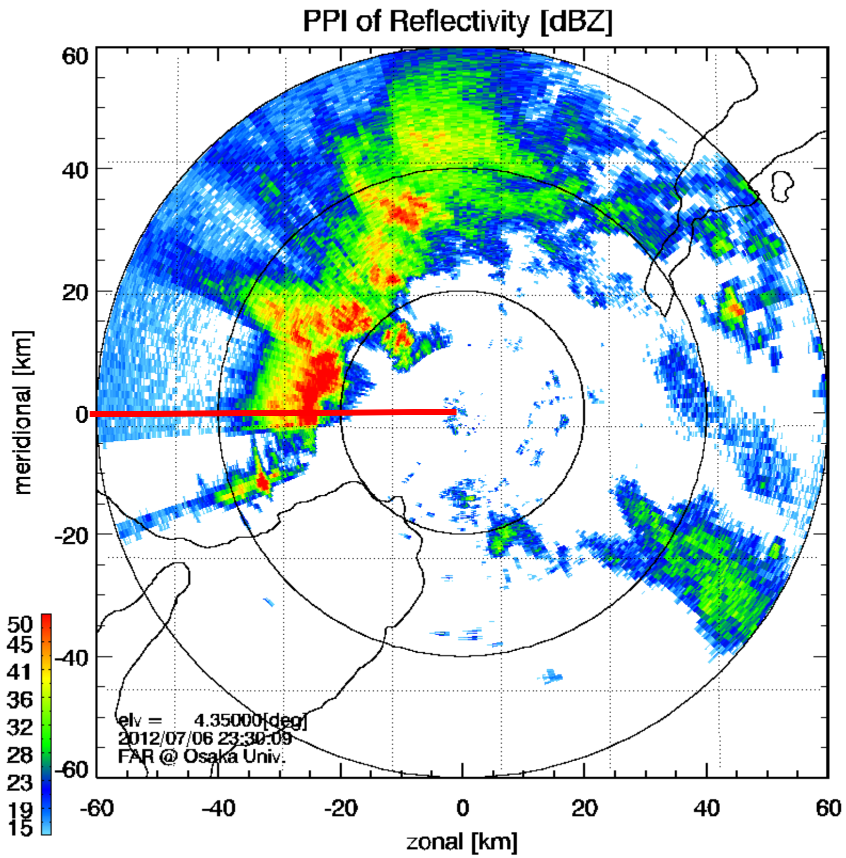


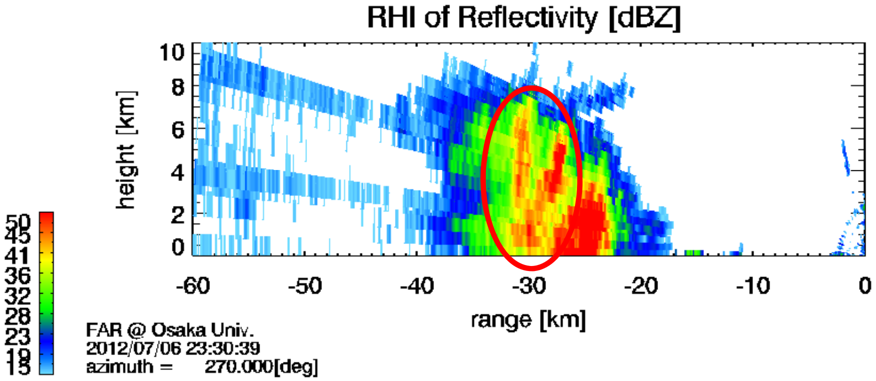
右図の赤い線に沿ったRHI



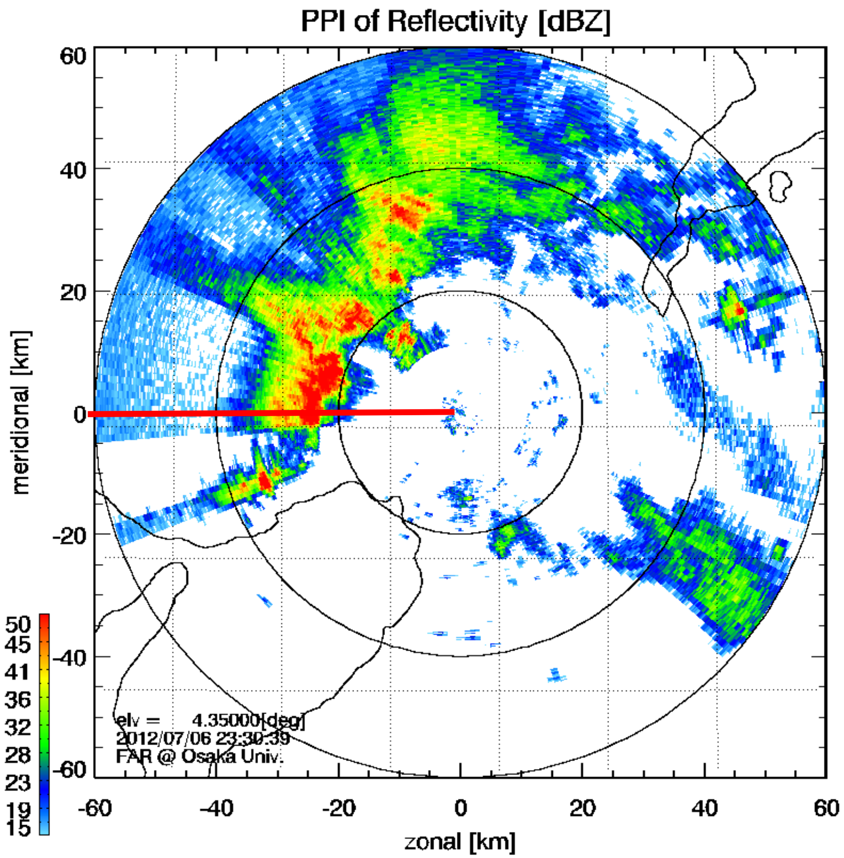
仰角4.35度におけるPPI

時間進展

2012年7月6日　23:30:39の観測結果



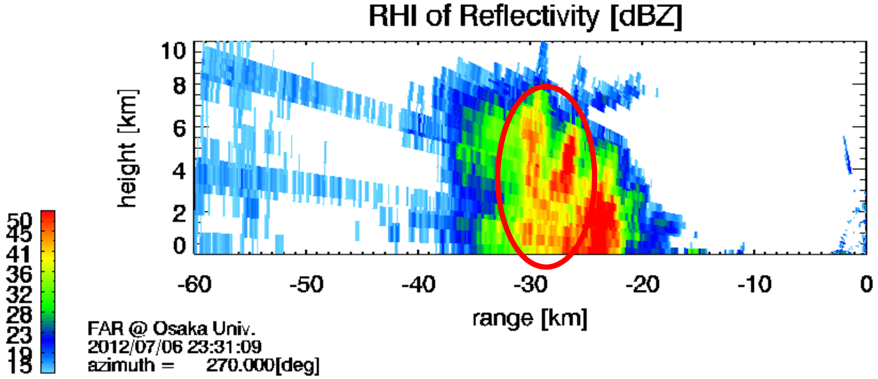
右図の赤い線に沿ったRHI



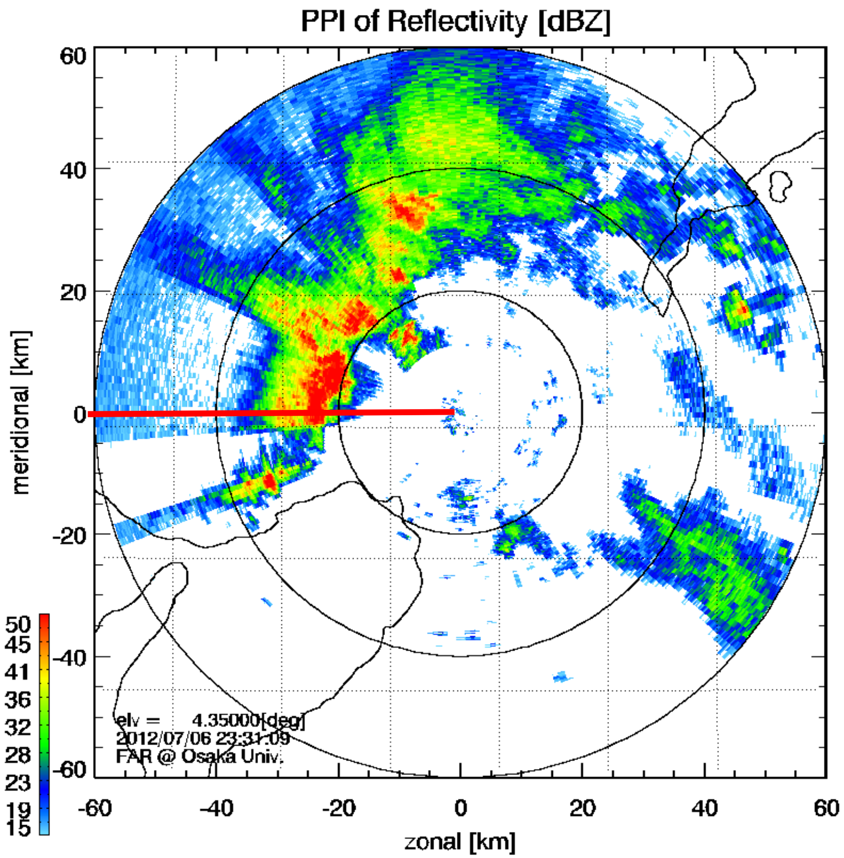
仰角4.35度におけるPPI

時間進展

2012年7月6日　23:31:09の観測結果



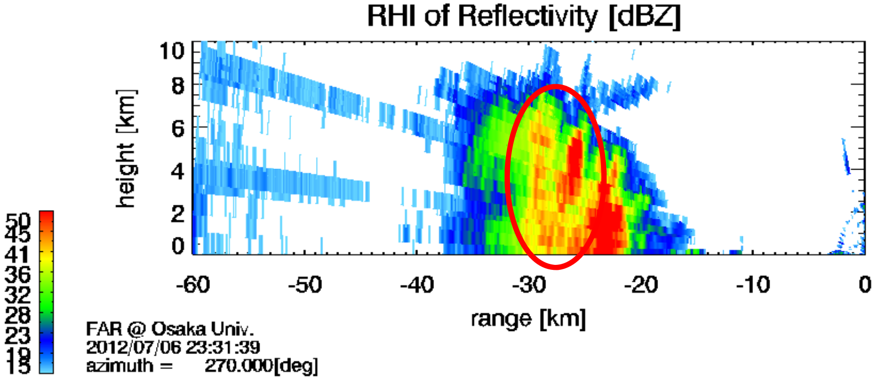
右図の赤い線に沿ったRHI



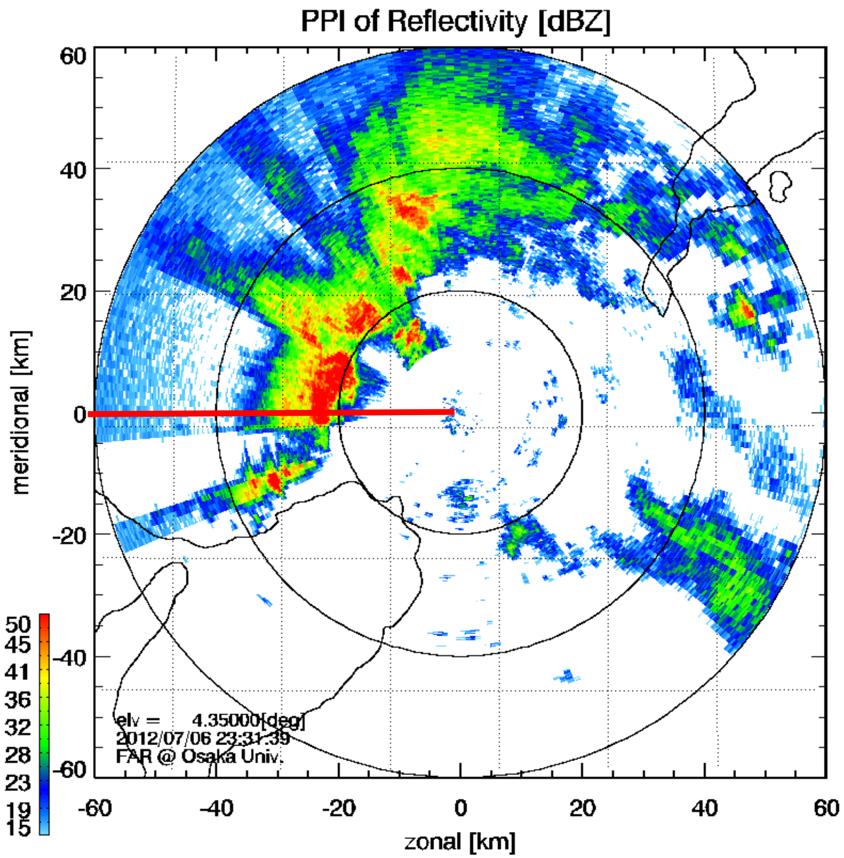
仰角4.35度におけるPPI

時間進展

2012年7月6日　23:31:39の観測結果



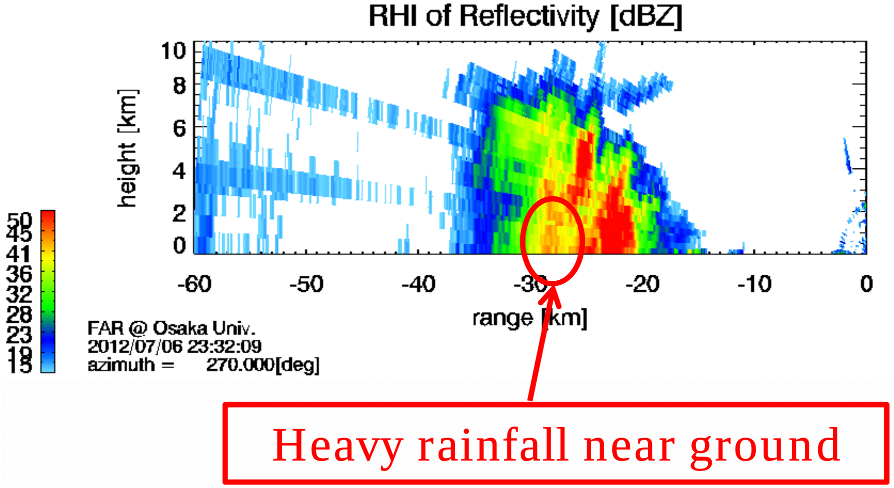
右図の赤い線に沿ったRHI

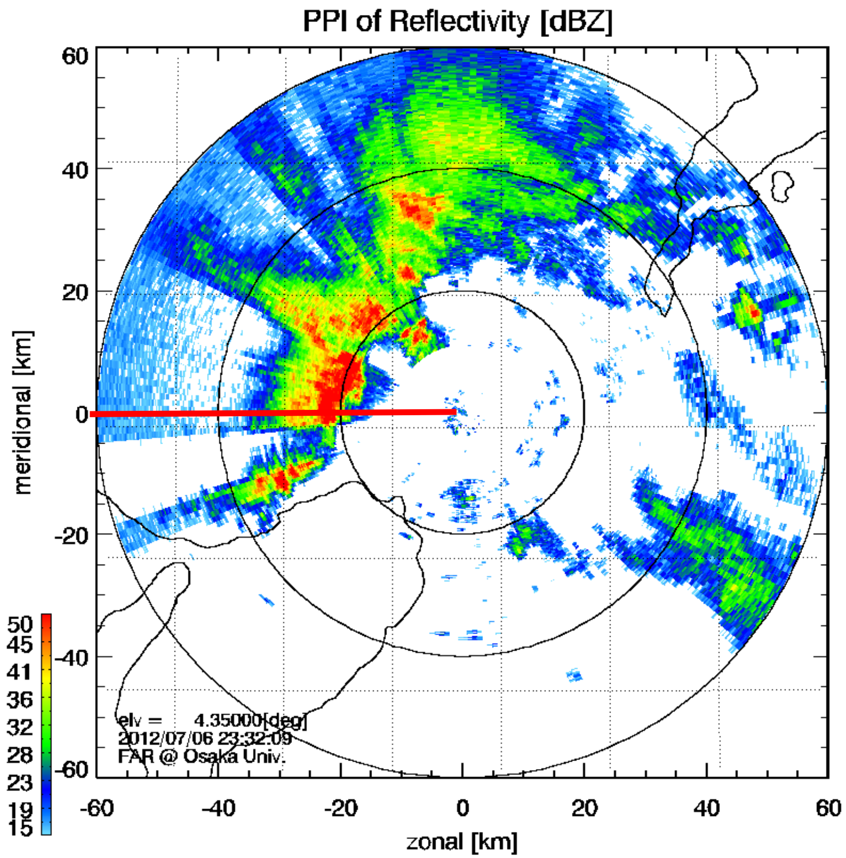


仰角4.35度におけるPPI

時間進展

2012年7月6日　23:32:09の観測結果





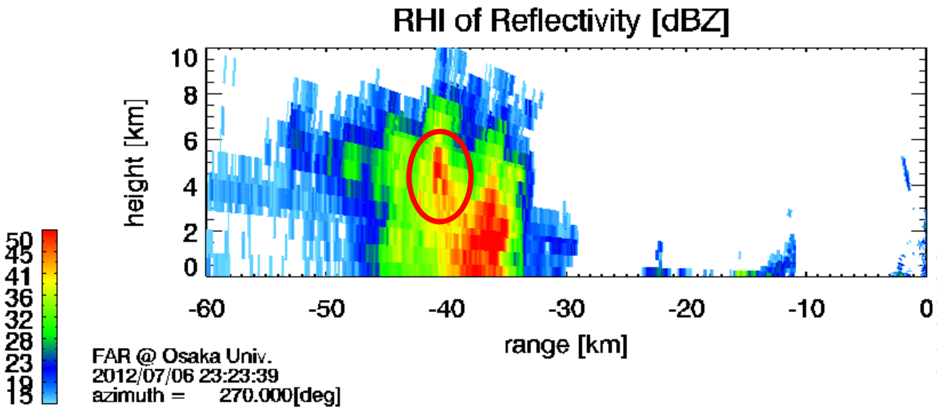
右図の赤い線に沿ったRHI

仰角4.35度におけるPPI

時間進展

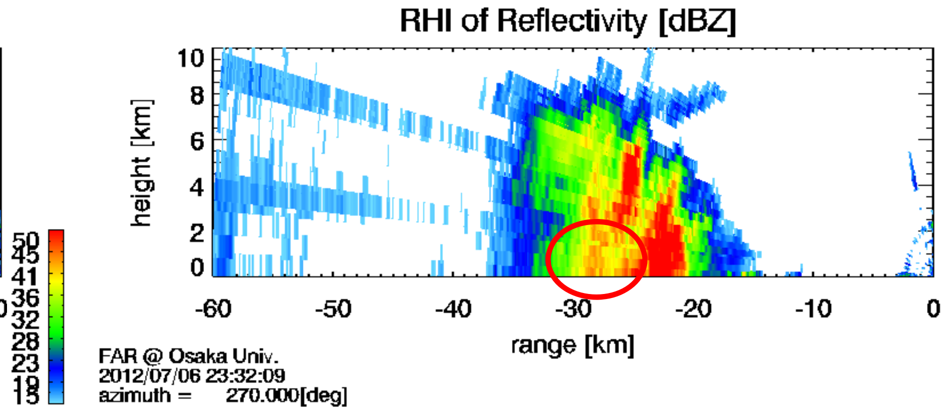
7/6 2012　23:23:39

Formation of the precipitation core



7/6 2012　23:32:09

The core touched down
in 8 min and 30 sec later

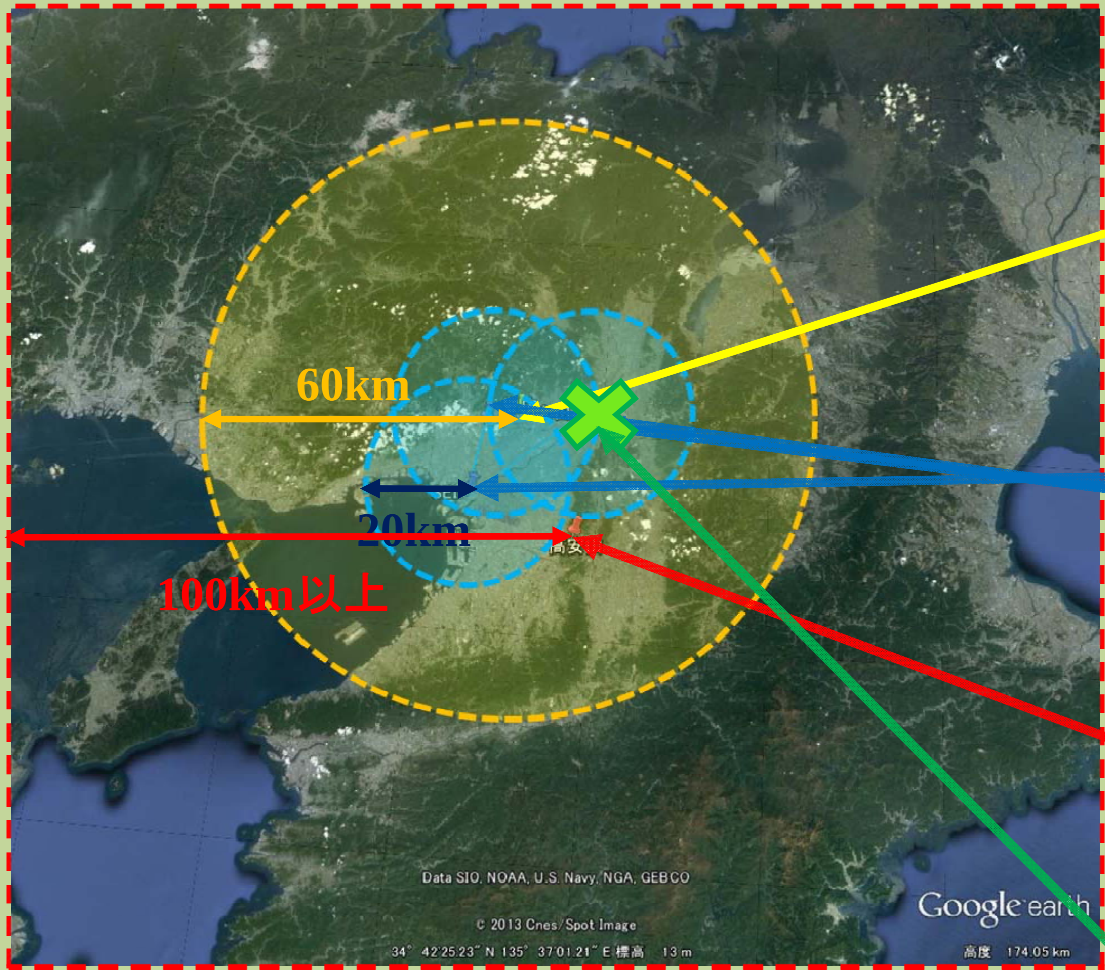


8 min. and 30 sec.

Comparison with other radars

- As is shown here, the Phased Array Radar shows impressive pictures with high resolution by taking a different transmitting and receiving approach from that of conventional weather radar using dish type antenna.
- It is very important to compare with other radar system and to clear the advantage and disadvantage of PAR.

Field Campaign in Osaka Urban Area

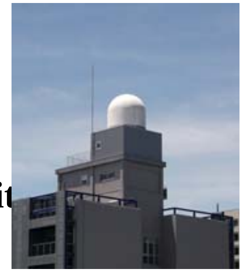


観測範囲

PAR　BBR　C-band Radar (全域)

PAR

@E3 building
Suita Campus
In Osaka University



BBR-network

@ Osaka Univ.
Hirakata
Osaka city

C-band Radar

@Takayasu
Yao, Osaka

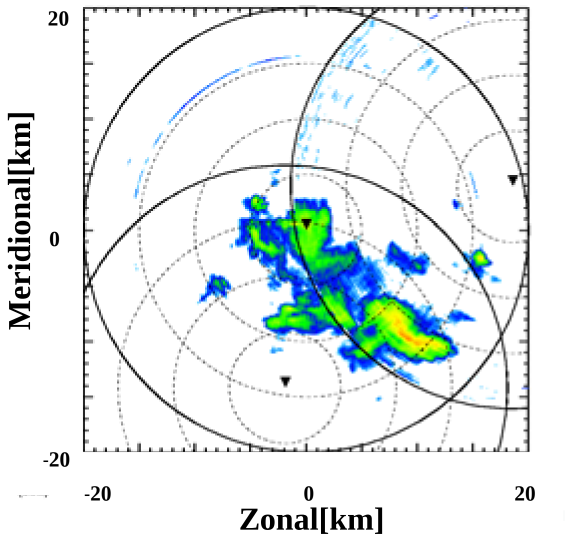
Disdrometer

@Hirakata

Comparison with BBR network at Ku and C band radar

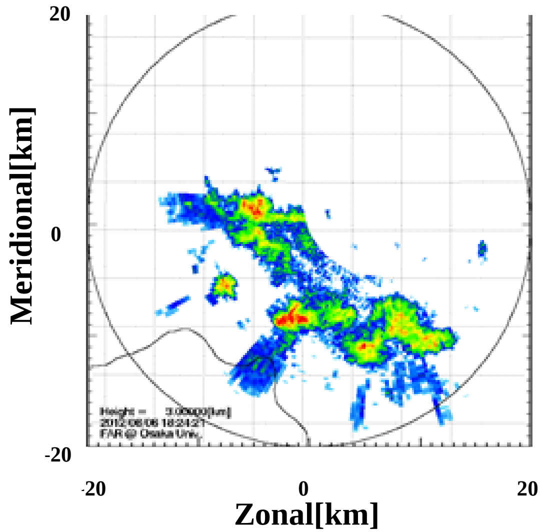
Date:2012 8/6 18:00 ~18:50

BBR-network(1 min.)



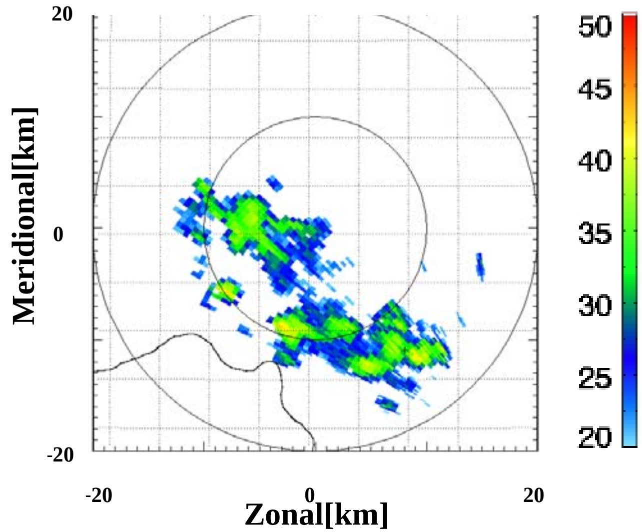
CAPPI
3km in height

PAR(30 sec.)



CAPPI
3km in height

C-band Radar(10 min.)

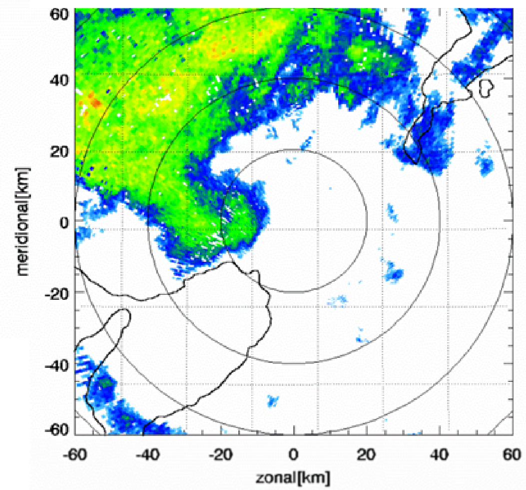


PPI
0.7° in elev.

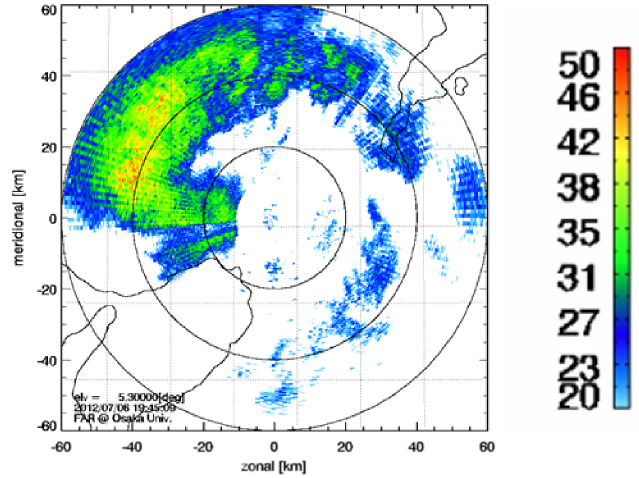
	Correlation	Variance
PAR・BBR	0.904	4.01dB

Comparison with C band radar

Date:2012 7/6 19:50



CBR PPI Elevation=2.55°



PAR PPI Elevation=5.3°

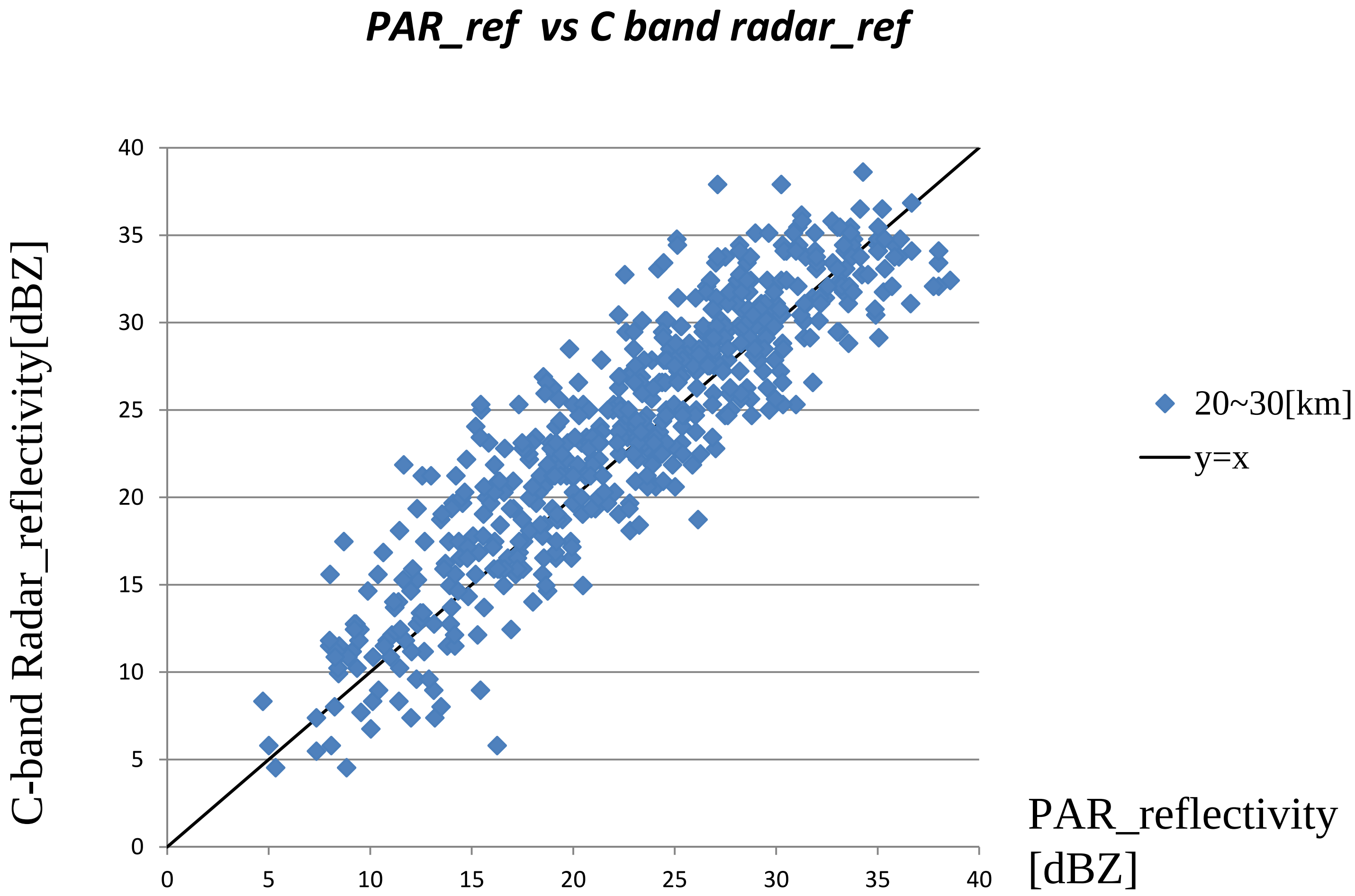
Range from PAR [km]	10~20	20~30	30~40	40~50	50~60
Correlation	0.902	0.901	0.779	0.645	0.601
STD [dB]	3.75	4.10	3.35	5.29	3.79

Correlation and STD strongly depends on the range

At close range, the correlation is very high, while at far range the correlation drops to 0.6 probably due to attenuation and beam broadening

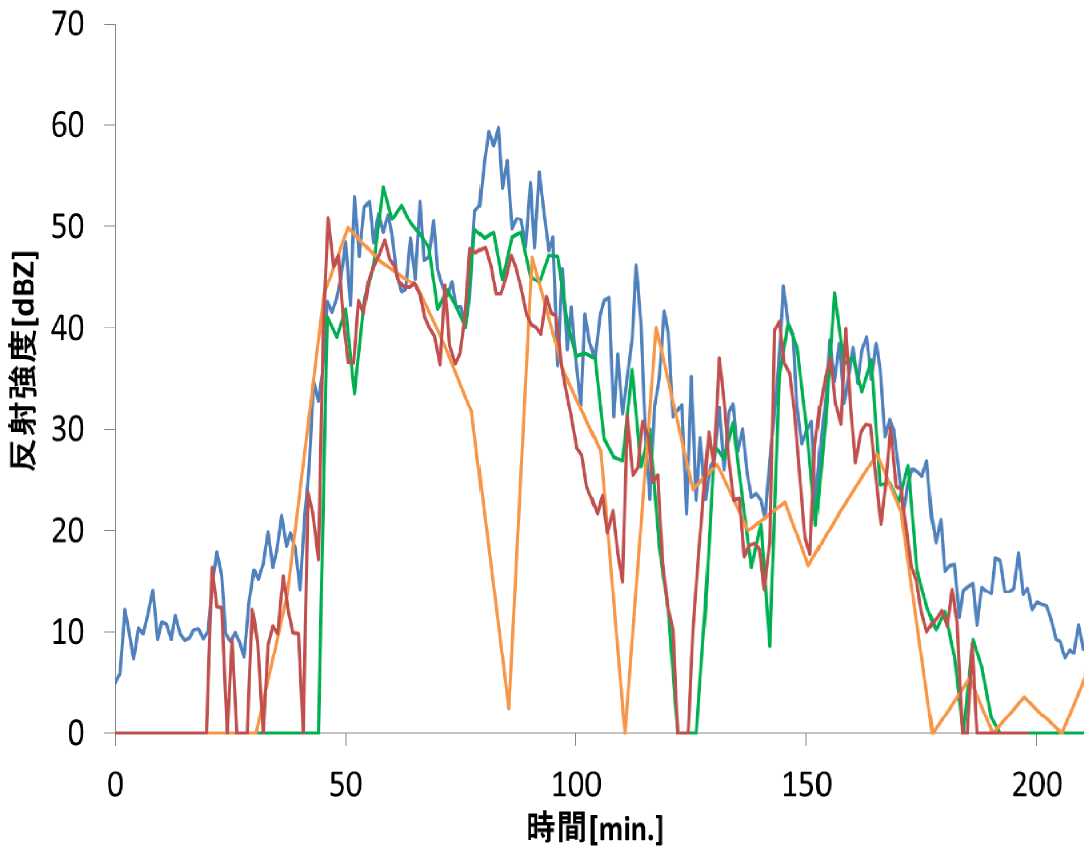
Comparison with C band radar

Date:2012 7/6 UTC 10:45



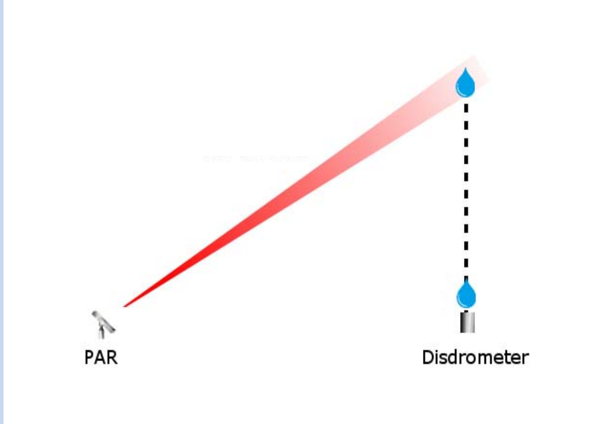
Comparison with disdrometer

Date:2012 7/22 15:50~19:10

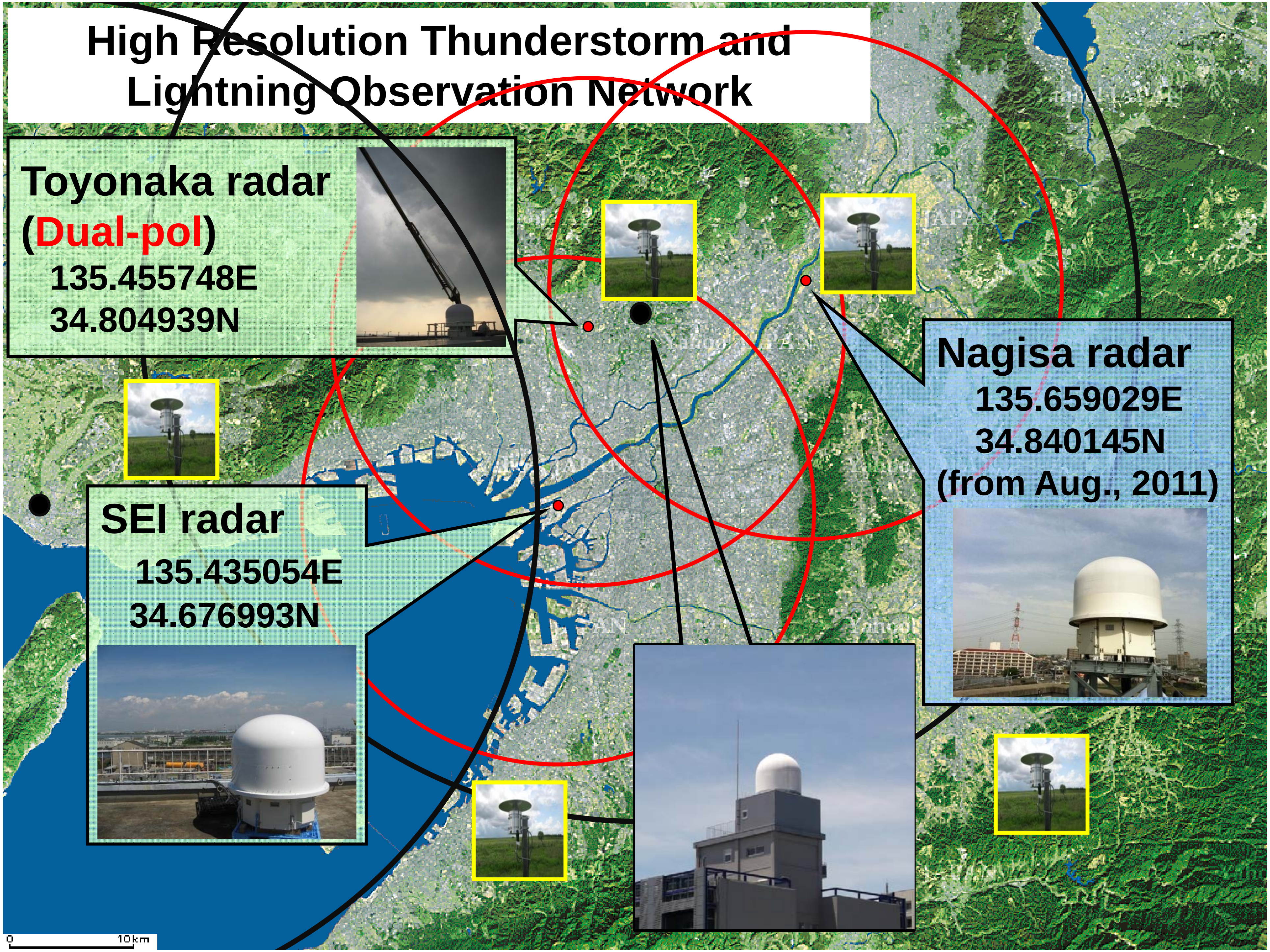


Blue : PAR（1km in height）
Red : BBR（100m in height)
Green : Disdrometer
Orange : C band radar（1km in height）

・PAR・C band radar observe the region at 1 km in height



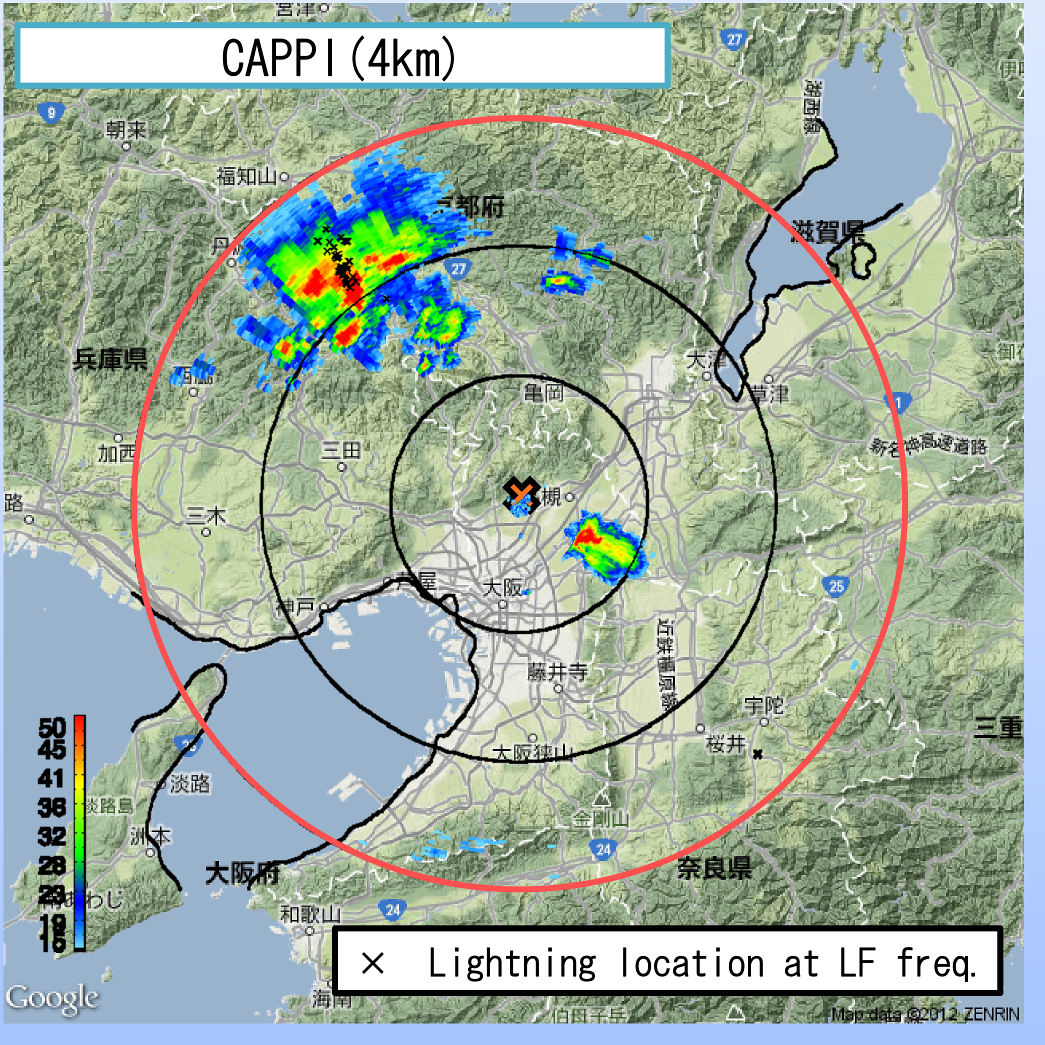
Basically the variation of PAR reflectivity matches well with that of disdrometer
・Correlation of PAR with disdrometer is 0.604 and std of 10 dB



High Resolution Thunderstorm and
Lightning Observation Network
Toyonaka radar
(Dual-pol)
135.455748E
34.804939N
Nagisa radar
135.659029E
34.840145N
(from Aug., 2011)
SEI radar
135.435054E
34.676993N
0
10km

Field campaign with lightning mapper

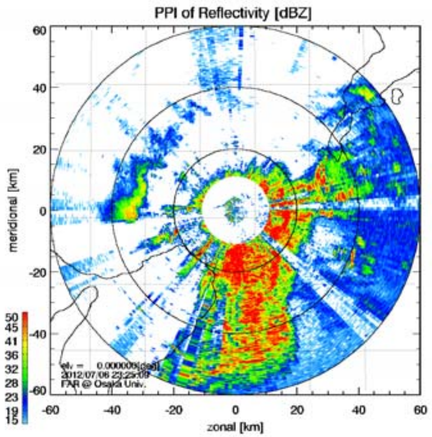
Sep. 6, 2012 16:00 - 18:00 (every 30. sec)



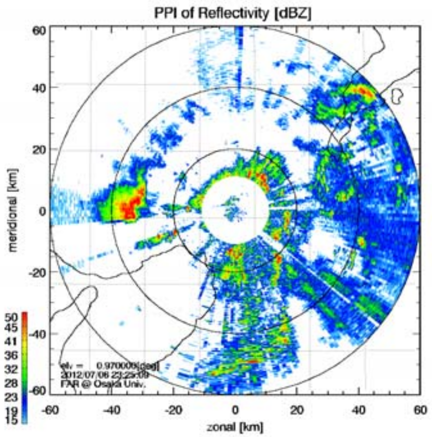
Initial Observation

Mode 5 July 6th 2012 23:25:09 PPI(Plan Position Indicator)

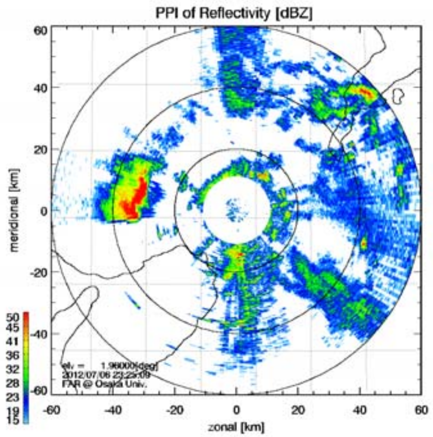
El. 0.00°



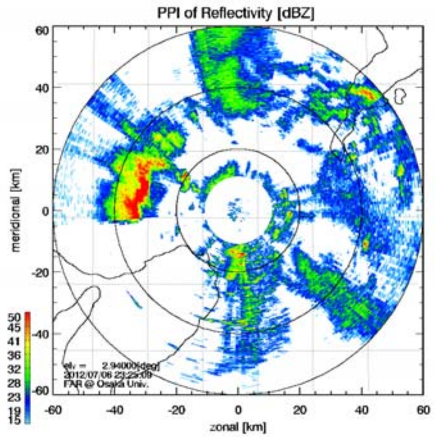
El. 0.97°



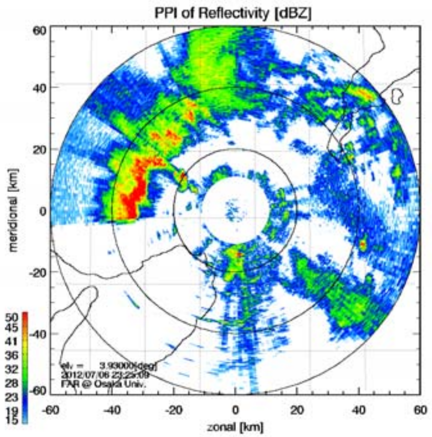
El. 1.97°



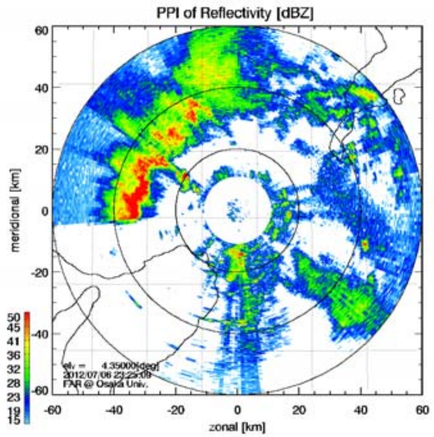
El. 2.94°



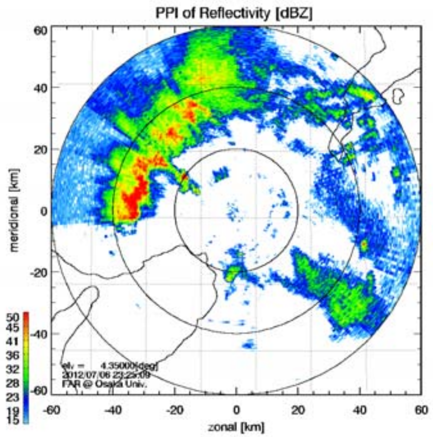
El. 3.93°



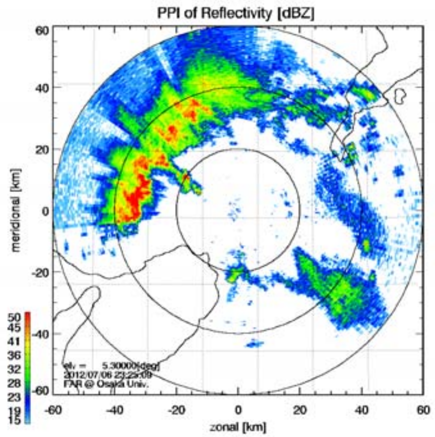
El. 4.35°



El. 4.35°



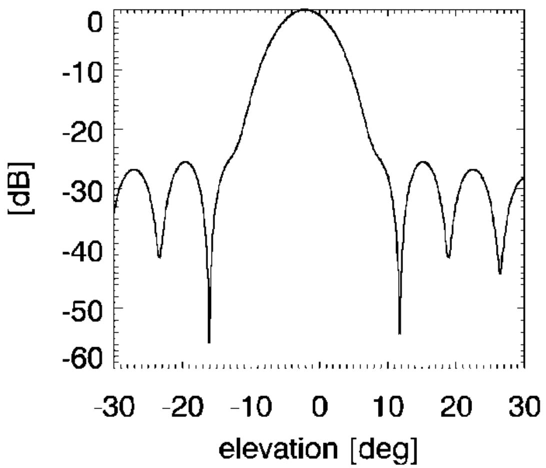
El. 5.30°



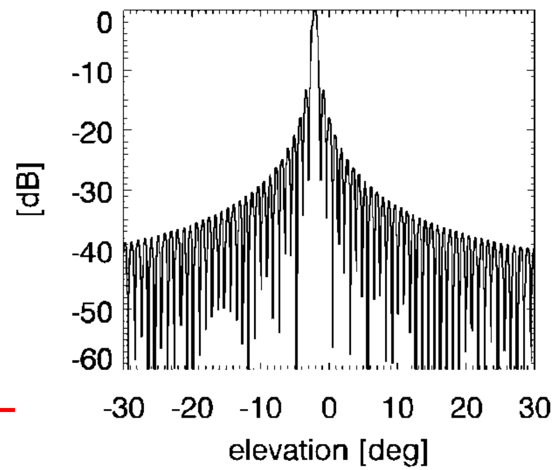
Problem

2-way beam pattern is poor

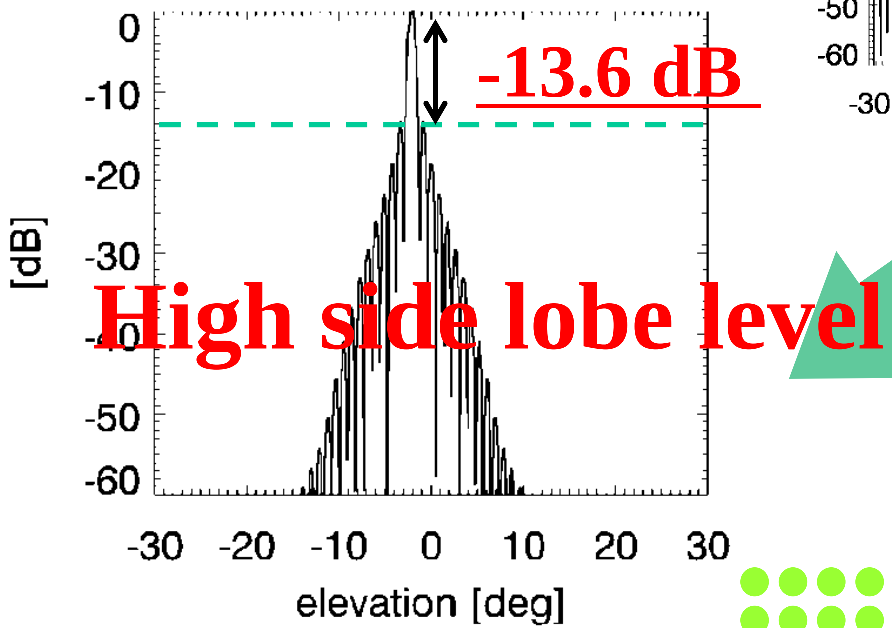
Fan beam pattern for transmitting



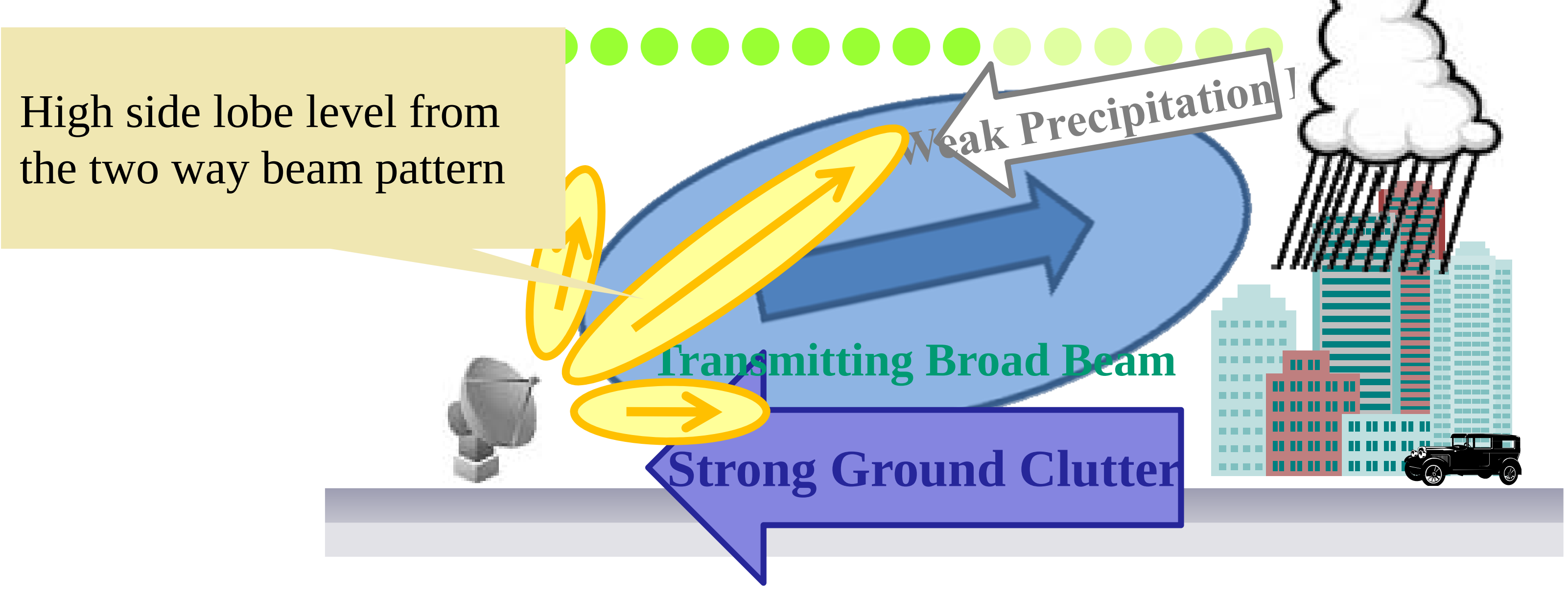
Receiving beam pattern by uniform phase shift



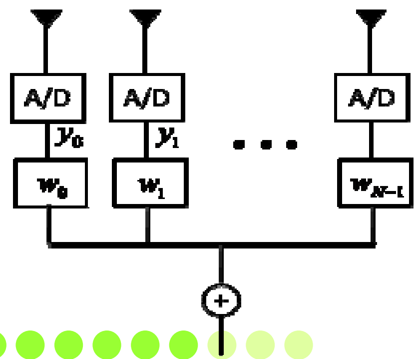
2-way beam pattern



Masking Problem



The received signal from precipitation will be seriously contaminated by the relatively high received power from ground clutter and strong precipitation echoes near by through the side lobes of the 2 way beam pattern.



In order to mitigate this problem, the best weighting factors at each antenna elements are required.
In this research a beam forming technique using the MMSE (Minimum Mean Square Error) formulation has been proposed and tested. This approach can adaptively mitigate the masking interference that results from the standard digital beam forming method in the vicinity of ground clutter and strong precipitation area

MMSE Beam Forming

MMSE cost function and solution

$$J_m = \min_{\mathbf{w}_{MMSE\,m}} \left[E\left[\left| x_{m,l} - \mathbf{w}_{MMSE\,m}^H \mathbf{y}_l \right|^2 \right] \right]$$

$$\Leftrightarrow \mathbf{w}_{MMSE\,m} = E[|\boxed{x(\theta_m)}|^2](\mathbf{S}\boxed{\mathbf{R}_x}\mathbf{S}^H + \mathbf{R}_v)^{-1}\mathbf{s}(\theta_m)$$

$\boxed{\mathbf{R}_x = E\left[\mathbf{x}_l \mathbf{x}_l^H\right] \approx \left[\frac{1}{L}\sum_{l=1}^{L} \mathbf{x}_l \mathbf{x}_l^H\right] * \mathbf{I}_{M\times M} \quad \text{: covariance matrix of } \mathbf{x}}$

$\mathbf{R}_v = E\left[\mathbf{v}_l \mathbf{v}_l^H\right] = \sigma_v \mathbf{I}_{M\times M}$: noise covariance matrix,

σ_v : standard deviation of thermal noise,

$E[\bullet]$: expectation, $\quad *$: Hadamard product

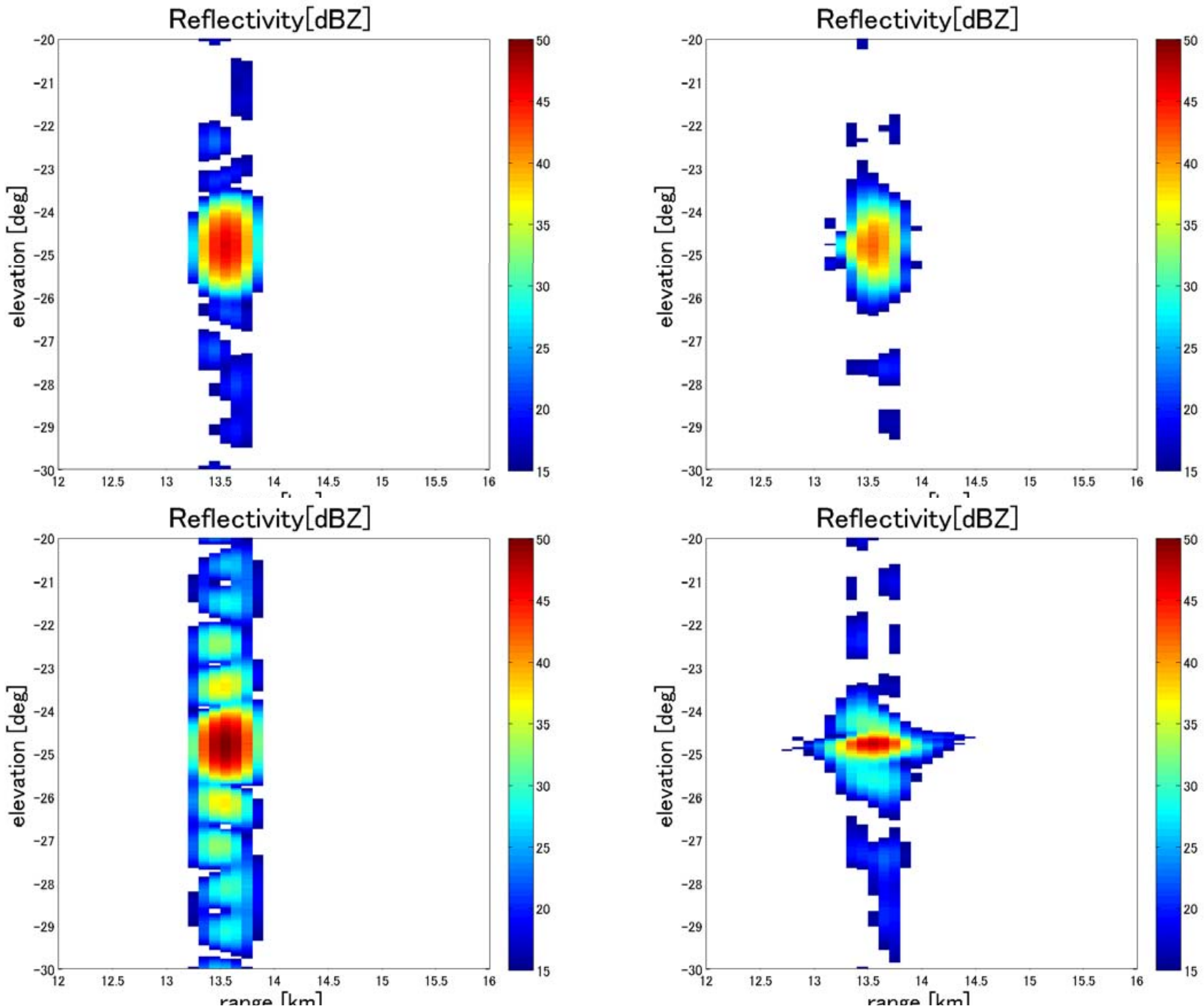
Echo from Airplane

2013/10/17
15:46:38
(Sunny)

BF | MMSE

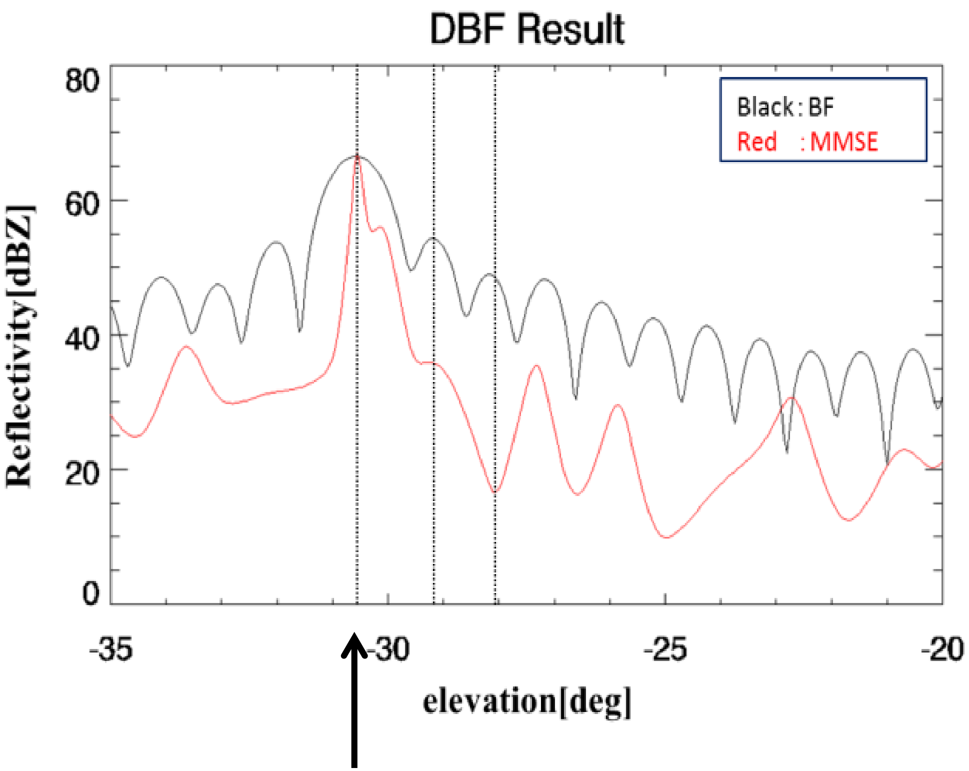
With Taylor Weight

Without Taylor Weight

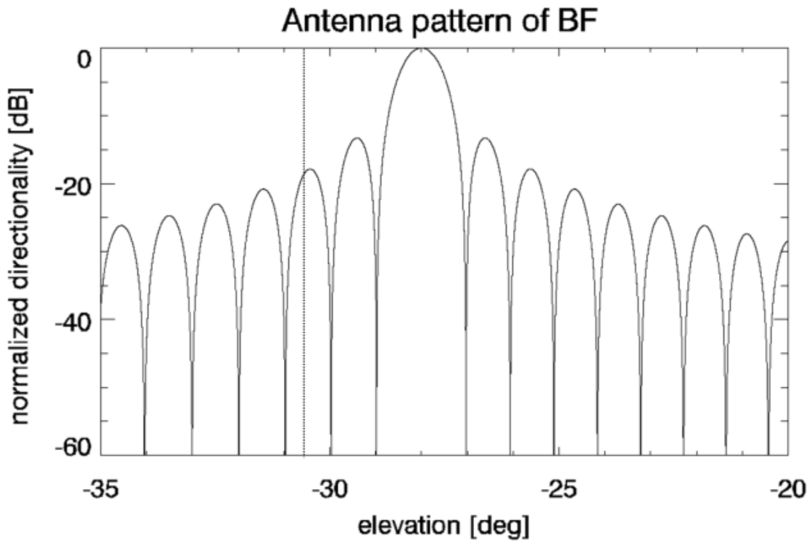


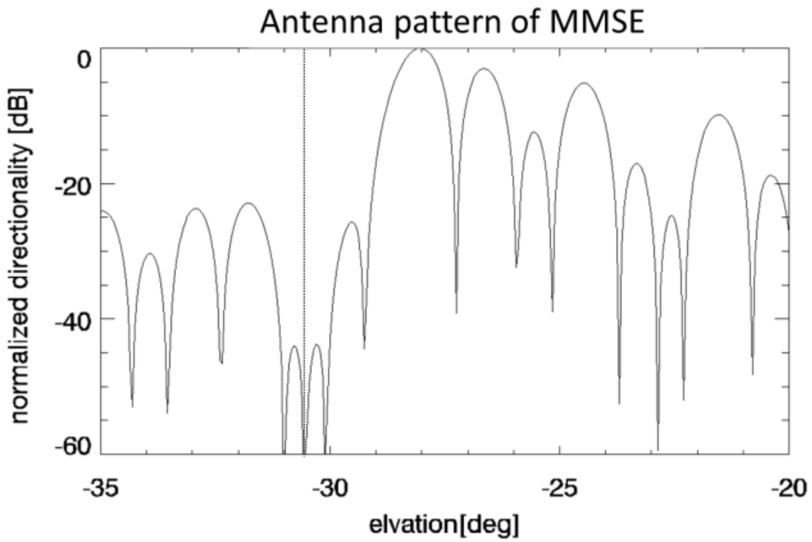
Reprocessing with MMSE

2013/01/31
15:21 (Sunny)
azimuth : 221.9deg， distance : 2.7km



Elevation 0 degree





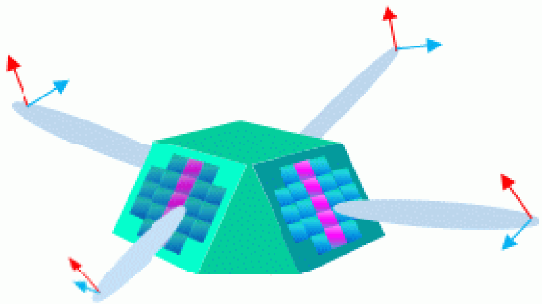
DEVELOPMENT OF THE POLARIMETRIC PHASED ARRAY RADAR SYSTEM

Dual-polarized PAR:

Vertical polarization

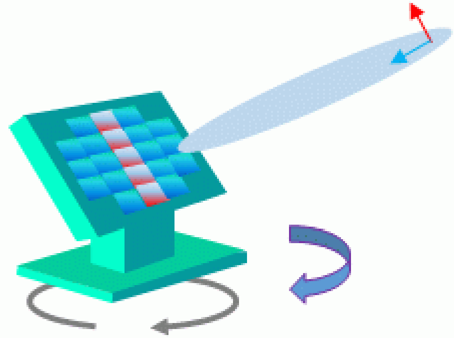
Horizontal polarization

Planar PAR (PPAR)



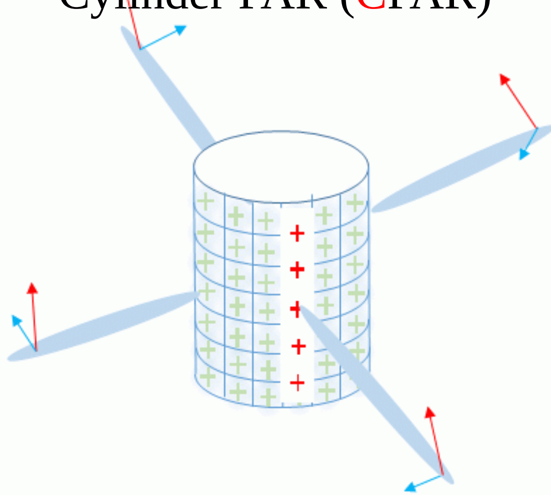
- 2-D Planar arrays with four faces
- Electrical scanning in elevation
  Electrical scanning in azimuth
- Tilted angle is set

Scanning PAR (SPAR)



- 2-D planar arrays antenna
- Electrical scanning in elevation
  Mechanical scanning in azimuth
- Tilted angle is set

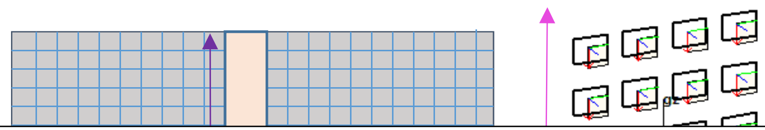
Cylinder PAR (CPAR)



- Cylinder arrays antenna
- Observation by shifting the column of active elements
- Four simultaneous beams

(Zhang et al., 2000)

Set parameters for PAR



Set

Set

Ca
fu
ch
p

parameter	value
Transmitting frequency	9.4[GHz]
Number of elements in radiation channel	92*4
Number of elements in reception channel	92*92
Spacings of array elements	16[mm]
Pulse repetition frequency	5.4[kHz]
Pulse number	256
Angle resolution	Every 2 degree

Parameters set for PAR

request

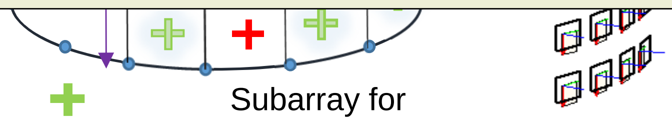
X band

Fan beam width: below 24.4°
Narrow beam width: below 1.43°

beam width: below 1.43°

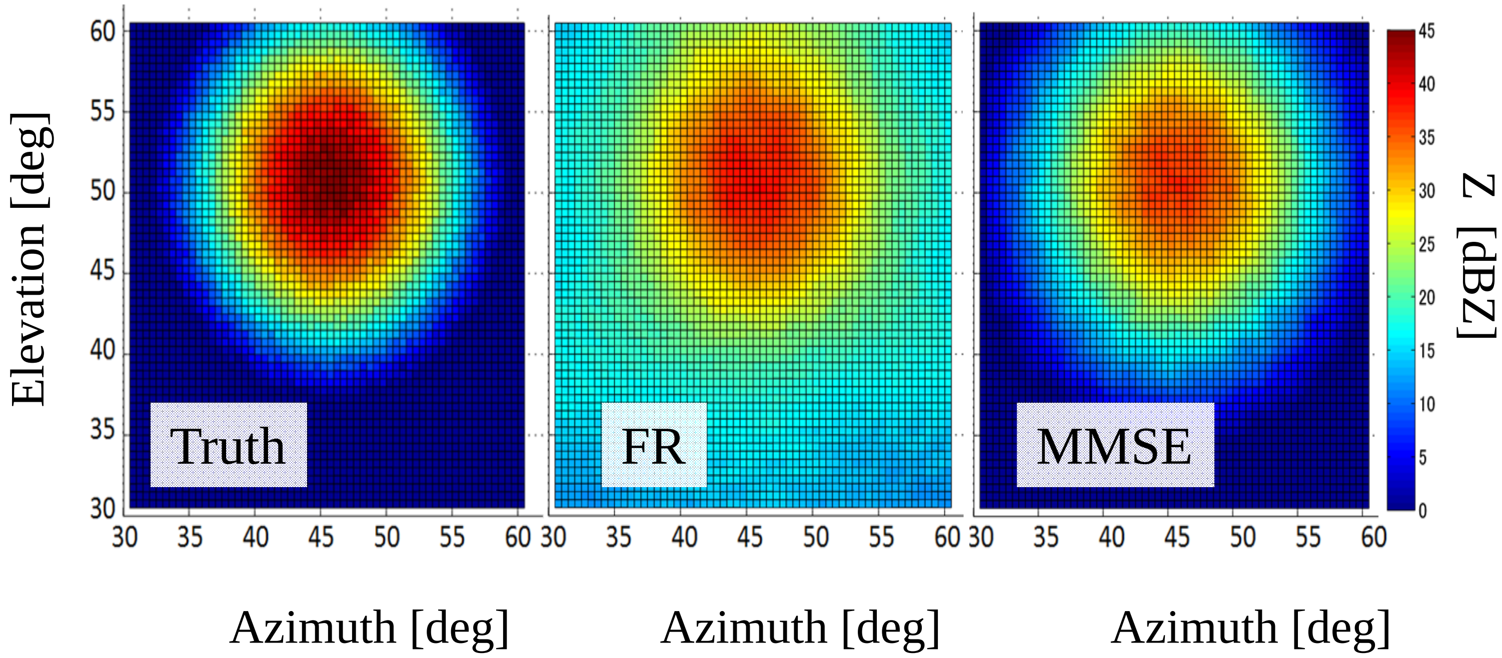
Avoid grating lobe

p
pe
with
p

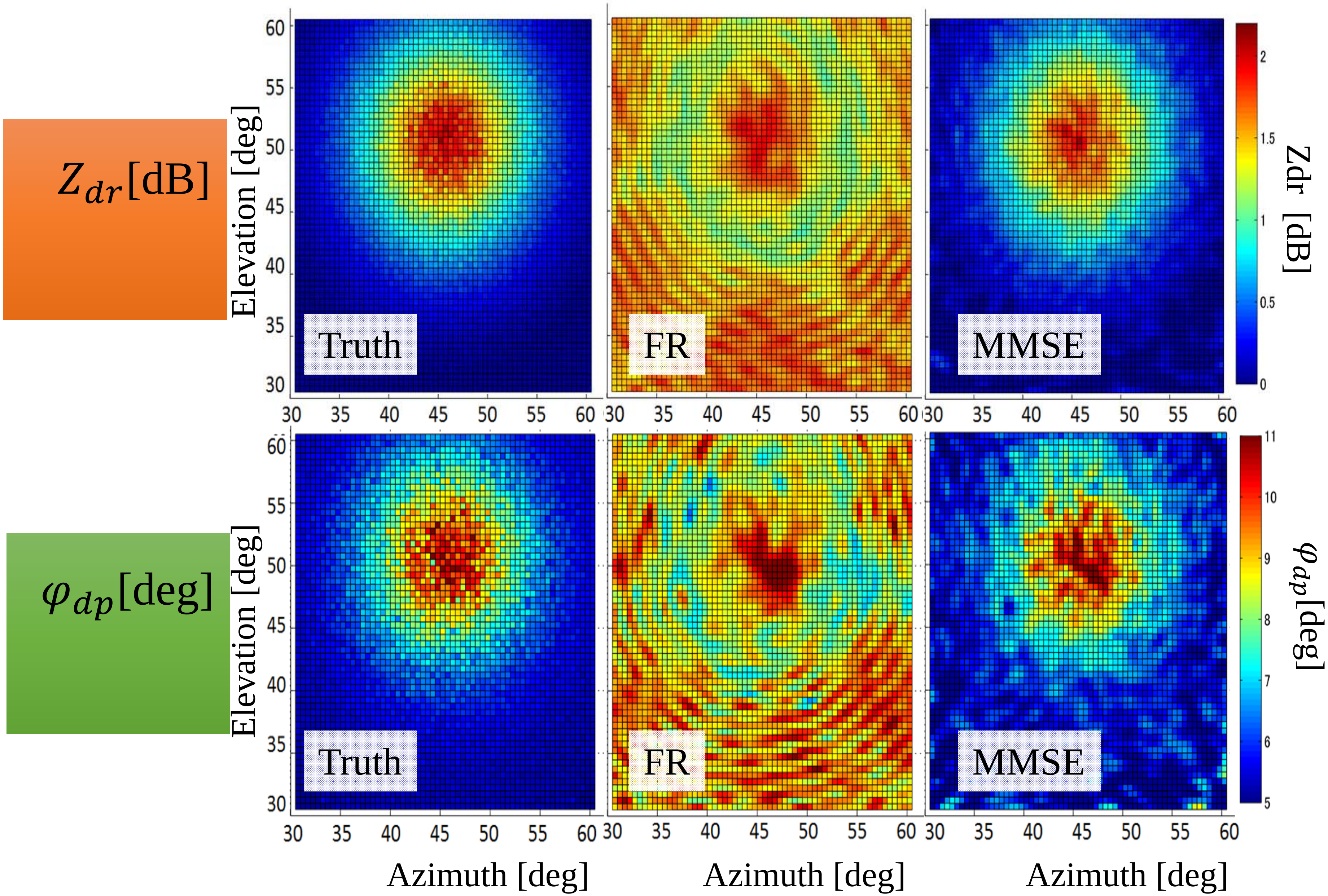


Antenna geometry for CPAR

Digital Beam Forming on the MP PAR



Digital Beam Forming on the MP PAR



Summary

- A new Phased Array Radar at X band was developed by Osaka University and Toshiba corporation under the grant of NICT.
- An initial observation results show the unique capability of the radar system.
- Comparison with other radar system and disdrometer shows a fairly good agreement in reflectivity.
- Osaka Phased Array Radar and Lightning Experiment Project and MP PAR development is under consideration.