# The MU radar experiment for searching radio echoes from EAS

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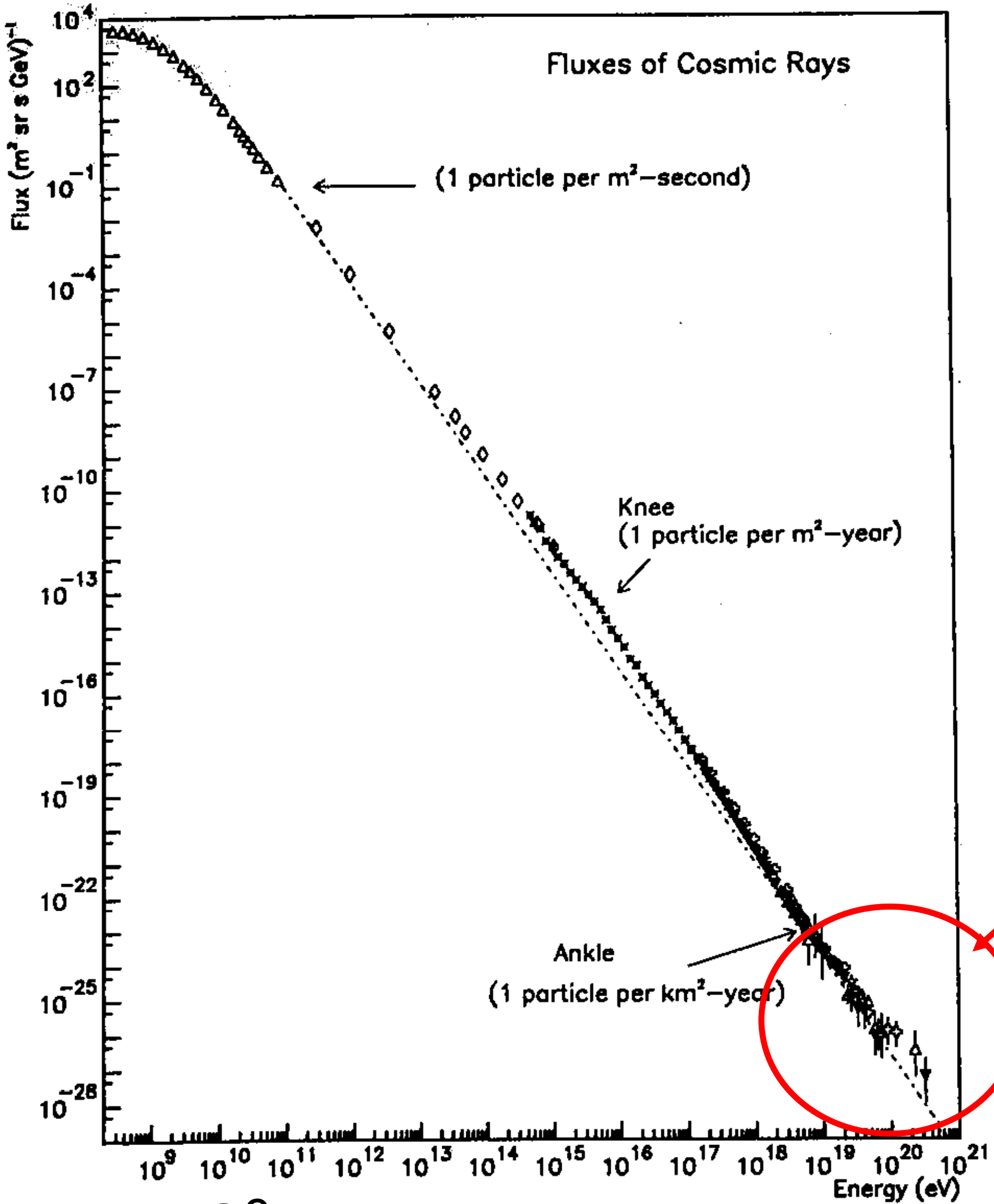
*MU radar, Kyoto Univ. at Shigaraki*

# Contents

Energy spectrum of cosmic rays; extending over 12 orders of energy




↑$10^9$eV

↑$10^{20}$eV

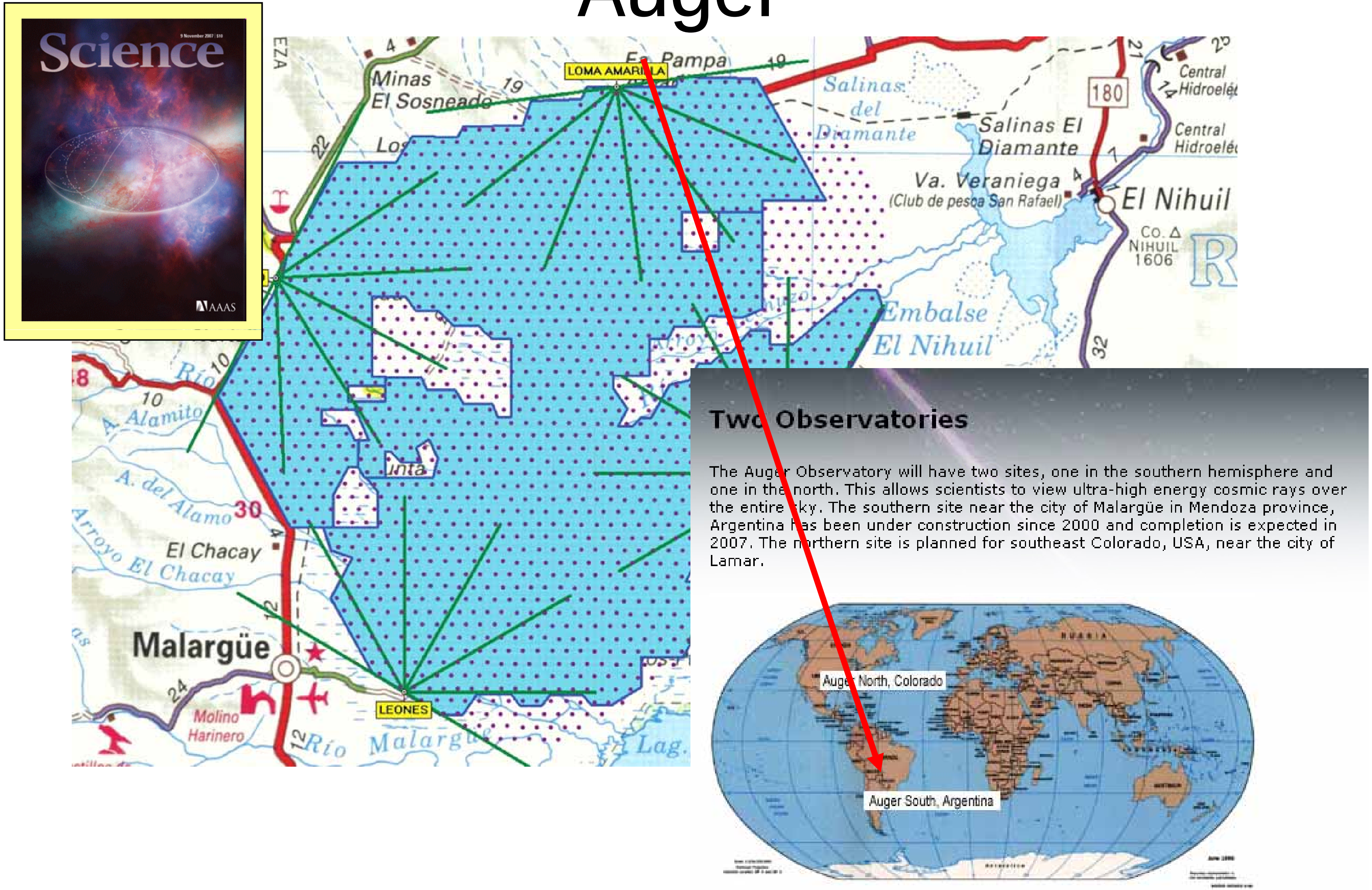
Origin of the ultra high energy cosmic rays (UHECRs) is a long-standing mystery in cosmic ray physics.

Very rare!
$1/1km^2 \cdot$ century!

Effective area 5165 km$^2$

http://www.auger.org/news/PRagn/AGN_correlation_more.html

# Auger




## Two Observatories

The Auger Observatory will have two sites, one in the southern hemisphere and one in the north. This allows scientists to view ultra-high energy cosmic rays over the entire sky. The southern site near the city of Malargüe in Mendoza province, Argentina has been under construction since 2000 and completion is expected in 2007. The northern site is planned for southeast Colorado, USA, near the city of Lamar.

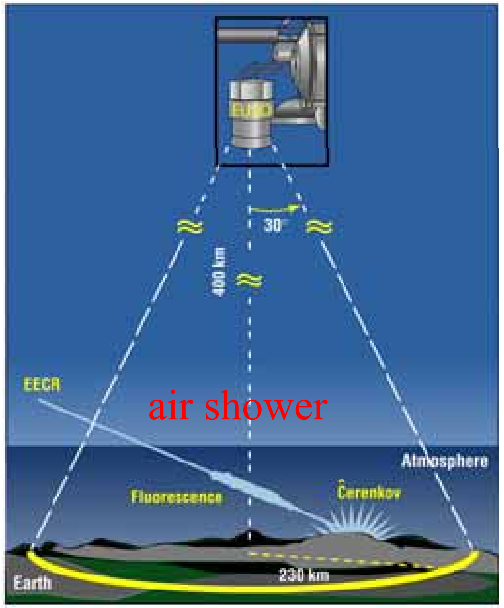


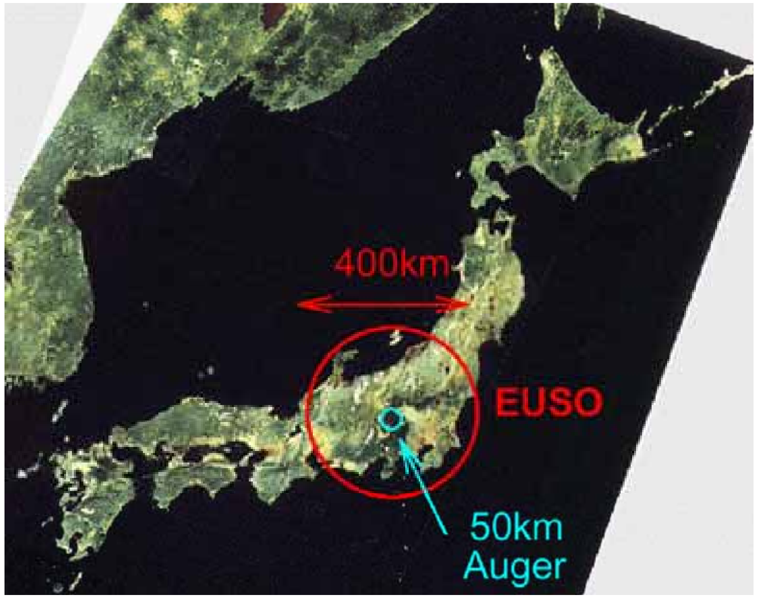
Now Pierre Auger Observatory is counting ~50 UHECRs in a year.

But we need more UHECRs.

....several thousands UHECRs are desirable for astrophysical study

Possible (expensive!) answer: *Extreme Universe Space Observatory (EUSO)*




→ Possible ground-based alternative:

Radio technique for UHECR detection

Passive technique ... detection of geo-synchrotron emission

detection of molecular Bremsstrahlung emission

...

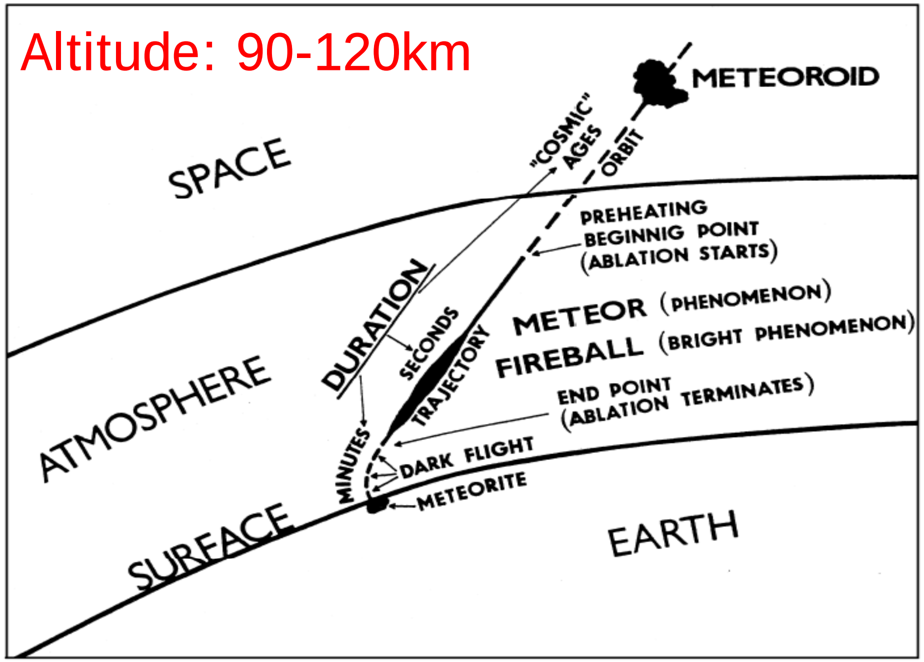
Active technique ... radar detection of echoes from UHECR air showers

## Similarity between meteors and cosmic rays (1)

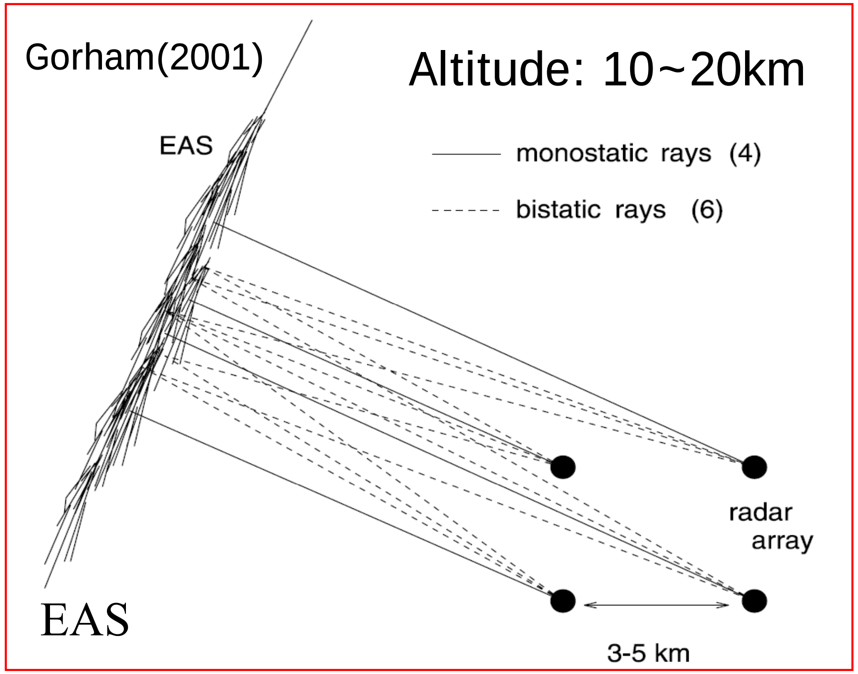
'Dust from beyond the solar system', Nature 380, 283 (1996)

Meteors and cosmic rays are both coming from extraterrestrial space.

# Similarity between meteors and cosmic rays (2)




$>10^{17}\sim10^{18}$eV



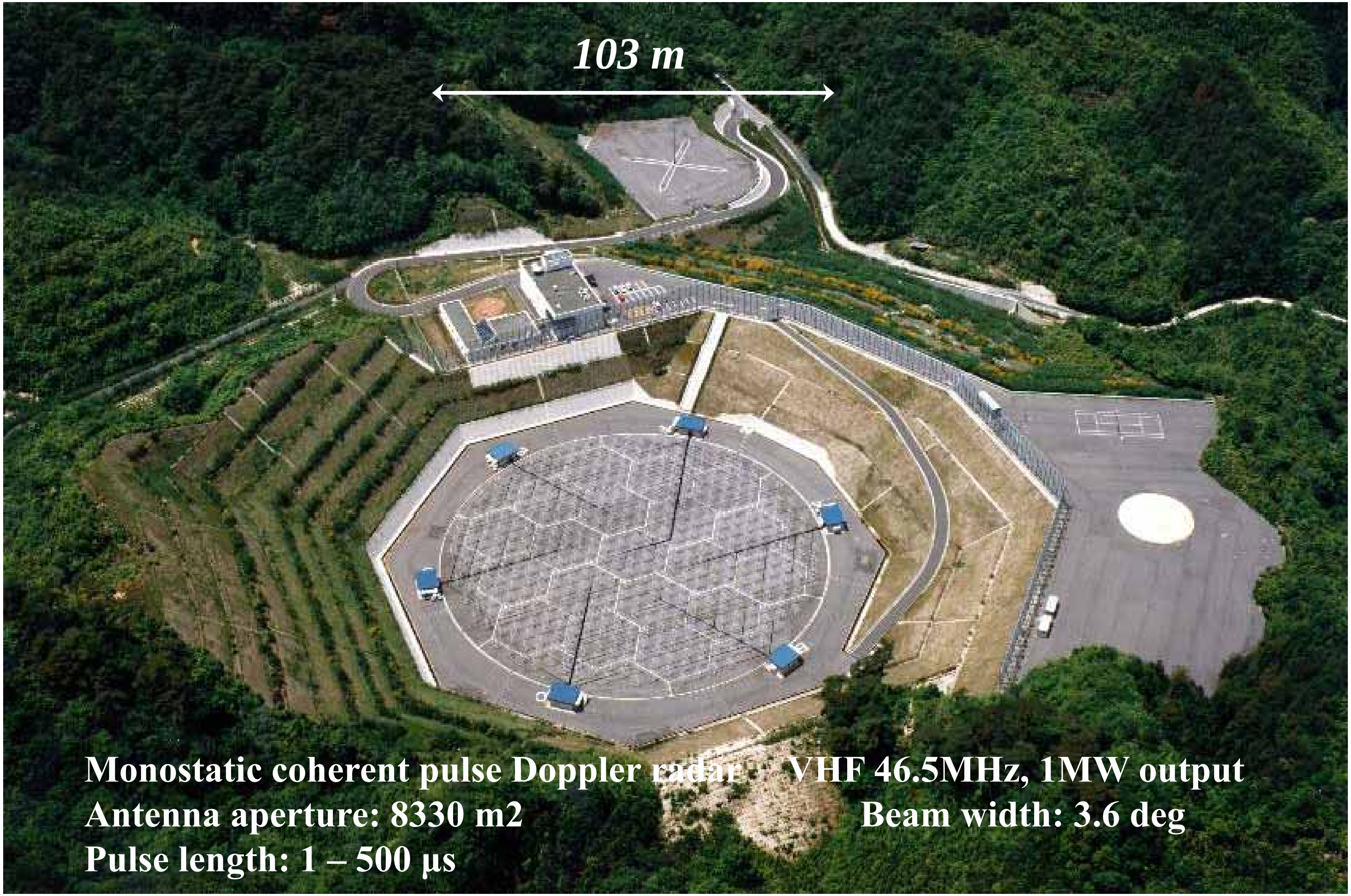

Dusts of several mm size vs. elementary particles

Similarity in total energy (several hundredths J ~ several J) → Similar-sized ionization column in the atmosphere

Since the radar detection of meteors is an established technique, we should be able to apply the radar technique to cosmic ray detection.

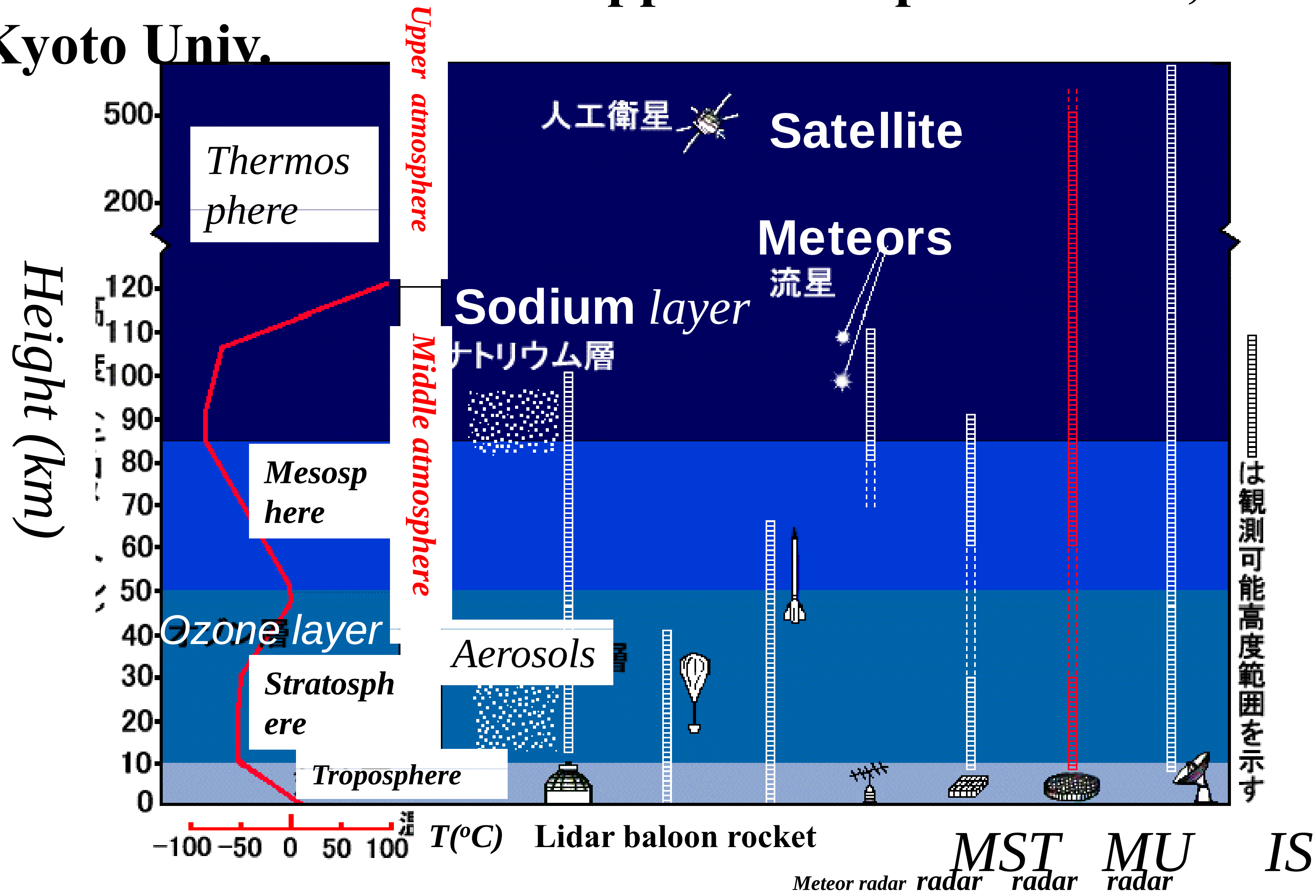
# What is the MU radar?

# MU radar (middle and upper atmosphere radar) since 1984

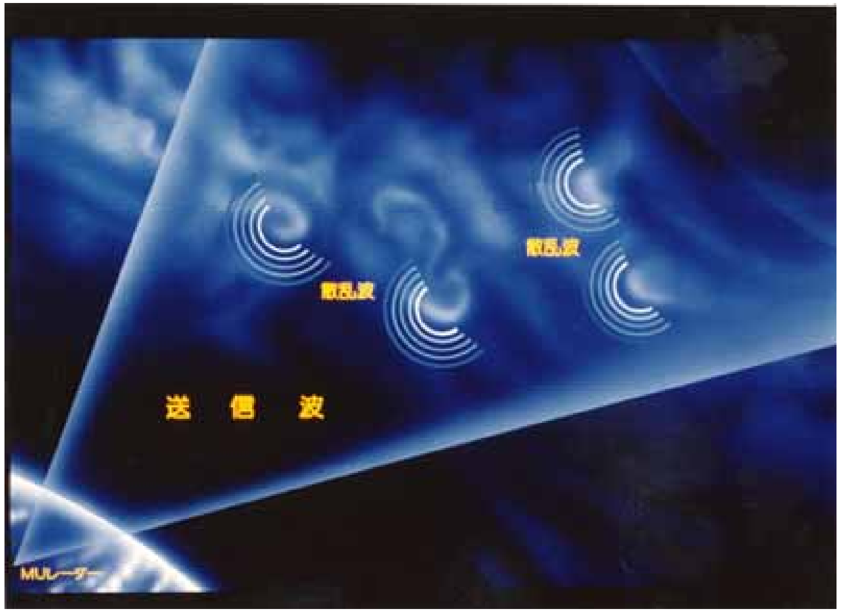


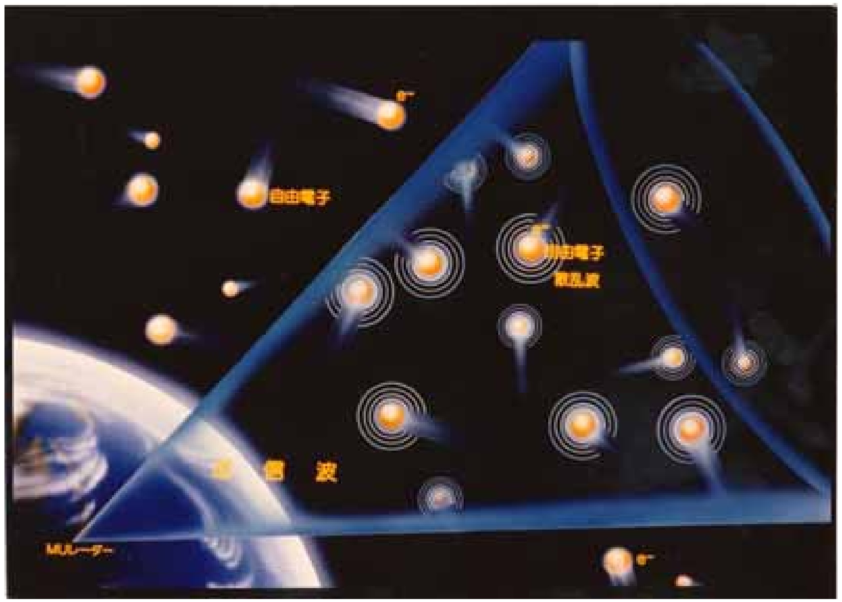
# Observation height of the MU radar

**MU radar: Middle and Upper Atmosphere radar, RISH, Kyoto Univ.**



# Target of atmospheric radar




**Atmospheric radar: Coherent scatter echo**

**perturbation of refractive index (humidity, density, electron density) due to turbulence**

**T～0.1s**

**Incoherent scatter echo**

**Ionospheric electrons**

**T～1ms**

Φ (δn): ------ turbulence intensity

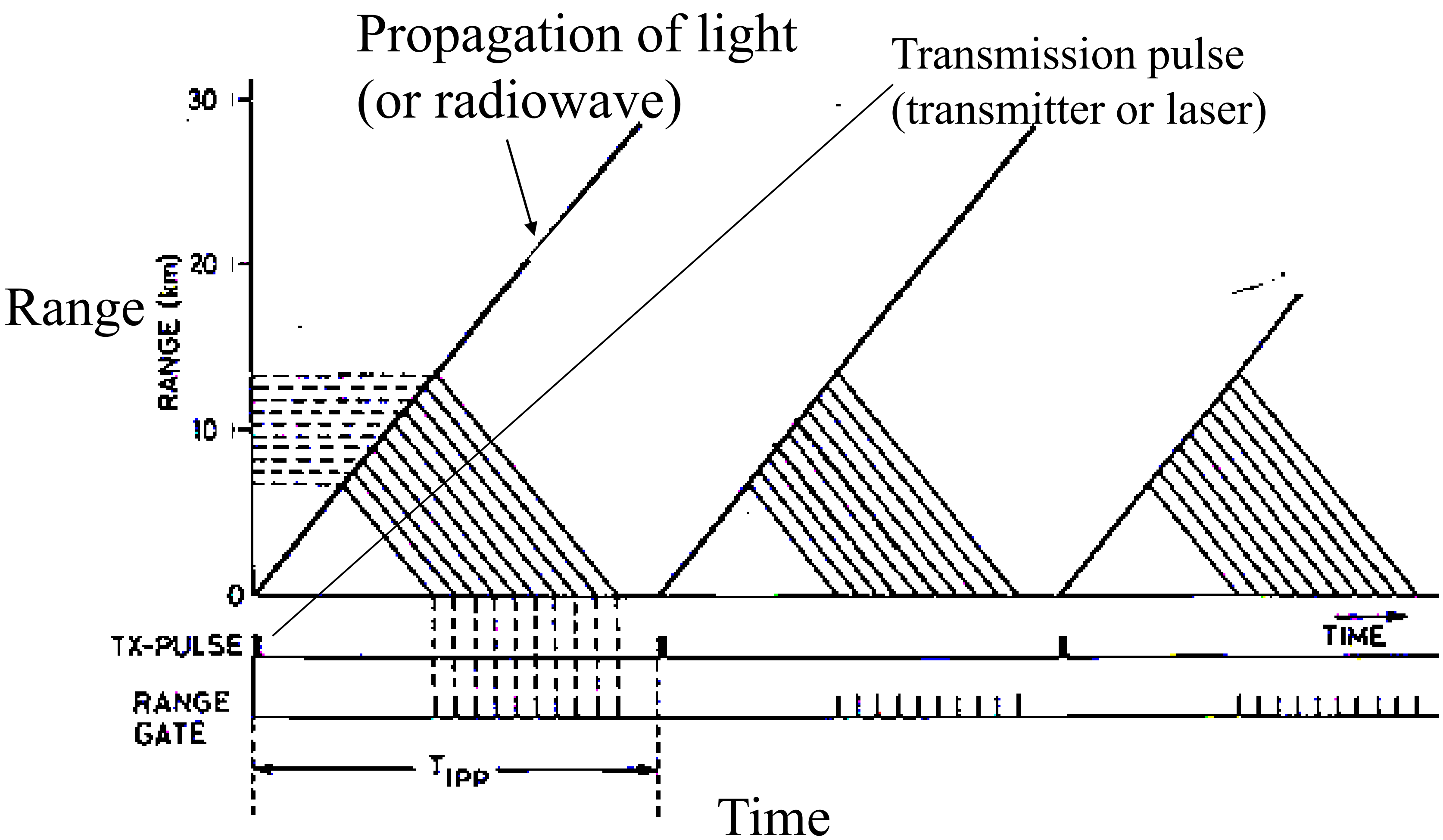
-------dn/dz refractive index gradient

Σ σ: density of very small scatterer

# Characteristics of radar and lidar observation

Measure atmospheric parameters as a function of range

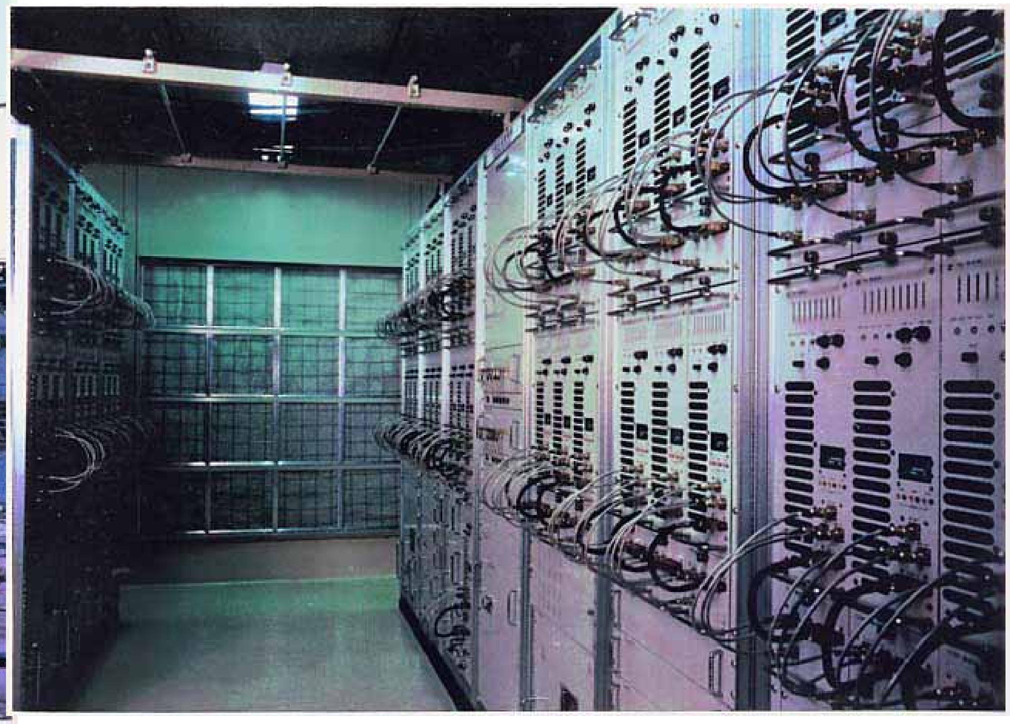
-> very good height resolution can be achieved



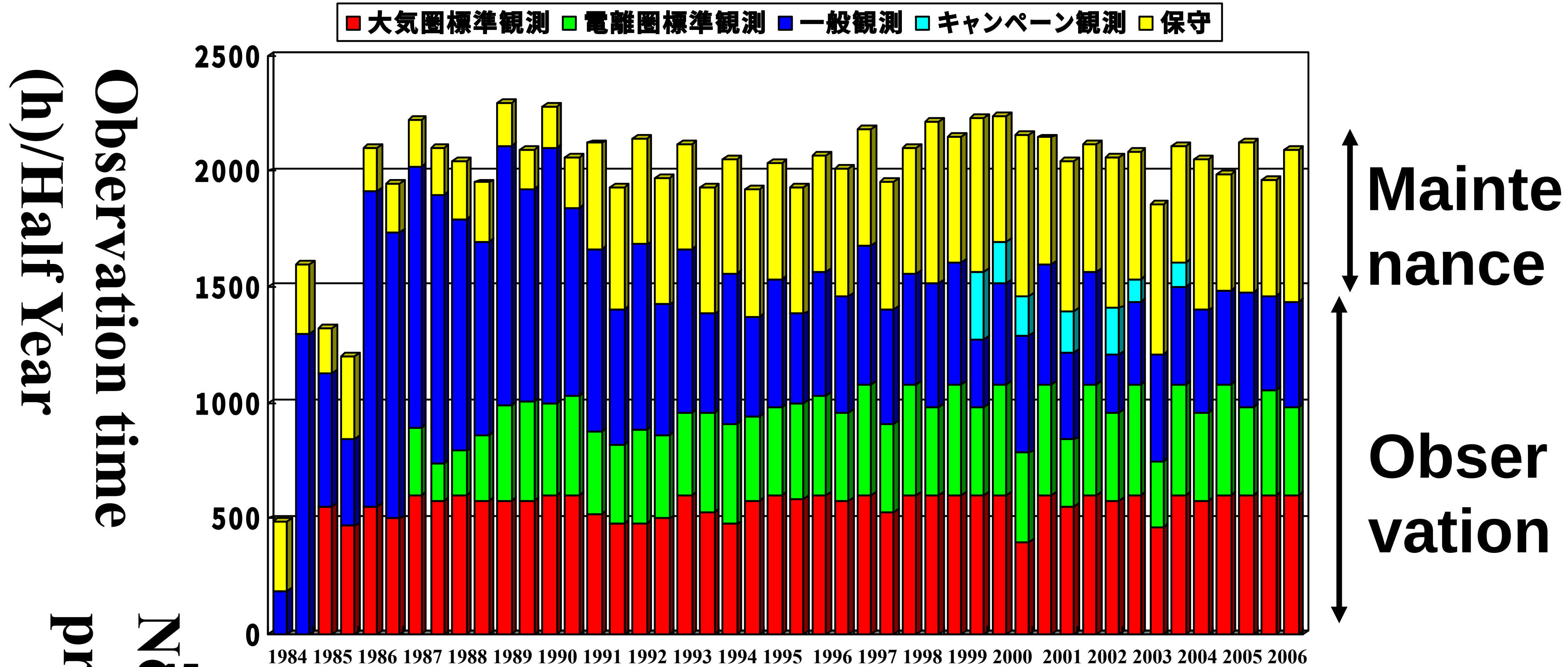
# MU radar (middle and upper atmosphere radar)

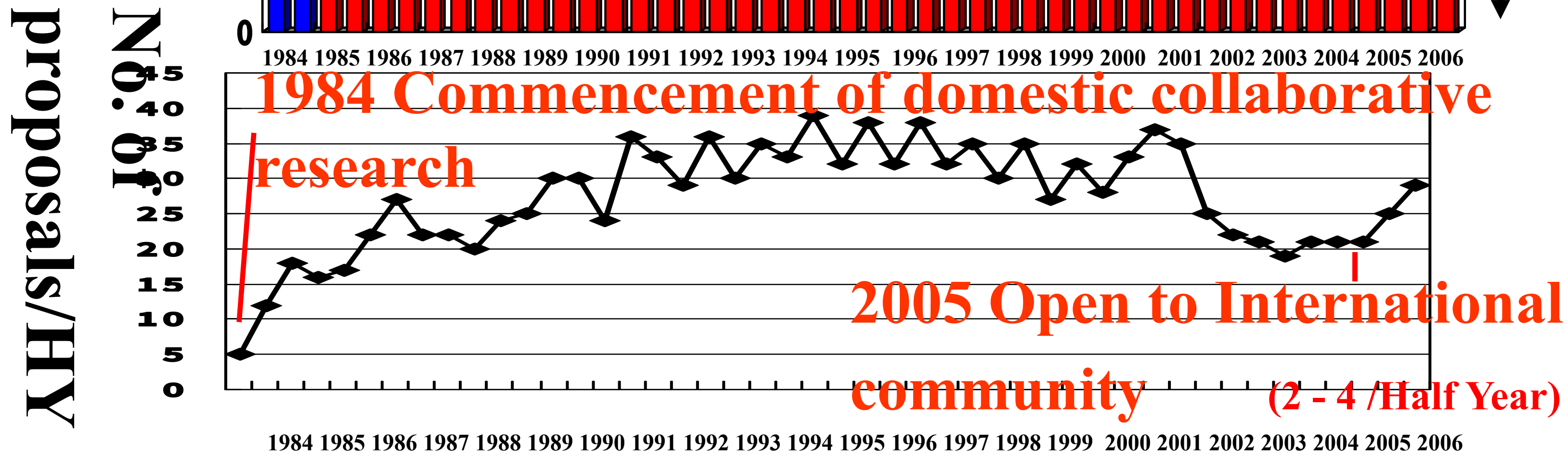
1. **Active phased array antenna (475 Yagis)**
   **beam can be steered pulse by pulse into 1657 directions**
2. **Flexible system design with computer control**
   **Change of observation set-up only takes 10 sec to 1 minute.**

***Most capable atmospheric radar In the world.***

# Machine time of the MU radar
# For collaborative research(1984 - 2006)



# MU radar observation:
## Effect of atmospheric wave on general circulation of the earth's atmosphere

------Role of atmospheric gravity waves-----

Radial wind fluctuation with a southward beam

Yamamoto, 1987.

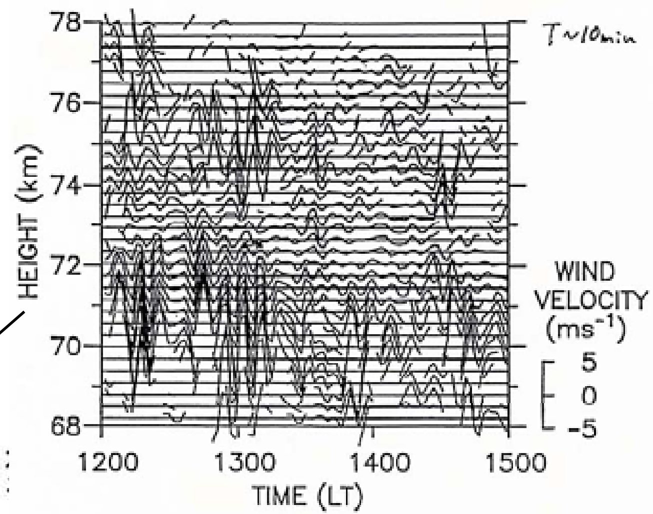



Figure 4.4: Radial wind fluctuations with periods ranging from 6 to 16 min observed in the southward beam on 8 February 1985.

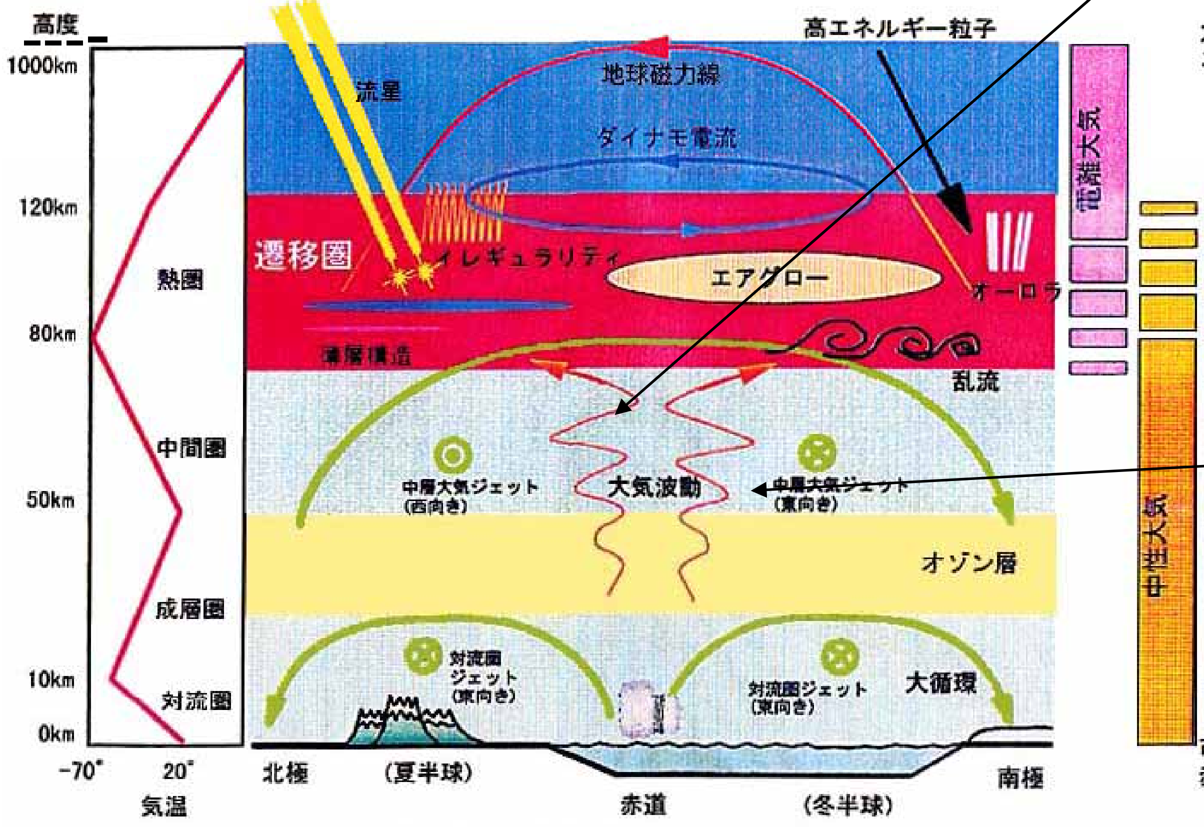
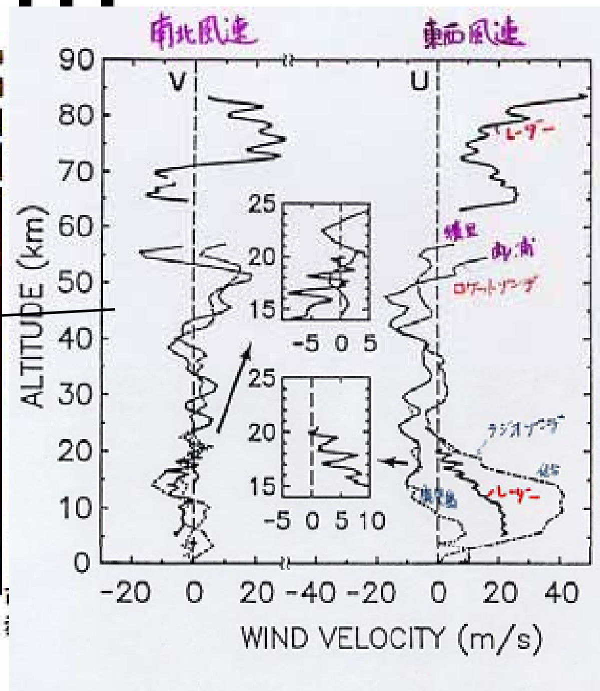
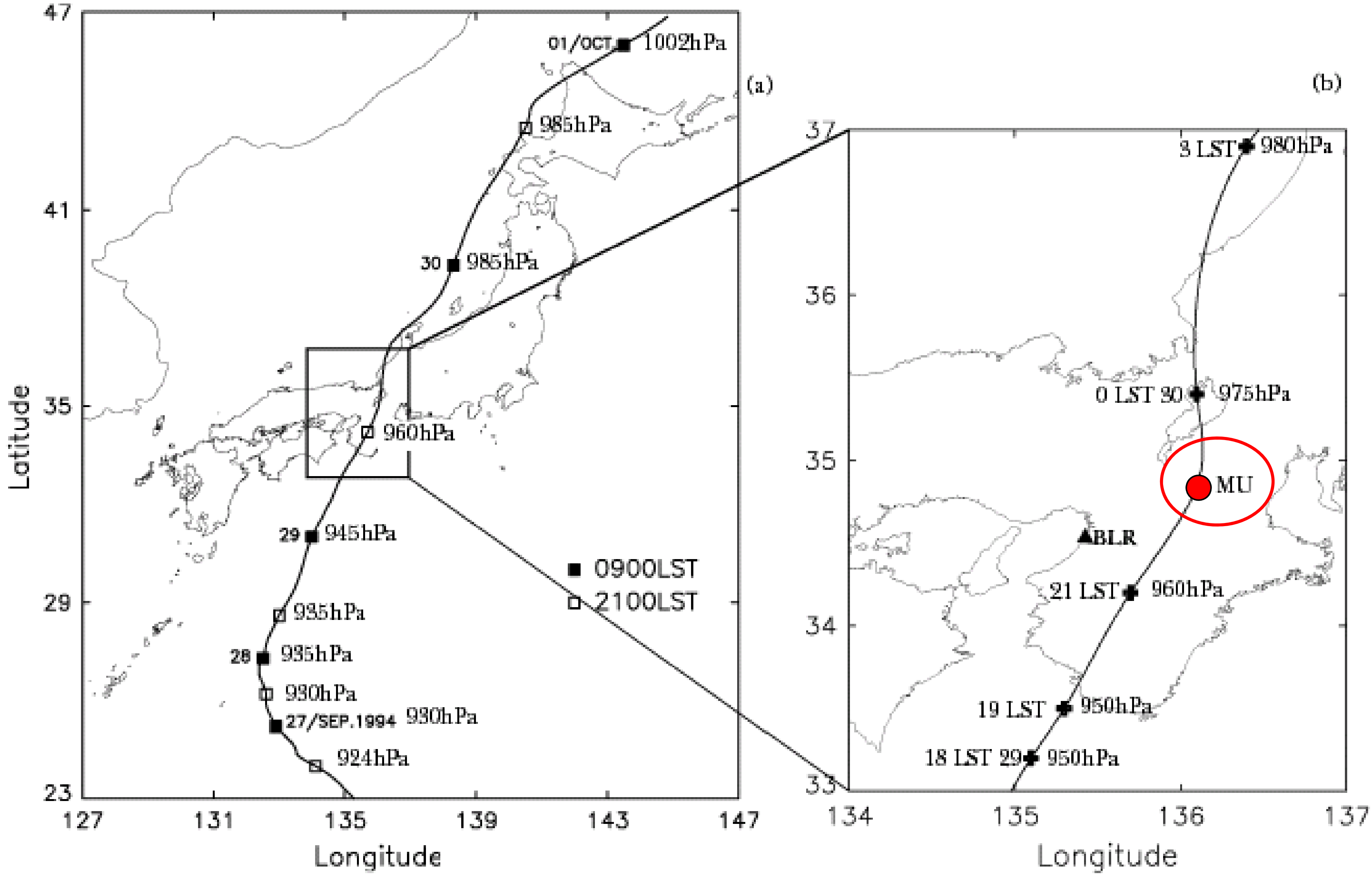



図3 本研究の対象となる地球大気遷移圏の概念図

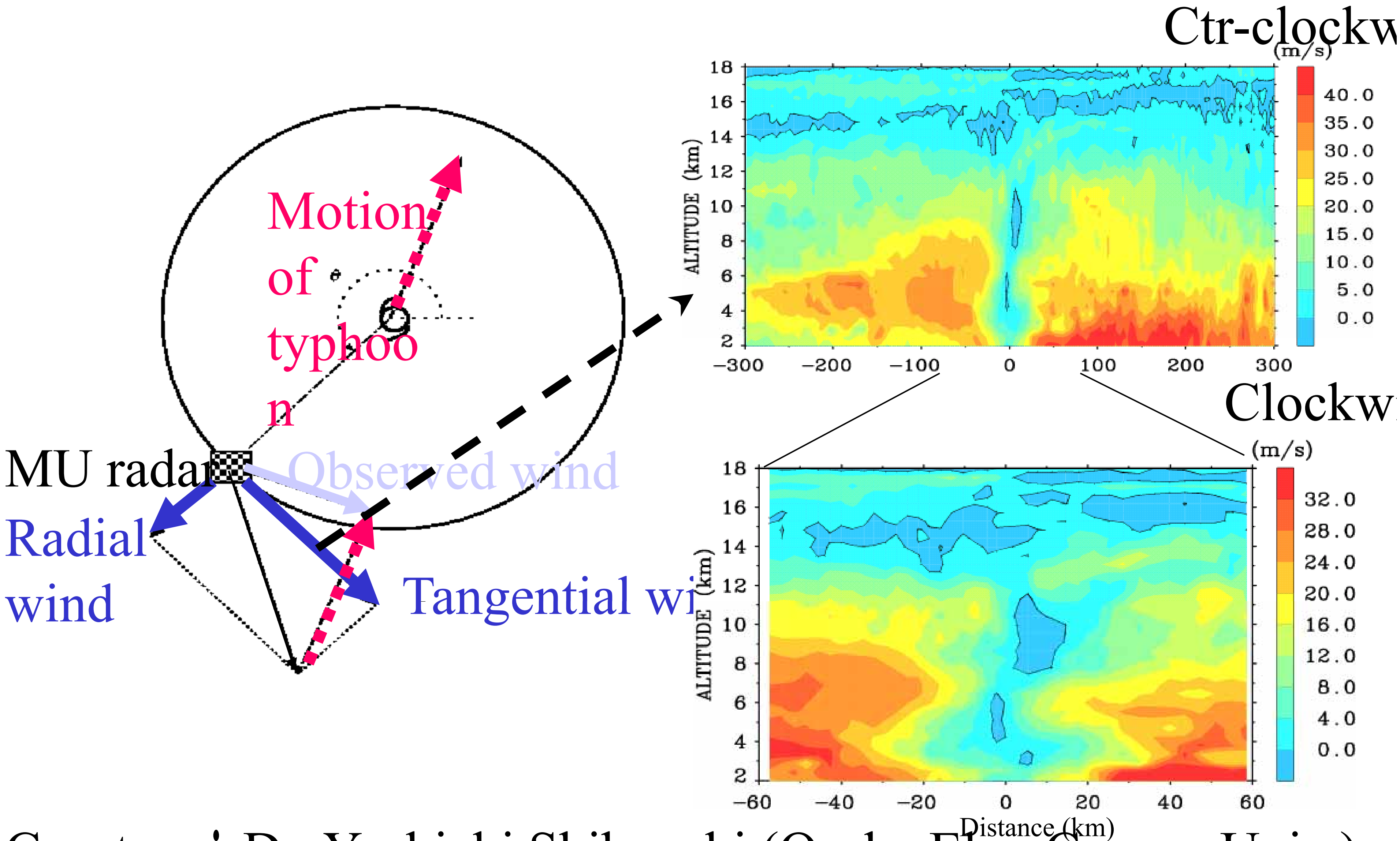


# Observation of typhoon (9426 typhoon：Orchid)




Courtesy：Dr. Yoshiaki Shibagaki (Osaka Elec-Comm. Univ.)

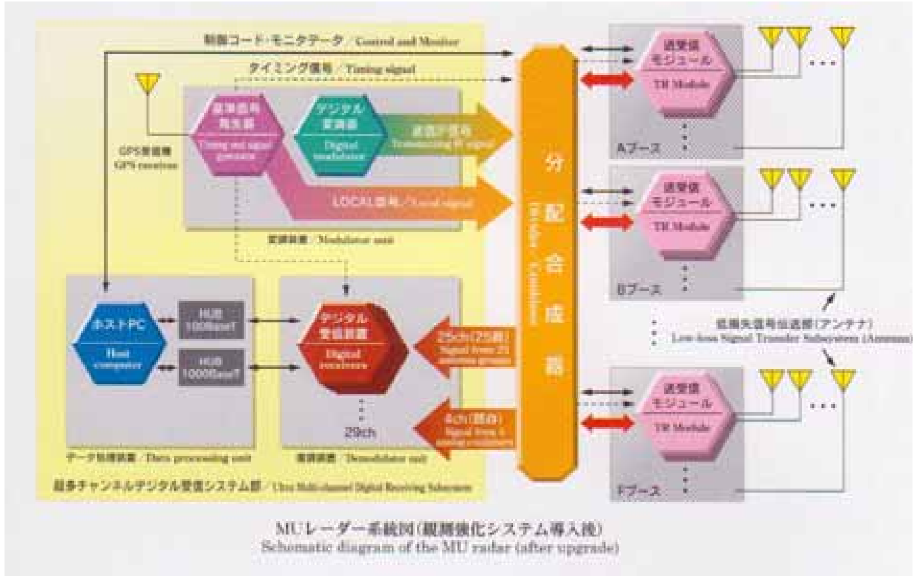
# Cross section of tangential wind around the Typhoon 9426

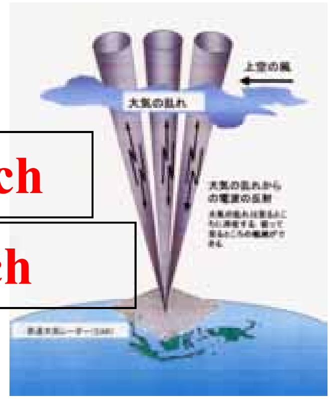



Courtesy：Dr. Yoshiaki Shibagaki (Osaka Elec-Comm. Univ.)

# The upgraded MU radar system (in 2004)

# Upgrade of the MU radar (2004)



Limited 4 ch

Full 4ch

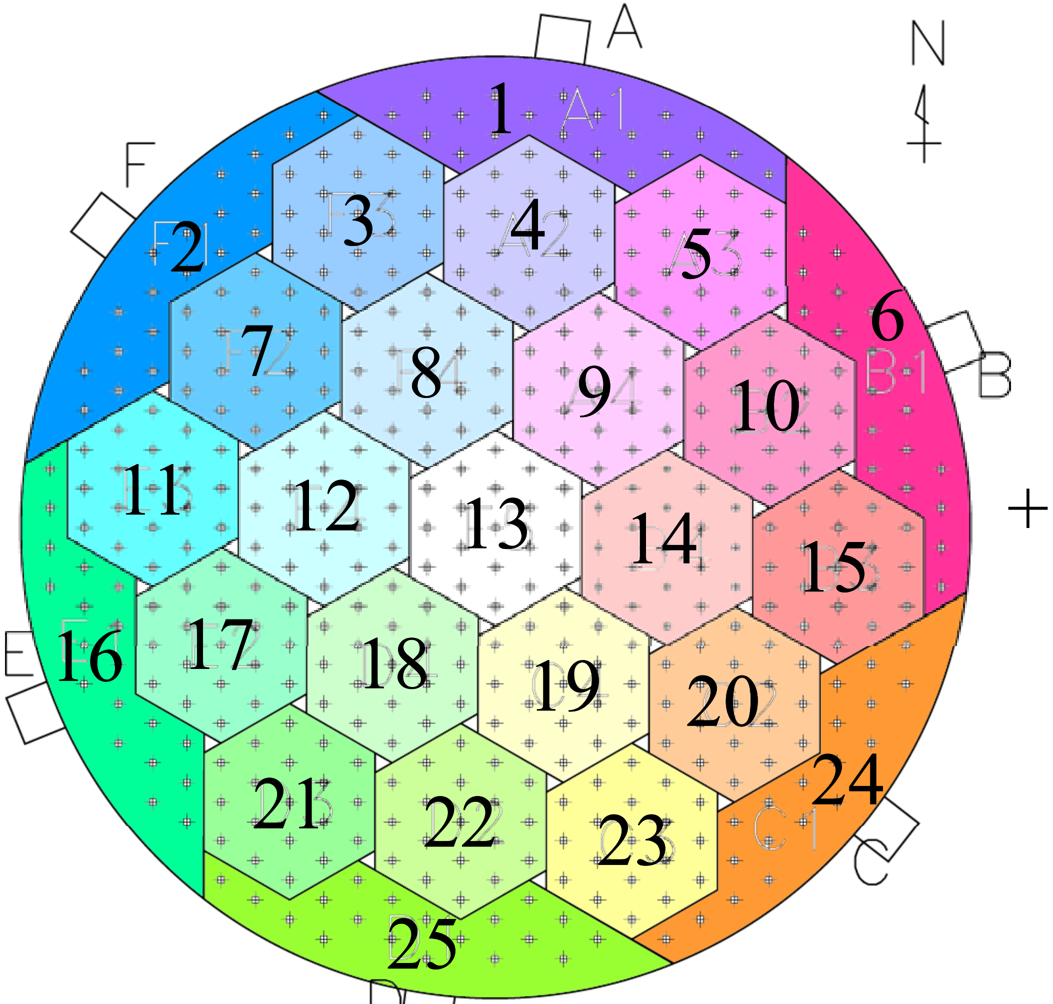
Digital 29 ch

**1984 MU radar installed.**
**1994 Upgrade of data taking system**
**1997 2000 Minor upgrades**
**(2001 Equatorial Atmosphere Radar in Indonesia)**
**2004 MU ultra-multichannel digital receiver system**
**frequency**

*IT-radar system*

**2005 International collaborative research**
**(2-4 proposals/HY)**

# Ultra-multichannel digital receiver sysrem of the MU radar



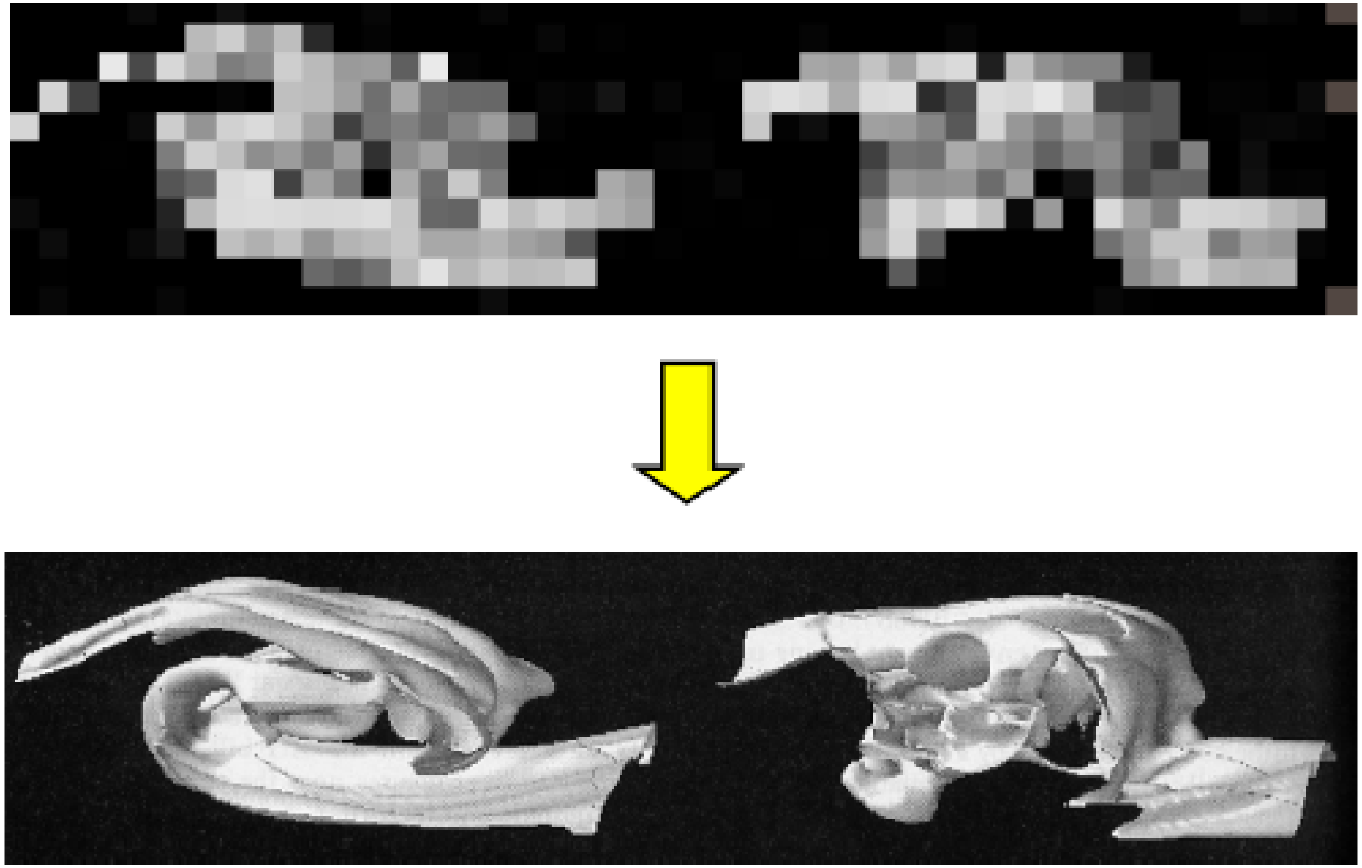

5 frequency
(from 46 – 47MHz)
Transmission and
Reception

Frequency domain interferometer for imaging in radial direction (z)

Spatial domain interferometer , imaging in transversal direction (x,y)

# New MU radar system is an imaging radar system

Detailed structure of turbulence layers is one of the research target



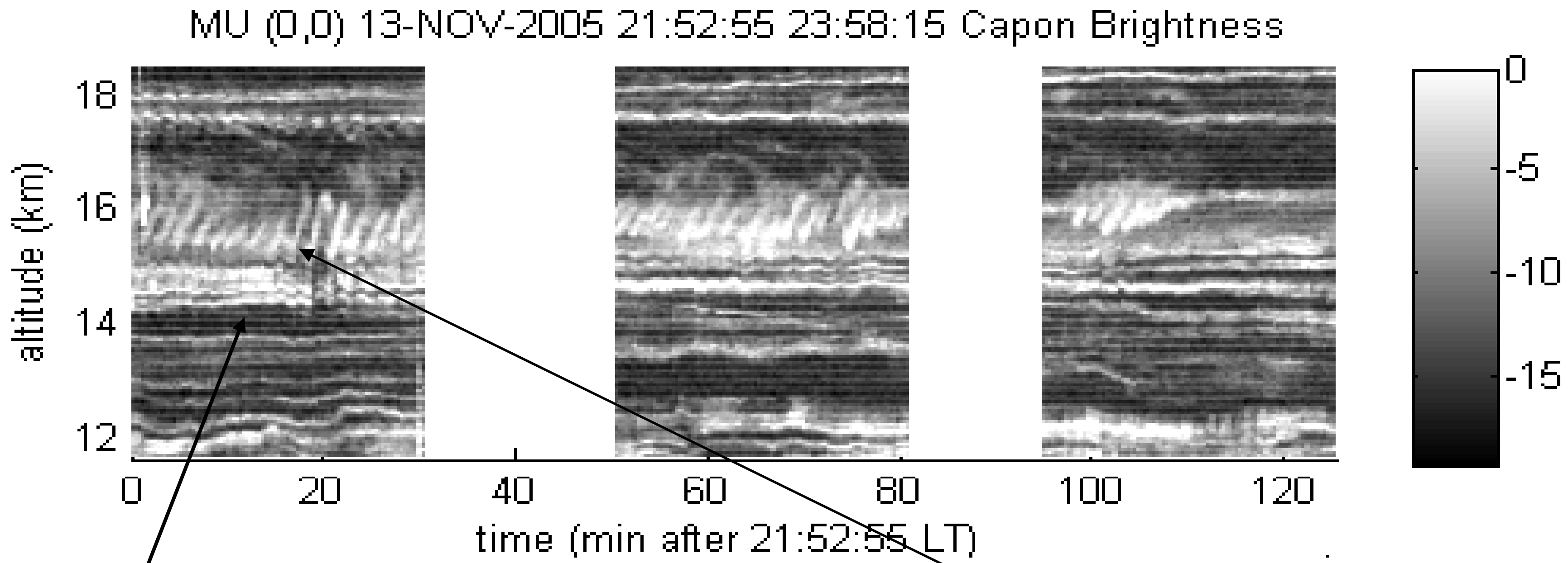
# Application of MU radar new system：

## Frequency Interferometer Imaging (Dr. H. Luce, LSEET-LEPI, France)

**Stable sheets and Turbulent structures by the range imaging**

Time resolution: *32.77 s*
After Capon processing

**物質輸送を司り大気環境変化の鍵を握る乱流等大気の微細構造の観測研究**




Thin layers are better resolved

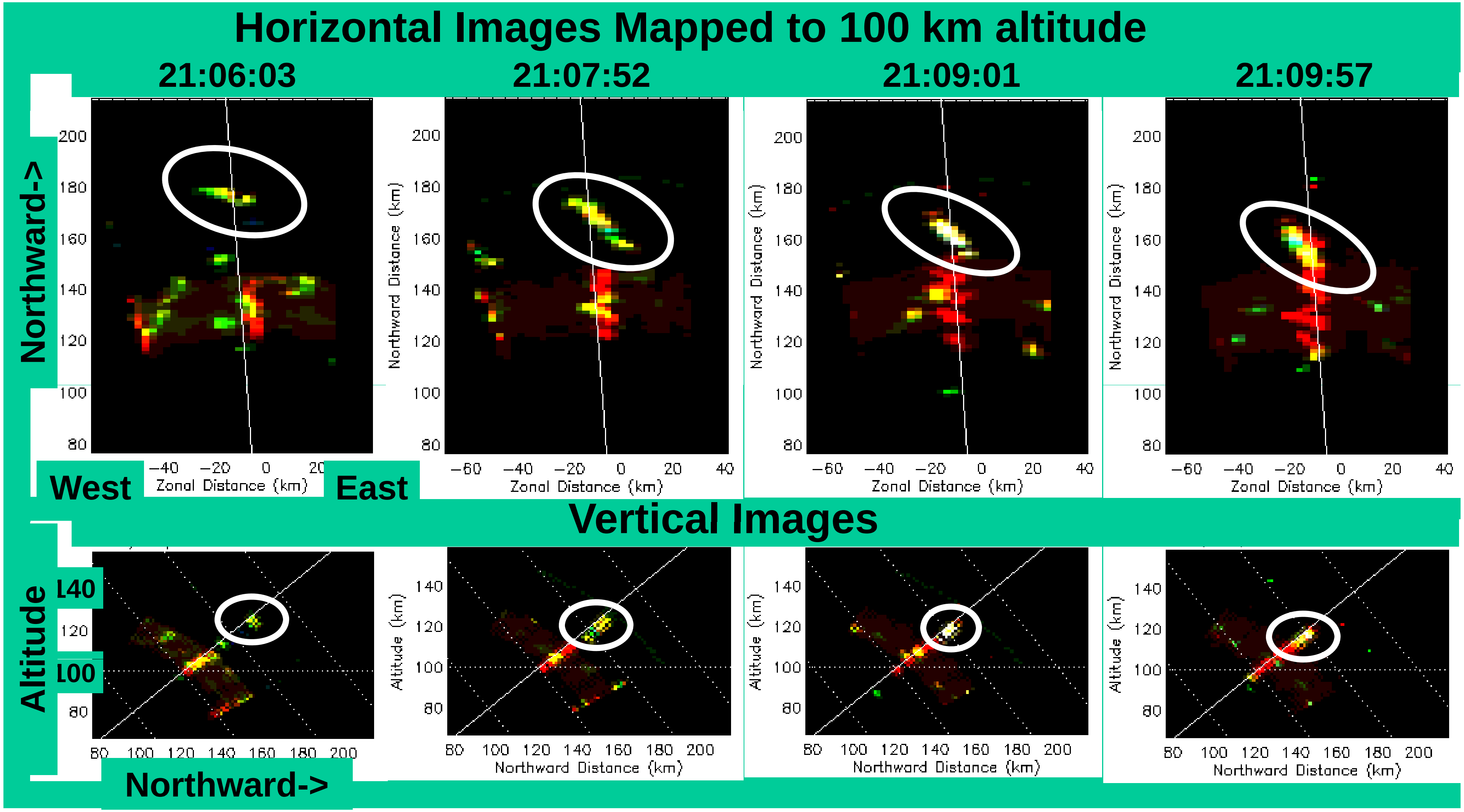
Some well-organized “S” structures become clearly visible after application of the Capon processing

(Luce et al., 2008)

Courtesy：Prof. S. Fukao

# 3-d imaging of quasi-periodic echo in the E-region Ionosshere (by S. Saito, NiCT, Japan)

02 June 2006




- High altitude (> 120 km) echoes.
- Band (ribbon) structure aligned NW-SE drifting SW.

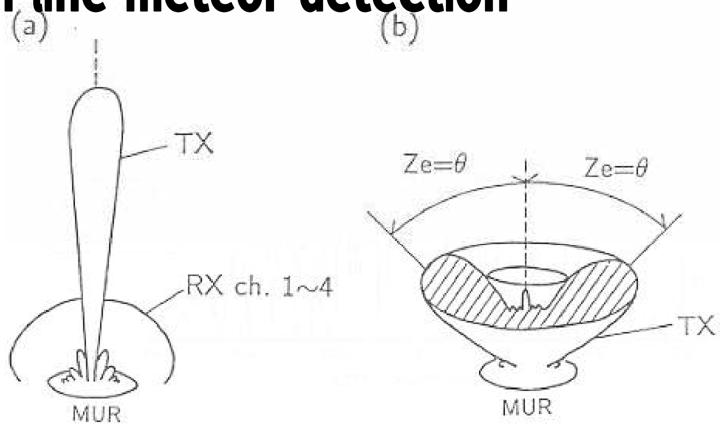
# Observation of meteor trails

# Meteor observation with new MU radar receiving system

April 30 – Mav 4. 2006

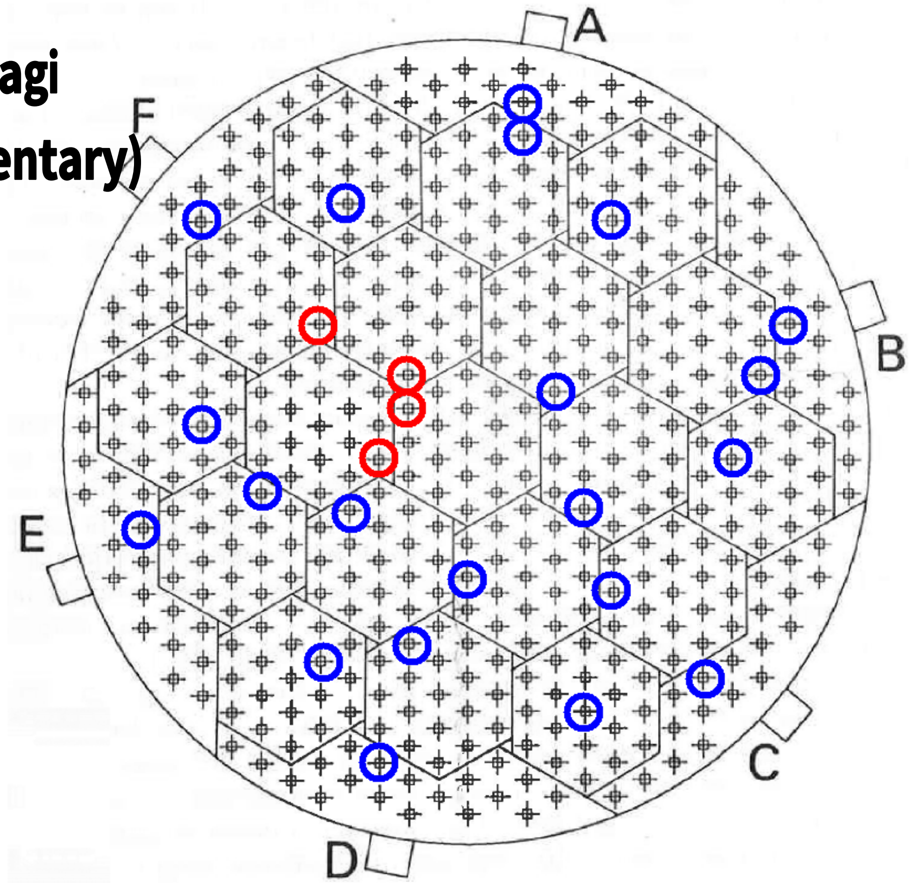
**Parameters**

- **Reception： 25 x 3-elememt crossed Yagi**
- **Pulse length ：0.9km （16 bit complementary)**
- **IPP ：2000 μs**
- **Coherent integration：2**
- **Sample range： 70～280km**
- **On line meteor detection**




Transmission beam pattern

Peak at 45 deg Zenith angle

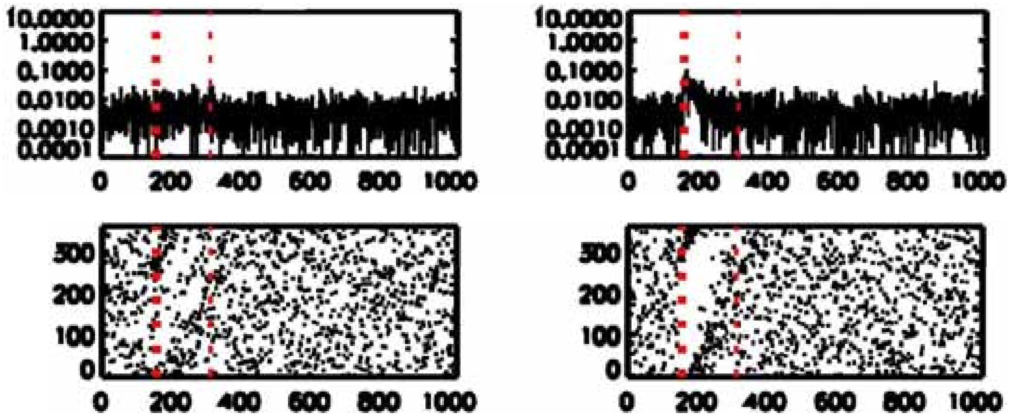



25 receiving antennas

Red: previous antenna set-up

# Coherent output of 25 ch signal

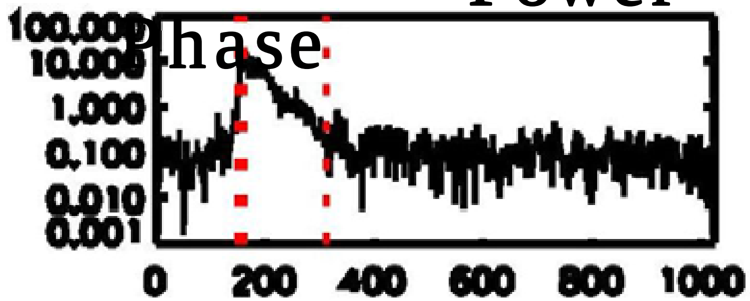
Antenna 1 Antenna 2

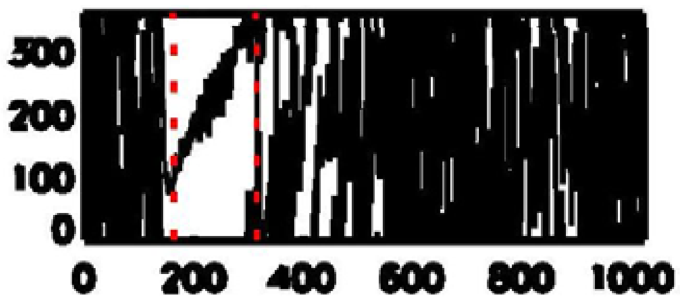



……. 全25出力

Power

Phase



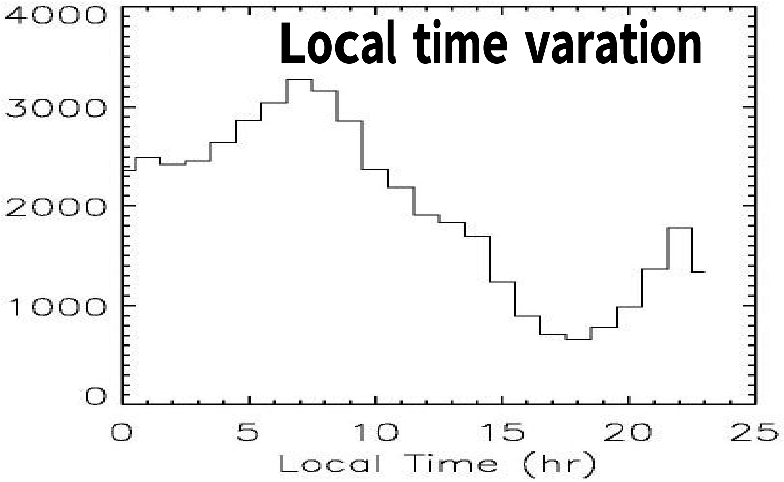

Time Time

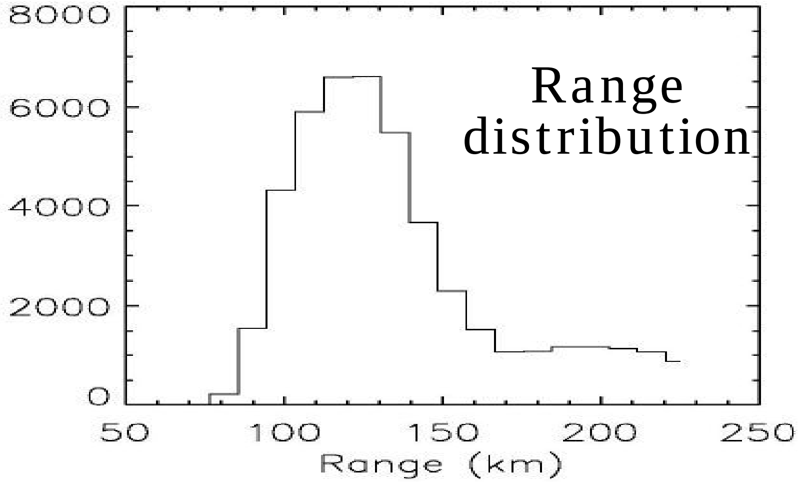
(×4msec) Improvement of S/N ratio by 14 dB

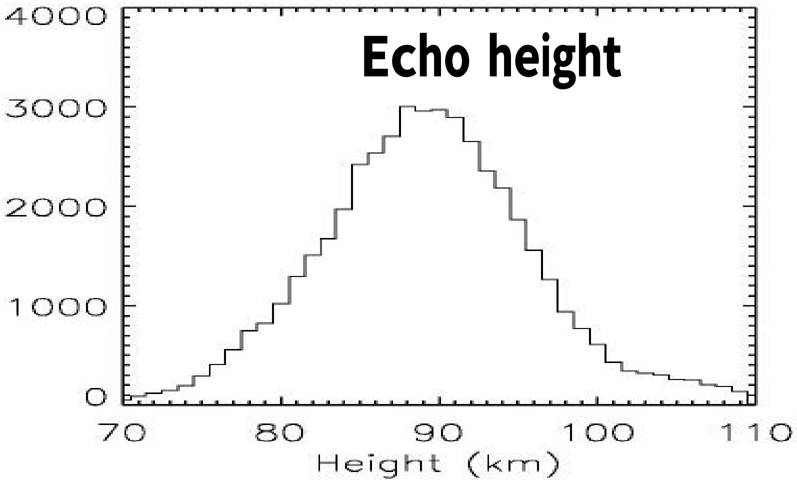
# Meteor echo distribution

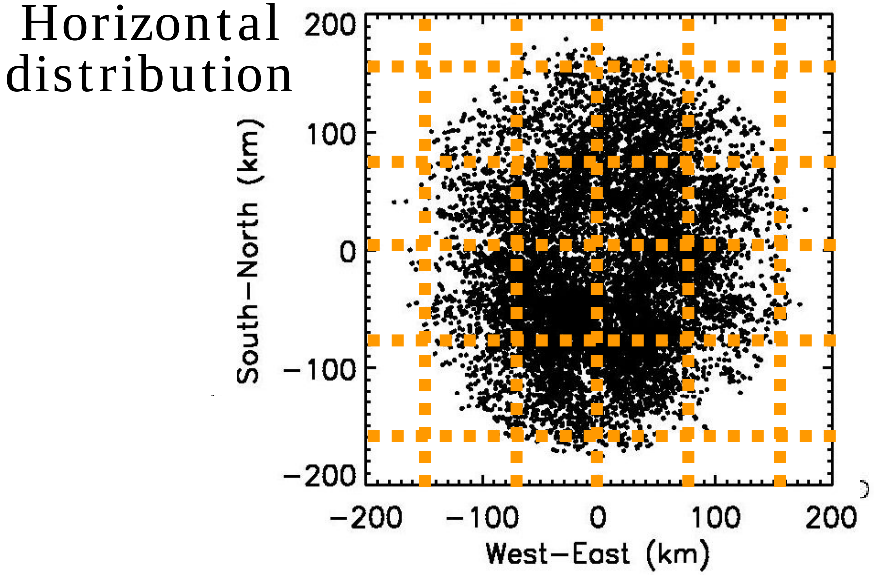
## 03/May/2006

**50,000 echoes /day**



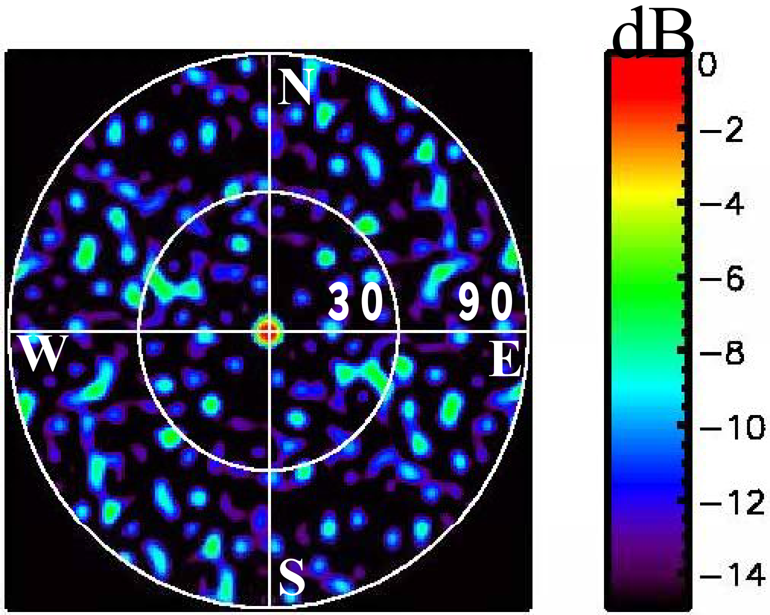



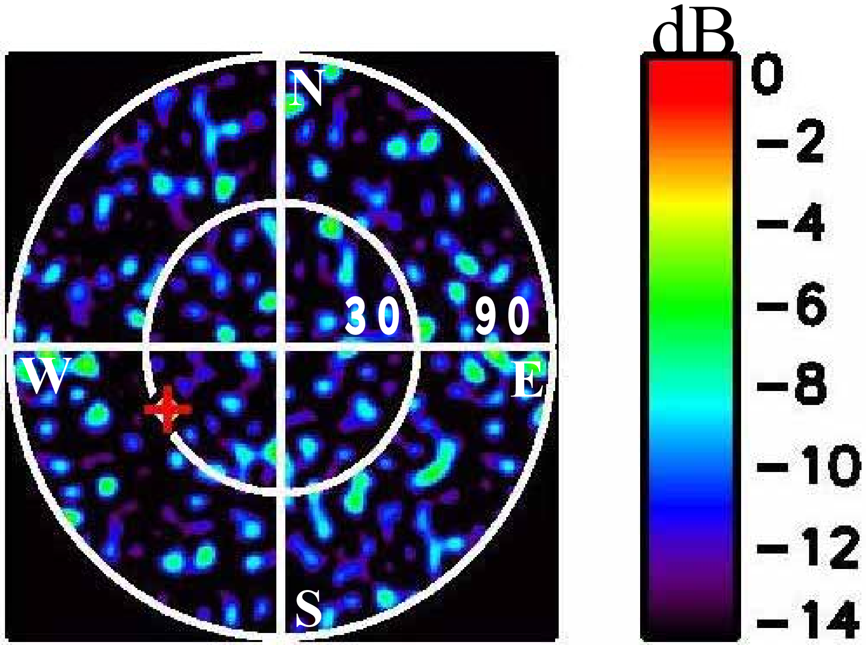
# Angle of arrival (AOA) estimation

-The receiving beam is very sharp

-AOA candidates are searched by steering the beam in all the possible directions rather than using a conventional interferometer technique

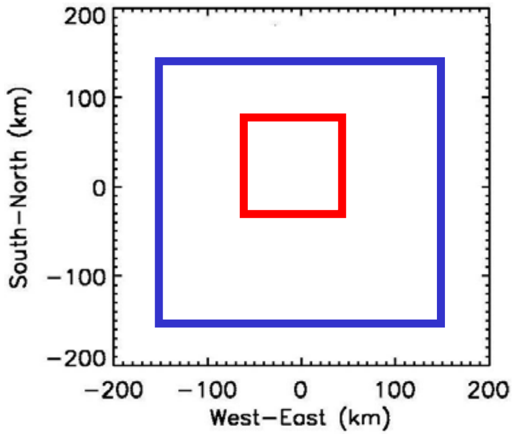


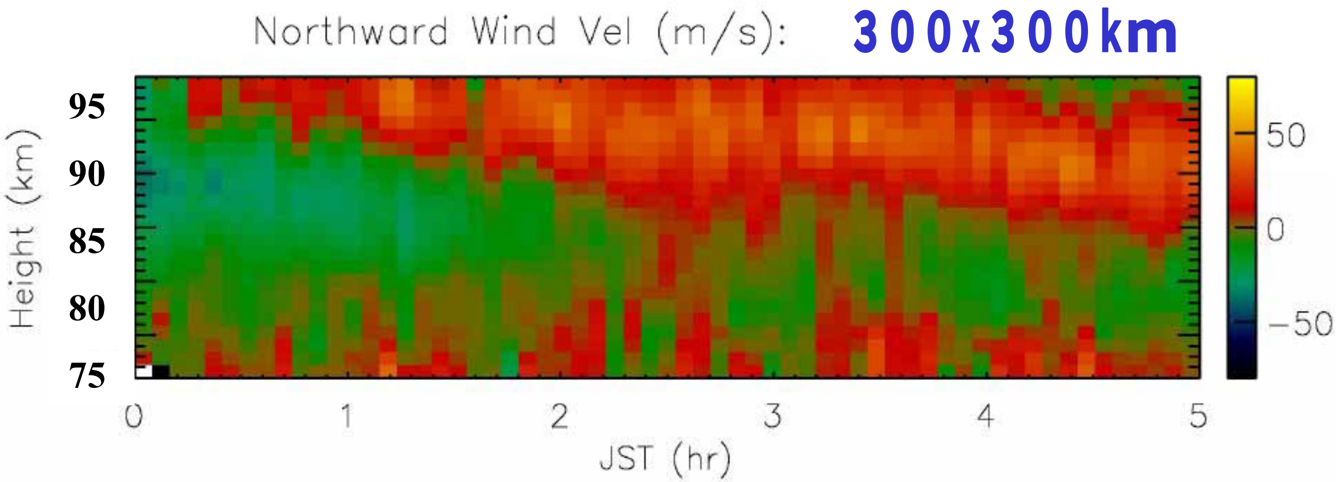

<u>Simulated</u> received power when AOA is assumed to be zenith



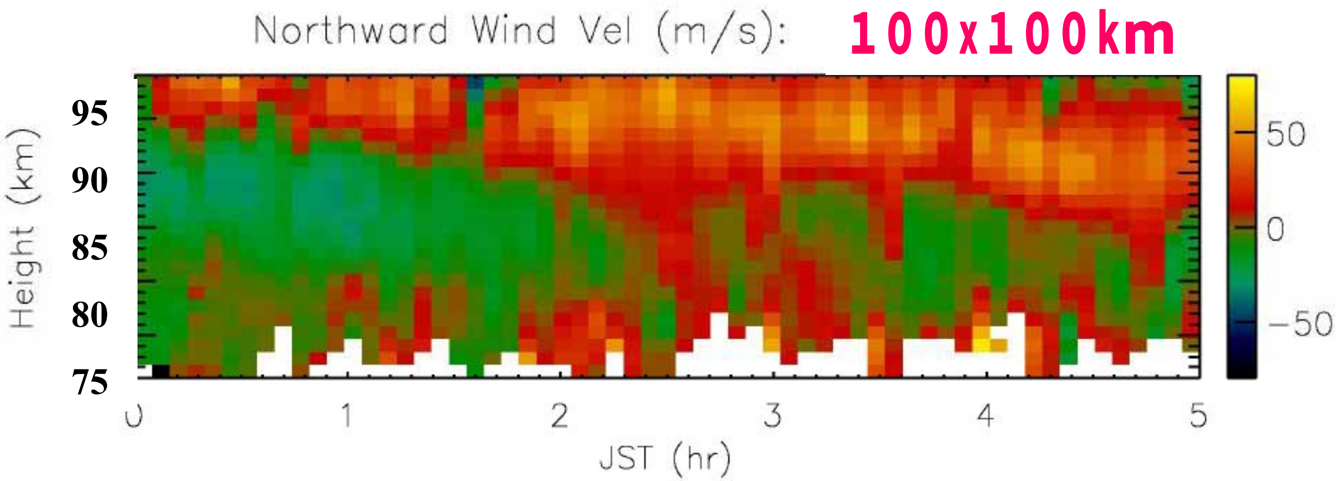

An example of estimated AOA using real data

# 00-06 LT May 3, 2006
# Northward wind velocities (10 min ave)



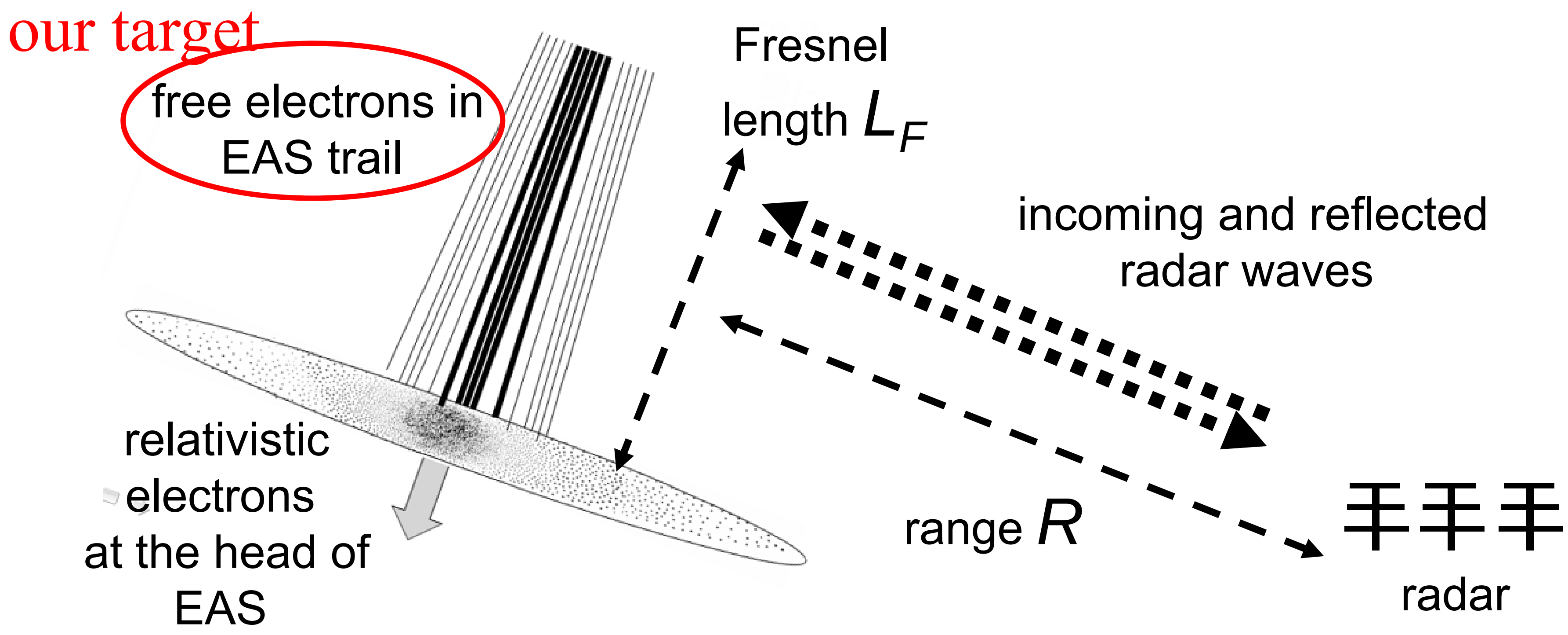



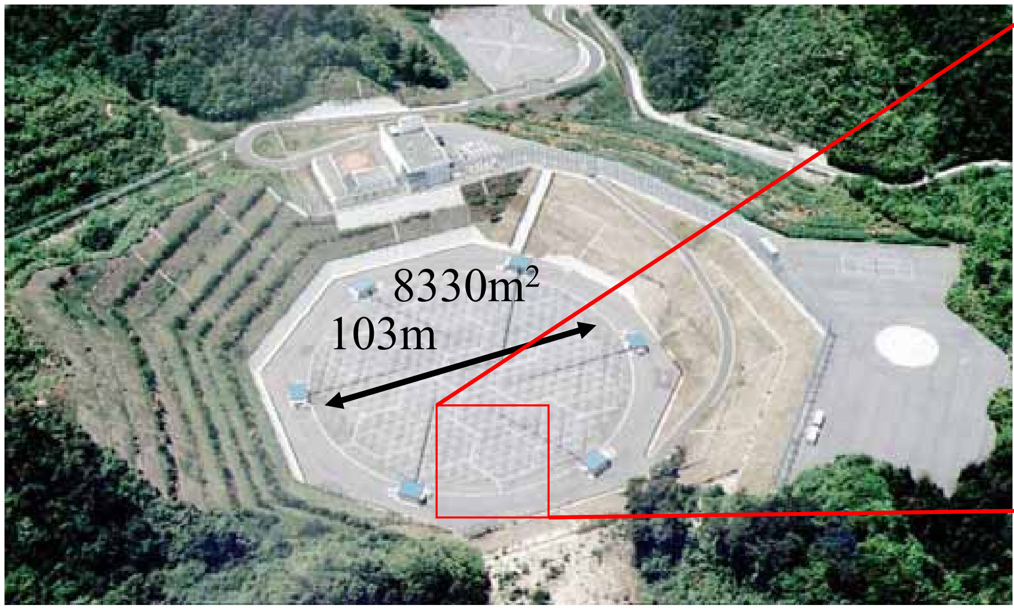

０３LT付近に小スケールの波動が捉えられていると考えられる。同時観測された大気光観測データ(塩川、名古屋大)と比較中



# EAS echo observations

What is the target




Shigaraki MU radar

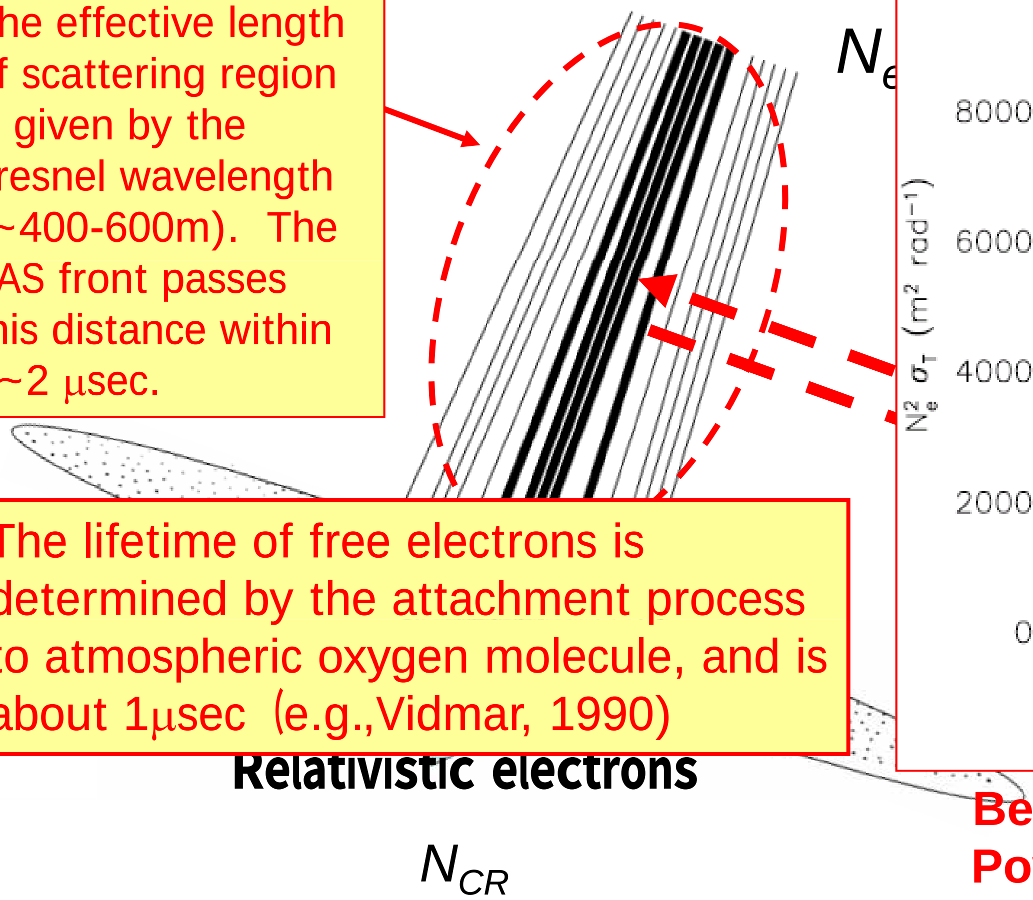

| | |
|---|---|
| Frequency: | 46.5MHz |
| Peak power: | 1MW |
| Average power: | 50kW |

*What is our target?* ★

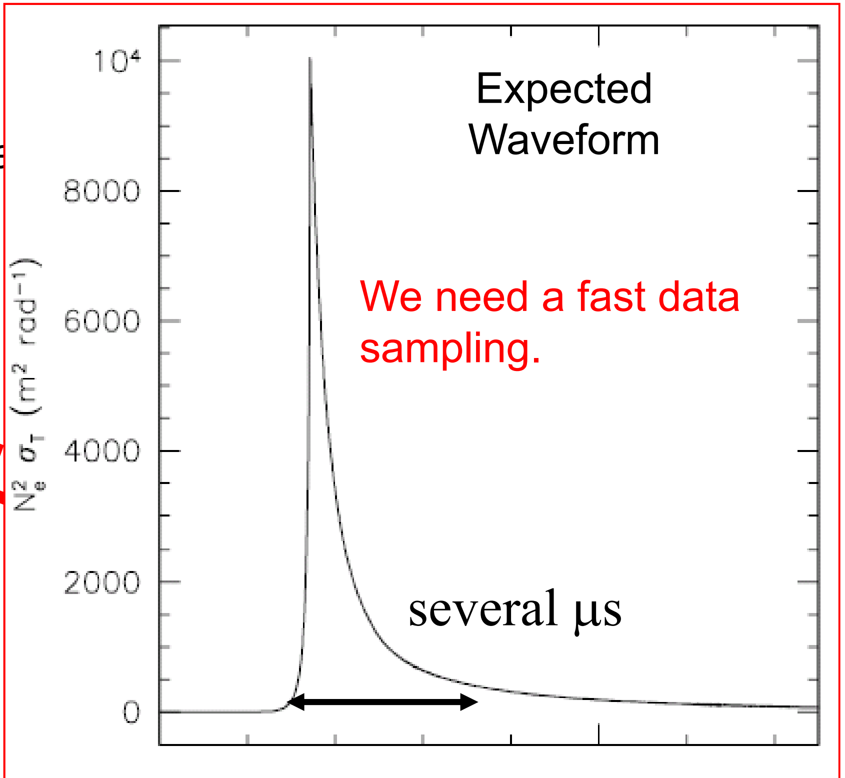
Condition for coherent backscattering by electrons in the ionized column of the EAS trail

EAS axis ⊥ propagation direction

The effective length of scattering region is given by the Fresnel wavelength (~400-600m). The EAS front passes this distance within 1~2 μsec.




The lifetime of free electrons is determined by the attachment process to atmospheric oxygen molecule, and is about 1μsec (e.g.,Vidmar, 1990)



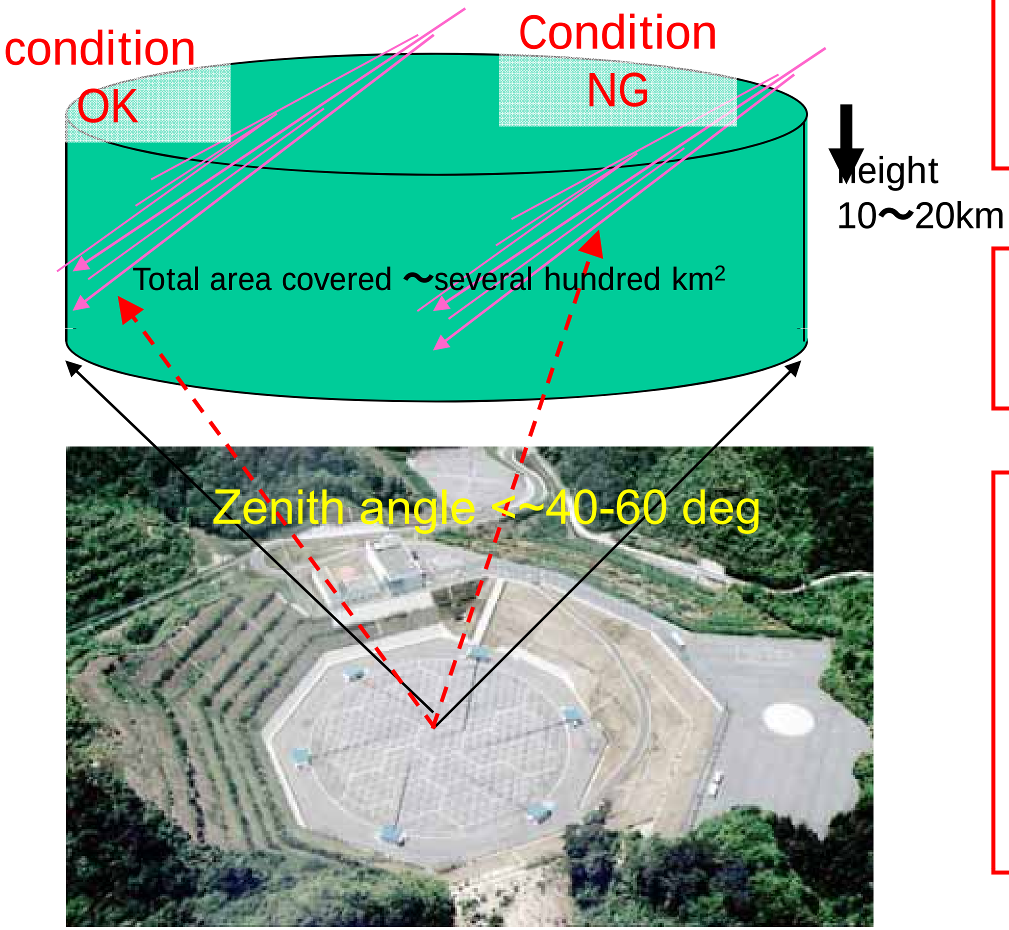

Predicted time profile (Gorham, 2001)

**Benefit of coherent scattering: Power of the scattered wave is proportional to $N_e^2$.**

*What is our target?*

★

EAS axis ⊥ propagation direction




Shigaraki MU radar

Geometrical condition
satisfied
〜 5%

↓

Limitation for backscatter radar

Limitation of pulse radar
duty ratio is 5% or less

Number of CRs to be detected by the MU radar ($0.05^2$=1/400 of incident CRs)

| | |
|---|---|
| $>10^{17}$ eV | several tens/day |
| $>10^{17.5}$eV | several/day |
| $>10^{18}$ eV | several $10^{-1}$/day |
| $>10^{18.5}$eV | several $10^{-2}$/day |

# Contents:

MU radar: system description

Trial EAS echo observation (1)

What is our target?

done

**Range determination**

**Direction finding**

The ‘best’ EAS echo candidate

Less significant EAS echo candidate

Trial EAS echo observation (2)

Energy estimation

Next step: Multiple transmitters + receivers

Realization of multiple stations for meteor echo case

# EAS echo observations

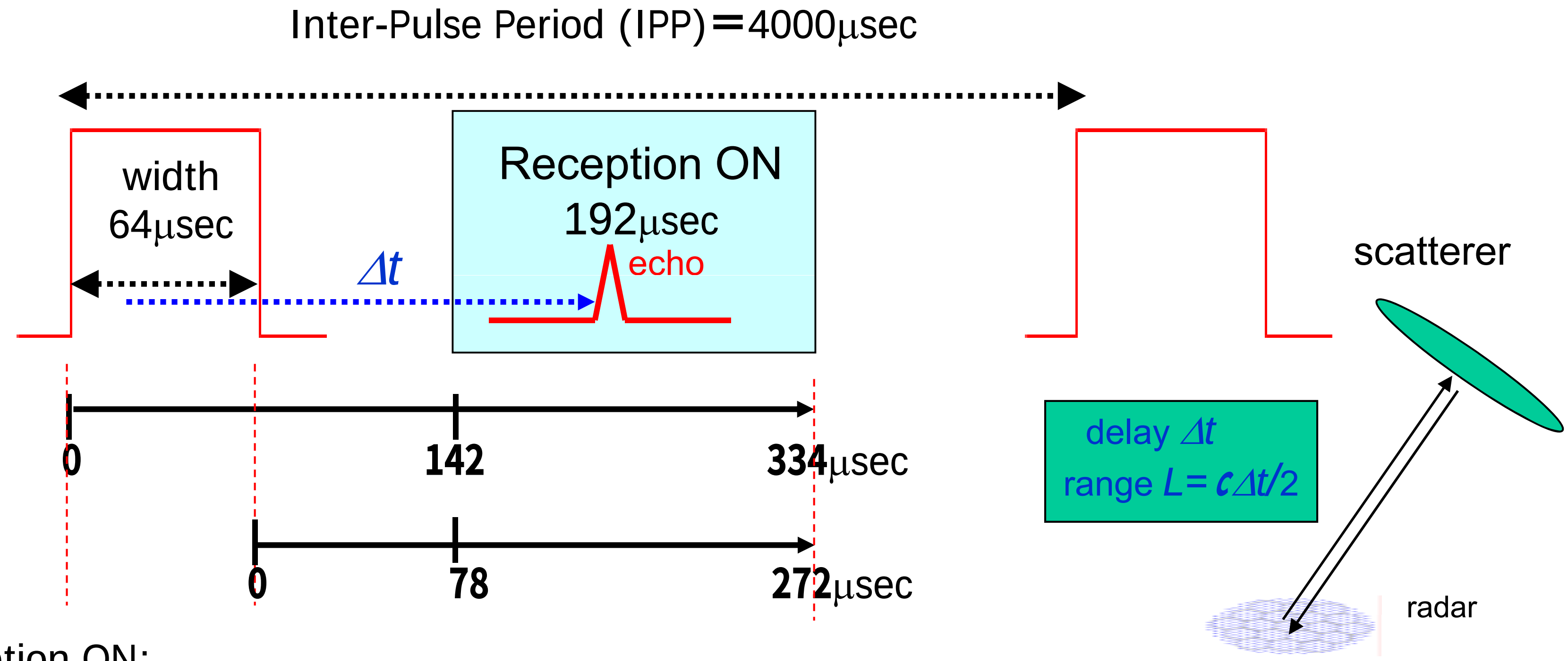
Range determination

Direction finding

# Range determination

★

Transmission/Reception Timing



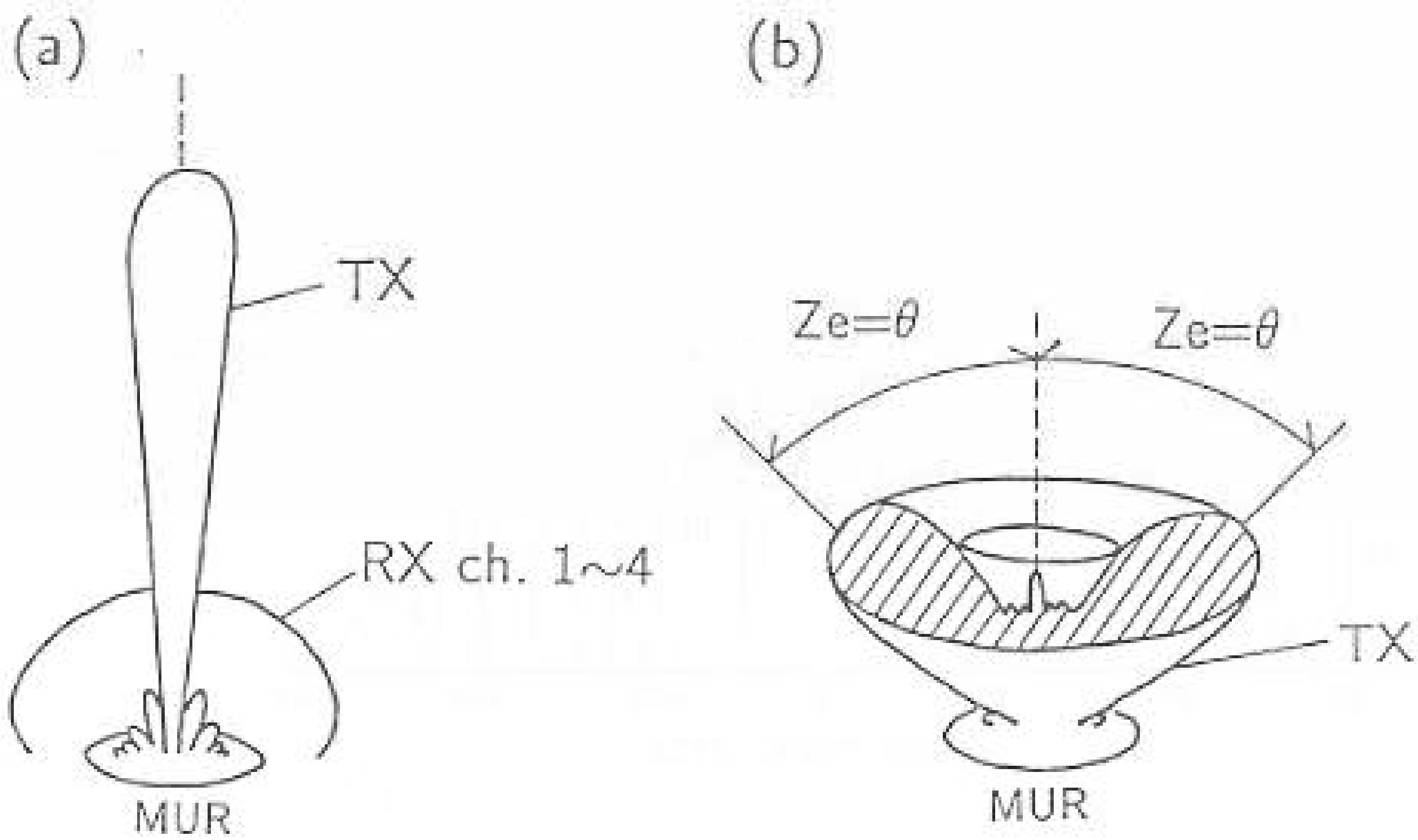

Reception ON:

From the head of the pulse: 142-334μsec (range 21.3-50.1km)

From the tail of the pulse: 78-272μsec (range 11.7-40.8km)

Since the expected length of EAS echoes is less than pulse width, uncertainty of ~10km (±5km) is unavoidable.

Sampling frequency 500kHz (sampling time = 2μsec )

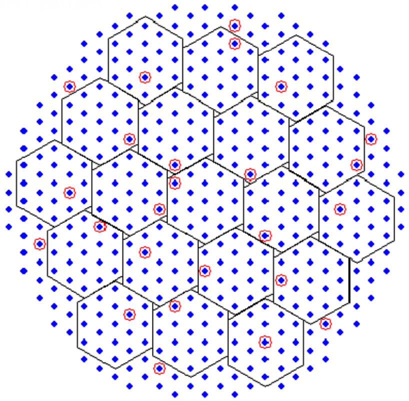



Ordinary beam pattern

**Transmission beam pattern**

**Peak at 45 deg Zenith angle**

# Direction finding



Out of 475 $\boxed{25}$ antennas are chosen.

Search of EAS position on the sky

↓

Aperture Synthesis in Radio Astronomy

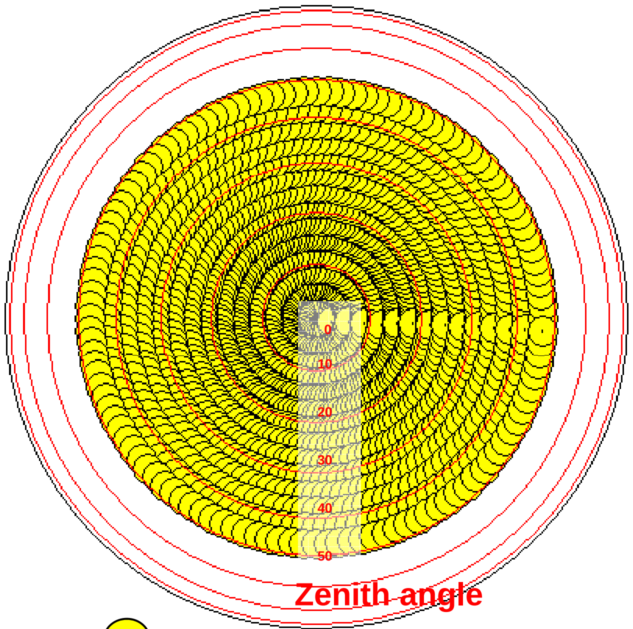
Correlation between i&j antenna outputs $(\Delta r_{ij} = r_i - r_j)$

↓ Fourier transformation

$$C_{ij} \rightarrow \sum_{ij} C\exp(-ik\Delta r_{ij}) = S(k)$$

$\boxed{1 <= i, j <= 25}$

Signal intensity (brightness temperature) toward the direction $k$




shows the size of antenna beam

1423 directions are set in the sky area of
zenith angle $\theta = 0\text{-}50^{o}$,
azimuthal angle $\phi = 0\text{-}360^{o}$.

We calculate the brightness temperature for each direction every 2μsec. Then we search the peak of the brightness temperature.

(This is a time-consuming procedure. On a PC with Core2Duo 3.16GHz, it takes 2 and half hours to process the data of 20 sec duration. ... factor 2h30m/20sec~450)

# EAS echo observations

The best candidate of EAS echo

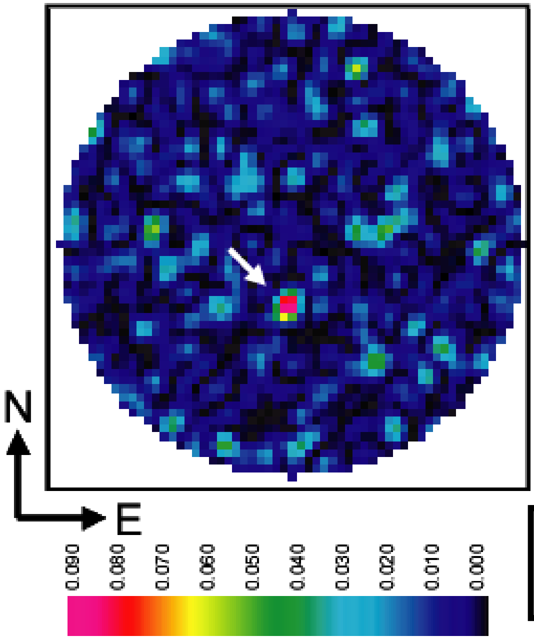
# Observations

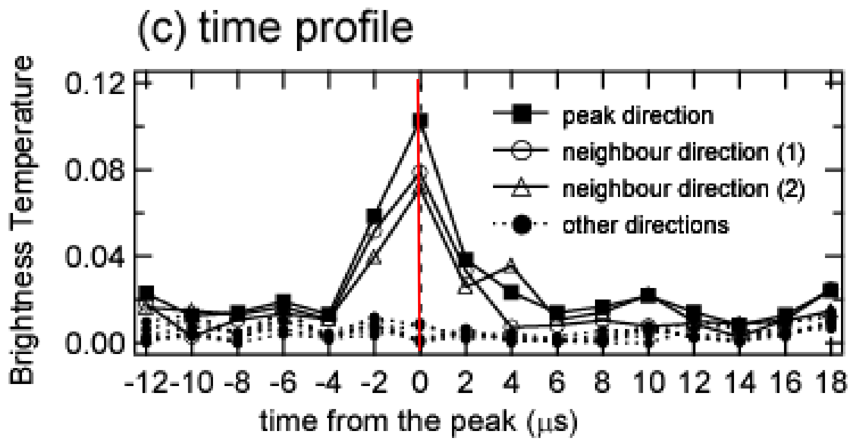
- December 2 – 3, 2008   for 8 hours
- Data analysis takes 500 times longer than the observation time
- The survey of EAS echo candidate has been fished only for the first 3 hours.

In the panel (a), the brightness temperature ($T_b$) sky map for the range $R$=24+4.8 km at 11:31:53.624 UT (02:31:53.624 LT) on 3 December 2009 is drawn. An EAS echo candidate (indicated by an arrow) was found at the direction of the zenith angle $q$ = 12$^o$ and the azimuth angle $f$=185$^o$.
The time variation of $T_b$ is shown in the panel (c), where the horizontal axis shows the time (ms) elapsed from the peak. A line with solid squares shows $T_b$ at the peak direction ($q$ = 12$^o$ , $f$=185$^o$). We see that the duration of the echo was 4-6us, which is close to the duration expected for EAS echoes.
We are tuning the MU system to optimize it for the detection of EAS echo candidates.

(a) observation (zenith angle<50$^o$)

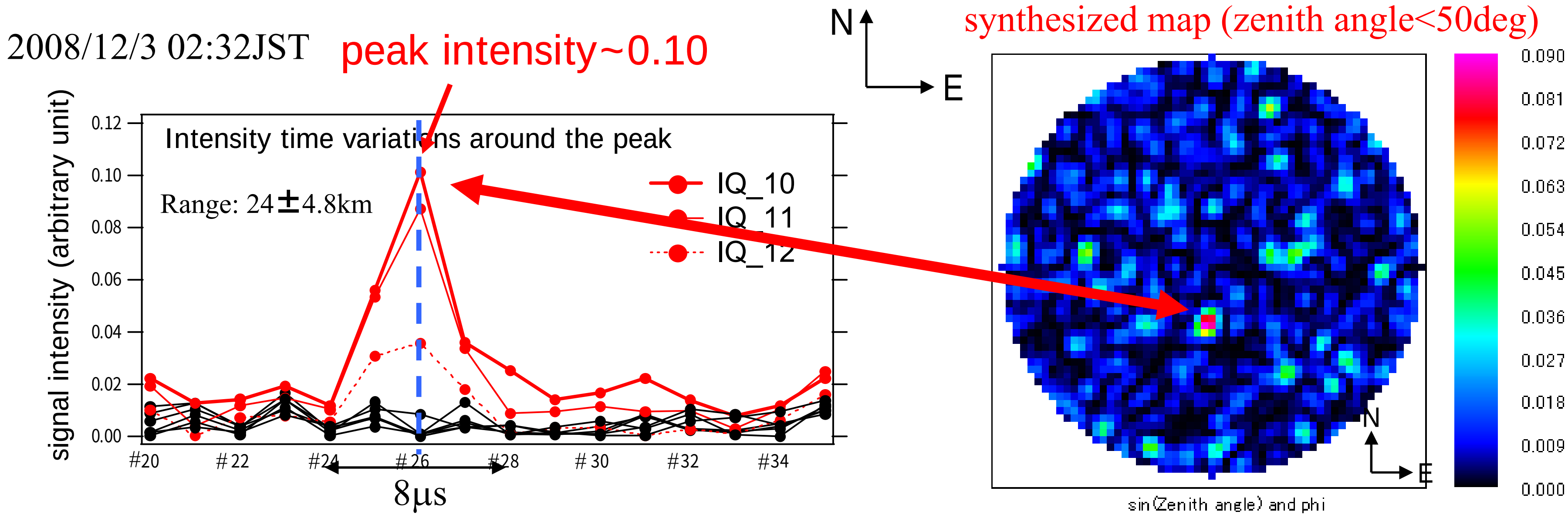
$T_b$ sky map




**Echo search takes 500 times longer!**

## *The 'best' EAS echo candidate*



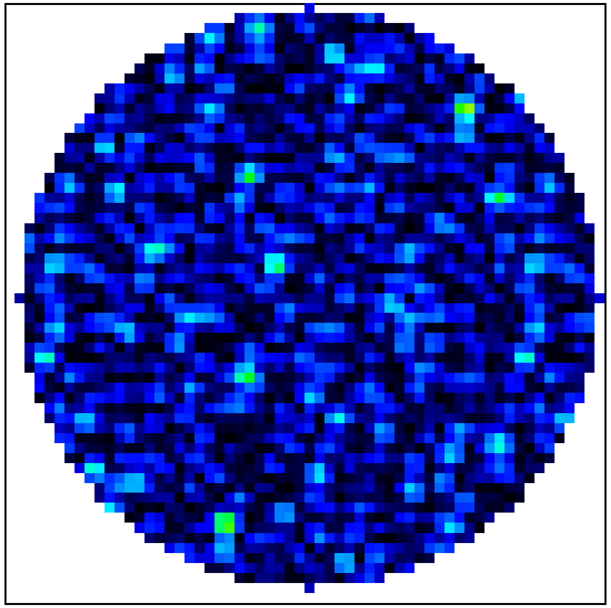

Time variations of signal intensity at the peak, and surrounding points

range=24.8±4.8km

12/3 02:31:53.6

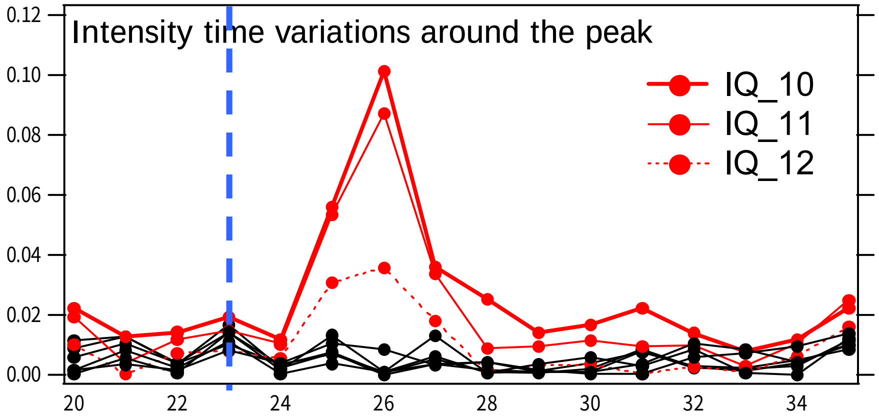
Time variation

6μsec before the peak



synthesized map

sin(Zenith angle) and phi

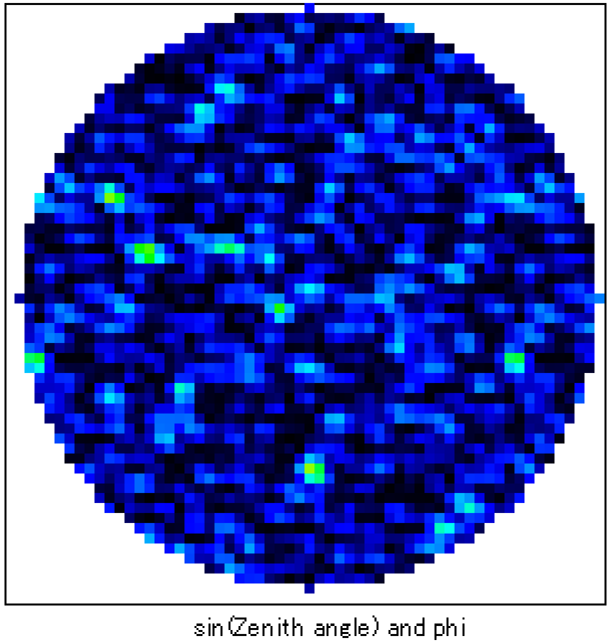



range=24.8±4.8km

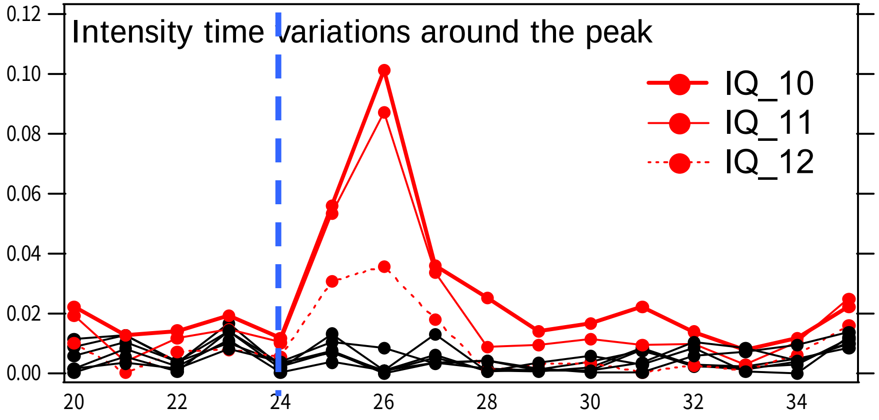
12/3 02:31:53.6

Time variation

4μsec before the peak




synthesized map



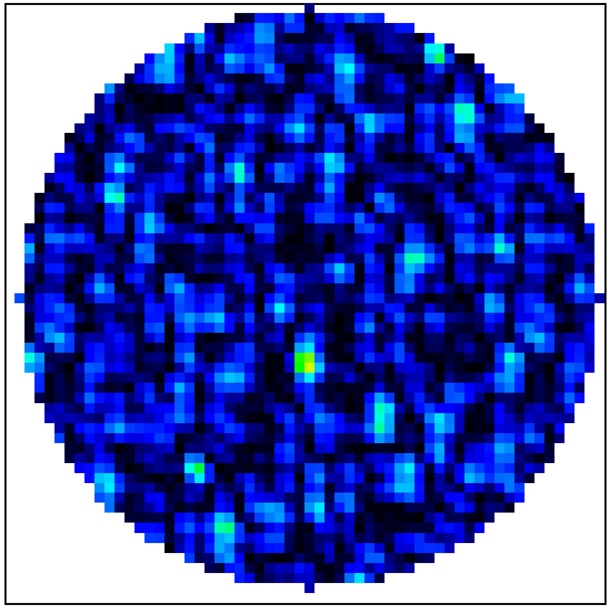

range=24.8±4.8km

12/3 02:31:53.6

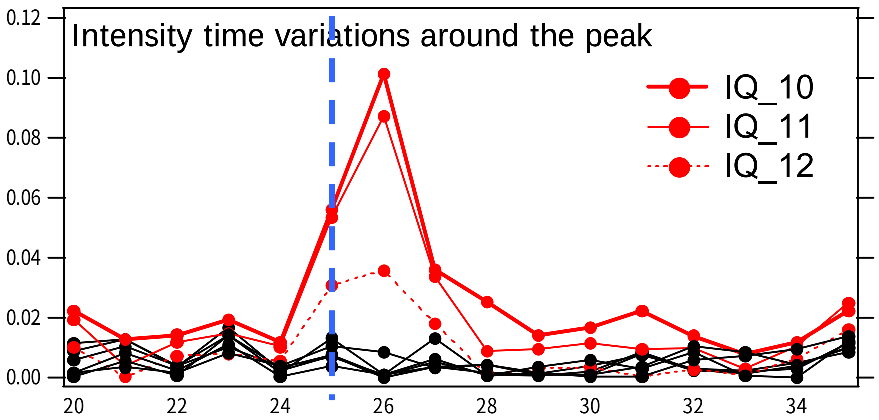
Time variation

2μsec before the peak

synthesized map



sin(Zenith angle) and phi

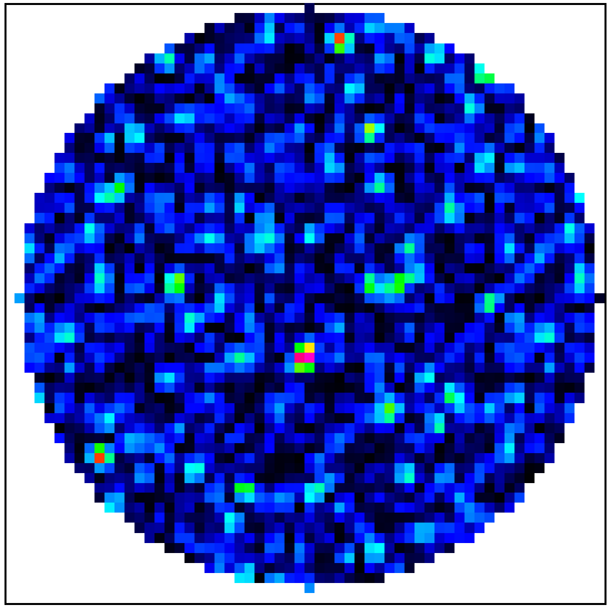



range=24.8±4.8km

12/3 02:31:53.6

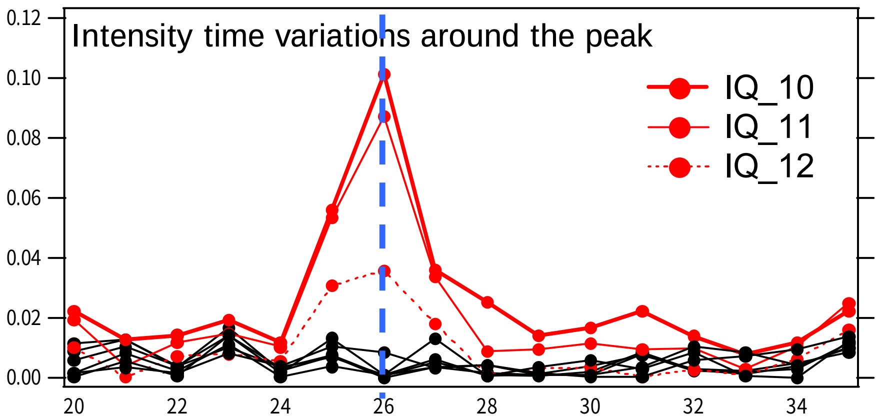
Time variation

Just at the peak



synthesized map

sin(Zenith angle) and phi

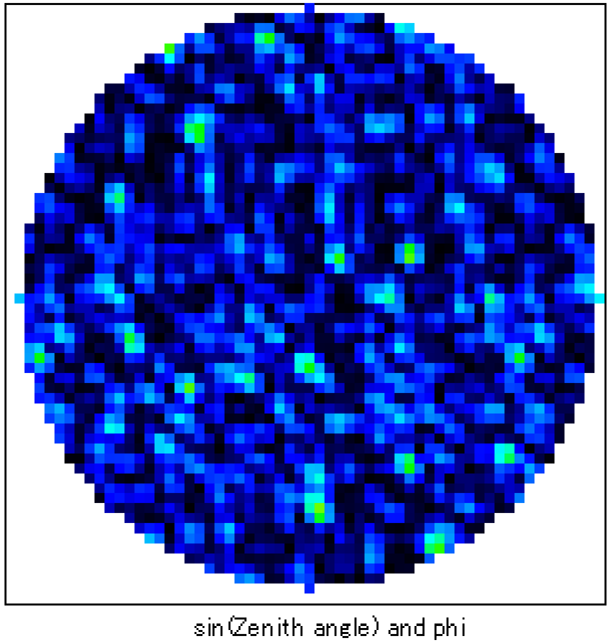



range=24.8±4.8km

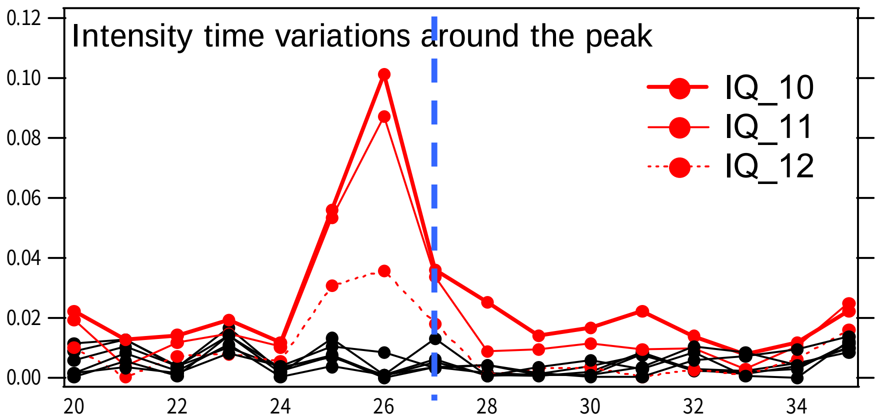
12/3 02:31:53.6

Time variation

2μsec after the peak




synthesized map



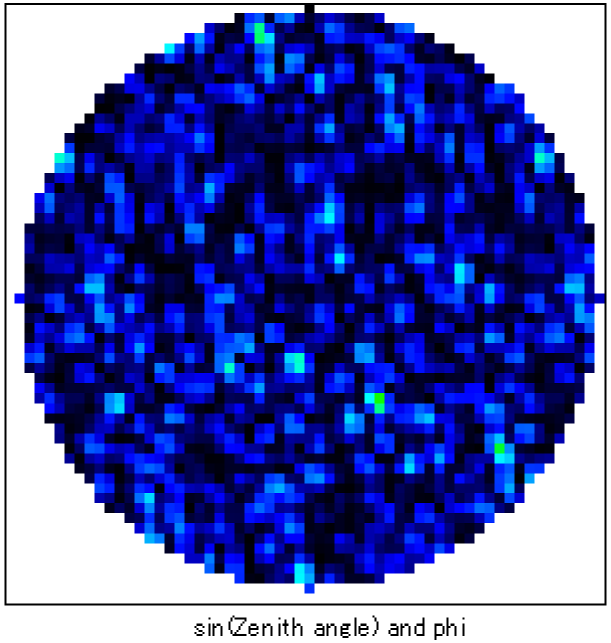

range=24.8±4.8km

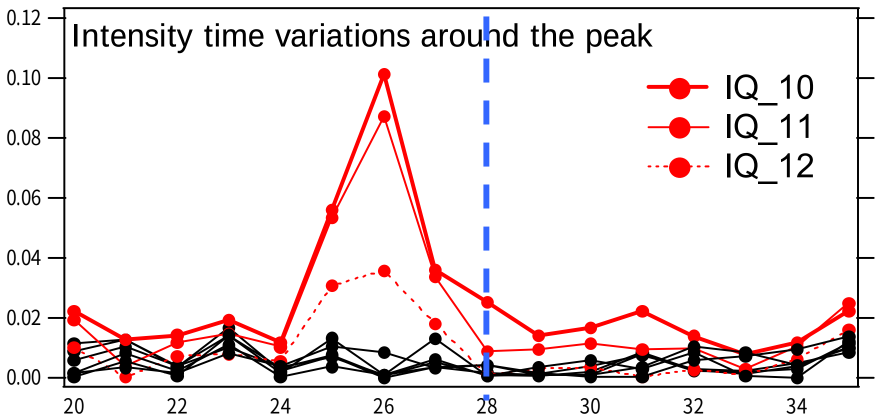
12/3 02:31:53.6

Time variation

4μsec after the peak

synthesized map



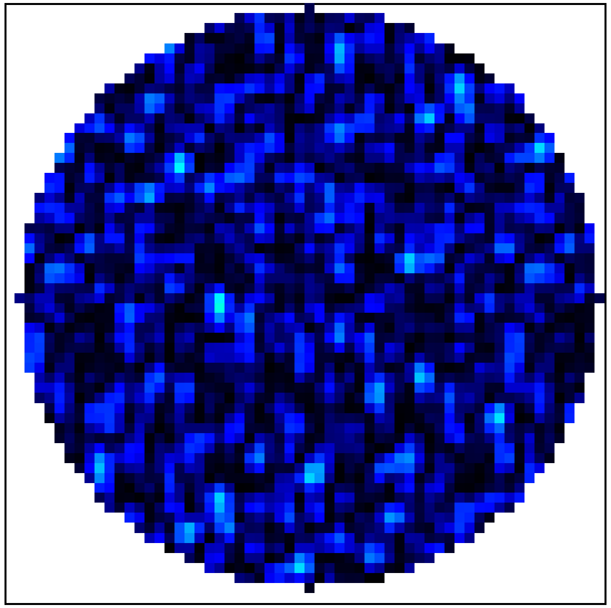




range=24.8±4.8km

12/3 02:31:53.6

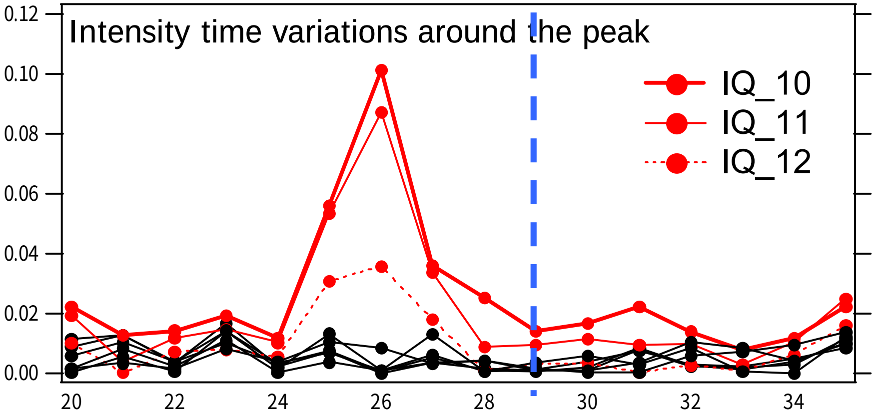
Time variation

6μsec after the peak



synthesized map

sin(Zenith angle) and phi

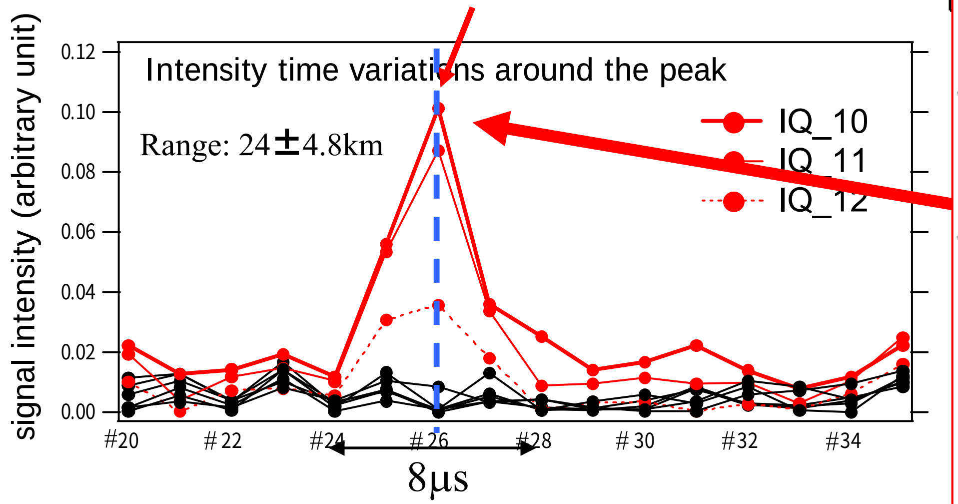


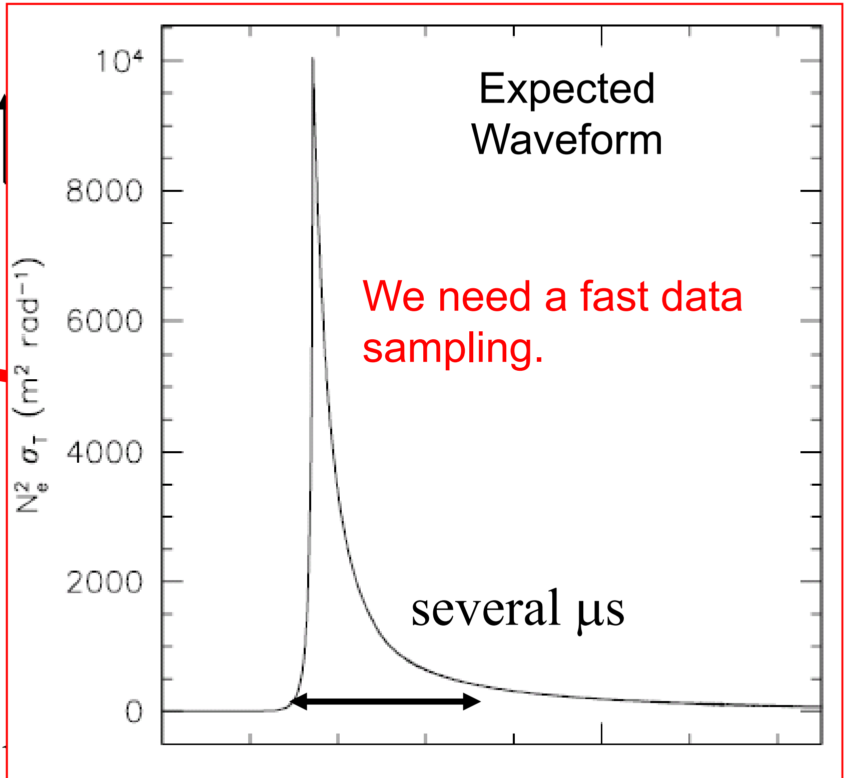

range=24.8±4.8km

# *The 'best' EAS echo candidate*

★

2008/12/3 02:32JST peak intensity~0.10




Predicted time profile (Gorham, 2001)

Time variations of signal intensity at the and surrounding points

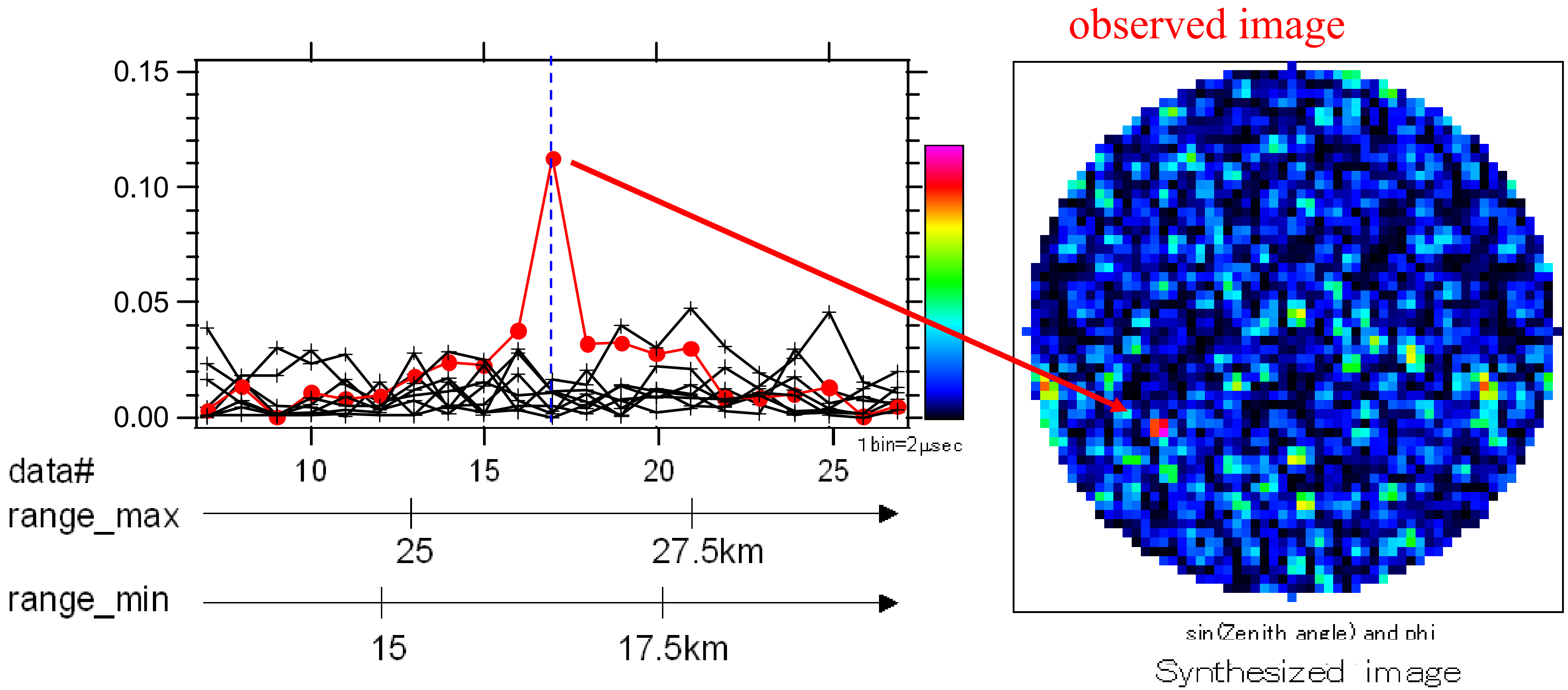
range=24.8±4.8km

# EAS echo observations

Example of less significant echo

MUI.080909.020441_CR+zen.txt

| BB | nn | hgh | Rmin | Rmax | Zmin | Zmax | zan | ph | IQsynthMax | IQsynthZen |
|---|---|---|---|---|---|---|---|---|---|---|
| 05 | 422 | 17 | 16.80 | 26.40 | 13.15 | 20.67 | 38.47 | 216.00 | 1.123E-001 | 3.092E-003 |

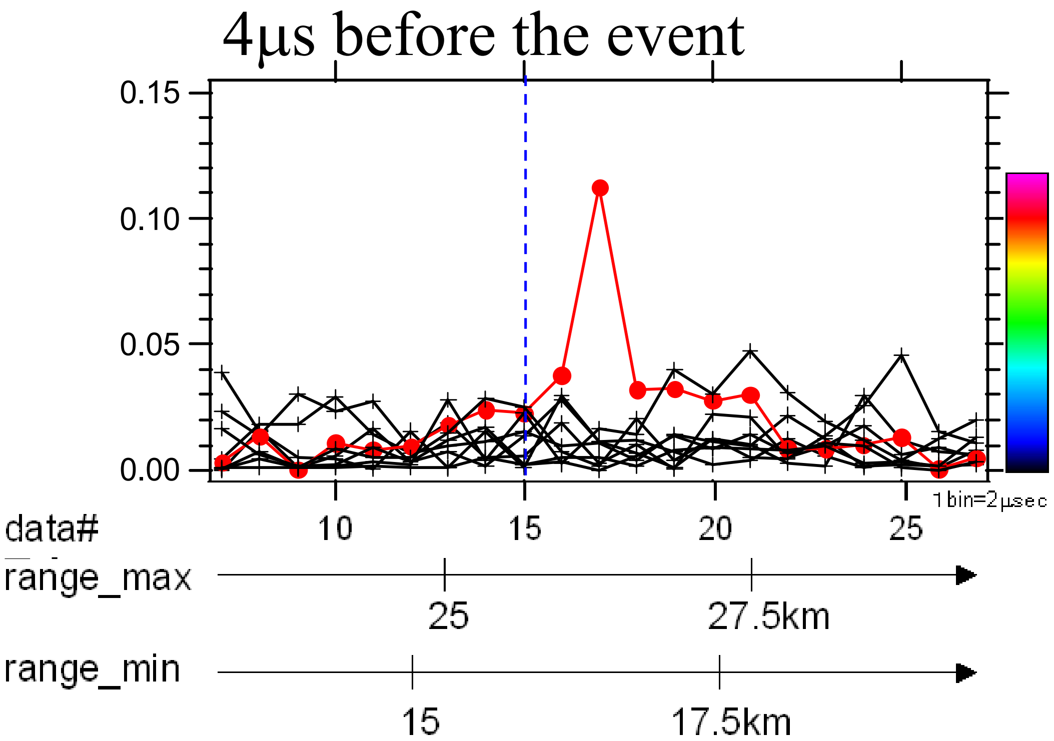


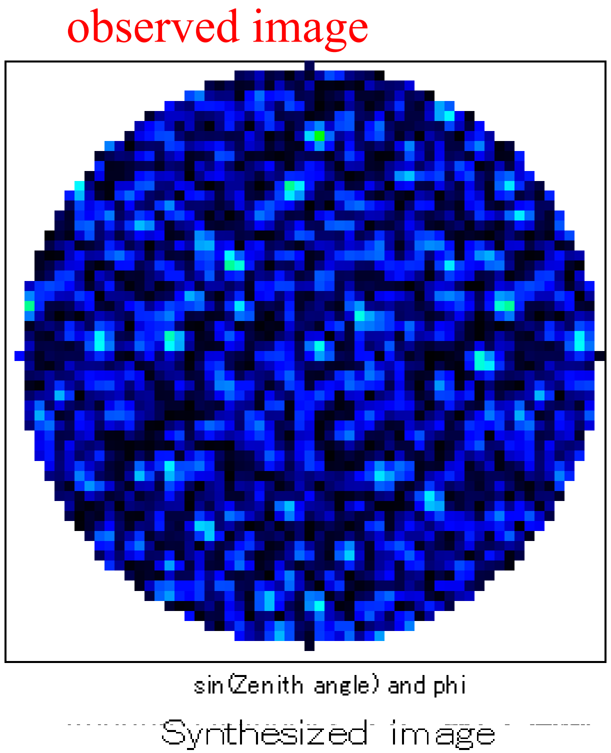

Less significant event at zenith angle=38.5 deg

(height=13.15-20.67km)

MUI.080909.020441_CR+zen.txt

| BB | nn | hgh | Rmin | Rmax | Zmin | Zmax | zan | ph | IQsynthMax | IQsynthZen |
|---|---|---|---|---|---|---|---|---|---|---|
| 05 | 422 | 17 | 16.80 | 26.40 | 13.15 | 20.67 | 38.47 | 216.00 | 1.123E-001 | 3.092E-003 |



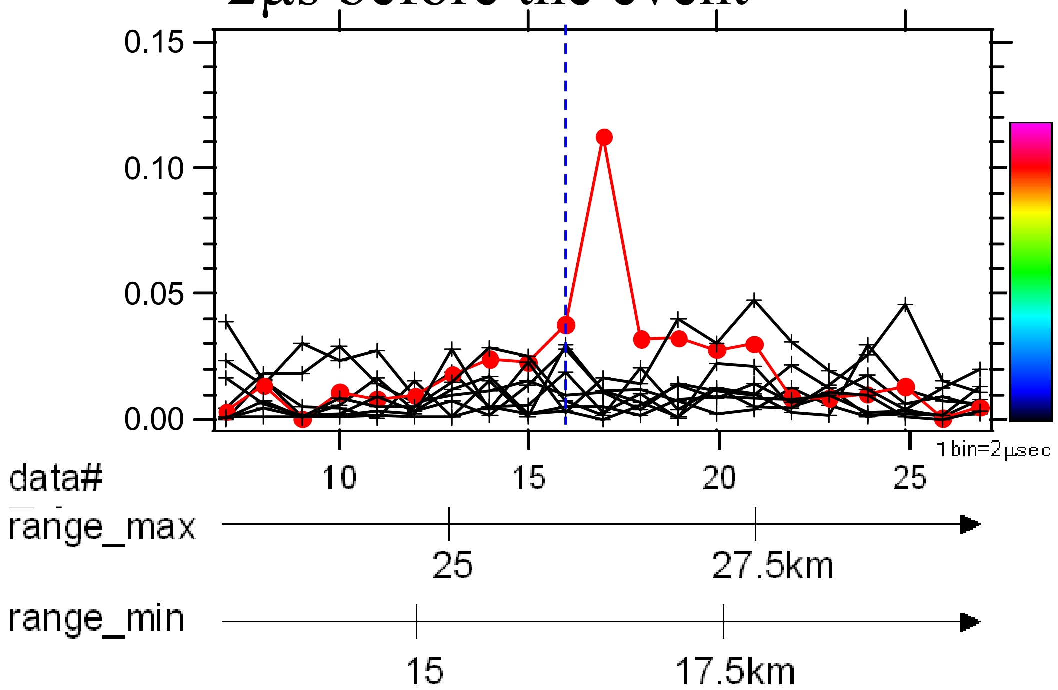

Less significant event at zenith angle=38.5 deg

(height=13.15-20.67km)

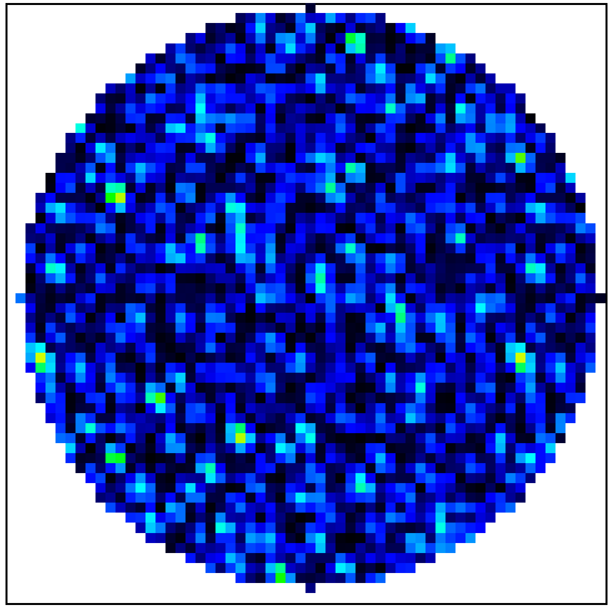
MUI.080909.020441_CR+zen.txt

| BB | nn | hgh | Rmin | Rmax | Zmin | Zmax | zan | ph | IQsynthMax | IQsynthZen |
|---|---|---|---|---|---|---|---|---|---|---|
| 05 | 422 | 17 | 16.80 | 26.40 | 13.15 | 20.67 | 38.47 | 216.00 | 1.123E-001 | 3.092E-003 |

2μs before the event




observed image



sin(Zenith angle) and phi

Synthesized image

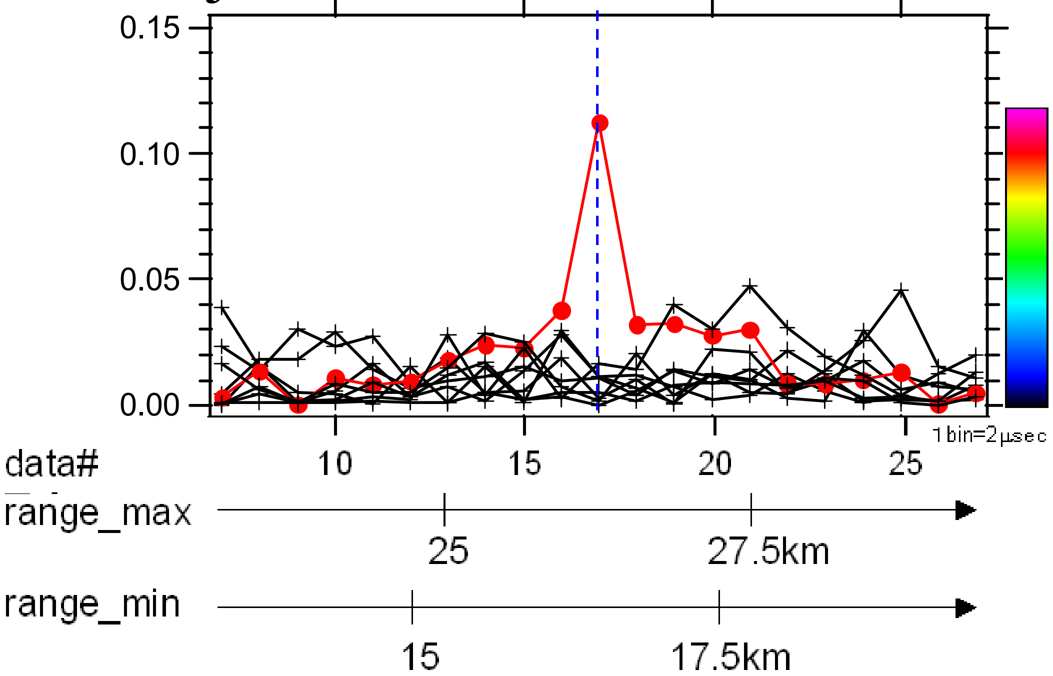
Less significant event at zenith angle=38.5 deg

(height=13.15-20.67km)

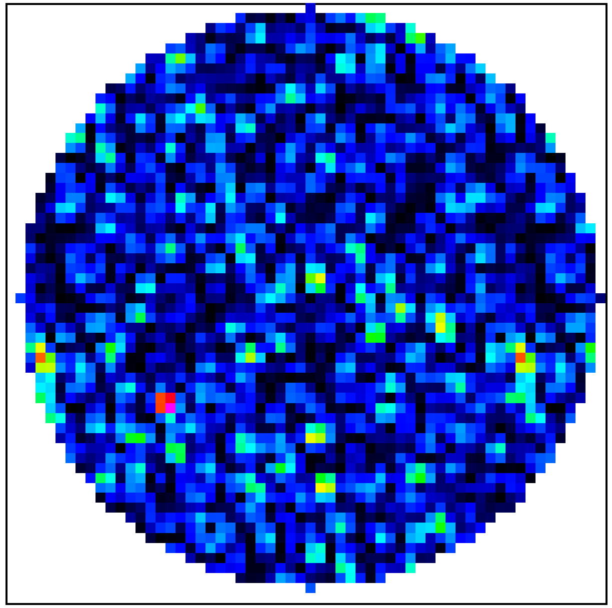
MUI.080909.020441_CR+zen.txt

| BB | nn | hgh | Rmin | Rmax | Zmin | Zmax | zan | ph | IQsynthMax | IQsynthZen |
|---|---|---|---|---|---|---|---|---|---|---|
| 05 | 422 | 17 | 16.80 | 26.40 | 13.15 | 20.67 | 38.47 | 216.00 | 1.123E-001 | 3.092E-003 |

just the event




observed image



sin(Zenith angle) and phi

Synthesized image

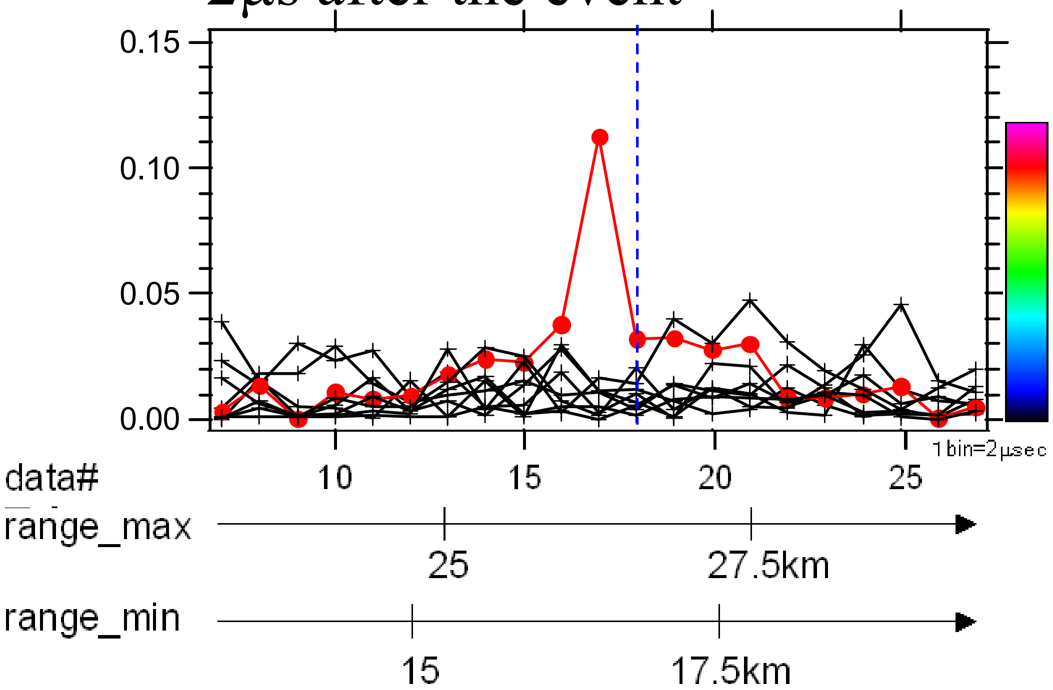
Less significant event at zenith angle=38.5 deg

(height=13.15-20.67km)

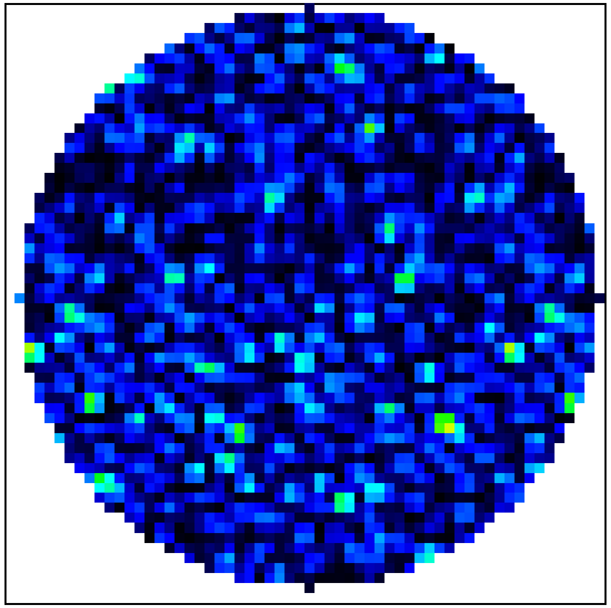
MUI.080909.020441_CR+zen.txt

| BB | nn | hgh | Rmin | Rmax | Zmin | Zmax | zan | ph | IQsynthMax | IQsynthZen |
|---|---|---|---|---|---|---|---|---|---|---|
| 05 | 422 | 17 | 16.80 | 26.40 | 13.15 | 20.67 | 38.47 | 216.00 | 1.123E-001 | 3.092E-003 |

2μs after the event




observed image



sin(Zenith angle) and phi

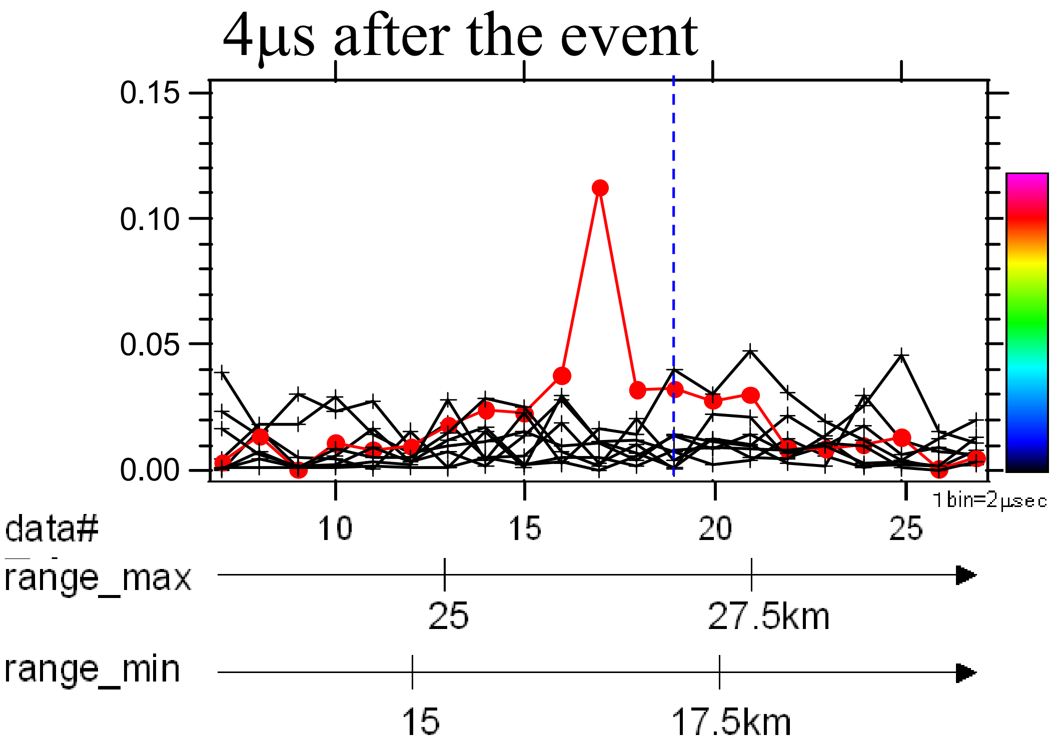
Synthesized image

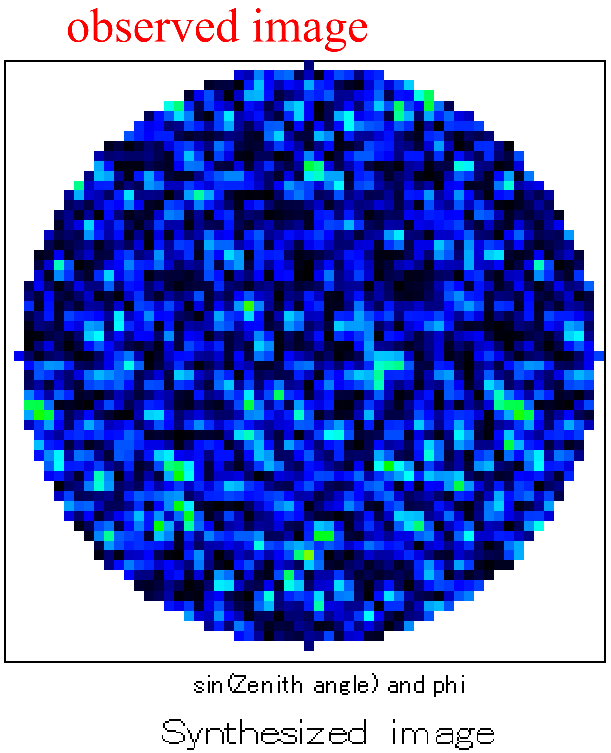
Less significant event at zenith angle=38.5 deg

(height=13.15-20.67km)

MUI.080909.020441_CR+zen.txt

| BB | nn | hgh | Rmin | Rmax | Zmin | Zmax | zan | ph | IQsynthMax | IQsynthZen |
|---|---|---|---|---|---|---|---|---|---|---|
| 05 | 422 | 17 | 16.80 | 26.40 | 13.15 | 20.67 | 38.47 | 216.00 | 1.123E-001 | 3.092E-003 |



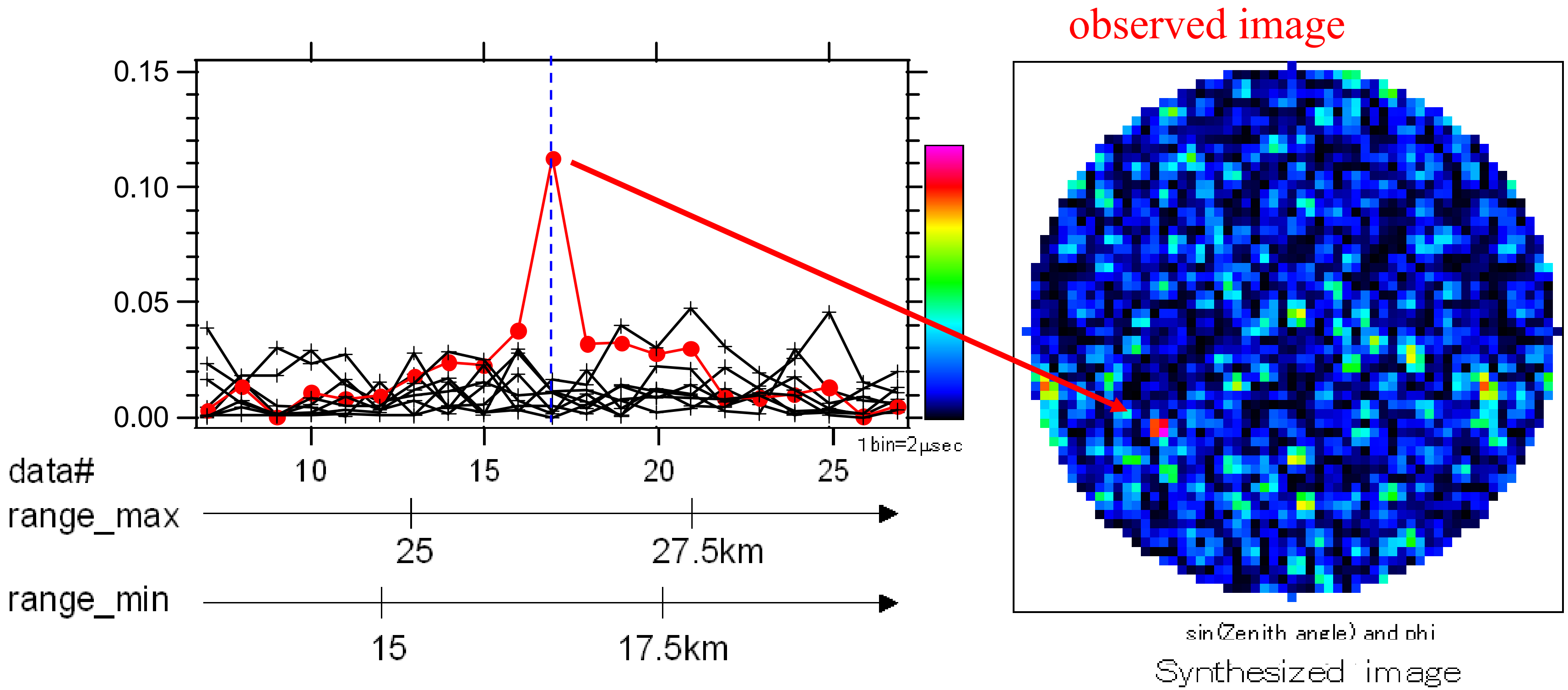




Less significant event at zenith angle=38.5 deg

(height=13.15-20.67km)

MUI.080909.020441_CR+zen.txt

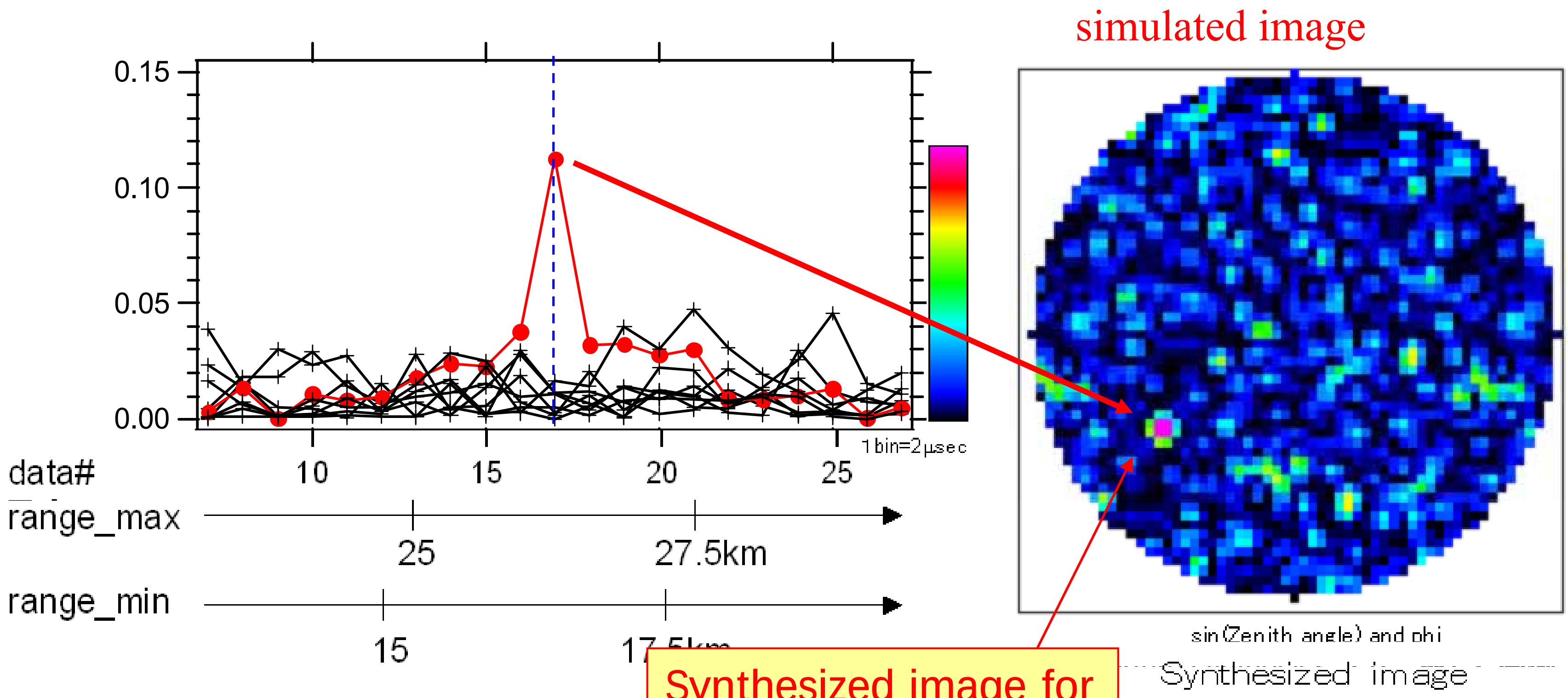
| BB | nn | hgh | Rmin | Rmax | Zmin | Zmax | zan | ph | IQsynthMax | IQsynthZen |
|---|---|---|---|---|---|---|---|---|---|---|
| 05 | 422 | 17 | 16.80 | 26.40 | 13.15 | 20.67 | 38.47 | 216.00 | 1.123E-001 | 3.092E-003 |




Less significant event at zenith angle=38.5 deg

(height=13.15-20.67km)

```
MUI.080909.020441_CR+zen.txt
BB   nn hgh    Rmin    Rmax    Zmin    Zmax     zan      ph    IQsynthMax   IQsynthZen
05  422   17   16.80   26.40   13.15   20.67   38.47 216.00   1.123E-001    3.092E-003
```



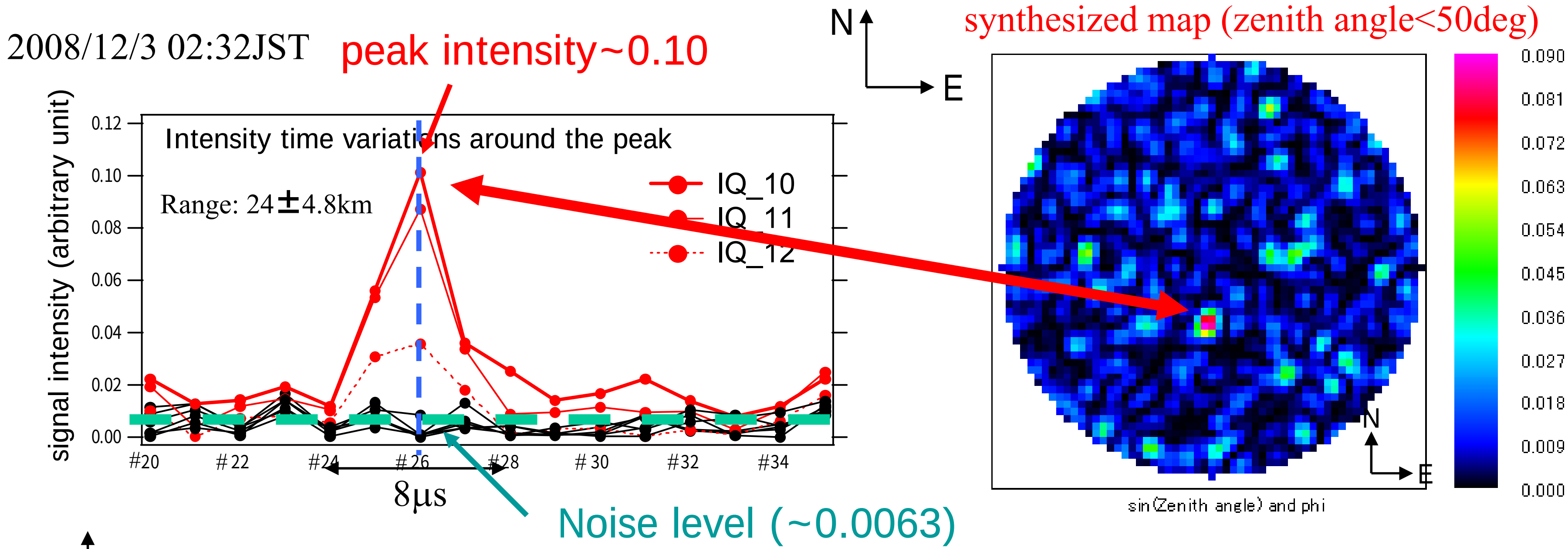

Synthesized image for a simulated signal coming from this direction. Subpeaks appearing on the sky map are due to the effect of antenna side lobes.

Less significan … =38.5 deg

(he …

# Calibration of System Sensitivity

*The 'best' EAS echo candidate*




We estimate S/N=0.10/0.0063~16.

Here noise temperature is determined by the galactic radio background, which is estimated to be ~10000K including the receiver's system temperature.

# Calibration of System Sensitivity

## *Galactic Radio Background and EAS Echo Power*

We assume that the noise temperatrue is $\boxed{T_N = 10^4 \text{ K}}$, which is the sum of galactic radio background and system noise. The receiver bandwidth of the MU radar, $\Delta f$, was set at 500 kHz for the trial observations between September 2008 and February 2009, so that the noise power $N$ is

***Noise intensity***

$$\boxed{N = k_B T_N \Delta f} = 1.38 \times 10^{-23} \times 10^4 \times 5 \times 10^5 = \boxed{6.9 \times 10^{-14} \text{ [W]}} \quad (1)$$

Since the EAS echo candidate at 02:31:51.6 JST on 3 December 2008 has $\boxed{S/N{=}16}$, the power of the backscattered wave, $P_r$, was estimated to be

***Signal intensity***

$$\boxed{P_r = 16 \times N} = 16 \times 6.9 \times 10^{-14} = \boxed{1.1 \times 10^{-12} \text{ [W]}} \quad (2)$$

Preliminary

## Radar Equation

$$P_r = \frac{\lambda^2}{(4\pi)^3 R^4} \boxed{\sigma_b} P_t G_t G_r \quad [\mathrm{W}]$$

where

| | | |
|---|---|---|
| $\lambda$: | wavelength | 6.4 m |
| $R$: | range (distance to EAS) | $24 \pm 4.8$ km … $R = 24 \times 10^3 R_{24}$ m ($R_{24}$=0.8~1.2) |
| $\sigma_b$ : | radar cross section | |
| $P_t$: | transmission power | 1MW |
| $G_t$: | transmission antenna gain | ~1 |
| $G_r$: | reception antenna gain | ~137 |

Substituting appropriate values to $\lambda$, $R$, $P_t$, $G_t$, $G_r$, we have

$$\boxed{P_r = 8.5 \times 10^{-12} R_{24}^{-4} \ \sigma_b \quad [\mathrm{W}]}$$

From the observation of an EAS candidate, we have obtained $\boxed{P_r = 1.1 \times 10^{-12}\ \mathrm{W}.}$
Finally, we obtain the estimation of the RCS,

$$\boxed{\sigma_b = 0.129 R_{24}^4 \quad [\mathrm{m}^2]}$$

Preliminary

dependence

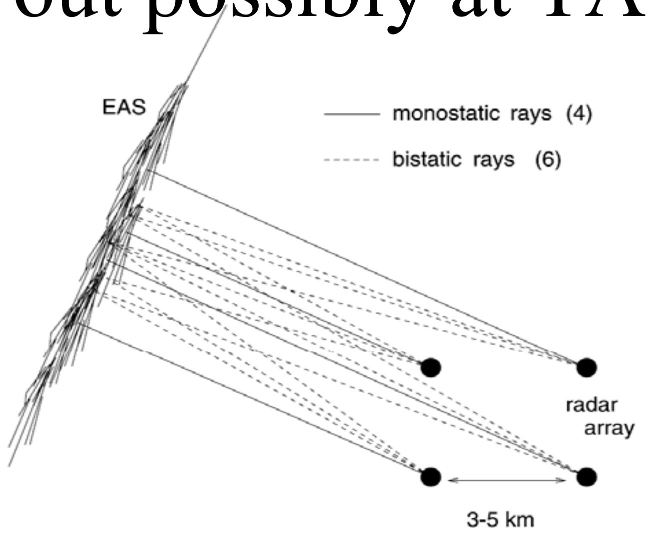
Cosmic ray energy, EAS structure, Geometrical condition for scattering

# Summary

- We applied a large VHF atmospheric radar (MU radar) for detection of EAS radar echoes, in order to investigate echo characteristics and feasibility of multistatic large aperture radar observations.
- Using a state-of-art multichannel receiving system, EAS echoes are scanned.
- From observations of about 3 hours, we have detected one EAS echo candidate and 4 possible signals.
- The echo length was ~4us (HMFW) or less. From the observed echo power, we are trying to get the energies of the cosmic ray particles responsible for these candidates.

# Summary (cnt'd) – future plan

- Since the echo duration is short, we will continue our survey with a faster sampling rate (up to 0.5 us) with the MU radar, for clarifying echo characteristics.
- After the investigations with the MU radar, we will design a set-up for field observations, and radar experiments with other EAS observation instruments will be carried out possibly at TA site, in Utah.



End