INITIAL OBSERVATION RESULTS FOR PRECIPITATION ON THE KU-BAND BROADBAND RADAR NETWORK

Ei-ichi Yoshikawa¹,², Satoru Yoshida¹, Takeshi Morimoto¹, Tomoo Ushio¹, Zen Kawasaki¹, and Tomoaki Mega³

Osaka University, Osaka, Japan¹
Colorado State University, CO., U.S.²
Kyoto University, Kyoto, Japan³

IGARSS 2011, Vancouver-Sendai, Jul. 29, 2011
Outline

1. Introduction
2. The Ku-band Broadband Radar (Ku-BBR)
   - Design concept
   - Observation accuracy
   - Observation result
3. The Ku-BBR Network
   - Deployment in Osaka
   - Initial observation Result
4. Conclusion
Introduction

Resolution of Conventional Weather Radar

○ Fronts, Hurricanes
○ Mesocyclones, Supercells, Squall lines
△ Thunderstorms, Macrobursts

100m

10min

Micro

Horizontal scale [m]

10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}

Mesom

1month
1week
1day
1min
Introduction

Resolution of the Ku-BBR Network

○ Fronts, Hurricanes
○ Mesocyclones, Supercells, Squall lines
○ Thunderstorms, Microbursts

△ Smaller phenomena?

1 min

Several meters

1 month
1 week
1 day

Micro
Mesoscale

Horizontal scale [m]
Introduction

The Ku-BBR Network

- **High resolution**
  - Range resolution: several meters
  - 3-dB beam width: 3 deg
  - Temporal resolution: 1 min/VoS

- **Short range (15 km) radar**
  - Min altitude: 14 m
  - Efficient for Troposphere (8 through 15 km altitude)

- **Multi-Radar Network**
  - Precipitation attenuation correction
  - High resolution grid retrieval
  - Wider area
Design Concept of the Ku-BBR

**High resolution**

- Pulse compression
  
  Gain: \( BT \)
  
  Range resolution: \( \frac{c}{2B} \)

\( B \): Band width (Hz), \( T \): Pulse width (sec),
\( c \): Light speed (m/sec)

**Wide Band Width**

- Ku-band
  
  - Band width of 80 MHz
    \( \Rightarrow \) Range resolution of 2 m (max)
  
  - In C- and X-band, it is difficult to obtain wide band width in Japan.

**Precipitation Attenuation**

- Short range: 15 km
  (Dual-polarization)

  - Polarimetric parameters are more sensitive in Ku-band than other low frequency radars.

**Wide Area & High Accuracy**

- Multi-radar network

  - Higher accuracy in overlapped area
  
  - Network approach for precipitation attenuation correction
**D/A Converter** generates IQ signals arbitrarily. (170 MHz (max), 14 bit)

**Bistatic Lens Antenna** to eliminate blind range

**Real-time Digital Signal Processing** for **Pulse Compression and Doppler Spectrum Estimation**
Signal Processing Unit

- First: Pulse compression, Second: Doppler spectrum estimation
- Parallel calculation with DSPs
  - First: 32 DSPs (32 bit integer, 1 GHz), Second 3 DSPs (Float, 300 MHz)

New FPGA system is in the process of production.
Fast Scanning System

Luneburg Lens (φ450 mm)

Primary Feed

Azimuth rotation
40 RPM (max)
30 RPM (usual)

Elevation rotation
### Specifications

<table>
<thead>
<tr>
<th>Name</th>
<th>Specifications</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational Frequency [GHz]</td>
<td><strong>15.75</strong></td>
<td></td>
</tr>
<tr>
<td>Operational Mode</td>
<td>Spiral, Conical, Fix</td>
<td></td>
</tr>
<tr>
<td>Band Width[MHz]</td>
<td><strong>80 (max)</strong></td>
<td>15.71 - 15.79 GHz</td>
</tr>
<tr>
<td>Coverage Az / EL [deg]</td>
<td>0-360 / 0-90</td>
<td></td>
</tr>
<tr>
<td>Coverage Range [km]</td>
<td><strong>15 km (16 dBZ)</strong></td>
<td>variable</td>
</tr>
<tr>
<td>Resolution Az / El [deg]</td>
<td>3 / 3</td>
<td></td>
</tr>
<tr>
<td>Resolution Range [m]</td>
<td><strong>2 (min)</strong></td>
<td>variable</td>
</tr>
<tr>
<td>Resolution Time/1scan [sec]</td>
<td><strong>60</strong></td>
<td></td>
</tr>
<tr>
<td>Power Consumption [kVA]</td>
<td>4kVA (max)</td>
<td></td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>500kg (max)</td>
<td></td>
</tr>
<tr>
<td><strong>Antenna</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gain [dBi]</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Beam Width [deg]</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear</td>
<td></td>
</tr>
<tr>
<td>Cross Polarization [dB]</td>
<td>25 (min)</td>
<td></td>
</tr>
<tr>
<td>Antenna Noise Temp. [K]</td>
<td>75 (typ)</td>
<td></td>
</tr>
<tr>
<td><strong>Transmitter &amp; Receiver</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission Power [W]</td>
<td>10(max)</td>
<td></td>
</tr>
<tr>
<td>Duty Ratio</td>
<td>variable</td>
<td></td>
</tr>
<tr>
<td>Noise figure [dB]</td>
<td>2 (max)</td>
<td></td>
</tr>
<tr>
<td><strong>Signal Processing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D/A</td>
<td>170MHz - 14bit</td>
<td>IQ 2ch</td>
</tr>
<tr>
<td>A/D</td>
<td>170MHz - 14bit</td>
<td>IQ 2ch</td>
</tr>
<tr>
<td>Range Gate [point]</td>
<td>32768</td>
<td></td>
</tr>
<tr>
<td>PRT [us]</td>
<td>variable</td>
<td></td>
</tr>
</tbody>
</table>
Observation Accuracy

Cross-validation with Joss-Waldvogel Disdrometer (JWD)

- Impact type disdrometer
- Rain drop diameter: 0.3 - 5.0 mm
- $Z_e$ is calculated by Mie theory

$$Z_e = \frac{\lambda^4}{\pi^5} \left| \frac{\varepsilon + 2}{\varepsilon - 1} \right|^2 \int \sigma_b(D) \cdot N(D) dD$$

$$\sigma_b = \frac{\lambda^2}{4\pi} \sum_{l=1}^{\infty} (-1)^l (2l + 1)(a_l - b_l)^2$$

$N(D)$: DSD

$\sigma_b$: Back Scattering coefficient from mie scattering
Observation Accuracy

- The high resolution reflectivity measurements of the BBR show fairly good agreement compared with JWD.
  - Correlation coefficient: 0.95, Standard deviation: 1.59 dBZ
Examples of Ku-BBR Observation

Vertical Pointing Mode

Time-Height Cross Section (Reflectivity)

Range resolution of several meters

Minimum observation height of 50 m
Examples of Ku-BBR Observation

Volume Scanning Mode

3D structure of strong vortex (Resolution of several meters, 1 min)
2(3)-BBR Network in Japan

Toyonaka radar
(Dual-pol)
135.455748E
34.804939N

SEI radar
135.435054E
34.676993N

Nagisa radar
135.659029E
34.840145N
(from Aug., 2011)

Osaka area, Japan
Integration clearly shows precipitation patterns because of the high temporal resolution.

Integration by using simple geometric weighting average.
Initial Observation Results

(a-2) Reflectivity in 1 km AGL

(b-2) Reflectivity in 1 km AGL

(c-2) Integrated Reflectivity in 1 km AGL

13:55:09 09/14/10
Initial Observation Results

(a-3) Reflectivity in 1 km AGL

(b-3) Reflectivity in 1 km AGL

(c-3) Integrated Reflectivity in 1 km AGL
Initial Observation Results

(a-4) Reflectivity in 1 km AGL

(b-4) Reflectivity in 1 km AGL

(c-4) Integrated Reflectivity in 1 km AGL

13:57:17 09/14/10
Initial Observation Results

(a-5) Reflectivity in 1 km AGL

(b-5) Reflectivity in 1 km AGL

(c-5) Integrated Reflectivity in 1 km AGL

13:58:21 09/14/10
Initial Observation Results

Clear shapes of precipitation are retrieved.

Thin-plate shaped pattern of the BBR still remains.
Conclusion

• We developed the Ku-BBR Network, a short-range and high-resolution weather radar network.
  – Range resolution of several meters
  – Temporal resolution of 1 min per volume scan (30 elevations)
  – Coverage of 50 – 15000 m in range

• Due to the high spatial resolution, reflectivity is accurately measured.
  – Reduction of the error from non-uniform beam filling
  – Very low Minimum detectable height

• Precipitation patterns are clearly shown by data integration
  – With a use of a simple weighting average
  – Due to the high temporal resolution
  – Integrated products will be improved by a network radar signal processing
Thank you for listening!

End
Integration clearly shows precipitation patterns because of the high temporal resolution.

Integration by using simple geometric weighting average.

13:54:05 09/14/10
Initial Observation Results

(a-2) Reflectivity in 1 km AGL

(b-2) Reflectivity in 1 km AGL

(c-2) Integrated Reflectivity in 1 km AGL
Initial Observation Results

(a-3) Reflectivity in 1 km AGL

(b-3) Reflectivity in 1 km AGL

(c-3) Integrated Reflectivity in 1 km AGL

13:56:13 09/14/10
Initial Observation Results

(a-5) Reflectivity in 1 km AGL

(b-5) Reflectivity in 1 km AGL

(c-5) Integrated Reflectivity in 1 km AGL

13:58:21 09/14/10
Introduction

Resolution of the BBR

Smaller phenomena??

○ Fronts, Hurricanes
○ Mesocyclones, Supercells, Squall lines
○ Thunderstorms, Microbursts

○ Cumulus, Tornadoes, Microbursts

1min

Several meters

Turbulence, Sound waves

Horizontal scale [m]

10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
Introduction

The BBR Network

- Unobservable area in low altitudes
  - in 0 deg elevation
  - 300 km range: 5 km altitude
  - 100 km range: 0.5 km altitude
  - 15 km range: 14 m altitude

- Needless area to be observed
  - Troposphere is below 8 through 15 km altitude

- High resolution
  - Range resolution: several meters
  - 3-dB beam width: 3 deg
  - Temporal resolution: 1 min/VoS

- Cover large area with multi radar

- Precipitation attenuation
1. The Ku-band BroadBand Radar (The Ku-BBR)
   - Theory
   - Observation accuracy
   - Initial observation result

2. The Ku-BBR Network
   - Theory
   - Deployment in Osaka
   - Initial Observation Result

3. A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network
   - Algorithm
   - Simulation Result
Chapter 1: The Ku-BBR

1. The Ku-band BroadBand Radar (The Ku-BBR)
   - Theory
   - Configuration
   - Initial observation result

2. The Ku-BBR Network
   - Theory
   - Deployment in Osaka
   - Initial Observation Result

3. A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network
   - Algorithm
   - Simulation Result
**Concept**

**High resolution**
- **Pulse compression**
  - Gain: \( BT \)
  - Range Resolution: \( \frac{c}{2B} \)

\( B \): Band width (Hz), \( T \): Pulse width (sec), \( c \): Light speed (m/sec)

**Wide Band Width**
- **Ku-band**
  - Band width of 80 MHz
  - \( \Rightarrow \) Range resolution of 2 m (max)
  - In C- and X-band, it is difficult to obtain wide band width in Japan.

**Precipitation Attenuation**
- **Designed as a short range polarimetric radar**
  - Polarimetric parameters are more sensitive in Ku-band than other low frequency radars.

**Wider Area & Higher Accuracy**
- **Radar network**
  - Higher accuracy in overlapped area
  - Network approach for precipitation attenuation correction

---

*Chapter 1 The Ku-BBR*
Pulse Compression for Distributed Particles

- **Pulse Compression**
  - gives us sufficient energy on a target for detection with **high range resolution** and **signal-to-noise ratio** (SNR).
  - is equivalent to **cross correlation** between transmitted and received signals (almost equal to auto correlation).

High power & short-duration pulse

Low power & long-modulated pulse
Chapter 1 The Ku-BBR

Pulse Compression for Distributed Particles

- Radar Equation for Precipitation Particles with Pulse Compression

\[
\overline{P}_r (r) = \frac{P_i G^2 \theta_h c \tau \pi^3}{2^{10} \ln(2) l \lambda^2 r^2} \left| \frac{\varepsilon^2 - 1}{\varepsilon^2 + 2} \right| Z
\]

- Radar equation (received power) does NOT actually change.
- High range resolution responding wide band width is accomplished.
- High SNR due to long pulse reduces to integrate pulses and allows one to scan rapidly.
**Configuration**

**D/A Converter** generates IQ signals **arbitrarily**. (170 MHz (max), 14 bit)

**Bistatic Lens Antenna** (36 dBi, 3 deg)

**Real-time Digital Signal Processing** for **Pulse Compression** and **Doppler Spectrum Estimation**

---

**Chapter 1** The Ku-BBR
Bistatic Lens Antenna System

- **Direct Coupling level**
  - Bistatic antenna (-70 dB) < Monostatic antenna with a duplexer
  - The nearest range is 50 m because we don’t need to turn the receiver off.

- **Simple Construction for Fast Scanning**
Bistatic Lens Antenna System

Azimuth rotation
40 RPM (max)
30 RPM (usual)

Elevation rotation
Signal Processing Unit

- First: Pulse compression, Second: Doppler spectrum estimation
- Parallel calculation with DSPs
  - First: 32 DSPs (32 bit integer, 1 GHz), Second 3 DSPs (Float, 300 MHz)

New FPGA system is in the process of production.

Chapter 1 The Ku-BBR
## Specifications

<table>
<thead>
<tr>
<th>Name</th>
<th>Specifications</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational Frequency [GHz]</td>
<td><strong>15.75</strong></td>
<td></td>
</tr>
<tr>
<td>Operational Mode</td>
<td>Spiral, Conical, Fix</td>
<td></td>
</tr>
<tr>
<td>Band Width [MHz]</td>
<td><strong>80 (max)</strong></td>
<td>15.71 - 15.79 GHz</td>
</tr>
<tr>
<td>Coverage Az / EL [deg]</td>
<td>0-360 / 0-90</td>
<td></td>
</tr>
<tr>
<td>Coverage Range [km]</td>
<td><strong>15 km (16 dBZ)</strong></td>
<td>variable</td>
</tr>
<tr>
<td>Resolution Az / El [deg]</td>
<td>3 / 3</td>
<td></td>
</tr>
<tr>
<td>Range [m]</td>
<td><strong>2 (min)</strong></td>
<td>variable</td>
</tr>
<tr>
<td>Time/1scan [sec]</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Power Consumption [kVA]</td>
<td>4kVA (max)</td>
<td></td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>500kg (max)</td>
<td></td>
</tr>
<tr>
<td><strong>Antenna</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gain [dBi]</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Beam Width [deg]</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear</td>
<td></td>
</tr>
<tr>
<td>Cross Polarization [dB]</td>
<td>25 (min)</td>
<td></td>
</tr>
<tr>
<td>Antenna Noise Temp. [K]</td>
<td>75 (typ)</td>
<td></td>
</tr>
<tr>
<td><strong>Transmitter &amp; Receiver</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission Power [W]</td>
<td>10(max)</td>
<td></td>
</tr>
<tr>
<td>Duty Ratio</td>
<td>variable</td>
<td></td>
</tr>
<tr>
<td>Noise figure [dB]</td>
<td>2 (max)</td>
<td></td>
</tr>
<tr>
<td><strong>Signal Processing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D/A</td>
<td>170MHz - 14bit</td>
<td>IQ 2ch</td>
</tr>
<tr>
<td>A/D</td>
<td>170MHz - 14bit</td>
<td>IQ 2ch</td>
</tr>
<tr>
<td>Range Gate [point]</td>
<td>32768</td>
<td></td>
</tr>
<tr>
<td>PRT [us]</td>
<td>variable</td>
<td></td>
</tr>
</tbody>
</table>
Observation Accuracy

Cross-validation with Joss-Waldvogel Disdrometer (JWD)

- Impact type disdrometer
- Rain drop diameter: 0.3 - 5.0 mm
- $Z_e$ is calculated by Mie theory

$$Z_e = \frac{\lambda^4}{\pi^5} \left| \frac{\varepsilon + 2}{\varepsilon - 1} \right|^2 \int \sigma_b(D) \cdot N(D) dD$$

$$\sigma_b = \frac{\lambda^2}{4\pi} \sum_{l=1}^{\infty} (-1)^l (2l + 1)(a_l - b_l)^2$$

$N(D)$: DSD

$\sigma_b$: Back Scattering coefficient from mie scattering
The high resolution reflectivity measurements of the BBR show fairly good agreement compared with JWD.

- Correlation coefficient: **0.95**, Standard deviation: **1.59 dBZ**
Comparison to C-band Radar

C-band radar (El = 0.09deg)  

The Ku-BBR (Base scan)

Highly attenuated

Fine structures are shown

Chapter 1  The Ku-BBR
Observation Result (Time series example)

Toyonaka, Osaka university

Chapter 1 The Ku-BBR
Example – tornado?

2nd elevation
(in altitudes of 0 m – 270 m, roughly)
Example – tornado?

3rd elevation
(in altitudes of 0 m – 450 m, roughly)
Example – tornado?

4th elevation
(in altitudes of 0 m – 640 m, roughly)
Example – tornado?

5th elevation
(in altitudes of 0 m – 820 m, roughly)
Example – tornado?

6\textsuperscript{th} elevation
(in altitudes of 0 m – 1000 m, roughly)
Example – tornado?

7th elevation
(in altitudes of 0 m – 1190 m, roughly)
Example – tornado?

8th elevation
(in altitudes of 0 m – 1370 m, roughly)
Chapter 1  The Ku-BBR

Example – tornado?

9th elevation
(in altitudes of 0 m – 1550 m, roughly)
Example – tornado?

10^{th} elevation
(in altitudes of 0 m – 1610 m, roughly)
Summary of Chapter 1

• We developed the Ku-BBR, a short-range and high-resolution weather radar.
  – Range resolution of several meters
  – Temporal resolution of 1 min per volume scan (30 elevations)
  – Coverage of 50 – 15000 m in range

• Due to the high spatial resolution, reflectivity is accurately measured.
  – Reduction of the error from non-uniform beam filling
  – Very low Minimum detectable height

• The Ku-BBR finely detected a small phenomena not resolved by a conventional C-band radar.

• The BBR is a strong tool to detect, analyze and predict these small scale phenomena.
Ch. 2: The Ku-BBR Network

1. The Ku-band BroadBand Radar (The Ku-BBR)
   - Theory
   - Observation accuracy
   - Initial observation result

2. The Ku-BBR Network
   - Theory
   - Deployment in Osaka
   - Initial Observation Result

3. A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network
   - Algorithm
   - Simulation Result
Network Approach of the Ku-BBR

- Single BBR

**Cross-range resolution**

- **785 m** in 15 km range
- **524 m** in 10 km range
- **262 m** in 5 km range
- **3 deg**

**Range resolution**

- Range resolution is very high.
- On the other hand, cross-range resolution is **100 times poorer** than range resolution in a range of 15 km.
- Composite average function (CAF) is a thin-plate shape.
Network Approach of the Ku-BBR

- The Ku-BBR Network

- CAFs of two radar nodes are overlapped.

- A weighting average of the two received powers is equivalent to that of the two CAFs.

- Overlapping two thin-plate shapes achieves several meter resolution in 2- or 3-D.
Equations

Single Radar Equation

\[ P(r_0) = \iiint \eta(r) I(r_0, r) dV \]

where,

Composite Average Function (CAF)

\[ I(r_0, r) = \frac{P_t g^2 \lambda^2 f^4 (\theta - \theta_0, \phi - \phi_0) |W_s(r_0, r)|^2}{(4\pi)^3 l^2(r) r^4} \]

Equivalent Reflectivity Factor

\[ \eta(r) = \int_0^\infty \sigma_b(D) N(D, r) dD \]

\[ dV = r^2 dr \sin \theta d\theta d\phi \]
Network Approach of the Ku-BBR

A Weighting Average of Received Signals Obtained by Each Radar Node

\[ \hat{P}(\mathbf{r}_0) = \sum_{n=1}^{N} w_n \bar{P}_n(\mathbf{r}_0) \]

\[ = \sum_{n=1}^{N} w_n \iiint \eta(\mathbf{r}) I_n(\mathbf{r}_0, \mathbf{r}) dV \]

\[ = \iiint \eta(\mathbf{r}) \sum_{n=1}^{N} w_n I_n(\mathbf{r}_0, \mathbf{r}) dV \]

\[ \equiv \iiint \eta(\mathbf{r}) \hat{I}(\mathbf{r}_0, \mathbf{r}) dV \]

where, \[ \sum_{n=1}^{N} w_n = 1 \]

A weighting average of received signals is translated to…

A weighting average of CAFs
Evaluation of Spatial Resolution

- Simulation in a two-BBR network on base scan

<table>
<thead>
<tr>
<th>Zonal range (km)</th>
<th>Meridional range (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-7, 0)</td>
<td>(-7, 0)</td>
</tr>
<tr>
<td>(7, 0)</td>
<td>(7, 0)</td>
</tr>
</tbody>
</table>

Overlapped area

Non-overlapped area
Evaluation of Spatial Resolution

- **Normalized CAF (NCAF)**
  - Single radar
    \[
    \bar{P}(r_0) = \frac{P_t g^2 \lambda^2}{(4\pi)^3 r_0^2 l^2(r_0)} \int_0^r \int_0^\pi \int_0^{2\pi} |W_s(r_0, r)|^2 f^4(\theta, \phi) \eta(r) dr d\theta d\phi
    \]
    \[
    \equiv \frac{P_t g^2 \lambda^2}{(4\pi)^3 r_0^2 l^2(r_0)} \iiint A(r_0, r) \eta(r) dr
    \]
  - Radar network
    \[
    \hat{P}(r_0) = \frac{P_t g^2 \lambda^2}{(4\pi)^3 l^2(r_0)} \iiint \eta(r) \sum_{n=1}^N \frac{w_n}{r_{0n}^2} A_n(r_0, r) dr
    \]
    \[
    \equiv \frac{P_t g^2 \lambda^2}{(4\pi)^3 l^2(r_0)} \iiint \eta(r) \hat{A}(r_0, r) dr
    \]
Evaluation of Spatial Resolution

- **Assumptions of Two BBR Simulation**
  - A Gaussian shape CAF
    \[ W_s = \exp \left( -\frac{(r - r_0)^2}{(r_h/2)^2} \ln 2 \right) \] : A Gaussian pulse
    \( \sigma = 7.5 \text{ m (corresponding to } B = 20 \text{ MHz}) \)

  - A Gaussian beam
    \[ f^4(\theta - \theta_0, \phi - \phi_0) = \exp \left( -\frac{(\theta - \theta_0)^2}{(\theta_h/2)^2} \ln 2 \right) \exp \left( -\frac{(\phi - \phi_0)^2}{(\phi_h/2)^2} \ln 2 \right) \] : A Gaussian beam
    \( \sigma = 3 \text{ deg} \)

  - A weighting function
    \[ w_n = \frac{r_n^2}{\sum_{n=1}^{N} r_n^2} \] : is equivalent to arithmetic average of reflectivity factors in anti-log

  - Precipitation at a point is *simultaneously* observed by each radar node
Single BBR vs Two BBR Network

NCAF in Single BBR (Node 1)

- 518 m cross-range resolution
- 7.5 m range resolution

Thin-plate shaped CAF

Averaged NCAF in Two BBR Network

- 10+^2 m spatial resolution

About 10 x 10 m resolution

Chapter 2 The Ku-BBR Network
Spatial resolution is NOT improved because the range and cross-range resolutions are comparable.
On the other hand, spatial resolution is **NOT** improved around the base-line because two CAF are not crossed.

A spatial resolution of $10+^2 \text{ m}^2$ is accomplished in Almost all region.
Deployment in Osaka Area, Japan

Toyonaka radar (polarimetric)
135.455748E
34.804939N

SEI radar
135.435054E
34.676993N
(from Jun., 2011)

Nagisa radar
135.659029E
34.840145N
Osaka area, Japan
(from Jun., 2011)
Initial Observation Results

(a-1) Reflectivity in 1 km AGL

(b-1) Reflectivity in 1 km AGL

(c-1) Integrated Reflectivity in 1 km AGL

Chapter 2 The Ku-BBR Network
Initial Observation Results

(a-2) Reflectivity in 1 km AGL

(b-2) Reflectivity in 1 km AGL

(c-2) Integrated Reflectivity in 1 km AGL

Chapter 2 The Ku-BBR Network
Initial Observation Results

Chapter 2 The Ku-BBR Network
Chapter 2 The Ku-BBR Network

Initial Observation Results

(a-4) Reflectivity in 1 km AGL

(b-4) Reflectivity in 1 km AGL

(c-4) Integrated Reflectivity in 1 km AGL

13:57:17 09/14/10
Chapter 2: The Ku-BBR Network
Summary of Chapter 2

• The Ku-BBR network accomplishes high spatial resolution in 2- or 3-D.
  – Crossed pattern of several thin-plate shaped CAFs accomplishes high spatial resolution of tens of meters in 2- or 3-D.
  – But spatial resolution around the baseline between two Ku-BBRs is not improved.
  – Three or more-BBR network accomplishes high spatial resolution in 3-D anywhere except for around the ground.

• Initial observation results showed high quality images.
  – Precipitation patterns are clearly shown.
  – Validation of the integrated data is one of our near future works.
Ch.3: Precipitation Attenuation Correction

1. The Ku-band BroadBand Radar (The Ku-BBR)
   – Theory
   – Observation accuracy
   – Initial observation result

2. The Ku-BBR Network
   – Theory
   – Deployment in Osaka
   – Initial Observation Result

3. A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network
   – Algorithm
   – Simulation Result
When assuming a static $k$-$Z$ relation, $k = \alpha Z^\beta$

$$Z_m(r) = Z(r) \exp\left[0.2 \ln 10 \int_0^r k(s) ds\right]$$

The equation is solved as...

$$Z(r) = Z_m(r) \exp\left[C - 0.2 \beta \ln 10 S(r)\right]^{-1/\beta} \quad \therefore S(r) = \int_0^r \alpha Z_m(s)^\beta ds$$

However, it is known that HB solution often outputs large errors...

$Z$ : (un-attenuated) reflectivity, $Z_m$ : measured (attenuated) reflectivity,

$k$ : specific attenuation (dB/km), $C$ : integral constant
What is the problem?

- **Deterministic approach**
  - Deterministic approaches (represented by HB solution) *accumulate estimate errors* in each range bin, as processing in range.
  - The solution is frequently *unstable* and *overshoots*.
    \[ \Rightarrow \text{Stochastic approach} \text{ is better [Haddad et al., 1996]}. \]

- **k-Z relation**
  - Using a constant $k$-$Z$ relation generates estimate errors of $k$ in each range bin.

- **Raindrop size distribution (DSD)**
  - DSD is the most important parameter in radar meteorology.
  - *DSD determines $k$, $Z$,* and so on (including rainfall rate, liquid water content…).
  - However, *it is very difficult to estimate DSD* in each range bin.
Proposal

• **Stochastic approach**
  - *A Kalman filter approach* is applied.
  - *Uncertainties* of estimates are also obtained.

• **Network**
  - Assuming *the same profile at cross points of beams from two radars*, estimates of two BBRs are *integrated with use of corresponding uncertainties*.
  - Uncertainty is also important for *data assimilation into weather numerical models* (Our future work).

• **DSD estimation**
  - In the BBR, *DSD in the lowest altitude of 50 m is accurately estimated*, compared with a ground-based equipment of disdrometer [*Yoshikawa et al., 2010*].
  - Thus, the BBR can *always obtain the initial condition of DSD*. 
Methodology – Basis

<Observation (in dB)>
\[ Z_m(r) = Z_e(r) - PIA(r) \]
\[ \therefore PIA(r) = 2 \int_0^r k(s) ds \]

\[ \text{Z}_e : \text{(un-attenuated) reflectivity (dBZ)} \]
\[ \text{Z}_m : \text{measured (attenuated) reflectivity (dB)} \]
\[ k : \text{specific attenuation (dB/km)} \]
\[ PIA : \text{Path-integrated attenuation (dB)} \]

<Gamma DSD [Ulbrich, 1983]>
\[ N(D) = N_0 D^\mu \exp(-\Lambda D) \]
\[ \therefore N_0 \approx 6 \times 10^3 \exp(0.9 \mu) \]

<Extended Kalman Filter>

\[ \Lambda'(r + \Delta r) = \Lambda'(r) + w_{\Lambda'} \]
\[ \mu(r + \Delta r) = \mu(r) + w_{\mu} \]
\[ PIA(r + \Delta r) = PIA(r) + 2\Delta r k(\mu(r), \Lambda'(r)) \]

\[ \text{Prediction :} \]
\[ \text{Filtering :} \]
\[ Z_m(r) = Z_e(\mu(r), \Lambda'(r)) - PIA(r) + v(r) \]
Methodology – Processing (1/2)

Step 1: Single-path retrieval
Retrievals in each beam starting with initial condition

Step 2: Trading estimate values only at cross points
Methodology – Processing (2/2)

**Step 3:**
Retrievals in each beam starting with traded cross points

**Step 4:** *Network retrieval*
Optimal estimation with use of all filtering
Simulation Model

True Ze on BBR1

True Ze on BBR2

Zm on BBR1

Zm on BBR2
Simulation Result – Reflectivity

Step 1
Single-path retrieval

Underestimate

BBR1 (dBZ)

Underestimate

BBR2 (dBZ)

Step 4
Network retrieval

Unstable a little

Corrected!
Simulation Result – Comparison to HB solution

HB solution

Overshoot

BBR1 (dBZ)

BBR2 (dBZ)

Network retrieval

Retrieved Ze on BBR1 (dBZ)

Retrieved Ze on BBR2 (dBZ)
Summary of Chapter 3

• A Kalman filter approach for precipitation attenuation correction in the Ku-BBR network is developed.
  – Gamma DSD
  – Stochastic approach with a use of Kalman filter
  – Cyclic optimization in the radar network environment.

• Simulation shown a high estimate accuracy.
  – Ze is accurately retrieved.
  – It is difficult to retrieve DSD parameters accurately.
  – Under consideration to use polarimetric parameters

• Estimate accuracy depends on variances of DSD parameters (now under tuning).

• Cross validation with disdrometer is our future work.
Thank you for listening!

End
Back up
観測可能高度

地形により更に制限を受ける。

Ku帯広帯域レーダの観測

空間分解能

・ パルス圧縮レーダの距離分解能

\[ \Delta r = \frac{c}{2B} \approx 2[m] \quad (\because B = 80[MHz]) \]

・ アンテナ指向性

\[ 2\theta_h = 3[\text{deg}] \]
Cバンドレーダとの比較（旧ver.）

Comparison of each method with C-band radar

- Zm of C-band radar
- Zm of BBR
- Retrieved Ze of BBR (an old version)
Cバンドレーダとの比較（旧ver.）
Precipitation Attenuation  – Mie solution

The solution for **back scattering cross section** and **absorption cross section** for a water particle of dielectric sphere is due to Mie.

\[
\frac{\sigma_s}{\pi r^2} = \xi_s(n, \chi) = \frac{2}{\chi^2} \sum_{l=1}^{\infty} (2l + 1) \Re\left( |a_l|^2 + |b_l|^2 \right)
\]

\[
\frac{\sigma_e}{\pi r^2} = \xi_e(n, \chi) = \frac{2}{\chi^2} \sum_{l=1}^{\infty} (2l + 1) \Re\{a_l + b_l\}
\]

\(\sigma_s\) : scattering cross section, \(\sigma_e\) : extinction cross section,

\(a_l, b_l\) : recursion formula for Bessel function,

\(n\) : refractive index, \(\chi = 2\pi r/\lambda\)
Precipitation Attenuation – Equation

\[
Z_m(r) = Z_e(r) - 2 \times 10^{-3} \int_0^r k(s) ds
\]

- \( Z_m(r) \): Measured Reflectivity
- \( Z_e(r) \): Equivalent Reflectivity
- \( k(s) \): Specific attenuation (dB/km)
- \( Z_\text{att} \): Path-Integrated Attenuation (PIA)

Chapter 3  A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network
Traditional Method for Correction

Assumptions

- B.C.: \( Z_m(r_0) = Z_e(r_0) \)
- k-Z relation: \( k(r) = \alpha Z_e(r)^\beta \)

Chapter 3 A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network
What is problem?

- **k-Z relation**
  - is dependent on DSD
  - yields errors in each range bin if its coefficients are constant.

- **Attenuation at Ku-band**
  - 10 – 100 times more than C-band
  - 4 – 6 times more than X-band

- **Deterministic Approach**
  - Errors in k-Z relation are accumulated.
  \[ \Rightarrow \text{Output is more unstable in longer ranges or with heavier precipitation.} \]
Proposed Algorithm

- Assuming a Gamma DSD
  \[ N(D) = N_0 D^\mu \exp(-\Lambda D) \]
  \[ \; \; [\therefore N_0 \approx 6 \times 10^3 \exp(0.9\mu) ] \]

- No attenuation in the nearest range
  \[ PIA(r_0) = 0 \]

- Applying an extended Kalman filter

**Prediction:**
\[
\begin{align*}
\Lambda'_{n+1} &= \Lambda'_n + w_{\Lambda'} \\
\mu_{n+1} &= \mu_n + w_{\mu}
\end{align*}
\]  
\[ \{ \therefore \exp(-\Lambda) := 1/(1+\exp(-\Lambda')) \} \]

**Filtering:**
\[ Z_{mn} = Z_e(\mu_n, \Lambda'_n) - PIA_n + v_n \]
Simulation – in single BBR

- **HB solution**
  - overestimates in large area
  - approaches infinity in strong precipitation

- **Proposed algorithm**
  - underestimates behind strong precipitation

---

**Chapter 3**  A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network
Algorithm in the BBR Network

**Step 1: Single-path retrieval**
corrects in each path with the boundary condition.

**Step 2: Data Trade**
exchanges corrected data at cross points.

*Chapter 3 A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network*
Algorithm in the BBR Network

**Step 3: Retrieval with Traded Data**
makes other correction data with Kalman algorithm **starting from each traded data**

**Step 4: Network retrieval**
optimally averages all the correction data **with covariance information**

*Chapter 3*  A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network
Simulation – in the BBR network

- Errors remaining in Step 1 is properly re-corrected with a use of radar network environment.

Chapter 3  A Kalman Filter Approach for Precipitation Attenuation Correction in the Ku-BBR Network
Seminar in CSU

Luneburg Lens Antenna

Jun. 24, 2011

Ei-ichi Yoshikawa
Lens Antenna Family

Dielectric (delay) lens  E-plane metal plate (fast) lens

http://www.engineering-eye.com/rpt/c003_antenna/popup/04/image020.html
What is Luneburg Lens?

“Luneberg lens” is spherical lens for microwave.

1944 Proposal as optical lens

1960~ Investigation as lens for microwave

Principle

Luneberg Lens

Microwave

Focal point

Dielectric constant

Dielectric Constant

$E_r = 2 - \left( \frac{r}{R} \right)^2$

$E_r$ : Dielectric Constant

r : Radius

R : Radius of lens

Relative radius of lens

(center) (surface)
Snell’s law  – excerpt from wikipedia

Snell's law states that the ratio of the sines of the angles of incidence and refraction is equivalent to the ratio of phase velocities in the two media, or equivalent to the opposite ratio of the indices of refraction:

\[
\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}
\]

- \(\theta\) : angle measured from the normal
- \(v\) : velocity of light in the respective medium
- \(n\) : refractive index of the respective medium
How to focus?

Simulation by a discretized function of dielectric constant
How to focus?

Simulation by a discretized function of dielectric constant
How to focus?

Simulation by a discretized function of dielectric constant
Focused Beam
Many Focal Points
Typical Application of Luneburg Lens

Several primary feeds are installed in advance

Primary feed

Luneberg Lens

Move a primary feed along to lens surface

Multi-beam Antenna

High Speed beam scanning Antenna

Frequency Range:
VHF - Ka-band
(45MHz) (50GHz)

Polarimetric capability
isolation > 30dB
Construction

Ideal construction

Gradation of dielectric constant

Difficult to form the lens

SEI lens construction

Piling up several Layers

High accuracy original analysis tool (FDTD method)
Material

Use special materials

SEI material
Special PP+special Ceramic

Special ceramic = fiber shape
Able to high dielectric constant

SEI lens
- High performance
- High productivity
- Low weight

General material (PS)
$\varepsilon_r \geq 1.7$ Impossible to form

Conventional lens
Center layers = High gravity bead foams are adhered by adhesives

- Low performance (adhesives: high tanδ)
- Hand made →high cost
- High weight

SUMITOMO ELECTRIC INDUSTRIES, LTD.
Hybrid Products Division