Clutter mitigation in a phased array radar system using the MMSE formulation

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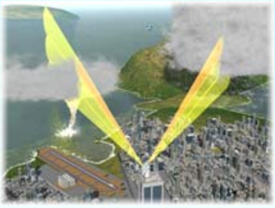
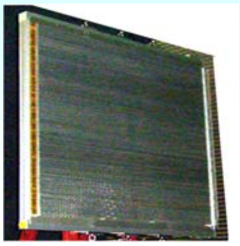
Background

A new phased array radar system for meteorological application has been developed by Toshiba Corporation and Osaka University under a grant of NICT. It is now well known that rapidly evolving severe weather phenomena (e.g., microbursts, severe thunderstorms, tornadoes) are a threat to our lives particularly in a densely populated area and the number of such phenomena tends to increase as a result of the global warming. Over the past decade, mechanically rotating radar systems at the C-band or S-band have been proved to be effective for weather surveillance especially in a wide area more than 100 km in range. However, rapidly evolving weather phenomena have temporal and spatial scales comparable to the resolution limit (-10 min. and -500m) of typical S-band or C-band radar systems, and cannot be fully resolved with these radar systems. In order to understand the fundamental process and dynamics of such fast changing weather phenomena, volumetric observations with both high temporal and spatial resolution are required. The phased array radar system under developing has been required to have the unique capability of scanning the whole sky with 100m and 10 second resolution up to 30 km in a cost effective manner. To achieve this goal, the system adopts the digital beam forming technique for elevation scanning and mechanically rotates the array antenna in azimuth direction within 10 seconds. The radar transmits a broad beam of several degrees with 24 antenna elements and receives the back scattered signal with 128 elements digitizing at each elements. Then by digitally forming the beam in the signal processor, the fast scanning is realized. Although the phased array radar system using the digital beam forming technique can estimate the 3 dimensional structure of the precipitation system within 10 seconds with 100 meter resolution, the received signal may also be seriously contaminated by the relatively high received power from ground clutter and strong precipitation echoes through the side lobes of the transmitting beam. To avoid this problem, a beam forming technique using the MMSE (Minimum Mean Square Error) formulation has been proposed and tested in this paper. 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.

A New Phased Array Radar System



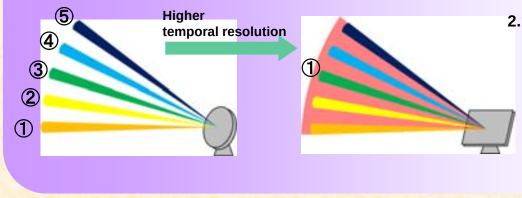
- **High speed volume scan of 10 sec** to detect severe storms **instantaneously**
- Especially for severe storms **developing rapidly in urban area**



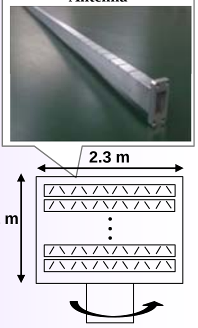
Scan system	**Elevation: Electronic scan** **Azimuth: Mechanical scan**
Coverage	3D scan (90 elevations) / 10 sec (- 1 min)
Parameters	Z_h, v_h, σ_{vh} (single-polarization)

Observation Strategy

- **Conventional radar**
  - observes **each elevation separately**
  - by 2-way sharp beams (transmission and reception)
- **PAWR**
  - observes **several elevations simultaneously**
  - by transmitting fan beam and digital beam forming

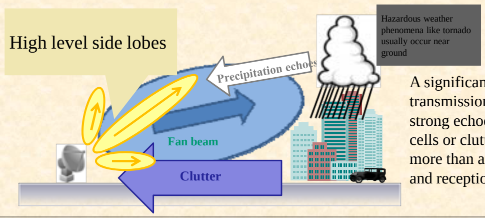


Waveguide Slot Array Antenna



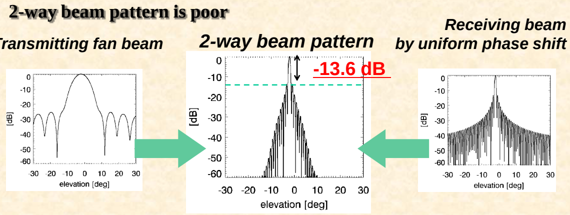
Mechanical Rotation for Azimuth with 6 RPM (max)

Problem



A significant problem of the fan beam transmission is huge side-lobes of strong echoes from strong precipitation cells or clutters, which is two times more than a sharp beam transmission and reception in dB.

★ 2-way beam pattern is poor



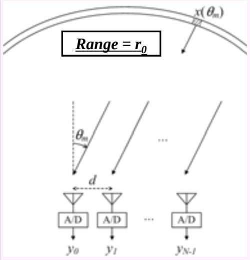
For example, while a sharp beam transmission and reception has a first side-lobe level of -39.2 dB from the main-lobe, a configuration of uniform and sharp beams has a first side-lobe level of -18.6 dB in the same angle. For the side-lobe reduction in phased array antenna system, adaptive DBF methods have been proposed.

MMSE Solution

Signal Model

unknown
known

Considering in a range bin (r_0)



M associated complex amplitudes

$$\mathbf{x}_l = \begin{bmatrix} x_{0,l} & x_{1,l} & \cdots & x_{M-1,l} \end{bmatrix}^T \in \mathbf{C}^{M\times 1}$$

N received complex amplitude

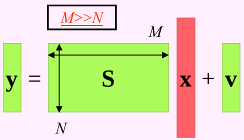
$$\mathbf{y}_l = \begin{bmatrix} y_{0,l} & y_{1,l} & \cdots & y_{M-1,l} \end{bmatrix}^T \in \mathbf{C}^{N\times 1}$$

Steering vector

$$\mathbf{s}(\theta) = \begin{bmatrix} 1 & e^{-j\frac{2\pi}{\lambda}d\cos\theta} & \cdots & e^{-j\frac{2\pi}{\lambda}(M-1)d\cos\theta} \end{bmatrix}^T$$

λ: wave length, l: pulse number

M>>N



$$\mathbf{y} = \mathbf{S}\mathbf{x} + \mathbf{v}$$

$$\mathbf{S} = \begin{bmatrix} \mathbf{s}(\theta_1) & \mathbf{s}(\theta_2) & \cdots & \mathbf{s}(\theta_N) \end{bmatrix} \in \mathbf{C}^{N\times M}$$

$\mathbf{v} \in \mathbf{C}^{N\times 1}$: Additive Gaussian noise vector

$$\hat{x}_{m,l} = \mathbf{w}_m^H \mathbf{y}_l$$

$$\hat{\mathbf{x}}_l = \begin{bmatrix} \hat{x}_{0,l} & \hat{x}_{1,l} & \cdots & \hat{x}_{M-1,l} \end{bmatrix} \in \mathbf{C}^{M\times 1}$$

$$\mathbf{w}_m = \begin{bmatrix} w_0 & w_1 & \cdots & w_{N-1} \end{bmatrix} \in \mathbf{C}^{N\times 1}$$

: Complex weighting vector

Phased array beam forming is …

- to calculate **a weighting average** of received signals in each element
- to calculate **an optimal weights**

MMSE Formulation

MMSE cost function and solution

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

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

$\mathbf{R}_x = E\left[\mathbf{x}_l\mathbf{x}_l^H\right] \approx \left[\frac{1}{L}\sum_{l=1}^{L}\mathbf{x}_l\mathbf{x}_l^H\right] * \mathbf{I}_{M\times M}$: 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, $E[\bullet]$: expectation,

σ_v : standard deviation of thermal noise, $*$: Hadamard product

Re-iterative super resolution (RISR) algorithm

1) Initialization (i=0)

As a prior information, FR solution is calculated.

$$\mathbf{w}_m|_0 \equiv \mathbf{w}_{FR\,m} = \mathbf{s}(\theta_m)$$

$$\hat{x}_{m,l}|_0 = \mathbf{w}_m^H|_0\,\mathbf{y}_l, \quad \hat{\mathbf{x}}_l|_0 = \begin{bmatrix} \hat{x}_{0,l} & \hat{x}_{1,l} & \cdots & \hat{x}_{M-1,l} \end{bmatrix}_0$$

2) Determination of MMSE weights

$$\mathbf{w}_m|_i = E[|x(\theta_m)|_i|^2](\mathbf{S}\mathbf{R}_x|_i\mathbf{S}^H + \mathbf{R}_v)^{-1}\mathbf{s}(\theta_m)$$

Now under improving

3) Gain control

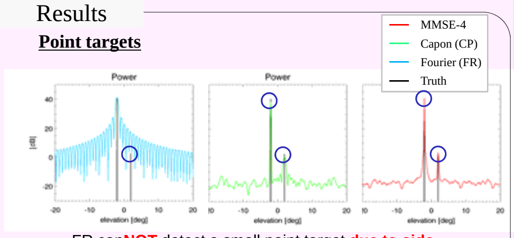
$\mathbf{w}_m|_i = g\,\mathbf{w}_m|_i$, g : gain control factor

4) Computation of MMSE solution and Re-iteration

$$\hat{x}_{m,l}|_{i+1} = \mathbf{w}_m^H|_i\,\mathbf{y}_l, \quad \hat{\mathbf{x}}_l|_{i+1} = \begin{bmatrix} \hat{x}_{0,l} & \hat{x}_{1,l} & \cdots & \hat{x}_{M-1,l} \end{bmatrix}_{i+1}$$

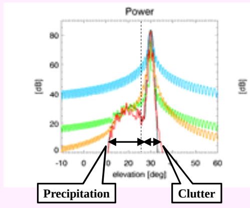
Results

Point targets



- FR can**NOT** detect a small point target **due to side-lobes**.
- CP and MMSE-4 suppress side-lobes and detect both the point targets **with high resolution**.

Precipitation Echoes with a strong clutter



- MMSEs **properly suppresses strong clutter**
- The iteration in MMSE improves the solution.

For the 2 dimensionally distributed target, while the processed signal with the conventional beam former method is seriously contaminated by the relatively high received power from ground clutter and strong precipitation echoes through the side lobes of the transmitting beam, the proposed MMSE based method succeeds to estimate the signal power from precipitation without the degradation of the ground clutter adequately. 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. The simulation results show that the proposed technique can correctly estimate the precipitation echo within a few dB even in the presence of a strong ground clutter that is more than 30 dB higher than the precipitation echo with 15 pulse repetition number. The MMSE based technique is shown to be superior to the standard DBF scenarios under the small number of pulse repetitions to achieve the rapid scanning.