

WPMC 2005

19 September 2005, Aalborg, Denmark

Array Calibration using Measured Data for Precise Angle-of-Arrival Estimation

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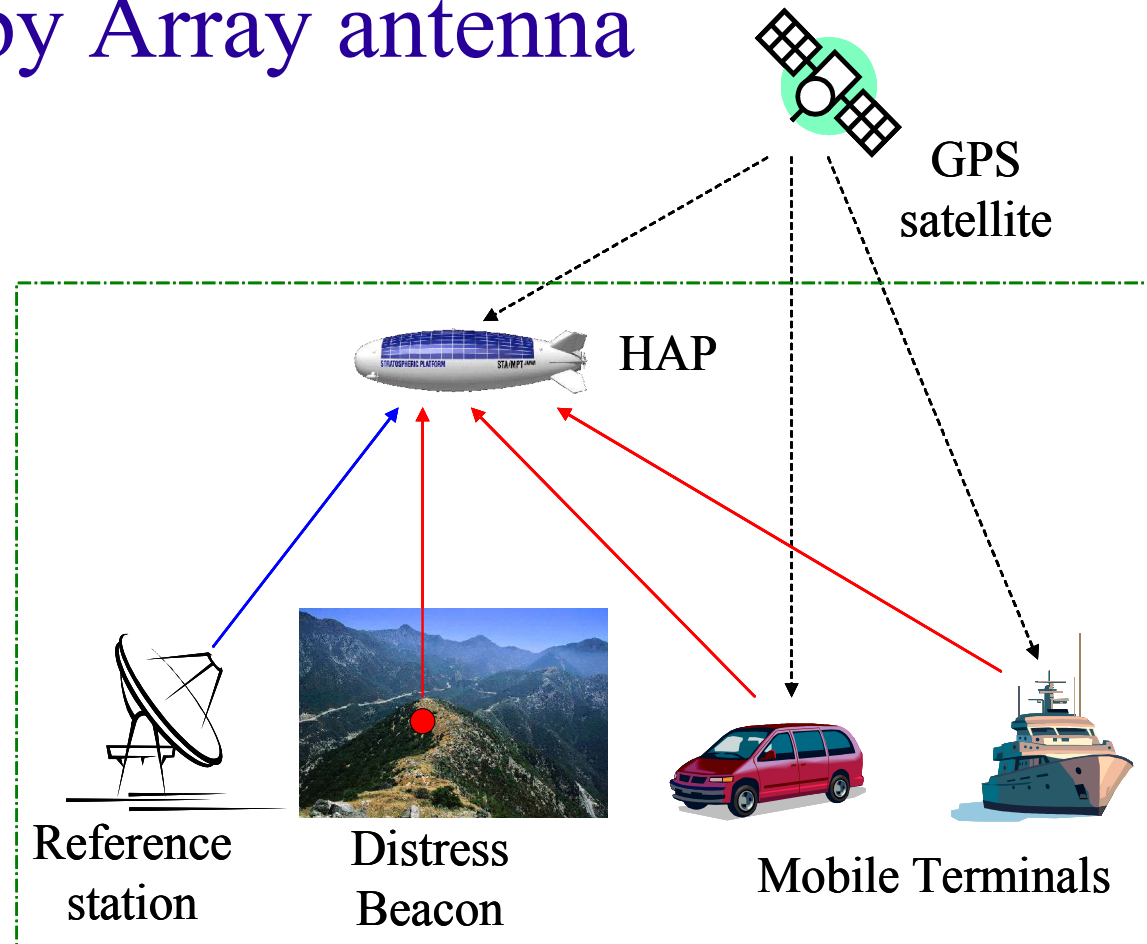
- Background
- Experiment and its specifications
- Array calibration methods and results
- Conclusions
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Background (1)

Mobile Localization by Array antenna

Applications:

- Mobile terminal localization
- Radio surveillance (monitoring illegal radio waves)
- Distress beacons
- Etc.



Focusing on AOA estimation of a signal impinging on an antenna array

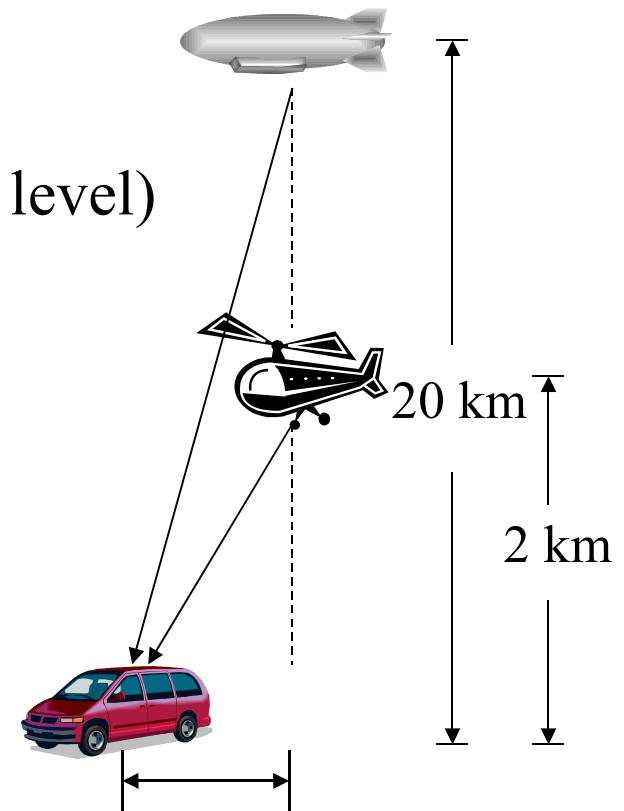
Background (2)

Required performance of AOA estimation

- To estimate AOAs precisely
 - 10m location accuracy the same as GPS
(Standard horizontal error : 95 % confidence level)

Antenna Height	Required Resolution
2 km	0.3 degrees
20 km	0.03 degrees

- High resolution of AOA estimation is required.
- To obtain a high performance of AOA estimation, the perfect array antenna is needed.



Experiment

Specifications of experiment Transmitter

Frequency	1.74 GHz
Antenna element	Patch antenna
Antenna gain	7 dBi
Tx power	1 W (30 dBm)
Modulation	GMSK

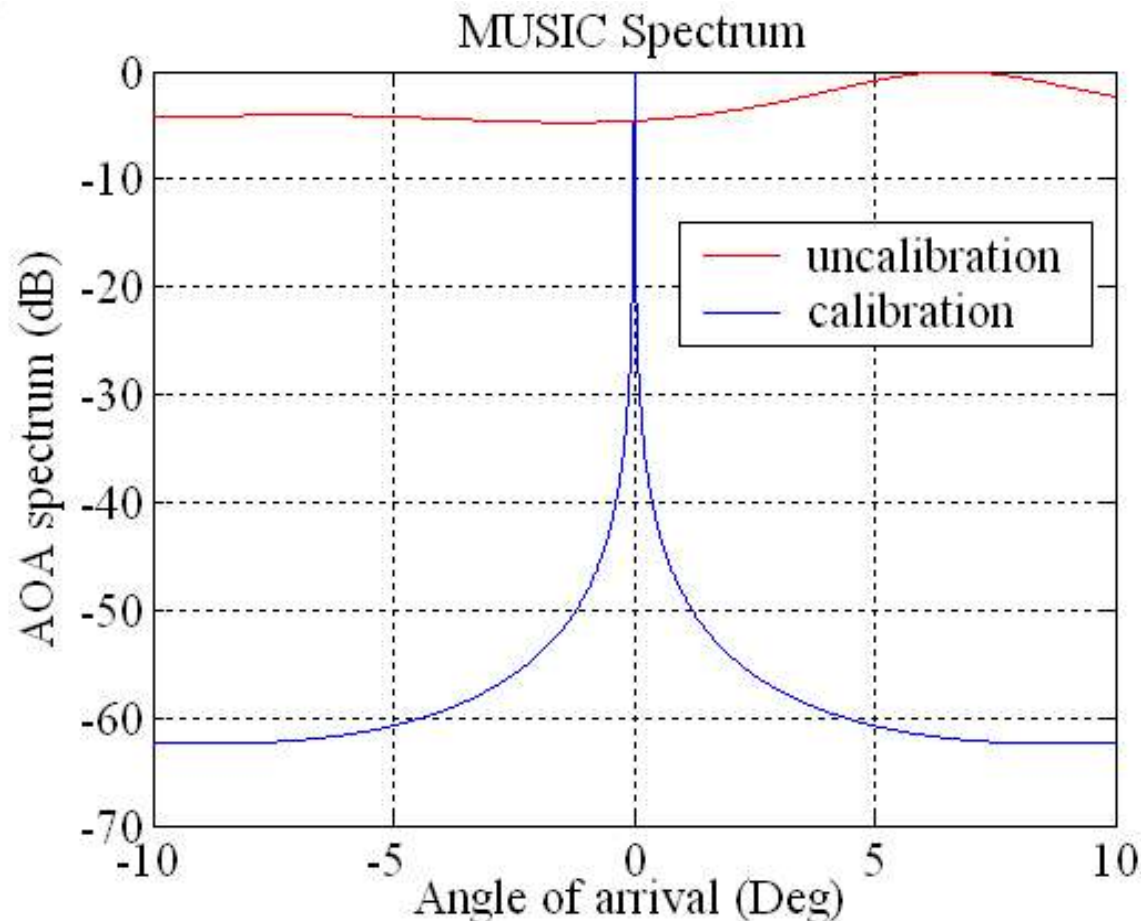
Antenna array

Shape of array	Uniform linear array
Number of elements	10
Element spacing	0.8λ
Antenna element	Patch antenna
Antenna gain	7 dBi

- To obtain data for evaluating characteristics of array antennas for precise AOA estimation
 - Two experiment scenarios, **anechoic chamber (ideal case) and open area**, are taken into account.

Problem from experiment

AOA Estimation Result



Signal arrives at antenna array at 0 degrees.

Low resolution of AOA estimation



Require
Antenna Array calibration

Signal Model

- Consider a single narrowband source impinging on an M -element antenna array, an array output vector can be expressed as

$$\mathbf{x}(t) = \mathbf{K}\mathbf{a}(\theta)s(t) + \mathbf{n}(t)$$

where $s(t)$ is the arriving signal

$\mathbf{n}(t)$ is the noise vector

$\mathbf{a}(\theta)$ is the steering vector

$\mathbf{K}$ is the $M \times M$ array-imperfection matrix
(describing amplitude and phase imperfection of array elements and mutual coupling, etc.)

The calibrated array output can be expressed as

$$\tilde{\mathbf{x}}(t) = \mathbf{C}\mathbf{x}(t)$$

where $\mathbf{C}$ is the the $M \times M$ calibration matrix and $\mathbf{C} = \mathbf{K}^{-1}$.

Array Calibration Methods

- How to obtain the calibration data?
- Three array calibration methods are proposed.
 - Amplitude and phase compensation technique
 - Phase approximation based on least square problem
 - Signal subspace approach
- The effectiveness of the proposed calibration methods is evaluated by estimating AOAs based on Multiple Signal Classification (MUSIC) algorithm.

Calibration method-1

Amplitude and Phase Compensation Technique

- In the case of signal impinging on the antenna array at 0 degrees, signal amplitude and phase of each element are theoretically same.
- However, imperfection of array because of implementation usually occurs.
 - Amplitude and phase mismatch of array elements is taken into account. (Assuming no mutual coupling)

The array imperfection matrix, $\mathbf{K}$, can be expressed as

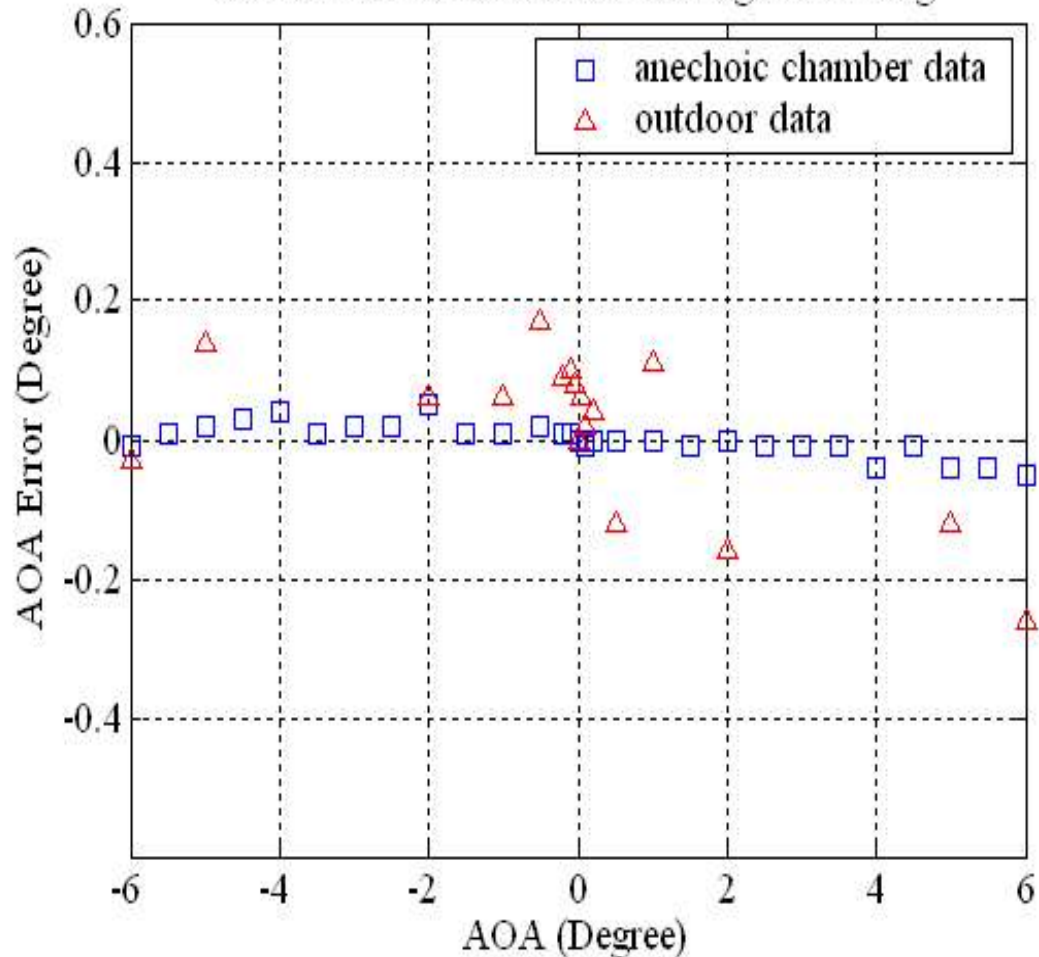
$$\mathbf{K} = \text{diag} [\alpha_1 e^{j\phi_1}, \alpha_2 e^{j\phi_2}, \dots, \alpha_m e^{j\phi_m}].$$

Therefore, the calibration matrix can be obtained by

$$\mathbf{C} = \mathbf{K}^{-1}.$$

Result of AOA Estimation Error (1)

Calibration data calculated from signal of 0 deg

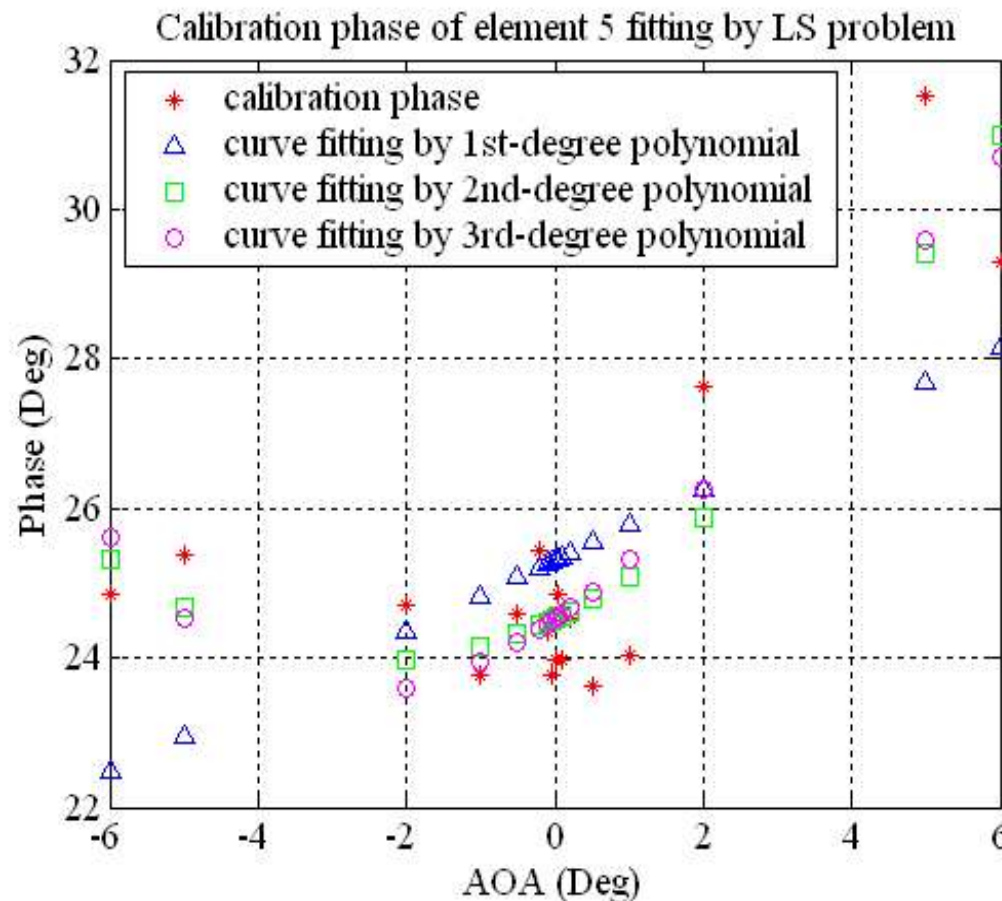


- Calibration data calculated from signal of 0 deg measured in anechoic chamber is effective to estimate AOAs of signals coming from other directions while that measured in outdoor is not.
- This calibration method, especially from the outdoor data, is good just to estimate AOA near AOA used to calculate calibration data.

Calibration method-2

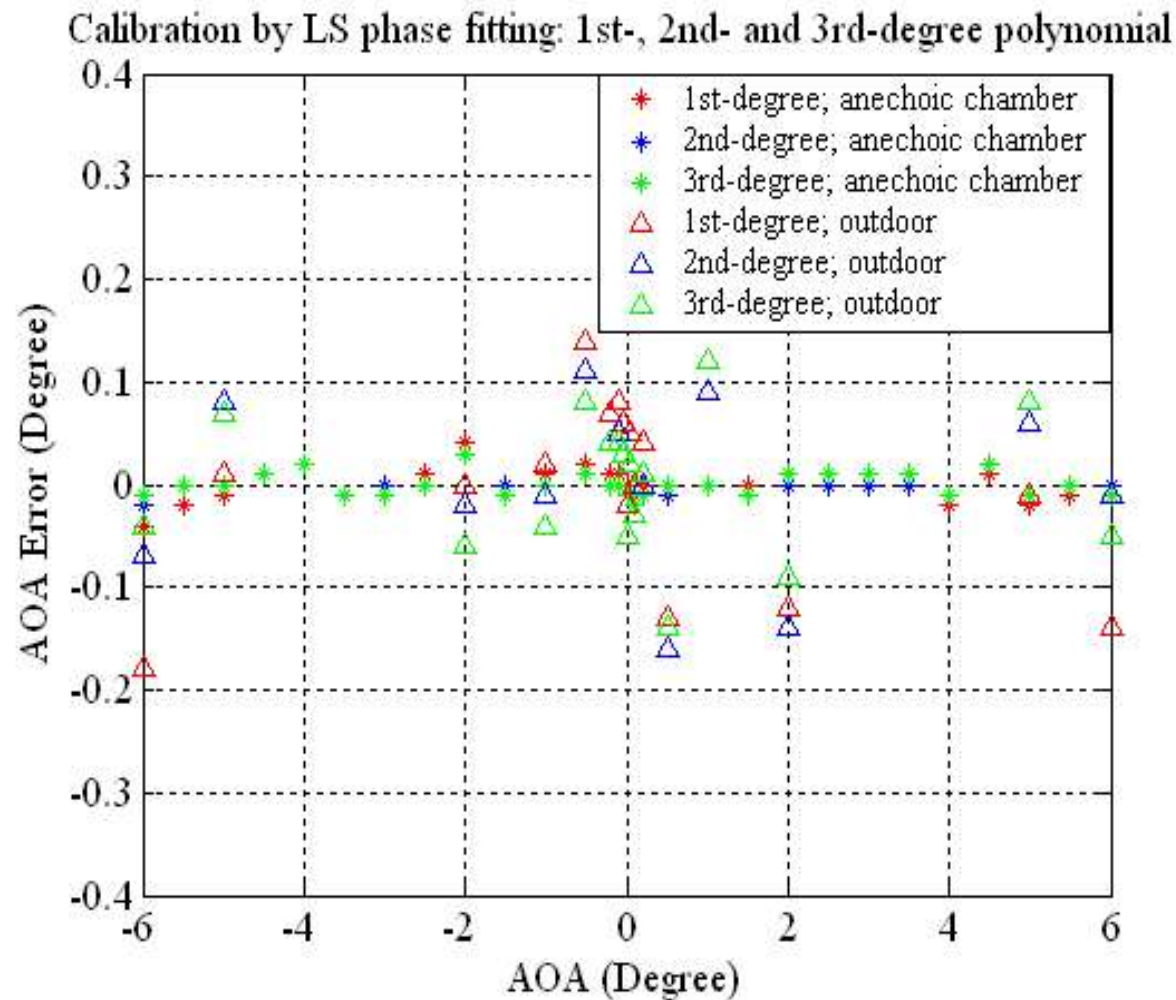
LS data fitting by the polynomials

- Calibration data as a function of angle based on calibration phase fitting using the LS technique is proposed.



Example of calibration phase of element 5th fitting by LS problem

Result of AOA Estimation Error (2)



The higher the degree LS fitting is used to estimate the calibration phase, the better improvement is obtained.

Calibration method-3

Signal Subspace Approach

The output covariance matrix of a single source can be written as

$$\mathbf{R} = E[\mathbf{x}(t) \mathbf{x}^H(t)] = \sigma_s^2 \mathbf{K} \mathbf{a}(\theta) \mathbf{a}(\theta)^H \mathbf{K}^H + \sigma_n^2 \mathbf{I}$$

For eigendecomposition, $\mathbf{R} = \lambda_1 \mathbf{u}_1 \mathbf{u}_1^H + \mathbf{U}_n \mathbf{\Lambda}_n \mathbf{U}_n^H$

From above eq., we can obtain a proportional relationship, $\mathbf{u}_1 \propto \mathbf{K} \mathbf{a}(\theta)$.

Procedure summary:

- 1) Find the output covariance matrix of each arriving signal; $\mathbf{R}(\theta_l)$
- 2) By eigendecomposition of $\mathbf{R}(\theta_l)$, signal eigenvector of each arriving signal $\mathbf{u}_1(l)$ is obtained. Then find $\mathbf{a}(\theta_l)$.
- 3) Estimate the error matrix;

$$[\mathbf{u}_1(1) \quad \mathbf{u}_1(2), \dots, \mathbf{u}_1(L)] = \mathbf{K} [\mathbf{a}(\theta_1) \quad \mathbf{a}(\theta_2), \dots, \mathbf{a}(\theta_L)],$$

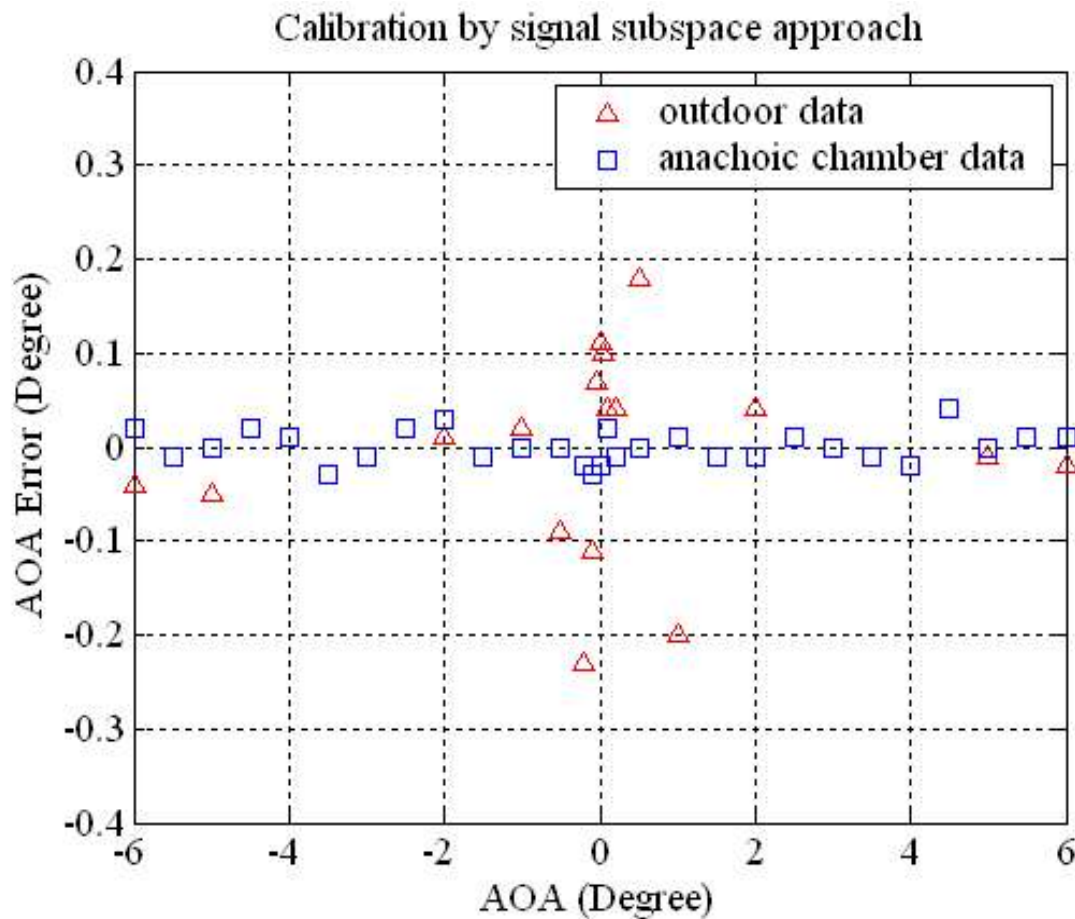
$$\mathbf{U}_s = \mathbf{K} \mathbf{A}$$

Then $\mathbf{K}$ can be estimated by

$$\mathbf{K} = \mathbf{U}_s \mathbf{A}^H (\mathbf{A} \mathbf{A}^H)^{-1},$$

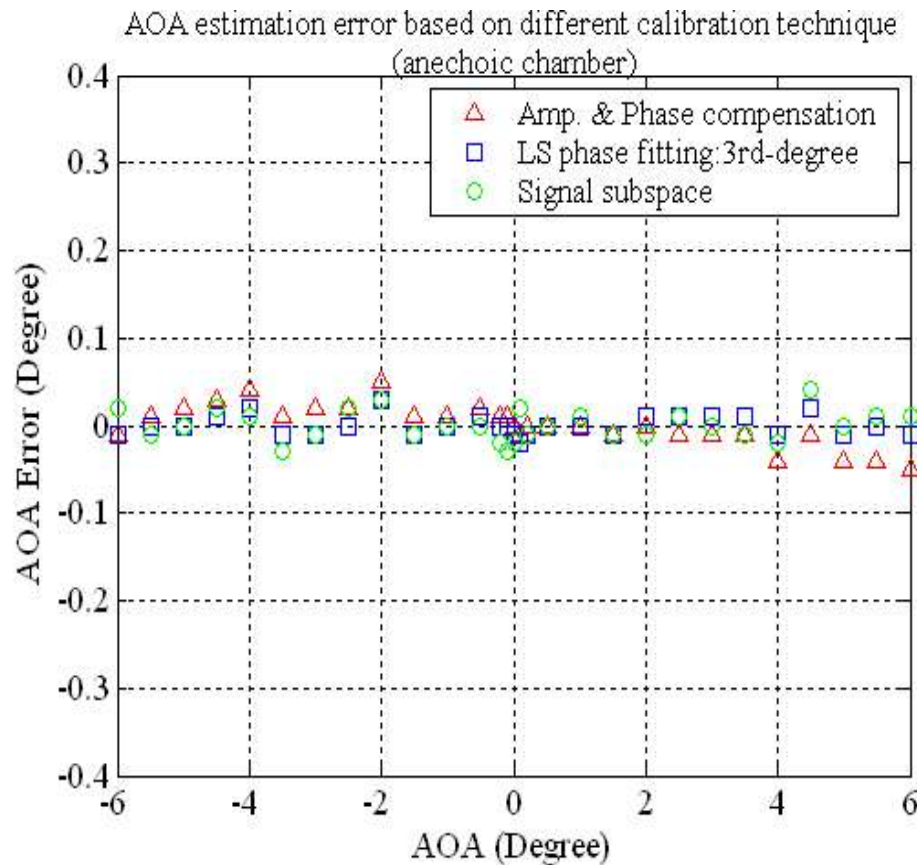
so the calibration matrix is $\mathbf{C} = \mathbf{K}^{-1}$.

Result of AOA Estimation Error (3)

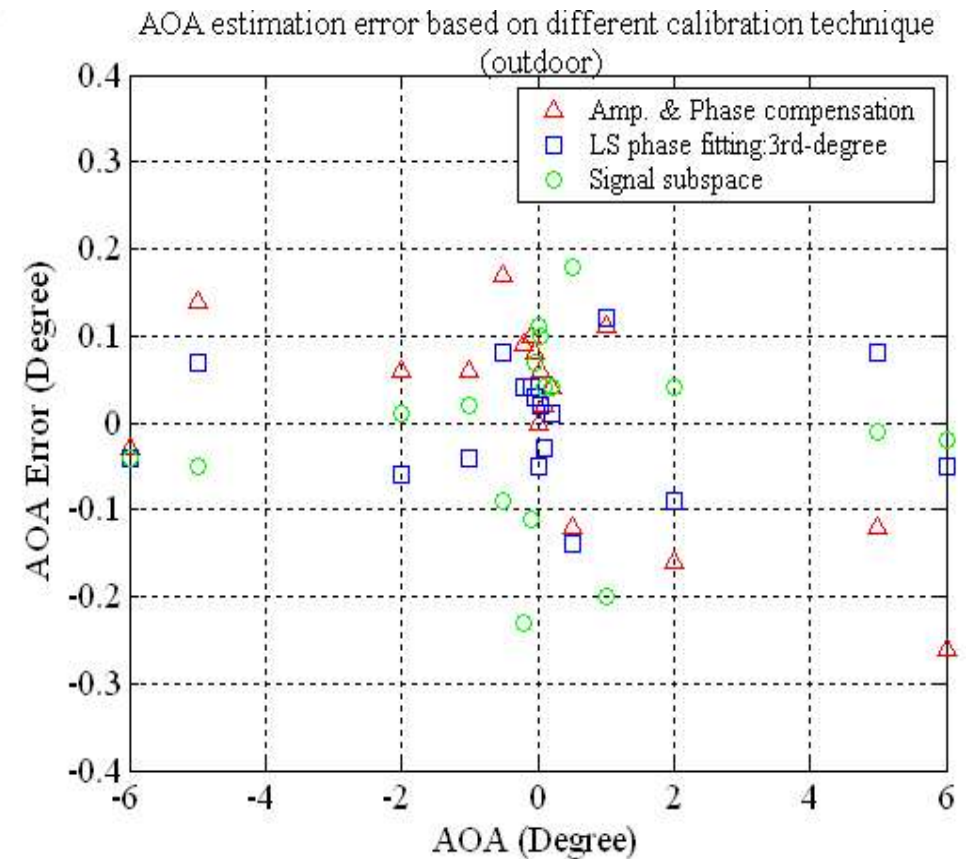


- Calibration data obtained from anechoic chamber data is effective to estimate AOA of all arriving signals.
- However, in the case of calibration data obtained from outdoor data, it is effective to estimate some AOA only.

Result of AOA Estimation Error (4)



- All calibration techniques obtained from anechoic chamber are effective to estimate all AOAs.



- All calibration techniques obtained from outdoor seem only effective to estimate some signal directions.

Conclusions

- Propose three array calibration methods
 - Amplitude and phase compensation technique
 - Phase approximation based on least square problem
 - Signal subspace approach
- Observe results: estimation errors in some outdoor-measured AOAs are still high which might be due to imperfect calibration data affected, for instance, by
 - Electromagnetic diffraction/ scatterers
 - Instability or imperfection of antenna array itself.
 - Etc.

Future works

- To correct the calibration error
 - the properties of the antenna array are needed to be clarified, e.g., concerning mutual coupling effect
 - Electromagnetic scatterer/ diffraction by using electromagnetic simulation
- Propose new calibration technique