Signal space separation (SSS) method for flat sensor arrays: Computer simulation study

Kensuke Sekihara[1,2]

[1]Tokyo Medical and Dental University
[2]Signal Analysis Inc.

Outline

- The signal space separation (SSS) method [1] decomposes the data vector into two components belonging to the internal and external subspaces. The method can efficiently remove the interference/artifacts overlapped onto MEG signals, because the internal and external subspaces respectively correspond to the signal and interference subspaces for (spherically shaped) helmet-type sensor arrays used in MEG.

- On the other hand, the SSS method is considered ineffective for non-spherically shaped sensor arrays. This paper investigates the possibility of applying the SSS method to a (non-spherical) flat sensor array conventionally used in MCG. A primary problem here is a leakage of signals to the external subspace. This leakage is found to cause a distortion in the signal magnetic field. In this paper, we show that this distortion can be corrected by using the SSS processed lead field.

Outline-continued

- The appropriate choice of the origin is found to be very important, because the noise gain of the SSS method strongly depends on the origin location, and inappropriate choices may cause severe SNR degradation. The empirical relationship between the noise gain and the origin location is derived and based on it, an appropriate location of the origin can be determined. Finally, a relationship between the interference shielding factor and sensor calibration errors is derived to provide a limit of calibration errors under a given shielding factor.

[References]

[1] Taulu, S., & Kajola, M. (2005). Presentation of electromagnetic multichannel data: the signal space separation method. *Journal of Applied Physics*, *97*(12), 124905.

Signal Space Separation Method

Assuming that the sensor region is source-free, magnetic field is expressed as

$$\boldsymbol{B}(\boldsymbol{r}) = -\mu_0 \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \alpha_{lm} \frac{\boldsymbol{\nu}_{lm}(\theta,\varphi)}{r^{l+2}} - \mu_0 \sum_{l=0}^{\infty} \sum_{m=-l}^{l} \beta_{lm} r^{l-1} \boldsymbol{\omega}_{lm}(\theta,\varphi)$$

$$= \boldsymbol{B}_{\mathrm{int}}(\boldsymbol{r}) + \boldsymbol{B}_{\mathrm{ext}}(\boldsymbol{r})$$

where $\boldsymbol{\nu}_{lm}(\theta,\varphi), \boldsymbol{\omega}_{lm}(\theta,\varphi)$ are vector spherical harmonics.

$\boldsymbol{B}_{\mathrm{int}}(\boldsymbol{r})$: Magnetic field generated within the internal region, which is a region closer to the origin than the sensor region.

$\boldsymbol{B}_{\mathrm{ext}}(\boldsymbol{r})$: Magnetic field generated within the external region, which is a region farther from the origin thanh the sensor region.

If clever choices of the origin can make signal sources to be in the internal region, and interference sources in the external region, this expansion provides a natural separation between the signal and interferences.

Data vector can be expressed using SSS basis vectors such that

$$\boldsymbol{b} = \begin{bmatrix} B(r_1) \\ \vdots \\ B(r_M) \end{bmatrix} = \sum_{l=1}^{L_\alpha} \sum_{m=-l}^{l} \alpha_{lm} \begin{bmatrix} \kappa_1^{lm} \\ \vdots \\ \kappa_M^{lm} \end{bmatrix} + \sum_{l=1}^{L_\beta} \sum_{m=-l}^{l} \beta_{lm} \begin{bmatrix} \lambda_1^{lm} \\ \vdots \\ \lambda_M^{lm} \end{bmatrix}$$

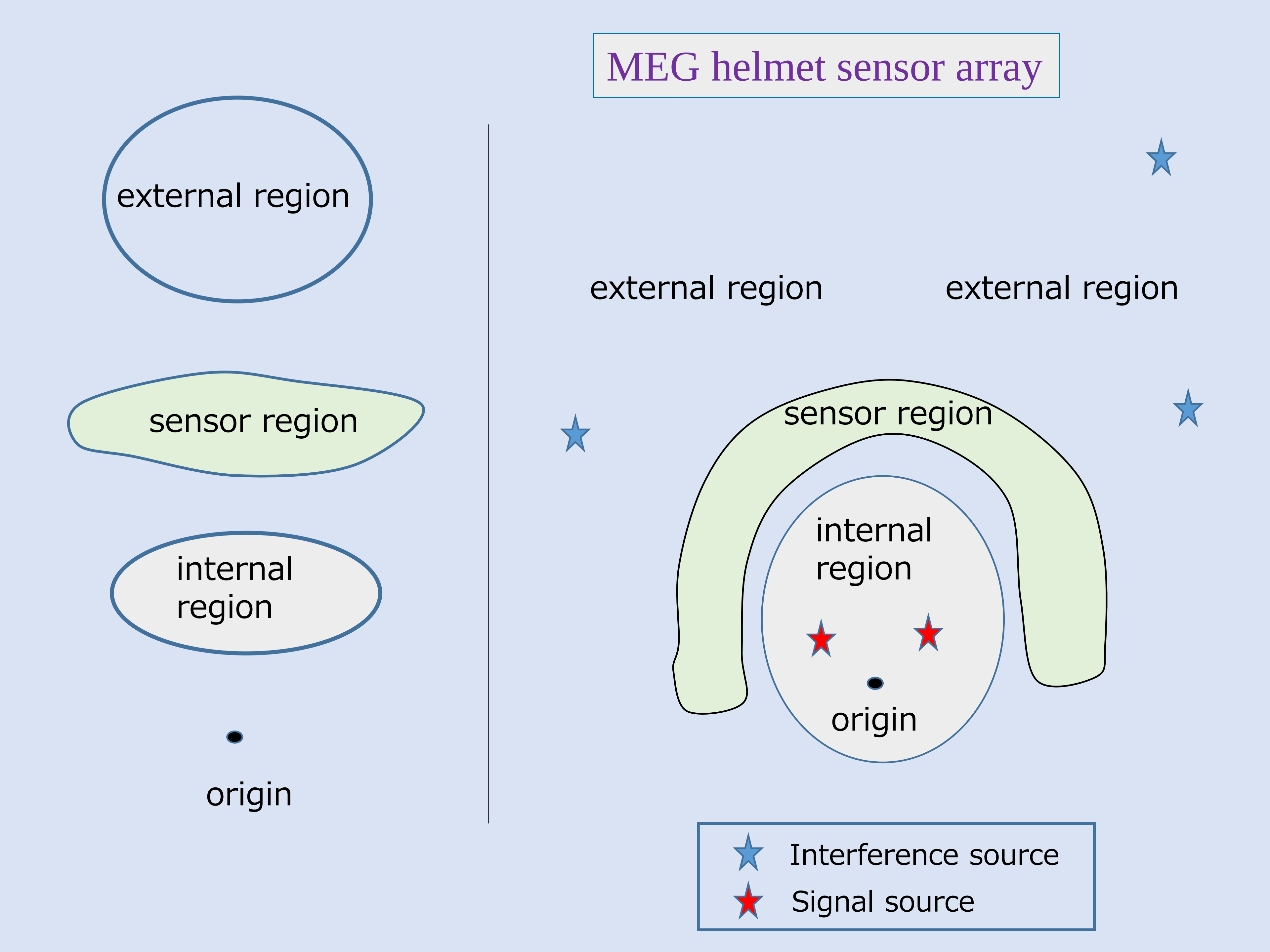
$$= \sum_{l=1}^{L_\alpha} \sum_{m=-l}^{l} \alpha_{lm} \boldsymbol{\kappa}^{lm} + \sum_{l=1}^{L_\beta} \sum_{m=-l}^{l} \beta_{lm} \boldsymbol{\lambda}^{lm}$$

$$= \left[\boldsymbol{\kappa}^{1,-1}, \boldsymbol{\kappa}^{1,1}, \ldots, \boldsymbol{\kappa}^{L_\alpha, L_\alpha} \right] \begin{bmatrix} \alpha_{1,-1} \\ \alpha_{1,1} \\ \vdots \\ \alpha_{L_\alpha, L_\alpha} \end{bmatrix} + \cdots = \boldsymbol{S}_{\text{int}} \boldsymbol{\alpha} + \boldsymbol{S}_{\text{ext}} \boldsymbol{\beta} = [\boldsymbol{S}_{\text{int}}, \boldsymbol{S}_{\text{ext}}] \begin{bmatrix} \boldsymbol{\alpha} \\ \boldsymbol{\beta} \end{bmatrix}$$

SSS signal and interference extractors are obtained as:

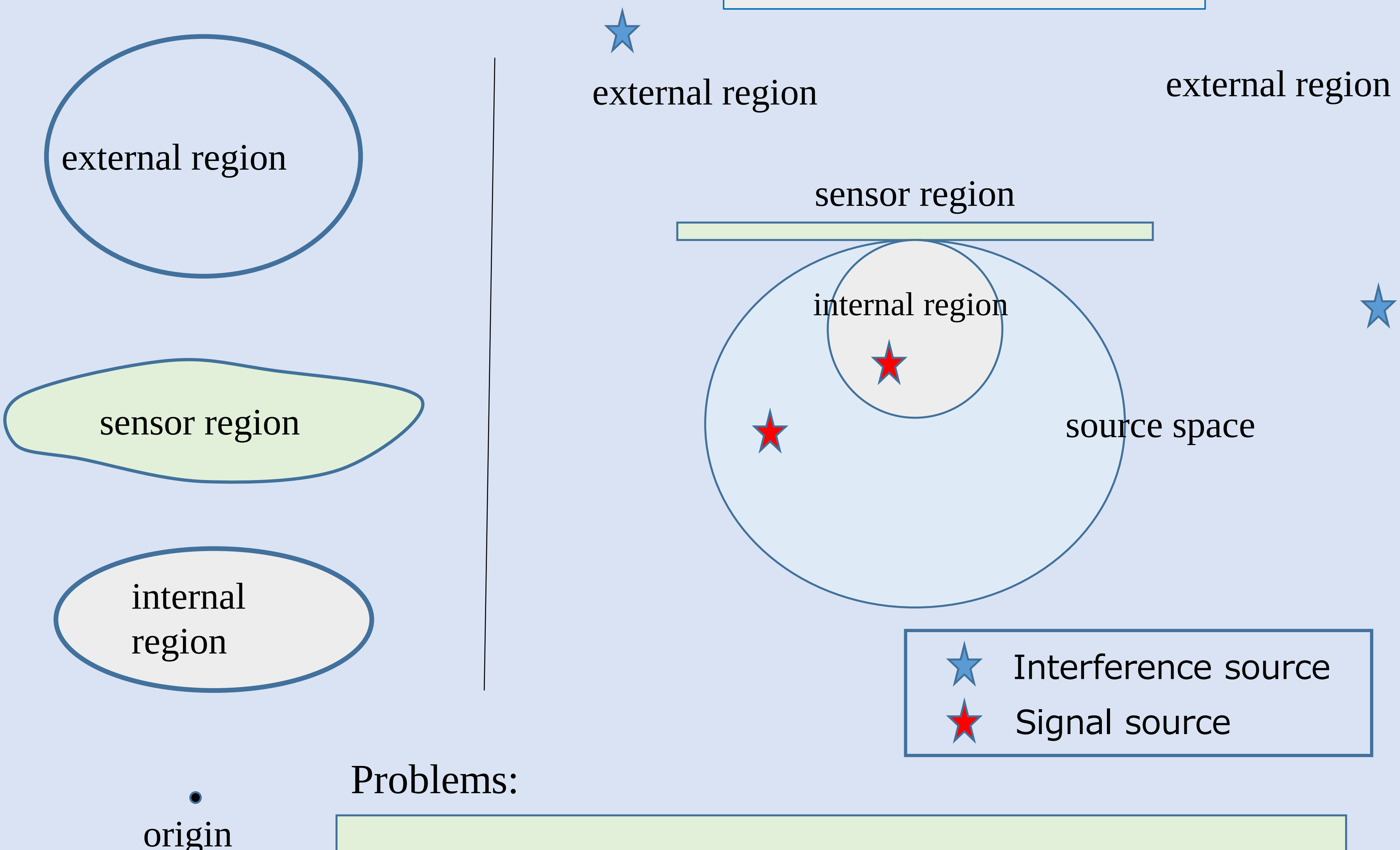
Signal: $$\boldsymbol{b}_{\text{int}} = \boldsymbol{S}_{\text{int}} \boldsymbol{S}_{\text{int}}^T [\boldsymbol{S}_{\text{int}} \boldsymbol{S}_{\text{int}}^T + \boldsymbol{S}_{\text{ext}} \boldsymbol{S}_{\text{ext}}^T]^{-1} \boldsymbol{b} = \boldsymbol{\Gamma}_{\text{int}} \boldsymbol{b}$$

Interference: $$\boldsymbol{b}_{\text{ext}} = \boldsymbol{S}_{\text{ext}} \boldsymbol{S}_{\text{ext}}^T [\boldsymbol{S}_{\text{int}} \boldsymbol{S}_{\text{int}}^T + \boldsymbol{S}_{\text{ext}} \boldsymbol{S}_{\text{ext}}^T]^{-1} \boldsymbol{b} = (\boldsymbol{I} - \boldsymbol{\Gamma}_{\text{int}}) \boldsymbol{b}$$



MEG helmet sensor array
external region
sensor region
internal region
origin
external region
external region
sensor region
internal region
origin
Interference source
Signal source

MCG flat sensor array

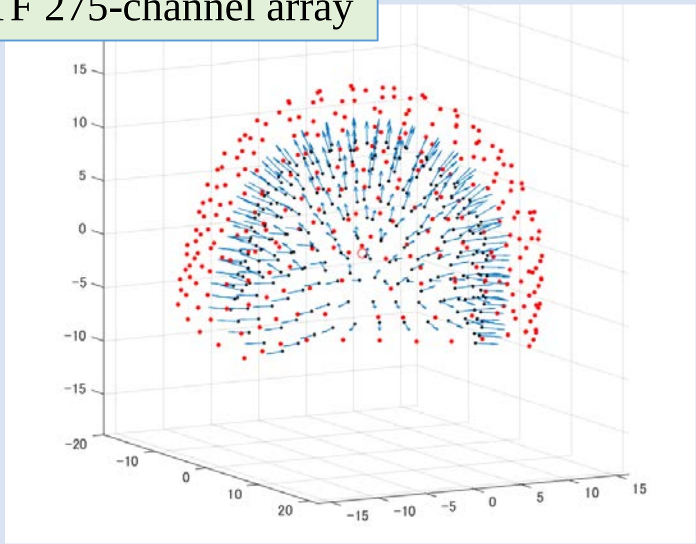


Problems:

- Signal sources may exist outside the internal region.
- Determination of the origin may not be straightforward.

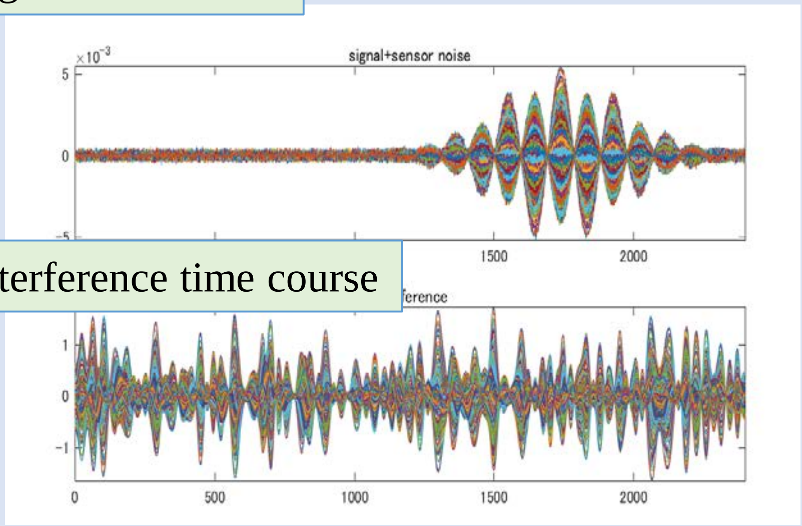
SSS Results for Helmet Sensor Array

CTF 275-channel array

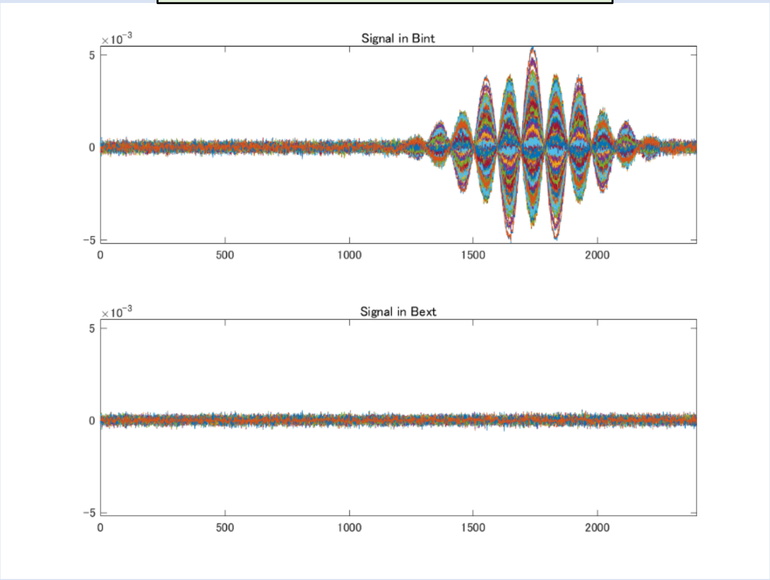


Signal time course

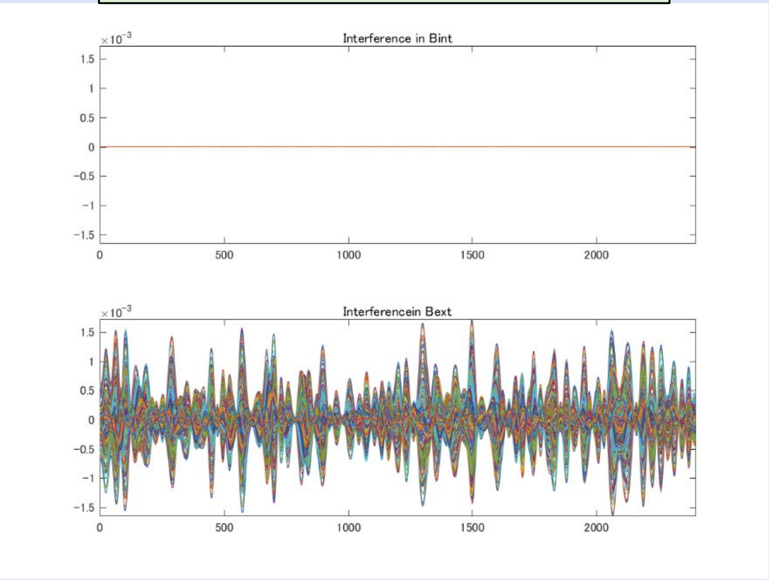
Interference time course



SSS results for signal

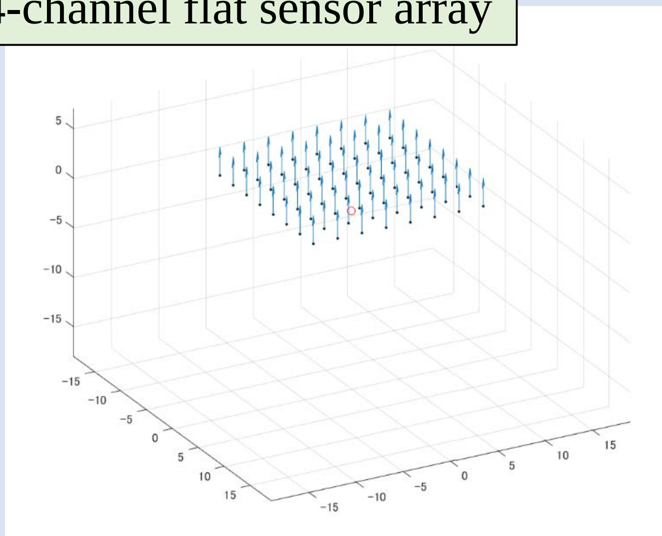


SSS results for interference



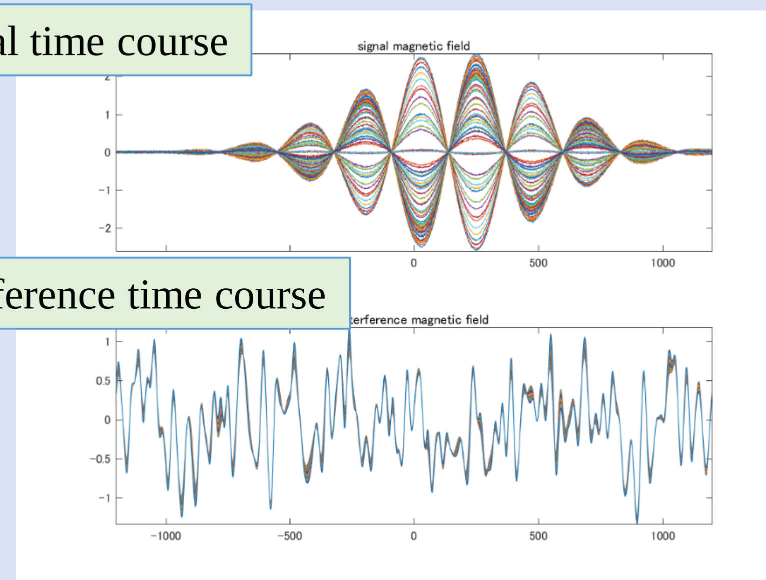
SSS Results for Flat Sensor Array

64-channel flat sensor array

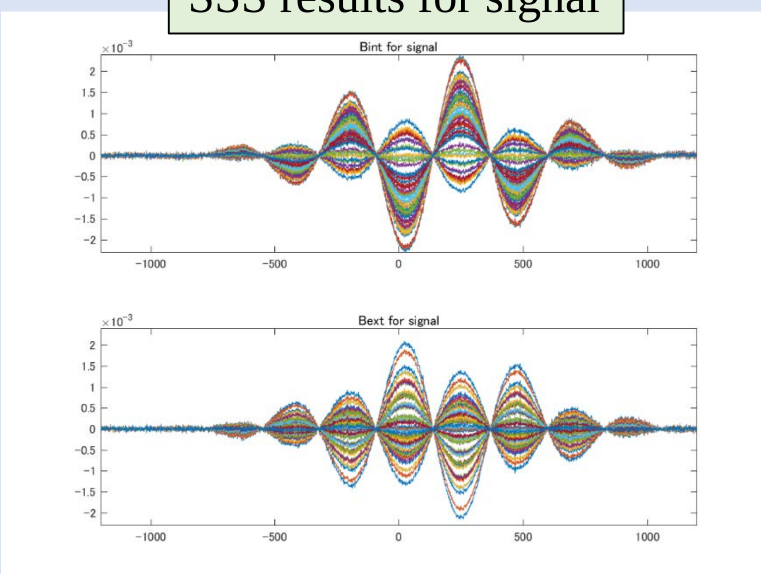


Signal time course

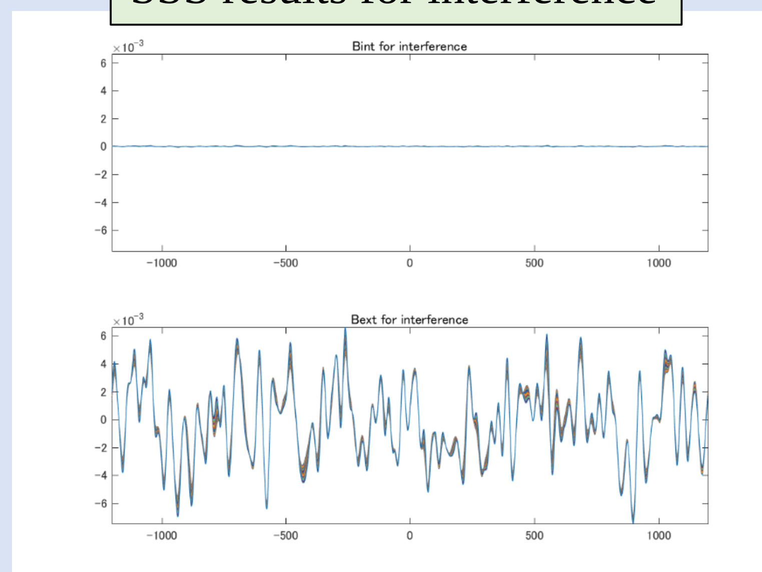
Interference time course



SSS results for signal



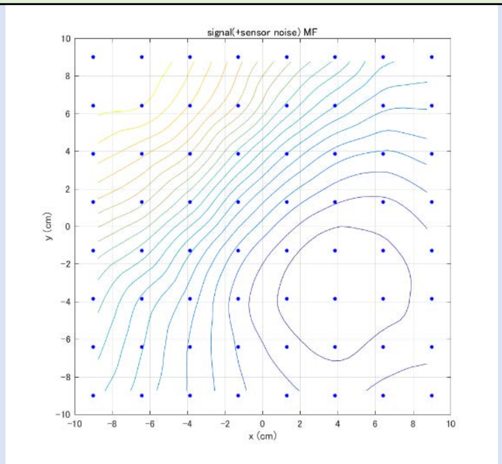
SSS results for interference



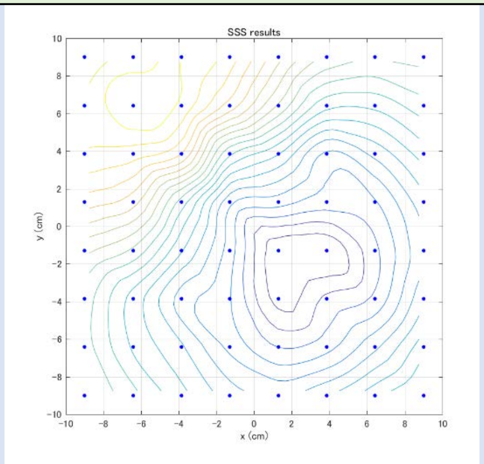
Interference is blocked!!

Signal Distortion

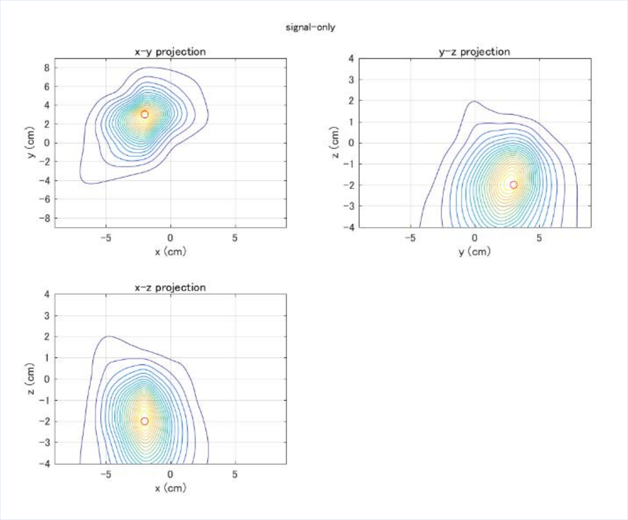
Field map of signal-only data



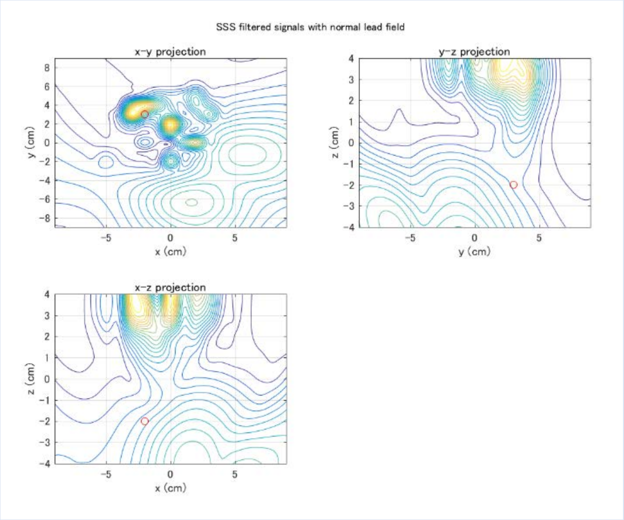
Field map of SSS processed data



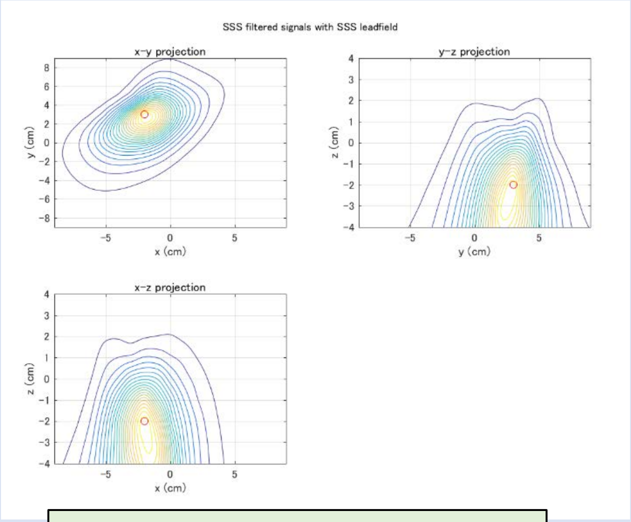
RENS beamformer source reconstruction results



Signal-only data

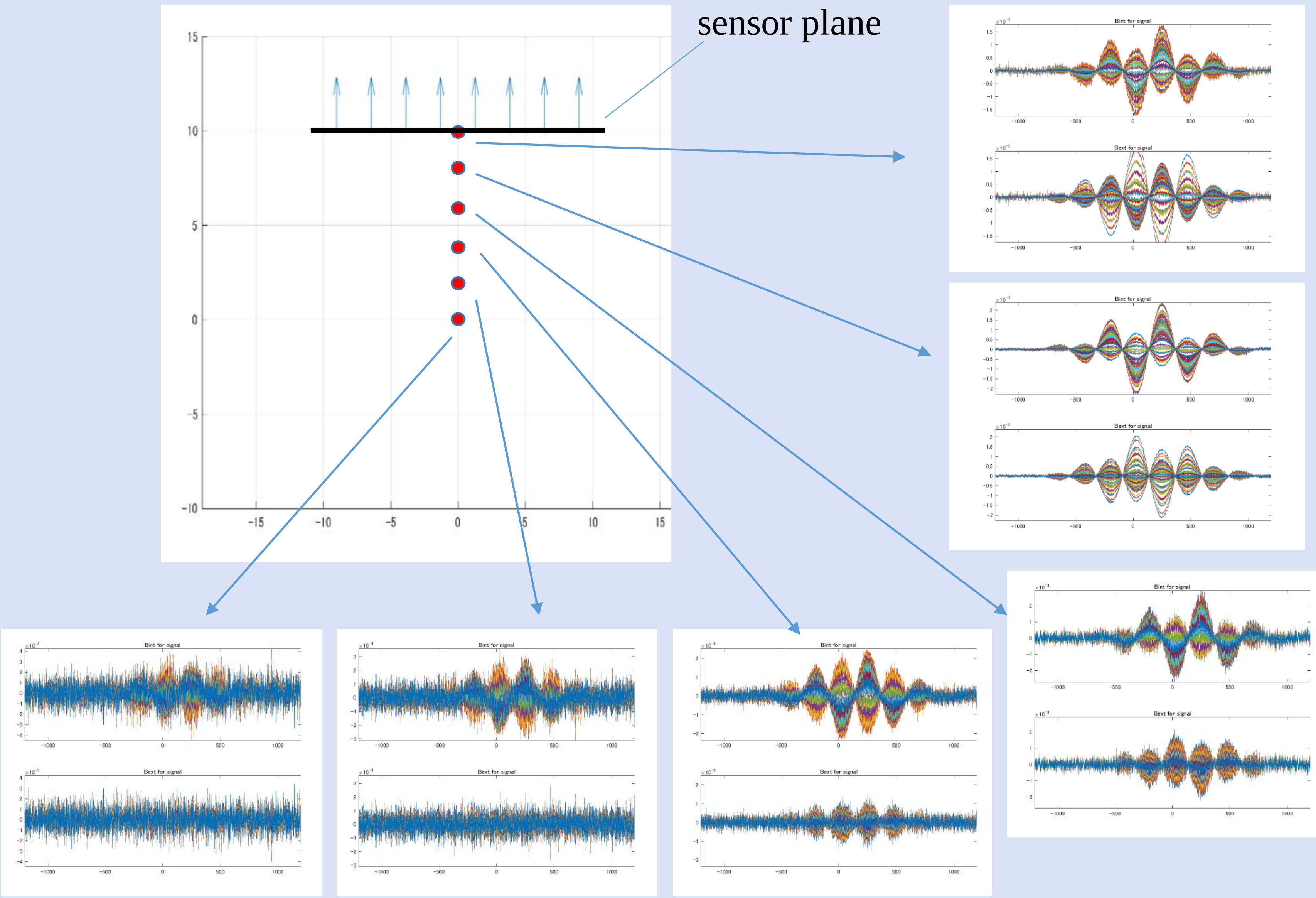


SSS processed data



SSS processed data with SSS-processed lead field

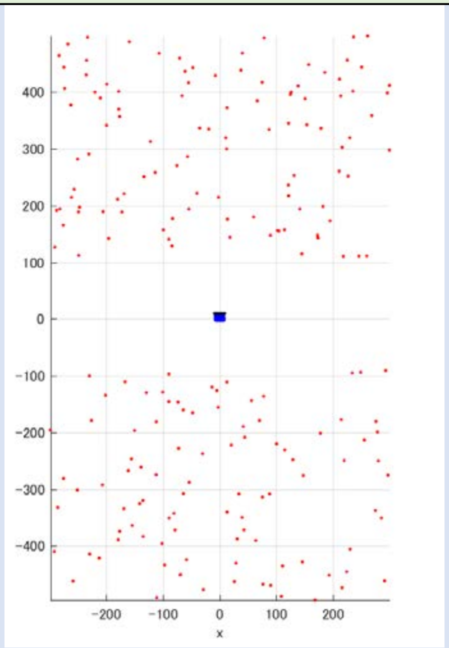
Noise Gain versus Origin Location



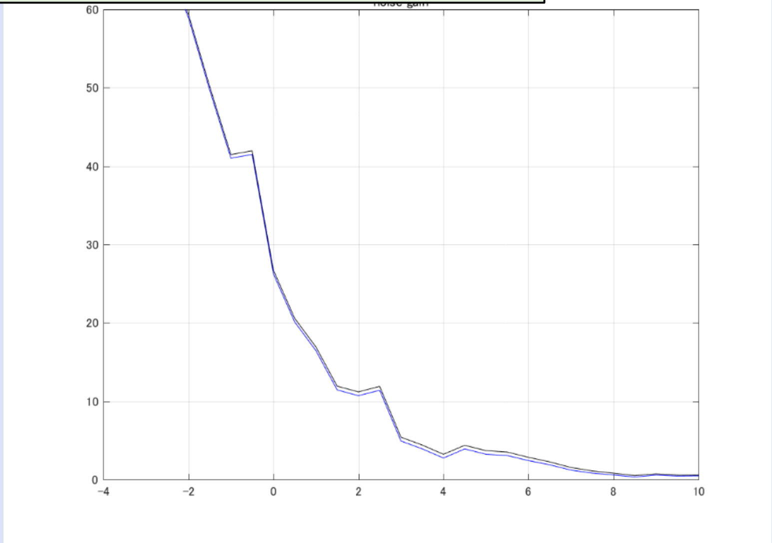
Noise gain changes depending on the origin location.

Monte Carlo Simulation Results

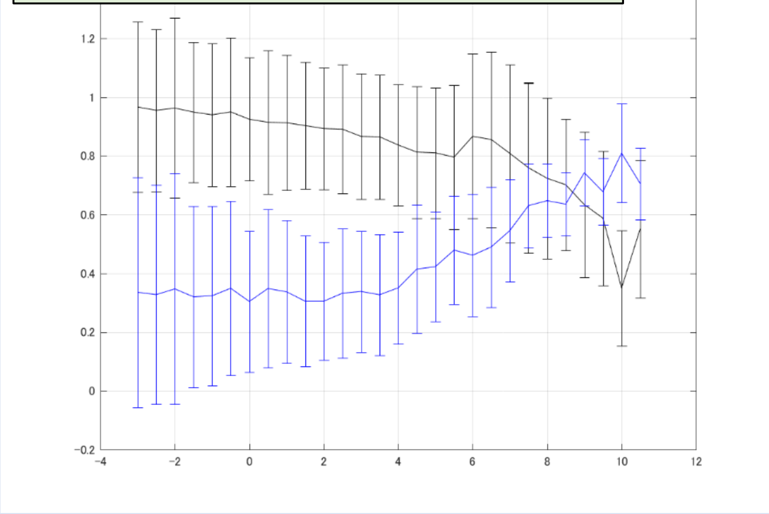
200 source location used in Monte Carlo experiments



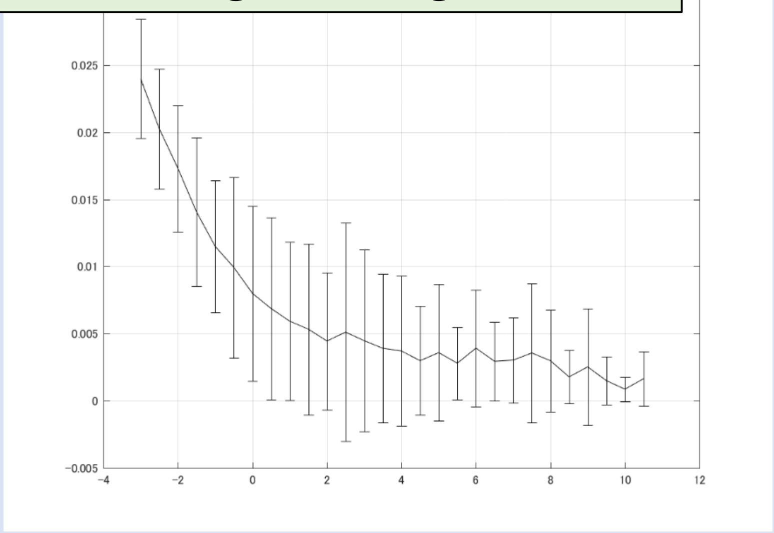
Noise gain vs origin location



Signal gain vs origin location

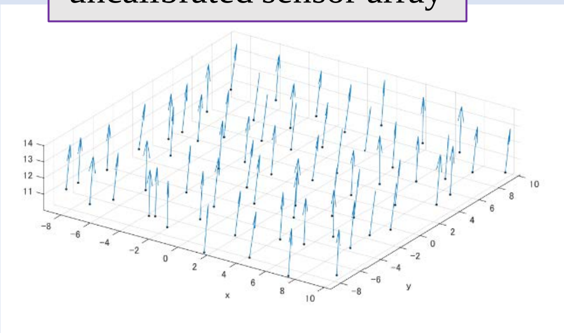


Interference gain vs origin location



Influence of Array Calibration Error

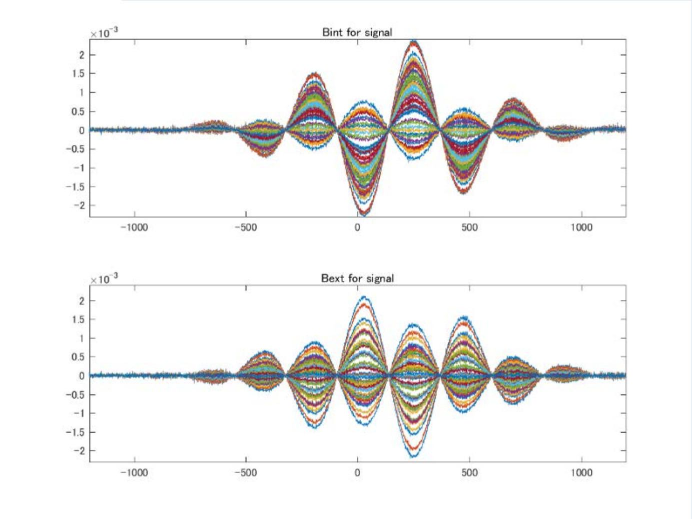
uncalibrated sensor array

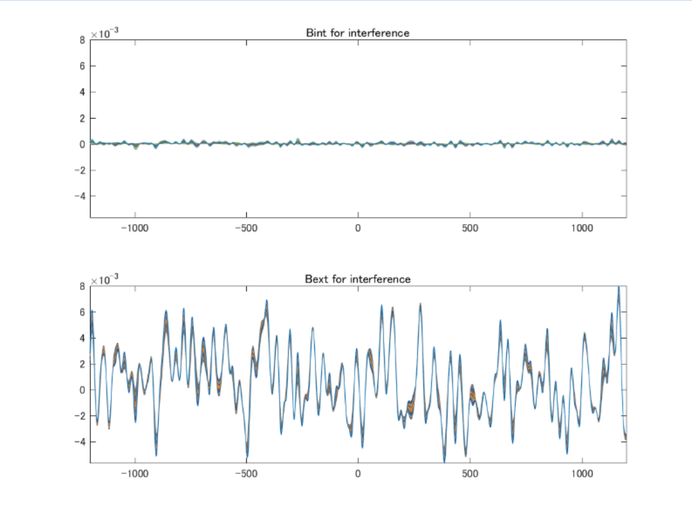


SSS results for signal

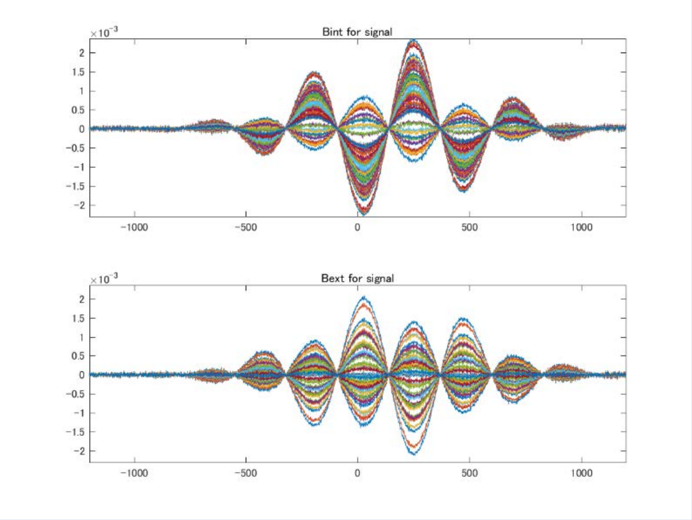
SSS results for interference

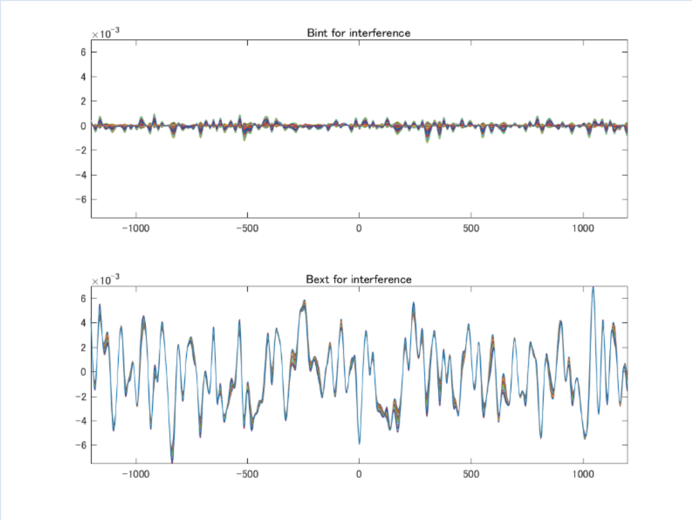
Calibration Error: 1%





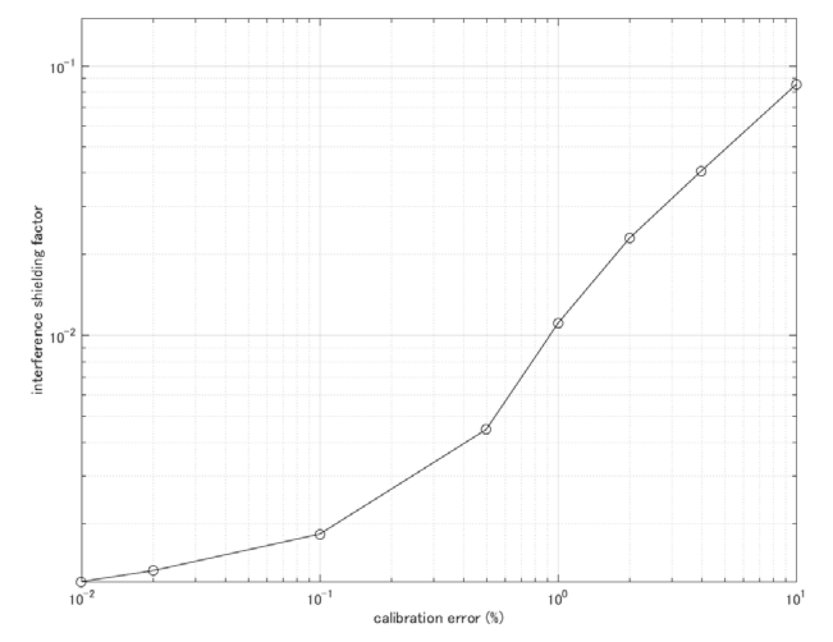
Calibration Error: 2.5%



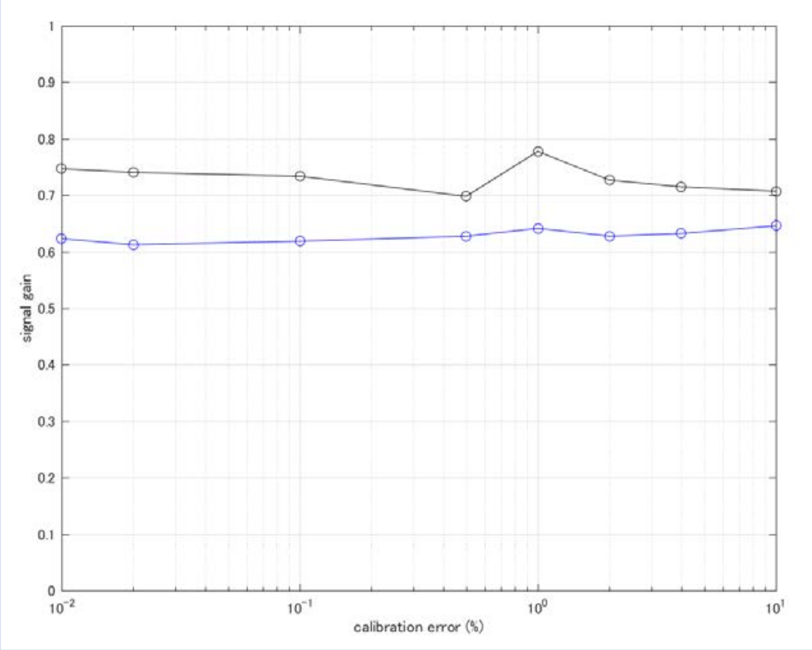


Influence of Array Calibration Error: Monte Carlo Simulation Results

Interference shielding factor vs calibration error



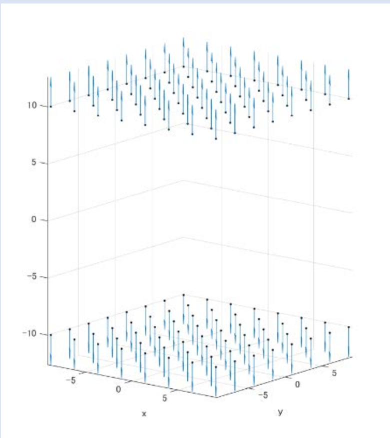
Signal gain vs calibration error

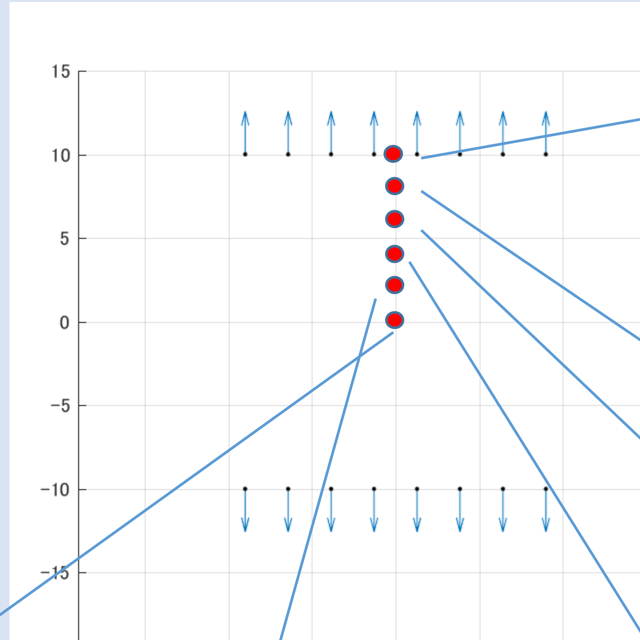


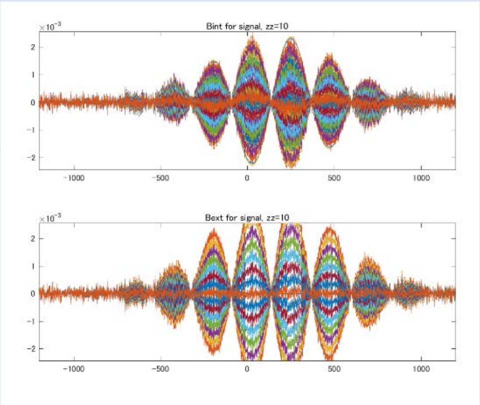
- **Interference shielding factor becomes worse almost linearly depending on calibration error.**
- **Signal gain does not depend on calibration error.**

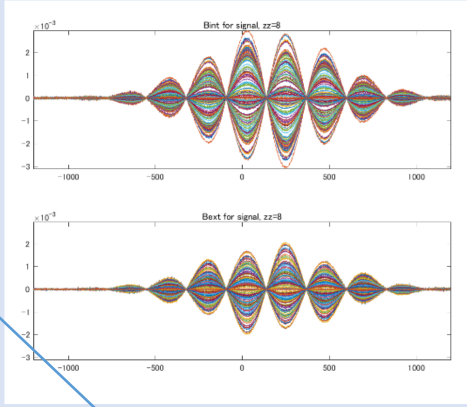
Noise Gain and Origin Location for Dual Flat Sensor Array

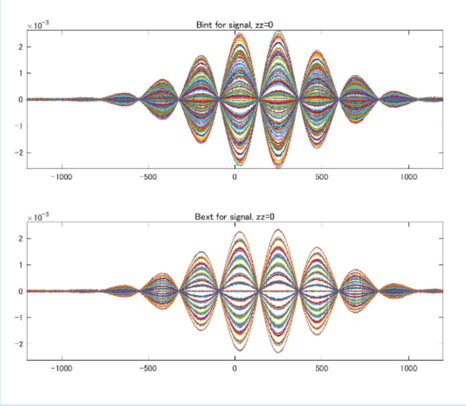
128-channel dual flat sensor array

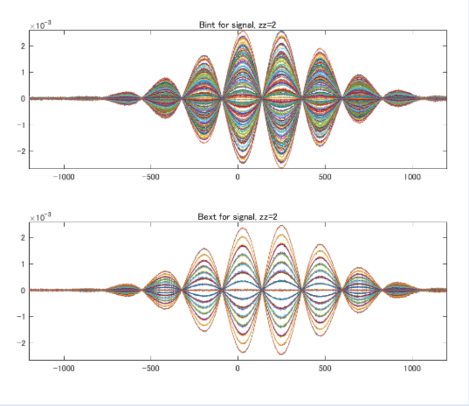


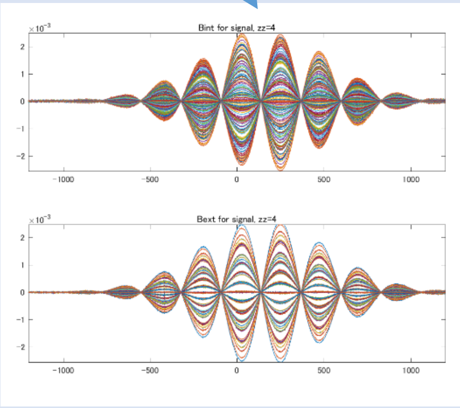


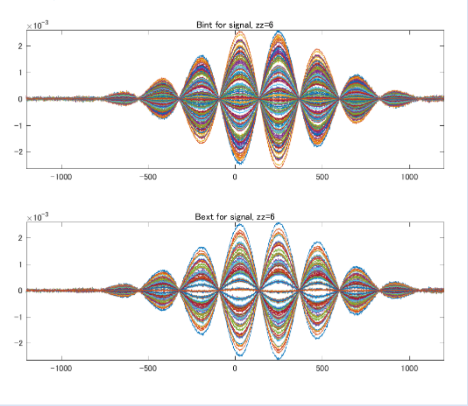






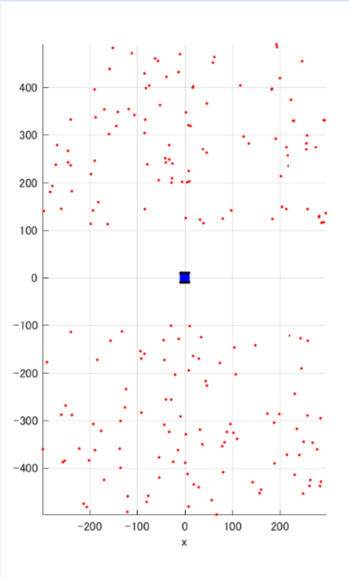




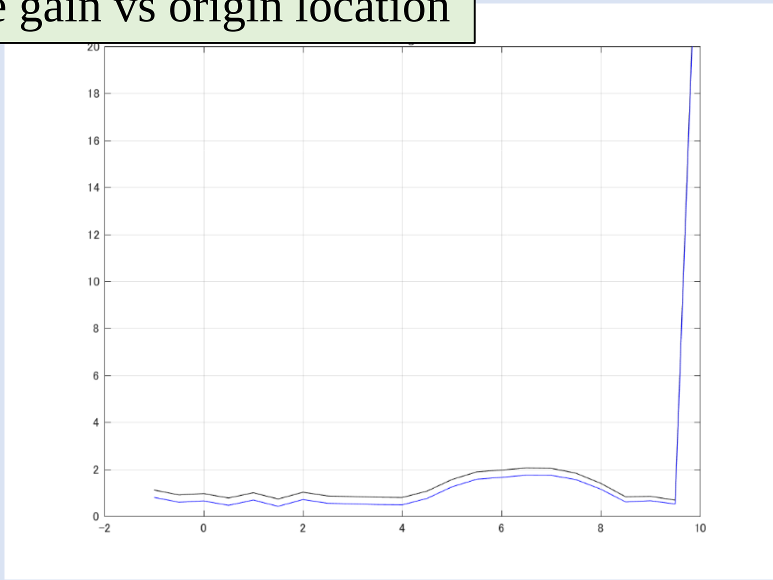


Monte Carlo Simulation Results for Dual Flat Sensor Arrays

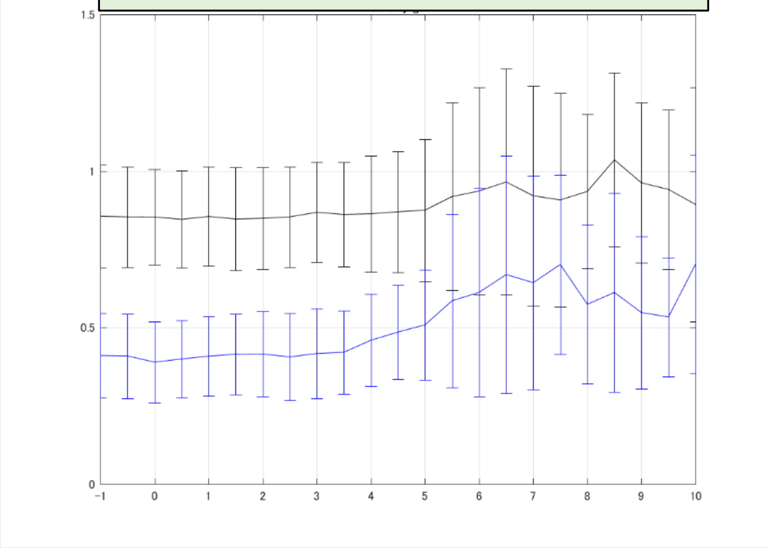
200 source location used in Monte Carlo experiments



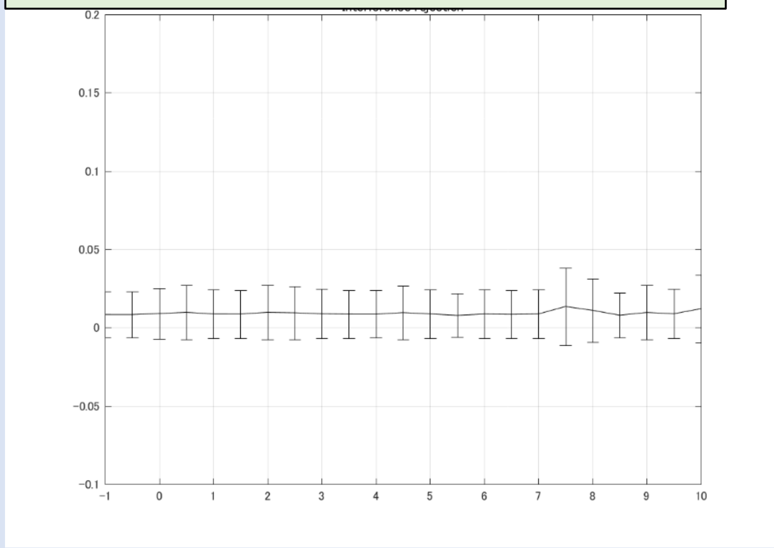
Noise gain vs origin location



Signal gain vs origin location

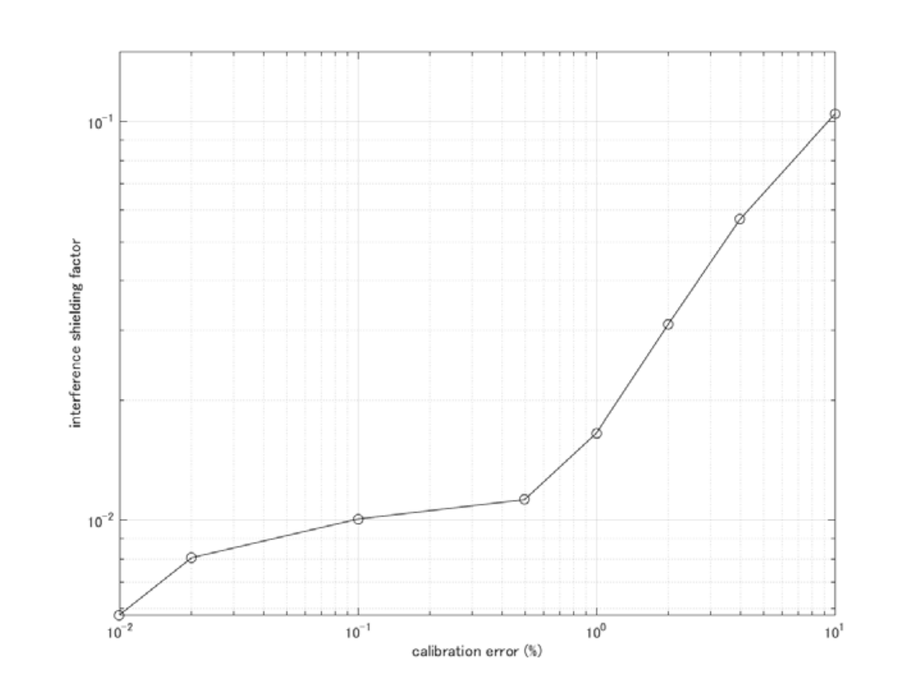


Interference gain vs origin location

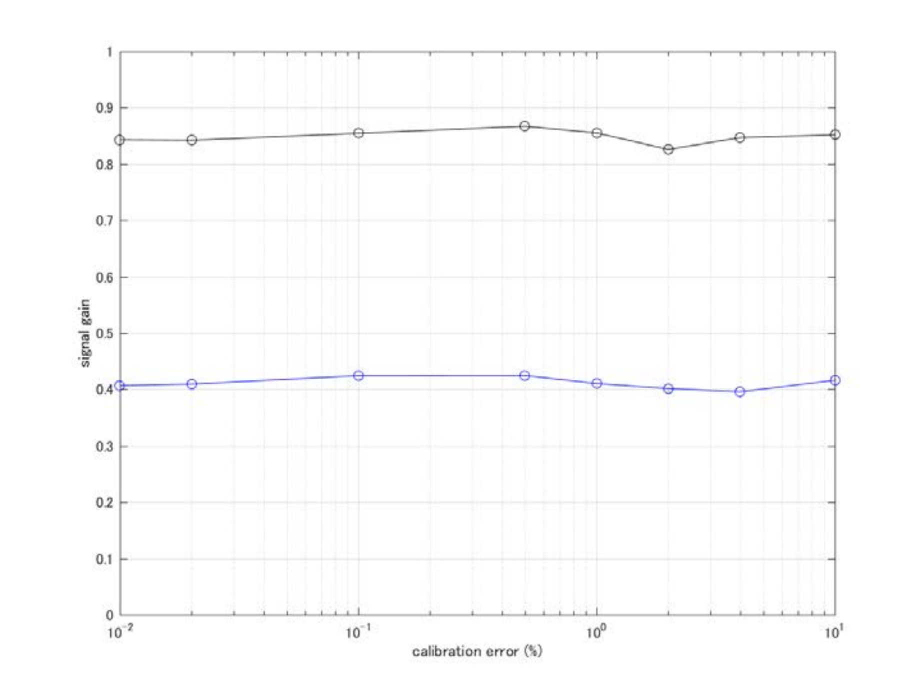


Influence of Array Calibration Error: Monte Carlo Simulation Results for Dual Flat Sensor Arrays

Interference shielding factor vs calibration error



Signal gain vs calibration error



Conclusions

- **SSS method is effective in removing interferences, even when flat sensor arrays are used.**

- **SSS-processed signal contains a distortion caused due to the leakage of the signal into the external components.**

- **SSS-processed signal can provide reasonable results of source localization, if SSS-processed sensor lead field is used.**

- **An optimum location of the origin should be explored by computer simulation that takes the noise gain, signal gain, and interference gain (shielding factor) into consideration.**

- **Array calibration errors degrade the shielding factor. However, the shielding factor of less than 1/100 can be attained if the calibration errors are less than 1%.**

- **Dual flat sensor array gives better SSS performance, but the difference between the dual and the single flat sensor arrays may be small.**

The paper “Subspace-based interference removal methods for multichannel biomagnetic sensor arrays” has been accepted for publication in Journal of Neural Engineering. The PDF can be downloaded from: