Signal space separation (SSS) method for a flat sensor array used in MCG: Computer simulation study

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Motivation and background

High-sensitive magneto-resistive (MR) sensors can lead to development of low-initial-cost and maintenance-free MCG systems. A prototype of such systems has been developed by TDK

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- One problem here is the removal of ambient noise magnetic fields, called environmental noise.
- This is because, in such new sensor systems, we cannot rely on the (traditional) hardware-based solutions:

They are:

1) gradiometer sensors.
   It is unknown if "gradiometer-type MR sensors" can be developed.
2) high/medium-quality MSRs.
   Use of such MSRs invalidates the goal of developing "low-cost" systems

My talk addresses the third option, development of software shielding methods, and focuses on the SSS method for environmental noise cancellation.

So far, SSS has been applied to data from MEG helmet sensor arrays.
What is the problem caused when SSS is applied to flat sensor data used in MCG?

SSS uses spherical harmonics expansion:

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

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

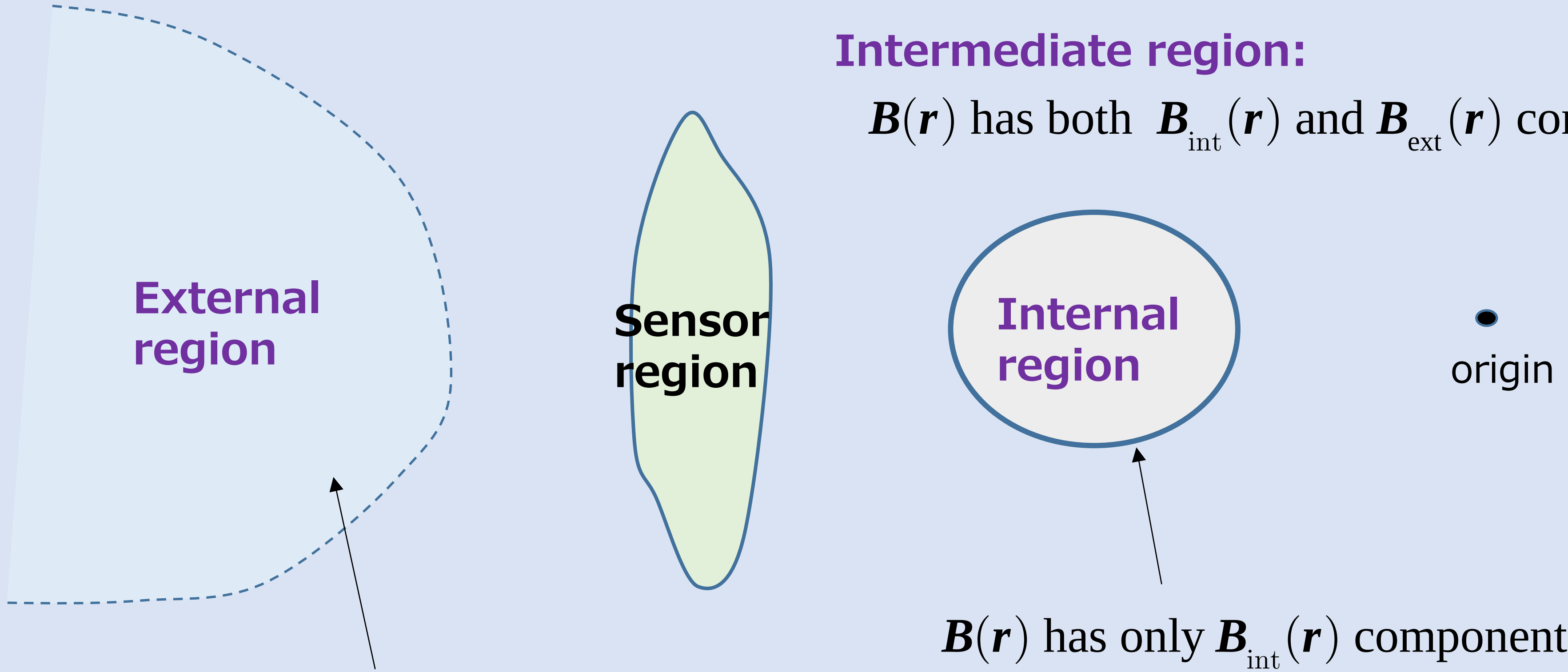
$\boldsymbol{B}_{\text{int}}(\boldsymbol{r})$: the internal components, generated from a region closer to the origin than sensors.

$\boldsymbol{B}_{\text{ext}}(\boldsymbol{r})$: the external components, generated from a region farther from the origin than sensors.

The source region is divided into three regions

Intermediate region:

$\boldsymbol{B}(\boldsymbol{r})$ has both $\boldsymbol{B}_{\text{int}}(\boldsymbol{r})$ and $\boldsymbol{B}_{\text{ext}}(\boldsymbol{r})$ components.



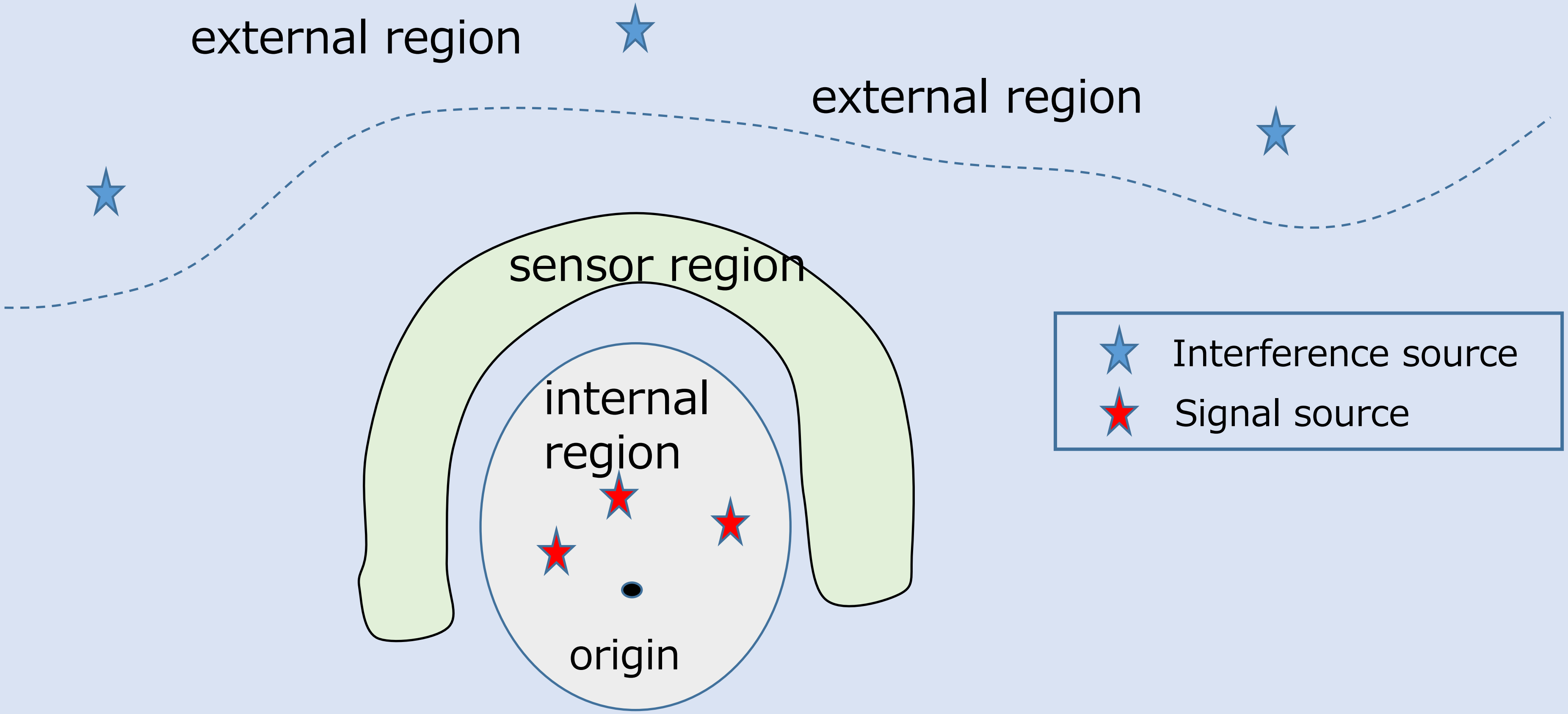
$\boldsymbol{B}(\boldsymbol{r})$ has only $\boldsymbol{B}_{\text{int}}(\boldsymbol{r})$ components.

$\boldsymbol{B}(\boldsymbol{r})$ has only $\boldsymbol{B}_{\text{ext}}(\boldsymbol{r})$ components.

A key fact: Where the internal and external regions are depends on the origin location, and the origin location is a user-defined parameter.

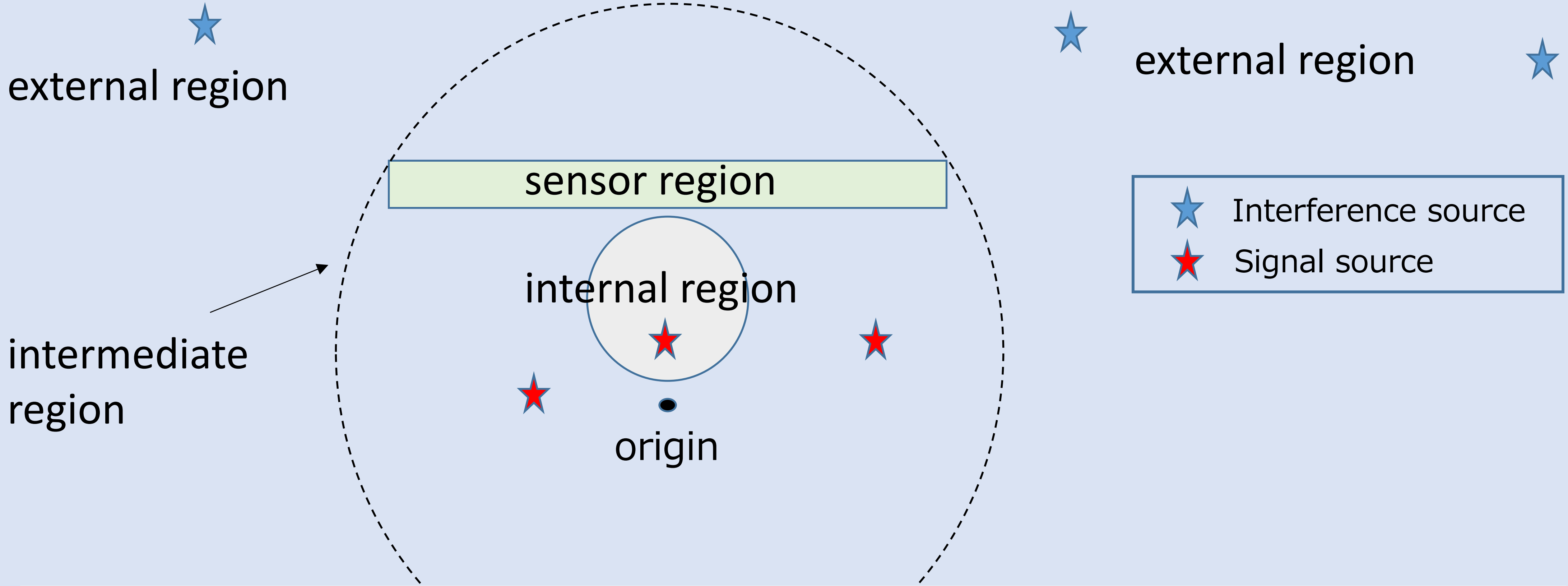
If clever choices of the origin can make signal sources to be in the internal region, and interference sources to be in the external region, the spherical harmonics expansion provides a natural separation between the signal and interference.

Such choices of the origin can be found for a helmet sensor array



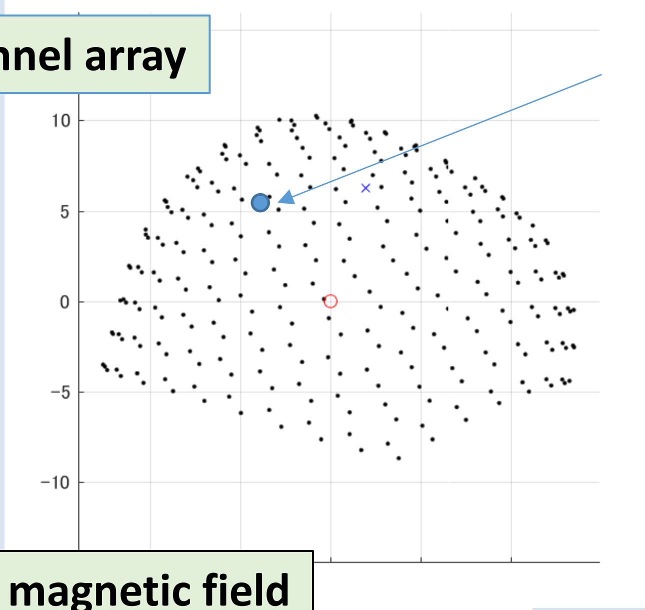
However, for a flat sensor array….

Since the internal region is very small, wherever the origin is set, most of signal sources are located in the intermediate region, and signal magnetic field has both components.



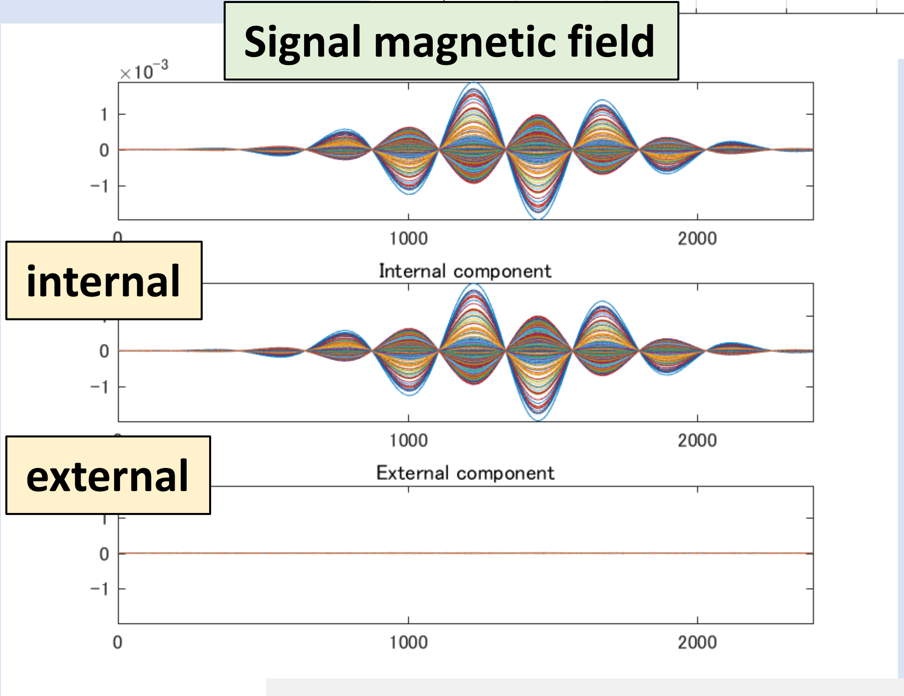
Only “environmental noise” is considered, and nearby-interference is excluded. Thus, interference sources are located in the external region.

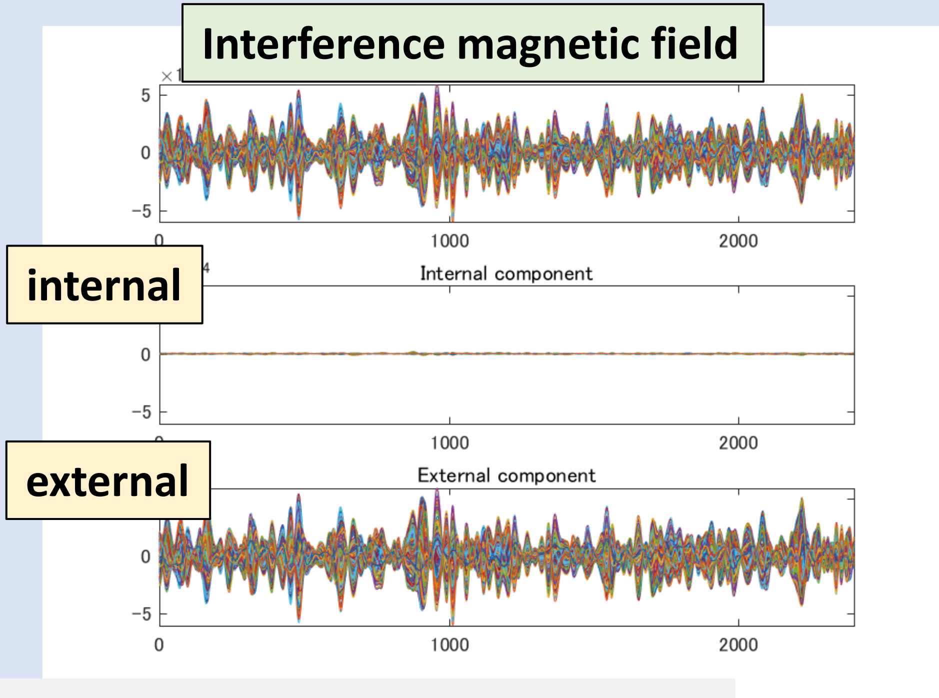
SSS Computer-Simulation Results for a Helmet Sensor Array



Signal source (near typical SI area)

Four interference sources:
distances to the sensor array: 2—5m

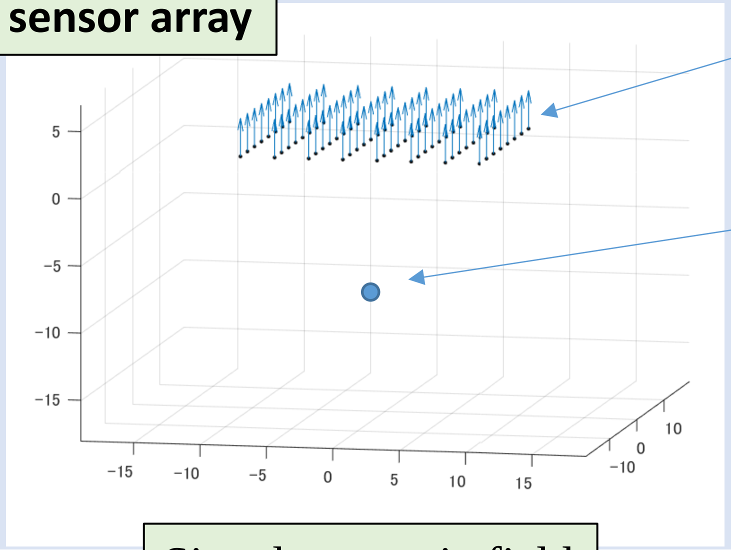




SSS can remove interference without distorting signal.

SSS Computer-Simulation Results for a Typical MCG Sensor Array

64-channel flat sensor array



8X8 sensors (measuring the normal component) are arranged on a flat plane covering an area of 20cm X20cm.

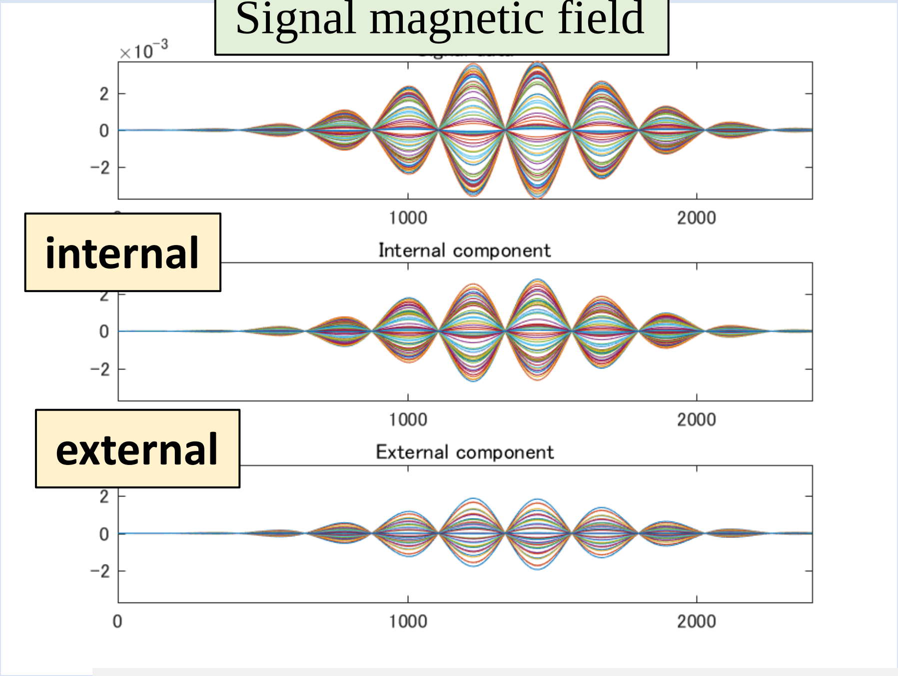
Signal source (10cm below the sensor plane)

Four interference sources exist.
Distances to the sensor array are 2—5m.

Signal magnetic field

internal

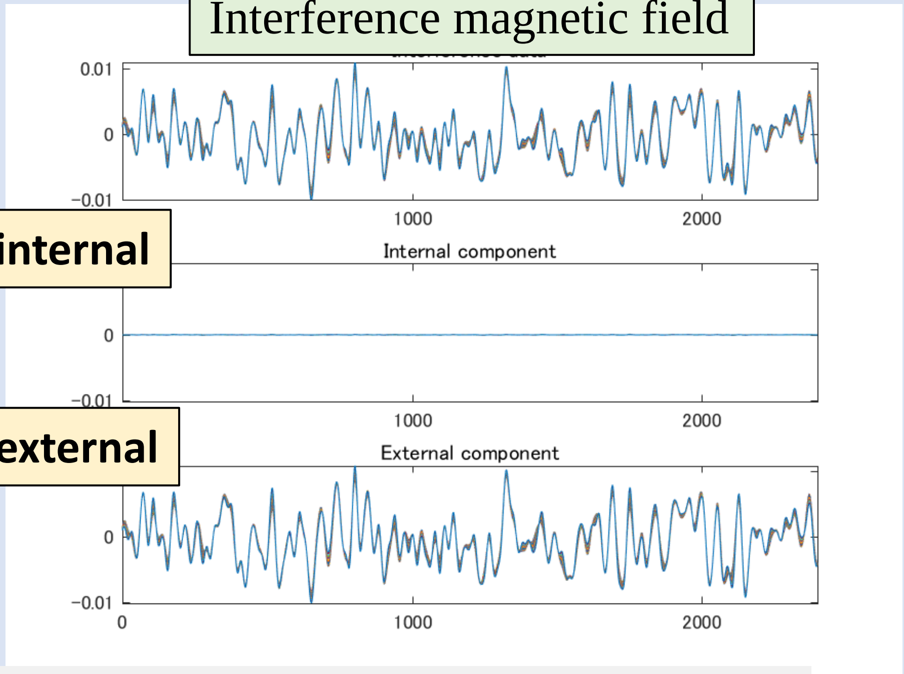
external



Interference magnetic field

internal

external

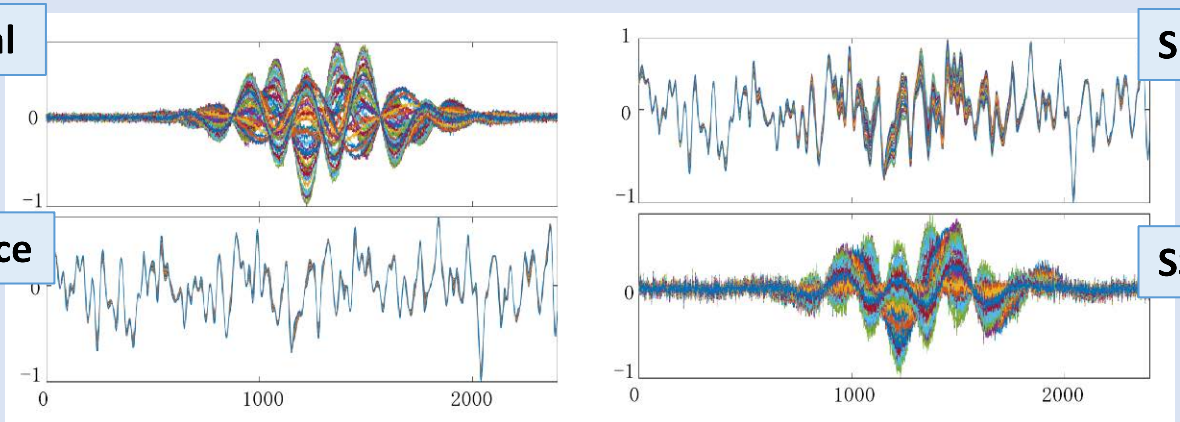


SSS can remove interference, but it distorts signal magnetic field.

Signal distortion can be corrected in source space analysis

Signal

Interference



Signal+interference

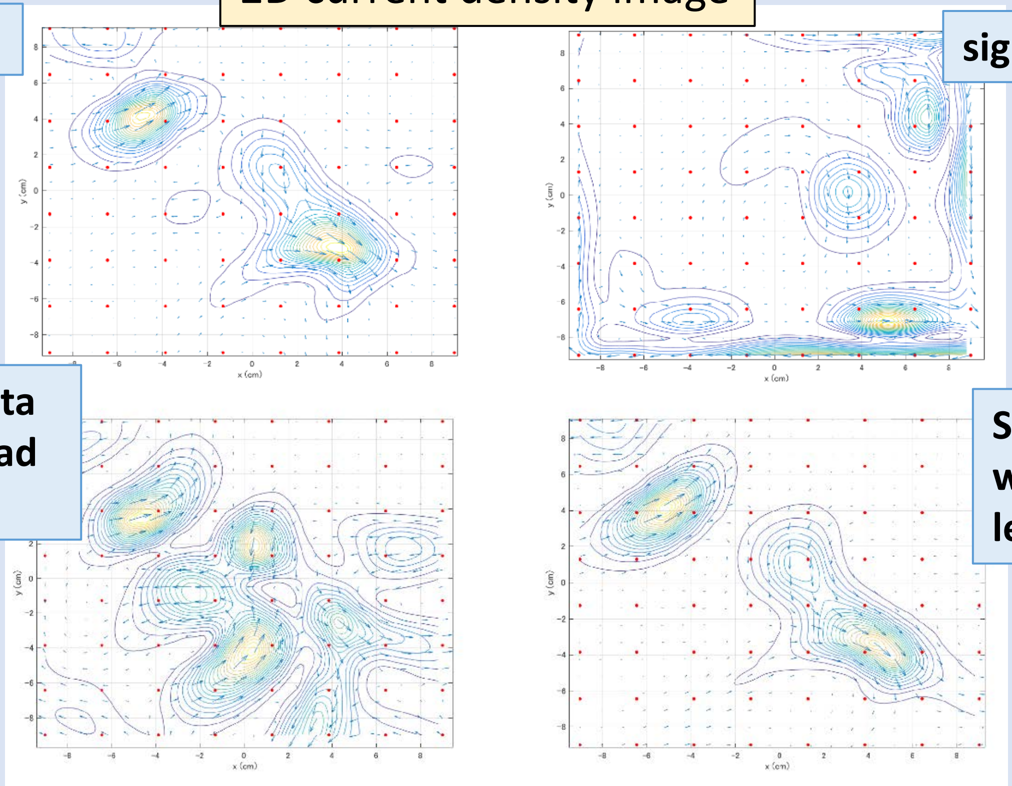
SSS-cleaned data

Interference is removed, but signal distortion exists.

2D current density image

Ground truth

signal+interference



SSS-cleaned data with normal lead field

SSS-cleaned data with SSS-filtered lead field

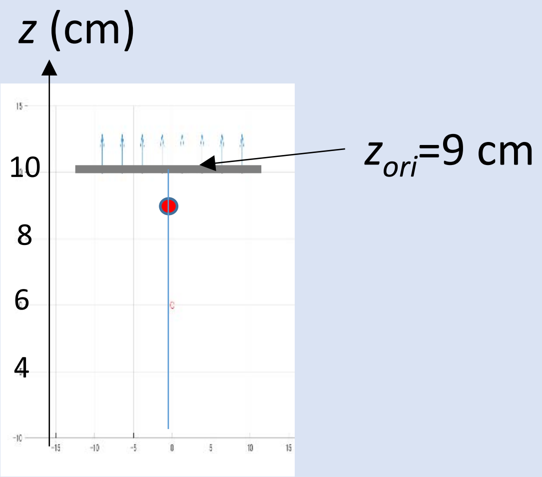
Image obtained with normal lead field contains distortion.

Image obtained with SSS filtered lead field is free of distortion.

Several numerical parameters affect the SSS performance, and they must be properly set.

Such parameters are:

z_{ori}: Location (z coordinate) of the origin.



L_C and L_D : Truncation values of the multipole order defined such that

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

Values of these parameters are determined by computing the performance measures below.

Signal gain:

$$G_S = \frac{\left\| \boldsymbol{P}_{\text{int}} \boldsymbol{B}_S \right\|}{\left\| \boldsymbol{B}_S \right\|}$$

Deviation from 1 is a measure of signal distortion.

Interference gain:

$$G_I = \frac{\left\| \boldsymbol{P}_{\text{int}} \boldsymbol{B}_I \right\|}{\left\| \boldsymbol{B}_I \right\|}$$

Proximity to 0 is a measure of shielding capability.

1/ G_I is called the shielding factor.

Noise gain:

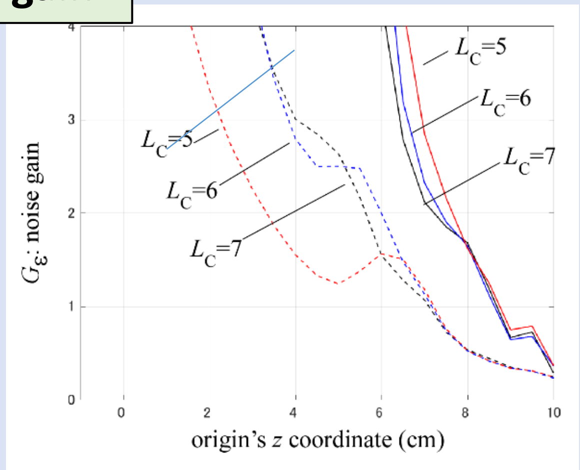
$$G_\varepsilon = \frac{1}{M} \sum_{j=1}^{M} \left[\boldsymbol{P}_{\text{int}} \boldsymbol{P}_{\text{int}}^T \right]_{j,j}$$

G_ε is a measure of noise amplification through the SSS procedure.

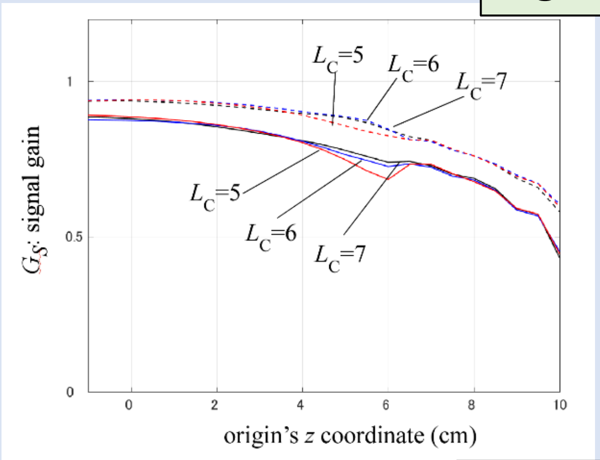
$\boldsymbol{P}_{\text{int}}$: **SSS internal-subspace projector**

These performance measures are computed with various parameters values.

Noise gain

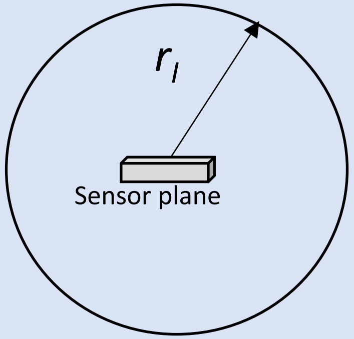


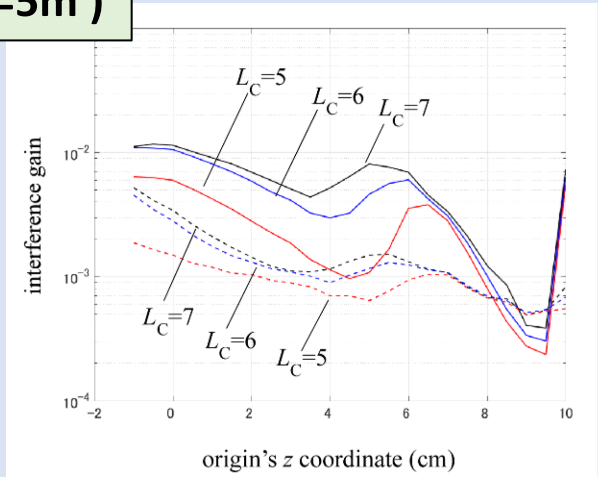
Signal gain



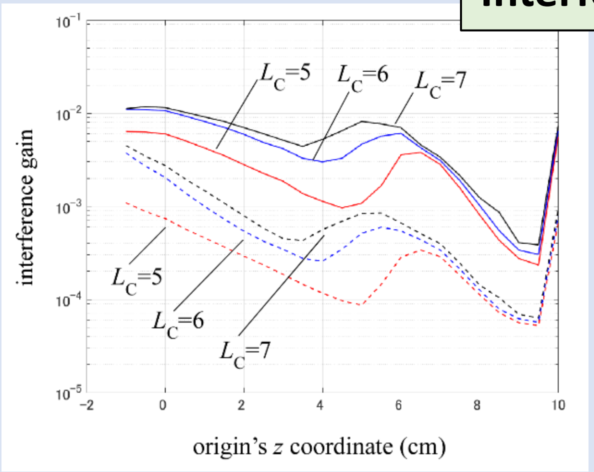
Dotted lines:
L_D =2
Solid lines:
L_D =3

Interference gain (r_I=5m)





Interference gain (r_I=20m)



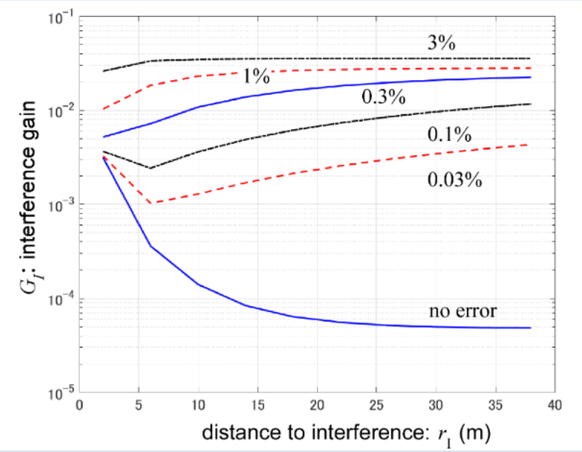
Dotted lines:
L_D =2
Solid lines:
L_D =3

Optimum values are determined such that: z_{ori} = 9cm, L_C=6 or 7, and L_D=2.

Interference gain is then evaluated assuming that sensor calibration errors exist.

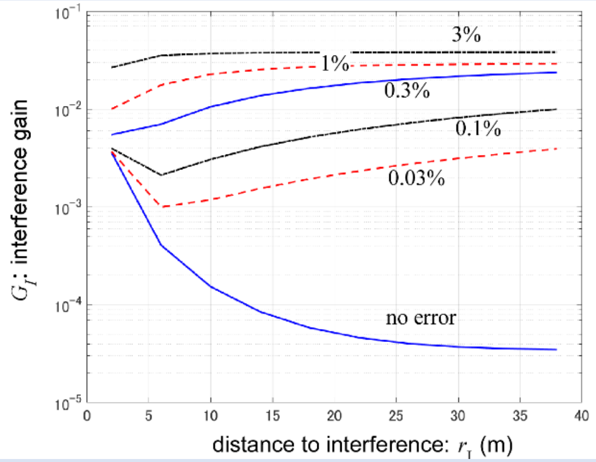
Typical existing MCG array

64 (8X8) (normal) sensors
Coverage: 20cmX20cm.



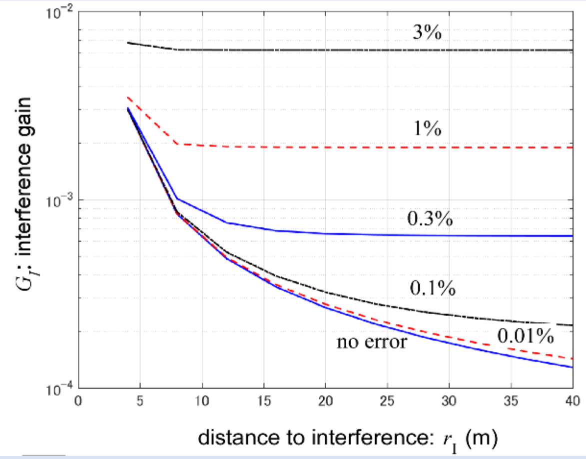
Larger array

100 (10X10) (normal) sensors
Coverage: 24cmX24cm.



Vector sensor array

36 (6X6) vector sensors (total 108 sensors)
Coverage: 20cmX20cm.



- **The typical existing MCG array and the larger array have similar shielding capabilities.**
- **In these arrays, shield factor reaches 50 with calibration errors of 0.3%, and 100 with errors of 0.1% .**
- **Vector arrays have a significantly improved shielding capability. The shield factor reaches 500 with errors of 1%, and reaches 1000 with errors of 0.3%.**

If you do not have a good calibration method, developing a vector sensor array is one choice.

As a summary, SSS is compared with gradiometer methodology

- Both provide capability of environmental noise cancellation.
- Both distort signal but the distortion is corrected by using (in some way) modified lead field in source space.
- SSS requires the sensor array to be precisely calibrated, and gradiometers require sensors to be precisely manufactured.

In conclusion, SSS can work as "software" gradiometers for newly-developed sensors in which the gradiometer configuration is difficult to implement.

Sekihara, K. (2018). Signal Space Separation Method for a Biomagnetic Sensor Array Arranged on a Flat Plane for Magnetocardiographic Applications: A Computer Simulation Study. *Journal of Healthcare Engineering, 2018*.

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