Localization of Coherent Sources by Simultaneous MEG and EEG Beamformer

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Abstract—Simultaneous magnetoencephalography (MEG) and electroencephalography (EEG) analysis is known generally to yield better localization performance than a single modality only. For simultaneous analysis, MEG and EEG data should be combined to maximize synergistic effects. Recently beamformer for simultaneous MEG/EEG analysis was proposed to localize both radial and tangential components well, while single-modality analyses could not detect them, or had relatively higher location-bias. In practice, most interesting brain sources are likely to be activated coherently; however, conventional beamformer may not work properly for such coherent sources. To overcome this difficulty, a linearly-constrained minimum variance (LCMV) beamformer may be used with a source suppression strategy. In this work, simultaneous MEG/EEG LCMV beamformer using source suppression was formulated firstly to investigate its capability over various suppression strategies. The localization performance of our proposed approach was examined mainly for coherent sources and compared thoroughly with the conventional simultaneous and single modality approaches, over various suppression strategies. For this purpose, we used numerous simulated data, as well as empirical auditory stimulation data. In addition, some strategic issues of simultaneous MEG/EEG analysis were discussed. Overall, we found that our simultaneous MEG/EEG LCMV beamformer using a source suppression strategy is greatly beneficial in localizing coherent sources.
II. INTRODUCTION

Brain source localization techniques using magnetoencephalography (MEG) and electroencephalography (EEG) have been of great interest in neuroscience because MEG/EEG could detect rapidly changing brain activation, that is, they have high temporal resolutions [1]-[4]. As for spatial resolution, MEG/EEG source localization is mathematically ill-posed because it has no unique solution and is very sensitive to noise [4]-[6]. Therefore, MEG/EEG is less sensitive in space than functional magnetic resonance image (fMRI). For several decades, researchers have attempted to develop methods to deal with these limitations. This has resulted in extensive study and commercialization of MEG/EEG source localization methods [4]-[5], [7]-[11].

In general, MEG provides relatively higher spatial resolution and smaller source-location bias than EEG. However, MEG is relatively silent to radially-oriented or deep sources, particularly in cases of spherical head models [2]-[4], [12]-[14]. While EEG is relatively sensitive to those cases, it tends to give relatively lower spatial resolution and thus yields greater source-location bias due to nonhomogeneous conductivity distribution within the head [15]-[16]. Even though MEG and EEG measure different physical information (magnetic field/electrical potential), they have the same underlying physics and try to detect the same electrical sources in the brain.

Thus, an integrative approach to MEG and EEG for simultaneous analysis appears intuitively sound. Studies have reported that simultaneous MEG/EEG analysis could be greatly beneficial in source localization when the MEG and EEG data are combined in an effective way [17]-[24] such as row normalization of lead-field matrices, row and column normalizations, minimization of mutual information for channel selectivity, weighted normalization, incorporation of intermodal noise covariance, use of Bayesian frame and so on. In addition to simulated data, such synergistic effects of simultaneous analysis were reported for various empirical data [23]-[25]. Despite these efforts, the best strategy for integrative MEG/EEG approach is still open to study and we believe that simultaneous analysis has not been investigated sufficiently, especially when it is compared with combining the approaches of MEG or EEG with fMRI [11, there-in].

Among various MEG/EEG source localization methods, a beamformer representing a kind of spatial filter acting on spatial or spatiotemporal data within sensor space offers great promise, in that it is robustly resistant to noise, relatively fast and accurate, and applicable for multi-sources without predetermination of source model order. It allows a neural signal produced only at a designated source point to pass, filtering out signals originating from other source points [26]. Therefore, even without a priori information on source quantity, beamformer can image brain activities within a source space effectively, under the assumption that sources are almost uncorrelated [27]-[33]. However, most brain sources of neuroscientists’ interest are coherent (correlated). Even though it was reported that beamformer is well able to reconstruct mildly coherent sources, it is quite challenging to localize strongly coherent sources. For this reason, a variant of beamformer, “the linearly constrained minimum-variance (LCMV) beamformer” [27] was proposed to be applicable for highly-correlated sources. Specifically, this beamformer is applied together with source suppression strategies [30], [32], which suppress sources in the designated region effectively.

Simultaneous MEG/EEG analysis in terms of beamformer had been not studied until our group’s work [19] was
reported recently. In [19], beamformer for simultaneous MEG and EEG analysis was formulated first and we investigated briefly how the synergistic effect of simultaneous analysis was beneficial. However, we observed that this simultaneous beamformer did not work properly for strongly coherent sources, an inherent limitation of beamformer, although most interesting brain signals (sources) are likely to be activated coherently [27]-[33]. This motivated us to conduct more thorough investigations of simultaneous analysis, because it is compelling, particularly, for coherent source localization.

In this work, we attempted to investigate the synergistic effects of simultaneous MEG/EEG analysis with respect to localization performance. Particularly, we focused on two dipole sources with various correlation levels: a tangentially-oriented dipole and a radially-oriented dipole. Further, the three-dipole problem (two correlated sources with one independent source) and empirical auditory stimulation were investigated. As a method of source localization, LCMV beamformer was adopted with five kinds of source suppression strategy—point, spherical region of radius 5mm, 10mm, 20mm, and 25mm—to avoid power-leakage interference between correlated sources [32]. These extensive studies provided a deeper understanding of strategic simultaneous analysis for localizing coherent sources. To the best of our knowledge, this kind of work has been lacking.

In this paper, we propose the use of simultaneous MEG/EEG beamformer analysis for coherent sources. In Section II, conventional simultaneous MEG/EEG beamformer is explained briefly. Subsequently, we formulated a theoretical LCMV for simultaneous analysis, with a source suppression strategy. In Section III, we present the configuration of the numerical model in MEG and EEG and the design of numerical experiments. In addition, empirical auditory stimulation experiment is described. The results of both numerical and empirical experiments conducted to verify the feasibility and capability of our proposed method are presented in Section IV. In Section V, we discuss thoroughly other efforts to achieve MEG/EEG beamforming, the problem of heavy noise, and other related issues. Finally, our concluding remark is summarized in Section VI.

III. SIMULTANEOUS MEG/EEG BEAMFORMER

A. Combining MEG and EEG data

There are critical differences between MEG and EEG, although their signals originate from the same neurophysiological processes [2]-[4]. MEG offers relatively better spatial resolution and smaller source-location bias than EEG because magnetic fields are less distorted by the skull and scalp than electric fields. EEG is relatively more sensitive than MEG to both tangential and radial sources, as well as deep sources, while MEG is silent to radial sources and less sensitive to deep sources. Thus, MEG can measure brain activities in the sulci selectively, whereas EEG can measure brain activities both in the sulci and at the top of the cortical gyri [2]-[4].

Based on these points, simultaneous MEG/EEG analysis could compensate for the weaknesses of each modality alone. However, simple concatenation without any ad-hoc procedures would cause large artifacts due to the unbalanced number of sensors and the different units (order) between MEG and EEG recordings. In this sense, the systematic measurement M,
which combines simultaneous MEG and EEG data, is presented. In order to combine two different modalities, they should be converted into unit-free (dimensionless) data. Defining the normalization matrix $S$ into (1) makes the unit-free measurement $M$ and lead-field of MEG/EEG $l(r)$, as formulated in the following:

$$\begin{align*}
M & := \begin{bmatrix} M_{\text{MEG}} \\ M_{\text{EEG}} \end{bmatrix},
l(r) & := \begin{bmatrix} l_{\text{MEG}}(r) \\ l_{\text{EEG}}(r) \end{bmatrix}, \\
S & = \text{diag} \left[ \frac{\alpha_1}{\|M_{\text{MEG}}\|}, \ldots, \frac{\alpha_{N_{\text{MEG}}}}{\|M_{\text{MEG}}\|}, \frac{\beta_1}{\|M_{\text{EEG}}\|}, \ldots, \frac{\beta_{N_{\text{EEG}}}}{\|M_{\text{EEG}}\|} \right].
\end{align*} \tag{1}$$

where $M_{\text{MEG}}$ and $M_{\text{EEG}}$ represent each single modality matrix of size $N_{\text{MEG}}$ (or $N_{\text{EEG}}$) × $T$ (=number of time samples) and unit-free $M$ is a matrix of size $N \times T$, ($N = N_{\text{MEG}} + N_{\text{EEG}}$), representing spatiotemporal data. Here $N_{\text{MEG}}$ and $N_{\text{EEG}}$ are the numbers of MEG channels and EEG channels, respectively. The $l_{\text{MEG}}(r)$ (or $l_{\text{EEG}}(r)$) denotes the single modality lead-field representing the sensitivity of the whole sensor array to source activity at $r$. The $\alpha$ and $\beta$ are weighting factors for each single modality, $\|\bullet\|$ represents the matrix norm, and diag[$v$] (for vector $v$) indicates a diagonal matrix, its diagonal being vector $v$. In this framework, there exist many ways on the determination of weighting factors. A fixed weighting factor for each modality is most conventional. A varying weighting over channels is possible, but should be determined carefully depending on the region of one’s interest. In this work, we follow the fixed weighting factors suggested in [19]:

$$\alpha = \frac{(\text{Total power of EEG})/(N_{\text{EEG}})}{(\text{Total power of MEG})/(N_{\text{MEG}})}, \beta = 1. \tag{2}$$

In [17], normalization of both column and row, and additional selective weighting was proposed. Weightings are selected to yield the minimum mutual information between MEG and EEG data. While adopting this approach may be interesting, it will be investigated in subsequent work. In this work the fixed weighting as noted in (2) will be considered only. We note when a Bayesian frame may also be introduced to integrate MEG and EEG [20], [24], this weighting determination may be not necessarily required.

B. Minimum-Variance (MV) Beamformer

Beamformer source imaging is a promising approach that can easily address spatiotemporal multi-dipole problems without a priori information on the number of sources and it is robustly resistant to noise. To localize uncorrelated sources from the continuous recordings of multichannel measurements like MEG/EEG, spatial filtering techniques may be adopted generally [9]. In this work, minimum variance (MV) beamforming is chosen as a source imaging technique [8]-[9], [34]-[35].

A vector-type spatial filter consists of a set of three weight vectors, $w_x(r)$, $w_y(r)$, and $w_z(r)$, depending on x, y, and z components of the source vector, respectively. Denoting the weight matrix by $W(r) = [w_x(r); w_y(r); w_z(r)]$, a vector-type beamformer is derived by solving the following constrained optimization problem:
\[ W(r) = \text{argmin} W^T CW, \text{ subject to } W^T (r) L(r) = I, \quad (3) \]

where \( C = (M(t)M^T(t))_n \) is a measurement covariance matrix estimated by the ensemble time average. \( L(r) = [l_x(r); l_y(r); l_z(r)] \) is the lead-field matrix and \( l_x(r) \) is a lead-field vector of unit-source activity oriented to \( \xi \)-axis at \( r \). The weight matrix, output source activity \( \hat{Q}(r,t) \) at \( r \), and output power of this vector-type spatial filter are expressed below:

\[
W(r) = C^{-1} L(r) \left[ L^T(r) C^{-1} L(r) \right]^{-1}, \\
\hat{Q}(r,t) = W(r)^T M(t) \\
\left\langle \hat{Q}(r,t)^2 \right\rangle = \left[ L^T(r) C^{-1} L(r) \right]^{-1}.
\]

When observing (4), output source power may increase falsely around the center of the head in the source imaging, because the lead-field becomes quite small around it. To avoid this difficulty, the constraint \( W^T (r) L(r) = [L(r)]I \) is applied in place of \( W^T (r) L(r) = I \) [8]-[9], [36]. This kind of beamformer is called array-gain beamformer [8]-[9]. Throughout this paper, this array-gain beamformer is used and expressed below:

\[
W(r) = \|L(r)\| \left[ C_{\Omega}^{-1} L(r) \left[ L^T(r) C_{\Omega}^{-1} L(r) \right]^{-1}, \\
\left\langle \hat{Q}(r,t)^2 \right\rangle = \|L(r)\|^2 \left[ L^T(r) C_{\Omega}^{-1} L(r) \right]^{-1}.
\]

C. Linearly constrained Minimum-Variance Beamformer with Source Suppression Strategy

The power-leakage interference between correlated sources in minimum-variance spatial filtering is understood as the main reason for failure in source localization [27]-[33]. Interesting neuronal activities are strongly correlated in most cases. Thus, to reduce the power leakage, the linearly-constrained minimum-variance (LCMV) beamformer along with a source suppression strategy is applicable. It can circumvent power-leakage problems by estimating sources of interest after separating the other correlated sources. Thus, we apply additional constraints to that at the source position of interest. These constraints may be added linearly via extended lead-field vectors (matrices) at the suppressing points [9], [30], [32]. In practice, it is less likely that the locations of the coherent sources are known. However, it may be possible to identify the approximate source locations or some extended region (cluster of positions) in which coherent sources could exist. Some research efforts on suppression region strategy will be discussed later.

In order to add the constraints, we defined a region (cluster of positions) in which to suppress sources correlated to the source of interest. Let the defined \( \Omega_R \) be the local region in which the coherent sources exist. Then, assuming the total of \( J \) position vectors (voxels) are located within the cluster \( \Omega_R \) and the locations of these voxels are defined as: \( r_{i1}, r_{i2}, \ldots, r_{ij} \), then the \( N \times 3J \) constraint matrix \( L_{\Omega} \) is defined such that:
Finally, the LCMV beamformer is derived by solving the following optimization problem:

\[
W(r) = \arg \min W^T C W
\]
subject to \(W^T (r) L(r) = I\), and \(W^T L = 0\).

Defining an \(N \times (3+3J)\) matrix \(\bar{L}\) as

\[
\bar{L} = [L, L_{\Omega}]
\]

the weight vector and output power are expressed as

\[
W(r) = C^{-1} \bar{L}(r) \left[ L^T (r) C^{-1} \bar{L}(r) \right]^{-1} s, \\
\left\langle \tilde{Q}(r, t)^2 \right\rangle = \left[ L^T (r) C^{-1} \bar{L}(r) \right]^{-1}.
\]

Here, \(s\) is a unit vector selecting one of the components of the lead-field vector of interest. The size of the suppressing cluster, \(L_{\Omega}\), can vary according to the measurement and suppression strategies. If the number of suppression voxels is smaller than the number of channels \(N\), (8) could give a reasonable result. However, if the number of voxels exceeds the rank, we need to reduce the dimension of matrix \(L_{\Omega}\) by applying singular-value decomposition (SVD) such that:

\[
\bar{L} = [L, a_1, \ldots, a_D]
\]

where \(a_i\) (i=1, \ldots, D) are singular vectors of \(L_{\Omega}\) corresponding to D significant singular values. In this work, the number of significant singular values, D was determined to account for over 95% of the variance of \(L_{\Omega}\).

IV. METHODS AND MATERIALS

A. Configurations for MEG and EEG

Through various numerical experiments, we investigated the feasibility of our formulated simultaneous MEG/EEG beamformer for coherent sources. The multi-shell (brain, skull, and scalp) spherical head model of outer radius 85mm was considered in this work. Current dipoles (two or three sources) were located in the inner-most layer (brain). The
relative conductivities for layers (brain, skull, scalp) were 1, 0.125 and 1, respectively. Relative radii of spherical layers from scalp to brain were 1 (85mm), 0.92, and 0.87. This model was referred to the EEG model in [16].

For the sensor geometry, we used the MEGVISION Yokogawa [37] system for MEG sensor geometry and LAXTHA WEEG-32 system [38] for EEG sensor geometry, respectively. Yokogawa MEG system consists of a 160 axial 1st-order gradiometer with a 50mm baseline on the spherical layer of radius 1.07, while the LAXTHA EEG system consists of 32 scalp-attached electrodes \{Cz, Fpz, Oz, Fz, AFz, FCz, CPz, T7, T8, C3, C4, Fp1, Fp2, F7, F8, O1, O2, P7, P8, F3, F4, P3, P4, Fe3, Fe4, Cp3, Cp4, Fc1, Fc2, Cp1, Cp2\}. The sampling rate in both systems was assumed to be 500Hz. Sinusoidal excitation (or damping sinusoidal) of amplitude 100 was considered for each current dipole source. To conserve the coherency between two sources, the frequency of the excitation was set to 10Hz, which is equal to a pair of sources. The acquisition time was set to 2s, which amounts to 1000 sample points. We generated synthetic data by adding white Gaussian noise to calculated sensor values. The signal-to-noise ratio (SNR, 10log_{10}SNR (dB)) is defined by $\frac{\|\text{measurement matrix}\|_F^2}{\|\text{noise matrix}\|_F^2}$, where $\|\cdot\|_F$ denotes the Frobenius norm.

For the assessment of the source localization, the sources were assumed to be located in a rectangular parallelepiped region (within brain region). This rectangular parallelepiped region is defined as $-6.5 \leq x \leq 6.5$, $-6.5 \leq y \leq 6.5$ and $1.5 \leq z \leq 7.0$ (cm) and three axes were determined as follows: the $+x$ axis is the direction from the origin to the nasion, the $+y$ axis is the direction to the left of the preauricular point, and the $+z$ axis is the direction perpendicular to the $x$ and $y$ axes. The beamforming scanning points were about 7500 with a scanning interval of 5mm, which is small enough to yield the point-spread sensitivity of the lead-field of the spatial filter at the source locations [8]-[9].

Throughout this paper, figures were depicted with three different views such as xy- (axial), xz- (sagittal), and yz- (coronal) plane projections. This yz-plane power projection maps were generated $P_{yz}(iy,iz) = \max_{i,j} P(ix,iy,iz)$ for each pixel point $(iy,iz)$. Similarly, xz-plane and xy-plan power projection maps were generated along projection directions y-axis and z-axis, respectively. However, yz-plane project maps (coronal view) only were illustrated for numerical experiments.

**B. Numerical and Empirical Experiments**

Simultaneous MEG/EEG beamformer was applied to various simulated data. As addressed in the previous section, 160 MEG gradiometers and 32 EEG electrodes, or a total 192 ($=N$) sensors were used. MEG and EEG sensors were uniformly distributed on the spherical shell (of relative radius 1.07) of the head model and on the scalp (of relative radius 1.0), respectively. For effective inversion of data covariance and higher output SNR [9], the inversion of data covariance matrix $(C + \epsilon I)^{-1}$ in place of $C^{-1}$ was used, where $\epsilon$ is a regularization factor [32], [39]. The regularization factor $\epsilon = \max \{\lambda_1, \lambda_2, ..., \lambda_{\text{max}}\} \times 10^{-5}$ was used, where $\lambda$ is the eigenvalue of the data covariance $C$. 
In this work, the following localization problems were generated for extensive investigation:

- **uncorrelated sources**: two-dipole problem

  In order to investigate the capability of simultaneous MEG/EEG, the source localization error over SNRs was estimated among MEG/EEG and each single modality (MEG only, EEG only). The Monte-Carlo simulation was conducted in the given spherical head model (brain region). In this point, we divided two source regions (left and right hemispheres). We generated tangential-only sources (dipoles) in the left hemisphere and radial-only sources (dipoles) in the right hemisphere, keeping two sources at least 30mm away. Two different excitations (each excitation is assigned to each dipole) yielding almost zero correlation were considered to generate uncorrelated sources. Firstly, 200 two-dipole problems were generated randomly in this manner. To yield 5 kinds of SNRs (-5, -2.5, 0, 2.5, 5 (dB)), a certain amount of white Gaussian noise was added to calculated sensor values; thus a total of 1000 two-dipole problems were prepared. The weighting factors of $\alpha$ and $\beta$ were determined based on (2) and the powers were reconstructed using (5).

- **coherent sources**: two-dipole problem

  Similar to the previous case, we assumed that two current dipoles were located and oriented (tangentially and radially) at the left and right hemispheres of a human brain, respectively. The frequency of the excitation was set to 10Hz (coherent with each other) and sinusoidal excitation was considered. To control the level of coherence between sources, the phase of the first dipole was fixed at 0° and the phase of the 2nd dipole varied from 0° to 90° with 5° increments (from 0° to 45°) and 15° increments (from 45° to 90°), respectively. We note that phase differences 0° represents no phase difference between two sinusoidal excitations, thus they are perfectly correlated with yielding a correlation value of 1. On the other, phase difference 90° represents that one is sinusoidal and the other is co-sinusoidal, thus they are perfectly independent, that is, uncorrelated; it yields a correlation value of 0. In addition, two different SNRs (0, 5dB) were considered by adding white noise to the synthetic signal. Thus, for each given dipole pair, a total of 26 kinds of coherent-source problems were generated. In this work, 100 randomly selected dipole pairs were used to generate a total of 2,600 kinds of coherent sources having various coherences.

  We defined the source suppression area $\Omega_R$ in (6) as follows:
  - point (viz. exact coherent source location)
  - spherical regions of radius 5, 10, 20, 25 (mm), centered at an exact source location within a given spherical head model

  For the spatial filter with various suppression strategies, reconstructed waveforms (powers) were compared to a conventional spatial filter without a suppression strategy. The weighting factors of $\alpha$ and $\beta$ were determined based on (2) and the powers were reconstructed using (5). The Monte-Carlo simulations were conducted with 2,600 two-dipole pair problems.

- **coherent sources**: three-dipole problem

  We further investigated the capability of our proposed simultaneous MEG/EEG with a source suppression
strategy by applying three-dipole problems. In the same way as the coherent two-dipole problem, two sources were generated (two sources oriented tangentially and radially were located variously 50mm away or above). In addition, a third source was generated at least 30mm away or above from the other two sources (a time course of 20Hz with amplitude 70 was used to be almost independent of other two sources). Correlation of the two sources was varied and the one remaining source was kept independent of others. Two different SNRs (0, 5dB) for each problem and seven different phase differences (0°, 15°, 30°, 45°, 60°, 75°, 90°) were considered. The weighting factors of α and β were determined in the same manner as two-dipole experiments. A total of 700 problems were generated and localization performance was investigated.

*coherent sources*: empirical auditory stimulation

Auditory stimulation (left or right ear) data under the simultaneous MEG/EEG measurement paradigm were acquired on a whole-head gradiometer MEGVISION Yokogawa system with 160 channels for MEG and 14 channels for EEG, respectively. MEG and EEG coordinates of channels were co-registered by applying basis transformation. In the empirical problem cases, x, y, and z coordinate axes were determined as follows: the +x axis is the direction to the right of the preauricular point, +y axis is the direction from the origin to the nasion, and the +z axis is the direction perpendicular to the x and y axes. A total of beamforming scanning points were 6239. The detailed experimental paradigm was as follows:

A healthy, 24-year-old male volunteer participated in the simultaneous MEG and EEG measurements after appropriate informed consent. The auditory stimulation of his left or right ear was conducted with eyes closed and all measurements were performed in a magnetically shielded room. An 80dB sound pressure and a 2Hz sampling were applied with 40ms plateau with 10ms rises and falls. Also, the inter-stimulus-interval (ISI) was randomized with a 2s duration (random 50%, 1-3 s). Data were digitized at 2kHz, low-pass filtered at 500Hz, as well as post-processed via a digital filter at 1-50Hz, excluding 50Hz due to the electrical power conditions in Japan. A total of 73 (right-ear) and 70 (left-ear) single trials were obtained. Each averaged data point with a 0-150 (0-300 samples) millisecond time window after the stimulation onset was analyzed.

A simultaneous MEG/EEG beamformer with a spherical region of radius 10mm source suppression strategy (suppression area is roughly determined empirically) was applied. In addition, the single modality analysis (MEG or EEG-only) was applied for comparison. Like to numerical experiments, the weighting factors were determined using (2).

V. RESULTS

A. Localization of Uncorrelated Sources

We comparatively applied 1000 uncorrelated two-dipole problems for conventional simultaneous MEG/EEG, MEG-only, and EEG-only approaches. Figure 1 depicts comparative source localization results of a typical two-dipole
problem between single modalities and simultaneous approaches for three different SNRs (-5, 0, 5 dB). It shows the reconstructed source power distributions of conventional beamformer by using (5). Here the rectangular and triangular black markers indicate true source locations, which are oriented tangentially and radially, respectively. In this case, two sources (time courses) had a correlation coefficient of approximately zero. Each column represents different SNRs. The first, second, and third rows indicate MEG, EEG, and simultaneous MEG/EEG source imaging results, respectively. The weighting factors of $\alpha$ for three different SNRs almost equal and has the value of about 0.01. The MEG/EEG (last row) reconstructed the true sources well, with better spatial resolution and smaller location bias than the EEG only (second row), while the MEG (first row) failed to detect the radial component of the source (triangular source). As SNR increases, overall localization performance tended to improve, regardless of modalities. As expected, simultaneous MEG/EEG analysis compensated for each weakness of MEG (silence on radial source) and EEG (low spatial resolution).
the source (triangular source). As SNR increased, overall localization performance tended to be better, regardless of modalities. As expected, the simultaneous MEG/EEG analysis compensated for each weakness of MEG (silence on radial source) and EEG (low spatial resolution). The weighting factors of $\alpha$ for three different SNRs almost equal and has the value of about 0.01.

In order to quantitatively investigate the capability of simultaneous MEG/EEG, the source localization error (mm) in Figure 2 over SNRs was estimated among MEG/EEG and each single modality (MEG only, EEG only). Figure 2 shows the average source localization errors and their standard deviations of simultaneous MEG/EEG, MEG only, and EEG only over SNRs. For better illustration of Figure 2, x-coordinates representing SNR were moved a little back and forth from the exact SNR. The dashed, dotted, and solid lines indicate the MEG, EEG, and MEG/EEG, respectively. The radially- and tangentially-oriented sources were reconstructed in the right and left hemispheres, respectively. The thick circular line indicates the averaged localization error among two sources. The rectangular line indicates the localization error of only tangential sources (in the left hemisphere). The triangular line denotes the localization error of only radial sources (in the right hemisphere). As expected, the localization error decreases as SNR increases. Because the MEG cannot detect the radial sources, the MEG error is represented by tangential sources only. Except for the MEG localization error distribution for tangential sources, the MEG/EEG localization error was much lower than the EEG only and MEG/EEG could well reconstruct both sources. This numerical experiment clearly demonstrated the advantage of simultaneous MEG/EEG analysis.

**B. Localization of Coherent Sources**

Extensive study was done for a large number of two-dipole problems with various correlation values ranging from 0 to 1. Figure 3 depicts comparative source localization results of a typical two-dipole problem between EEG single modality and simultaneous approaches for SNR of 5dB. It shows the reconstructed powers of the spatial filter over varying phase differences ($15^\circ$, $30^\circ$, $90^\circ$) between sources, in which the correlation coefficient varied from 0.97, 0.87, to 0 between sources. We note that among 13 kinds of correlations, three representative cases were depicted here. The rows represent the EEG only and simultaneous MEG/EEG reconstructions with the conventional beamformer approach in (5), and LCMV beamformer with source suppression strategy (spherical region of radius 20mm), respectively. Each column
represents the phase difference between sources of 15°, 30°, and 90°, respectively. The weighting factors of $\alpha$ for three different phases (15°, 30°, and 90°) varied from 0.01, 0.015, and 0.017. Interestingly, these values increase (a little bit) as...
degree of source correlations decrease because from the (2), perhaps, the power-leakage interference between correlated sources decreases. As expected, radial source was not localized in the MEG case (not shown), while both sources were localized by the EEG and MEG/EEG analyses. In the EEG case (first two rows), the conventional beamformer (first row) could yield significantly larger location error as the source correlation effect gets increased. On the other hand, the suppression beamformer (second row) reasonably well localized the true source locations regardless of source correlation effect. In the same manner, two coherent sources were more focally localized by the MEG/EEG analysis with suppression (forth row) than the conventional spatial filter approach without suppression (third row) especially in the case of strong correlation sources. From following these points, the MEG/EEG analysis approach has two distinct benefits: it can detect the radial source regardless of high source correlation, and its reconstructions are much better than those of an EEG-only analysis. Even strongly coherent sources are effectively localized with source suppression strategy. In short, the source suppression strategy was so effective in localizing strongly coherent sources. In addition, it was reconfirmed that the simultaneous MEG/EEG shows its superiority over the single modality.
Figure 4 presents the average source localization error over various source correlations (phase difference between sources varying from $0^\circ$ to $90^\circ$), with respect to various source suppression strategies, such as point (dotted cross line), spherical region of radius 5 mm (dashed x line), 10 mm (dashed triangular line), 20 mm (dashed rectangular line), and 25 mm (dashed diamond line), to avoid power-leakage interference between coherent sources. The left and right figure represent EEG only and simultaneous MEG/EEG analysis, respectively. Top and bottom figures represent two different SNRs of 5dB and 0dB, respectively.

Figure 4 presents the average source localization error over various source correlations (phase difference between sources varying from $0^\circ$ to $90^\circ$), with respect to various source suppression strategies, such as point (dotted cross line), spherical region of radius 5 mm (dashed x line), 10 mm (dashed triangular line), 20 mm (dashed rectangular line), and 25 mm (dashed diamond line), to avoid power-leakage interference between coherent sources. The conventional beamformer approach is represented by the solid circular line. The left and right figures represent EEG only and simultaneous MEG/EEG analysis, respectively. Top and bottom figures represent two different SNRs of 5dB and 0dB, respectively. The Monte-Carlo simulations were conducted with 2,600 two-dipole pair problems. They were generated to apply the simultaneous MEG/EEG beamformer or EEG-only beamformer with and without a source suppression strategy. We excluded the MEG-only analysis because MEG cannot detect the radial component; thus the localization-error distribution of tangential sources is similar to the simultaneous MEG/EEG analysis.

As expected, the localization error of the conventional spatial filter became larger when the correlation of sources became gradually stronger. In the EEG case (left column figure), the error of the conventional beamformer decreased as
the correlation of sources weakened. Interestingly, beamformer with a suppression strategy yielded almost uniform localization error over varying source correlations. We observed that this localization error level was close to the suppression region size (that is, radius of the suppressed spherical region), so canonical errors may happen near each suppression region boundary. Even the MEG/EEG case (right column) showed a similar trend to the EEG case, except that it yielded relatively lower uniform localization error level for beamformer with a suppression strategy than in the EEG case. Evidently, localization-error distribution for the point suppression is practically zero, which means it could prevent the power leakage between coherent sources perfectly. We addressed the two points in more detail observing from the Figure 4:

- **Increasing-error tendency as the source correlation decreases** (particularly, EEG-5dB-25mm source suppression case; first row left column):
  
  In general, the mutual information between sources increases as degree of correlation increases. That means, the pure signal power (i.e., SNR) may reduce as correlation increases. In the suppression beamformer point of view, when suppressions are applied, the outer suppression sources are regarded the signal power, otherwise, the inner suppression sources are considered to be noise. In this sense, when source correlation gets large (mutual information is relatively higher than those of the independent case) the SNR (power of the outer suppression region/power of the inner suppression region) has the relatively higher value than the independent source case. In short, the effect of noise may increase when source correlation decreases. We confirmed the above effect through simulation and understood the happened tendency.

- **Increasing-error tendency as the size of suppression region increases**:

  The localization error increases as the source suppression region increases as shown in Figure 4. Interestingly, we observed that this localization error level was close to the suppression region size (that is, radius of the suppressed spherical region). As mentioned above, when we consider the suppression beamformer’s view, the do suppression (inner suppression sources) means to be considered noise (i.e., non-interesting signal). Therefore, beamformer makes the same measurement anywhere in the combination of suppressions between coherent sources. That means the uniqueness is disappeared to make same measurement. Finally, the degree of freedom increases as the suppression region size increases. That’s why we observed the canonical error may happen near each suppression region boundary. In practice, the values of averaged ratio of localization error to suppression region sizes (5, 10, 20, and 25mm) were 0.9193 (EEG 5dB case; 0.7823, 0.8205, 0.9905, and 1.0838 for each), 1.0290 (EEG 0dB case; 0.9981, 0.9274, 1.0573, and 1.1333 for each), 0.4869 (MEG/EEG 5dB case), and 0.8092 (MEG/EEG 0dB case). These ratios demonstrate the tendency of canonical errors.
Overall, the suppressions produced a better performance than the conventional one when the source correlations were strong. In conclusion, the performance of simultaneous MEG/EEG analysis was far better than EEG-only, and an improved localization effect of a suppression strategy is substantially more promising in simultaneous analysis than EEG-only.

We further investigated the capability of our proposed simultaneous MEG/EEG with a source suppression strategy by applying three-dipole problems as illustrated in the simulation section. For 700 kinds of three-dipole configurations (two sources oriented tangentially and radially were located variously 50mm away or above; the remaining source was located 30mm away or above from the other two sources; correlation of the two sources was varied and the one remaining source was kept independent of others), localization performance was investigated. Figure 5 shows the reconstructed powers of the spatial filter of a three-dipole (typical) case for different phase differences, such as 0°, 30°, 60°, and 90° (each column). The first and second rows indicate conventional and suppression approaches, respectively. The tangentially and radially-oriented sources are represented as rectangular and triangular shaped black markers, respectively, and the remaining independent source is represented as a diamond shape black marker. The source suppression region and SNR were set to 5mm and 5dB, respectively. The weighting factors of α for four different phases varied from 0.01 (0° and 30°), 0.012 (60°), and 0.015 (90°).

Overall, the suppressions produced a better performance than the conventional one when the source correlations were strong. In conclusion, the performance of simultaneous MEG/EEG analysis was far better than EEG-only, and an improved localization effect of a suppression strategy is substantially more promising in simultaneous analysis than EEG-only.
Simultaneous MEG/EEG beamformer (first row), especially, could yield source location errors due to source correlation effects, while the independent source was not affected in simultaneous MEG/EEG analyses with and without suppression. On the contrary, the suppression beamformer (second row) localized the true source locations well, including correlation sources. Moreover, all three sources (regardless of the independent source) seemed to be more focally localized by the suppression simultaneous MEG/EEG analysis (second row) than the conventional spatial filter approach (first row). We observed that two coherent sources in these three-dipole problems (not shown) demonstrated a similar tendency to the previous two-dipole (coherent source) problems.

C. Empirical Experiments

In this section, our proposed simultaneous MEG/EEG beamformer was applied to empirical simultaneous MEG/EEG data. As mentioned in Section III-B, auditory stimulation (left/right ear) data under the simultaneous MEG/EEG measurement paradigm were acquired. A simultaneous MEG/EEG beamformer with a spherical region of radius 10mm source suppression strategy (suppression area is roughly determined empirically) was applied. In addition, the single modality analysis (MEG or EEG-only) was applied for comparison. The weighting factor was about 0.01 obtained using (2).

Literature [30] reported that auditory stimulated neuronal data (MEG or EEG) were induced by strong coherent sources, which may be not easily localized through conventional beamforming approaches. Figure 6 illustrates comparative results of the conventional and our proposed approaches using source suppression. As shown in Figure 6,
beamformer with a source suppression strategy for the averaged left auditory stimulation data yielded considerable focal source activity in both the right and left temporal areas (last three columns), which is relevant to the existing literature (see [30] and there-in), while the conventional beamformers (first three columns) failed to reconstruct sources due to their correlation effects. It is again noted that simultaneous MEG/EEG beamformer with a suppression strategy yielded far more focal sources than others. The averaged right auditory stimulation data yielded relatively less focal but the similar behaviors to the left stimulation one (not shown). This demonstrated that simultaneous MEG/EEG analysis with a suppression strategy has a notable advantage over other single modality or conventional MEG/EEG analyses.

VI. DISCUSSION

A. Other Strategies for simultaneous MEG/EEG

In this work, simultaneous MEG/EEG analysis was formulated by incorporating the normalization matrix $S$ with weighting factors $\alpha$ and $\beta$ to obtain unit-free combined measurements. To obtain weighting factors, we used the criterion (2) suggested in [19]. Our criterion here was not optimal in the sense of localization performance. We observed that even slight changes of fixed weighting might yield differences in performance. Generally, determining weighting factors may depend on computational configurations (sensor geometry, head geometry, localization methodology and so on) and region of interest. Alternatively, it is possible to give the varying weighting factors at each channel, based on statistical significance estimated from sensor measurement distribution (for example, topography plot).

In addition, it is possible to give selective weighting of the contributions from either modality by using the correlation distribution between measurement and lead-field vectors [40]. Intuitively, if the brain source is active at a specific location, the correlation distribution at that location may have a higher value than that at other locations; this may play a key role in obtaining a priori information on weighting factors.

Further, combining MEG and EEG measurements may be performed with the principal components of EEG representing a signal subspace. Applying SVD to EEG measurement, we can obtain some principal features from EEG, and then concatenate the MEG measurement. Usually, the empirically heavy noisy EEG data yield a relatively slight negative effect compared to the MEG data. In this sense, using the principal features in place of the whole EEG features could reduce this negative effect.

The limitation is that the proposed combination is close to the summation of two different linear systems even though various weighting techniques enhance the advantage of MEG and EEG (the choice of optimal weight factors is more beneficial). Therefore, if the MEG (tangential components) and EEG (radial components) lead-fields can be combined into an integrated linear system in a reasonable way, the directional sensitivities of two different modalities will be enhanced simultaneously. As related work that minimizes the mutual information between MEG and EEG, lead-fields offer us the direction we may wish to follow [17].
B. Source Suppression for Coherent Sources

In this work, simultaneous MEG/EEG beamformer analysis using LCMV with source suppression (with various areas) was proposed for coherent sources. Although the point suppression was the most effective to localize and reconstruct the coherent sources, it is difficult, in general, to expect to know where to place the point-suppression constraint because we are not sure of the exact location of the correlated source. We used an empirically-determined source-suppression region for empirical data analysis in the previous section. However, this strategy is very limitedly applicable. As an alternative, an iterative process of decreasing the region of suppression from a wide range (hemisphere) to a focused point (reasonable final size) may offer a solution [32]. For this iterative approach, the criterion should be given carefully as a noticeable characteristic changing monotonically over the size of the suppression region. We observed in preliminary results that the phase distortion (from original source) of a reconstructed source is reduced as the suppression region is reduced. We are currently investigating whether this characteristic may be used for implementing this iterative process.

Another possible problem exists for coherent sources that are too closely located. We cannot guarantee the independence between two lead-field vectors at each source location. Therefore, the degree of the suppression accuracy depends on the point-spread sensitivity function of the sensor system at the source positions [8]-[9], [32], which is an intrinsic indicator of a potential beamformer spatial resolution.

In this work, we only considered the suppression regions of sphere centered at a coherent source. In real situation, it is hard to determine the suppression region centered at a source. For this reason, considering cases that a coherent source is not centered at the suppression region, we found that there was no substantial performance difference in source imaging. Further, shape of the suppression region does not matter in this regard.

Functional connectivity and directivity studies are in the mainstream of brain research. To conduct these studies, we believe source localization within the cortical region is essential. Thus, our simultaneous MEG/EEG analysis (in the case of coherent sources using LCMV with source suppression) is potentially useful. However, conventional beamformer may yield relative source phase distortions, which is a considerable risk in conducting connectivity analyses on brain cortex. Our preliminary results show that phase distortion is substantially reduced at a reasonable degree of source suppression, even for coherent, or strongly correlated, sources oscillating at the same frequency. At this point, we believe that our simultaneous approach is very useful in analyzing source connectivity and corresponding subsequent work is currently in progress.

C. Empirical Data Analysis

To illustrate the synergistic effect of simultaneous MEG/EEG analysis, we investigated the configuration of tangential and radial-only oriented sources in this work. Even this case (particularly, radial-only source) may rarely happen, we have witnessed an epileptic signal with a radially-oriented single source at the Biomag 2006 conference presentation (unpublished). Although such empirical epileptic data are quite good for our research purpose, they are currently unavailable to us. Efforts are underway to obtain this type of empirical data.
D. Reduction of noise effect: eigenspace-projected filter

In general, due to considerable noise, the estimated source activity obtained from an MV or even LCMV beamformer may include source imaging distortion or noise sources. To yield a more noise-resistant approach, eigenspace projections may be used. In a manner similar to our beamformer formulation addressed in Section II, eigenspace-projected spatial filters [9], [35] incorporating a source suppression strategy as additional constraints may be formulated (an eigenspace-projected spatial filter reduced noise effects by projecting onto the signal subspace). Eigenspace-projected LCMV filters usually showed slightly more focal results than conventional LCMV for both simulated and empirical data (not shown).

VII. CONCLUSIONS

In this work, we proposed the use of simultaneous MEG/EEG beamformer incorporating source suppression strategies. For numerous coherent-source problems having various configurations, we investigated the capability of our proposed simultaneous analysis extensively over various source suppression strategies. Our findings are summarized as follows:

- We reconfirmed that regardless of using/not using source suppression strategies, simultaneous MEG/EEG analysis was far more beneficial in improving source localization by comparison with single modalities such as EEG-only and MEG-only.
- For strongly coherent sources, approaches with source suppression strategies far surpassed conventional approaches. Further, simultaneous analysis with source suppression strategies (formulated here) yielding better performance than others is more promising in the application of functional connectivity and other research.
- We observed that all approaches with source suppression yielded almost uniform localization performance over various correlation values, while simultaneous approach had better performance.
- Small suppression region strategy such as point or spherical region of small radius (≤10mm) is most preferable for better localization performance. For this utilization in practice, any source suppression strategies in an automatic way may be developed, and this is currently under investigation.

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Simultaneous MEG/EEG Beamformer for Coherent Sources


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