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How Many Channels are Needed for MEG?

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ABSTRACT

Channel count in modern MEG systems has been steadily increasing, but are more channels necessary? Assuming that the spatial sampling considerations are satisfied, this question can be answered by examining the MEG system's ability to localize and resolve brain sources. For the simple situation where only uncorrelated sensor noise is present, dipole localization accuracy monotonically increases with increasing number of channels, while for spatially correlated brain noise the accuracy increases only until the number of channels reaches 100 to 200. Beyond this limit the inter-channel separation is comparable to the brain noise correlation distance and increasing the channel count does not help. Contrary to the above dipole result, we show by simulations with up to several thousand channels, that if the data is analyzed by beamformers even in the presence of correlated brain noise, the two-source resolvability and single-source localization accuracy monotonically improve with increasing number of channels. We demonstrate such behavior for a 275 channels system, where we have inserted an artificial dipole into real measured brain noise and resampled the number of channels to 138. Beamformer analysis of the data shows markedly improved localization accuracy when the number of channels is increased from 138 to 275. This finding also signifies that the beamformer performance is not limited by system imperfections when the number of channels is as large as 275. To clarify these results, we illustrate analytically the mechanism of beamformer resolution dependence on the number of channels, using an example of a simple system containing two dipole sources, and uncorrelated sensor noise.

KEY WORDS

Magnetoencephalograpy, MEG, Channel density, Beamformers, Synthetic aperture magnetometry, SAM

INTRODUCTION

The answer to the question about how many channels are needed for MEG ultimately depends on what we want to measure, character of the noise present in the system, and on how we want to analyze the data. We first examine the effect of noise on the MEG dipole localization accuracy and review spatial sampling requirements. Then we shall describe simulations of the beamformer behavior as a function of the number of channels and demonstrate the results on actual 275 channel MEG measurement. We conclude the discussion by a simple analytical example which provides insight into the beamformer behavior when the number of channels is changed.

METHODS AND RESULTS

For uncorrelated sensor white noise, the required number of channels is determined by spatial sampling arguments [Ahonen, 1993] and by dipole localization accuracy requirements [Vrba, 2002]. Sampling considerations suggest that the number of channels, M, should be large for superficial sources and for high signal-to-noise ratio (SNR), while localization error reduces with increasing number of channels (as $1/\sqrt{M}$ for a single equivalent current dipole (ECD)).

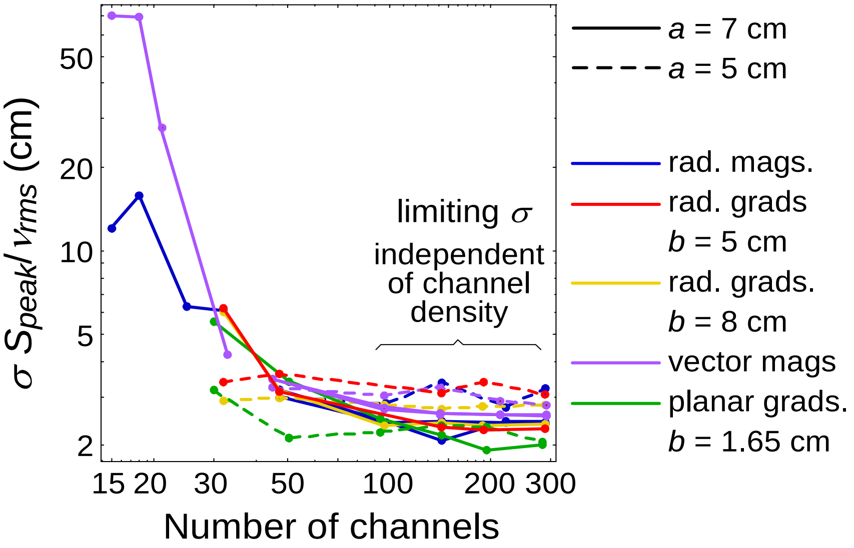

Figure 1. Standard deviation of the ECD localization error; this is normalized by rms noise and peak signal in the presence of brain noise, simulated by randomly oriented and randomly distributed 1000 ECDs throughout the model volume. The hemispherical sensor shell has a radius of 10.7 cm, dipole magnitude q = 10 nAm, dipoles at distances of a = 5 and 7 cm from the model sphere center. The sensor types and corresponding brain noise amplitudes were: radial magnetometers, 30.4 fT rms; tangential magnetometer, 17.2 fT rms; radial gradiometers with 5 cm baseline, 24.2 fT rms; radial gradiometers with 8 cm baseline, 27.1 fT rms; planar gradiometers, 11.5 fT rms.

The brain noise is spatially correlated among channels and the above simple arguments do not apply. The ECD localization errors derived by Monte-Carlo simulations of brain noise are shown in Fig. 1. It was found that over a wide range of ECD positions, sensor types, and sensor shell radii, and for the number of channels $M > 100$, the standard deviation of the localized ECD positions becomes independent of the number of channels [Vrba, 2002] and can be approximated by $\sigma \approx \beta_c v_{rms} / S_{peak}$, where σ is rms value of the standard deviations of the localization accuracy along three orthogonal directions, v_{rms} is the rms value of the brain noise, S_{peak} is the peak signal corresponding to the investigated ECD, and the constant of proportionality $\beta_c \approx 2.6$ cm. The saturation of the ECD localization error for large number of channels corresponds to the channel density at which the inter-channel spacing becomes comparable or shorter than the brain noise correlation distance of about 3 to 5 cm [de Munck, 1992]. Correlation distance is defined as a distance along the scalp at which the correlation coefficient is reduced to 0.5.

When the MEG signals are analyzed by beamformers (SAM) [Robinson, 1999], it is shown that significantly larger number of channels may be more beneficial than that indicated in Fig. 1. The SAM Z^2 analysis of single source peak width and resolution of two sources in simulated brain noise are shown as a function of the number of channels in Fig. 2 ($Z^2 = P/N$, where P is the power and N is the sensor noise power projected by SAM). To evaluate a single source peak width, we have computed SAM Z^2 depth profile through the source and plotted full-width-half-maximum (FWHM) of the peak as a function of the number of channels for dipole magnitudes of 3, 5, and 7 nAm in Fig.2a. The peak width monotonically decreases with increasing number of channels (indicating monotonically improving resolution), and the saturation has not been reached up to the maximum computed number of channels of 2000.

Computation of two-source resolution proceeded by positioning two dipoles symmetrically about the sensor shell axis, on an arc with radius a = 9 cm. The dipoles were parallel, equal amplitude q = 10 nAm,

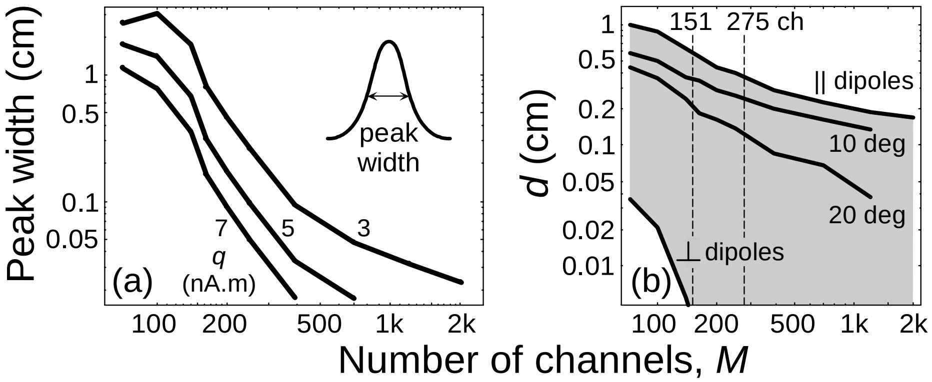

Figure 2. Peak width and two source resolution for SAM beamformer in the presence of brain noise simulated by 1000 dipoles randomly distributed between the radii of 6 and 8 cm and with random orientation and random amplitude uniformly distributed in the range from 0.5 to 3 nAm. Sensor shell is a spherical segment extending from vertex to $3\pi/4$ and with radius = 11.2 cm. Sensors were radial gradiometers with 5 cm baseline, roughly uniformly distributed over the sensor shell. The considered number of channels was 72, 100, 140, 162, 200, 250, 390, 698, 1212, and 2025 (with corresponding inter-channel separations of 4.80, 3.92, 3.19, 3.08, 2.73, 2.40, 1.94, 1.46, 1.10, and 0.84 cm); sensor white noise level was 5 fT rms/√Hz.(a) Peak width of SAM Z^2 depth profile through a single source.(b) Distance *d* at which two sources are resolved by SAM. Gray region corresponds to all dipole orientations.

and inclined at 0, 10, 20 deg, or perpendicular. SAM was scanned along the arc on which the dipoles are located and the dipole separation, *d*, at which they were resolved was computed and is plotted as a function of the number of channels. This is illustrated in Fig.2b. Dipoles were considered resolved if the SAM scan along the arc through the two dipoles exhibited a dip between the dipoles. Similar to the single source peak width, the SAM resolution of two sources also monotonically improves up to the largest considered number of channels. The resolution of two ECDs is poorest when they are parallel, but it dramatically improves when the angle between them increases, and is best for perpendicular ECDs.

Simulations in Fig. 2 were performed assuming a perfect MEG system. At a certain level of imperfections, for example inaccurate relative sensor gains or inaccurately known sensor positions, the real MEG performance is expected to become worse than that obtained by the idealized simulations. We have determined that this limit has not yet been reached by the existing CTF 275 MEG systems. We have measured brain noise in an unshielded environment and added a synthetic ECD with 20 nA-m magnitude to it. We then roughly uniformly, spatially resampled the 275 channel system to 138 channels. Using the original and resampled data, we have constructed SAM Z^2 volumetric images of the synthetic source and constructed 3D contours of FWHM of the Z^2 peak. The contours for 275 and resampled 138 channel systems are shown in Fig. 3.

Reduction of the number of channels from 275 to 138 degrades the spatial resolution and dramatically increases the dimension of the 3D contours in Fig. 3. The 275 channel 3D contours are reasonably well centered on the true dipole position, however, when the number of channels is reduced to 138, the center of gravity of the contours moves away from the true dipole position.

The SAM spatial resolution improvement by increasing the number of channels can be illustrated for a simple model of target, $q_1(t)$, and interferer, $q_2(t)$, in a model sphere when only uncorrelated sensor noise

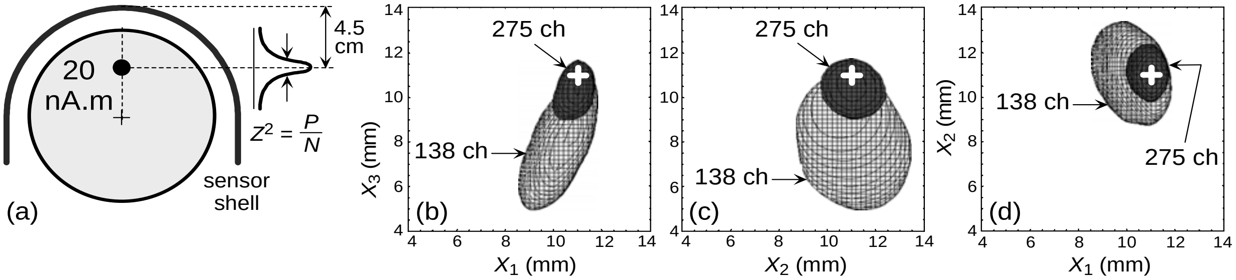

Figure 3. Effect of spatial resampling on SAM beamformer spatial resolution. (a) Geometry for computations. Brain noise was measured in unshielded environment by CTF 275 MEG system. Synthetic ECD with 20 nAm magnitude and positioned about 4.5 cm below the sensor array was added to the measured brain noise. Dipole orientation was parallel to the prevailing local brain noise source orientation. SAM Z^2 volumetric image was computed, and 3D contours of FWHM were constructed. Then the 275 channel sensor array was roughly uniformly resampled to 138 channels and the same SAM Z^2 image was constructed using the identical data. (b, c, d) Three orthogonal views of 3D contours of SAM Z^2 images corresponding to the original 275 channel and the resampled 138 channel sensor arrays. White '+' is the true source position, the dark region is the 275 channel 3D contours, and the light gray region is the 138 channel 3D contour.

is present. When the SAM is positioned on the target, the synthetic channel output, s(t), (without the noise term) is

$$s(t) \approx q_1(t) + q_2(t) \frac{|\mathbf{B}_2|}{|\mathbf{B}_1|} \frac{\cos \lambda}{M \cdot SNR_2 \left(1 - \cos^2 \lambda\right)} \tag{1}$$

where $\mathbf{B}_1$ and $\mathbf{B}_2$ are the target and interferer forward solution vectors, λ is the angle between them, and SNR_2 is the interferer SNR given by $SNR_2 = q_2^2 |\mathbf{B}_2|^2 / M v_{rms}^2$ [Vrba, 2002]. Eq. 1 illustrates that the interference is inversely proportional to M, and that the SAM resolution is expected to improve with increasing M.

DISCUSSION

Spatial sampling considerations and dipole localization accuracy lead to the requirement that the number of channels should be in the range from about one to several hundreds. However, beamformer simulations indicate that even in the presence of brain noise, the MEG systems can benefit from significantly larger number of channels. We have tested this finding by spatially resampling 275 channel MEG system. The result is consistent with the simulation predictions and indicates that the 275 channel MEG system is adequately accurate such that the limits of beamformer performance are not reached and the increase of the number of channels is expected to increase the spatial resolution.

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