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A Comparison of Vector and Radial Magnetometer Arrays for Whole-head Magnetoencephalography

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A Comparison of Vector and Radial Magnetometer Arrays for Whole-head Magnetoencephalography

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Introduction

The number of detectors in magnetometer arrays for magnetoencephalography (MEG) has been steadily increasing, with systems containing 200 or more detectors now possible. It is of considerable interest to know how best to configure such a large array. In particular, is it useful to measure all three components of the magnetic field, rather than just the radial component? This paper compares the information content provided by three different magnetometer arrays for whole-head measurements, using a definition of information content developed by Kemppainen and Ilmoniemi [2].

Magnetometer configurations

The three different magnetometer configurations shown below were compared. In all configurations, the magnetometer sites were approximately uniformly distributed over a spherical cap of radius 13 cm centered on the top of the head and extending 105° from the center to the rim, thus covering slightly more than a hemisphere. Each magnetometer channel was assumed to have independent zero-mean gaussian measurement noise with standard deviation 50 fT. The Name column of the table below gives the name used to refer to the magnetometer configuration in this paper. The Type column indicates whether radial or vector magnetometers were used. The Sites column gives the number of locations at which a magnetometer was placed, and the Channels column gives the total number of channels measured. The Information column gives the total information obtained, in bits, computed by the method described below.

Magnetometer configurations compared				
Name	Type	Sites	Channels	Information
246R	Radial	246	246	150
246V	Vector	82	246	130
82R	Radial	82	82	98

Source model

The head was modelled as a homogeneous conducting sphere of radius 10.5 cm, and the volume currents and magnetic fields were computed using the equations derived by Sarvas [3]. The primary current sources in the brain were modelled as a grid of 1072 three-component current dipoles at a 1.0 cm spacing within a hemispherical volume of radius 9.0 cm. It is convenient to refer to the vertex of this source hemisphere as the north pole. Each dipole component was assumed to be a zero-mean independent gaussian random variable with standard deviation 1.0 nA-m; this was chosen to yield a peak signal amplitude of about 200 fT, which is typical for visual evoked field measurements in magnetoencephalography [1].

Figure 1 shows the RMS signal amplitude at each detector in the 246V configuration for this source model. The detectors are arranged so that detectors 1–82 measure the radial component of the field, detectors 83–164 the eastward component, and 165–246 the northward component. Within each block, the detectors are arranged from the north pole to the equator; the RMS amplitude decreases as the detectors move away from the north pole. The maximum signal amplitude is about 200 fT.

Information content

Suppose that $y = x + n$ is a measurement of a true signal x corrupted by independent additive measurement noise n , that the signal x is normally distributed with variance α^2 , and that the noise n is normally distributed with variance σ^2 .

We know from Shannon [4] that the information about the signal x contained in the measurement y is

$$R = H(y) - H(n) \quad ,$$

Figure 1. The RMS signal amplitude at each detector in the 246V configuration for this source model. The detectors are arranged so that detectors 1–82 measure the radial component of the field, detectors 83–164 the eastward component, and 165–246 the northward component. Within each block, the detectors are arranged from the north pole to the equator; the RMS amplitude decreases as the detectors move away from the north pole. The maximum signal amplitude is about 200 fT, which is typical for visual evoked field measurements.

which is the entropy of y minus the entropy contributed by the noise n . Furthermore, the entropy of a gaussian random variable with variance σ^2 is, in bits, $H = \frac{1}{2} \log_2(2\pi e \sigma^2)$. Then the measurement y is normally distributed with variance $\alpha^2 + \sigma^2$ and the received information is, in bits,

$$R = \frac{1}{2} \log_2 \left(\frac{\alpha^2 + \sigma^2}{\sigma^2} \right) = \frac{1}{2} \log_2 \left(1 + \frac{\alpha^2}{\sigma^2} \right) = \frac{1}{2} \log_2 (1 + \text{SNR}) \quad ,$$

where SNR is the signal-to-noise power ratio α^2/σ^2 .

Since the different channels of a magnetometer array are correlated, it is not legitimate to simply sum the information content of each channel. The singular value decomposition (SVD) or Karhunen-Loève transformation may be used to define synthetic channels which are uncorrelated but contain the same information as the measured channels. The SNR for one of these synthetic channels is

$$\text{SNR}_k = \frac{\alpha^2 \lambda_k^2}{\sigma^2} \quad ,$$

where α^2 is the source variance, λ_k is the singular value for the k th synthetic channel, and σ^2 is the noise variance. Thus a semilog plot of the singular value spectrum is, apart from scale, a plot of the SNR (in dB) for these synthetic channels.

Furthermore, the total information content of all the channels is

$$R = \frac{1}{2} \sum_k \log_2 \left(1 + \frac{\alpha^2 \lambda_k^2}{\sigma^2} \right) \quad ,$$

Figure 2. The three curves above correspond to the 246R (top), 246V, and 82R (bottom) magnetometer configurations. The information content of a configuration is roughly proportional to the area under the SVD spectrum and above the 0 dB line, so the 246R configuration provides the most information, followed by the 246V and 82R configurations. The curves do not diverge or cross until well below the 0 dB line, indicating that the magnetometer configurations differ in SNR but not in intrinsic resolution at the assumed source and noise levels.

which is roughly proportional to the area under the singular value curve and above the 0 dB line.

The number of synthetic channels with SNR greater than zero indicates the number of resolvable distinct measurements made by the system and may be taken as a very rough measure of the system resolution.

Results

The shape of the singular value spectrum, as shown in Figure 2, was almost identical for the three magnetometer configurations, but the 246R configuration was displaced upwards relative to the 246V, and the 82R displaced downward. Figure 3 shows the SNR difference in more detail and reveals that the 246R configuration was displaced upwards by about 2.3 dB, and the 82R displaced downward by about 2.5 dB. Thus the 246R configuration provided the most information, with the 246V and 82R configurations following in that order. The fact that the singular value spectrum is shifted but not changed in shape indicates that a 82R configuration with a 4.8 dB reduction in measurement noise, or a 246V configuration with a 2.3 dB reduction in noise, would provide the same information content as the 246R configuration.

Differences in the intrinsic resolution of the three configurations, as evidenced by the divergence or intersection of two SVD spectra, are not significant for the assumed source and noise amplitudes. The divergence between the 82R and 246V configurations appears at about -10 dB, so there would be no resolution difference until the SNR improves by 10 dB. Similarly, the intersection between the 246V and 246R curves would not be significant without a 40 dB improvement in SNR.

Thus, at the source and noise amplitudes assumed here, these configurations differ only in the SNR that they achieve but not in their resolution.

Moderate changes in the source configuration, in the radius and angular coverage of the detector array, or in the assumed signal and noise amplitudes did not affect the differences between the detector configurations.

Figure 3. The top curve below shows the SNR improvement of the 246R configuration over the 246V configuration, for each SVD channel. The lower curve shows the 82R configuration relative to the 246V configuration.

Conclusions

For whole-head magnetoencephalography of distributed sources and assuming that the measurement error consists of uncorrelated sensor noise rather than correlated brain noise: (1) The spatial resolution is limited by the signal-to-noise ratio rather than by spatial sampling in the magnetometer array. (2) Each of the following changes will yield approximately the same improvement in information content: decreasing the RMS measurement noise by 3 dB; increasing the RMS signal amplitude by 3 dB (perhaps by moving the detectors closer to the head); doubling the number of detector sites; or replacing radial detectors by vector detectors at the same sites. (3) For a given number of sites, vector magnetometers provide more information; but for a given number of measurement channels, radial magnetometers provide more information.

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