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Calibration and localization of optically pumped magnetometers using electromagnetic coils

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Introduction

- Optically pumped magnetometers (OPMs) enable on-scalp magnetoencephalography (MEG)
- Methods have been developed to calibrate an OPM array as well as to coregister it with the subject's MRI images
- We show that large electromagnetic coils can be used to calibrate and localize OPMs for MEG [1]
- We first measure the magnetic fields of the coils using a fluxgate magnetometer
- We fit vector spherical harmonics (VSH) models to the measurements
- Using the VSH models and measuring the OPM responses to the excited coils, the OPM can be calibrated and localized

Mathematical methods

- OPM sensor with gain vector $\mathbf{g} = g\mathbf{n}$ (g is the OPM gain (V/T) and $\mathbf{n}$ is the OPM orientation) and position $\mathbf{r}$
- Minimize the error between the coil field measurements by the OPM (y_i) and the field models $\vec{B}_i(\vec{r})$

$$\underset{\mathbf{g},\mathbf{r},\mathbf{n}}{\operatorname{argmin}} \sum_{i=1}^{N} \left(y_i - g\vec{B}_i(\mathbf{r}) \cdot \mathbf{n}\right)^2 \quad (1)$$

- If only homogeneous and first-order gradient fields are modeled, the OPM parameters can be found by solving a system of linear equations

$$\mathbf{g} = \mathbf{H}^{\dagger}\mathbf{b}_{\mathrm{H}}$$
$$\mathbf{r} = \mathbf{G}^{\dagger}(\mathbf{b}_{\mathrm{G}} - \mathbf{H}_{\mathrm{G}}\mathbf{g}) \quad (2)$$

Sandia OPM-MEG system

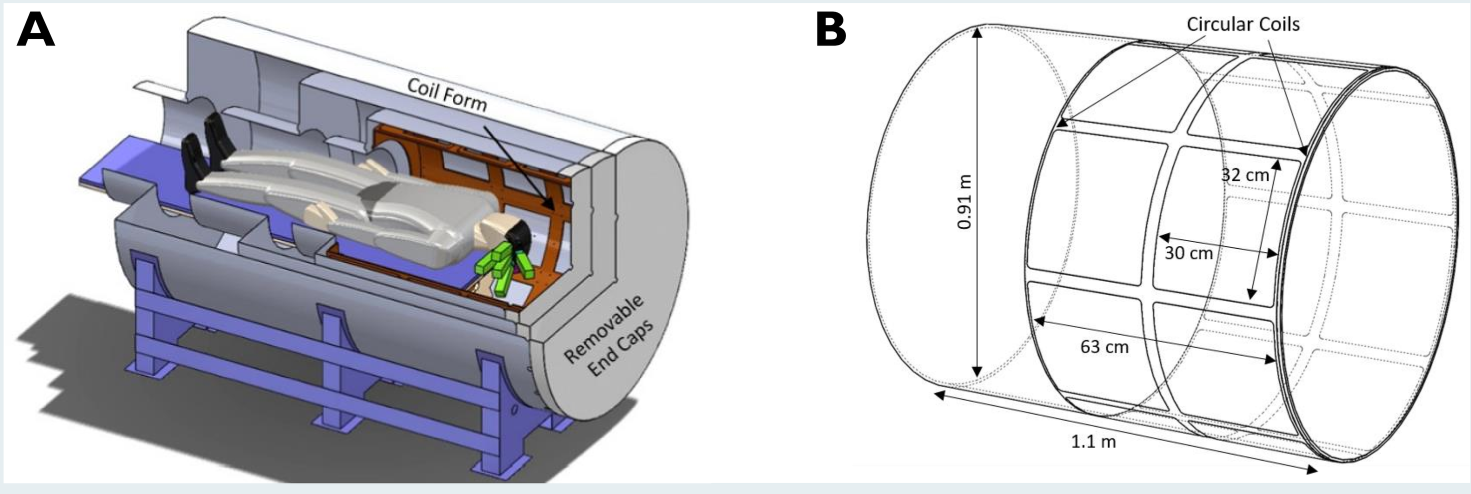


Fig. 1: A: The Sandia OPM-MEG system [2] comprising a cylindrical magnetic shield and dual-axis OPM sensors [3] (green). A coil form for 16 rectangular and 2 circular shield coils (shown in B) is highlighted.

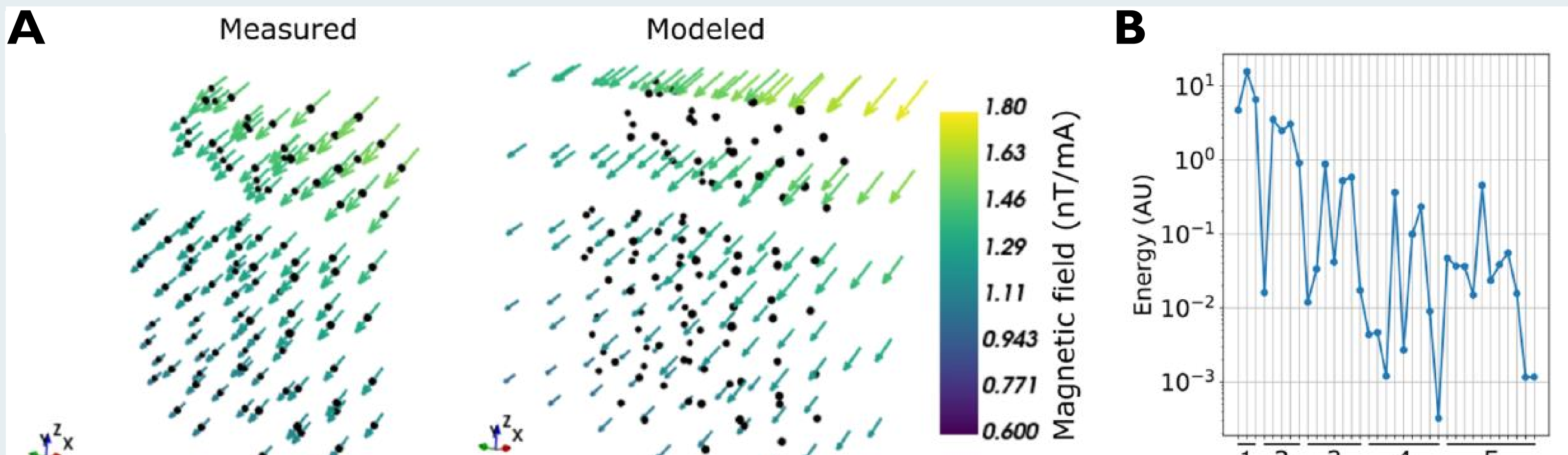
Calibration and localization procedure

1. Measure the magnetic fields of the shield coils with a fluxgate magnetometer
   1. Fit VSH models to the measurements
2. Using the VSH models, compute coil currents for exciting homogeneous and first-order gradient fields
3. Measure the OPM response to the homogeneous and gradient fields
   1. Compute initial OPM gain and orientation ($\mathbf{g_0}$) as well as position ($\mathbf{r_0}$) using Eq. 2
   2. Optional: Fine tune $\mathbf{g_0}$ and $\mathbf{r_0}$ by optimizing Eq. 1 with the full VSH models of the homogeneous and gradient fields
4. Excite shield coils individually
   1. Find the sensor parameters (**g, r**) by optimizing Eq. 1 using the full VSH models. Use $\mathbf{g_0}$ and $\mathbf{r_0}$ as initial estimates.

Magnetic field measurements and models

Fig. 2: An example of measured coil field and its VSH fit.

A. The measured field and its VSH extrapolation.
B. The distribution of the magnetic energy of the coil field across the VSH components.



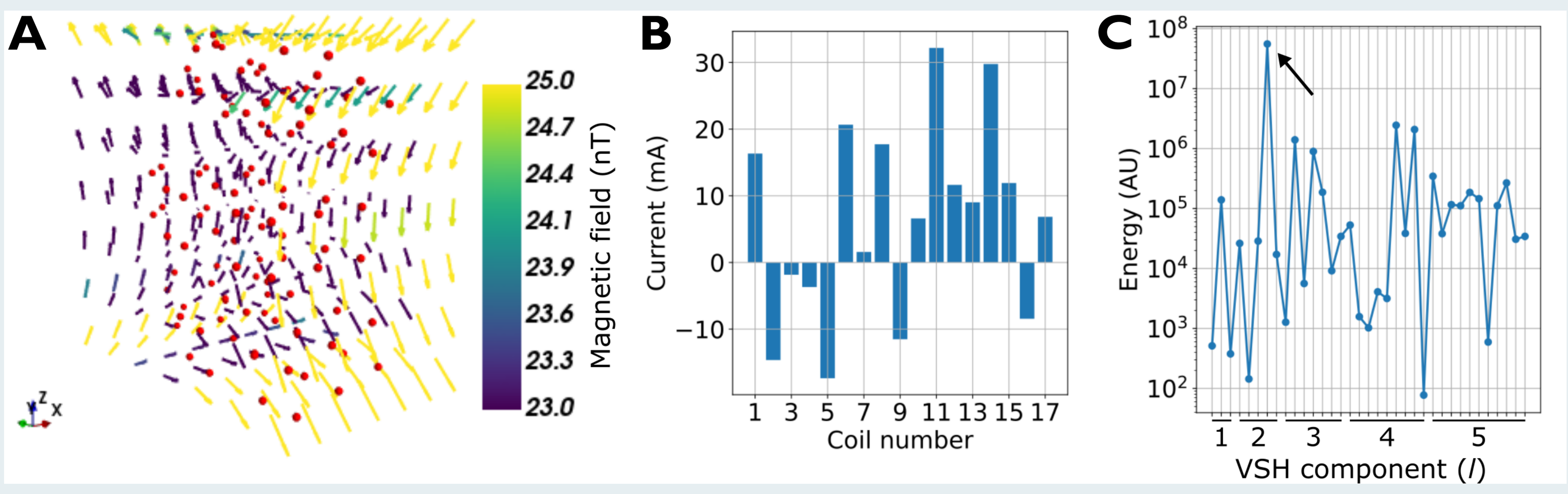


Fig. 3: Generation of a gradient field (A) with the shield coils.

B. The calculated currents across the shield coils that generate the field.
C. The distribution of the field energy across the VSH components.

Fluxgate validation

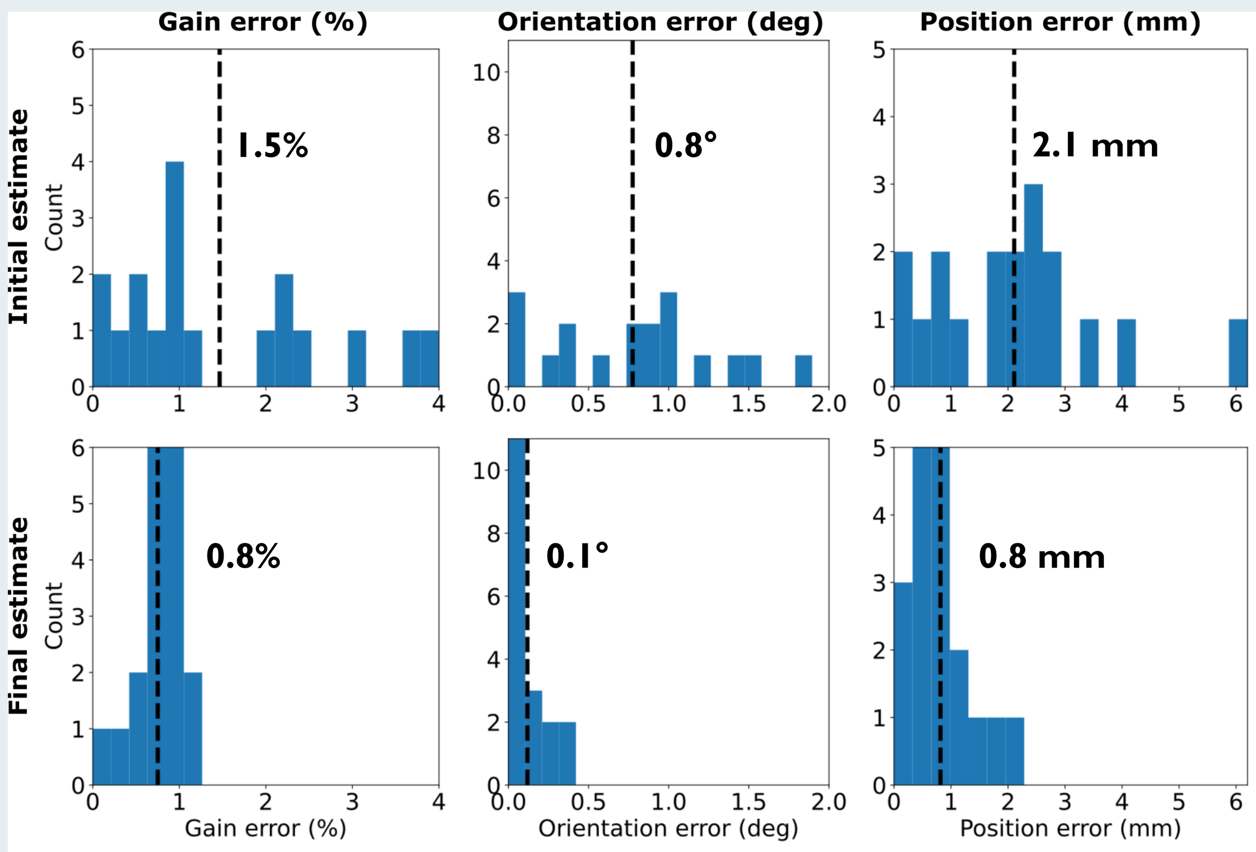


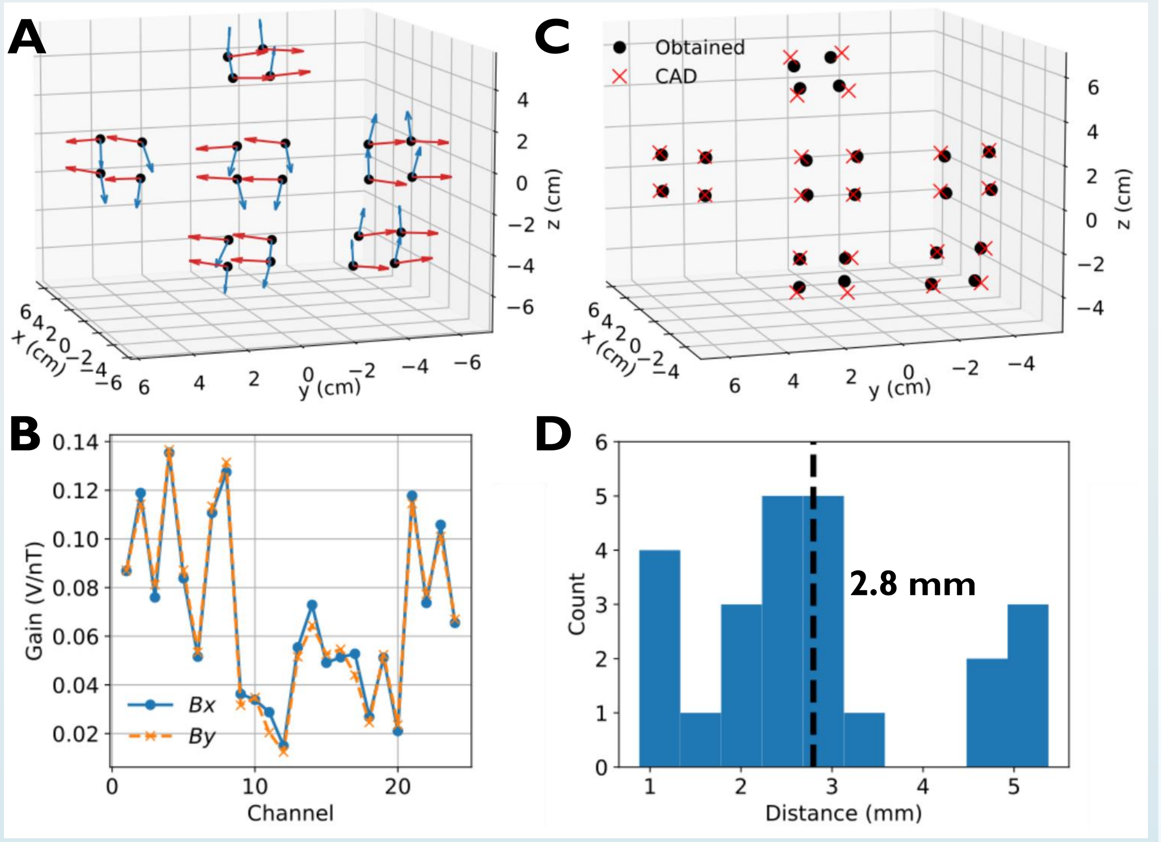
Fig. 4: Using the method to calibrate the fluxgate magnetometer with known gain, orientation and position.

- Top: Error histograms of the initial fluxgate parameters (step 3.1.). Dashed line shows the average error.
- Bottom: Errors after full optimization (step 4.1.)

OPM sensor array calibration and localization

Fig. 5: Calibration of a 48-channel OPM array using the method.

A. The obtained OPM positions and orientations. Each position shares two OPM channels with nearly orthogonal orientations (*Bx*, *By*).
B. The OPM gains across the channels.
C. Comparison of the obtained OPM positions to the CAD model of the array.
D. Histogram of the distances between the obtained and the CAD positions.



Magnetic dipole localization

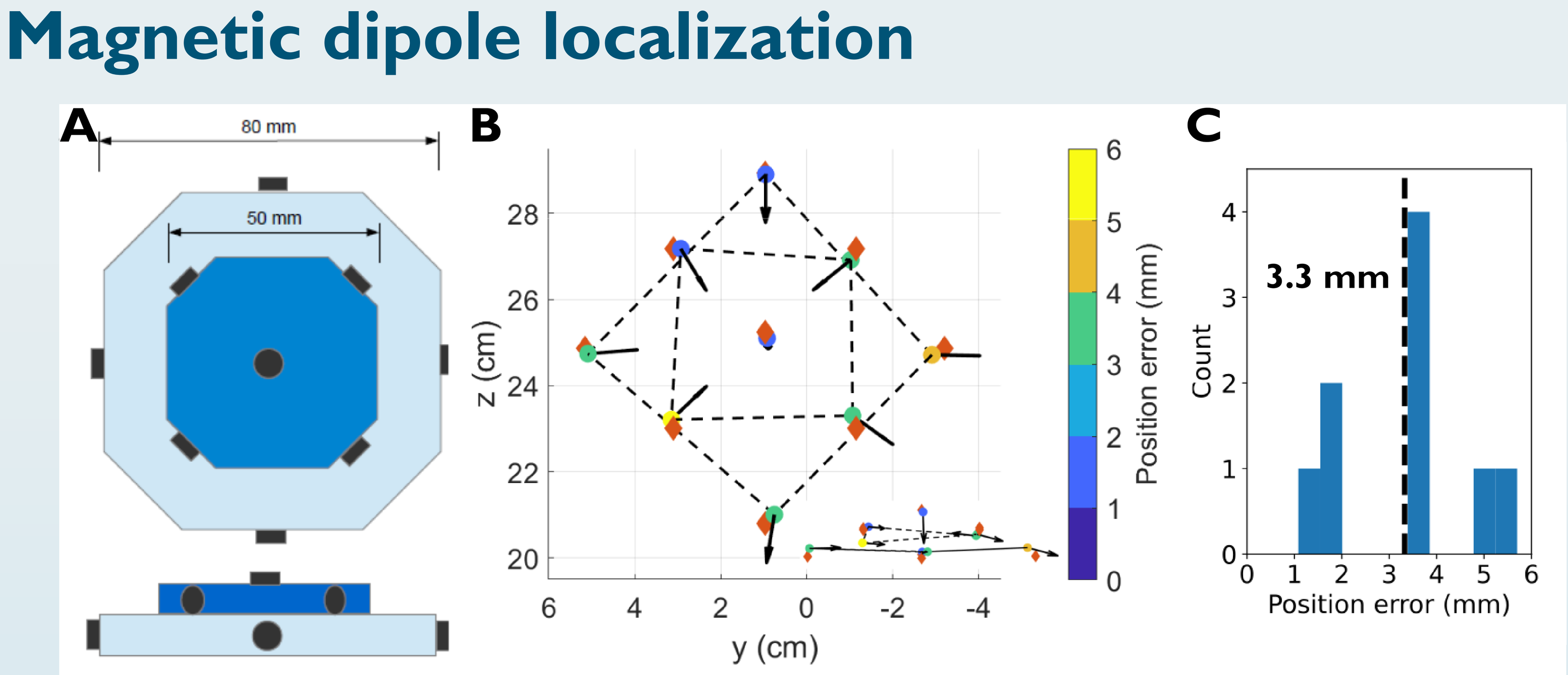


Fig. 6: Using the calibrated OPM array in Fig. 5 to localize magnetic dipoles in a phantom (shown in A).

B. The localized dipole positions (dots) and the CAD positions (diamonds). The dots are colored according to the localization error.
C. Dipole localization error across the dipoles.

Conclusions

By calibrating a 48-channel OPM array with the method, we could localize magnetic dipoles with an accuracy of 3.3 mm demonstrating the potential of the method for OPM-MEG. The method is also fast enough to be used in every OPM-MEG measurement.

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