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Calibration and localization of optically pumped magnetometers using electromagnetic coils

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Early Career Researcher Award Finalist

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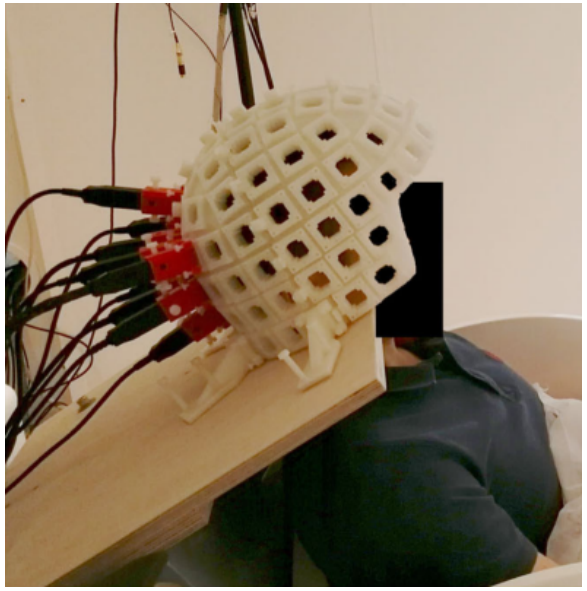
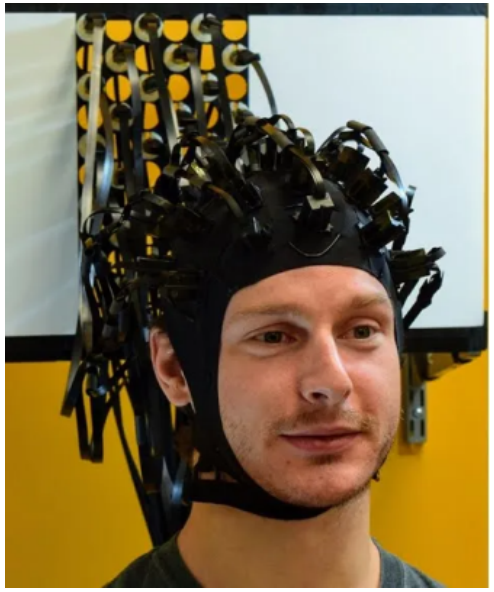
Introduction

- OPMs enable on-scalp MEG
- OPM positions can be optimized/personalized for each subject
  - Helmet with adjustable sensor depths
  - MEG cap
- Need to quickly measure the OPM positions as well as gains and orientations before each measurement
- OPM calibration and localization with large electromagnetic coils (*Iivanainen et al. 2021)*

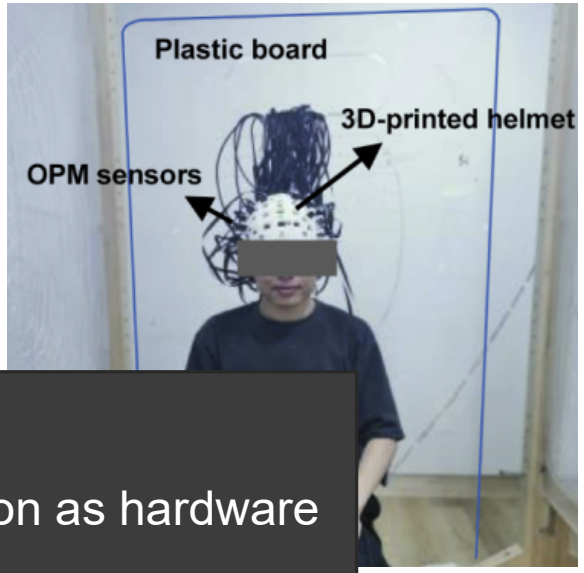


Iivanainen et al. 2019



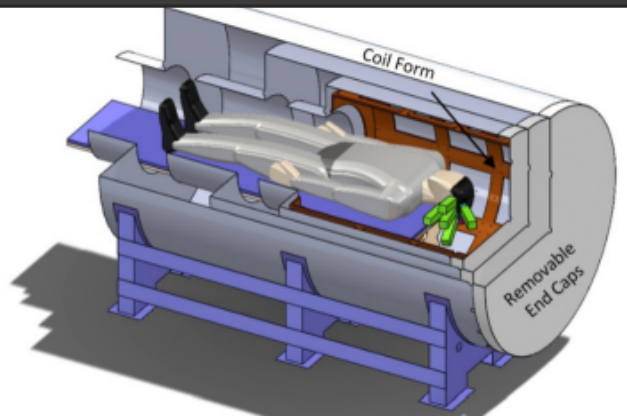
QuSpin Inc.

Some OPM-MEG systems



Use large electromagnetic coils for OPM calibration and localization as hardware already exists!

Iivanainen et al. 2019

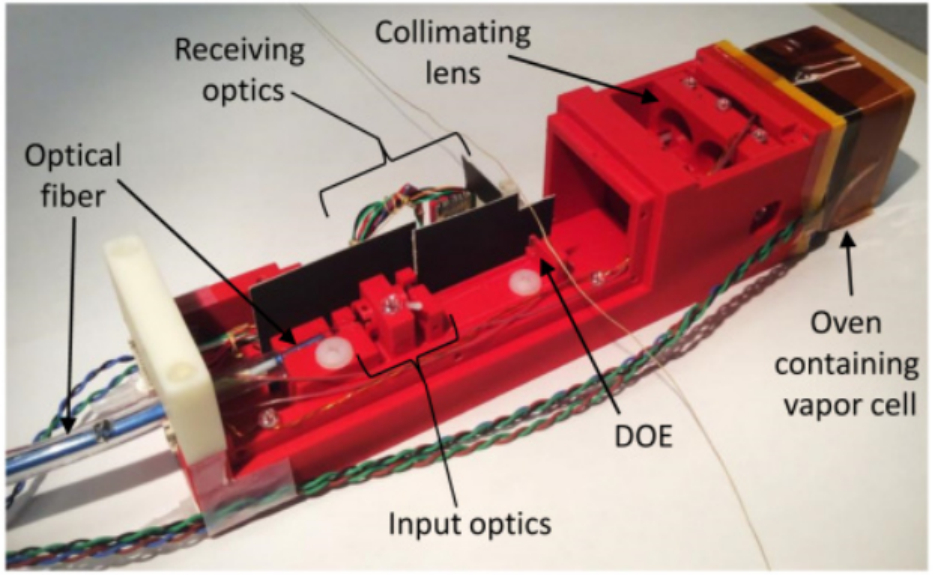


Borna et al. 2020

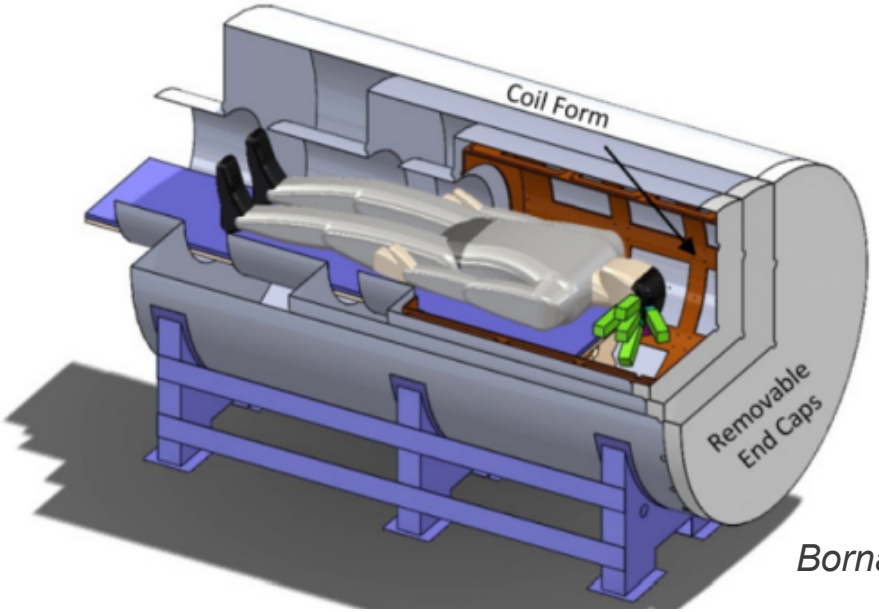
Holmes et al. 2021

Sandia OPM-MEG system

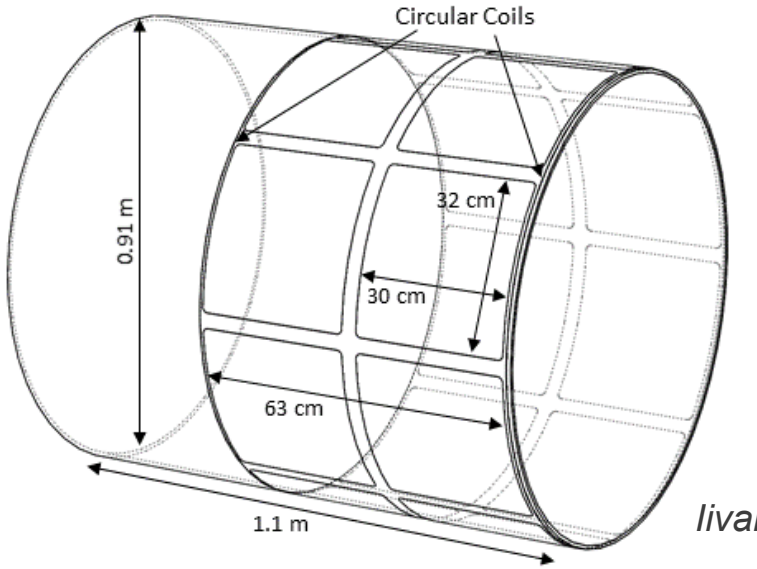
- 6 dual-axis OPMs with 4 channels
  = 48 channels
- Person-sized magnetic shield
- 16 rectangular and 2 circular shield coils



Colombo et al. 2016

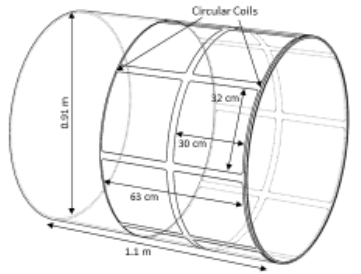


Borna et al. 2020



Iivanainen et al. 2021

Calibration method



1. **Measure the magnetic fields of the shield coils with a fluxgate magnetometer**
   A. Fit vector spherical harmonic (VSH) models to the measurements

$$\vec{B}_i(\vec{r}) = -\mu_0 \sum_{l=1}^{\infty} \sum_{m=-l}^{l} \beta_i^{lm} r^{l-1} \sqrt{l(2l+1)}\, \vec{W}_{lm}(\theta, \varphi)$$

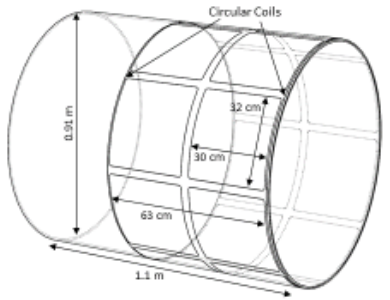
2. **Get initial estimates for OPM gain, orientation as well as position**
   A. Using the VSH models, compute coil currents for exciting homogeneous and first-order gradient fields
   B. Measure the OPM response to the homogeneous and gradient fields
   C. 2x pseudoinverse to get the OPM parameters

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

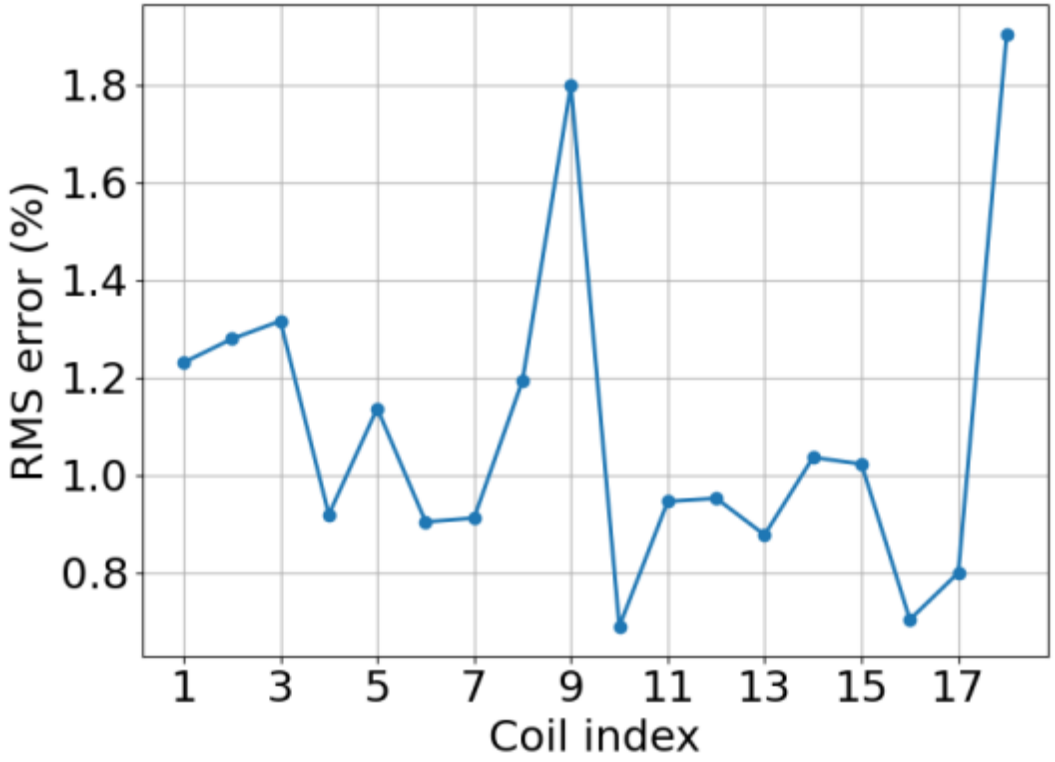
3. **Fine tune the initial estimates**
   A. Excite shield coils individually
   B. Find the sensor parameters by non-linear optimization using the full VSH models. Use parameters obtained from step 2.C as initial estimates

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

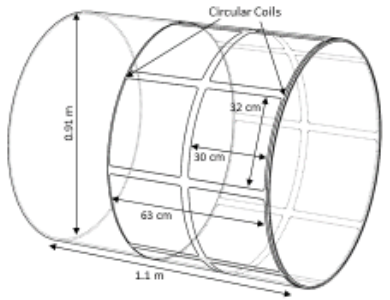
Vector-spherical harmonic (VSH) fits

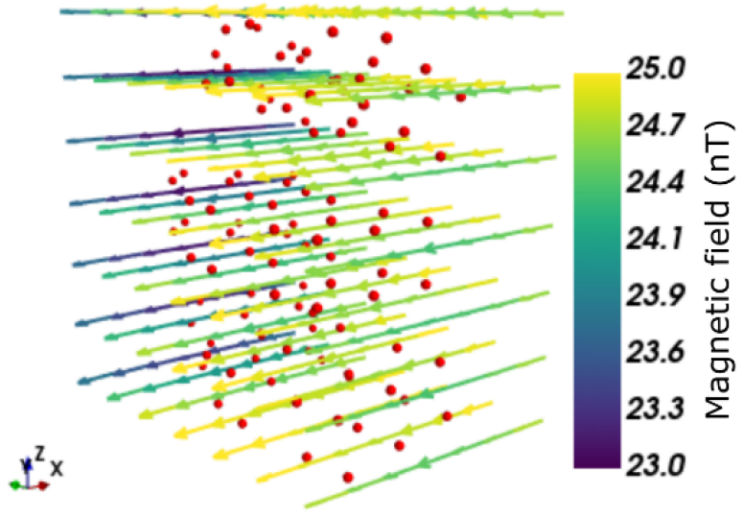


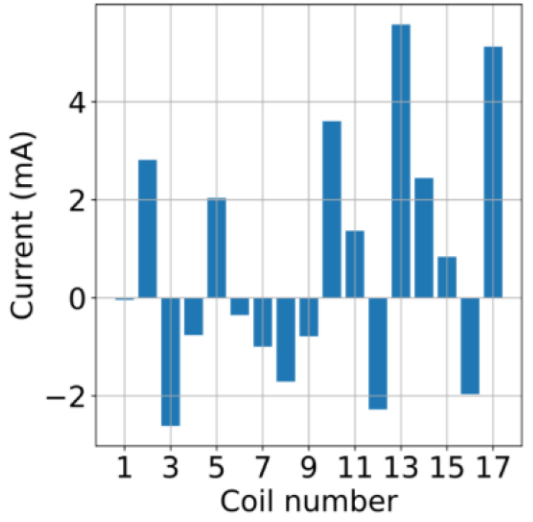
- Triaxial fluxgate measurement of the fields of the shield coils at 108 positions
- VSH model up to degree *l* = 5 (35 components)

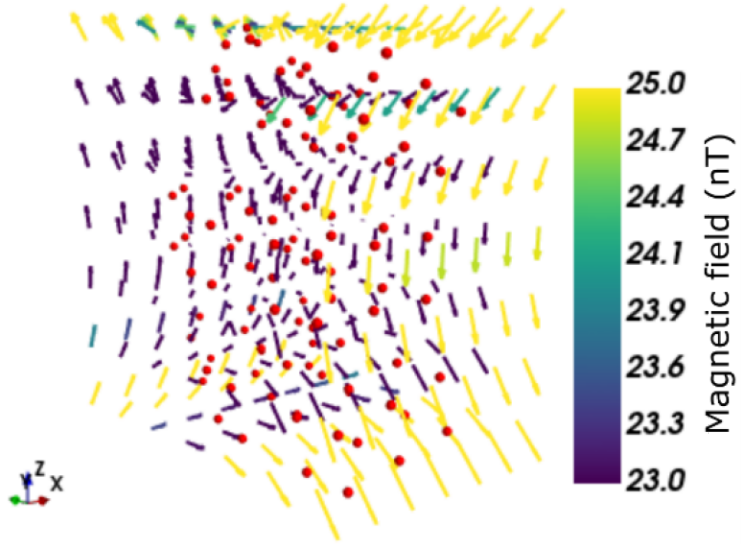


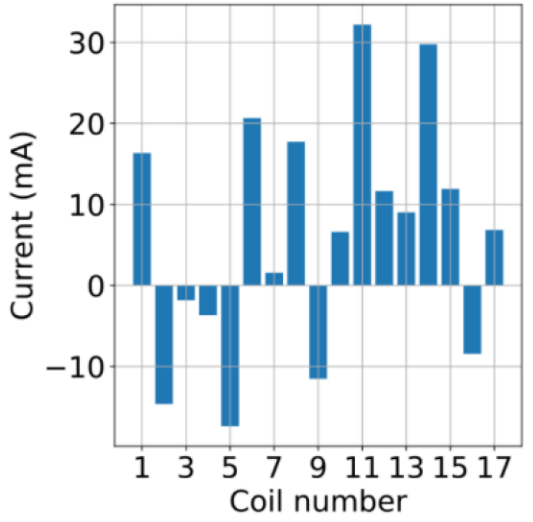
Homogeneous and gradient fields



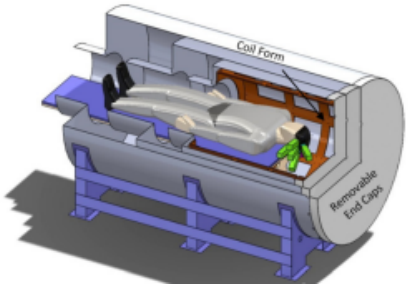


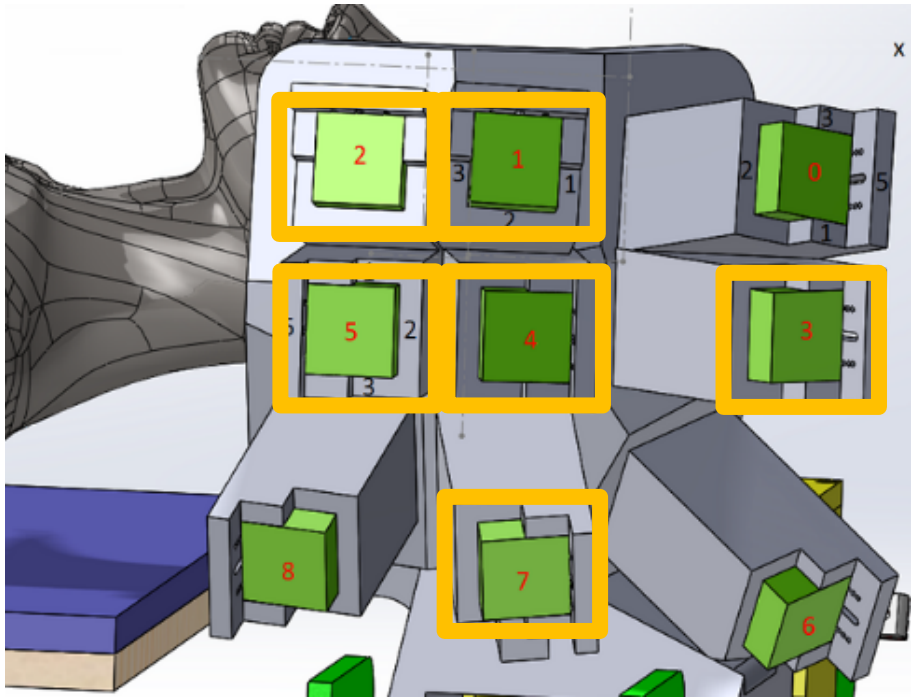


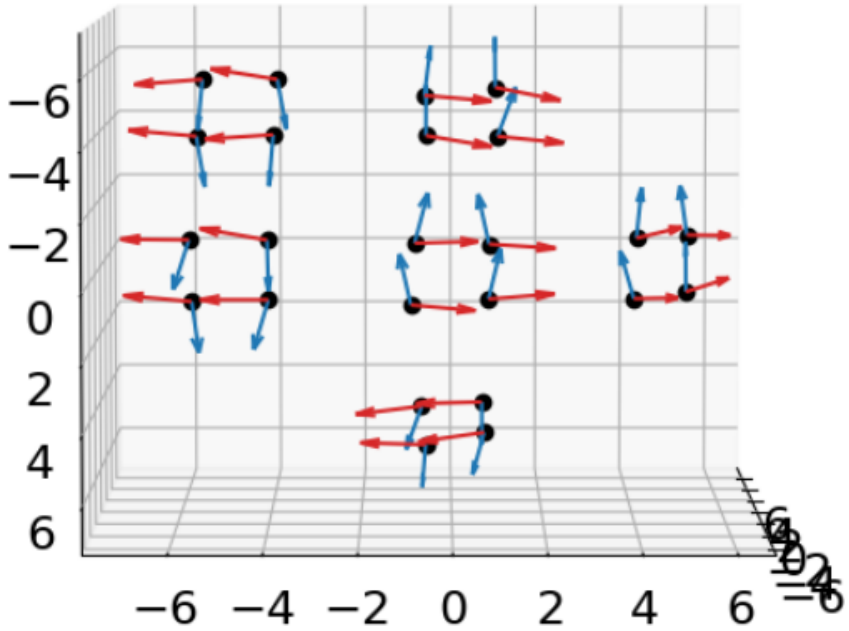


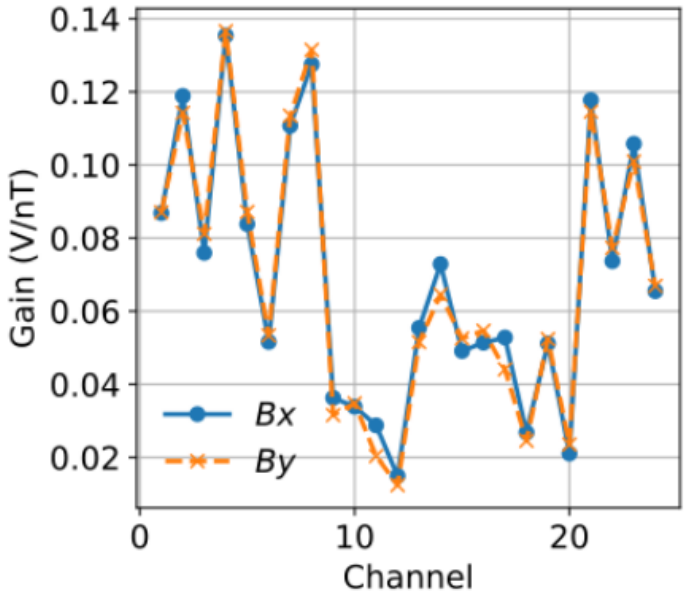


Calibration of the OPM array



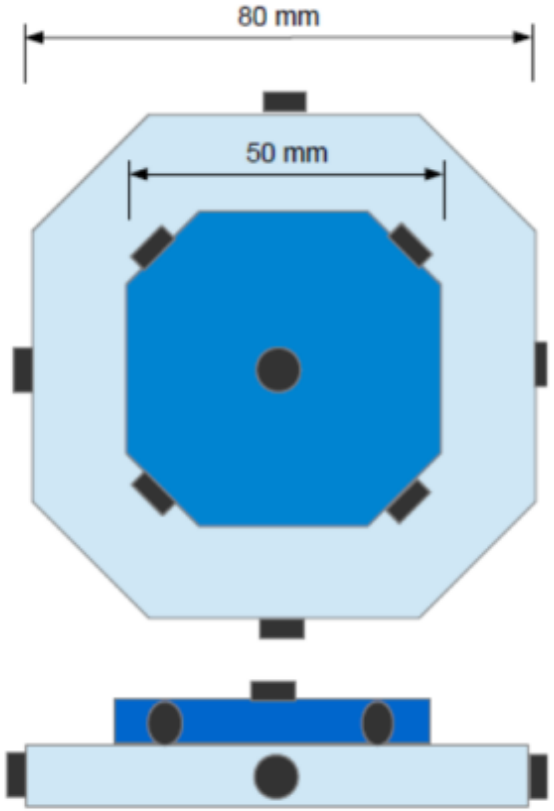


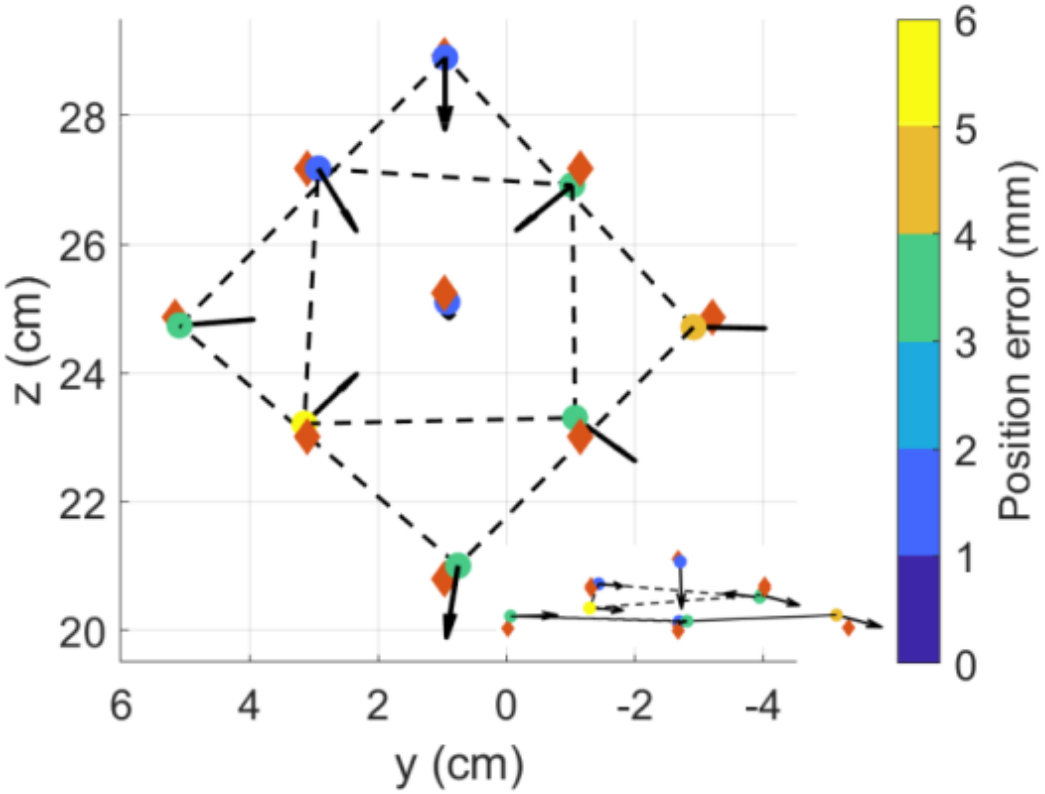


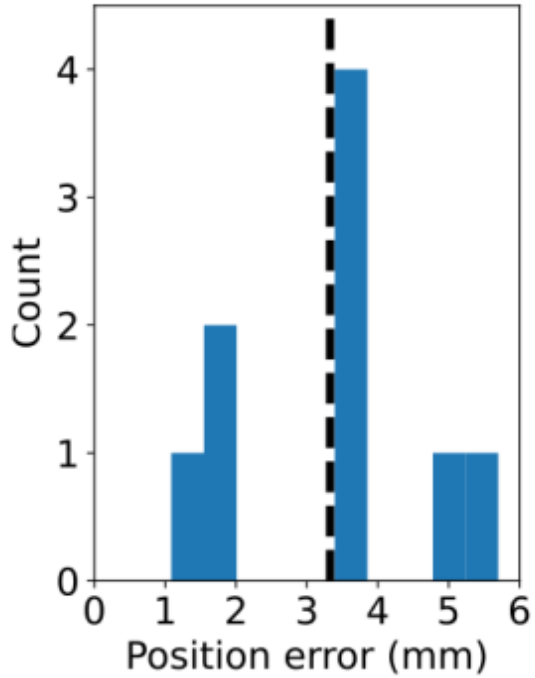


Average error to the CAD model: 2.8 mm

Localizing magnetic dipoles with the OPM array





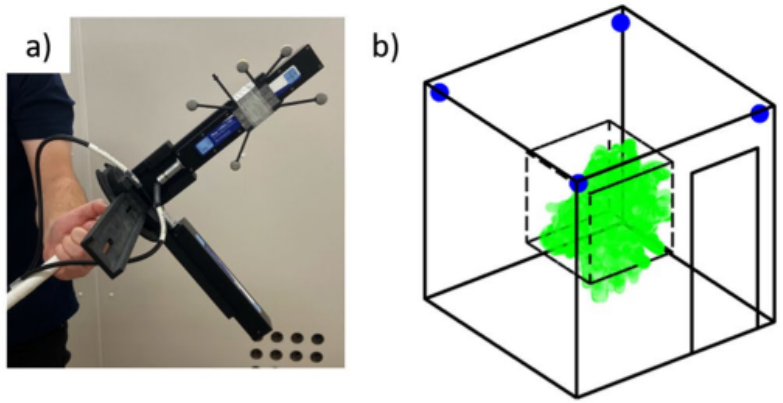


Position error:

- Mean: 3.3 mm
- Range: 1.1—5.7 mm

Conclusions

- With the calibrated 48-channel OPM array, we could localize magnetic dipoles in a phantom with a mean error of 3.3 mm
- Addition of HPI coils or other methods to the pipeline to get the OPM-MRI coregistration
- Further analysis of the calibration accuracy using a more accurate phantom
  - Sensor count and coverage vs. calibration vs. phantom accuracy
- Possible to construct the VSH field coil models rather quickly with optical tracking (*Rea et al. 2021; Mellor et al. 2022; Holmes et al. 2022)*
- Real-time OPM calibration and localization



Holmes et al. 2022

Thank you!