Benchmarking SQUID and OPM Magnetoencephalography with a Dry Phantom: Source Localization Accuracy and its Dependence on Sensor Count

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Abstract

Magnetoencephalography (MEG) noninvasively records the magnetic fields of neuronal activity using either established cryogenic SQUID sensors or emerging optically pumped magnetometers (OPMs), which need no cooling and can sit closer to the scalp. Human comparisons are confounded by physiology, so we benchmarked both technologies on a dry phantom emulating 50 equivalent current dipoles (ECDs), measured by both a SQUID (Kanazawa Institute of Technology) and an OPM sensor system (HEDscan) in the same shielded room at NYU Abu Dhabi. Drive currents of 10 and 100 µA varied signal to noise ratio; sources were reconstructed with the Sarvas formula and scored against CT calibrated ECD positions. Placing OPMs closer to the source gave a peak signal 3 to 4× larger than SQUID (6.6 vs 2.2 pT), yet OPM localization error was about three times larger: 3.48 ± 0.58 mm versus 1.07 ± 0.17 mm at 10 µA, and 2.77 versus 0.74 mm at 100 µA. Controlled analyses showed this gap was not explained by signal to noise ratio, channel count, or spatial coverage; a 90 channel SQUID subset still reached 1.56 mm, and only around 40 SQUID channels were needed to match the 90 channel OPM accuracy (3.13 mm), implicating OPM sensor array calibration as the dominant factor. A companion study resampling subsets of 30 to 90 of the 96 OPM sensors characterizes how accuracy improves and plateaus with array size, guiding cost effective, incrementally expandable OPM MEG. A dry phantom thus offers a reproducible, physiology free benchmark for cross technology comparison, identifying calibration, rather than noise or sensor count, as the key lever for improving OPM source localization.

Keywords: magnetoencephalography; SQUID; optically pumped magnetometers; dry phantom; source localization; sensor array scalability

Background

Magnetoencephalography (MEG) noninvasively records the weak magnetic fields of neuronal activity. Two sensor technologies dominate: the established cryogenic **SQUID** and the emerging **optically pumped magnetometer (OPM)**, which needs no liquid helium cooling and can sit closer to the scalp.

Prior SQUID versus OPM comparisons rely on human data, where physiology confounds a fair hardware level assessment. We use a **dry phantom** to deliver a reproducible, physiology free benchmark for cross technology comparison.

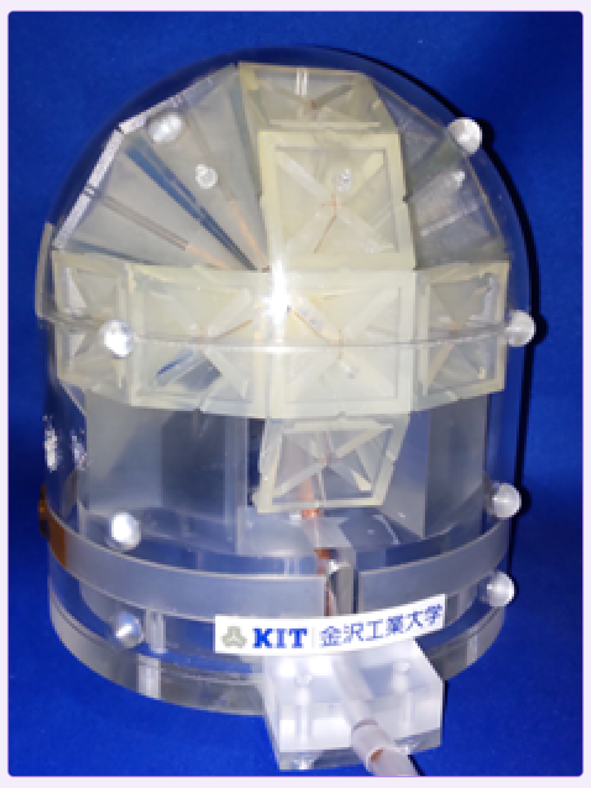
Methods

A dry phantom emulating **50 equivalent current dipoles (ECDs)** on a 65 mm sphere was measured by a **202 channel axial gradiometer SQUID** and a **90 channel OPM** system (HEDscan, FieldLine) in the **same shielded room** at NYUAD, on the same day.

Drive currents of **10 µA** and **100 µA** varied SNR. Sources were reconstructed with the **Sarvas formula** and scored against **CT calibrated** ECD positions.

Experimental setup

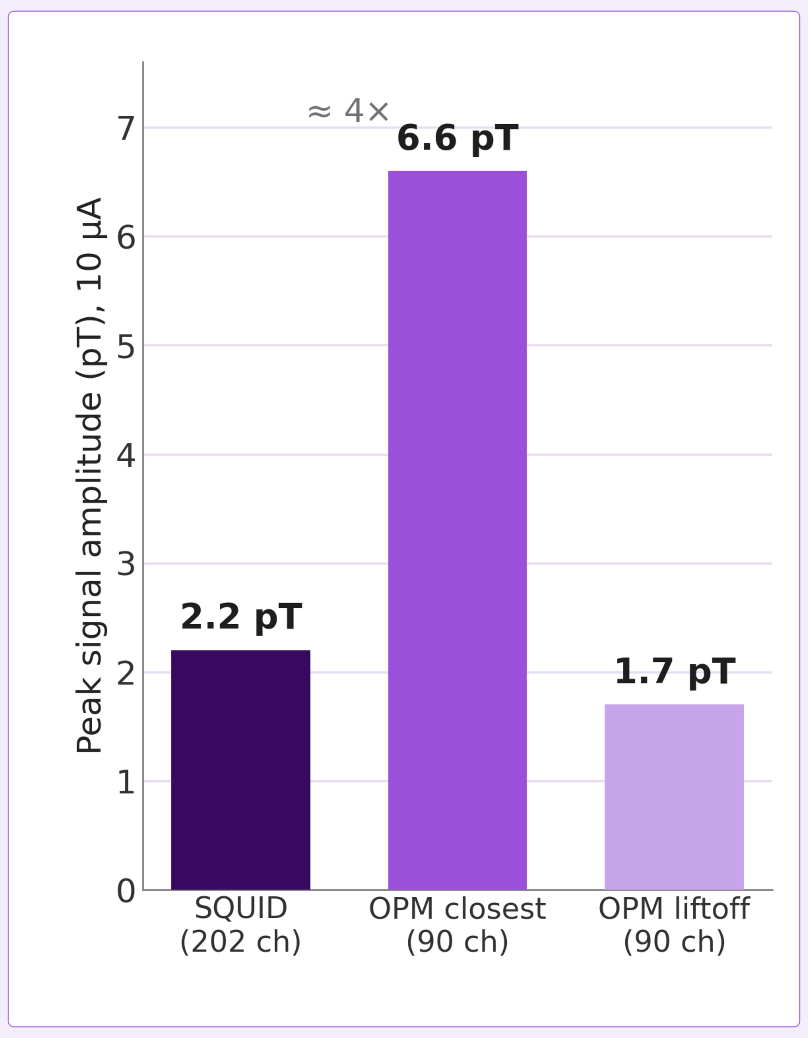
OPM (left), SQUID (right) in one MSR.



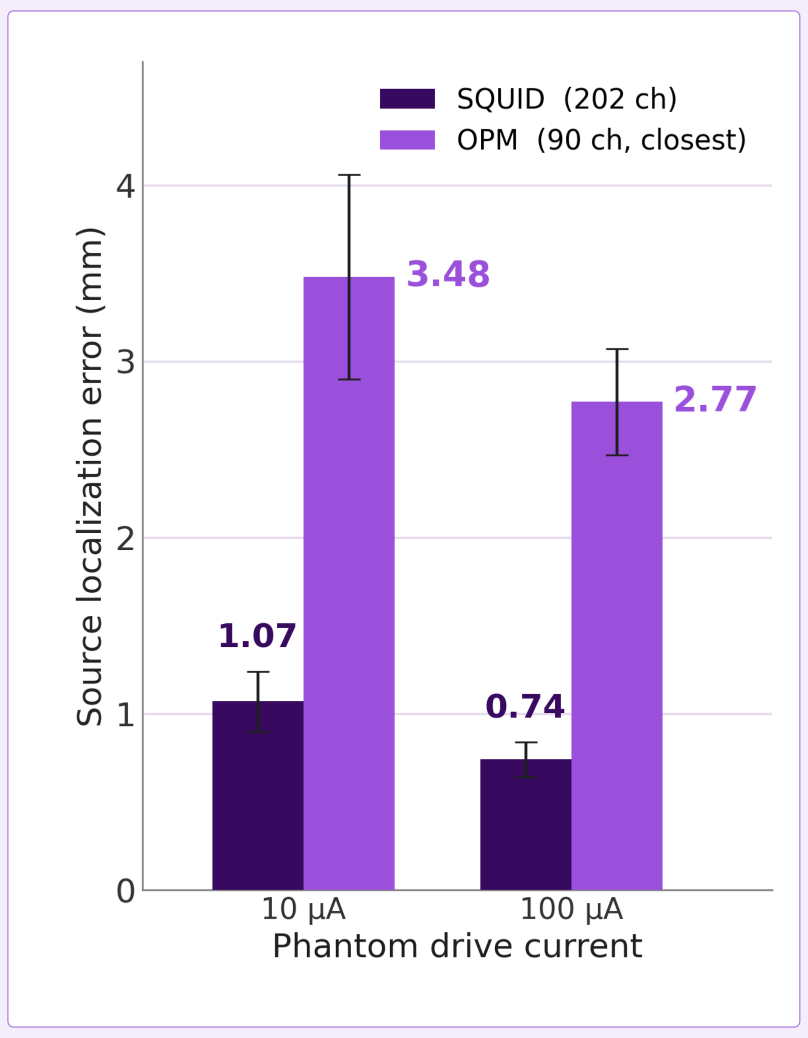
Dry phantom: 50 triangular coils (KIT).

Sensor to source distance: 54.6 mm (SQUID) vs 25.1 mm (OPM, closest).

Results: phantom comparison



Peak signal amplitude (10 µA).



Source localization error by drive current.

OPMs placed closer to the source give a **3 to 4× larger** peak signal (6.6 vs 2.2 pT), yet localize **about 3× less accurately**: 3.48 ± 0.58 mm vs 1.07 ± 0.17 mm at 10 µA, and 2.77 vs 0.74 mm at 100 µA.

Key finding. Stronger OPM signals do **not** translate into better localization. The accuracy gap persists across drive currents.

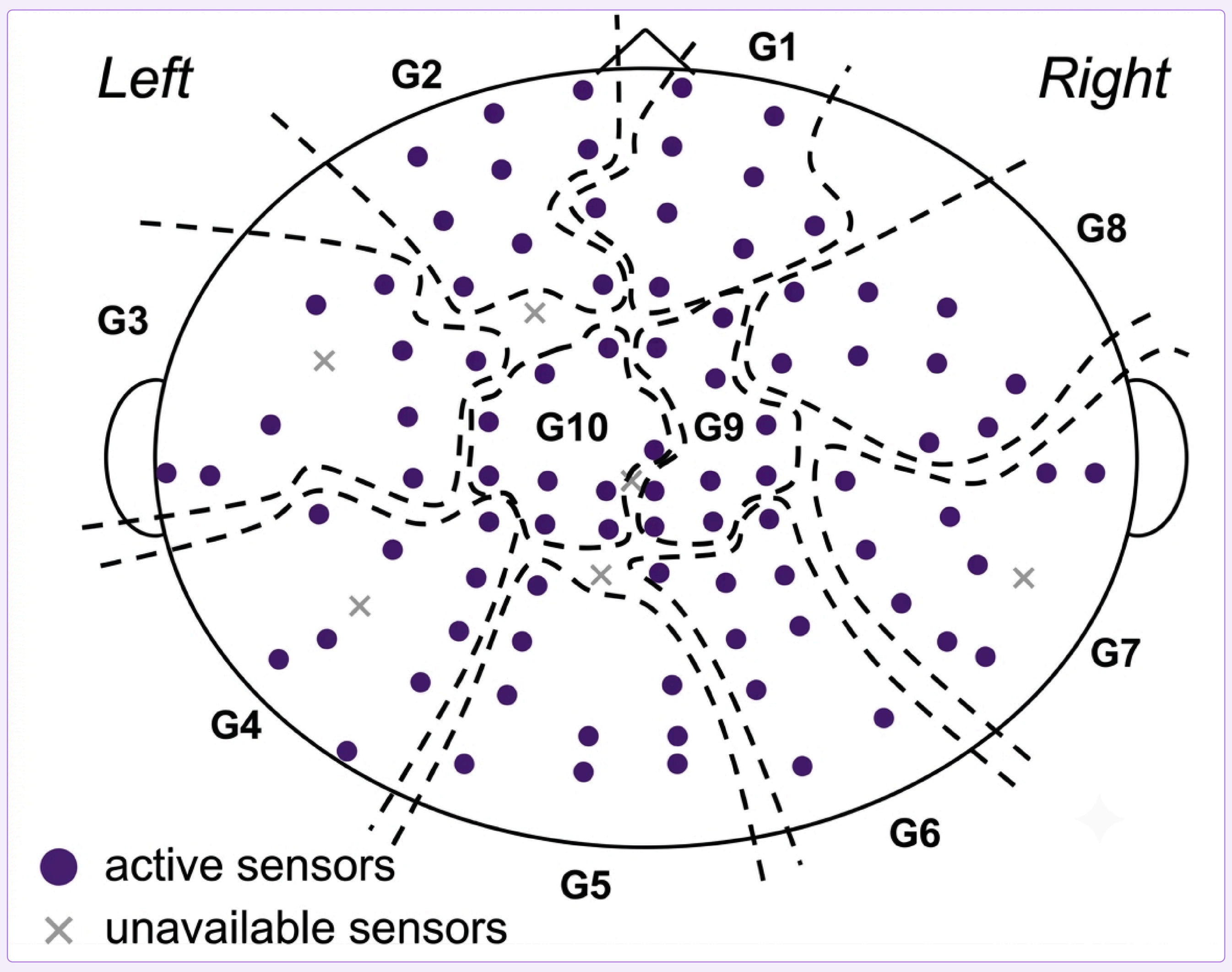
Why is OPM error larger?

Controlled analyses ruled out the obvious suspects. The gap is **not** from SNR (it persists at 100 µA), **nor** channel count (a 90 channel SQUID subset reached 1.56 mm, and only around 40 SQUID channels matched the 90 channel OPM accuracy, 3.13 vs 3.48 mm), **nor** spatial coverage.

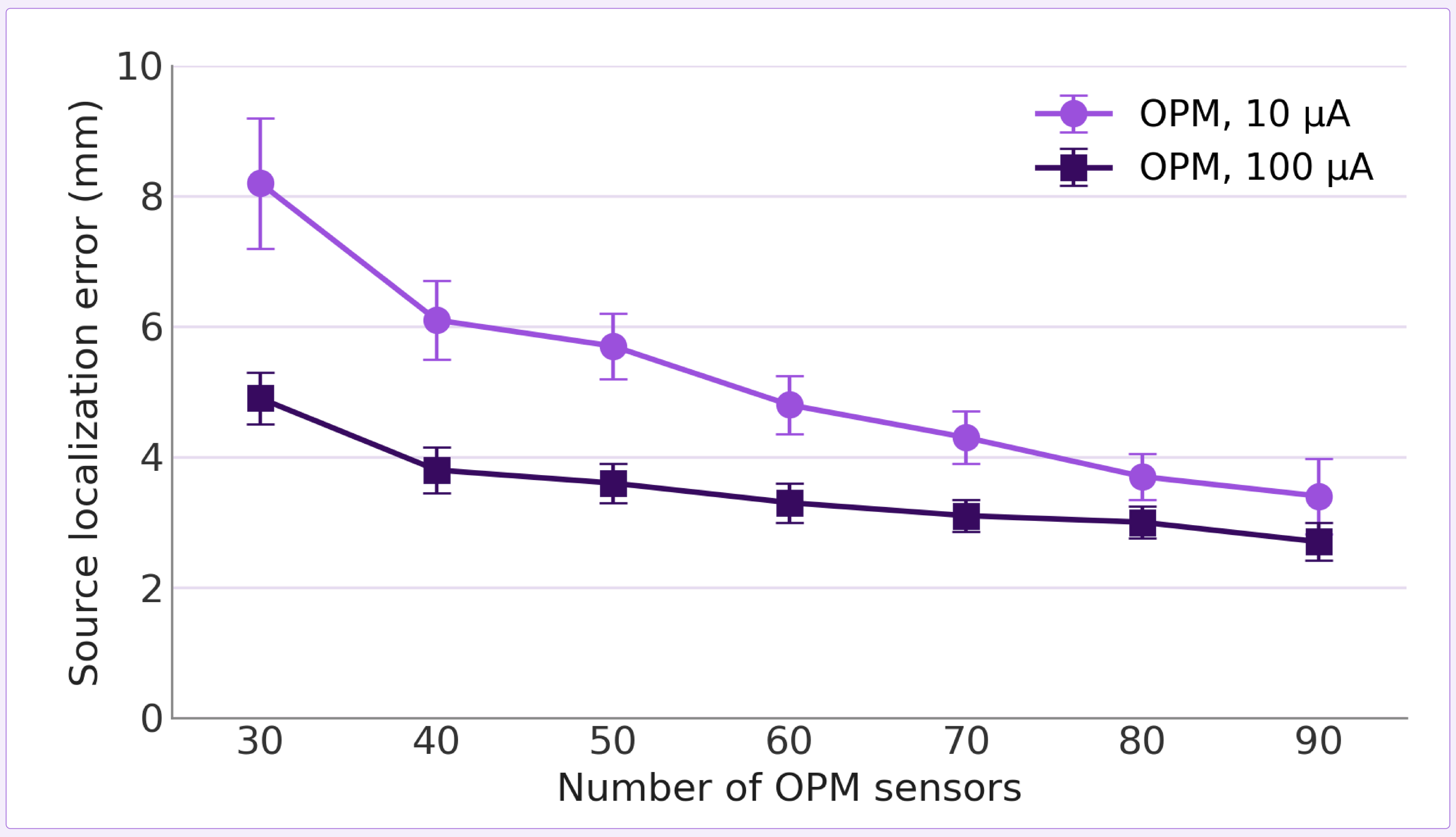
The dominant remaining factor is **OPM sensor array calibration**, namely per sensor position, orientation and gain.

Results: scaling the OPM array

Sensor selection. The 90 sensor array was divided into 10 spatial groups (G1 to G10). Equal numbers were drawn from each group to form 30 to 80 sensor subsets, and the analysis was repeated 8 times per sensor count to keep the coverage spatially balanced (Oyama et al., JBBS 2026).



OPM Sensor groups G1 to G10.



Error versus sensor count at 10 and 100 µA; mean ± expanded uncertainty. Accuracy improves and plateaus with array size.

Conclusions

A dry phantom delivers a reproducible, physiology free benchmark for cross technology MEG comparison. OPMs produce markedly stronger signals but currently trail SQUID in localization accuracy, with **sensor array calibration**, not noise or channel count, the decisive factor. Quantifying the accuracy versus sensor count tradeoff gives laboratories practical guidance for scaling modular OPM arrays, and establishes the dry phantom as a shared reference for benchmarking future sensor technologies under identical, physiology free conditions.

Reference. Oyama, D. & Zaatiti, H. Phantom Based Approach for Comparing Conventional and Optically Pumped Magnetometer Magnetoencephalography Systems. *Sensors* **2025**, 25(7), 2063. doi:10.3390/s25072063 (CC BY).
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