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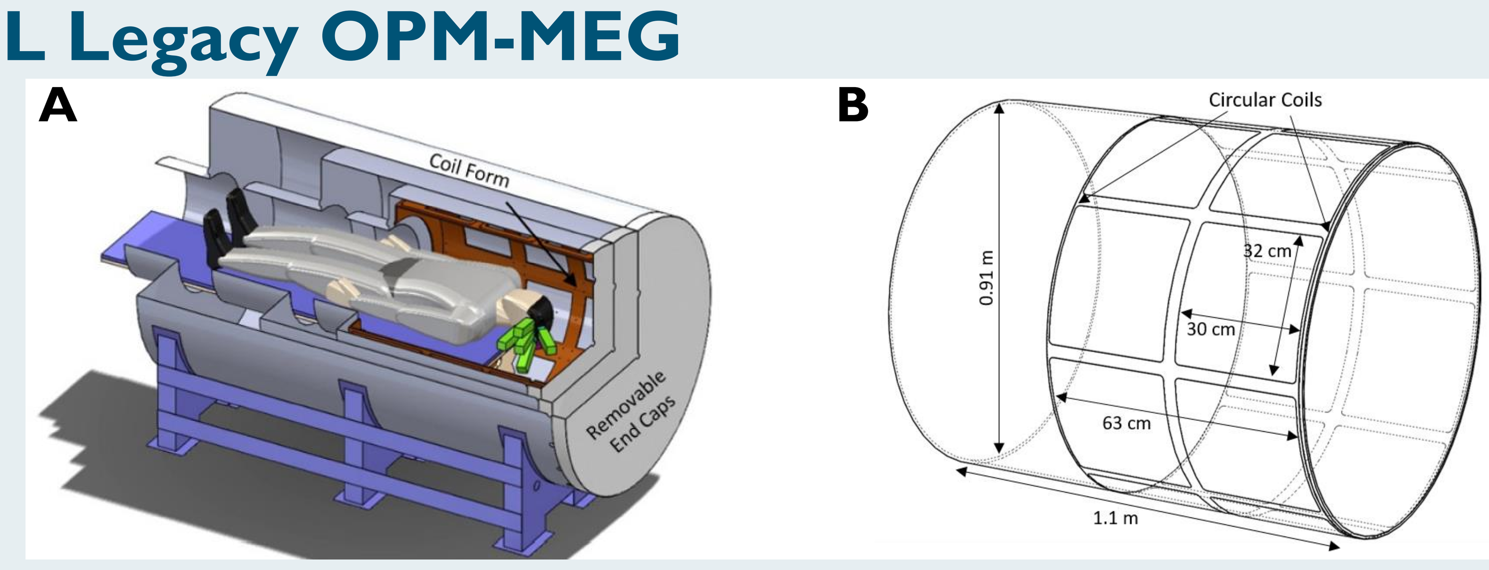
Impact of Cross-Axis Projection Error of Optically Pumped Magnetometers on Calibration Accuracy of OPM-MEG Systems

Amir Borna[1], Joonas Iivanainen[1], Tony R. Carter[1], Julia M. Stephen[2], Jim McKay[3], Samu Taulu[4] and Peter D. D. Schwindt[1]
[1]Sandia National Laboratories; [2]Mind Research Network; [3]Candoo systems Inc.; [4]University Of Washington

Introduction

- Multi-axis magnetic signals in the presence of small remnant static magnetic fields, not violating the spin-exchange-relaxation-free (SERF) criteria introduce significant error terms in OPM's output signal: Cross-Axis Projection Errors (CAPE) [1]
- CAPE manifests in terms of gain and phase errors.
- The gain and phase errors degrade the localization accuracy of magnetic dipole moments used in the calibration process.
- In this work we analyze the localization degradation of magnetic dipole moments due to CAPE.

SNL Legacy OPM-MEG

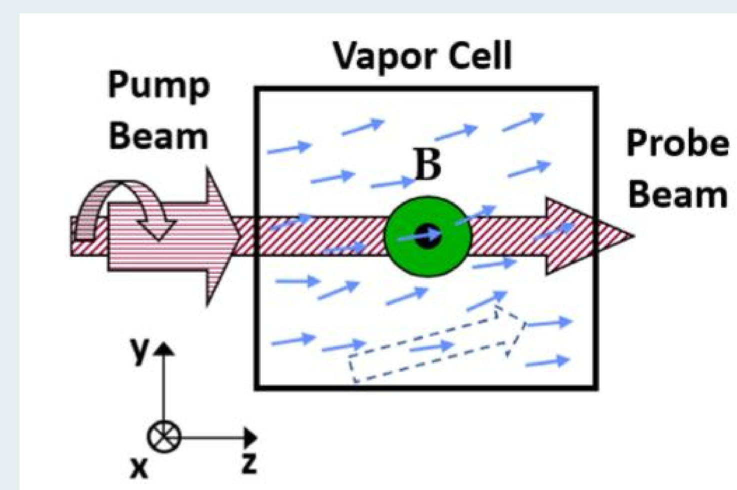


A: The Sandia Stationary OPM-MEG System [2] composed of six 4-channel dual-axis OPM sensors [3]. **B**: 18 fixed coils embedded in the shield and used for calibration of the OPM sensors.

Minimizing CAPE for SNL's Stationary OPM-MEG

- The shield is degaussed using embedded wires
- The low spatial frequency components of the remnant magnetic field is zeroed using 18 shield coils.
- The remaining background magnetic field is iteratively nulled using on-sensor coils for sensor specific X, Y, and Z axes.

CAPE Theory



The OPM Coordinate

- Ideal OPM response at the modulation frequency

$$P_z = R_{op}\tau\, J_0\left(\frac{\gamma B_m}{q\omega_m}\right) J_1\left(\frac{\gamma B_m}{q\omega_m}\right) \frac{\gamma\tau \widehat{B_{xs}}(t)}{1+\left(\gamma\tau\widehat{B_{xs}}(t)\right)^2} \sin(\omega_m t)$$

- OPM response at the modulation frequency including the gain and phase errors

$$P_z = f(B_x, B_y, B_z) \approx G_{OPM}\, Re\{\widehat{B_{xs}}(t) e^{i(\theta_{OPM}+\theta_{CAPE})}\} + O_{CAPE}$$

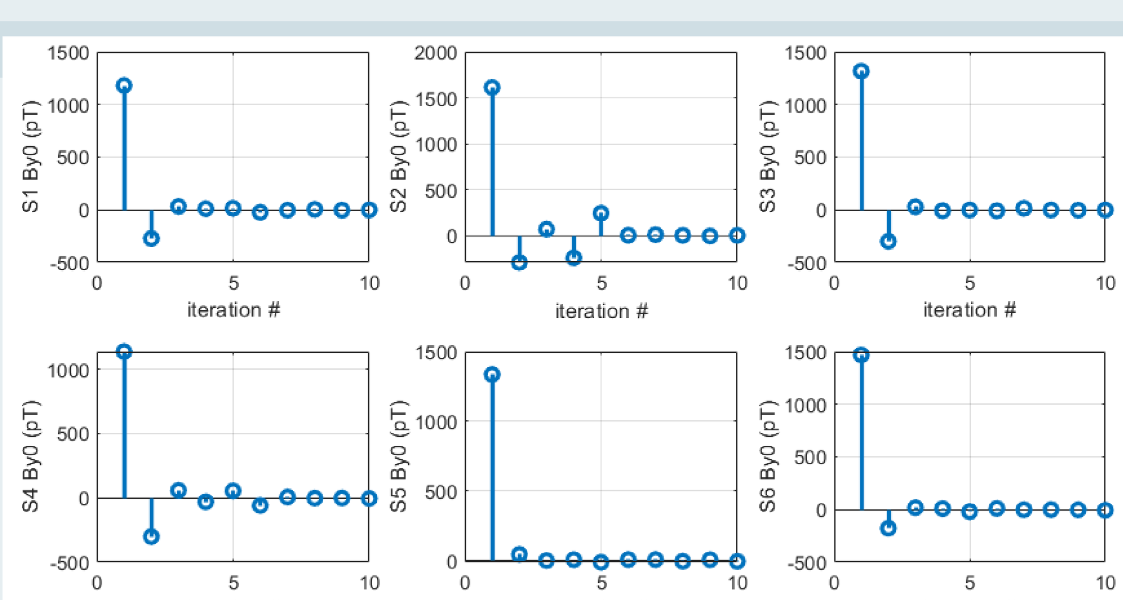
$$G_{OPM} \approx R_{op}\tau\, J_0\left(\frac{\gamma B_m}{q\omega_m}\right) J_1\left(\frac{\gamma B_m}{q\omega_m}\right)\gamma\tau$$ Ideal OPM Gain with no CAPE error

$$O_{CAPE} \approx -G_2 B_y B_z - G_3 \widehat{B_{xs}}(t)\left(B_y^2 + B_z^2\right)$$ Amplitude Error

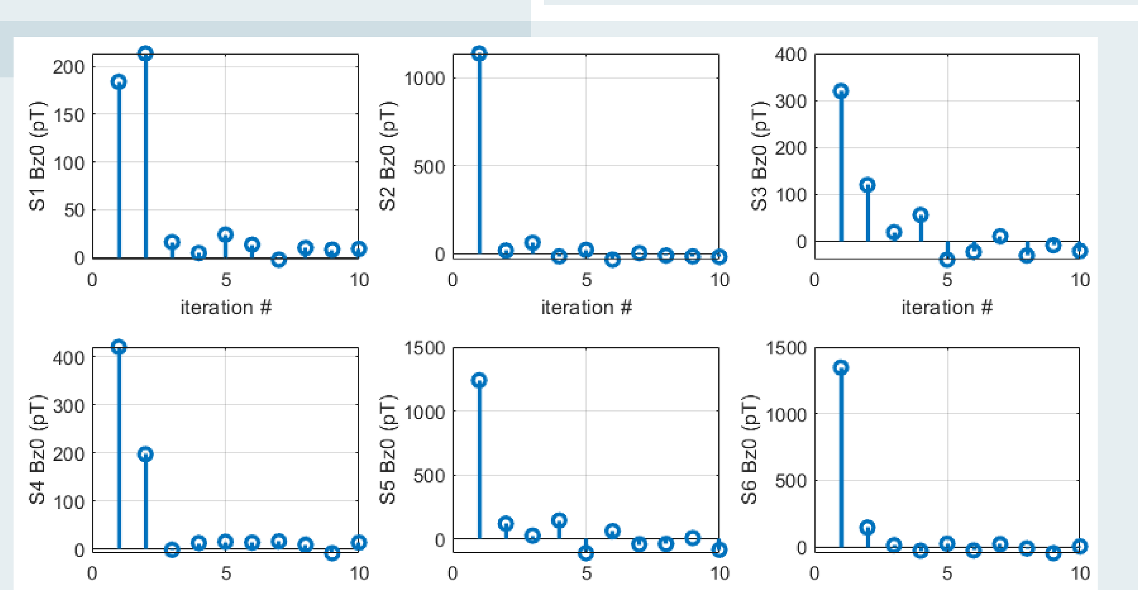
$$\begin{cases} G_2 = R_{op}\tau\, J_0^3\left(\frac{\gamma B_m}{q\omega_m}\right) J_1\left(\frac{\gamma B_m}{q\omega_m}\right)\gamma^2\tau^2 \\ G_3 = R_{op}\tau\, J_0^3\left(\frac{\gamma B_m}{q\omega_m}\right) J_1\left(\frac{\gamma B_m}{q\omega_m}\right)\gamma^3\tau^3 \end{cases}$$ Coefficients of the Amplitude Error Terms

$$\varphi_{y,z} \approx arctan\left(\frac{-G_2 B_{y0,z0}}{G_{OPM}}\right)$$ A side effect of the amplitude error term is rotation of the OPM's sensitive axis

$$G_\varphi \approx \left(G_{OPM} - G_3\left(B_{y0}^2 + B_{z0}^2\right)\right)$$ OPM Gain Considering the CAPE

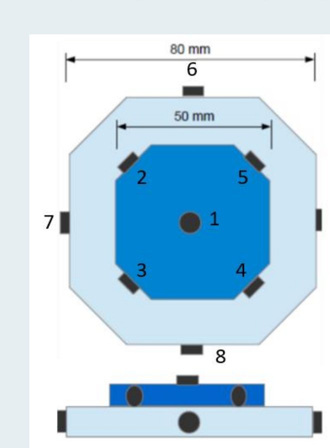


Nulling B_{y0} for 6 sensors in 10 iterations

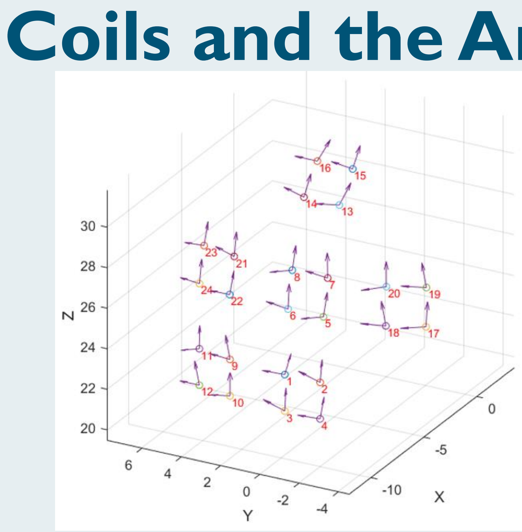


Nulling B_{z0} for 6 sensors in 10 iterations

The Calibration Coils and the Array

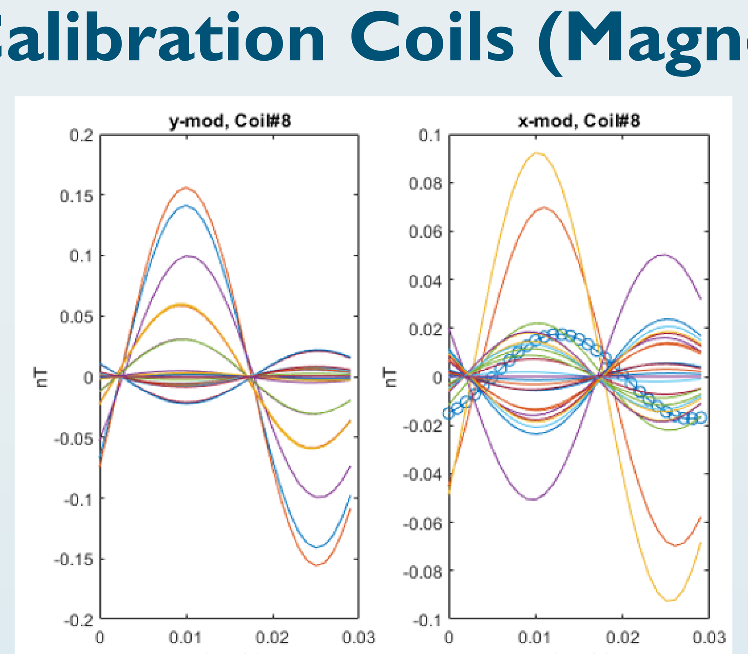


9 Coils installed in front of the array

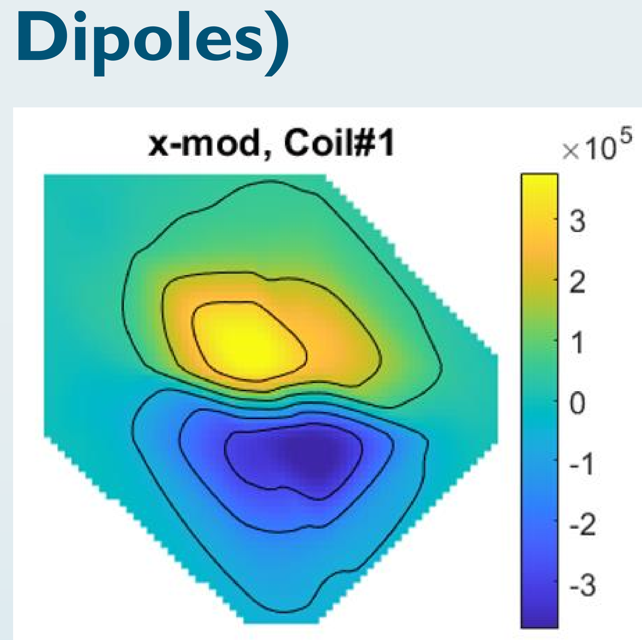


The array calibrated using shield coils

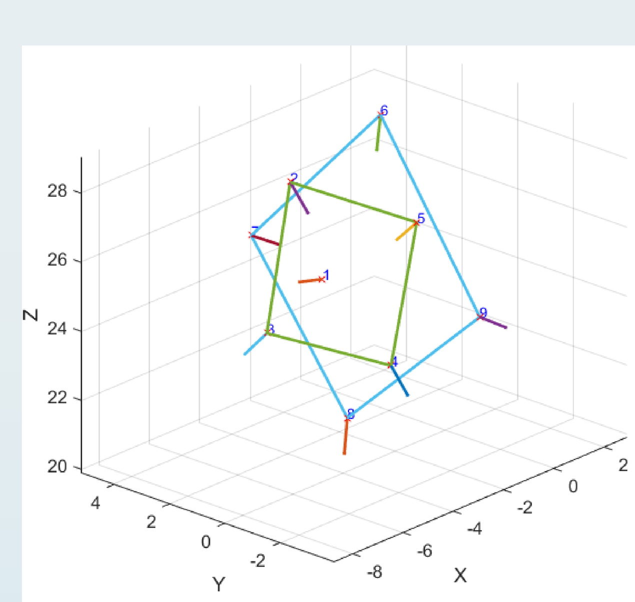
The Calibration Coils (Magnetic Dipoles)



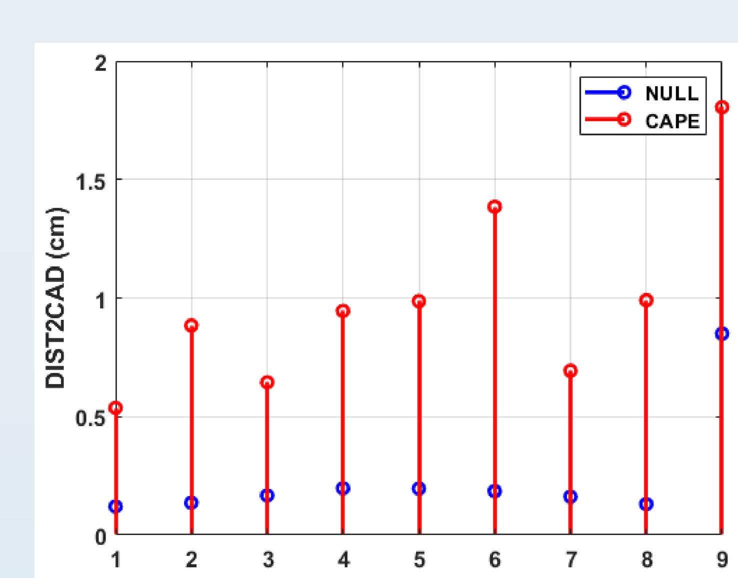
Time domain OPM-MEG response



Resulting fieldmap from the center coil (#1)



Localized Magnetic Dipoles for channel location calibration



Distance b/w coils CAD and localized positions for NULL/CAPE (B_{z0}<3 nT)

Conclusions

By using an iterative gradient-descent algorithm and activating on-sensor coils, the background magnetic field in a stationary OPM-MEG system is nulled and consequently the impacts of CAPE is diminished. The resulting system shows superior localization/calibration capability compared to a system suffering from CAPE.

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[1] J. Iivanainen, *et al.*, Sensors, **22**, 3059 (2022)
[2] A. Borna, *et al.*, Phys Med Biol, **62**, 8909 (2017)
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