Magnetoencephalography (MEG) in the Biophysics Group

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The Physics Division Review Committee
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Outline

- ***Background & Introduction***
  The Superconducting Imaging Surface (SIS) MEG system in context to brain imaging & other MEG systems.
- ***The SIS-MEG system***
  Status of the SIS-MEG system
  Recent results obtained with the LANL SIS MEG System
- ***Summary & Future Plans***
  Summary of status & results
  Future directions & opportunities for SIS-MEG

Our Collaborators

Albuquerque Veterans Administration Hospital
MIND Institute
Sandia National Laboratory
University of Minnesota / VAMC Minneapolis
University of New Mexico

NIS-Division – J. Mosher

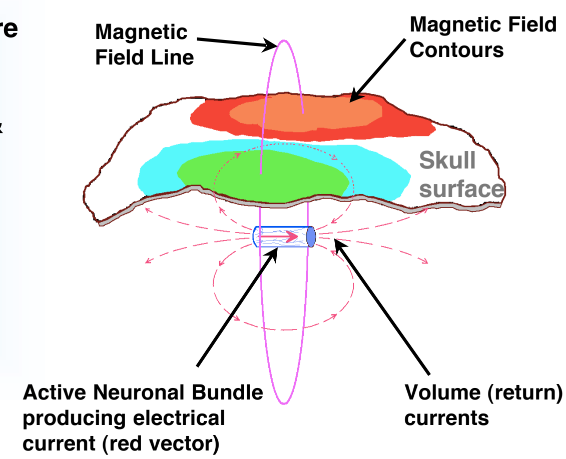
Funding

NIH/NINDS; DOE/OBER
MIND Institute; LANL LDRD

Background & Introduction

Goal: Noninvasively measure Brain function with high temporal resolution and sufficient spatial definition & signal-to-noise to enable the most accurate source localization.

Address instrumentation issues: Cost, Robustness, Shielding, State-of-art technologies, Precision & Accuracy.



The SIS System - Motivation *(& history)*

Novel Basic Imaging concept *(Flynn et al.)*

Image neuronal currents on superconducting surface

Inherent Shielding & Imaging properties

Meissner effect of SIS eliminates most external fields (□□independent)

Improved Performance at Lower Cost

Lower noise, simple SQUID sensor design, materials, fabrication methods.

Incorporate state-of-art Technologies

Control system & real-time analysis tools (MEGAN, Brainstorm)
State-of-art SQUID electronics & sampling technology

Prohibitively expensive for industry

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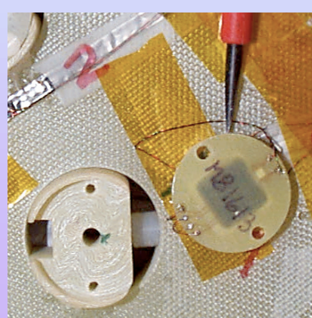
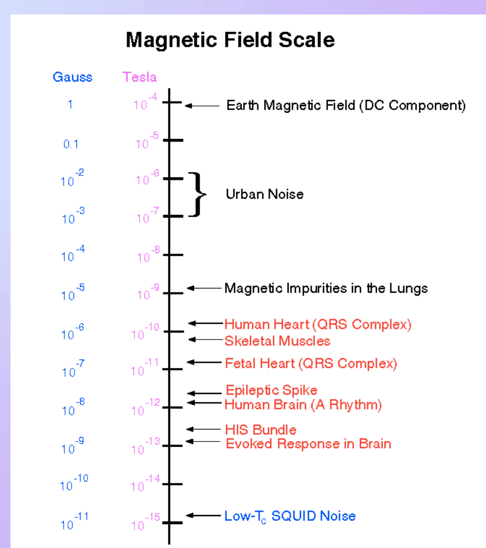
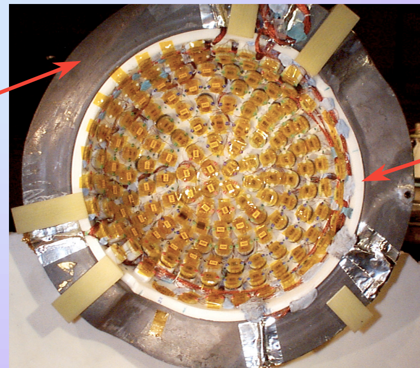
SQUIDs are the Most Sensitive Magnetic Field Sensors Known





The LANL Whole-Head SIS-MEG System

Lead Superconducting Imaging Surface (SIS) "helmet".



SQUID array inside SIS "helmet" with all sensors.

Corian®-like support and mounting structure. (DuPont/LANL Patent)

The cryogenic column is immersed in liquid helium at ~4 Kelvins.

MEG with the SIS-MEG system
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Goal of Magnetic Measurements

Study Neuronal Activity:

temporal evolution, spatial localization & evolution

Requirements:

Maximal S/N
Precision/Accuracy of sensor array & sensors …
(assumed but rarely discussed)
Complete & accurate description of the forward physics

Magnetic field distribution measured outside the head

↓ ↓ ↓ ↓

Estimation of source location and temporal evolution

One of the greatest challenges for the SIS-MEG system was describing the forward physics …

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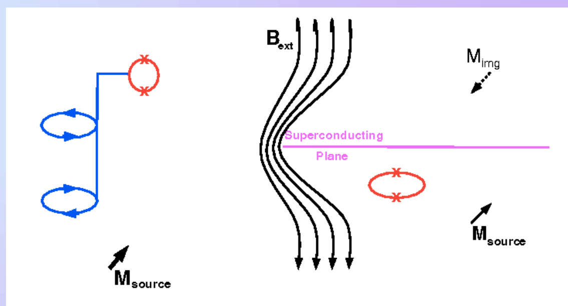
Analytic Approaches to Describing SIS-MEG Forward physics



Current-loop dipole $\mathbf{M}_{source}$ located at $\mathbf{r}=(x_0,y_0,z_0)$, and $\mathbf{M}_{img}$ located at $\mathbf{r}' =(x_0,y_0,-z_0)$.

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left[\left(3\frac{\mathbf{M}\cdot\mathbf{R}}{R^5}\mathbf{R} - \frac{\mathbf{M}}{R^3}\right) + \left(3\frac{\mathbf{M}'\cdot\mathbf{R}'}{(R')^5}\mathbf{R}' - \frac{\mathbf{M}'}{(R')^3}\right)\right]$$

Planar Imaging-Surface

Current dipole $\mathbf{Q}_{source}$ located at $\mathbf{r}_0$, and $\mathbf{Q}_{img}$ located at $\mathbf{r}'=(a/\,\mathbf{r}_0)^2\,\mathbf{r}_0$

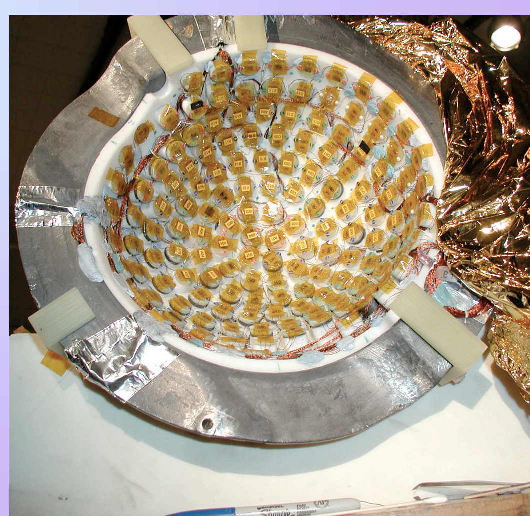
$$\mathbf{r}\cdot\mathbf{B} = -\frac{\mu_0}{4\pi}\mathbf{r}\cdot(\mathbf{Q}\times\mathbf{r}_0)\left[\frac{1}{R^3} - \left(\frac{a}{r_0}\right)^3\frac{1}{(R')^3}\right]$$

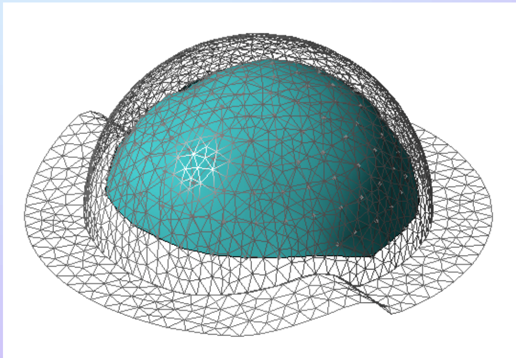
Spherical Imaging-Surface

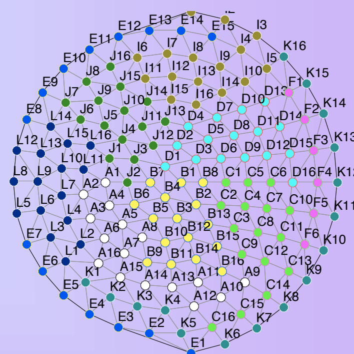
But not feasible for complex geometries

Effect of Complex shape of SIS Helmet:

Hemispherical helmet with ear cut-outs and brim.







FEM mesh following the as-built geometry of the SIS. **left:** gray mesh represents the SIS, vertices of teal colored surface denotes SQUID positions, **right:** and flattened rendition of SQUID sensor array with sensor numeration.

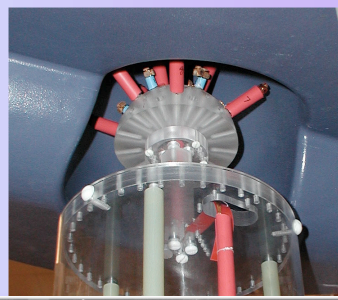
FEM Model Implementation

- FEM description of as-built SIS implemented (Volegov, et al.)
- Meissner currents concentrated along element edges, Use $B_{\perp}$(surface)=0 boundary condition
- SIS divided into 2734 triangular elements
- Magnetic field at each element is superposition of the primary field and the fields produced by all triangular elements.
- Using Biot-Savart, sum primary field and fields produced by all triangular elements.

$$\sum_{j=1}^{m} A_{ij} I_j = -b_i, \quad i = \overline{1,m}$$

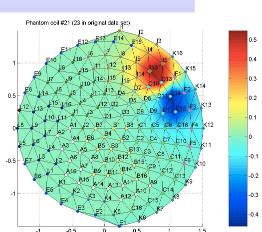
$$A_{ij} = \frac{\mu_0}{4\pi} \cdot \mathbf{n}_i \cdot \sum_{k=0}^{2} [\mathbf{r}_{ij}^{(k)} \times \mathbf{r}_{ij}^{(k+1)}] \frac{(r_{ij}^{(k)} + r_{ij}^{(k+1)})}{r_{ij}^{(k)} r_{ij}^{(k+1)} (r_{ij}^{(k)} r_{ij}^{(k+1)} + (\mathbf{r}_{ij}^{(k)} \cdot \mathbf{r}_{ij}^{(k+1)}))},$$

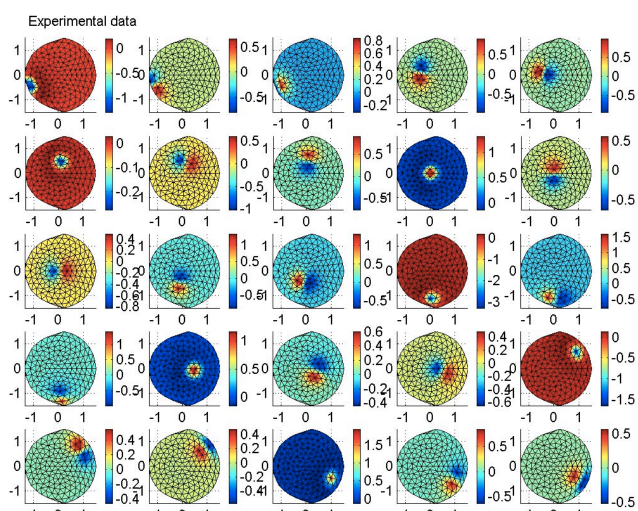
$$b_i = \mathbf{n}_i \cdot \mathbf{B}_p(\mathbf{p}_i), \quad \mathbf{r}_{ij}^{(k)} = \mathbf{p}_i - \mathbf{v}_j^{(k \bmod 3)}$$

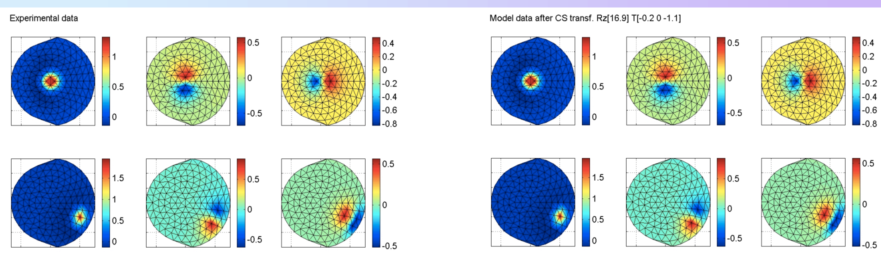


Precision phantoms with ***well defined source model*** used to test the SIS-MEG system & description of Forward Physics

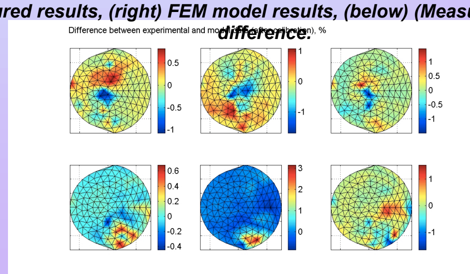
Experimental Data from subset of 50 phantom locations measured shown here.





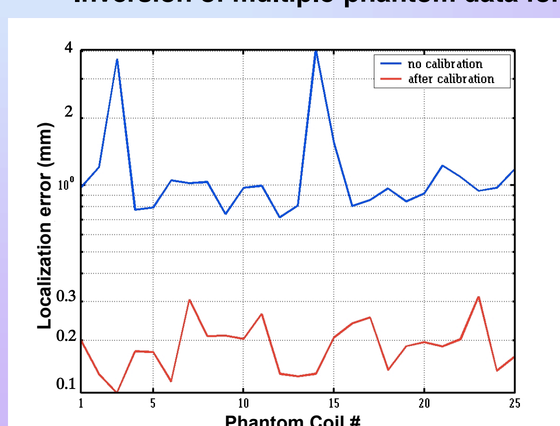


Magnetic field distributions for 6 phantom sources near the apex and edge of the SIS helmet. (left) Measured results, (right) FEM model results, (below) (Measured - FEM model) difference.



Effect of SQUID calibration

SQUID location, orientation, sensitivity calibrated by Inversion of multiple-phantom data for each SQUID



Before calibration

After calibration

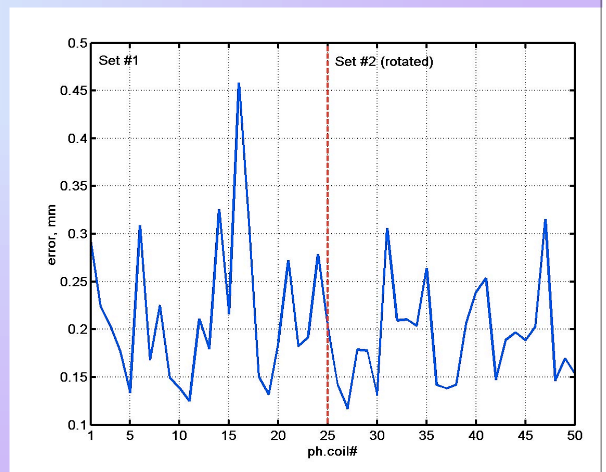
50-coil set Independent Phantom Localization

<Precision> = <0.25mm for <u>all</u> phantom coils.

– previous best reported in literature ~1.5mm

Phantom coil #16 mislocated (during inspection process)

S/N ~20 for equivalent of 770 epochs. Maximal signal nominal 100-500fT.

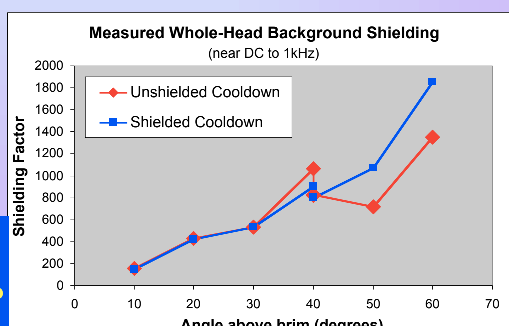


Multi-dipole, orthogonal time series data. Using calibrated SQUID positions, sensitivities

Background Shielding

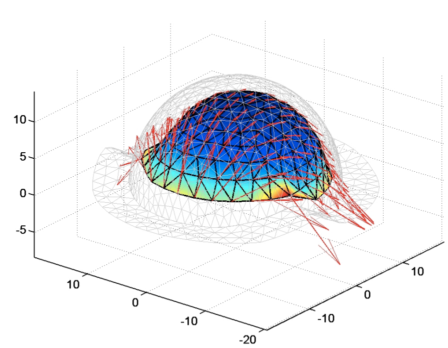
Frequency independent !!
Inherrent (low cost)
Strongly source dependent.

Near helmet edges: Shielding factor observed from ~15 to ~170

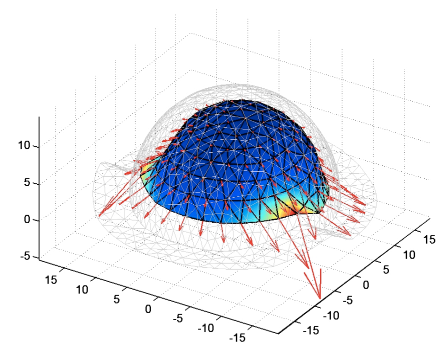


Near helmet apex: Shielding factor observed from ~200 to ~1900

Background Field Model Results: Effect of Background Source



Dipole at 2m, right



Uniform Z-Field

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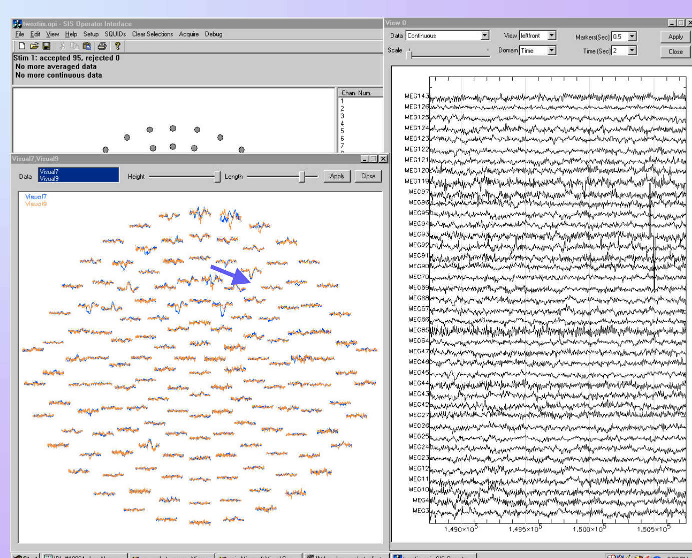
Sample Data Acquisition "OPI" screen showing various data representations and a simulated real time (~subsec) source localization.



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Conclusions

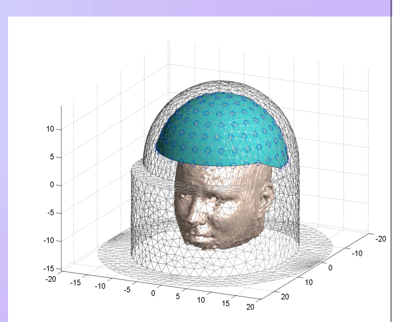
- *Completed FEM description for SIS forward physics (applicable to any superconducting surface)*
- *Demonstrated excellent agreement between FEM model and experimental results.*

- ~2 orders of magnitude frequency-independent shielding demonstrated.
- *0.25mm mean localization accuracy demonstrated for phantom sources.*

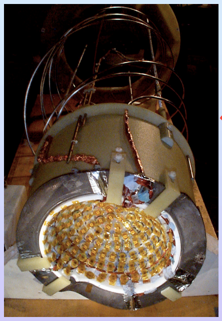
- *Data acquisition system complete/tested*
- *Real-time source localization in progress (new LDRD)*

Near-Term Plans

- *Locate SIS-MEG system at VA-Albuquerque. Perform efficacy studies with human 'normal.' – NIH, MIND*
- *Move SIS-MEG system to VAMC-Minn. Perform preliminary measurements on monkeys with implanted electrodes ("gold standard"). NIH Continuation grant to build SIS-MEG optimized for monkeys & incorporating lessons learned.*



- Conduct experiments focused on real-time single event analysis with 'feedback.' (Perlmutter, Tang at UNM/VA-Albuq.) - MIND

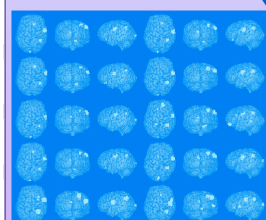


Instrumentation Research

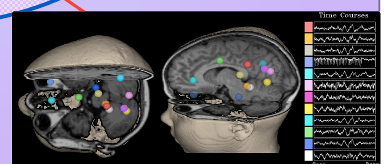
Advanced MRI and fMRI Research

Functional Brain Imaging

Visualization



Modeling & Computation



Physics
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End

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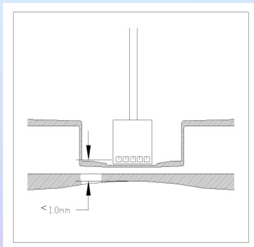
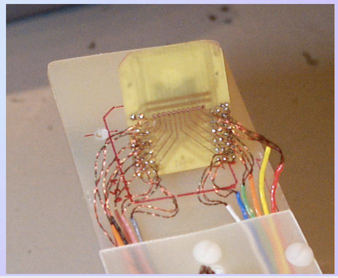
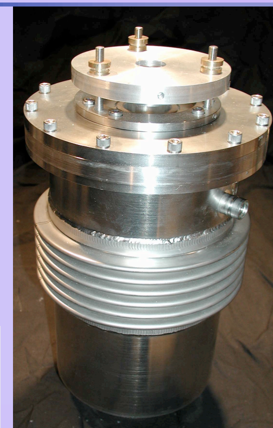
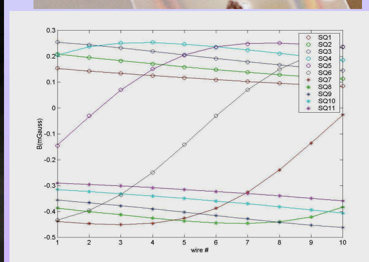
□-MEG SQUID array & Dewar









High resolution MEG to observe activity at the level of cortical columns