Multi-channel SQUID-based Ultra-Low Field Magnetic Resonance Imaging in Unshielded Environment

Andrei Matlashov, Per Magnelind, Shaun Newman, Henrik Sandin, Algis Urbaitis, Petr Volegov, Michelle Espy

Los Alamos National Laboratory
matlachov@lanl.gov
Motivation

**Magnetic Resonance Imaging (MRI):**
- best method for non-invasive imaging of soft tissue anatomy
- saves countless lives each year

**Conventional (high-field) MRI:**
- only in large well-funded medical centers
- is not available in rural settings
- is not deployable to emergency situations or battlefield hospitals

**Ultra-low field (ULF) MRI**
- pulsed pre-polarization at $< 0.3$ T
- sensitive Superconducting Quantum Interference Device (SQUID) detection
- greatly relaxed measurement field homogeneity
- presence of metal is not an issue
- can be light and made portable
Outline

• Model: How accurate can we simulate ULF MR Images?
  o MATLAB model
  o SNR and Resolution
  o How close is our model to reality?
• Highly Shielded ULF MRI System
• Unshielded ULF MRI System
  o Unshielded ULF MRI of a Gelatin-Agar Phantom
  o Noise Compensation at 8.6 kHz Larmor frequency
• Summary
Modeling (McGill University Model)

- A MATLAB model of the geometry
- Reciprocity to model NMR signals; Bloch equations;
- Realistic digital brain model of anatomy

Eleven high-resolution (0.5x0.5x0.5 mm) volumes describing content of a voxel

<table>
<thead>
<tr>
<th>Tissue name</th>
<th>PD</th>
<th>$T_1$ (ms)</th>
<th>$T_2$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 CSF</td>
<td>1</td>
<td>4360</td>
<td>329</td>
</tr>
<tr>
<td>2 GREY MATTER</td>
<td>0.86</td>
<td>635</td>
<td>83</td>
</tr>
<tr>
<td>3 WHITE MATTER</td>
<td>0.77</td>
<td>360</td>
<td>70</td>
</tr>
<tr>
<td>4 FAT</td>
<td>1</td>
<td>350</td>
<td>70</td>
</tr>
<tr>
<td>5 MUSCLE</td>
<td>1</td>
<td>120</td>
<td>47</td>
</tr>
<tr>
<td>6 MUSCLE/SKIN</td>
<td>1</td>
<td>120</td>
<td>47</td>
</tr>
<tr>
<td>7 SKULL</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8 VESSELS</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9 CONNECTIVE</td>
<td>0.77</td>
<td>500</td>
<td>61</td>
</tr>
<tr>
<td>10 DURA MATTER</td>
<td>1</td>
<td>2569</td>
<td>329</td>
</tr>
<tr>
<td>11 BONE MARROW</td>
<td>0.77</td>
<td>500</td>
<td>70</td>
</tr>
</tbody>
</table>

McConnell Brain Imaging Centre, Montreal Neurological Institute, McGill University.
Modeling: SNR and Resolution

Imaging parameters:

**Polarization Field: 100 mT**
- Polarization inversion time: 750 ms
- Polarization time: 750 ms
- Delay time: 10 ms
- Encoding time: 35 ms
- Acquisition time: 70 ms

\[N_y \text{ (phase)}: \quad 103\]
\[N_z \text{ (phase)}: \quad 41\]

Readout gradient, \(G_x\): 7.00 Hz/mm
Phase gradient, \(G_y\): 7.00 Hz/mm
Phase gradient, \(G_z\): 3.00 Hz/mm
Voxel size:
- 2.04 ×
- 2.04 ×
- 4.76 mm³

Total imaging time: 106.5 minutes

**Noise, 1.80 fT/Hz\(^{1/2}\)**

\[\text{O} \quad 1 \text{ cm}^3 \text{ blood inclusion}\]
Modeling: SNR and Resolution

Imaging parameters:

Polarization Field: 250 mT
- Polarization inversion time: 750 ms
- Polarization time: 750 ms
- Delay time: 10 ms
- Encoding time: 35 ms
- Acquisition time: 70 ms

- $N_y$ (phase): 103
- $N_z$ (phase): 41
- Readout gradient, $G_x$: 7.00 Hz/mm
- Phase gradient, $G_y$: 7.00 Hz/mm
- Phase gradient, $G_z$: 3.00 Hz/mm
- Voxel size: $2.04 \times 2.04 \times 4.76 \text{ mm}^3$

Total imaging time: 106.5 minutes

Noise, 0.90 fT/Hz$^{1/2}$

O $\rightarrow$ 1 cm$^3$ blood inclusion
How Good is Our Modeling

Model

Reality: MRI inside MSR
Shielded ULF MRI System & LANL

2-layer Magnetically shielded Room, $S = 1000$ at 1 Hz

Ø 90 mm second-order gradiometers, $N = 0.4 \times 10^{-15} \text{T/Hz}^{1/2}$

Pre-polarizing Field: 100 mT

Larmor Frequency: 8.3 kHz

<table>
<thead>
<tr>
<th>Gradients</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase encoding, $G_y$</td>
<td>47.6 $\mu$T/m (2 Hz/mm) @ 5.3 A</td>
</tr>
<tr>
<td>Phase encoding, $G_z$</td>
<td>221.7 $\mu$T/m (9 Hz/mm) @ 10.8 A</td>
</tr>
<tr>
<td>Readout, $G_x$</td>
<td>248 $\mu$T/m (11 Hz/mm) @ 25.5 A</td>
</tr>
</tbody>
</table>


Shielded ULF MRI System & LANL

Copper coil (Litz wire)
Liquid Nitrogen cooling
0.5 Ohm at 75K, 3 Ohm at RT
L = 0.19 H
Bp = 100 mT at 100 A

2.0 fT/Hz^{1/2}
Unshielded ULF MRI System & LANL

$B_m$ continuously ON - power supply with a large capacitor across its terminals to reduce the noise. Gradients and spin-flip field were generated by battery-powered current generators receiving input voltages from an NI-6733 card. $B_p$ was generated by 2–3 sealed 12 V lead-acid car batteries in series and ramped down through banks of solid-state switches (40 mT at 40 A). Spin-flip coil placed on top of the pre-polarization coil.

3 pairs of square Helmholtz coils cancel the Earth’s magnetic field below 1 mG ($10^{-7}$ T).
ULF MRI of a “Blood Inclusion”

ULF MR Images of 1 cm³ “blood inclusion” using a phantom made of gelatin-agar mixtures:

Gelatin-agar “white matter” with $T_2 \sim 120$ ms (the surrounding tissue) and “blood” with $T_2 \sim 300$ ms (white dot)

Unshielded MRI was recorded at $B_p = 65$ mT and pre-polarization time $t_p = 2.5$ s, during “low-noise time period”

2D resolution is about $3 \times 3$ mm²

Four averages (6.5 minutes per one image)

Reference channels

- Manual Ambient DC field compensation
- A low-frequency dynamic cancellation system is being tested to enable automatic adjustments.
- Reference two vector magnetometers and one gradiometer configuration was initially implemented and tested.
- Current configuration includes only one vertically oriented reference magnetometer.
- Electronic compensation and software compensation have been tested and compared.
- In both cases it was possible to completely eliminate noise lines from all range of our NMR signals with central Larmor frequency 8630 Hz.

Ambient Field deviation in ULF MRI system location

- Compensation works only if the gradiometers are placed under the pre-polarization coil and the coil is shunted with a resistor, $R < 500$ Ohm.
- If $B_p$ coil is not shunted or if the gradiometers are moved away, this technique does not work.
- Hypothetically the pre-polarization coil makes the high frequency noise recorded by gradiometers highly correlated with the signal picked up by the nearby reference magnetometer.
Power spectral densities of seven SQUID gradiometers inside the MRI dewar, and one external magnetometer in a separate dewar:

Gradiometers pick-up Johnson noise from shunted $B_p$ coil at $T=75K$

$R_{\text{shunt}} = 0 \text{ Ohm}$

SQ 1 has intrinsic noise about $1.2 \text{ fT/Hz}^{1/2}$

SQ 2–7 pick up $2.4 \text{ fT/Hz}^{1/2}$ Johnson noise from thermal shields inside the dewar
Noise in Unshielded Conditions

Power spectral densities of seven SQUID gradiometers inside the MRI dewar, and one external magnetometer in a separate dewar:

\( R_{SH} = 500 \text{ Ohm} \) : Johnson noise becomes much smaller at a higher shunt resistor
Signals with and without Compensation

Top panels (A–C) show time-domain echo signals from 2D imaging, and the bottom panels (D–F) show the power spectral densities (PSDs) of the echo signals:

(A,D) no noise-cancellation,
(B,E) post-processing software noise-cancellation using the external reference magnetometer signal,
(C,F) real-time electronic noise-cancellation using the external magnetometer.
ULF MRI of a Water Phantom

2D single-shot MRIs of seven vials of water:

A) Data acquired without any noise cancellation.
B) Noise cancellation in post-processing cancellation using the external magnetometer signal.
C) Real-time electronic noise cancellation using the external magnetometer.

The phantom consisted of seven 24 mm diameter and 20 mm tall cylinders with pure water located on hexagonal corners with one cylinder in the center. The distance between their centers was 35 mm.
Experimental Surroundings

1T magnet with a pulsed-tube cryo-cooler that generates a lot of noise at 1-10 kHz range (from its power supply)

It located 10 m away from MRI system.

A busy road is placed 15 m away from the MRI system location.
Summary

- SNR of ULF MR Images can be accurately predicted using computer simulations.
- The possibility of providing ULF MRI using moderately balanced SQUID-based gradiometers in unshielded environment has been experimentally demonstrated.
- We proposed a simple and very effective method for high frequency noise cancellation that allows ULF MRI systems to work in noisy urban locations.
- We’ve built a prototype of an unshielded ULF MRI system that can be used for quick internal bleeding diagnostic in emergency situations.