

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
Department of Physics, Applied Modern Physics Group
Los Alamos National Laboratory
Los Alamos, USA
matlach@lanl.gov

Abstract—Magnetic Resonance Imaging (MRI) is the best method for non-invasive imaging of soft tissue anatomy. A conventional MRI relies on 1.5–3 T fixed strength magnetic fields, with parts-per-million homogeneity, requiring large and expensive magnets. MRI can be done at ultra-low magnetic fields (ULF) with Larmor frequencies of a few kHz with much more modest magnetic system requirements. However the ULF regime requires a very sensitive detection system. A candidate detection system is based on SQUID gradiometers. A conventional SQUID gradiometer based detection system requires effective shielding from all ambient electromagnetic noise. Large shielded structures, such as magnetically shielded or eddy-current rooms, can be used for proof-of-principles experiments but do not lead to practical deployable instruments. Our goal is to develop a technique in which a SQUID-based detector array could be deployed without the limitation imposed by the requirement for a shielded structure. We have tested the 7-channel ULF MRI system located in unshielded environment inside a modern physics laboratory. It was possible to significantly suppress most of the electromagnetic interference by subtracting a signal from a one-channel reference magnetometer. We believe that the pre-polarization coil influence makes kHz-range frequency noise in gradiometer channels very well correlated with signal from the magnetometer.

Keywords—ULF MRI; SQUID; shielding; noise compensation

I. INTRODUCTION

Conventional medical MRI systems use strong static magnetic fields. They can only be used in highly controlled settings in well-funded medical centers. Traditional high-field MRI is not available in rural settings, is not deployable to emergency situations or battlefield hospitals, and is more expensive than what poor and developing countries can afford leaving billions of people without access to this powerful diagnostic tool.

In the early 2000's John Clarke's group showed possibility of doing MRI at ultra-low magnetic fields (ULF) by combining SQUID-based detection with pre-polarization methods [1]. Since that time several compelling demonstrations of ULF MRI using this approach have been shown [2, 3, 4].

However, ULF MRI systems suffer from long imaging times, and poor quality images compared to traditional MRI.

These systems remain confined to the laboratory due to the strict requirements for a low noise environment isolated from almost all ambient electromagnetic fields. Nevertheless, the ULF regime shows many important benefits for some unique applications. These include high tissue contrast, absence of susceptibility artifacts and imaging in the presence of metal, just to name some. The benefits combined with the relaxed requirements for magnetic field generation may enable ULF MRI systems to be utilized clinically or perhaps in situations where traditional MRI cannot go, for example emergency response where the exclusion of metal is not possible, or places where the cost and infrastructure of high field MRI systems cannot be borne.

Previously we have demonstrated MRI from a seven-channel SQUID-based system that achieves moderate brain image quality inside a two-layer magnetically shielded room (MSR) [5]. However, our final goal is unshielded ULF MRI operation. In [5] we also published our first results using an unshielded ULF MRI system. In this paper we present new results on further improvement of high frequency noise rejection in unshielded environment.

II. METHODS

A. Unshielded ULF MRI Hardware

The ULF MRI system working in an unshielded environment consisted of gradient and measurement field coils of the same kind as described in [5, 6]. The cryostat and SQUID-based axial-gradiometer sensors system were the same 7-channel system as used in [3]. We estimated that gradiometers have an unbalance level for a uniform field and gradient of about 0.3%. Three pairs of square Helmholtz coils, surrounding the gradient coil system, were used for cancellation of the Earth's magnetic field. The cancellation coils were powered by three power supplies and adjusted until a fluxgate in the sample space showed fields below 10^{-7} T in three directions. The Earth's field cancellation currents require adjustment only once or twice a day. A low-frequency dynamic cancellation system is being tested to enable automatic adjustments.

The horizontal measurement field, B_M , was generated by a square quad-coil system constantly connected to a low noise

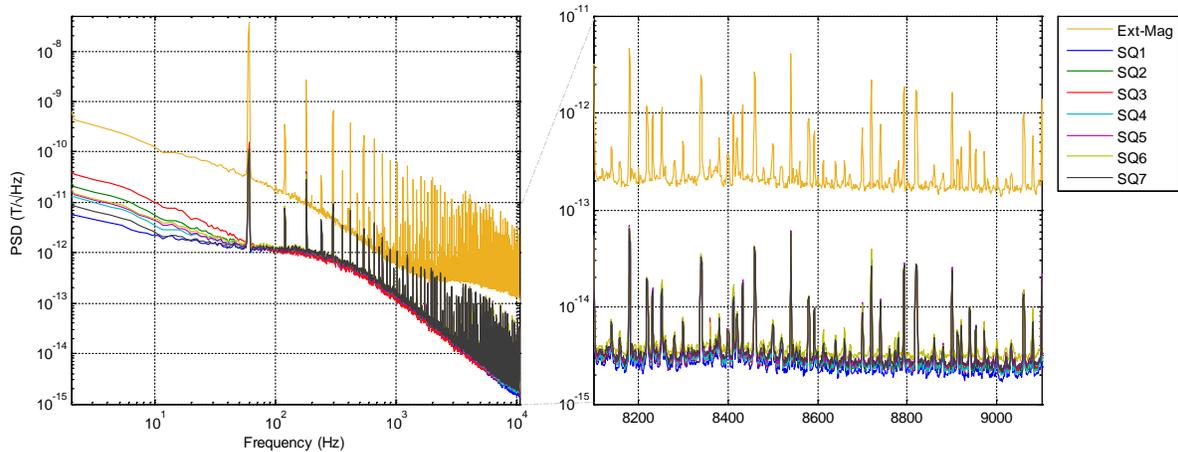


Fig. 1. Power spectral densities of seven SQUID gradiometers inside the MRI dewar, and one external magnetometer in a separate dewar.

power supply. The donut-shaped pre-polarization coil with liquid nitrogen cooling generates a vertically oriented 40 mT field perpendicular to B_M . The coil is described in [5, 7]. This coil is connected to two sealed 12 V lead-acid batteries in series and ramped down through banks of solid-state switches. Despite the linear 8 ms ramp-down of the 40 A current through the pre-polarization coil, we believe eddy currents within the coil itself created an adiabatic ramp-down condition and precession had to be induced by a spin-flip coil placed on top of the pre-polarization coil.

The 7-channel gradiometer system is placed along the axis of the pre-polarizing coil 5 cm above its upper surface. A second one-channel standalone reference system is used for ambient noise measurements. This system includes a 1.6 mm diameter pick-up loop connected to CE2Blue SQUID sensor that forms a magnetometer that measures a vertical component of ambient magnetic noise [8]. The magnetometer is placed in the same plane with the pre-polarizing coil 110 cm away along the direction of the B_M field.

The system is located inside a building where no efforts have been made to create a low-noise environment. There are electrical panels and power transformers located in many places. It has all day luminescent lights. This building also has other adjacent technical buildings filled with a wide range of power and frequency equipment used for experiments and a street with car traffic is located 10 m away.

The imaging parameters were the same as reported in [5].

B. RFI Shielding and Ambient Noise

The ULF MRI system has a radio-frequency interference (RFI) shield made of two layers of gold-plated Mylar that wraps the bottom area of the fiberglass cryostat containing the gradiometers. The upper part of the cryostat is also wrapped with two layers of fine copper cloth. The SQUID feedback units, PFL-100 [9], are mounted on the top flange of the cryostat and connected to the control unit, PCI-1000, with seven 15 foot long DB9 cables. The reference magnetometer is wrapped with gold-plated Mylar inside its standalone fiberglass cryostat. It is connected to PCI-1800 electronics [9].

III. RESULTS AND DISCUSSION

Fig. 1 demonstrates spectra of the ambient noise in the seven gradiometer channels and the reference channel in the entire measured frequency range (left) and in a small window around the Larmor frequency (right). There are a lot of narrow lines in whole frequency range including those in close proximity to the Larmor frequency $f_L = 8.63$ kHz. Some of these lines have stable frequency and amplitude and some lines change significantly during the 6.5 minute period of acquiring data for 2D images. The reference magnetometer signal spectrum looks very similar to the spectra of the gradiometers, although it is placed 110 cm away and connected to different SQUID electronics. It means that we are dealing with actual external magnetic signals generated by surrounding equipment. These signals do not arise from external RF signals mixing with the SQUID electronics modulation frequency, which is a possible consequence of inadequate RFI shielding or improper grounding of electronic units used in our MRI system. In this case the noise lines in the gradiometer signal can be compensated by subtracting a properly scaled signal from the reference magnetometer. The main noise source is a pump for a cryo-cooled magnet used for another experiment in our building about 10 m away. That cryo-cooler was not present when we acquired our previous unshielded MRIs [5].

Fig. 2 shows NMR echoes recorded by seven gradiometers without and with compensation from the stand-alone magnetometer. We have tested both real-time electronic compensation and software compensation using recorded signals. In both cases it was possible to almost completely eliminate noisy lines from all range of our NMR signals. But such effective compensation works only if the gradiometers are placed right under the pre-polarization coil and the coil is shunted with a 500 Ohm or smaller resistor. If the coil is not shunted or if the gradiometers are moved away from the coil, this technique does not work at all. We believe that the large pre-polarization coil somehow makes the external high frequency noise recorded by gradiometers highly correlated with the signal picked up by the reference magnetometer.

2D MR images recorded with and without noise compensation are shown in Fig. 3. An ambient gradient along

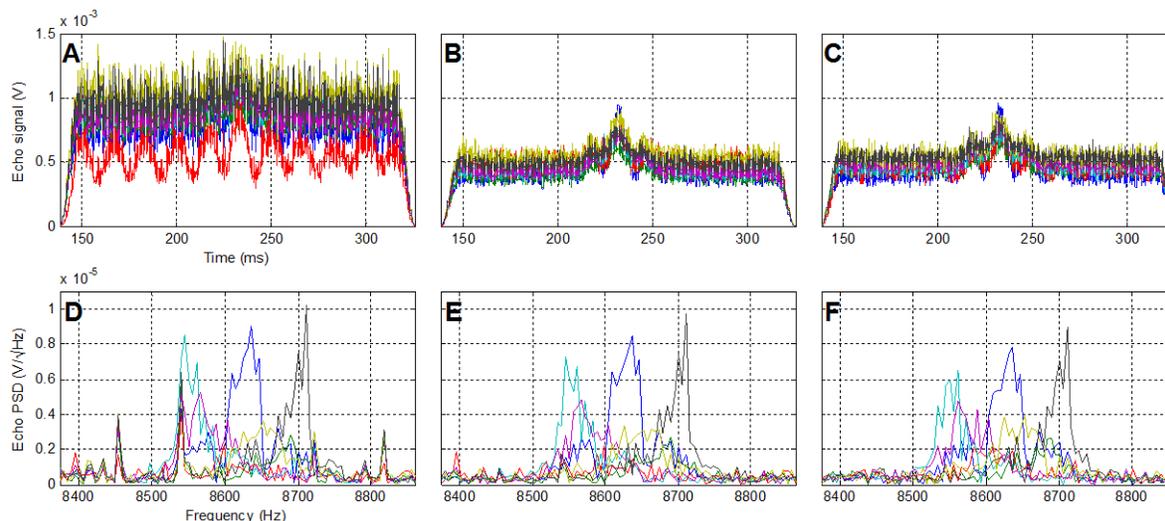


Fig. 2. Top panels (A–C) show time-domain echo signals from 2D imaging, and the bottom panels (D–F) show the power spectral densities (PSDs) of the echo signals. (A,D) no noise-cancellation, (B,E) post-processing noise-cancellation using the external magnetometer, and (C,F) electronic noise-cancellation using an external magnetometer. The color coding of the seven SQUID signals is the same as in Fig. 1.

the phase-encoding direction was corrected for. The images provide proof of principle results to illustrate the efficacy of using an external reference channel for noise cancellation, either in post-processing or by electronic cancellation. This simple noise compensation method allows our ULF MRI system to work without any large size shields in noisy urban location.

IV. CONCLUSION

In this work we demonstrated the possibility of providing ultra-low field magnetic resonance imaging using moderately balanced SQUID-based gradiometers in unshielded environment. We proposed a very simple and effective method for high frequency noise compensation that allows the system to work in noisy urban locations.

REFERENCES

- [1] J. Clarke, M. Hatridge, and M. Mößle, “SQUID detected magnetic resonance in microtesla fields,” *Annu. Rev. Biomed. Eng.*, vol. 9, pp. 389–413, 2007.
- [2] B. Inglis, et al., “MRI of the human brain at 130 microtesla,” *Proc. Nat. Academy Sci. U.S.A.*, vol. 110, no. 48, pp. 19194–19201, 2013.
- [3] P. E. Magnelind, et al., “Co-registration of interleaved MEG and ULF MRI using a 7 Channel low-Tc SQUID system,” *IEEE Trans. Appl. Supercond.*, vol. 21, pp. 456–460, 2011.
- [4] P. T. Vesanen et al., “Hybrid ultra-low-field MRI and magnetoencephalography system based on a commercial whole-head neuromagnetometer,” *Magn. Reson. Med.*, vol. 69, no. 6, pp. 1795–1804, 2013.
- [5] M. Espy et al., “Progress toward a deployable SQUID-based ultra-low field MRI system for anatomical imaging,” *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, 1601705, 2015.
- [6] M. Espy et al., “Ultra-low-field MRI for the detection of liquid explosives,” *Supercond. Sci. Technol.*, vol. 23, no. 3, 034023, 2010.
- [7] J. R. Sims et al., “Low-noise pulsed pre-polarization magnet systems for ultra-low field NMR,” *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp.752–755, 2010.
- [8] <http://www.supracon.com/en/sensors.html>
- [9] <http://www.starcryo.com/pcsquid.htm>

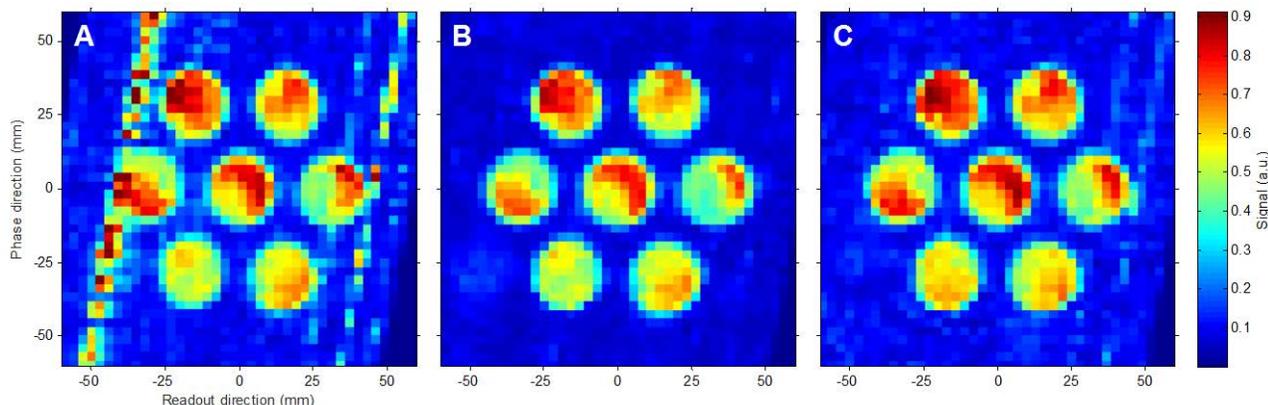


Fig. 3. 2D MRIs of seven vials of water. A) Data acquired without any noise cancellation. B) Noise cancellation in post-processing cancellation using the external magnetometer signal. C) Electronic noise cancellation using an external magnetometer. Images are single averages.