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Co-registration of MEG and ULF MRI using a 7 channel low-T_c SQUID system

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Abstract—

***Index Terms*—magnetoencephalography, microtesla, magnetic resonance imaging.**

I. INTRODUCTION

In human brain imaging, e.g. pre-surgical mapping, it is highly desired to obtain images with high spatial and temporal resolution. However, no single imaging device is capable of producing both a high spatial resolution anatomical image and a high temporal resolution functional image.

During the last couple of years significant efforts have been directed towards magnetic resonance imaging (MRI) in fields comparable to the Earth's field [1]-[11], i.e. microtesla fields, or lower fields. The fields in this range are called ultra-low fields (ULF). Interestingly, the idea of magnetic resonance at microtesla fields is more than 50 years old [12].

In ULF MR it is essential to use pre-polarization to increase the signal-to-noise ratio of the signal from the precessing spins, since the magnetization from the measurement field alone is very small. Even with the present level of pre-polarization the ULF images are not as highly resolved as their high-field counterparts.

By using a 7 channel system equipped with low transition temperature (T_c) Superconducting QUantum Interference Devices (SQUIDs) to perform both ULF MRI and magnetoencephalography (MEG; [13]), it is possible to co-register a lower resolution ULF MR image and an MEG image obtained during one run. Thereby, the MEG data is aligned to the ULF MR image after performing a calibration run with a phantom. The ULF MR image can then be used to align the MEG data onto a high-field MR image.

Recently, our group presented the first brain images obtained by ULF MRI [6]. The MR imaging was combined with an MEG session performed a posteriori. The subject's head was moved in between the MRI run and the MEG run and no reference coils were used to quantify the translation. The main reason for the translation of the head was to improve the coverage of the auditory evoked response.

In this paper, we report interleaved ULF MRI and MEG measurements co-registered in the same system.

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II. EXPERIMENTAL

The ULF MRI/MEG system used here is described in detail in, e.g., [5]. In brief, it consists of a helium cryostat with seven wire-wound 2nd order gradiometers, which are coupled to CE2Blue SQUIDs [14] through circuits with SW1 cryo-switches [14]. The gradiometers have a diameter of 37 mm, a baseline of 60 mm, and are positioned with a 45 mm spacing in a hexagonal pattern around one in the center. The corresponding magnetic flux density noise of the gradiometers are 1.2-2.8 $\mathrm{fT/Hz^{1/2}}$.

The MRI fields were generated by copper coils powered by car batteries for low noise performance. A 3D Fourier imaging protocol was used (see Fig. 1) with frequency encoding, $G_x = dB_z/dx = \pm 150\ \mu T/m$, phase encoding, $|G_z| = |dB_z/dz| \leq 140\ \mu T/m$ (51 encoding steps) and $|G_y| = |dB_z/dy| \leq 66\ \mu T/m$ (9 encoding steps). The resulting voxel size was $3 \times 3 \times 6\ mm^3$. The encoding time was 28 ms and the acquisition time was 56 ms.

The pre-polarization coils were cooled by liquid nitrogen. The pre-polarization field, B_p, was ~30 mT field. To provide insulation for the subject NanoPore [15] vacuum insulated panels were used in addition to cellfoam panels.

The measurement field, Bm, was 94 μT which corresponds to a Larmor frequency of 4 kHz.

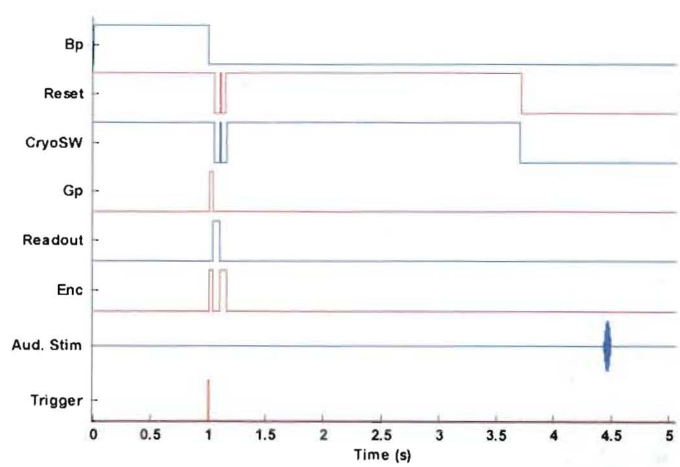

Fig. 1. Pulse sequence for the ULF-MRI and MEG co-registration showing the timing of the pre-polarization, the MR imaging protocol, and the auditory stimulus.

The auditory stimulus consisted of a 68 ms long, one-lobe sinc pulse with a 2 kHz frequency. The wait time, t_{wait}, in between the last step of the MRI protocol and the beginning of the auditory stimulus was 3.3 s. The SQUIDs were turned on 0.7 s before the on-set of the stimulus.

The pulse sequence provides one MEG epoch for each *k*-space point. In the imaging protocol there were 51×9 = 459 points.

These experiments were approved by the Los Alamos Institutional Review Board and informed consent was obtained from the involved subject.

III. Results

We have measured interleaved ULF-MRI and MEG in our 7 channel low-T_c SQUID system. The results are reported below.

A. Coordinate systems calibration

A phantom with water vials and small coils attached to each vial was used to investigate the transformation between the MEG and MRI coordinate systems. The vials were placed at different heights and with different distances in-between each other.

Fig. with calibration

B. Magnetoencephalography

The MEG epochs without steps in the data were averaged for each channel. Fig. 2 show the MEG data and the auditory stimulus. Peaks of different polarity are visible ~100 ms after the stimulus on-set. These peaks show the N100m response of the auditory cortex. The N100m peak values are shown as a field map on-top of the subject's head in Fig. 3.

By using the field map in Fig. 3 a dipole model of the auditory response is fitted to the MEG data, as shown in the bottom right panel of Fig. 4. The quality of the fit ...

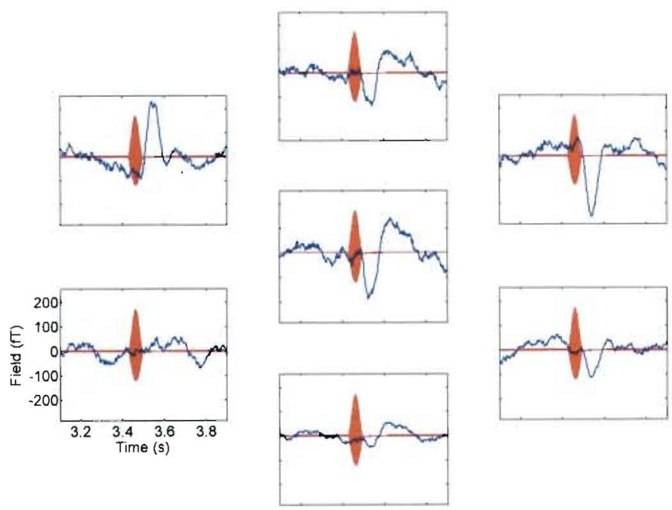

Fig. 2. MEG signals from the 7 channels with the auditory stimulus. The subfigures are arranged in the same arrangement as the channels in the system.

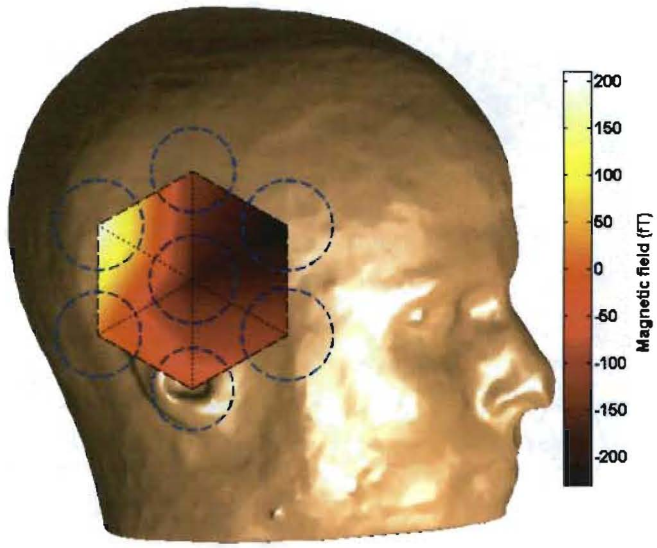

Fig. 3. Magnetic field map of the N100m response (peaks at 100 ms after stimulus on-set in Fig. 2) overlaid on the subject's scalp.

C. Ultra-low field MRI

The resulting image slices are shown in Fig. 4. The total imaging time was ~XX min.

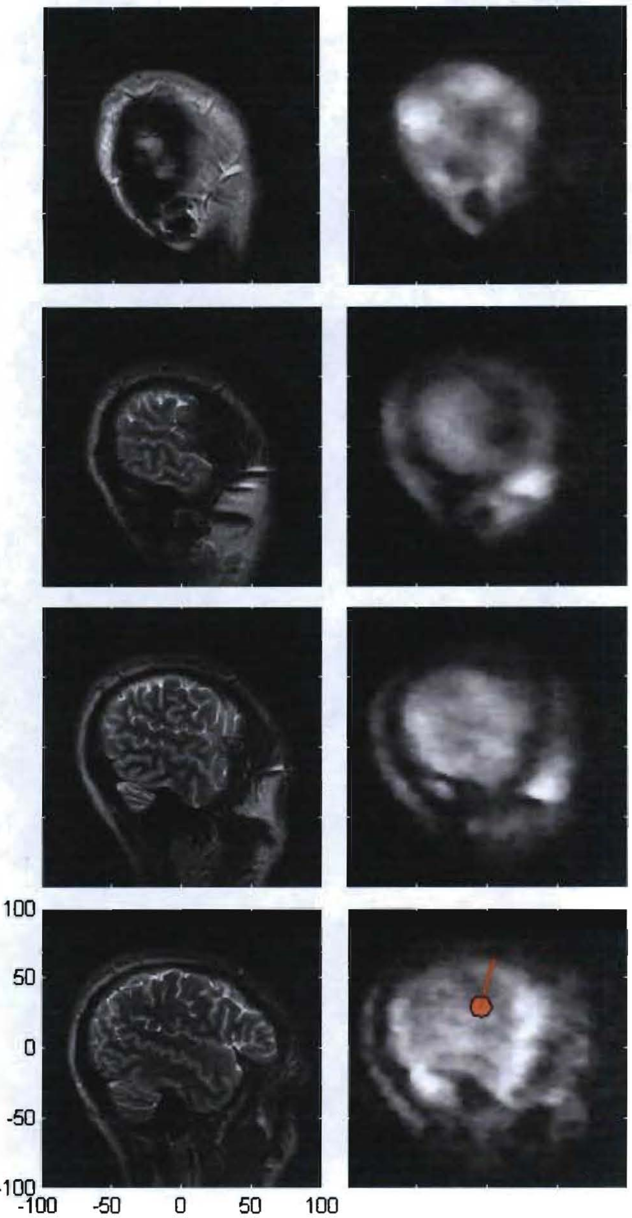

Fig. 4. High-field (left column) and ULF (right column) MR slices. The high-field slices were imaged in a 3 T system while the ULF slices were imaged at a 94 μT field.

IV. Discussion

Co-registration
Resolution, 3
Imaging time - transients

A. Transients

from the walls of the MSR [16]

Magnetic fields from magnetization of the MSR and eddy-currents in the μ-metal dominate [16]

However, the time constant in the μ-metal layer is <1 ms while it is ~1 s for the aluminum [16].

Reduce waiting time (imaging time).

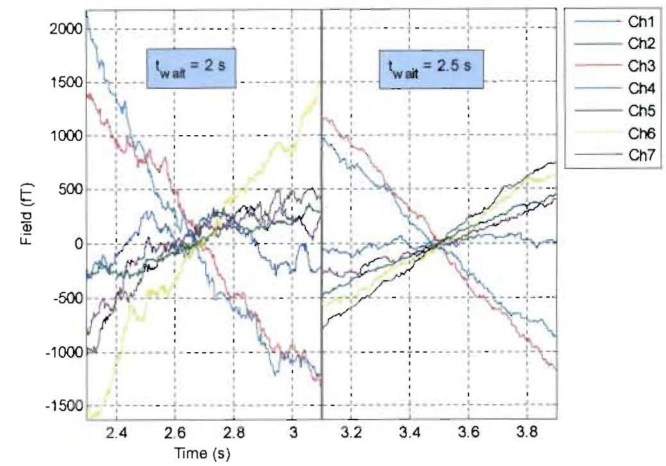

Fig. 5. SQUID signals after different waiting times after the MRI pulses.

B. Co-registration error

In multi-modal imaging there have been reports of co-registration error as small as 1-2 mm [17]. In our system we observed a co-registration error of ~X mm. With the present resolution of the ULF MRI one needs to rely on ...

V. Conclusion

first co-registered ULF MRI and MEG, proof of principle, multi-channel, whole-head system

Acknowledgment

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