Real-time Noise Reduction: 4D Neuroimaging 2500WH System

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Abstract

The 2500WH MEG system by 4D Neuroimaging has magnetometer detectors that rely on real-time noise reduction in addition to shielding of a magnetically shielded room. Theoretically, the set of reference magnetometers and gradiometers, distant from the recording array, are sufficient to remove environmental noise through first order spatial variation within the shielded room. However, in magnetically shielded rooms, environmental magnetic fields in the center of the room are minimized while high order spatial variations are increased. The proportion of the high order field components that are remove from the MEG data depends on the correlation of the high order components with the low order components as well as the configuration of the active noise reduction system. In addition to reducing environmental noise, the real-time noise reduction hardware/software introduces noise into MEG signals. The actual performance of the noise reduction system depends on operational characteristics of the hardware/software as well as environmental noise characteristic of the MEG installation site. We examined the procedures used to calculate reference channel weight factors. Second, we assessed the performance characteristics of the noise reduction hardware/software including input-output response characteristics. Third, we consider briefly the implication of the noise reduction performance on the MEG data for typical MEG applications, (signal averaged evoked responses, epileptic spike activity, and power spectral analysis).

Introduction

The active noise reduction system employed in the Model 2500WH Neuromagnetometer system, (4D Neuroimaging), is implemented as a two stage filter [1]. The first stage filtering, (analog fixed weight filtering), is performed before high pass filtering, signal amplification and analog to digital conversion. The purpose of this stage is to remove sufficient high amplitude noise to keep the detector signals within the dynamic range of the A/D converter. This stage removes the majority of the high amplitude low frequency environmental noise components that dominate the noise spectrum in a magnetically shielded room. In this analog filtering stage, a weighted combination of three orthogonal magnetometer reference coils measuring nearby environmental noise is subtracted from the signal of each measurement magnetometer.

The second stage of the filtering, (digital fixed weight filtering), occurs after all the electronic gain stages and analog to digital conversion. This stage, utilizes the noise data from the three reference magnetometers and a set of five reference gradiometers. However, the large dynamic range of the reference magnetometer data requires analog to digital conversion at two different sensitivities. Thus, the signal of each reference magnetometer is split into two data streams. One is digitized with a very low sensitivity and adequately quantifies very large amplitude environmental noise. However, low amplitude environmental noise components in the signal introduce A/D bit noise in this data stream. The second data stream is 1.0 Hz high pass filtered to remove the low frequency high amplitude noise. This data is digitized with sufficient sensitivity to avoid significant bit noise. Thus, a fixed weighted combination of these eleven environmental noise reference channels is used to quantify environmental noise remaining in the MEG detector channel data.

Theoretically, a fixed weighted combination of three reference magnetometers and five gradiometer signals is sufficient to eliminate environmental noise when high amplitude second order spatial gradients of the noise field are absent. Unfortunately, in magnetically shielded rooms, second order spatial gradients are increased relative to outside the room. Therefore, an optimal set of noise reduction weights are obtained when derived from MEG and reference channel data containing environmental noise representative of the recording site. However, if the amplitude of the environmental noise is not sufficiently high, the low gain reference channel data will be primarily bit noise and not adequately represent the reference magnetometer signal. In this case, a magnet is moved and oscillated around the magnetic shielded room to create and artificial large amplitude reference signal. The reference channel filter weights produced by this technique will be adequate for obtaining useful MEG data. However, these noise reduction weights not optimal for removing real environmental noise.

Further, the performance of this fixed weight noise reduction system is affected by electronic noise included in the reference channel data. In the limit where the amplitude of the environmental signal is zero, this filtering technique adds electronic noise from the reference channels to the MEG signal channels such that noise is increased. In our study, high frequency noise was often added to the MEG data in the digital noise reduction stage even when environmental noise is present.

The analog stage of the filter is described by the equation:

$$B_{analog} + N_a = (B_s + N_s) - W_m (R_m + N_m) \qquad (1)$$

B_{analog} is the m channels by n time points array of analog filtered MEG data with most high amplitude environmental noise removed. B_s is the m channels by n time points array of acquired MEG data containing environmental noise. R_m is the 3 channels by n time points array of reference magnetometer environmental noise data. In this equation, the electronic noise components of the raw MEG signal, the reference magnetometers and the filter output are represented as separate terms, N_a , N_s and N_m. W_m is the fixed weight noise reduction matrix.

The digital stage is represented by a similar equation:

$$B_{digital} + N_d = (B_{analog} + N_a) - W_d(R_d + N_d) \qquad (2)$$

B_d is the m channels by n time points array of MEG data containing environmental noise. R_d is the 3 channels by n time points array of reference magnetometer environmental noise data. N_d is the electronic noise component of the filtered data which includes noise from the reference channels introduced by both stages of the filtering. W_d is the digital fixed weight matrix.

The filtering properties of any linear filtering system can represented by a frequency response function in the frequency domain. $H(f)$ is the filter frequency response at frequency, f, and $|H(f)^2|$ = Power spectrum of filter output divided by the power spectrum of the filter input data [2]. Thus, the amplification or attenuation of the filter can be quantified for each component of the data. Neither the analog nor the digital filtering stages are linear. However, $|H(f)^2|$ is very useful for quantifying the performance of this noise reduction system If environmental noise is absent or low amplitude in both the signal and reference channels, uncorrelated electronic reference channel noise will be added to the signal channels and $|H(f)^2|$ will be greater than one at each frequency, (increased output signal noise).

For the digital filtering stage, $|H(f)^2|$ was calculated for noise reduction weights optimized for a specific set of environmental artifacts as well as for noise reduction optimized to the artificial magnetic noise. The frequency response of the system was determined for noise sources that changed location and frequency as well as a noise source with a fixed location and frequency. Also, $|H(f)^2|$ is a function of the high pass filter because the digital noise reduction occurs after the high pass filter has been applied to the MEG signal channels, (not to the reference channels). For the analog filtering stage $|H(f)^2|$ was estimated because it is not possible to exactly determine the analog magnetometer signals from the recorded low sensitivity reference magnetometer data. $|H(f)^2|$ was estimated using separate epochs of MEG data recorded with and without analog filtering.

Methods

Three environmental noise conditions were investigated. The first condition consisted of low amplitude environmental noise characteristic of evening and weekend studies at our laboratory. Second, wide spectrum noise, was generated by rotating a magnet outside the shielded room with a variable speed motor. During data collection the position of the magnet was moved around the room. In addition, the speed of magnet rotation (0.5 to approximately 40 Hz) was randomly changed. The third environmental noise condition consisted of rotating the magnet at a fixed position one meter away from the door of the shielded room at a fixed frequency. Four rotational frequencies were tested, (0.7Hz, 5Hz, 11Hz and 16 Hz).

Noise cancellation filter weights were calculated using data generated by the artificial magnetic artifact technique or based on variable frequency noise generated at 5 locations around the shielded room. One of these locations was the test site for the fixed noise source study. Thus, the second set of fixed filter weights were optimized for the specific environmental noise source.

For each test condition, thirty seconds of MEG data and reference channel data were acquired and digitized at 678 Hz and a 200 Hz band pass window. Separate runs were performed with all combinations of high pass filter settings, (DC, 0.01Hz, 1.0Hz) and with fixed weight filtering options, (no weights, analog only, analog and digital).

Digital filter noise cancellation, (Equation 2), was applied to runs that were analog filtered only. Power Spectra of the input analog filtered MEG data and the output analog plus digital filtered MEG data were calculated (1024 sample FFT). A channel average frequency response was constructed from average MEG channel power spectra determined separately for before and after noise reduction.

Data were processed using our MEG data analysis and imaging software [3].

Results

The frequency response amplitude, $|H(f)^2|$, of the analog fixed weight noise reduction stage was estimated from MEG data with DC high pass filter settings and 4 different environmental noise conditions. The average of the separate estimates is shown in Figure 1. The individual estimates were similar to the average result.

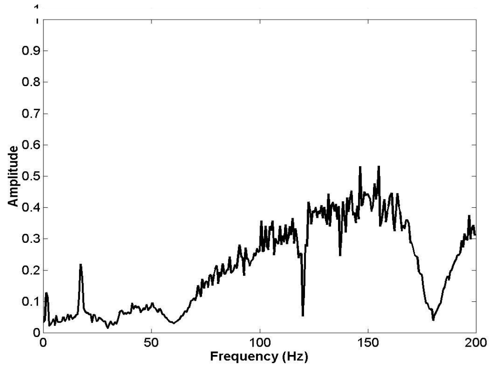

Figure 1: Estimate of the analog filter frequency response, $|H(f)^2|$

The frequency response of the analog filter has good attenuation for low frequency noise as well as 60 Hz and higher harmonics. The loss of effectiveness at high frequency is likely due to high frequency electronic noise in the reference data.

The frequency response of the digital noise reduction stage was directly calculated. In figure 2, the frequency response is shown for 0.01 high pass filtered data with a moving variable frequency noise source.

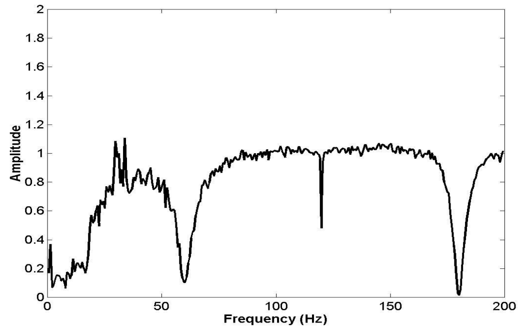

Figure 2: Filter frequency response, $|H(f)^2|$, with a moving variable frequency noise source.

The noise reduction filter used to generate Figures 1 and 2 was constructed using the artificial noise technique. However, in figure 3, the noise reduction weights were optimized to remove noise from 5 sites including the site of the environmental noise. In this figure, the frequency response attenuation of noise at 5 Hz averaged 0.01 across the MEG channels. The environmental noise attenuation of the optimum filter is compared to the previous general noise reduction filter in the following table.

Frequency (Hz)	0.7	5	11	16
Optimum Filter Attenuation	0.27	0.01	0.02	0.03
General Filter Attenuation	0.66	0.83	0.58	1.13

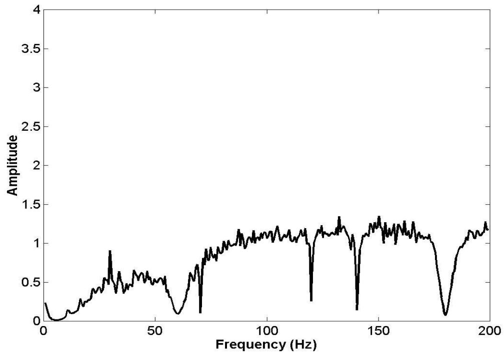

Figure 3: The calculated digital filter frequency response, $|H(f)^2|$, with optimal filter weights.

Discussion

These results demonstrate that that the fixed weight noise reduction system employed in the model 2500 WH Neuromagnetometer system has a complex frequency response that depends on many factors. In general, both stages of the noise reduction system substantially attenuate noise at frequencies below 50 Hz. However, the digital noise reduction filter can add electronic noise to the MEG data usually at frequencies above 20 Hz. Thus, MEG studies that involve analysis and comparison of frequency spectra may be compromised by spectral distortion. Examination of the noise reduction frequency response and the power spectrum of the removed signal can be used to assess the amount of spectral distortion. In the time domain, inclusion of high frequency noise and residual environmental artifact are usually not a significant problem. This type of signal distortion is attenuated in evoked response studies with signal averaging. Also, it is insignificant in evaluation of large amplitude epileptic spike activity.

Finally, this frequency response analysis applies only to the components of the MEG signal that involve environmental artifact and electronic noise. Equations 1 and 2 do not contain the components of the MEG data that emanate from the subject.

Acknowledgements

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Literature

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[3] MEG Tools for Matlab, available at: http://rambutan/phy.oakland.edu/~meg