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AUTHOR(S) Paul S. Lewis

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ADAPTIVE ENHANCEMENT OF MAGNETOENCEPHALOGRAPHIC SIGNALS VIA MULTICHANNEL FILTERING

Paul S. Lewis
Los Alamos National Laboratory*
Mechanical and Electronic Engineering
MS J580, Los Alamos, NM, 87545, U.S.A.

Abstract

A time-varying spatial/temporal filter for enhancing multichannel magnetoencephalographic (MEG) recordings of evoked responses is described. This filter is based on projections derived from a combination of measured data and *a priori* models of the expected response. It produces estimates of the evoked fields in single trial measurements. These estimates can reduce the need for signal averaging in some situations. The filter uses the *a priori* model information to enhance responses where they exist, but avoids creating responses that do not exist. Examples are included of the filter's application to both MEG single trial data containing an auditory evoked field and control data with no evoked field.

1 Introduction

In magnetoencephalography (MEG), the magnetic fields produced by the electrical activity of the brain are measured on the surface of the head. In contrast, electroencephalography (EEG) measures the potentials produced by this activity. MEG is used extensively in the study of evoked neuromagnetic fields. These fields are produced by the brain's involuntary responses to simple stimuli, such as tones or light patterns. In evoked field (EF) studies, a controlled set of stimuli are presented to the subject and the magnetic field of the response is measured at a number of locations. This is not an easy task, as EFs are quite weak, ranging from 10 to 10^3 femtotesla (fT) [1]. To measure these weak fields, multichannel sensors, based on superconducting quantum interference devices (SQUIDs), are used.

In EF measurements, noise and interference from a number of sources must be overcome. One source of interference is external magnetic fields, which can be of the order of 10^8 to 10^9 fT for urban background noise and $7 \cdot 10^{10}$ fT for the earth's steady field [1]. Interference from external fields can be effectively eliminated by taking measurements in a magnetically shielded room and using SQUID sensors wired as second order gradiometers [2].

More difficult sources of noise and interference are neural background activity and intrinsic sensor noise. Neural background activity is unrelated to the stimuli and can produce temporally and spatially correlated fields of 10^2 to 10^3 fT. Intrinsic sensor noise is essentially white over the measurement band and uncorrelated from channel to channel. The magnitude of this noise depends on the particular sensor, but is of the order of 20 fT/$\sqrt{\text{Hz}}$, or about a 140 fT standard deviation for a 50 Hz band. Because of the presence of intrinsic sensor noise and neural background activity, the signal-to-noise (SNR) ratio of EF measurements is quite poor, ranging from 0 to −20 dB and worse.

To overcome the poor SNR and permit EFs to be measured, signal averaging of a number (~ 25–1000) of distinct trials is generally employed. In the ideal case, where from trial to trial the signal replicates exactly and the noise is uncorrelated, averaging of N trials improves the SNR by a factor of $\sqrt{N}$. Although signal averaging is the predominant technique used in MEG, it suffers from several drawbacks. From a practical point of view, averaging requires a large number of trials to obtain a single EF measurement. From a theoretical point of view, the brain's response varies from trial to trial and averaging does not allow this variation to be observed.

2 Single Trial Enhancement

This paper addresses the issue of improving the SNR of single trial EF measurements. Although this area has not been previously studied in the context of MEG signals, it has been addressed in the closely related realm of EEG evoked potentials (EP's) [3]. Most efforts have concentrated on single channel enhancement, in which the times series of each physical measurement location is processed independently. The predominant approach has been to approximate some sort of "Wiener-like" filter in either the time or frequency domain. All of these single channel "temporal" approaches basically rely on separating signal from noise based on frequency difference alone. For most EF and EP measurements, the signal and noise bands overlap considerably, thereby severely limiting the potential of a single channel approach. Because both EF and EP measurements are generally made with multiple recording channels, it is possible to use spatial information in enhancing single trial measurements. This has been proposed by one group in the context of EP measurements [4], but their approach is quite involved and requires many stringent assumptions about the nature of both the signal and noise.

This paper presents a simple adaptive multichannel enhancement technique, based on linear projections, that utilizes both spatial and temporal information. As with all previously proposed techniques, it requires the *a priori* knowledge of the general shape of the underlying signals at

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each measurement point. In a clinical setting, this knowledge may come from previous measurements, in which case the technique can serve to both enhance the single trial measurements and reduce the overall number of trials necessary for signal averaging. In a research setting, this knowledge may come directly from an ensemble average. In this case the goal is not to reduce the number of trials to be averaged, but rather to perform an *a posteriori* estimate of the varying response in each trial.

Given that a set of model signals exist for each of the measurement channels, the crux of the enhancement problem is how to use this information in a manner that enhances evoked responses when they exist but does not create them where they do not exist. To satisfy this condition involves a tradeoff. Utilization of the model information involves forcing the measured data to take on some subset of the model's characteristics. If the subset is too small, no enhancement takes place. If the subset is too large, the model is just recreated, independent of any characteristics of the actual underlying signal. The approach outlined in the next two sections uses time-varying projection operations to selectively force the data to take on selected properties of the model, without totally constraining the output *a priori*.

3 Enhancement Via Spatial Projection

One method of using the model information to enhance the single trial measurements is force the sample-by-sample spatial distribution of the measurements to match that of the model. The effect is to use the spatial information of the model to enhance the temporal information of the measurements. Mathematically, this is accomplished by a linear projection. Denoting the n channel model and measurement signals by the n-dimensional vector time series s_t and y_t respectively, the result of spatial projection enhancement, x_t, can be expressed as 5

$$x_t = \frac{s_t s'_t}{s'_t s_t} y_t \tag{1}$$

Under ideal conditions, in which the spatial distributions of the underlying signal are the same as those of the model and the noise is distributed uniformly over all n dimensions, this approach yields an SNR improvement of $\sqrt{n}$.

An example of the application of this technique is illustrated in Figs. 1-5. The EF data used in this and following examples were collected at the MEG facility of the Los Alamos National Laboratory. The EFs are responses to an auditory stimulus recorded with a seven sensor SQUID system. Each of the seven sensors is configured as a second order gradiometer. The measurements were bandpass filtered to 1-50 Hz and digitized at a 500 Hz sample rate. Data were collected both with and without the stimulus present.

Figure 1 shows the seven model signals used. These were derived by low pass filtering (15 Hz) 100 trial averages. Figure 2 shows eight individual trials collected at channel 1, along with their average. No response is discernible in the individual trials, but a response at 100 ms is visible in their average. Figure 3 shows a control set of eight individual trials, along with their average. These trials were collected under the same conditions, except that no stimulus was provided to the subject. The individual trials are not noticeably different from those of Fig. 2, but no response is visible in the average.

A spatial projection filter was applied to both sets of signals, using the signal model of Fig. 1. Figure 4 shows the enhanced results for the data in which a stimulus was present. The signals are still noisy, but consistent responses are visible at 100 ms. Their average is cleaner than the corresponding average of the unfiltered signals. In contrast, Fig. 5 shows the results of the spatial projection filter applied to the control data. Here the variance of the individual trials has been reduced, but no clear temporal pattern is apparent in either the individual trials or their average. Hence this filter has enhanced the response where it exists, but has not "created" a response where it does not exist.

The enhancement shown in Fig. 4 is apparent, but not dramatic. This is to be expected. Because there are only seven measurement channels, the most SNR improvement that could be expected is a factor of $\sqrt{7} \approx 2.6$ or 8.5 dB. The SNR of the data is approximately 0 dB for the initial large peak (at 100 ms) and approximately -10 dB for the later peaks. One way to increase the enhancement is to use SQUID arrays with a larger number of channels. This approach may be feasible in the future, but seven-channel arrays are about the limit of currently available technology. In the next section, a method is presented for partially circumventing the channel limitation by utilizing some of the temporal pattern information of the model signals.

4 Enhancement Via Spatial and Temporal Projection

EFs are transient responses and are finite in duration. As a result, projection can also be applied along the temporal patterns. Define the tn-dimensional "stacked" vectors

$$S_t = \begin{bmatrix} s_t \\ \vdots \\ s_1 \end{bmatrix}, \quad Y_t = \begin{bmatrix} y_t \\ \vdots \\ y_1 \end{bmatrix}, \text{ and } X_t = \begin{bmatrix} x_t \\ \vdots \\ x_1 \end{bmatrix}. \tag{2}$$

For m time samples, a total spatial and temporal projection corresponds to

$$X_m = \frac{S_m S'_m}{S'_m S_m} Y_m \tag{3}$$

In theory, this total spatial and temporal projection should increase the SNR by $\sqrt{mn}$. However, in reality the overconstraint problem discussed in Section 2 appears. This total spatial and temporal projection forces the measurements to assume both the spatial and temporal shape of the model, leaving no degrees of freedom to account for any variation between the underlying signal and the model. This is apparent because the result of this projection is always a scaled version of the original model. Hence the enhancement has been constrained to the point at which it produces no new information.

To allow use of temporal pattern information, yet avoid complete *a priori* specification of the underlying signal, windowing can be employed. The function of a window is to limit the influence of the temporal portion of the projection to a local neighborhood. There is a basic tradeoff between the enhancement obtained, which increases with window size, and the flexibility of the final estimate, which decreases with window size. At one extreme is the total spatial and temporal projection, whereas at the other is the spatial projection discussed in the previous section.

Many types of windows can be employed. Some of the variable factors are whether the window is one sided or two sided, and whether it is finite or not. Experiments have been conducted at Los Alamos with a filter employing an infinite one-sided exponential decay window. This window was picked because it is causal and easily implemented. With this window, the enhancement at each time sample is obtained from an exponentially weighted projection over the current and previous time samples. This windowed projection is defined by

$$\chi_t = \frac{S_t S'_t \Lambda_t}{S'_t \Lambda_t S_t} y_t , \tag{4}$$

where $\Lambda_t = \mathrm{diag}\{\lambda^0 \mathbf{I}\ \lambda^1 \mathbf{I} \cdots \lambda^{t-1} \mathbf{I}\}$ is a $tn \times tn$ block diagonal matrix and $0 < \lambda < 1$. The enhanced signal at t is then taken from the first n rows of χ_t. This enhancement can be defined recursively as

$$x_t = s_t \frac{\sum_{i=1}^{t} \lambda^{t-i} s'_i y_i}{\sum_{i=1}^{t} \lambda^{t-i} s'_i s_i} . \tag{5}$$

The exponential parameter λ controls the effective size of the window and consequently the tradeoff between enhancement and solution constraint. Note that for $\lambda = 0$, (5) simplifies to the spatial projection (1) of Section 3.

Figure 6 shows the result of this windowed spatial temporal projection filter applied to the EF data of Fig. 2. A value of $\lambda = 0.84$ was used. An evoked response at 100 ms is clearly visible in all of the single trials and the average signal is much less noisy than in the previous examples. Figure 7 shows the results of this same filter applied to the control data of Fig. 3. Here no consistent response is seen in the individual trials and no response is evident in the average. This example demonstrates that careful use of temporal information can improve the basic spatial projection filter without overly constraining the solution and creating responses where none exist.

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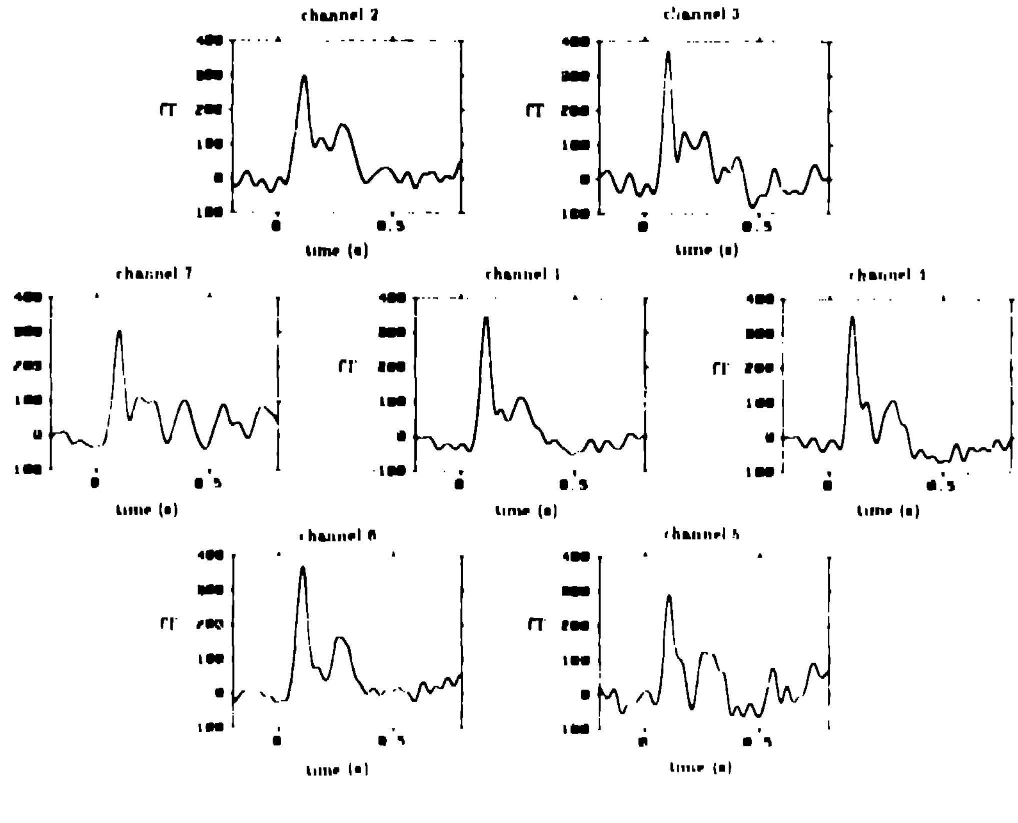

Fig. 1. *Model signals for the seven channels. Time 0 is stimulus onset.*

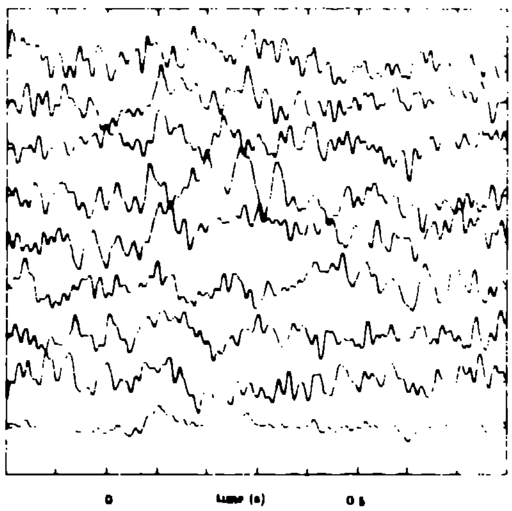

Fig. 2. *Data containing auditory EFs. The upper eight curves are single trial measurements from channel 1. The bottom curve is their average.*

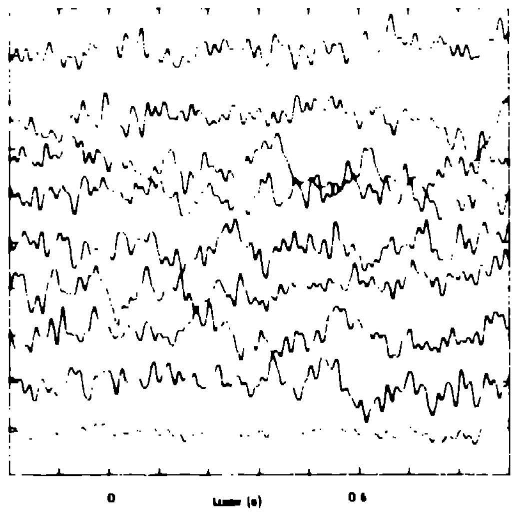

Fig. 3. *Control data without EFs. The upper eight curves are single trial measurements from channel 1. The bottom curve is their average.*

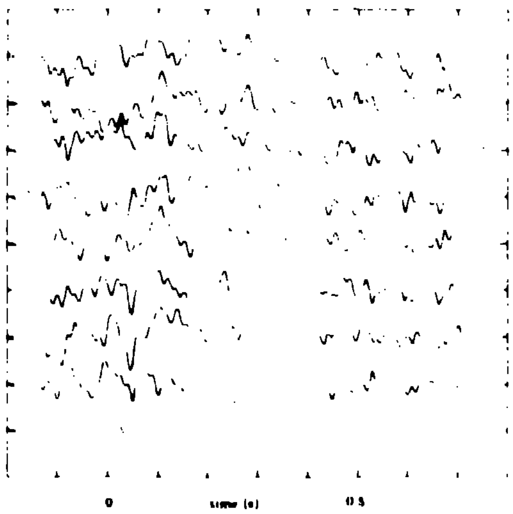

Fig. 4. *Spatial projection filtering of the EF data.*

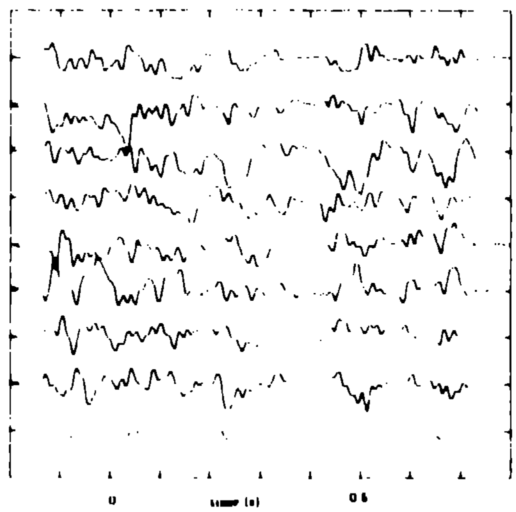

Fig. 5. *Spatial projection filtering of the control data.*

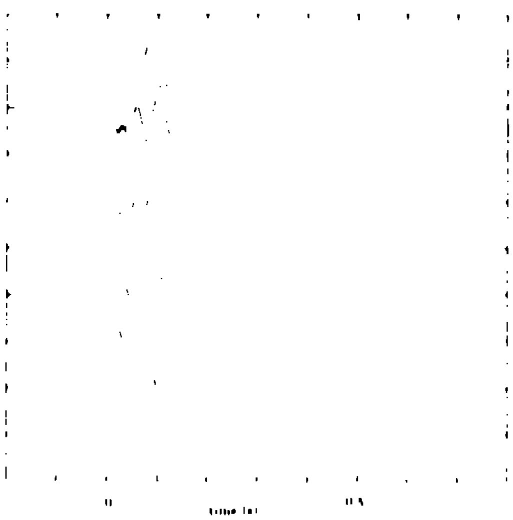

Fig. 6. *Spatial and temporal projection filtering of the EF data for λ = 0.84*

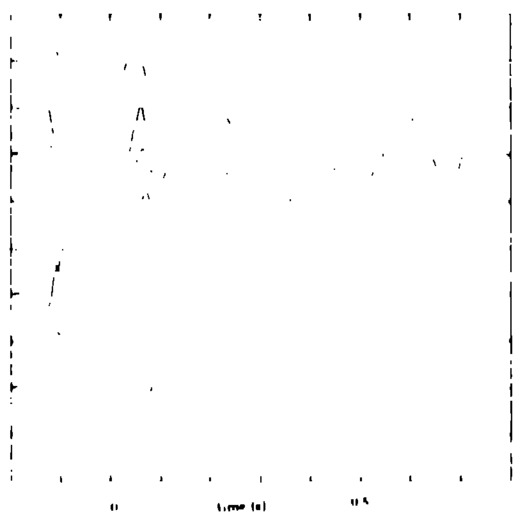

Fig. 7. *Spatial and temporal projection filtering of the control data for λ = 0.84*