Synthetic Gradiometer Systems for MEG

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***Abstract*--This paper will describe features and performance of low-Tc whole-cortex MEG systems which utilise synthetic gradiometers to achieve a high level of environmental noise cancellation (MEG = magneto-encephalography). The near field MEG sensitivities achieved through use of synthetic gradiometers typically range from 3 to 7 fT/√Hz above 1 Hz in moderately shielded rooms and less than 10 fT/√Hz above a few Hz in open environments. This performance has been observed for fixed vertical and also adjustable MEG systems which can tilt between vertical and horizontal orientations.**

I. INTRODUCTION

SQUID-based systems for neuromagnetic measurements have evolved over the past decade from systems with relatively few channels to sophisticated, multi-channel instruments containing >100 SQUIDs coupled to digital electronics and powerful signal processing software [1]-[4]. For example, over the past 6 years, there have been installed world-wide at least 35 whole cortex instruments for MEG i.e. for monitoring the weak magnetic signals generated by electrical activity in the human cortex. These MEG systems represent the largest application area of low-Tc SQUIDs with an installed base of at least 5,000 SQUID sensors.

In 1992 [3], CTF introduced a 64-channel whole cortex MEG system based on radial 1st order gradiometer sensors with formation of higher order (2nd and 3rd) gradiometer response in software using a set of reference channels. This noise cancellation concept is now termed synthetic gradiometry and it can provide very good signal to noise (S/N) for MEG sources even when the MEG system is operated in open (unshielded) environments, provided the magnetic background does not exceed system slew rate limits. These synthetic gradiometer systems for MEG have evolved from 64 channels (64-site) to the present 151-channel (151-site), adjustable orientation version, suitable for MEG measurements on subjects in seated, reclining or supine positions [5]. In what follows, the basic principles of synthetic gradiometers will be briefly reviewed, including typical system characteristics and results of the noise cancellation operation at various sites. To illustrate the performance, examples of MEG measurements will be presented.

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II. SYNTHETIC GRADIOMETERS

A. Basic Principles

Synthetic gradiometers consist of primary and refererence sensing coil(s), each connected to its own SQUID sensor. The signals from the primary sensors are combined with the reference signals in software or firmware using suitable weighting coefficients to form gradiometers of the desired order [6]. Schematic examples of synthetic noise cancellation systems are shown in Fig.1 based on (a) magnetometers, (b) planar and (c) radial hardware 1st order gradiometers. The outputs of the noise cancellation process may be written in terms of the primary sensor output σ and N reference outputs r_i, i = 1,..N:

$$s = \sigma - \sum_{i=1}^{N} \xi_i r_i \qquad (1)$$

where ξ_i are the weighting coefficients for the gradiometer order desired. The weighting coefficients can be determined to yield noise cancellation with different characteristics [6] e.g. they can be determined adaptively, or can represent gradiometer systems, etc. If the coefficients are constructed to represent higher order synthetic gradiometers, then they are projected to be independent of time, dewar orientation, and the site noise characteristics, features found in practice. On the other hand, the coefficients determined adaptively depend on the character of the environmental noise and must be re-evaluated whenever the latter changes. However, for fixed-orientation MEG systems and fixed-geometry interference sources, the adaptive approach can be quite effective [6].

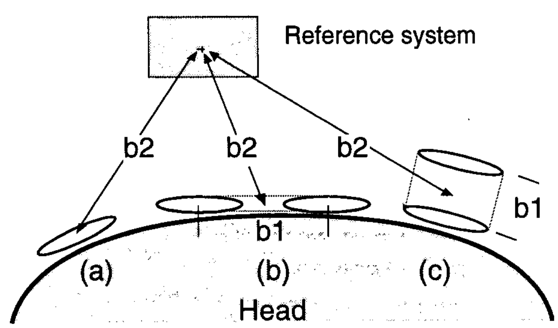

Fig.1. Synthetic noise cancellation systems based on (a) magnetometers (b) planar 1st order gradiometers (c) radial 1st order gradiometers. The reference system may consist of magnetometers and tensor gradiometers etc depending on the synthetic gradiometer order desired. Here b_1 represents the primary sensor baseline and b_2 the secondary baseline between primary sensor and reference system.

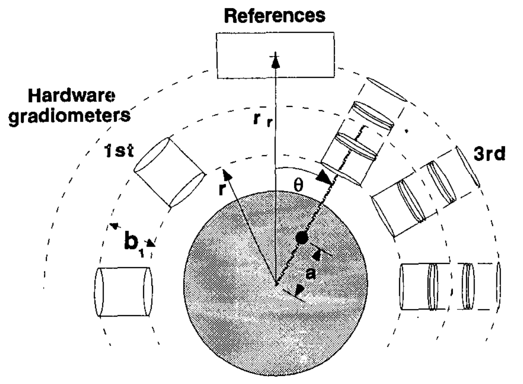

Fig. 2: Geometry for hardware and synthetic gradiometer simulations. All hardware radial gradiometers are positioned with the inner coil at radius r. The 3rd order hardware gradiometers have total length equal to the r_r -r where r_r is the radial distance to the reference centre. The dipole is positioned distance 'a' from the centre of the conducting sphere.

B. Synthetic Gradiometer Properties

Prior to the synthetic approach, all gradiometers were of the hardware type [7], [8] some of whose properties are often mistakenly attributed to the synthetic gradiometers. From the MEG viewpoint, there are however, several major differences between hardware and synthetic gradiometers [9]:

(i) Hardware gradiometers have all coils connected in series to the same SQUID sensor and can significantly reduce the detected brain signal, especially if the baselines are short. On the other hand, synthetic gradiometers behave quite differently and depending on the system design and detection configuration, may either decrease or increase the detected brain signal.

(ii) The change of signal amplitude detected by synthetic gradiometers is smaller than the signal reduction by hardware gradiometers of the same order.

(iii) Since synthetic gradiometers significantly reduce the environmental noise, but have only a small effect on the detected signal, the S/N ratio is improved and as a result, the accuracy of the source analysis.

(iv) Many primary sensors can be serviced by a single reference system and the concept has proven fruitful in designing compact, low-noise multi-channel MEG systems.

A correct forward solution for the primary sensors must include the reference forward solutions and their respective coefficients. Thus, synthetic gradiometers introduce no errors into the inverse solution. To gain quantitative insight into the signal detection properties of synthetic gradiometers, extensive simulations and experiments have been carried out. Fig. 2 illustrates the modelling theme for some recently reported simulations [9]. The brain is represented by a conducting sphere and the proximal coils of the hardware gradiometers are positioned at radius r from the sphere centre. A current dipole is positioned at distance 'a' from the sphere centre and the dipolar fields are calculated [10]. The simulations confirmed properties (i) and (ii) above and are summarized in Fig. 3. Here the differences between synthetic 3rd order and hardware 1st order gradiometer signals are

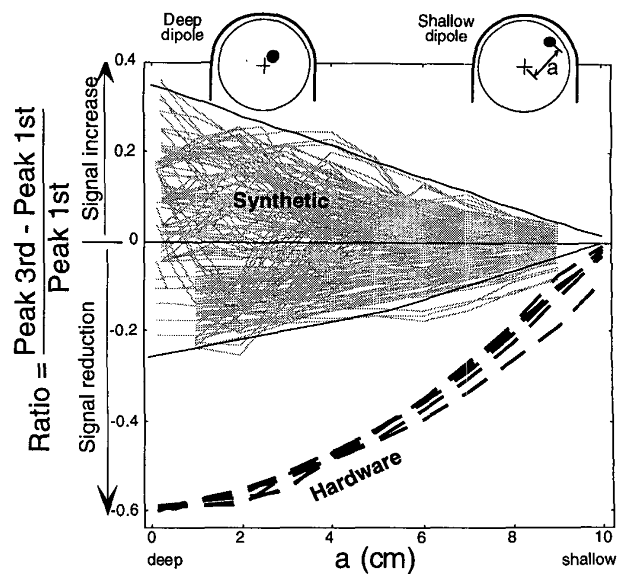

Fig 3: Relative peak signal magnitude change by synthetic and hardware 3rd-order gradiometers relative to hardware 1st order gradiometers with 5 cm baselines. The synthetic 3rd order gradiometers are based on CTF's 151 channel system.
Gray lines - synthetic 3rd-order gradiometer simulations for dipoles position at different distances from the model sphere centre 'a' along 17 different straight lines with origin at the sphere centre and distributed roughly uniformly in the upper hemisphere. For each position the dipole was oriented in 2 perpendicular directions and for each simulation, the 3rd-order gradiometers signals were synthesized using 6 different reference configurations (=198 different simulations).
Solid black lines - approximate envelope of 3rd order gradiometer simulations.
Dashed lines - simulations for the 3rd-order hardware gradiometers (1-3-3-1 coil configuration) and length = r_r-r (Fig. 2). To capture the peak signal, the hradware gradiometers were positioned in a plane passing through the dipole and perpendicular to it. Different lines correspond to dipole positions at θ = 0, $\pi/8$, $\pi/4$, $3\pi/8$, $\pi/2$, $5\pi/8$ where θ is the dipole position angle measured from the vertical.

normalized by the 1st order gradiometer signals, and are plotted as a function of the dipole distance 'a' from the sphere centre. These 3rd order gradiometer simulations roughly fill a symmetrical wedge (gray lines) about the zero position indicating that, depending on the orientation and position of the dipole and the reference configuration, the synthetic 3rd order gradiometer response can be either larger or smaller than the hardware 1st order gradiometer signal. On the other hand, the hardware 3rd order gradiometers always decrease the signal and for the hardware gradiometers with the illustrated geometry, this reduction (dashed lines in Fig.3) is at least a factor of 2 larger than the signal change (increase or decrease) due to the synthetic 3rd order gradiometers.

C. Baseline optimization

The radial 1st order gradiometer sensors in the whole cortex MEG systems have been designed for optimum S/N ratio relative to brain signals and environmental noise, by a suitable choice of their baseline lengths, b_1. The baseline optimization is a compromise between the magnitude of the detected brain signal and the detected environmental noise.

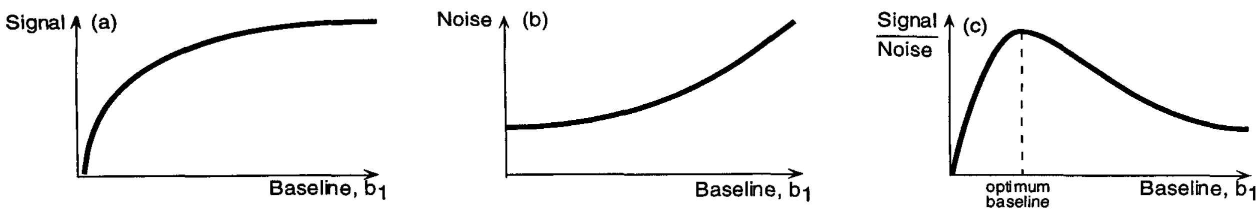

Fig.4. Baseline otimization for hardware 1st order gradiometers. (a) Dependence of signal strength on baseline; (b) dependence of measured (environmental) noise n_{rms} on baseline (2); (c) dependence of S/N ratio on baseline.

Both the brain signal and the detected noise will increase with baseline, but because of their different functional dependencies, the S/N ratio peaks at a certain "optimum" baseline. If the noise detected by the SQUID system consists of white instrumental noise and environmental low frequency noise, then the detected, integrated rms noise (n_{rms}) in a bandwidth Δf may be written as [11]:

$$n_{rms} = n_w \sqrt{\Delta f + \frac{f_1}{(2k-1)}\left(\frac{b_1}{b_o}\right)^2 \left(\frac{f_o}{f_1}\right)^{2k} \left(1-\left(\frac{f_1}{f_1+\Delta f}\right)^{2k-1}\right)} \quad (2)$$

where n_w = white noise spectral density (rms/$\sqrt{\text{Hz}}$), f_1 = frequency band lower limit, f_o = low frequency noise onset for baseline b_o. k is an exponent describing the behaviour of low frequency noise which may be written as: $n_{low} = n_w \cdot (b_l/b_o) \cdot (f_o/f)^k$. The detected brain signal is computed using a spherical, conducting medium model [10] and it is shown schematically together with the environmental noise (2) as functions of hardware baseline length in Figs. 4 (a), (b), and the resulting S/N ratio in Fig. 4(c). The region in the vicinity of the S/N ratio peak corresponds to the optimum sensor performance and the gradiometer baseline should be chosen close to the peak.

The dependence of the detected environmental noise on the gradiometer baseline was verified experimentally by constructing synthetic 1st order gradiometers with different baselines and measuring their noise as a function of baseline length, both within a shielded room and unshielded. As expected, the detected noise was found to be proportional to the baseline length. We have measured the noise within shielded rooms at various MEG sites and analysed the noise in order to compute the optimum baselines. In all cases, the optimum hardware baselines were found to be quite short, in the range 2 to 10 cm, depending on the observation frequency and the environmental noise magnitude. For most conditions, a radial 1st order gradiometer baseline of b_1 = 5 cm provided an optimum S/N ratio, and this value has been selected for the installed whole cortex MEG systems.

III. WHOLE CORTEX MEG SYSTEMS

A. System Description

All CTF whole cortex MEG systems so far have incorporated the synthetic gradiometer noise cancellation approach with radial 1st order gradiometer sensors. These primary sensors have 2 cm diameter coils and 5 cm baselines and are combined with 26-32 reference channels. The 64 and 143 channel systems were of fixed orientation suitable for seated subject measurements. Recently, several adjustable-orientation whole cortex systems with 151 channels have been installed in Europe [5]. These allow tilting of the sensor system from 15^o from vertical to fully horizontal (Fig. 5).

The DC SQUIDs [3] for the MEG systems are operated in analogue mode with the flux locked loop completed digitally [12], to ensure uniform transfer functions and synchronous timing across all channels. The flux-slipping technique [13] allows flux locked loop tracking over a 32 bit dynamic range, enabling the system to function effectively in unshielded environments. In its present configuration (Fig. 6), the system electronics allows up to 76 EEG channels, 16 A/D-D/A channels, 16 trigger channels, and sample rates up to 4000 samples/sec for a total of about 300 channels (sample rates can be higher for fewer channels). The electronics provides automated "set and forget" tuning for all SQUID and flux locked loop parameters, exhibiting high immunity to EMI and SQUID circuit fluxing. The Programmable Gate Array/Digital Signal Processor electronics system provides powerful signal processing capabilities including (a) real-time filtering, re-sampling and higher order gradiometer synthesis and (b) display and real-time execution of various functions such as FFT, covariance and its inverse and cross-power updates, coherence calculation, and spatial filtering.

B. Noise performance

The effectiveness of the synthetic gradiometer noise cancellation process for MEG systems has been validated at a number of sites, - within shielded rooms and also in non-shielded (urban/industrial) environments. The reference system

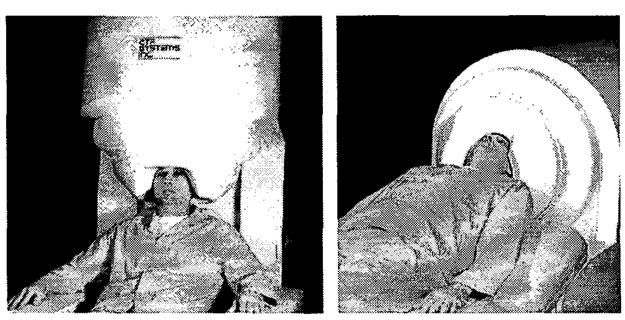

Fig 5. Photographs of adjustable whole cortex 151 channel MEG system. The system is designed to accommodate subjects in seated (left) reclining and supine positions (right).

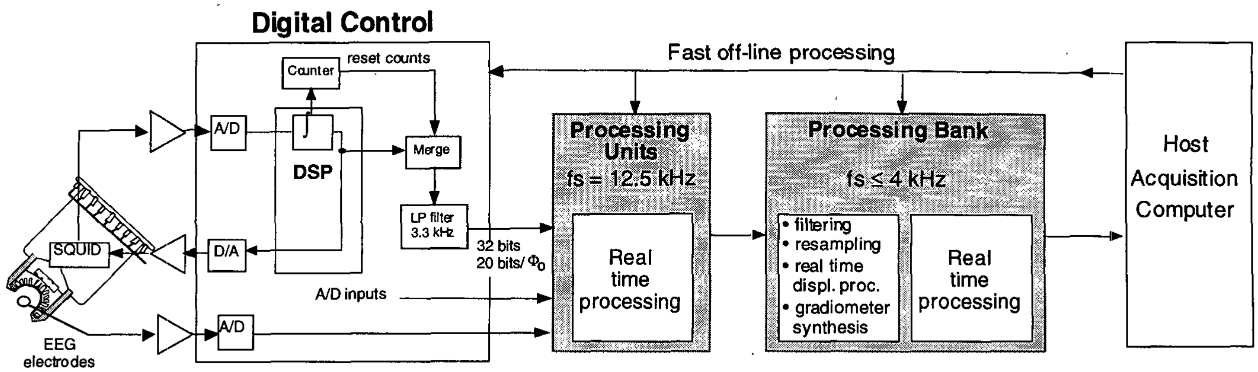

Fig.6. Block diagram of electronics system functions . The architecture provides control and real time processing for all MEG, EEG and A/D input channels as well as fast off-line processing for computationally intensive signal processing tasks. The flux slipping loop has 1Φo resets, a 32 bit dynamic range and a measured linearity of better than 1 part in 10^6. A total of about 300 channels can be accommodated at samples rates up to 4 kHz.

allows formation of 1st, 2nd and 3rd order gradiometers either in real time, or off-line after the data have been collected, since the reference and primary sensor data are recorded simultaneously. These procedures can significantly reduce the environmental noise fields and gradients which can be present in shielded rooms especially at low frequencies. Fig. 7(a) shows the measured noise of a 151-channel system inside a shielded room (Vacuumschmelze Ak3b) and provides a comparison of magnetometer, 1st order and 3rd order gradiometer modes at low frequencies < 10 Hz [5]. Rms noise levels averaged over all channels are also shown for 1st and 3rd order gradient formation and this is 2, and 3 to 4 orders of magnitude respectively below the magnetometer noise for frequencies ≤ 0.5 Hz. The synthetic noise cancellation for 3rd order gradiometer formation is estimated to provide a noise attenuation factor of ≈ 10^4. Combined with a low frequency room attenuation of ≈ 50, the total noise attenuation factor in 3rd order gradiometer mode inside the shielded rooms is estimated to be ≈ $5x10^5$. Fig. 7(b) provides a white noise histogram for the 151 channels (estimated from data in the frequency range 4 - 6.5 Hz), showing that most sensors in 1st and 3rd order gradiometer synthetic modes have noise in the range 4 - 5 fT rms/√Hz and 87% have noise ≤ 6 fT rms/√Hz. The strong similarity between 1st and 3rd order gradiometer histograms indicates the synthetic processing to the higher gradient order leaves the white noise unaffected, but provides a dramatic improvement for low frequencies less than a few Hz.

The noise performances of three adjustable 151-channel systems and a fixed vertical 143-channel system are compared in Fig. 8 (day-time measurements,[5]). All data were acquired inside shielded rooms and only the rms averages for magnetometer and 3rd gradiometer channels are shown. The following features are evident:

• the bare magnetometer noise performance inside the rooms precludes their use as primary MEG sensors;

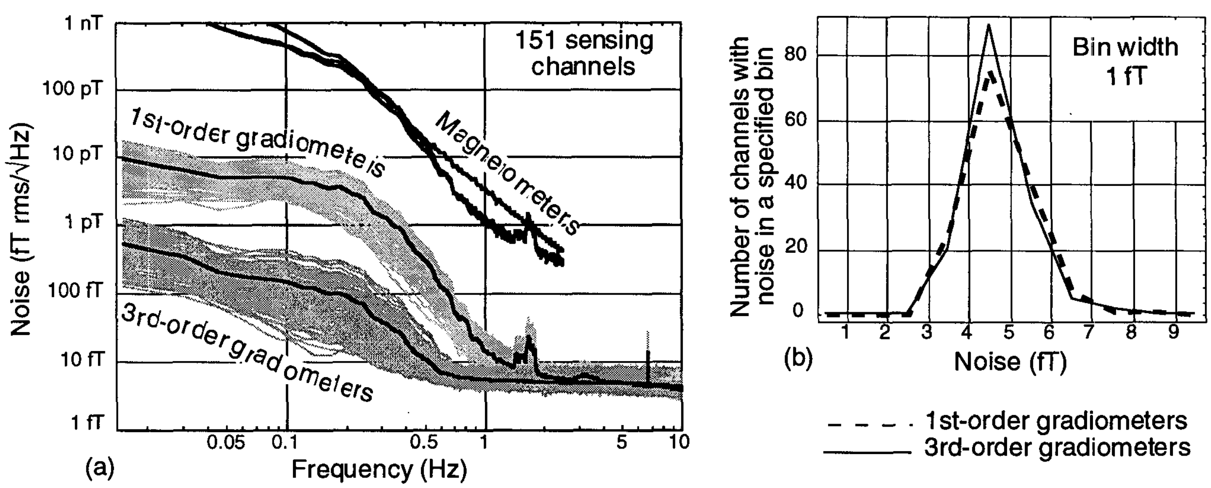

Fig. 7. Noise performance of an adjustable , 151 channel MEG system inside a shielded room (Amsterdam site). Sample rate = 62.5 Hz, points/trial = 4096, number of trials = 100, bandwidth = DC to 15 Hz. (a) Noise vs frequency for magnetometers (3 orthogonal components), hardware 1st- and synthetic-3rd order gradiometers. All 151 traces for 1st order and 3rd order gradiometers are shown in gray, and the rms averages for each as embedded black lines. The line at about 7 Hz is only present in the 1st gradiometer spectra and is eliminated in 3rd order gradiometer mode as are the small heaps 1.5 and 3 Hz. (b) White noise histograms for all 151 channels estimated in the frequency range 4 to 6.5 Hz; dashed - 1st order grad. mode; solid - 3rd order grad. mode.

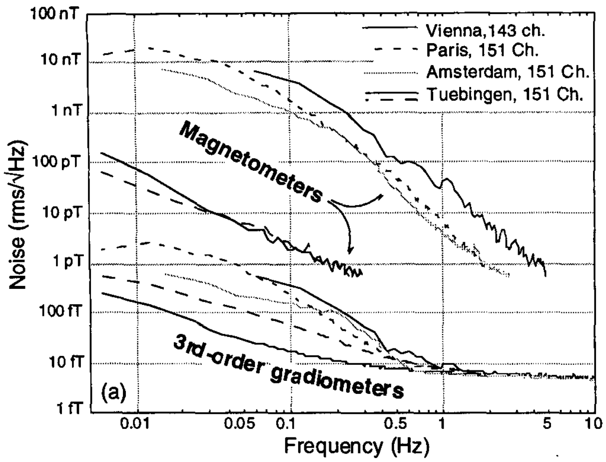

Fig. 8. Noise performance of three 151 channel systems (Fig. 5) and one 143 channel MEG system. All recordings were made during the daytime, within shielded rooms and the lines represent rms averages of all 151 channels. Included is the environmental noise background (magnetometers) and also the MEG system noise after noise cancellation by 3rd order gradiometer formation.

• the majority of the 600 channels in 4 MEG systems in 3rd order gradiometer mode have noise≤ 6fT rms/√Hz above 1 Hz;
• there is some variability of noise levels observed in 3rd order gradiometer mode below about 0.5 Hz and this may be related to penetration into the room of residual noise from vehicular traffic, etc. Environmental noise parameters determined in shielded rooms at various sites are listed in Table I; (f_0 and k are defined in (2)).

An important property of the adjustable MEG systems (Fig.5) is that the noise cancellation should be independent of dewar orientation. This is verified in Fig. 9 where almost identical noise levels are observed at 15° and 70° from vertical for a 151-channel system (Paris site). In addition, based on many installations, the coefficients ξ_i in (1), which are factory-set for optimum performance, appear to be quite stable with passage of time, thermal cycling, etc.

IV. Examples Of MEG Measurements

An epilepsy study of an 8-year old boy was conducted using a 151 channel, adjustable MEG system, unshielded in an urban undustrial environment [5]. Due to the small head of the subject, there were large gaps between the scalp and the helmet surface (3-4 cm). Fig. 10 shows time series overlays of both an interictal spike activity (single trial) and an AEF measurement (average of 94 trials). Excellent S/N was obtained for both types of signals despite the large gaps.

Recently, a novel noise cancellation and mapping technique termed Synthetic Aperture Magnetometry (SAM) has been introduced [14], [15], which utilizes the array properties of the whole cortex MEG system to eliminate environmental noise and also unwanted local biomagnetic disturbances. The spatial selectivity of SAM can be controlled and in its lowest selectivity mode SAM is equivalent to the "Signal Space Projection" techniques [16]. A demonstration

TABLE I
ENVIRONMENTAL NOISE PARAMETERS AT VARIOUS MEG SITES

		Gradiometer Order		
Location		1st	2nd	3rd
Osaka[1]	f_0^2(Hz)	≈ 1	≈ 0.6	0.5 - 1
	k^2	≈ 2	1.5 - 1.8	≈ 1
Sendai	f_0(Hz)	≈ 1	≈ 0.5	0.3
	k	2.5 - 3	≈ 2.5	1 - 1.2
Vienna	f_0(Hz)	1 - 4	****	0.5 - 2
	k	2.5	****	0.9 - 2
Amsterdam	f_0(Hz)	1.3 - 2	1.4 - 2	****
	k	≈ 2	1.5 - 1.8	0.5 - 0.9

1. Only night data available 2. see (2). ***** parameters not determined

of the SAM method is shown in Fig. 11 applied to the interictal spike data from the epilepsy study of Fig. 10(a), in order to determine the source location of the spike. The MEG epilepsy data can be transformed by the SAM method into a statistical probability map which is overlaid on 3 orthogonal MRI images of the subject's brain. The bright spots seen in the 3 orthogonal views represent the location of highest probability for epileptic activity.

V. Conclusions

The properties of synthetic gradiometers for MEG systems have been briefly reviewed. Their use provides excellent noise cancellation for operation within shielded rooms and also allows unshielded operation in urban environments provided the background noise is not too severe. We have found the synthetic noise cancellation procedure to be remarkably consistent at all MEG sites. This, coupled with the MEG digital electronics and advanced signal processing, both on-and off-line, provides MEG instrumentation eminently suited to clinical and research measurements of neuromagnetic fields.

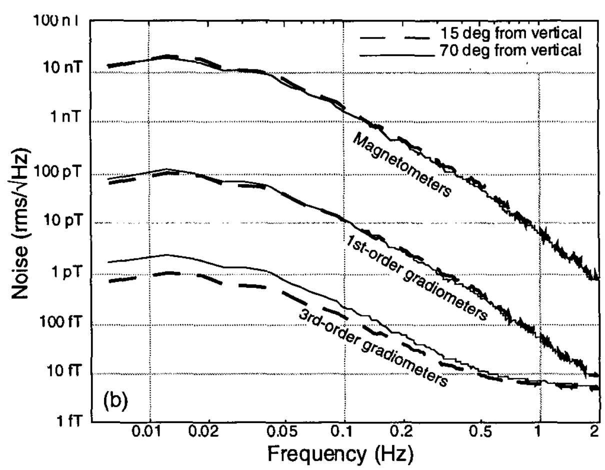

Fig. 9. Magnetometer and MEG system noise levels for 1st order and 3rd order gradiometer formation for a 151 channel adjustable MEG system at 15° and 75° from vertical in a shielded room (Paris site).

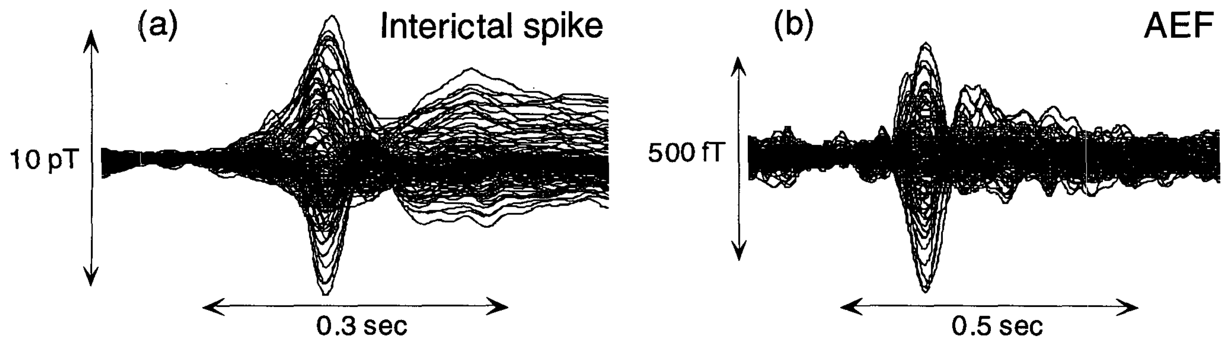

Fig. 10. Measurements of an 8-year old boy with epilepsy, represented by time series overlays of all 151 channels of an adjustable whole cortex MEG system (Fig. 5), using synthetic noise cancellation in 3rd order gradiometer mode (system unshielded).(a) Interictal epilepsy spike, sample rate = 1250 Hz, bandwidth DC - 40 Hz, single trial. (b) Auditory evoked field (AEF) measurement, sample rate = 625 Hz, bandwidth = DC - 40 Hz, average of 94 trials.

Fig. 11. MEG signals of epileptic activity (Fig. 10(a)) are shown transformed into a functional image identifying its location within the brain. These images show the statistical probability of high-frequency spike activity superimposed on the patient's MRI. The bright spot seen in the three orthogonal views is the location of highest probability for epileptic activity. Epileptic activity was recorded from an 8-year old boy using a 151-channel whole-cortex MEG system (CTF Systems Inc Omega-151a), without magnetic shielding. The MEG signals were transformed into three-dimensional source probability maps using synthetic aperture magnetometry (SAM) [14], [15].

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