Supplemental material: presented at Biomag 2002 meeting (Jiri and Coppola)

It is proposed to improve the beamformer resolution by optimizing the signal processing methods. For example, the following will be considered: methods for detection of correlated signals, cortical segmentation, improvement of the beamformer spatial resolution, optimization of the spatio-temporal beamformer behaviour, effects of various parameters on beamformer resolution and corrective action if required (e.g., gain and phase difference between channels, crosstalk, sensor position and orientation uncertainty, precision of measurement, computational precision, registration errors, sensor linearity). The beamformer performance improvement by signal processing will be additive to that obtained by hardware means (increasing the number of channels and reducting the sensor to brain distance).

Realization that the beamformer resolution can be improved by increasing the number of channels goes contrary to the experience which one may have had with more conventional MEG analysis by e.g., equivalent current dipoles (ECD). The ECD reconstruction accuracy is limited by the uncorrelated sensor and correlated brain noise (the brain noise is dominant). Once the number of channels becomes sufficiently high, such that the inter-channel distance is comparable to the brain noise correlation distance, further increase of the number of channels does not improve the accuracy of the ECD analysis. This is illustrated by simulations in Fig.1.a, where the standard deviation of the reconstructed dipole positions (suitably normalized) is shown as a function of the number of channels for simulated brain noise. In this example, when the number of channels is greater than about 100, the dipole positioning error does not improve by increasing the channel count. This result is valid for a range of ECD distances from the model sphere center and range of different sensor configurations. If the brain noise was absent and only the uncorrelated sensor noise was present, then the ECD accuracy would monotonically improve as $1/\sqrt{M}$, where M is the number of channels.

The beamformer situation is different. Roughly speaking, the beamformers remove most of the correlated noise and are less affected by it. One can imagine that in a simple case where all correlated brain noise was removed by the beamformers, the beamformer resolution would be limited only by the uncorrelated sensor noise, and similar to the ECD analysis, would monotonically improve with increasing number of channels as $1/\sqrt{M}$. In practice, not all correlated brain noise is removed by the beamformers. However more correlated noise is removed for larger M, and in many cases the resolution improvement with increasing M can be dramatic.

The beamformer output is a nonlinear function of the source amplitudes, orientations, and positions, and the beamformer resolution cannot be described by a simple number, but has to be investigated as a function of system parameters. The improvement of the beamformer resolution for increasing M is shown in Fig.1.b and c (note that the channel scale extends to 2000 in Fig.1.b and c, while it was only to 300 in Fig.1.a).

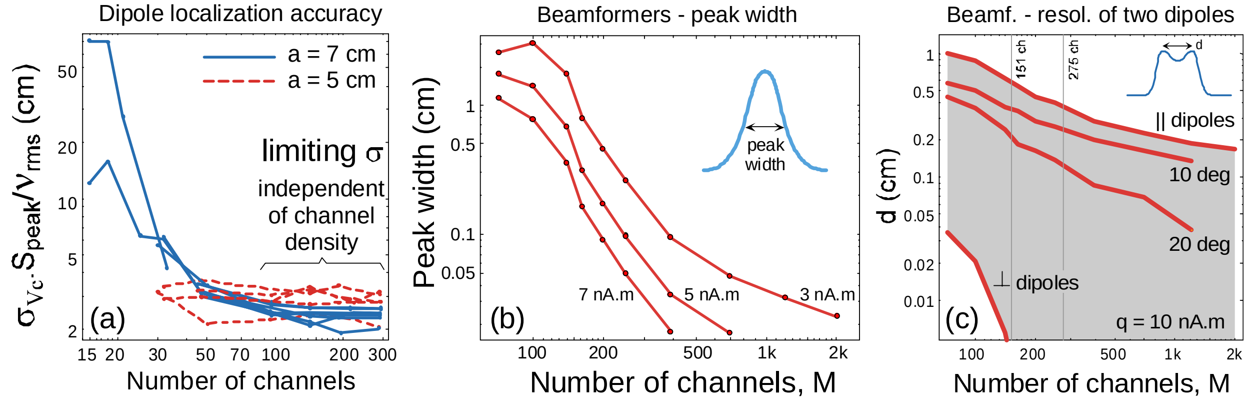

Fig.1: Demonstration of the benefits of increased channel number using simulated brain and sensor noise. (a) For ECD analysis the benefit saturates for the number of channels greater than about 100; (b) SAM beamformer peak width for a single dipole in the conducting medium of the brain. The peak width monotonically decreases with increasing M; (c) SAM beamformer resolution of two dipoles with different relative orientation. The shaded area covers all possible dipole orientations. The resolution again monotonically improves with increasing M up to the maximum investigated M.

Peak width of a relatively superficial source embedded in simulated brain noise is shown in Fig.1.b as a function of the number of channels, M. For the three investigated source magnitudes the spatial resolution (peak width) is improving with increasing M up to the largest investigated M = 2000 channels. The resolution of two dipoles by beamformers is shown as a function of M and relative dipole orientation in Fig.1.c. For all orientations, the resolution is better for larger M. The improvement is slowest for parallel dipoles and becomes more dramatic as the angle between the dipoles increases. The same simulations also show that the source resolution improves when the distance between the sensors and the sources decreases.

The improvement of the beamformer resolution with increasing number of channels is shown in Fig.2.a, b, and c for a dipolar source inserted into the brain noise measured by a 275 channel system in an unshielded environment. 3D contours of half amplitude beamformer response are shown by red shapes. When the sensor array was spatially resampled to 138 channels, the same 3D contours exhibited 6.2 times larger volume (about 1.8 times larger linear dimension).

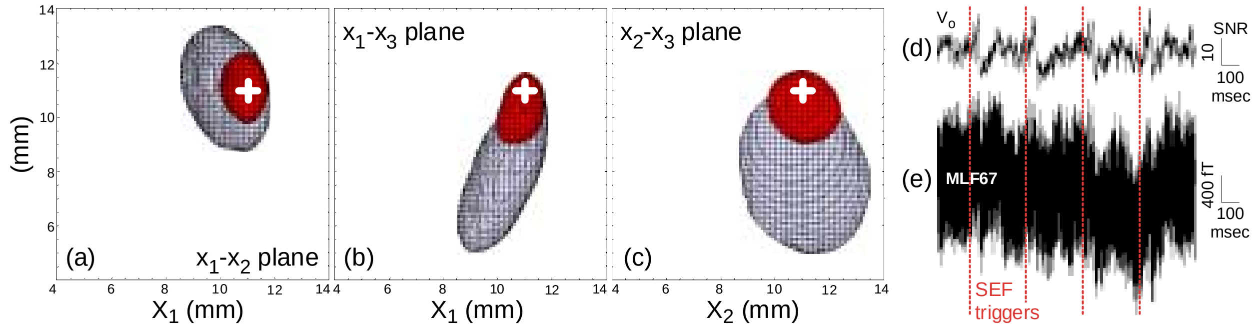

Fig.2: Demonstration of the benefits of increased channel number using measured brain and sensor noise in an unshielded environment with 3rd-order gradiometer noise cancellation. (a, b, c) Dipole with 20 nA.m moment was inserted into measured brain noise, roughly 4.5 cm below the sensors. The half-amplitude 3D contours of normalized beamformer power are projected into x_1-x_2, x_1-x_3, and x_2-x_3 planes. White "+" indicates the exact dipole position. Red shapes – 275 channel system, volume 6.1 mm^3, gray shapes – 275 channel system resampled to 138 channels, volume 37.8 mm^3; (d) Synthetic electrode output during median nerve electrical stimulation (SEF), dashed lines indicate onset of the stimulus, bandwidth dc to 300 Hz; (e) MEG channel corresponding to the largest magnitude SEF signal, bandwidth dc to 300 Hz and with power line notches.

The brain response to the electrically stimulated median nerve was also measured by the 275 channel system in an unshielded environment. A beamformer synthetic electrode was positioned at the location of maximum beamformer response to SEF, and its output in Fig.2.d clearly shows unaveraged response to the SEF stimulus (despite the fact that the present generation of the unshielded MEG systems operates with noise increased by crosstalk). For comparison purpose, an MEG channel corresponding to maximum SEF response is shown in Fig.2.e. Even though the output of this channel was also filtered by power line notches (while the synthetic electrode in Fig.2.d was not), it does not show any discernible SEF signal. The results in Fig.2 illustrate the importance of a large number of channels for synthesis of beamformer outputs, and the crucial difference between the beamformer synthetic electrodes and sensors placed on the scalp surface. The synthetic electrodes eliminate interference from other brain regions, while the interference is mixed with target signals in conventional scalp sensors (either MEG or EEG).