Accelerated large scale spherical model forward solutions for the EEG/MEG using CUDA

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Background:

- Forward solution for electroencephalography (EEG) and magnetoencephalography (MEG) refers to the calculation of the electric and magnetic fields at sensor locations for given electric dipole parameters (location and orientation) and a given head model.
- Source localization (inverse) methods utilized for finding epileptogenic foci depend on the forward solution. Commonly used imaging approaches to the inverse solution require the calculation of forward solution at a dense grid of dipole locations throughout the brain volume.
- Realistic head models utilize the Boundary Element / Finite Element models to improve the accuracy of the forward solution. However, spherical (single and multi-sphere) models are still routinely used in clinical applications for EEG/MEG based localizations where speed of solution is as critical as the accuracy.
- Although the single dipole solution for spherical model is fast, the computation time drastically increases when the solution is calculated for a large number of dipoles and sensor locations.

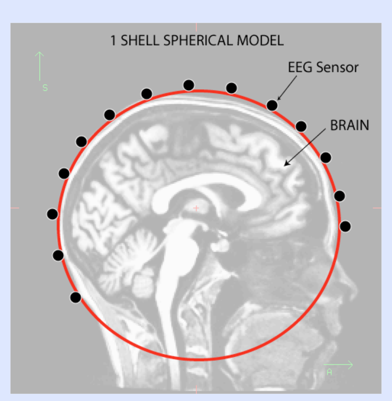
Specific Aim:

To investigate the utility of a CUDA based approach to improve the speed of the spherical model EEG and MEG forward solution for large scale 3-D dipole grid (on order of 10000 and up) and sensor locations (on order of 100 and up).

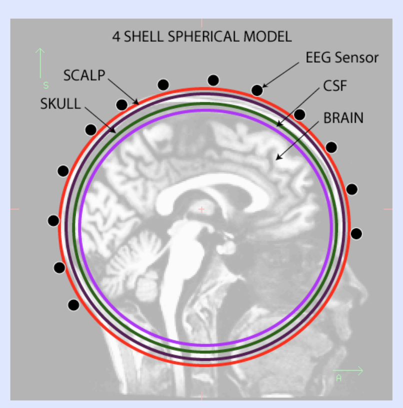
Methods:

The spherical solutions that are utilized for comparing the timings of CPU and CUDA-GPU implementation are as follows:

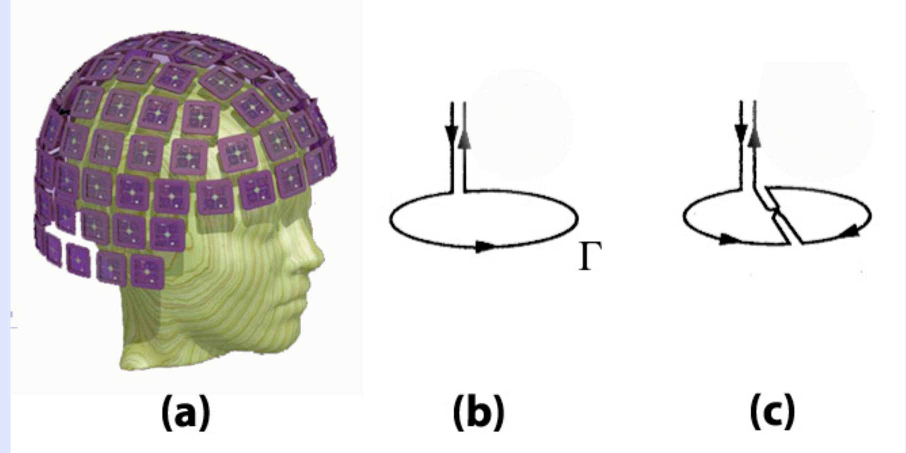
1. Single sphere solution for electric potential as measured by EEG where the head is modeled as a single sphere: solution as per Frank [1].
2. Four sphere solution for electric potential (EEG) where the head is modeled as four concentric spheres representing the brain, inner skull, outer skull and scalp surfaces respectively: solution given in Cuffin and Cohen [2].
3. Single sphere solution for magnetic field measured using MEG where the head is modeled as a single sphere: solution given in Sarvas [3].



1 shell sphere



4 shell sphere

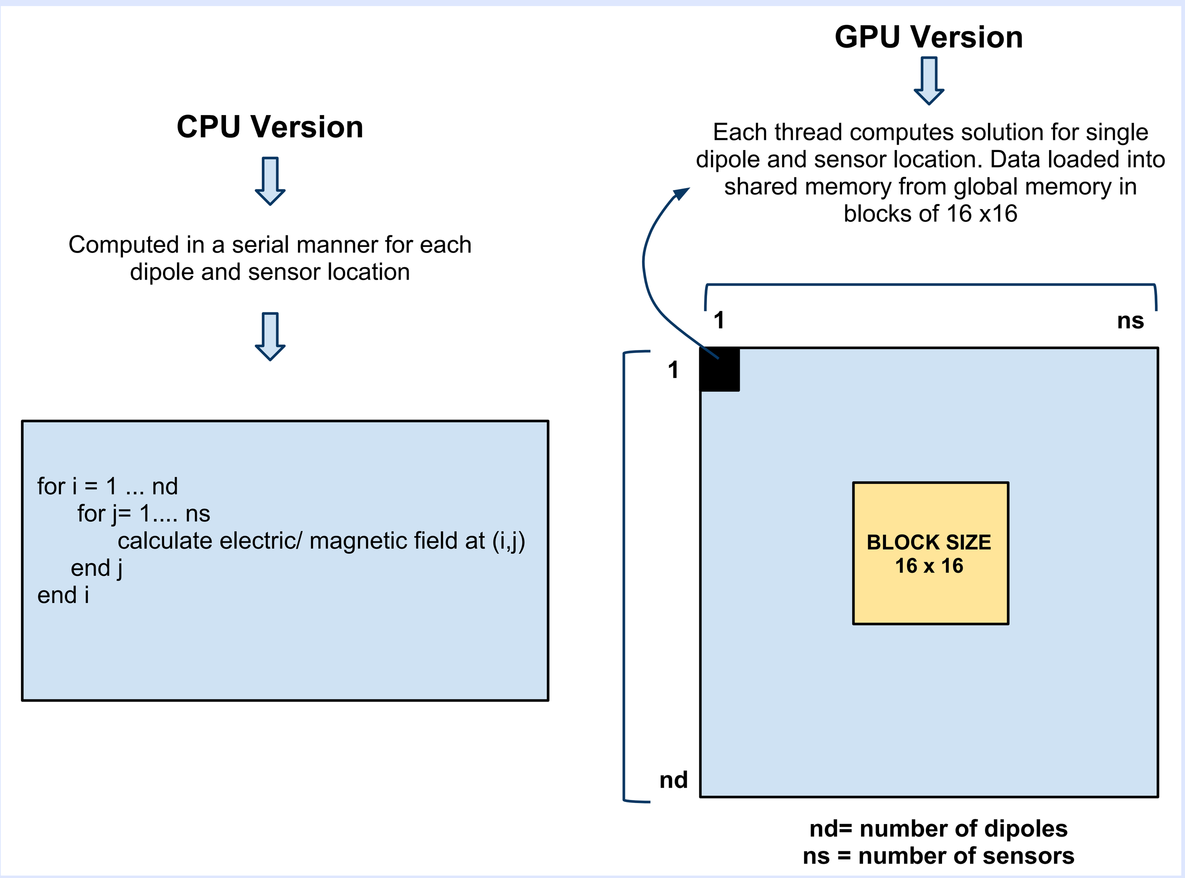


(a) 306 MEG sensors (b) Magnetometer (c) Planar Gradiometer

Dipole locations: Dipoles are distributed at randomly assigned locations and orientations inside the head volume. Multiple grid sizes ranging from 50 dipoles to 248049 dipoles are simulated. The largest dipole grid (248049 dipoles) corresponds to a dense rectangular grid with 2 mm spacing between adjacent locations.

Sensor locations: For the EEG, sensor locations vary from 50 to 5000 randomly selected locations on the outermost scalp surface. For the MEG, the sensor locations are a fixed number at 306 (102 magnetometers and 102 pairs of gradiometers), based on the Elekta Neuromag system. However, each sensor location requires numerical integration over integration points covering the pickup coil loops of the sensor. The most accurate description consisting of 8 integration points for each gradiometer and 16 points for each magnetometer is utilized. Thus, the total number of sensor locations for magnetic field calculation increases to 3264 locations.

CPU vs GPU Implementation



For CPU vs GPU comparisons we use the following combinations of dipole locations (nd) and sensor locations (ns): nd x ns

1. For EEG, matrix sizes from 50 x 50 to 5000 x 5000 are used. Although the sensor sizes above 200 are over the practical limit, these cases are useful for simulations, especially when the results of realistic methods like BEM and FEM need to tested against spherical model solutions.
2. A second set corresponding to more realistic cases where sensor size is on the order of 100: 10000 x 100, 20000 x 100 and 248049.
3. Similarly for the MEG, grid sizes vary from 50 x 306 to 248049 x 306.

CPU solution:

Analytical solutions for a single dipole and sensor location described in the references listed above are extended for the case of multiple dipoles and sensor locations. A **double precision** 'C' implementation was run on a Linux desktop machine (ubuntu 10.04) with intel core i7 CPU 920 @ 2.67 GHz and 8GB RAM.

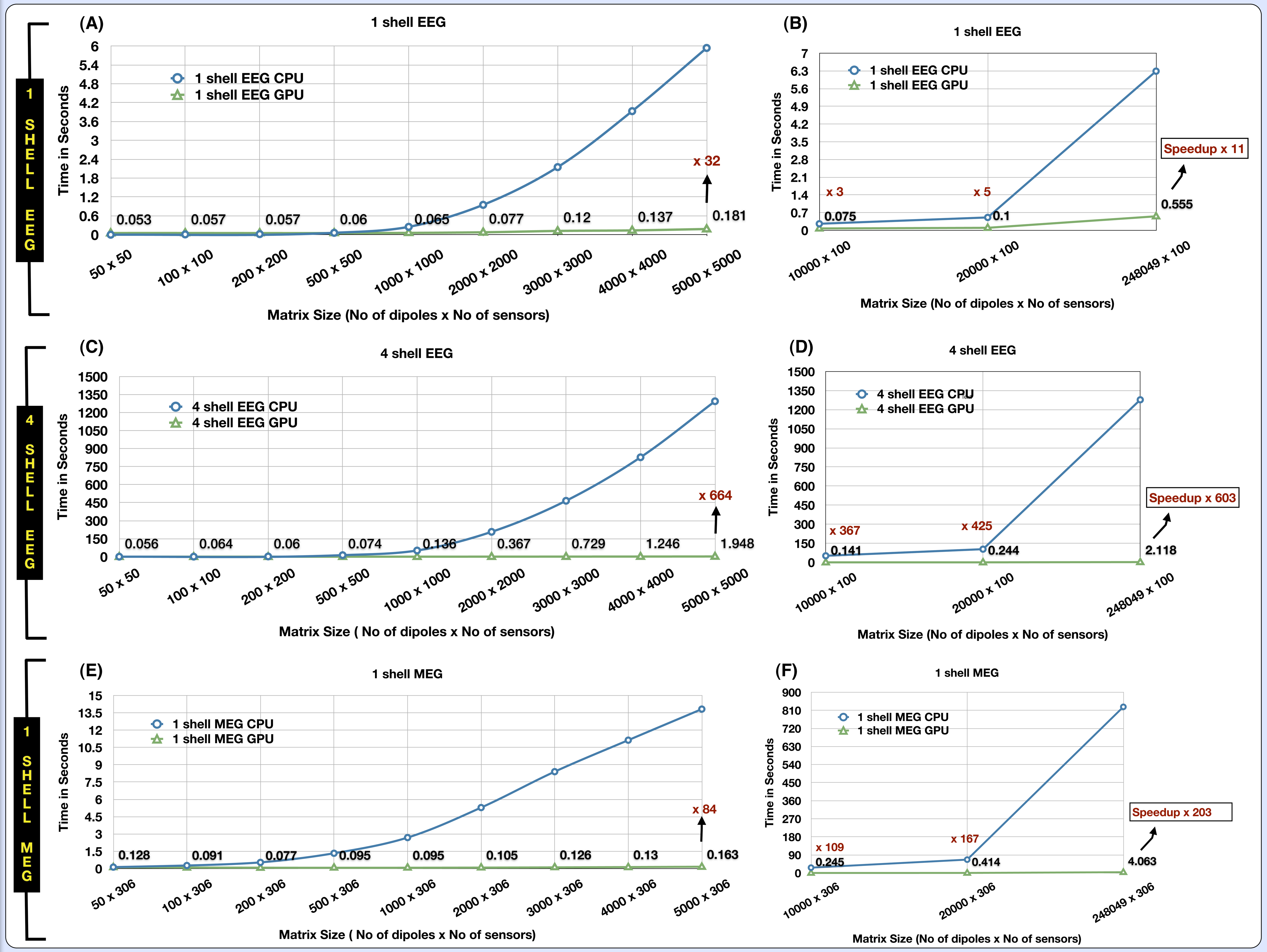
GPU implementation:

CUDA version of the C code was implemented in **single precision** and run on a **NVIDIA GTX 260 card** on the same desktop machine (CUDA version 3.1). The following strategy was utilized:

- Each thread computed the forward solution for a single dipole and sensor location. The 'for' and 'if-then' loops are optimized for CUDA whenever possible.
- Dipole and sensor location data is loaded from global memory to shared memory on the GPU in blocks of 16 x 16.
- For MEG forward solution, each thread computes the integration of fields at points over pickup coils of each MEG sensor.

Results: CPU vs GPU

Figure shows the comparison of computation time (in seconds) between CPU and GPU code for 1 shell EEG, 4 shell EEG and 1 shell MEG forward solution at varying grid sizes. For EEG, the plots in the right column (B & D) plot computation time for a practical number of sensor locations (on order of 100). Due to small numerical values of the CUDA computational time, the time in seconds is listed adjacent to the data symbol. Also, at large sensor locations the speedup factor is marked in red adjacent to the CUDA execution time.



- L2 norm error between single precision CUDA code and double precision C code is less than 5 e-4.
- The speedup for 1 shell EEG model is not significant for smaller scale models (grid sizes 500 and under). However for larger dipole/sensor grids, a speedup by a factor of 32 is achieved. The CUDA code execution time in all cases is under 600 ms.
- For the case of 4-shell model, substantial speedup is achieved for large-scale grids. For the practical cases of dense dipole grids (10000 and up) and 100 sensors speedup factor of 300 and above is achieved. For the densest grid, (248049 x 100) the execution time improved by a factor of 600! The CUDA version computes the solution under 1 second for all cases (except the densest grid, where it takes about 2 sec), whereas the C version can take up till 21 minutes.
- For the 1 shell MEG solution, the speedup is also substantial with sub-second performance of the CUDA code for most cases. The worst-case computation time for C version was 13 minutes. Speedup by a factor of 100 and above is achieved for dense dipole grids (10000 and up).

Conclusions:

- **Significant speedup in the time for calculation of the EEG and MEG forward solution is achieved using CUDA for large-scale dipole and sensor locations without any loss of accuracy. Computation time was reduced to under 1 second for most cases using CUDA.**
- **As expected, CUDA had the biggest impact for more complex solutions. For example, the 4 shell model involves the computation of legendre's polynomials which when transferred to the GPU gave the highest speedup in computation time. In contrast, the CUDA implementation of the simple single shell EEG solution does not provide any significant speedup.**
- **Although the single dipole solution for a single shell MEG solution is not complex and can be computed quickly with serial C code, the computation time increases with integration over multiple locations covering the pickup coil of each MEG sensor. The CUDA code reduces the computation time by spreading the computation over multiple threads.**
- **These results show that by using a CUDA-based solution, an instantaneous solution can now be obtained for extremely dense grids on a consumer desktop computer, thereby making it an attractive strategy for clinical applications. One can expect similar benefits for more complex forward solutions such as the BEM and the FEM by carefully adapting the CPU code and optimizing it for the GPU and thereby expedite their adoption in clinical applications. This will be investigated in a future study.**

References:

1. Frank E. Electric Potential Produced by Two Point Current Sources in a Homogeneous Conducting sphere. Journal of Applied Science. 1952;23(11):1225-8.
2. Cuffin BN, and Cohen, David. Comparison of the magnetoencephalogram and electroencephalogram. Electroenceph Clin Neurophysiol. 1979;77:132-46.
3. Sarvas J. Basic mathematical and electromagnetic concepts of the biomagnetic inverse problem. Phys Med Biol. 1987;32:11-22.

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