High Performance Computing on GPU for Electromagnetic Logging

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Abstract. *The article deals with the development of software and algorithmic techniques for multidimensional modeling and inversion of electromagnetic logs. With many new oil and gas fields being developed in difficult geological conditions, the requirements tend to be higher for reliability and efficiency of log data interpretation. Within this research various programs and algorithms were created for electromagnetic logs modeling with the use of high-performance computing on GPUs of personal computers. On the basis of approximate approaches the effective parallel algorithms for forward computing in two-dimension geoelectric models were developed. Comparative performance assessments of the diagram computations of the oil saturated reservoir are obtained on the CPU and GPU.*

1 Introduction

In the research of geological environment around the oil and gas wells the reconstruction of spatial distribution of rocks conductivities plays an important role. The high-frequency electromagnetic logging (HIL) is intensively developed in recent decades [1]. The development of interpretation systems depends largely on the efficient mathematical modeling of electric diagrams in environments with a complex spatial distribution of the geoelectric parameters.

Solving two- and three-dimensional problems in full production for this purpose are ineffective due to their high resource intensity To reduce the time of computations the parallel computations on clusters or multiprocessor computer systems are used. This is applicable for single numerical experiments but not for the automated interpretation systems which are usually based on personal computers.

Currently, the application of graphics processors to accelerate the computation is attracts researchers' attention in dealing with contemporary problems in various scientific fields. In contrast to the central processing units (CPUs) the modern GPUs specially designed for extremely fast processing of large volumes of graphical data in hundreds parallel threads. This is facilitated by a specially developed technology Nvidia CUDA. CUDA is a general purpose parallel computing architecture – with a new parallel programming model and instruction set architecture – that leverages the parallel compute engine in NVIDIA GPUs to solve many complex computational problems in a more efficient way than on a CPU. CUDA comes with a software environment that allows developers to use C as a high-level programming language.

All this indicates that the acceleration of the geoelectrical problems solving can be achieved through GPUs. We obtain performance estimates for the calculation of diagrams of high-frequency electromagnetic logging in typical two-dimensional geoelectric models on the GPUs and CPUs.

2 Problem solving

Consider a two-dimensional geoelectric axisymmetric model, which includes a stack of plane-parallel layers with horizontal boundaries, and a vertical well of circular cross-section. Each layer may contain a zone of infiltration and or flanking area, which are separated from each other and well and reservoir by coaxial cylindrical boundaries (Fig. 1). Each area bordered by vertical and horizontal boundaries, has a particular electrical conductivity σ_{jl}, $j=1,\dots,N_z$, $l=1,\dots,N_r(j)$, where N_z - number of layers, $N_r(j)$ - number of cylindrical zones in the layer. In the rest of the medium the conductivity is a function of two spatial coordinates $\sigma(r,z)$.

For solution of the two-dimensional direct problem of high-frequency electromagnetic sounding in conductive media approach described in [2] is used. In this article the complete linearized staging of boundary problem and its solution are given. The solution of problem is the determination of a component of electric and magnetic fields on the axis of symmetry of two-dimensional model that is divided into areas with various conductivities by system of plane-parallel and coaxial cylindrical boundaries.

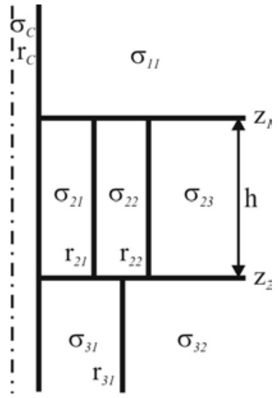

Fig.1. Two-dimensional geoelectric model

This approach consists of providing two-dimensional distribution of conductivity and electric field initiated by inductive source, as a sum of $\sigma(r,z) = \sigma^b(p) + \delta\sigma(r,z)$ and $\mathbf{E} = \mathbf{E^b} + \boldsymbol{\delta}\mathbf{E}$ respectively. Here $\sigma^b(p)$ is one-dimensional conductivity distribution and $\mathbf{E^b}$ is electric field in the background model, $\delta\sigma(r,z)$ and $\boldsymbol{\delta}\mathbf{E}$ - their relatively small perturbations. Note that σ^b is a function from one of the spatial coordinates ($\sigma^b(r)$, $\sigma^b(z)$) or is a constant $\sigma^b = \sigma_0$ (homogeneous medium). Knowing this the determining of the electric field in two-dimensional conductive medium solves to the following integral equation:

$$\mathbf{E}(r_0, z_0|r, z) = \mathbf{E^b}(r_0, z_0|r, z) - 2\pi\int_S \delta k^2(r', z')\mathbf{G^E}(r', z'|r, z)\mathbf{E}(r_0, z_0 \,|\, r', z')dS\,. \tag{1}$$

Here $\mathbf{E^b}(r_0, z_0 \,|\, r, z)$ - is the electric field in the background model with the conductivity distribution $\sigma^b(p)$, $\mathbf{G^E}(r', z' \,|\, r, z)$ - is the Green's function for the electric field, $\delta k^2(r,z)$ - perturbation of the wave number square associated with relatively small spatial variation of conductivity, (r_0, z_0), (r,z) and (r', z') - coordinates of the generator and receiver coins and integration point. Axial symmetry leads to a two-dimensional integration of the heterogeneity area S in the plane $\varphi = \text{const}$.

Probes of the high-frequency electromagnetic logging measures relative signal characteristics such as phase shift or attenuation of the amplitude. Linear representation of the difference between the phases is the following

$$\Delta\varphi \approx \Delta\varphi^b + \delta\sigma G\,. \tag{2}$$

Where $\Delta\varphi^b$ - phase difference in the background, $\delta\sigma$ - conductivity perturbation, G is two-dimensional integral in accordance with (1). Note that the accuracy of a linear presentation depends on the background model, heterogeneity size and the relative conductivity contrasts in the medium.

3 Integration scheme

Integration of G in accordance with the medium parameterization by conductivity perturbations $\delta\sigma_{jl}$ in areas S is ordered by $j = 1,\ldots,N_z$, $l = 1,\ldots,N_r(j)$. The overall integration scheme is shown on Fig. 2.

Note that the areas $\delta\sigma_{jl}$ differs in size, so to ensure convergence of integration it is necessary to unify the integration grid. To this effect we split each area $\delta\sigma_{jl}$ to smaller sizes δ along z and r axes, where δ is determined by skin-layer in the background model. In this case, each area of conductivity perturbations will be characterized by their splitting numbers n_z and n_r. For the integration in subarea δ we use Gauss method with n_g-pointed quadrature.

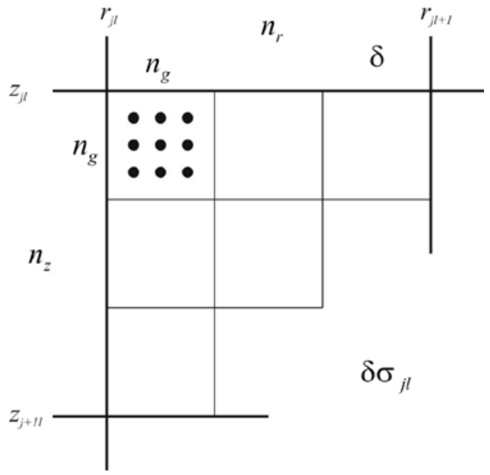

Fig.2. Integration scheme

Thus, the computation of the integral G can be reduced to three double integration. In such scheme corresponding values can be calculated in parallel at different stages of integration. Integration scheme can be effectively implemented on GPU which leads to the valuable performance gain. Let's describe integration algorithm implemented on GPU.

4 Computational algorithm

Note that the linearization of relative characteristics of electromagnetic fields, which leads to real values, is independent and is important for the direct and inverse problems. All computations are performed in real numbers. Algorithm implemented with Nvidia CUDA.

With Nvidia CUDA technology algorithm of G integral computation through integration scheme described above naturally falls on the CUDA programming model and does not require a specific organization of memory for storing data and intermediate calculations, which makes it easy to understand and implement.

In the implemented algorithm the integration area is divided into $n_z \times n_r$ subareas. The two-dimensional integral is calculated per each subarea. For n_g-point Gauss quadrature the $n_g \times n_g$ numbers should be calculated and summarized. So, in order to calculate integral we should summarize all its values in each subarea. Thus, the algorithm kernel is parameterized by number of integration subareas and number of Gauss quadrature. That's why we use two-dimensional blocks and grids with indexes blockID.z/blockID.r and threadID.z/threadID.r respectively. Each integration subarea is handled by a separate block, each thread of block calculates integrands function in a single point of Gauss quadrature. Computing results of each thread are stored in shared memory. The kernel configuration reflects the structure of integration area (Fig. 3).

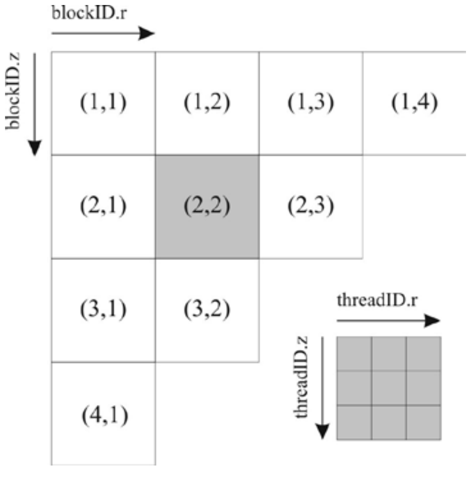

Fig.3. CUDA model

5 Analysis of diagrams and Performance comparison

Consider the two-dimensional modeling, which is necessary for research of the low-capacity layers (less than the length of probe). Let's analyze the geoelectric model, typical for terrigenous sections of oil and gas fields in Western Siberia. In this article the apparent conductivities for the HIL probes are given: (IK05 – length is 0.5 m, frequency 14 MHz; IK07 – 0.7 m, 7 MHz; IK10 – 1.0 m, 3.5 MHz; IK14 – 1.4 m, 1.75 MHz; IK20 – 2.0 m, 875 kHz).

The model of floating oil saturated reservoir is used for algorithm testing. The model consists of borehole (σ_C =1/2 S/m, r_C =0.1 m), oil saturated reservoir with invaded and fringing zones (h =2 m, σ_{23} =1/8 S/m, r_{22} =0.6 m, σ_{22} =1/4 S/m, r_{21} =0.4 m, σ_{21} =1/20 S/m), underlying water saturated reservoir with an invaded zone (σ_{32} =1/5 S/m, r_{31} =0.5 m, σ_{31} =1/25 S/m) and overlying clay deposits (σ_{11} =1/4 S/m) (Fig. 1).

On the Fig. 4. the synthetic diagrams of apparent conductivity for the HIL probes are given. In order to verify the calculations the finite-difference program for calculating the diagrams was used [3]. As we can see, the results of approximate numerical simulations properly fit with results of finite-difference method.

Throughout the interval, with 4-fold relative contrast relative probes error doesn't exceed 5%. So, for oil and water saturated reservoirs relative error for the probes IK05 and IK07 is about 3 and 2.5%, and for the probes IK10 IK20 – 1-2%. At the mud interval the relative error slightly increased for all probes. The maximum relative errors related to a short high-frequency probes, because the linear approximation gives a reasonable accuracy at low relative contrast and the relatively low frequencies.

For the long length probes the relative errors doesn't not exceed 5% even at high relative contrasts. Approximation (3), as a correction of the phase function makes it possible to obtain more accurate values of apparent conductivity. The assumption that the spatial variation of electrical conductivity in a high frequency range only leads to a change in a phase component of electric or magnetic field. Large amount of numerical simulations and comparison of diagrams in two-dimensional models of terrigenous collectors shows high efficiency of the proposed approach.

With respect to high frequency electromagnetic logging usage of a linear representation of the phase differences (2) allows calculations with relative error no more than 5% in a fairly wide range of model parameters.

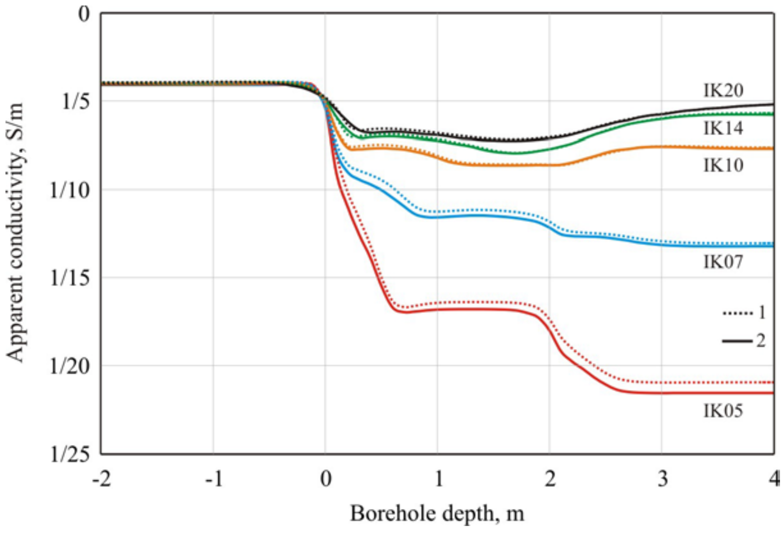

Fig.4. Synthetic diagrams of waterfowl oil saturated reservoir overlapped with clays. Approximate (1) and finite-difference (2) approaches

Performance estimates for the oil saturated models diagram simulations are obtained on Intel Core 2 Quad 2.4 GHz and graphics cards Nvidia. Note that the algorithms for the regular CPU and for the graphics cards are fully identical. On the Fig.5. the times of the apparent conductivity σ_{κ} calculations are given for the five HIL probes in the vertical log. As we can see, the GPU computations are more 20-50 times faster then identical CPU computations.

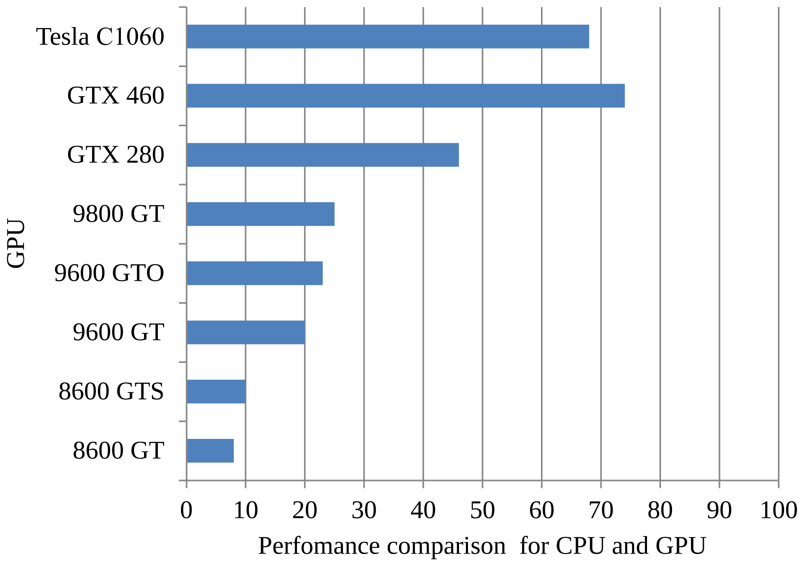

Fig.5. Performance comparison for CPU and GPU

6 Conclusion

An effective algorithm of high-frequency logging diagram simulations of oil- and gas- wells is developed for the graphics processors. Performance estimations for the two-dimensional models simulations on the CPUs and GPUs are obtained. It is shown that GPU computations are 20-50 times faster than identical calculations on CPU. Large amount of numerical simulations and comparison of diagrams in two-dimensional models of terrigenous collectors shows high efficiency of the proposed approach.

In conclusion, it should be noted that the GPU computing results have shown a significant performance increasing for solving various problems of modern geoelectrics. This indicates the feasibility of new generation automated interpretation systems.

References

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