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Parallel Processing For Gravity Inversion

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Abstract

In this paper results of recent updates of a simple algorithm for the inversion of gravity anomalies for 3D geosections in parallel computer systems are presented. A relaxation iterative principle was used updating step by step the geosection distribution of mass density. Selection of updates was done on basis of least squares error match of the update effect with the observed anomaly. Locally weighted least squares combined with the linear trend were used to obtain good inversion results for two-body geosections.

Keywords Parallel systems, Gravity inversion, Geophysics

I. Introduction

In the paper we present recent results obtained for the inversion of gravity anomalies in parallel computer systems. Inversion of geophysical anomalies is an old problem from the beginning of geophysics. For decades a multitude of manual and computer-based methods are developed. The problem is typically "ill-posed", from a mathematical point of view the traditional inversion implies mapping from a 2D array of measured ground surface values into a 3D array of voluminous physical parameters of the geosection [1][2].

Because of the physical and mathematical complexity of geophysical inversion [3], the problem is "attacked" through different methods simplifying the conditions. A typical traditionally used simplification has been reduction of dimensions through mapping a profile of 1D array of measured values into a 2D array representing a cross-section of geological structures, leading to a reduction of the volume of data and of calculations [4]. Other applied constraints include limitation to convex bodies [5], rectangular 3D prisms [6], stochastic methods [7] etc, just to mention few cases. The uncertainty character of the problem is considered by some scholars [8].

Despite decades of development, inversion remains problematic. A typical case of problematic 2D inversion of a two body geosection is given in [9] (Fig. 1).

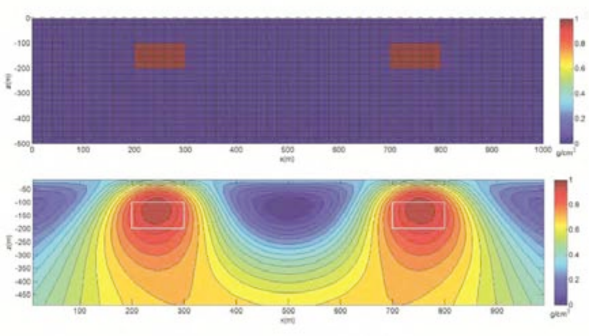

Figure 1: Typical inversion of two-body model.

Exploitation of parallel computer systems made easier the 3D inversion and different methods are experimented as in [10 - 13]. In our work we experimented a simple algorithm GIM (Geophysical Inversion and Modeling) for the 3D inversion of gravity anomalies aiming to compensate the simplicity of the algorithm with the increase of the volume of calculations made possible in parallel systems. The work started in framework of European FP7 project HP-SEE and first calculations were carried out in the HP Cluster Platform Express 7000 operated by the Institute of Information and Communication Technologies, Bulgarian Academy of Sciences in Sofia, Bulgaria and the SGE system of the NIIFI Supercomputing Center at University of Pècs, Hungary. Recent results are obtained using the small parallel system in Faculty of Information Technology of Polytechnic University in Tirana.

II. The methodology of the work

The idea of algorithm CLEAN developed by Högbom [14] for the interpretation of radio-astronomy data was used. The algorithm is based on a simple relaxation principle - iterative approximation of geosection structures through small updates that offer the best approximation of the anomaly in each iteration. Gravity was considered as the simplest case of physical fields used in geophysics. The 3D geosection was modeled with a 3D array of elementary cuboids. In each iteration the cuboid that generates a gravity effect (elementary anomaly) which shape best approximates the observed anomaly is selected, and its mass density is modified with a predefined quantity. The effect of this increased quantity of mass density for the selected cuboid is subtracted from the observed anomaly and the whole process is repeated. In each iteration the 3D array of cuboids is scanned and for each cuboid the gravity effect in each point of the 2D array of observed anomaly is calculated (one elementary calculation for each couple cuboid - anomaly point). As result, with the supposition that dimensions of 2D and 3D arrays are N^2 and N^3, the complexity of the algorithm resulted O(N^8).

The parallelisation of the algorithm was done using both OpenMP and MPI techniques. For each iteration the scanning of the 3D array of cuboids was split in different threads and calculated in different computing cores. For the scalability of the algorithm the variations of runtime as function of the number of cores and the size of the 2D & 3D arrays. In order to reduce time delays from inter-process communication, only metadata for selected cuboids were exchanged between processes and each process had to repeat the subtraction of elementary anomalies from the observed one. Results of the work were presented in [15 - 20]. The least squares error was used as approximation metrics to evaluate how the shape of an elementary anomaly matches the observed anomaly. A modified least squares metrics was used for this purpose. In the first version of the algorithm the simple least squares error formula was used for each cuboid:

$$Err = \sum (G_{ij} - c * A_{ij} - d)^2 \qquad (1)$$

where: G_{ij} is observed anomaly value in the point (i,j) of the 2D array, A_{ij} is anomaly effect in the point (i,j) of the 2D array from the 3D cuboid with fictitious mass density of one unit. Two constants "c" and "d" were calculated to give the least error for each cuboid of the 3D geosection array, and the cuboid with the least error was selected modifying its mass density with a predefined quantity.

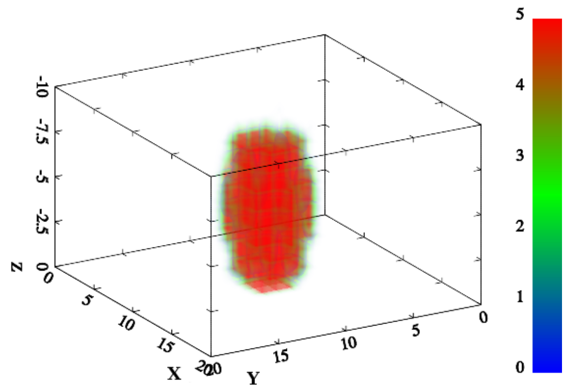

Figure 2: Inversion of single body model.

Experiments with the simple algorithm gave good results for the inversion of the gravity anomaly of a single vertical prismatic body (Fig. 2), while for multi-body geosections the results were characterized by the presence of a false depth central body instead of separate vertical prisms. The evolution of relaxation process of the algorithm was investigated joining together the central cross-section of the 3D geosection for each iteration, shaping a "carrot" that describes how the body was generated through iterations (shown in Fig. 3, see also Fig. 1):

It is visible from the Fig. 3 that the "focus" of the algorithm is the generation of a single depth body which anomaly approximates the observed one, and only remained anomaly is used for the generation of two shallow bodies that correspond with the tops of

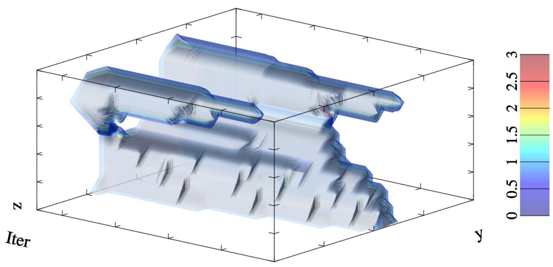

Figure 3: Evolution of inversion of the two-body model with the simple algorithm.

two original prismatic bodies (the same as in Fig. 1).

The modification of least squares error formula was done in three stages. First, the calculation of the error was limited in the part of the 2D array of observed anomaly points where the gravity effect of the cuboid is more significant. Second, weighted squares errors were used. Third, a linear local trend of the observed anomaly was considered:

$$Err = \sum W_{ij} * (G_{ij} - c * A_{ij} - d_i * i - d_j * j - e)^2 \quad (2)$$

where: W_{ij} is weights calculated on basis of A_{ij} values that $A_{ij} > L$; L is predefined threshold for definition of the calculation area; constants c, d_i, d_j and e were calculated to give the least error for each cuboid of the 3D geosection array. After the third modification of the least squares error formula, subtraction of the local linear trend, the evolution of inversion for the anomaly of two vertical prismatic bodies resulted in two realistic separate vertical "carrots".

III. Results of gravity anomaly inversion

The new algorithm was tested with synthetic anomalies generated in a 3D geosection with size 4,000x4,000x2,000 meters, and discretized with cuboids with edges 400m, 200m, 100m, 50m. The same mesh was used for the ground surface 2D array of observed anomaly. The same software was used to produce observed anomalies used as input for the inversion. Two cases were modeled, a single vertical prism 400x400x1,600m in depth -400m, and two vertical prisms of the same size in distance 1,600m. Scalability of the algorithm resulted similar for OpenMP (Fig. 4 and Fig. 5) and MPI.

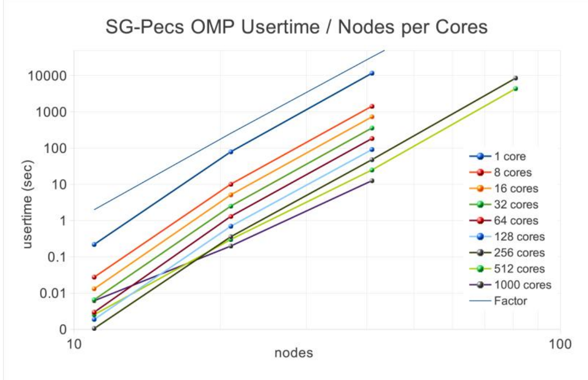

Figure 4: Scalability per model size.

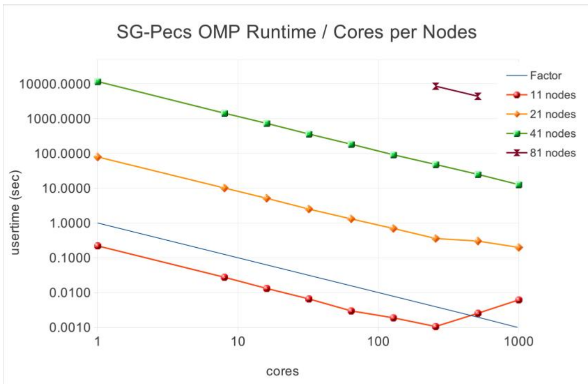

Figure 5: Scalability per number of cores.

Variation of runtime resulted the same as theoretically predicted. Runtime as function of model size (Fig. 4 is with factor O(N^8), while as function of number of cores C it is with factor O(C^{-1}). Only for small models parallelized with a great number of threads the scalability is spoiled due to the overhead of inter-process communication. In the case of the two body model, when the modified least squares formula was used, the evolution of geosection proceeded differently from the case of Fig. 1, instead both bodies were developed in parallel as shown in Fig. 6:

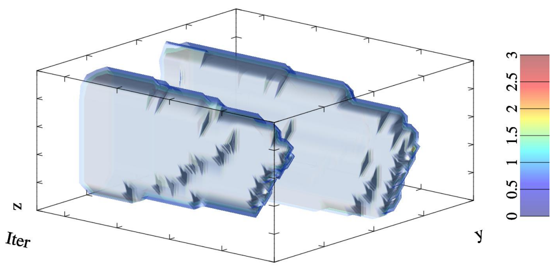

Figure 6: Inversion of two-body model with modified algorithm.

The final result of two body anomaly inversion is presented in Fig. 7. The difference in the volume of two inverted bodies is result of a small difference of the mass density of the original prisms.

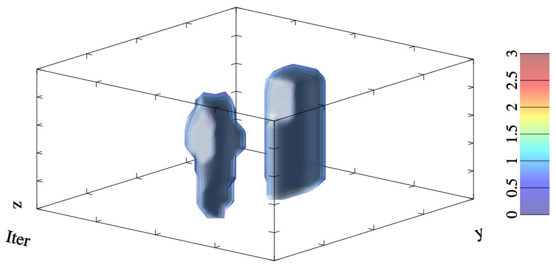

Figure 7: modified inversion of two body anomaly.

With the modified inversion algorithm there is clear contrast between the bodies and surrounding medium, and there is no in-depth bridging between two bodies as in the case of simple algorithm.

Scalability (Fig. 8) of the modified algorithm for the two body model was done in two ways. Digitized geosections with 200m and 100m sized cuboid were used, each with two cases of mass density step of 1.0 and 0.1 G/cm^3 for selected cuboids. Parallelization was done with 1 to 128 MPI processes using two schemes: a) running in a single computer node with 8 cores; and b) running in two computer node blocks interconnected with a 1Gbps Ethernet switch. The walltime experienced a jump when number of processes bypassed that of cores and increased in case of the small model while remaining almost constant for the medium-sized model. While when processes were distributed in all cores a small decrease of the trend was observed despite the low bandwidth of the interconnecting switch, an indication that the software may be run in multi-grid environment.

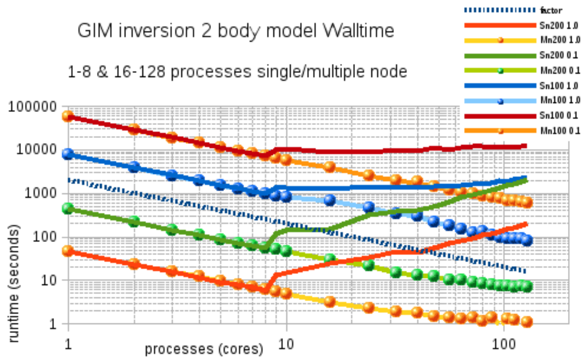

Figure 8: Scalability of two-body inversion.

IV. Conclusions

The principle of algorithm CLEAN of Högbom [14] was applied for the 3D inversion of gravity anomalies in parallel computer systems. The complexity of the algorithm resulted $O(N^8)$ for the ill-defined iterative process of mapping from a 2D array of surveyed anomaly values into a 3D array of mass density of the geosection. Parallelization was done using OpenMP and MPI. Calculations for a geosection 4,000x4,000x2,000m discretized with a step of 50m succeeded in 3 hours using 1,000 cores.

The relaxation iterative process was based on selection of the best cuboid which effect matched better the observed anomaly, using least squares error method. Experiments resulted successful for single body models while gave wrong three-lobe structures for two body models. In order to resolve this problem the best cuboid was selected calculating locally the weighted least squares error only for points around the cuboid, subtracting the linear trend and using the shape of cuboid's anomaly as weights. This modification made possible to obtain good inversion approximation of the two-body model.

Complexity of algorithm is polynomial of 8^{-th} order that requires ultra scale parallel computer or multi-grid systems to obtain results for models with metric necessary for complex multi-method engineering works - the observed runtimes are for the inversion of gravity that is the simplest case (scalar field which scattering does not depend on environment heterogeneity) in the complex of geophysical methods. Inversion of anomalies for magnetic and electrical fields would require calculation of vectorial fields which scattering is dependent on environment heterogeneity and anisotropy.

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