

Python for HPC geophysical electromagnetic applications: experiences and perspectives

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Abstract—Nowadays, the electromagnetic modelling are a fundamental tool in geophysics due to their wide field of application: hydrocarbon and mineral exploration, reservoir monitoring, CO₂ storage characterization, geothermal reservoir imaging and many others. In particular, the 3D CSEM forward modelling (FM) is an established tool in the oil & gas industry because of the hope that the application of such methods would eventually lead to the direct detection of hydrocarbons through their insulating properties. Although 3D CSEM FM is nowadays a well-known geophysical prospecting tool and his fundamental mathematical theory is well-established, the state-of-art shows a relative scarcity of robust, flexible, modular and open-source codes to simulate these problems on HPC platforms, which is crucial in the future goal of solving inverse problems. In this talk we describe our experience and perspectives in the development of an HPC python code for the 3D CSEM FM, namely, PETGEM. We focus on three points: 1) 3D CSEM FM theory from a practical point of view, 2) PETGEM features and Python potential for HPC applications, and 3) Modelling results of real-life 3D CSEM FM cases. These points depict that PETGEM could be an attractive and competitive HPC tool to simulate real-scale of 3D CSEM FM in geophysics.

Index Terms—Python, HPC, electromagnetic modelling, geophysics.

I. 3D CSEM FM THEORY

Regardless of the scope or scale of the surveys, exploration geophysics methods are based on studying the propagation of the different physical fields within the Earth. In the context of geophysical exploration, the main target of these methods is to build a constrained model of geology, lithology and fluid properties based upon which commercial decisions about reservoir exploration, development and management can be made [7]. Nowadays, the three main technologies in applied geophysics are: seismic methods, potential field methods (magnetic and gravity approaches) and electromagnetic methods. Each of these methods processes a set of data within an integrated framework, so that the resultant Earth model is coherent with all data used in its construction.

In the oil & gas sector, the seismic methods have become a standard technique for obtaining high-resolution images of structure and stratigraphy of the Earth. However, seismic data have extremely poor sensitivity to changes in the type of fluids, such as water, brine, oil & gas. It is the main reason why in some scenarios it is difficult, if not impossible, to determine fluid properties from seismic data. The drawback of the seismic method of determining the presence of oil in a formation, encouraged the development of new methods

aimed to strengthen the models and reduce uncertainty. In this sense, the electromagnetic methods (EM) have received special attention from industry and academia. On top of that, the last decade has been a period of rapid growth for EM in geophysics, mostly because of their industrial adoption. In particular, the three-dimensional marine controlled-source electromagnetic forward modelling (3D CSEM FM) method has become an important technique for reducing ambiguities in data interpretation in hydrocarbon exploration.

In 3D CSEM FM a deep-towed electric dipole transmitter is used to produce a low frequency electromagnetic signal (primary field) which interacts with the electrically conductive Earth and induces eddy currents that become sources of a new electromagnetic signal (secondary field). The two fields, the primary and the secondary one, add up to a resultant field, which is measured by remote receivers placed on the seabed. Since the electromagnetic field at low frequencies, for which displacement currents are negligible, depends mainly on the electric conductivity distribution of the ground, it is possible to detect thin resistive layers beneath the seabed by studying the received signal [7]. Operating frequencies of transmitters in CSEM may range between 0.1 and 10 Hz, and the choice depends on the dimensions of a model. In most studies, typical frequencies vary from 0.25 to 1 Hz, which means that for source-receiver offsets of 1012 km, the penetration depth of the method can extend to several kilometres below the seabed [5], [7]. The main disadvantage of 3D CSEM FM is its relatively low resolution compared to seismic imaging. Therefore, marine CSEM is often used in conjunction with seismic surveying as the latter helps to constrain the resistivity model.

II. HPC PYTHON TOOL FOR 3D CSEM FM

In order to be able to predict the electromagnetic signature of a given geological structure, modelling tools provide us with synthetic results which we can then compare to real data. Additionally, in the multi-core and many-core era, parallelization is a crucial issue. Edge Finite Element Method (EFEM) offer good scalability potential. Its low DOF number after primary/secondary field decomposition make them potentially fast, which is crucial in the future goal of solving inverse problems which might involve over 100,000 realizations. As consequence, in past 2 decades the modelling tools have become one of the pillars for the simulation

of numerical methods which main goal is elucidating the fundamental mechanisms behind simplified abstractions of complex phenomena in different areas. The 3D CSEM FM in geophysics is no exception and the scientific community has developed important contributions in this field. In this regard some examples of modelling tools for geophysical prospecting are [1], [6], [7], [8], [9], [10], [11]. However, the tools that full fit needs for the solution of real models are commercial and often are inaccessible to the wider scientific community. Furthermore, details of their implemented methods are generally hidden behind a black box, which could lead to a situation in which the formulation could be unknown. Due to the discretization method employed, not all codes that are affordable to community are capable of dealing with complex geometries such as models including bathymetries. Additionally there are few parallel codes that are flexible, modular, efficient, scalable and can deliver good performance. On top of that, we have developed and documented a new open-source modelling code for 3D CSEM FM in geophysics using Python and its parallel and vectorized techniques on HPC platforms, namely, the Parallel Edge-based Tool for Geophysical Electromagnetic Modelling (PETGEM). Its based on tetrahedral meshes, as these are the easiest to scale-up to very large domains or arbitrary shape, and is written mostly in Python with heavy use of mpi4py and petsc4py packages for parallel computations. Other scientific Python packages used include: H5py for binary data format support, Numpy for efficient array manipulation and Scipy algorithms. PETGEM allow users to specify edge-based variational forms of $H(\text{curl})$ for the simulation of electromagnetic fields in real 3D CSEM FM on shared-memory/distributed-memory HPC platforms. Many features have gradually been included, such as modules for EFEM data structures and a set of Python wrappers for the use of efficient solvers and preconditioners suitable for the resulting matrix system. PETGEM is now a complete package particularly suited for the 3D CSEM FM aiming to foster our understanding about EM in geophysics and its coupling with HPC technologies. Since it was intended tackle realistic problems, its data structure was designed to cope simultaneously three key requirements: accuracy, flexibility and efficiency. In addition the adopted algorithms has the possibility to easily add or remove components without having to rewrite large parts of the code. This approach leads to optimal performance in terms of development and computation time, in other words, PETGEM uses Python as a glue language for interconnecting different modules of codes written in compiled languages. By exploiting this methodology, complex scientific modelling codes can take advantage of the best attributes of both worlds: the efficient high-level data structures and a simple but effective approach to object-oriented programming of Python, and the well-know efficiency of compiled languages for numerically intensive computations.

III. RESULTS AND CODE AVAILABILITY

We have verified the PETGEM solutions by comparison to well-established CSEM models. In [2] we described the simulation results for a canonical model of an off-shore hydrocarbon reservoir. Additionally, in [3] we presented a 3D CSEM

FM with bathymetry. This model is especially interesting because the EFEM allow precise and efficient representations of arbitrarily complex geological structures such as seafloor bathymetry without critically increasing problem sizes. In both cases, the numerical solutions obtained with PETGEM were found in good agreement with reference models. Finally, in [4] we depicted some performance improvements for the parallel assembly of EFEM matrices. The code is available at <http://petgem.bsc.es> or by requesting the author (octavio.castillo@bsc.es). The code is supplied in a manner to ease the immediate execution under Linux platforms.

IV. CONCLUSIONS

The 3D CSEM modelling is well established and widely used in industry and academy to define and characterize bodies by its electric resistivity, which help us to conduct exploration campaigns with a significant reduction of costs and risks. On the other hand, simulation and modelling tools help us to formalize and simplify the complexity we observe in nature. This simplification together to HPC advances allow us to render natural phenomena treatable and testable. We developed and documented the PETGEM as a new open-source tool to promote the use and understanding of 3D CSEM FM in geophysics using HPC architectures and Python. Future work will focus on the study of code performance in other modeling scenarios. This effort, we hope, will foster our understanding about the 3D CSEM modelling and its coupling with HPC technologies.

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