Python for HPC geophysical electromagnetic applications: experiences and perspectives

Octavio Castillo-Reyes, Josep de la Puente and José María Cela
Geosciences Applications Group
Computer Applications in Science & Engineering
Barcelona Supercomputing Center-Centro Nacional de Supercomputación (BSC-CNS)

***Abstract*—Nowadays, the electromagnetic modelling are a fundamental tool in geophysics due to their wide field of application: hydrocarbon and mineral exploration, reservoir monitoring, CO_2 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 scarsity 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(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 posibility 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.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 644202. The research leading to these results has received funding from the European Union's Horizon 2020 Programme (2014-2020) and from Brazilian Ministry of Science, Technology and Innovation through Rede Nacional de Pesquisa (RNP) under the HPC4E Project (www.hpc4e.eu), grant agreement No. 689772. In addition, authors gratefully acknowledge the support from the Mexican National Council for Science and Technology (CONACyT).

References

[1] **Alumbaugh, D. L. and Newman, G. A. and Prevost, L. and Shadid, J. N. (1996)**. Three-dimensional wideband electromagnetic modeling on massively parallel computers. Radio Science. Wiley Online Library.

[2] **Castillo-Reyes, O., de la Puente, J., Puzyrev, V., Cela, J. M. (2016)**. Edge-based parallel framework for the simulation of 3D CSEM surveys. ICE, Society of Exploration Geophysicists.

[3] **Castillo-Reyes, O., de la Puente, J., Cela, J. M. (2017-submitted)**. PETGEM V1.0: Parallel code for 3D CSEM forward modelling in geophysics using edge finite elements Geoscientific Model Development Journal.

[4] **Castillo-Reyes, O., de la Puente, J., Cela, J. M. (2016)**. Improving edge finite element assembly for geophysical electromagnetic modelling on shared-memory architectures. IEEE.

[5] **Hanif, N. H.and Hussain, N. and Yahya, N. and Daud, H. and Yahya, N. and Noh, M. (2011)**. 1D Modeling of Controlled-Source Electromagnetic (CSEM) Data using Finite Element Method for Hydrocarbon Detection in Shallow Water. Proceedings of the International MultiConference of Engineers and Computer Scientists.

[6] **Key, K. and Weiss, C.** (**2006**). Adaptive finite-element modeling using unstructured grids: The 2D magnetotelluric example. Geophysics.
[7] **Koldan, J.** (**2013**). Numerical solution of 3-D electromagnetic problems in exploration geophysics and its implementation on massively parallel computers. PhD thesis, Polytechnic University of Catalonia.
[8] **Li, Y. and Dai, S.** (**2011**). Finite element modelling of marine controlled-source electromagnetic responses in two-dimensional dipping anisotropic onductivity structures. Geophysical Journal International.
[9] **Mackie, R. L. and Smith, J. T. and Madden, T. R.** (**1994**). Three-dimensional electromagnetic modeling using finite difference equations: The magnetotelluric example. Radio Science. Wiley Online Library.
[10] **Newman, G. A. and Alumbaugh, D. L.** (**2002**). Three-dimensional induction logging problems, Part 2: A finite-difference solution. Geophysics.
[11] **Xiong, Z. and Raiche, A. and Sugeng, F.** (**2000**). Efficient solution of full domain 3D electromagnetic modelling problems. Exploration Geophysics.

Octavio Castillo-Reyes has his barchelor's in Computer Systems engineering from Xalapa Institute of Technology, Mexico and M.Sc. In Networks and Telecommunications from Atenas Veracruzana University, Mexico. He has previously worked as lecturer at the University of Veracruz, particularly in the Master in Telematic Engineering and Bachelor in Administrative Computer Systems. His scientific interests range in the broad fields of computational methods, finite element method, multiprocessor architectures, parallel programming, python, performance and workload characterization. Octavio Castillo Reyes is currently associate PhD student at Barcelona Supercomputing Center under the supervision of PhD. José María Cela Espn and PhD Josep de la Puente. His doctoral thesis is about Edge-based finite element method for the solution of electromagnetic problems in geophysics and its coupling on HPC architectures. Octavio Castillo is supported by a studentship from Mexican National Council for Science and Technology (CONACYT).