A New Array System for Multiphysics (MT, LOTEM, and Microseismics) with Focus on Reservoir Monitoring

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Abstract. Over the last 6 years we developed an array system for electromagnetic acquisition (magnetotelluric & long offset transient electromagnetics [LOTEM]) that includes microseismic acquisition. While predominantly used for magnetotellurics, we focus on the autonomous operation as reservoir monitoring system including a shallow borehole receiver and 100/150 KVA transmitter. A marine extension is also under development. For Enhanced Oil recovery (EOR), in addition to reservoir flood front movements, reservoir seal integrity has become an issue [1]. Seal integrity is best addressed with microseismics while the water flood front is best addressed with electromagnetics. Since the flooded reservoir is conductive and the hydrocarbon saturated part is resistive, you need both magnetic and electric fields. The fluid imaging is addressed using electromagnetics. To overcome the volume-focus inherent to electromagnetics a new methodology to focus the sensitivity under the receiver is proposed. Field data and 3D modeling confirm this could increase the efficiency of LOTEM to reservoir monitoring.

INTRODUCTION & BACKGROUND

Standard applications for Controlled Source Electromagnetics (CSEM) have been in exploration. Onshore, only limited applications have been done for geothermal/hydrocarbon applications in the past 20 years [4]. The biggest market, a multi-billion-dollar market, is EOR. Thus, we focus here on the implementation of CSEM for monitoring.

EOR is always challenged by knowing the oil/water (or steam) front. Only limited geophysical techniques are applied. Reservoir seal integrity is best addressed with microseismics [1] and water flood front best with electromagnetics. Since the flooded reservoir is conductive and the hydrocarbon saturated part is resistive you need both magnetic and electric fields. After careful 3D feasibility and noise tests, we have selected CSEM in the time domain as the most sensitive method [2,3]. From the 3D modeling, we derived as key requirement that borehole and surface data needed to be integrated by measuring between surface to borehole and calibrated using conventional logs including anisotropy. This would significantly reduce the risk [4]. 4D Geophysical datasets obtained are images of the evolution of the reservoir using its production history. They show physical reservoir changes during production, a result of change in pores or injection fluids displacement. Geophysical data away the wellbores improves lateral reservoir understanding. The engineers are enabled to obtain a higher recovery factor.

Figure 1 gives an overview of the hardware components. The system follows seismic architecture [17], and a complete seismic/EM node is displayed on the upper left side. To its right is the marine equivalent and at the bottom right the controlled source transmitter. Recently, also 150 KVA version capable to produce up to 250 A of this have been deployed. On the lower left side is a picture of a laboratory prototype for a deep borehole tool that utilizes the infrastructure of a commercial borehole tool. In the center is the setup diagram of our recent shallow borehole tool. All systems can measure seismic and EM signal in in one unit at the same time. The array acquisition system can record from DC to 40 kHz with almost any geophysical receiver. The acquisition system and CSEM transmitter are autonomous and can operate various methods using a scheduler or can be controlled via web access.

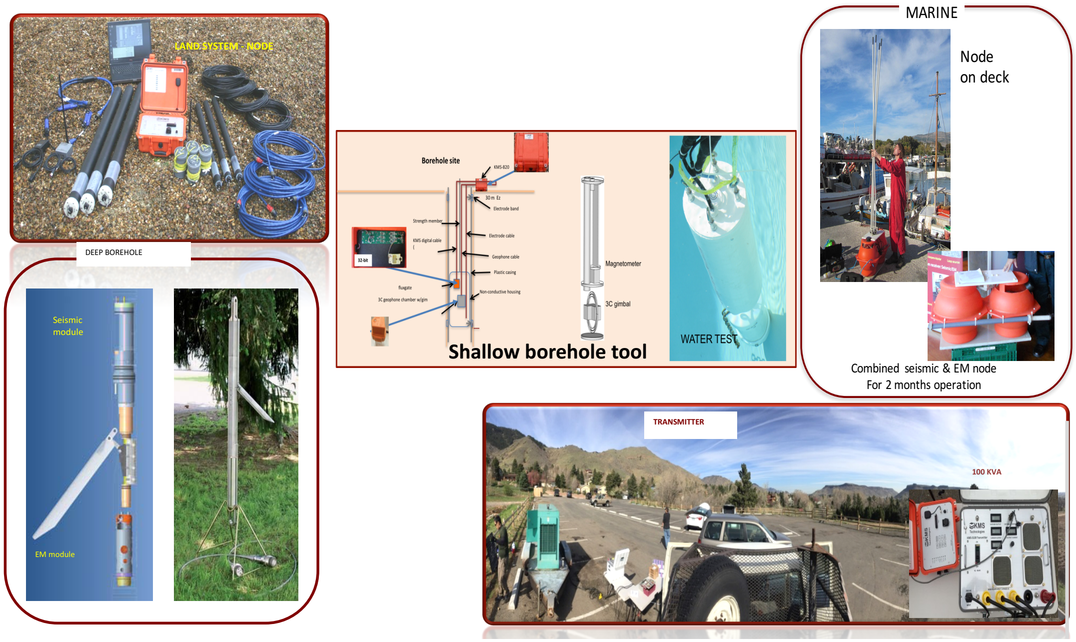

FIGURE 1: System hardware examples for the multi-physics array electromagnetic system.

These system components make up a reservoir monitoring system whose layout is in Figure 2. Here, we see the layout with 3 cross dipole transmitters to get tensor measurements and determine the electrical anisotropy of the reservoir and the layers above and below. We have 3 lines with multiple receivers, nodes and wired sub-acquisition units, its mix shown in the table in the figure. A shallow (20-30 m) borehole tool is deployed at every node locations. It measures 3-component (3C) magnetic and electric fields as well as the 3C microseismic signal. A reference receiver is used for noise rejection. The combinations of electromagnetics and seismic was proposed by Strack and Vozoff [8] and Thomsen [9] and is now possible with modern technology.

Microseismic sensors

Site	KMS instrument	Ex & Ey	Hz	3C fluxgate H	3C geophone	Shallow borehole tool
	820	x	x	x	x	x
	831	x			x	

E – electric field sensors
H – magnetic field sensors

Shallow Borehole Tool – KMS-888 includes 3C seismic, 3C magnetic & 3C electric sensors

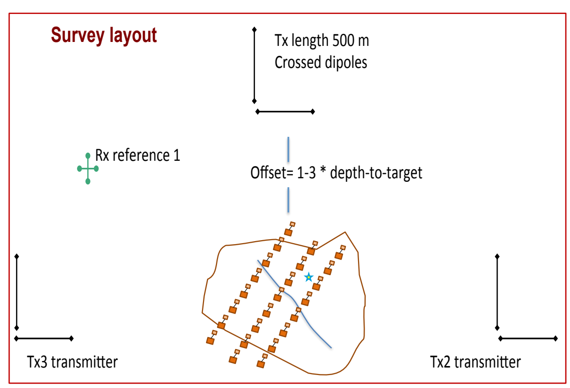

FIGURE 2. Generic survey layout for monitoring applications for a flood front using multi-physics geophysical sensors.

Challenges to EM methods are the information focus and noise. We address this by using differential focusing methods known as Focused Source EM (FSEM) [10, 11, 12, 13] and adding shallow/deep boreholes to the system [14, 15]. In addition, we use array data processing methods to optimize the noise rejection. This methodology is described in Figure 3. The FSEM configuration works like focused borehole laterologs. The differences between adjacent receivers is subtracted and appropriately normalized to only produce a sensitivity to the vertical electric field.

Figure 3. shows on the left the sensitivity (2D) for different receiver offsets for frequency and time domain. In the frequency domain, we sample the entire volume between transmitter and receiver and in the time domain we are sensitive to a volume below the receiver **and** a volume below the transmitter. Applying the FSEM technique, we obtain mostly sensitivity below the receiver as depicted on the right of the figure, showing the response for the methods for a 3D reservoir target at 2 km depth. The CSEM methods yields an anomaly of 40% while the FSEM is much larger. Another benefit of applying FSEM is that it removes near surface effects.

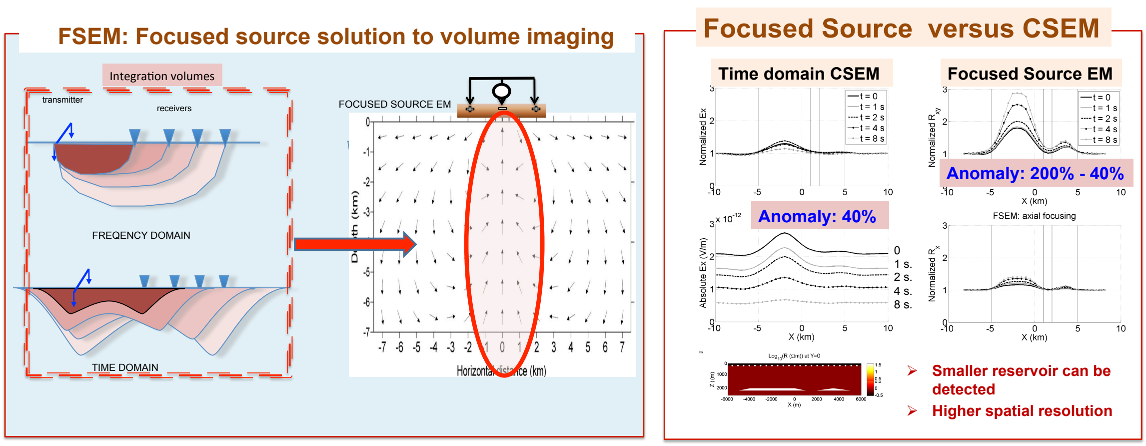

FIGURE 3. Summary sensitivity plots on the left and on the right Focused Source EM (FSEM). On the right are 3D modeling results for a 2-km depth reservoir model for time domain and FSEM.

PROPOSED METHODOLOGY

Measuring the right components and using the right operations parameters requires a careful approach. We use 3D Feasibility Studies and design the optimum survey parameters. Over the past 30+ years using this approach in many surveys around the world we always achieved consistency between Feasibility modeling and survey. Albeit, in more than 50% of the cases, the anomaly is too small to apply EM. Key element in the design of any monitoring is a strategy combining 3D modeling, geologic and petrophysical model, flooding operations and acquisition parameters.

First, we select several candidate reservoirs. Based on the resistivity signature derived from logs we then select one for 3D Feasibility. Since most hydrocarbon reservoirs are electrically anisotropic and consist of resistive (oil) and conductive (brine) targets, every monitoring project with a 3D modeling feasibility uses well logs to derive the anisotropic resistivity models and seismic horizons for the reservoir boundaries. After fluid substitution, we can estimate the expected anomaly. We concluded from several cases (US, Middle East and Asia) that magnetic and electrical tensor measurements are required. When modern anisotropy logs are absent, the anisotropy is estimated using equivalence principle first suggested by Keller [16]. An example from a geothermal reservoir in the USA is shown in Figure 4. The colored curves correspond to different offsets and show a ± 10% anomaly. The models were constrained by 3D seismic (Horizon 3 & 4) by matching the reservoir depth to the seismic layers. Noise test data over the reservoir using different sensors was added (right side). The results are converted to sensor voltages using the transmitter and receiver parameters. Getting the very best signal-to-noise ratio is paramount to ensure reliable data. On the right of Figure 4, the voltages for layout on its left are shown. Different sensor thresholds are marked in the figure. Here, the air coil gave best results. From this, we propose a field layout as in Figure 2. We also carried out a pilot field installation and partially confirmed the prediction from 3D modeling.

CONCLUSIONS

CSEM methods are used for geothermal exploration and only to a limited extend for land hydrocarbon exploration. Offshore they are becoming part of the routine workflow. The interest in land electromagnetic applications has increased to appoint that a complete new generation of technology exists including new array acquisition hardware, transmitter, shallow borehole sensors and processing and 3D interpretation methods.

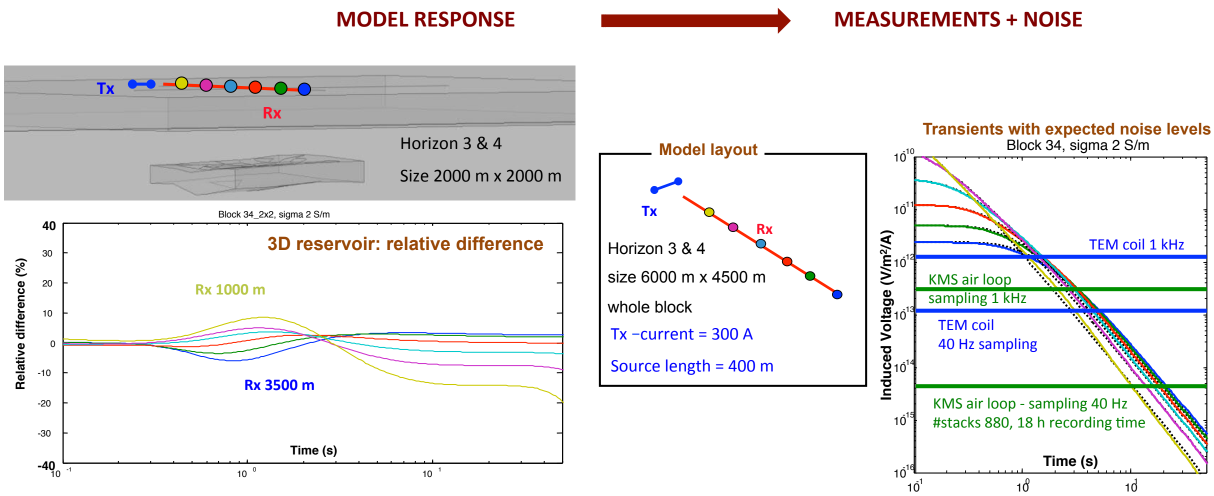

FIGURE 4. Example 3D model and its response where the receivers are located at the surface along a profile. Noise test results (right) superimposed on the 3D modeling results (converted to voltages).

The real potential for CSEM methods lies is reservoir monitoring and its various applications. Among the geophysical methods, electromagnetic methods are the most suitable methods for this task as they allow fluid imaging. To find the sweat spot in applications careful Feasibility study can reduce the risk to carry out Pilot for water/steam flooding and greatly contribute to the production effort.

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