2025-2026 Moncrief Grand Challenge Award Final Report

Awardee: **Carlos Torres-Verdín, Professor, Brian James Jennings Memorial Endowed Chair in Petroleum and Geosystems Engineering**
Hildebrand Department of Petroleum and Geosystems Engineering

Research Award Title: **Real-Time 3D Inversion of Deep-Sensing Borehole Electromagnetic Measurements for Reactive Well Navigation Across Spatially Complex Rocks: Applications to Subsurface Water/Energy Production, CO_2 Sequestration, Hydrogen Storage, and Geothermal Systems**

Research Summary

High-angle and horizontal wells have been widely used during the last 25 years to navigate through the subsurface while targeting a variety of fluids, minerals, and energy resources. Drilling and navigating deep high-angle wells is overly expensive, time consuming, and unsafe because of extremely variable and uncertain rock mechanical properties. The process of well navigation is commonly driven by measurements acquired at or near the drill bit, which sense rock properties within less than 0.3 m away from the well trajectory. These measurements are not ideal for well navigation and reactive feedback control because what is being sensed in close proximity to the well often cannot be extrapolated ahead or around the drill bit to adjust the well trajectory. Drilling and service companies have recently developed a new set of deep-sensing, low-frequency borehole electromagnetic (EM) measurements capable of detecting rock electrical resistivity ahead and around of the drill bit to distances between 10 to 50 meters. The outstanding technical/engineering challenge is to accomplish real-time 3D inversion of the measurements for effective (real time) reactive adjustment of the well trajectory during navigation.

Deep-sensing borehole EM measurements are typically acquired every 1 m along the well trajectory, each sampling point consisting of at least 4 activation frequencies in the range from 20 kHz to 4 MHz and 4 different tri-axial antenna configurations/spacings for the transmission and detection of signals. Numerically simulating these measurements along a 4-km well trajectory (a common occurrence) and 3D subsurface variations of electrical resistivity requires more than 2 CPU hours on TACC with the most efficient and massively parallel finite-volume or finite-element numerical algorithms. Inverting/imaging the measurements into 3D subsurface variations of electrical resistivity around the well trajectory is not only CPU-time and memory demanding on TACC but also extremely unstable and non-unique in the presence of measurement noise.

This project successfully developed and verified efficient and robust 3D inversion methods for the interpretation of deep-sensing borehole EM measurements during reactive subsurface well navigation. The latter inversion algorithms are based on gradient-based minimization of the data misfit (i.e., the quadratic difference between the measurements and their numerical simulations) implemented on massively parallel computers, yielding spatial distributions of anisotropic electrical resistivity together with their uncertainty.

Research Results

Specific accomplishments achieved during the duration of this award are as follows:

(1) Implemented existing finite-volume codes for the 3D numerical simulation of deep-sensing borehole EM measurements for their execution on TACC with multi-CPU parallelization (linear solvers + multi-acquisition locations along the well trajectory).
(2) Developed and verified fast 1D "curtain" gradient-based inversion methods to interpret borehole EM measurements acquired along arbitrary well trajectories several kilometers in length. The inversion algorithm is referenced to a background 3D model and delivers "pixelized" results for anisotropic electrical resistivity and its uncertainty within minutes of CPU time.
(3) Based on the data misfit stemming from fast 1D inversions, local 2D gradient-based inversions were implemented (where needed along the well trajectory) via gradient-based minimization The 2D inversion algorithm was implemented on multi-CPU nodes (both linear solvers and adjoint calculations) and delivers "pixelized" results for anisotropic electrical resistivity and its uncertainty within minutes of CPU time.
(4) Based on the data misfit stemming from 2D inversions, local 3D gradient-based inversions were implemented (where needed along the well trajectory) via gradient-based minimization. The 3D inversion algorithm delivers "pixelized" results for anisotropic electrical resistivity and its uncertainty within minutes of CPU time.

The above 1D, 2D, and 3D sequential inversion algorithms were successfully tested and verified using (a) challenging 3D synthetic models and arbitrary well trajectories (inspired by field measurements), and (b) actual field measurements. Figure 1 below shows an example of results obtained with the developed 1D, 2D, and 3D sequential inversion algorithms when implemented on field measurements acquired in the North Sea (provided by Aker BP).

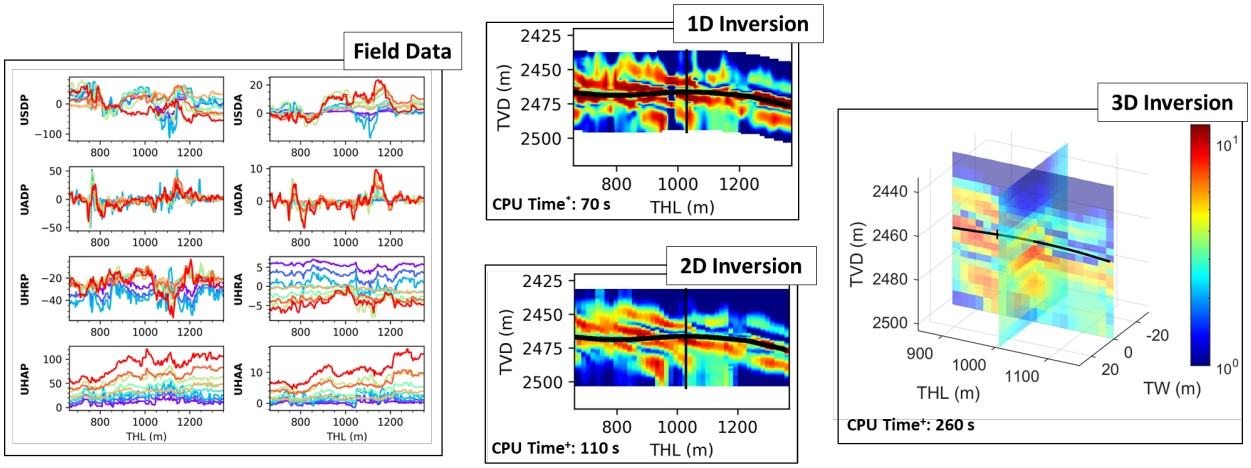

Figure 1. Example of inversion-based interpretation of deep-sensing borehole EM measurements acquired along a 1.4 km well trajectory in the North Sea. The left panel shows the tri-axial electromagnetic measurements, while the remaining panels show the well trajectory (curved black line) and the spatial distribution of electrical resistivity (red and blue are high and low values of electrical resistivity in ohm-m, respectively, with the color scale described in the right panel) interpreted using 1D, 2D, and 3D sequential inversion algorithms. TVD = true vertical depth, and THL = true horizontal length. Inverted electrical resistivity images around the well trajectory shown in color include isolated high-resistivity features not intersected by the well trajectory which correspond to oil-bearing sandstones. Data courtesy of Aker BP.

Journal Publications Stemming from this Award

Saputra, W. and Torres-Verdín, C., Ambia, J., Klappauf, B.G., Zhan, W., Jahani, N., Zimmerling, J., Druskin, V., Davydycheva, S., Davydychev, I., and Fjeldberg, E.R., 2025, *Recent developments and verifications of multi-dimensional and data-adaptive inversion of borehole UDAR measurements*: **Petrophysics**, v. 67, no. 1, pp. 173-189.

Saputra, W., Torres-Verdín, C., Jahani, N., Zimmerling, J.J., Druskin, V., and Davydycheva, S., 2026, *Some common pitfalls in the inversion of borehole UDAR measurement*: **Petrophysics**, accepted for publication.

Saputra, W., Rabinovich, M., Martakov, S., Fjeldberg, E.R., Torres-Verdín, C., 2026, *Rapid Data-Adaptive 1D Occam's Inversion of Ultra-Deep Azimuthal Resistivity Measurements with Uncertainty Quantification*: **Geophysics**, under review.

Saputra, W., Fjeldberg, E.R., Zimmerling, J., Torres-Verdín, C., 2026, *Rapid 2D Occam's Inversion of Ultra-Deep Borehole Azimuthal Resistivity Measurements*: **Geophysical Journal International**, under review.

Saputra, W., Fjeldberg, E.R., Zimmerling, J., Torres-Verdín, C., 2026, *Rapid 3D Occam's Inversion of Ultra-Deep Borehole Azimuthal Resistivity Measurements*: under preparation.

Conference Extended Abstracts Stemming from this Award

Saputra, W., **Torres-Verdín, C.**, Jahani, N., Zimmerling, J.J., Druskin, V., and Davydycheva, S., 2026, *Rapid adaptive 2D/3D UDAR inversion: leveraging a new block Gauss-Radau solver and adjoint solutions* (Expanded Abstract): **Ultra Deep Azimuthal Resistivity (UDAR), Society of Petrophysicists and Well Log Analysts (SPWLA) Topical Conference**, London, UK, March 23-25.

Saputra, W., Torres-Verdín, C., Jahani, N., Zimmerling, J.J., Druskin, V., and Davydycheva, S., 2026, *Some common pitfalls in the inversion of borehole UDAR measurements* (Expanded Abstract): **Ultra Deep Azimuthal Resistivity (UDAR), Society of Petrophysicists and Well Log Analysts (SPWLA) Topical Conference**, London, UK, March 23-25.