AI-Enhanced Physics-Based Modeling and Sensor Fusion for Mud Level Estimation in Deep Well Pipes

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The 3d Saudi Aramco Upstream Digital Hackathon

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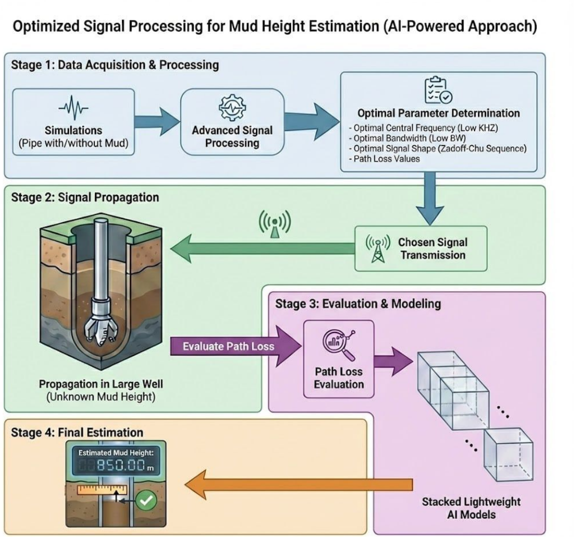
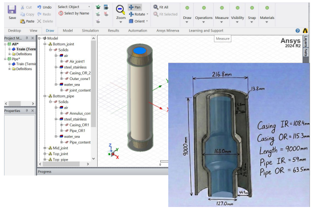
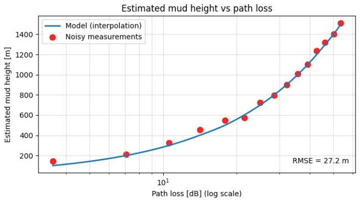
Simulation & Signal Optimization







Accuracy ~ 98 %

Abstract

Lost circulation during drilling causes formation damage and wellbore instability, making reliable fluid-level monitoring critical. Conventional methods fail in the noisy annulus environment (vibrations, gases, dust). This project develops a non-intrusive measurement system combining physics-based simulation (HFSS) with deep-learning signal optimization and multi-sensor fusion. A 1 m hardware prototype equipped with several sensors was tested under realistic noise conditions. Machine-learning models achieved centimeter-level mud-height estimation accuracy, significantly outperforming single-sensor market solutions and enabling real-time monitoring via an integrated dashboard.

Physics-Based Modeling

The annulus, drill pipe, casing, and fluid domains were modeled using API 5DP / ISO 11961–compliant dimensions. A single 9 m section was simulated to characterize wave propagation and identify optimal frequency, bandwidth, and transmitter parameters. Whole-well propagation to 1.5 km depth is then predicted using lightweight machine-learning models combined with advanced signal-processing–based channel equalization, enabling reliable mud-level estimation.

System Prototyping

A 1-meter scaled prototype featured a 3D-printed wellbore and motorized drill pipe to mimic drilling conditions. Surface-mounted sensors collected data under varying mud levels and noise, fused via machine learning to estimate height with errors under a few centimeters. A real-time dashboard processes inputs and displays mud levels for operator decisions.

Key Insights

- **Physics-based HFSS modeling** → Realistic wellbore geometry and material modeling reveal propagation behavior that cannot be inferred from simplified or analytical models.
- **Signal Design is Critical** → Proper selection of frequency, bandwidth, and waveform significantly improves resilience to noise and structural losses.
- **AI-extended simulation** → Lightweight AI models extrapolate high-fidelity 9 meter simulations to kilometer-scale wellbores without prohibitive computational cost.
- **Multi-sensor fusion** → Combining complementary measurements provides more robust mud-level estimation than single-sensor approaches under realistic noise conditions.

Hardware Prototype & Sensor Fusion