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Affordable and Fast Geosteering Inversion Using A Physics-Driven Deep Learning Network

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Outline

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Introduction
Background

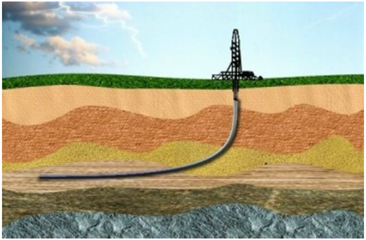

Figure 1: The schema of directional drilling. (www.amerexco.com)

- Geosteering is a key technique in directional drilling.
  - The sensors on drilling tool could collect electromagnetic data.
  - The drilling angle would be adjusted by analyzing collected data.
- Logging and drilling need to be synchronous.
- Two methods for logging.

Introduction
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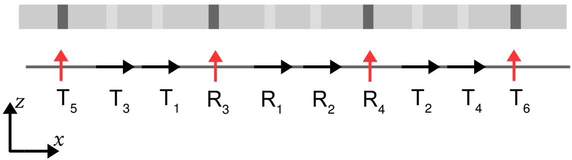

Figure 2: FWI logging tool with antennas.

- The drilling tool has antennas in different directions.
- T represents transmitting antennas, and R represents receiving antennas.
- The collected data for each receiver is a combination of the reflected transmitting signals.

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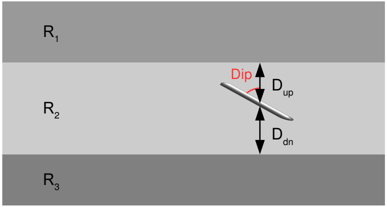


Figure 3: Directional drilling schema for an example of 3-layer model.

- The earth model are formulated by geophysical parameters.
- R represents resistivities, $\mathrm{D_{up}}$ and $\mathrm{D_{dn}}$ are boundaries, and Dip is the dip angle.
- The observed measurements are collected by the receiving antennas.

Introduction
Background

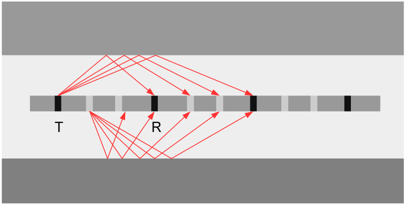


Figure 4: The wave propagation during drilling.

- The transmitted EM signal would be reflected when meeting the boundaries of different media.
- The received signal for each R is a combination of different reflected waves from different transmitters.

Introduction
Problem

Geosteering Inverse Problem

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \mathscr{L}(\mathbf{x}) = \arg\min_{\mathbf{x}} \|\mathbf{y} - \mathscr{F}(\mathbf{x})\|_2^2 + \lambda \mathscr{R}(\mathbf{x}). \tag{1}$$

$$\frac{\partial \mathscr{L}}{\partial \mathbf{x}} = 2(\mathbf{y} - \mathscr{F}(\mathbf{x}))\frac{\partial \mathscr{F}}{\partial \mathbf{x}} + \lambda \frac{\partial \mathscr{R}}{\partial \mathbf{x}}. \tag{2}$$

- In (1), the electromagnetic forward model could be regarded as a function $\mathscr{F}$ which accepts the earth model and produces synthetic measurements. $\mathscr{R}$ is a regularization term.
- (2) is usually used in deterministic optimization [1, 2]. The gradient $\frac{\partial \mathscr{F}}{\partial \mathbf{x}}$ is a *Jacobian* matrix which could be numerically calculated.

Introduction
Challenge

- Two methods for logging.

Table 1: Different logging methods.

	On ground	Underground
Data Amount	Inadequate	Adequate
Computation	Fast	Slow
Memory	Large	Small

- On ground method.
  - Data is not enough but hardware is powerful.
  - Use optimization method.
- Underground method.
  - All data is available but hardware is limited.
  - Use lookup table.

Introduction
Challenge

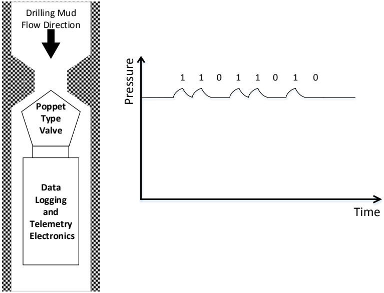


Figure 5: Positive Pulse Pressure Wave Generator and Corresponding Pressure Waveform with Encoded Digital Data. [3]

- The collected data need to be transmitted back to the ground by pressure wave.
- The communication rate would be a bottle neck.

Introduction
Challenge

Table X	Table Y
0x0000: A=0, B=0, C=0	0x0000: F(0, 0, 0)
0x0001: A=0, B=0, C=1	0x0001: F(0, 0, 1)
0x0002: A=0, B=0, C=2	0x0002: F(0, 0, 2)
...	...
0x0013: A=0, B=0, C=19	0x0013: F(0, 0, 19)
0x0014: A=0, B=1, C=0	0x0014: F(0, 1, 0)
0x0015: A=0, B=1, C=1	0x0015: F(0, 1, 1)
...	...
0x018F: A=0, B=19, C=19	0x018F: F(0, 19, 19)
0x0190: A=1, B=0, C=0	0x0190: F(1, 0, 0)
...	...
0x1F3F: A=19, B=19, C=19	0x1F3F: F(19, 19, 19)

Figure 6: Lookup table method for fast estimation of the inversion.

- Use the best-matched sample in the table to estimate a coarse solution.
- Drawbacks:
  - Large memory consumption.
  - Samples are extremely coarse.

Outline

Proposed Method
Network Structure

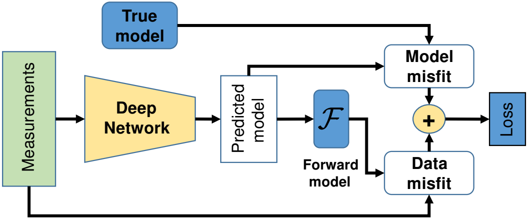


Figure 7: The deep physics-driven CNN structure.

- The deep network is a 1D network which is adapted from VGG16 model. The model is trained by Adam optimizer [4].
- Each convolutional layer composes of a convolution, an instance normalization [5] and a PReLu activation [6].
- The loss function of the network includes a model misfit ($\|\mathbf{x}-\hat{\mathbf{x}}\|$) and a data misfit ($\|\mathbf{y}-\mathscr{F}(\hat{\mathbf{x}})\|$).

Proposed Method
Back Propagation

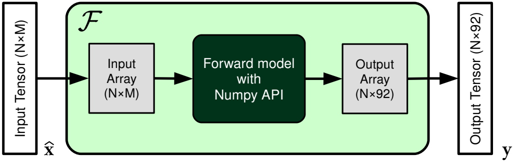


Figure 8: The implement of the forward model.

- The forward model function is highly nonlinear.
- It accepts the earth model parameter ($1 \times M$ vector) and produces the synthetic measurements (1×92 vector).
- We use N to represent N samples.

Proposed Method

Back Propagation

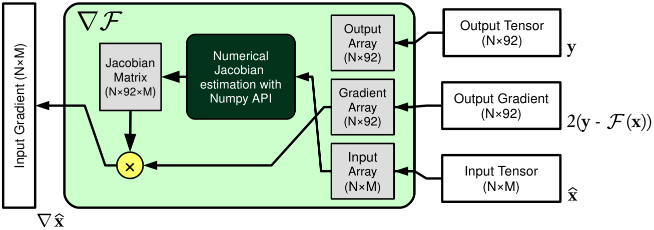


Figure 9: The implement of the forward model.

- The back-propagation only uses the current synthetic input of the forward model ($\hat{\mathbf{x}}$) and the gradient from the next layer ($2(\mathbf{y} - \mathscr{F}(\mathbf{x}))$).
- The gradient would be back-propagated to the previous layer in the deep network.

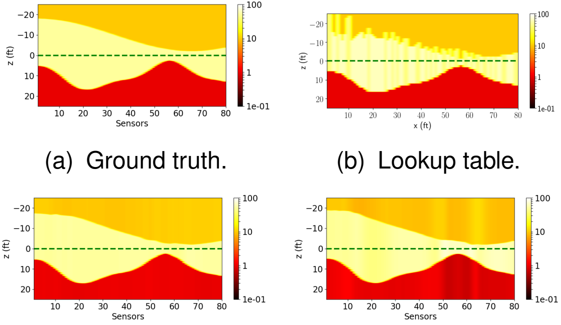
Proposed Method
Advantages

- The network could be deployed for underground method.
  - The network is totally **feed-forward** and only requires **light computation** (about 0.3s for 80 points). The lookup table is slower (about 60s) while the optimization method is much slower (about 400s).
  - The network has **a small data size** (lower than 30MB) compared to a lookup table (about 1.6GB), which requires **lower memory consumption**.
- The network could make use of **all data** by taking advantage of underground method, while the optimization method could not.
- The network could get a far more **accurate prediction** compared to lookup table.
- The **computational cost** of the network **would not increase** with the data amount.

Outline

Results

Example: 3-layer model inversion



(a) Ground truth. (b) Lookup table.

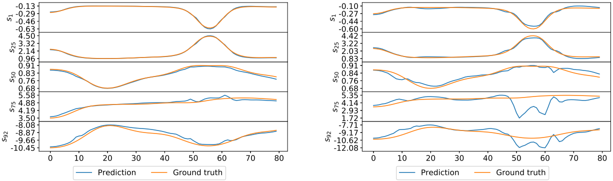
(c) DNN with physics. (d) DNN without physics.

Figure 10: The result of an example.

- The results show the comparison of the predicted earth models.
- The proposed network achieves better resistivity prediction compared to that of the conventional data-driven network.

Results

Example: 3-layer model inversion



(a) With physics engine. (b) Without physics engine.

Figure 11: The result of an example.

- We select some curves which show that the physics-driven network could achieve a better curve fitness.

Results
Numerical Tests

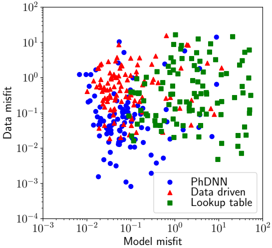


Figure 12: The numerical tests over compared methods.

- We generated 100 examples earth models like the shown one.
- The test over the 100 examples show that compared to the data-driven network, the proposed one could achieve the same model misfit but a better data misfit.

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Reference

Ack.

Q&A

Reference I

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Acknowledgment

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Q&A