Next-generation Geological Model Updating and Ranking for Improved Oil Recovery*  
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Abstract  
The conventional oil production practices recover, on average, approximately one third of the original oil in place with estimated remaining mobile oil. To increase the overall production, large investments are made in Improved Oil Recovery (IOR) of which success greatly depends on the ability to estimate volumes and locations of bypassed oil from available historical data using History Matching techniques. We present a new approach with the potential to more accurately capture uncertainty of the inherent geological model, facilitate accurate description of reservoir heterogeneities and honor the conceptual depositional model.  
The novelty lies in direct interfacing between Next-generation geological modeling and forward simulator. Efficient model parameterization that enables rapid generation of model updates in wave-number domain is used to characterize the main features of geologic uncertainty space: structural, stratigraphic, facies and petrophysical properties. Model inversion workflow is based on multi-step Bayesian Markov chain Monte Carlo (MCMC). Traditional MCMC methods provide most rigorous sampling of posterior distribution but suffer from high computational cost. We implement an approach where proxy model is guided by streamline-based sensitivities, dispensing with the need to run forward simulation for every model realization, thus significantly reducing the computation time. An ensemble of sufficiently diverse model realizations is generated at the high-resolution geological scale that secures more accurate results by obeying known geostatistics and well constraints.  
The workflow is validated on a case-study combining geological model with ~1M cells, four different depositional environments and 30 wells with 10-year water-flood history. A history match indicates significant reduction in the misfit between observed and simulated water-cut curves, even for producers with difficult non-monotonic behavior.
Finally, the method is described to rank dynamically the reconciled model realizations for identifying the highest potential, to capture bypassed oil and implement IOR solutions. The main features include use of fast streamline simulations to calculate dynamic model responses (e.g. recovery factors), evaluate their dissimilarity with pattern-recognition techniques and assigning of a few realizations, representative for production forecasting, to full-physics simulation.

References


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Outline

- Objective…
- Uncertainty in Geological Models
- History Matching and Uncertainty Management
- Next-generation Geological Modeling
- Model Parameterization and Reduction
- Model Inversion:
  - Multi-stage Markov chain Monte Carlo…
  - Validation
- Dynamic Model Ranking
  - Validation
- Summary & Conclusions
Objective…

All-in-one Uncertainty Quantification Workflow fully integrated on a unified database

- Minimum or no model up-scaling,
- Include multiple types/scales of data and 1st order effects,
- Capture full range of outcomes,
- Reduce analysis & decision time.

Coupling Geo-modeling, Reservoir modeling, Wells and Surface Network Models in...
... Big-loop Reservoir Management

1. Geo-cellular model
2. Seismic constraints
3. Dynamic data: reservoir, wells, facilities...
4. Uncertainty
5. Updates: production data, 4D seismic, logs...

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Uncertainty in Geological Models

High Resolution Geological Model (HRGM)

- **Structural model**
  defines gross volumes

- **Stratigraphic model**
  layering controls lateral connectivity
  variogram range controls vertical connectivity

- **Facies model**
  controls depositional continuity

- **Petrophysical model**
  defines property distribution

Uncertainty impact:

Higher

Lower
Bayesian inference: assessing parameter uncertainty

Gaussian form of likelihood term

\[
p_{d|m}(d | m) \propto \exp \left[ -\frac{1}{2} (d - g(m))^T C^{-1}_d (d - g(m)) \right]
\]

Gaussian form of prior term

\[
p_{m}(m) \propto \exp \left[ -\frac{1}{2} (m - m^0)^T C^{-1}_M (m - m^0) \right]
\]

Bayesian model

\[
p_{m|d}(m | d) = \frac{p_{d|m}(d | m)p_{m}(m)}{p_d(d)}
\]

\[
m = \text{model} \quad d = \text{data} \quad g = \text{simulator}
\]
History Matching in a nutshell…

… a systematic procedure of altering a reservoir simulation model to reproduce the dynamic field response by honoring geological constraints!

… **OBJECTIVE:** Minimize the error between measured and simulated response!

**DATA USED:**
- Production data
- Pressure data
- Other (temp profiles, saturation distribution…)

**The Future of AHM**
- Intelligent and intensive use of cluster computing.
- Ensemble-based methods to capture model uncertainty.
- Hierarchical ranking of model uncertainties.
- Optimal model resolution.
Quantitative Uncertainty Management

- High-resolution static model
- Model parameterization
- PROBABILISTIC INVERSION
- Streamline sensitivities
- Dynamic production data
- Flow simulator
- Analysis & Ranking of HM-ed Models
- Ranked HM-ed models
- Forecast of Production

Assisted History Matching
Dynamic Model Ranking
Next-generation Geological Modeling

Stratigraphic modeling
- Lithotype proportions: accurate and efficient representation of geological non-stationarity (trends)

Facies modeling
- Lithotype rules
- Vertical Proportion Matrices: define how the facies behave vertically over the area of the reservoir

Facies simulation
- Geologically driven: ultra sophisticated, simple to use, combine different variogram model types, each exhibiting different anisotropic conditions.
Generation of Geo-model Realizations

**Statigraphic grid**  
**Rules for Facies Simulation**  
**Rules for PP Simulation**

**Next-generation Geo Modeling API**

**Facies model**  
**Porosity model**

Challenges for AHM workflow

- Preserve realism of high-resolution model.
- Retain distribution of main features that have control over depositional connectivity, *i.e.* facies.
- Perform **FAST** model updating.

Model parameterization
Model Parameterization

HIGHLIGHTS

• **Speed**: wave-number approach eliminates the need for prior Cov matrix inversion

• **Geological realism**: adheres to the geological detail of the initial static model.

• **Versatility**: preserves low frequency moments of the image, which correspond to large features, *e.g.* facies

• **Statistical soundness**: produces statistically unbiased prior model realization.

• **Flexibility**: fully applicable to multi-million-sized models.

Initial log-perm model

Log-perm maps, Brugge fluvial, top-layer, 9 realizations
Multi-stage Markov chain Monte Carlo (MCMC) - I

Proxy Likelihood Model

For a proposed transition

\[ \delta m = m^* - m^i \]

the change in model parameters to the change in forward model response is related via streamline sensitivity matrix \( S \):

\[ \delta d = S \delta m \]

Streamline Sensitivities: derivatives of a streamline travel time with respect to model parameters e.g. permeability, porosity, BHP, fluid saturation…
Multi-stage Markov chain Monte Carlo (MCMC) - II

Generate model realizations

- Calculate exact likelihood

- Generate new proposal

- Calculate approximate likelihood with sensitivities

- Accepted?
  - yes
  - Forward simulation (response & sensitivities)
  - Calculate exact likelihood
  - Accepted?
    - yes
    - Promote proposal
    - Convergence achieved?
      - no
      - Collect proposal
      - no
  - no
- yes
- yes

Acceptance Criterion – Stage 1
Standard Metropolis - Hastings

Acceptance Criterion – Stage 2
Standard Metropolis - Hastings
Multi-stage Markov chain Monte Carlo (MCMC) - III

Generate model realizations
  ↓
Calculate exact likelihood
  ↓
Generate new proposal
  ↓
Calculate approximate likelihood with sensitivities
  ↓
Accepted?
    no
    Forward simulation (response & sensitivities)
    ↓
    Calculate exact likelihood
    ↓
    Accepted?
      no
      Convergence achieved?
        no
        Collect proposal
        ↓
        yes
        yes
    yes
    yes
  yes
Stage 1

Convergence diagnostics

Entropy, $S$

$$S = -\left\langle p_{m|d} \log(p_{m|d}(m|d)) \right\rangle$$
Interfacing Geological Modeling and Simulator

Next-generation geological model

Stage 1

Node 1
Model Realization 1
Simulator run 1
Proxy Model 1
Sample OF model update 1
Simulator run 1
Sample OF model update 1
Stage 2

Node 2
Model Realization 2
Simulator run 2
Proxy Model 2
Sample OF model update 2
Simulator run 2
Sample OF model update 2

Node n
Model Realization n
Simulator run n
Proxy Model n
Sample OF model update n
Simulator run n
Sample OF model update n

Convergence test
Data analysis

Reservoir (forward) simulation is most time consuming step!

- Use of cluster and parallel CPU computation is imperative!
- Considerable gains in effective computation time!
- Example simulation: ~3h /w 1 Quad; ~45 min /w 4 Quads.

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Validation: benchmark model

Next-generation Geo-model: Brugge field

- 4 depositional systems, 1 fault
- Grid: 211 x 76 x 56 → ~900k cells
- 20 producers, 10 injectors: all vertical, perforating through all 56 layers
Water-cut Curves

Prior model realizations

Posterior model realizations

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Water-cut Curves: mean & variance

Mean

Variance

- prior model
- posterior model
- observed data
- initial model
Convergence Diagnostics

Conventional MCMC can be 4-5 times slower…!
History-matched Permeability Models

Layer 1 of three model realizations (log-perm scale).
Dynamic Model Ranking - I

... Assisted History Matching is inherently ill-posed and can generate non-geological realizations. Such models are **NOT** suitable for production forecasting!

Fast flow simulations on models

Connectivity-distance matrix

```
<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>θ₁₁</td>
<td>θ₁₂</td>
<td>θ₁₃</td>
</tr>
<tr>
<td>2</td>
<td>θ₂₁</td>
<td>θ₂₂</td>
<td>θ₂₃</td>
</tr>
<tr>
<td>3</td>
<td>θ₃₁</td>
<td>θ₃₂</td>
<td>θ₃₃</td>
</tr>
</tbody>
</table>
```

\[ θ_{ki} = \sqrt{\sum_{re} (RF_k - RF_i)^2} \]

Post-MDS matrix with data-point map in Euclidean domain

```
<table>
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</thead>
<tbody>
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</tr>
<tr>
<td>3</td>
<td>T₃₁</td>
<td>T₃₂</td>
<td>T₃₃</td>
</tr>
</tbody>
</table>
```

Non-linear Euclidean domain

Kernel K-means Clustering

Only model responses closest to cluster centroids in \( E \) domain are simulated with full-physics simulator to construct the URF cdf!

Modified from:
Scheidt & Caers, 2009;
Alpak et al., 2010.
Dynamic Model Ranking - II

Validation: arbitrary “synthetic” dataset, with 100 recovery factor curves…

Recovery factor (RF) curves

...optimal number of clusters

...selected clusters with centroids

...generated URF cdf with simulated cluster centroid RF data…

Recovery factor curves associated with cluster centroids…
Quantifying and ranking the impact of uncertainty in underlying geological models is of fundamental importance when reconciling with dynamic data!

Workflow introduces novel aspects to quantification of uncertainty for Integrated Asset Management and Production Forecasting:

a) Integrates and dynamically interfaces reservoir simulator with next-generation Geological modeling. Future development will consider multi-level approach to history-match reservoir pressures and define/update pore scale features – followed by well-by-well HM.

b) History-matching of well production data interfaces high-resolution subsurface models and robust model parameterization and updating, with great adherence to geological detail!

c) Fully automated, parallel and load-distributed, without compromising statistical rigor – applicable to large-scale, real-time projects!

d) Uncertainty ranking of history-matched models to intelligently select an optimal geological model that secures the best (most likely) response for production forecasting!

The workflow is currently being developed and implemented in collaboration with the Middle East partner.