Use of 4D Seismic and Production Data for History Matching and Optimisation—Application to Norne (Norway)

SPE Applied Technology Workshop, 14–16 June 2011, Rica Nidelven Hotel, Trondheim, Norway

Scribe's Report

Wednesday, 15 June

Keynote Speaker Session

Session Managers: Lars Høier, Statoil and Jon Kleppe, NTNU

Opening Remarks

Session managers introduced the objective of the workshop. They reminded that enough time is assigned for discussions and audiences are very welcome to ask all questions.

They also highlighted that Statoil released massive data of Norne field for education and research. In addition to several field case studies, several posters would be presented during coffee breaks.

Key Note Speaker

Paul Van Den Hoek, Shell

COUPLED HISTORY MATCHING OF PRODUCTION AND 4D SEISMIC DATA

- Time-Lapse Seismic and Production Data Integration
  - Use of derivatives / adjoints (hard-coded in in-house reservoir simulator at well locations)
  - “Pseudowells” at locations of 4D seismic measurements
- SYNTHETIC FIELD
  - Fairly homogeneous initial permeability field, with reduced permeability in z direction
  - Significant differences in the saturation front between “pre-HM” field and the truth
  - Wells are operating on liquid constraints that were obtained from historical data

- Coupled AHM of production and 4D seismic (offshore Europe)

  - Reservoir property changes between a base and a monitor time determined by seismic inversion
  - Gradients with respect to several reservoir parameters (a.o. porosities and permeabilities) provides valuable understanding of boundaries and reservoir connectivity
  - Very efficient method as production and seismic front matches are improved substantially (1 order of magnitude) within a few iterations (10 hrs to achieve match)

- AHM Application to W Africa reservoir – PRODUCTION + 4D

  - Uncertain parameters; Total 18 parameters: model selection parameters, KvKh, permeability multipliers, connectivity factor et al.
  - Optimization method; PSO (particle swarm optimization); stochastic optimization, gradient-free
  - Data and objective function; 4D data: amplitude attributes; 4D inclusion: Focus only on the fluid front; The objective function is defined as the pixel difference between the binary maps, plus the difference between production history minus simulated history

- Application to W Africa reservoir (Three scenarios):

  - Base case model (production history matching using ED – from Asset)
  - Updated model using only production data (PSO)
  - Updated model using both 4D seismic and production data (PSO)

  ED=Experimental Design
  PSO=Particle Swarm Optimization method

- Saturation difference using only production data; The fluid fronts are partially corrected

- Saturation difference using both production and 4D seismic data; The fluid fronts are successfully corrected

- Conclusions

  - “Efficient” AHM methods to assimilate 4D seismic data simultaneously with production data
  - Adding 4D seismic on top of production data reduces uncertainties in reservoir parameters & can change “base case” results
  - 4D can provide significant extra information about areal distribution of reservoir properties (e.g. permeability) in flooded zones

Discussion:

How to use 4D seismic to improve reservoir models?

- Qualitative vs. quantitative – is quantitative use needed? Is quantitative use achievable? If yes, how?
- Consistency with geology
- "4D seismic could help us with areal petrophysics"

Full seismic inversion (3D / 4D)

- Stochastic vs. deterministic
- We do depend on a prior – to which extent is this acceptable?
- "Close-the-loop"-feedback towards geology – downscaling issues etc.
- Do we always need full inversion or can we do with attributes in certain (which?) cases?

To which extent will quantitative incorporation of 4D seismic results into improving our production forecast?

- Dependence on (type of) business decision
    - E.g. NFA vs. infill drilling vs. SFR development vs. IOR->EOR …

What is quantitative or qualitative? For Africa case all were based on the maps but in the early case it used to plot permeability profile. In the seismic, quantitative is going through 4D to saturation and pressure but here it was toward permeability and not necessarily through saturation and pressure.

It is risky to use one initial guess and derivative and it is a general problem. Using several times with several priors will decrease that risk.

How frequent is the 4D seismic? As showed in the last case, 3 sets of 4D seismic.

There are three permeabilities per grid block and no parameterization has been used.

Session I: The Norne Field and Benchmark Case

Session Managers: Jan Inge Skagen, and Fridtjof Nyhavn

Speaker # 1: Jan Inge Skagen, Statoil

Norne – tail production with a great potential

- Norne Exploration history
    - Awarded 1986
        - Statoil (Operator),
        - Eni Norge AS partner
        - Petoro AS partner

- Why has Norne been successful with respect to reserves development ?
    - "Nice" reservoir:
        - Good quality sand in Not, Ile and Tofte

        - Phi= 25-30 % , k = 50-3000 mD
        - 140 m HC-column (110m oil and overlying gas-cap)
        - Pres = 273 bar @2639 m TVD, Tres=98C
        - Pb=250 bar, GOR= 111
        - Oil density= 0.7 g/cc , Viscocity = 0.5 cp
        - Bo=1.32 , Bg=0.0047
        - Wettabiliy: mixed

- <u>First some key reservoir data</u>
        - Laterally homogenous reservoir
        - Faults and carbonate cemented zones have a significant influence on the flow pattern
        - Barrier modelling is important:
        - Carbonate cemented layers
        - Faults

- <u>Norne Drainage Strategy</u>

    - By PDO in 1997 the drainage strategy was depletion, gas injection in Not in the gas cap and sea water injection in the undelaying Tofte Fm.
    - 1998: Gas injection in Not was stopped due to rapid pressure build up. Gas was injection in Tofte instead alternating with sea water injection.
    - 2005: Gas injection was stopped due to gas migrating to Not shale building up pressure close to fracture pressure.
    - 2016: From approximately 2016 the gas cap will be produced.
- <u>The first 4D monitor survey over Norne was acquired in 2001. After that 5 new monitors have been acquired over Norne, approximately every 2nd year.</u>

- <u>4D in reservoir management</u>
    - Planning wells
        - 17 wells drilled based on 4D
    - Updating reservoir models
    - 4D value ~4.3 billion NOK (~0.7 billion USD)

- <u>Norne main field and recovery</u>
    - We still got about 9% to produce from the Norne main field
    - 4D acquisition is of significant importance in identifying small target less than 300k Sm3.
    - Realizing the small targets with the TTRD/TTML technique by utilising the Category B vessel.
    - Another 2-5% increase in recovery factor.

- <u>Norne main field and FPSO</u>

- We recover about 60% of the existing hydrocarbons (World record for subsea fields !!).
- We have 7 templates installed on the main field seafloor.
- We have drilled 27 wells on the main field
- 19 producers and 8 injectors
- Only 10 wells are producing , many of them have a water-cut of more than 80%.

Discussion:

What was the policy about data acquisition? The value of data acquisition is well acknowledged in this work and the fact that it will be paid back later is strongly considered.

Is water injection the primary method or other methods such as polymer or surfactant methods have been used? Water injection was almost the primary method and polymer or surfactant injections have not been used.

Have all segments been produced? Yes, all segments have been produced.

Do the 4D results and pilot well observations match? Yes, they qualitatively match.

To what extent quantitative data seems necessary? Data acquisition especially for oil pockets seems necessary.

Speaker #2: Bjarne Foss, NTNU/IO Center

Introduction to Benchmark Case

- Main research areas
  - Drilling
  - Reservoir management and Production optimization
  - Operations and Maintenance
  - Work processes

- Reservoir and well models
  - (Tool: Eclipse)

- Network model
  - (Tool: GAP)

- Process model
  - (Tool: HYSIS)

Research funding (Research Council of Norway); Research partners (NTNU, Sintef and IFE); Collaborating International academic partners and industrial partners.

- Background
  - The Norne pilot project is the first benchmark case based on real field data

- It was established through discussions between the IO Centre at NTNU and Norne Field Operations
- The benchmark and integrated data set is hosted and supported by the IO center at NTNU
- It is accessible for non-commercial research and education at universities and in research institutions/companies
- The Norne field on the Norwegian Continental Shelf is operated by Statoil, ENI and Petoro

- Scope and Objectives
  - Explore the use of a real integrated data set for research purposes
  - Test and compare the merits of a variety of methods for history matching and closed loop reservoir management
  - Publication of scientific results
  - The exploration of a new business model – Open innovation
  - The sharing of results and new knowledge with the Norne Field organization, Statoil and IO Center participants
  - Identify issues to improve the Norne benchmark case
  - The integrated dataset is presently used in courses, semester projects and theses work by students and researchers at NTNU and IO Center partners

Discussion:
More information and also, contact details are available on the website.

Speaker # 3: Stein Krogstad, Sintef/IO Center

Model Reduction and Coarsening Based on Local PODs

- Motivation
  - Reuse of computations:
    - Often multiple simulations are run with slightly varying input.
    - Can we reuse computations from one simulation to the next for increased efficiency?
- Goal
  - A coarsened model with fine model accuracy close to previous full simulation runs.
- Here
  - Use a local POD-approach to construct local (multiscale) flux-bases spanning snapshots from previous simulation runs.

- Full simulation of Norne model – basis for pressure
  - Partition grid into coarse blocks
  - Perform SVD for pressure in each block
  - Sort all singular values, truncate, and collect corresponding local bases

- Localized Basis for Model Reduction
    - Why?
        - Local changes $\Rightarrow$ local updates
        - Aim at more *process independence* than with global basis
        - Possible to include underlying coarse discretization
            - Avoid need of jacobian from simulator?
        - High number of basis functions only where needed
- Numerical Examples
    - Procedure:
        1. Run one tuning simulation
        2. Collect fluxes over each coarse grid interfaces and compute truncated SVDs
        3. Compute (interface) multiscale basis functions
        4. Collect remaining snapshot span for each block and compute truncated SVDs to get local block bases
        5. New simulation with different configuration is performed using multiscale and block bases.

- Concluding Remarks

    - Except for very coarse grids, good match between coarse models and reference
    - Strong gravity effects require many basis functions, but if effects are local, methodology can still be efficient
    - Finer coarse grids $\Rightarrow$ more process independence and less storage (but more degrees of freedom ...).

Discussion:

It is tried to make the method non-process based. Then it will not be important how much far from tuning do we run.

Session II: Norne Comparative Case Study

Session Managers: Richard Rwechungura, Mohsen Dadashpour and Nan Cheng

Speaker # 1: Amit Suman, Stanford University

Joint Inversion of Production and Time-Lapse Seismic Data of Norne Field

- Smart Fields; data, updated detailed model, update reduced model, optimization, controls, production System.

- Joint Inversion for Norne
  - Use of 4D seismic and production data for history matching and optimization – application to Norne
  - Focus on Norne segment E

- Norne Field Segment E
  - Southern part of Norwegian sea
  - 3 producer and 2 injector wells in segment E
    - Five prime zones: Garn,Not, Ile, Tofte , Tilje

- Particle Swarm Optimization
  - Successfully used in other branches of engineering
  - Use in geosciences still remains restrained

- Three tuning parameters: Inertia, local acceleration and global acceleration.
- Permeability models are generated based on PORO-PERM relationship for each zone.
- 70th PCA coefficient (value =0.35) has one tenth value of highest PCA coefficient (value=3.5). Thus 70 no. of PCA coefficients selected for analysis.
- All compressibilities are in the order of e-09(1/pa)
- 5 sets of relative permeability curves are selected for variations
- Total 99 parameters for optimization
- Seismic data is in time domain but reservoir models are in depth
- Comparison of relative RMS amplitude change on top of segment E (10.7 for observed data)
- The best model is obtained after 20 iterations. Several models can be selected instead of one best model

- Conclusions
  - Particle swarm optimization method is applied for joint inversion of time lapse and production data of Norne field
  - Next step is to explore different versions of PSO specially PP-PSO and CP-PSO (explorative in nature)
  - In future either seismic attributes or seismic interpreted properties would be compared over the whole reservoir model

Discussion:

Was only saturation considered? Pressure was considered, too. The core data was not available for investigation the changes of velocity.

The vertical resolution is on the surface only and the reservoir resolution is not a matter of discussion.
The E-segment data was considered. For production data two options could be considered: whole field, or E-segment. It is important that they are connected.
Cleaning data is an important issue.
First, data was not organized. Second, there was some information which was not necessary.
What information regarding geology of reservoir is provided? To which extreme this data makes sense from geological perspective? Most of geological data were prepared but geological model is not ready at this phase, maybe it will be ready for the next phase.

Speaker # 2: Drosos Kourounis, Stanford University

Adjoint Gradient-Based Optimization of the Norne Benchmark Case Using Eclipse and ADGPRS

- Reservoir model
    - Grid 46x112x22, 113344 grid cells, 44927 are active
    - Porosity ranges from 25% to 30%
    - Permeability varies from 20 to 2500 mD.

- Optimizing with Eclipse
    - Strategy
        - Unconstrained gradient-based optimization
            - Ignore nonlinear constraints, use only bound constraints
            - Optimize the whole Norne field using Eclipse300
            - Forward the optimal solution to Eclipse100 to enforce the constraints
        - Constrained gradient-based optimization
            - Let the optimizer handle the constraints
            - Optimize the whole Norne field using Eclipse300
            - Forward the optimal solution to Eclipse100 to enforce the constraints

    - Controls
        - Injectors on water rate control
        - Producers on liquid rate control
    - Objective: NPV
    - Nonlinear constraints
- Gradient free optimization with Eclipse
    - Strategy
        - Injectors and producers on BHP control
        - Nonlinear constraints active during the simulation
        - Apply Hooke-Jeeves algorithm starting from several initial guesses
    - Scenarios considered
        - Optimize only the controls of the E segment wells

        - Optimize the controls of all the wells
    - Optimization methods
        - Short term optimization
            - Optimize the controls of each report step separately; consider each control step as a separate optimization problem
            - The final optimal solution will be the combination of the optimal solutions from each control step
        - Long term optimization
            - Optimize at the same time all controls for all wells for all control steps

- Conclusions
    - Gradient free methods revealed that there is still room for improvement
    - The short term optimization on the coarse description of the model performed well for the E-segment but failed for the whole field as it was worse than the base case on the fine computational model

Discussion:

With two injectors there is a higher recovery? It was up to 2008. It belongs to E-segment but the result belong to full field would be different.

It is always nice to optimize but it has to have physical sense.

It was based on NPV and with different optimization parameters it would be different.

In this work one set of optimal values has been used (NPV). The optimization with more uncertainties would be different.

Speaker # 3: Slawomir Szklarz and Lies Peters, TU Delft/TNO

History Matching of a region of the Norne Field with the Ensemble Kalman Filter

- History matching - Ensemble Kalman Filter
- EnKF – sequentional monte carlo method
- Boundary Treatment; Coarse Grid; 44431 grid points to 9771
- Model in JOA Jewel Suite; Model deck from ECLIPSE100 imported to JOA Jewel Suite
- Necessary edits has been performed in the deck. Some Keywords commented out.
- Sensitivity analysis; Finding field properties highly influencing production
- Conclusions
    - Well dependent results
    - Cost of the experiment (Ensemble size, nr of assimilation times, updated properties)
    - Strong influence of initial ensemble on the results
    - EnKF as a tool to detect problems in the model

Discussion:

There were 60 models? Just the mean has been looked.

The results for well E-3AH has not been updated caused some errors.
Correlation based on lab data has been used for relative permeability and J-function.

Speaker # 4: Eric Bhark, Texas A & M

Multiscale Parameterization and Streamline-Based Dynamic Data Integration for Production Optimization

- <u>Objective</u>
    - Develop optimal production strategy (2005 to 2008)
    - Production and seismic data integration

- <u>Conceptual approach</u>
    - Deterministic perspective
    - Single, history matched model (to 12/2003)
    - Global parameters defined
        - Faults and transmissibility multipliers
        - Saturation regions
            - Relative perm, capillary pressure
        - Large-scale permeability & porosity heterogeneity with multipliers
    - Data integration
        - Minimal calibration of prior

- <u>Productiondataintegration</u>
    - Calibrate permeability heterogeneity to fluid rates (to 12/04)
    - Multiscale parameterization (global to local scales)

- <u>Seismic data integration</u>
    - Match (time lapse) changesin acoustic impedance by adjusting water front movement (Sw)
    - Streamline-based techniques

- <u>Production optimization strategy</u>
    - Optimize constrained well rates through forecast period
    - Objective of improving sweep efficiency (fluid arrival time equality along streamlines)

- <u>Parameterization</u>
    - Grid-connectivity-based transform (GCT)
    - GCT basis vectors

- <u>Summary</u>
    - Production data integration

        - Global to local permeability calibration
            - Multiscaleparameterization
        - Minimally update (pre-calibrated) prior model
    - (Sequential) Seismic data integration
        - Match change in acoustic impedance between 2001 and 2003
        - Calibrate cell permeability based-on streamlines traced from producers
            - Cell saturations through water front movement
        - Well-captured positive changes
    - Production schedule optimization
        - Established base scenario of E-3H-sidetrack (large remaining oil pore volume) and F-1H gas injection (lower costs)
        - Improved RF and NPV by equalization and reduction of fluid travel times

<u>Discussion</u>:
Parameterization of whole field with 71 parameters.
Negatives in acoustic impedance mean changes associated only with water movements.
Finite difference and convergency? This sensitivity is based on incompressible assumption and gas is present.
It is already a good match by production. The prior here is a good case.

Speaker #5: Ola T Miljeteig and Anass Nii-Armah Ammah, NTNU

Using Production and 4D Seismic Data for History Matching and EOR Optimization on the Norne Field

- <u>History matching</u>
    - Chosen approach
    - Seismic data in history matching
    - Results
    - Thoughts/Remarks

- <u>Production Optimization</u>
    - Well pattern optimization
    - Low salinity waterflooding
    - Thoughts/Remarks

- <u>Manual history matching approach</u>
- <u>Matching mainly oil production rates & water cuts</u>
- <u>Qualitative use of seismic data (Matching OWCs from seismic)</u>
- <u>Used the provided Eclipse 100 coarse-grid model</u>
- <u>Visualization and plotting mainly in FloViz and Eclipse Office, but:</u>
- <u>Petrel for visualization of faults and comparison with seismic</u>

- Conclusions of history matching part
  - Improved match with production data
  - Seismic OWCs helped invalidate some potential models
  - But:
  - Problems matching the OWC from 2001
  - Still had problems deciding on which history match was “the best”?
  - Fine-tuning proved time consuming (Limited value?)

- Production optimization:
  - Remaining oil, mostly in the Ile Formation
  - Low-salinity front doesn’t reach production wells

- Conclusions of production optimization part
  - Managed to increase NPV considerably
  - Increased recovery factor in the E-segment from 48.82% to 52.78% with two sidetracked wells
  - Little/No effect of Low Salinity Water Injection:
    - Low-salinity water doesn’t propagate fast enough
    - E01-fault acts as barrier for low-salinity water

Discussion:
Changing relative permeability then microsweep and macrosweep must be considered and analyzed.
This process was manual and took almost 12 weeks for history matching.
Did you use log data? The already captured data have been used and assumed to be imported.
How did you apply two contacts or equilibrium regions? It is changed respect to time.

Thursday, 16 June

Session III: Similar Case Studies

Session Managers: Rob Arts and David Echeverria Ciaurri

Speaker # 1: Xuri Huang, SunRise PetroSolutions

Close the loop between geophysics and reservoir engineering:
A HM and optimization view

- Use reservoir and production data to further update seismic interpretation and vice versa
- Data-based
- Model-based
- Choose pilot-point using time-lapse seismic difference!
- Find a rock model which builds a relationship between reservoir properties (dynamic and static) and seismic responses.
- Screen the synthetic seismic with observed for seismic mismatch
- Modify the reservoir according to seismic mismatch

- Optimization of Production case
  - Optimization generates a new injection rate distribution by constraining the process using the seismic difference attribute
  - Seismic constraint improves the history matching

- Summary
  - By close-the-loop in model domain, seismic data can help to update the reservoir model.
  - Inversion based for HM may help engineers to use the seismic data, but the reservoir model should loop with inversion process.
  - It is feasible to use seismic data for production optimization

Discussion:
How do you move between seismic and reservoir model scale? If you have mismatch so probably something is missed, e.g. sands, faults, etc.
You captured most of the rock model then some resolution missed? Seismic and reservoir model in the first step must be match logically.
About rock model; and locally match? This is manual and interactive; so, you switch try several time.

Speaker # 2: Geir Evensen, Statoil

Integrated workflow for model updating and conditioning on 4D seismic data

- Approach
  - Updateable structural models with uncertainty.
  - Use of 3D/4D seismic data when building the static geological model.

- Automated work process from geological modelling to simulated profiles.
- Multiple realizations are used to represent and propagate uncertainty.
- Conditioning the whole model chain on dynamic data using ensemble methods

- <u>Grane field case</u>
  - Deformed turbidite reservoir, highly irregular reservoir base and top.
  - Sand injections above reservoir.
  - Pressure support by injecting imported gas
  - Produced from long horizontal wells located just above the oil-water contact.
  - 4D surveys: 2005, 2007, 2009

- <u>Within the EnKF framework it is possible to include 4D seismic as one type of measurement.</u>
- <u>A petro elastic model is included in the loop to forward model the reservoir properties to synthetic seismic.</u>
- <u>Different types of seismic should be possible to include in this optimisation, and by using the Grane as a test case, we have the possibility to test different types of input. It can be a fluid contact, a 4D time shift, 4D inversion data or any other 4D attribute.</u>
- <u>Sand Probability from 3D and 4D inversion data</u>
- <u>Uncertainties in the structural model; Velocity model from Seabed to Top-Reservoir</u>

- <u>Summary</u>
  - Example of successful big-loop conditioning of a field model on 3D and 4D seismic data and production data.
  - Workflow is implemented in the Grane field unit, and is currently being developed for Snorre as well.
  - Methodological framework is mathematically consistent and pragmatic solution methods are used.
  - Advice: Spend 90% of your time on the static model description!
-

<u>Discussion</u>:
Uncertainty is mostly velocity model? Also, porosity and permeability.

When talking about propagation of uncertainties, how many models do you use for that? 60 models have been used for that but less would be better for computations.

The number of models is not important. You need sufficient number of models to capture the HM to 4D time shift.

In this case there was a good match even with prior models, so we just do a fine tuning.

90% of the time was for static model. Static model has its uncertainties can be solved by dynamic models.

In the workflow there was a flexibility to assign uncertainties to parameters.

Speaker # 3: Pallav Sarma, Chevron

Enhancement of the CPR Preconditioner for Efficient Solution of the Adjoint Equation, and Application to Large Scale Models

- Introduction to the adjoint equations
- Derivation of the CPRA preconditioner
- Validation of the CPRA preconditioner
- Application to production optimization

- To develop a preconditioner that
  - efficiently solves a linear equation with transpose of the Jacobian matrix from a fully implicit reservoir simulator

  and, therefore,
  - enables solution of the adjoint equations for large and/or complex models that cannot be solved by vanilla solvers

- Issues with solution of the adjoint equations:
  - Generalized preconditioners are impractical for solving the adjoint equations for large and/or complex reservoir models.
  - Preconditioners specialized for reservoir simulation such as Constrained Pressure Residual (CPR) and Nested Factorization (NF) cannot be directly applied to the adjoint equations.

- Validation and application
  - Case 1: Synthetic case (blackoil model); 264 active grids; 2 water injectors and 1 producer
  - Case 2: Field P case (blackoil model); 39,265 active grids; 5 water injectors and 5 producers
  - Case 3: Field L case (blackoil model); 164,281 active grids; 11 water injectors and 15 producers

- Well Control Optimization of Field L
  - Both adjoint-based and ensemble-based gradients (SPE121307) are applied for comparison purposes
  - ~17% increase in NPV is obtained. Adjoint approach requires ~10 simulations (including adjoint simulations) whereas ensemble approach requires ~600 simulations
  - Increase in NPV is a result of reduced water injection and production
  - Some wells are slowly opened up by the optimizer, resulting in more oil production.
  - Most wells produce at the same oil rate or more as the base case

- <u>Summary</u>
    - A new preconditioner - CPRA - has been developed to solve the adjoint equations efficiently.
    - Adjoint simulations with the CPRA preconditioner take about the same time at most as corresponding forward simulations with the CPR preconditioner.
    - A production optimization case study has further validated the CPRA preconditioner's accuracy, efficiency, and the capability to perform long term optimization.

<u>Discussion:</u>

Have you tried to look at sweep instead NPV? The streamline methods are better for investigating sweep.

The method is to first optimize NPV and then continuing work on that by optimizing sweep efficiency and recovery factor.

Mostly WI is based on simulation; did you use other methods for waterflooding? This tool is more generalized and has been used by other teams.

Speaker # 4: Alexandre Emerick and Al Reynolds, Petrobras

History Matching Marlim Field Using the Ensemble Kalman FilterRepsol not currently in a shale gas venture

- <u>EnKF is a Monte Carlo method in which an ensemble of models (states) is used to describe the mean and covariance.</u>
- <u>Computational efficiency demands to use small ensembles (typically ~100 models).</u>
    - Covariance localization
        - Distance-based covariance localization is a standard fix:
            - Simple and computationally efficient.
            - Determining appropriate correlation lengths for localization is difficult.
        - Localization should include at least:
            - Region of influence of the data (sensitivity).
                - We approximate computing drainage areas (streamlines or pseudo-tracer).
            - Underlying correlation length of the geological model.
- <u>Marlim field – History matching</u>
    - manual history matching
    - 7.6 years for history matching and 2.4 years to compare predictions
    - EnKF and EnKF with localization
    - Initial ensemble (permeability field):
        - 200 models.
        - Sequential Gaussian simulation.
        - "Hard data": permeabilities from well tests.

- Measurements
    - Wells controlled by oil rate and water injection rates.
    - Observations: water rate at producing wells.
    - Standard deviation of measurement errors:
        - Estimated by smoothing the observed data using a moving average and subtracting the observations from the smoothed data.
        - Final average standard deviation: 10% of the data value.

- Half-iteration EnKF
    - EnKF may present consistency problems between the updated vector of model parameters and updated primary variables of the simulator.
    - A simple fix is to rerun simulations from time zero after each data assimilation (HI-EnKF).
    - HI-EnKF increases significantly the computational cost of EnKF.
    - We can save computational time if we rerun only when the average change in the updated ensemble is large.

- Conclusions
    - We defined the localization region based on the prior covariance and the "sensitivity" region.
    - Localization compared to standard EnKF:
        - Smoother ensemble mean.
        - Higher variance in the final ensemble.
        - Better data matches and predictions.
    - Localization compared to the manual history-matched model:
        - Far more geologically realistic models.
        - Better data matches and predictions.
    - HI-EnKF:
        - Significant improvement in data matches and predictions.
        - Computational efficiency can be improved by rerunning the ensemble only when "large" changes in the state occurs.

Discussion:

In term of methodology, this method can be applied to any kind of data.

Why 200 models? People usually use 100 but here 200 models are used and was interests to use even more but it was just a matter of computations.

Session IV: Closed Loop Reservoir Management

Session Managers: Bjarne Foss and Trond Mannseth

Speaker # 1: Dean Oliver, Uni CIPR

Current status and key challenges in ensemble-based history matching

- <u>Two requirements of a good history match</u>
  - The history-matched model should look plausible to the geologis.
  - It should be able to reproduce past observations to a reasonable tolerance.

- <u>Computation of gradient of S is required for minimization</u>
- <u>Key Problems of History Matching Algorithms</u>
  - Large effort involved in matching production data for one realization.
    - Efficient methods require computation of the gradient of data mismatch.
    - Code for an adjoint computation requires access to the simulator source code and storage of intermediate state variables.
    - Time for one history match is on the order of 100 simulations.
  - Uncertainty estimation requires multiple history matches.
  - A need for updating (assimilate new data without destroying matched old data)

- <u>Ensemble Kalman filter</u>
  - Alternative to traditional history matching
    - Adjoint code is not needed
    - Can build upon any reservoir simulator
  - Sequential data assimilation
  - Provides uncertainty quantification
  - Suitable for parallel computing
  - Better convergence behavior (maybe)

- <u>Generating samples from the posterior pdf</u>
- <u>Brugge Field: SPE-ATW Test Case</u>
  - <u>A test case for data assimilation and production optimization methods on a waterflooded oil reservoir</u>
  - <u>Real field data is invaluable for testing history matching and data assimilation.</u>
  - <u>Synthetic cases are necessary for testing closed-loop reservoir optimization.</u>

- <u>Summary</u>
  - General
    - The EnKF (without iteration) often works remarkably well for history matching - even for nonlinear problems with non-Gaussian variables.
    - Multiple history-matched models are obtained - some uncertainty assessment
  - Data
    - Incorporates production data and time-lapse seismic.

- Variables
    - Gridblock permeability, porosity, and NTG.
    - I Relative perm parameters, uid contacts, fault transmissibility and average layer properties.
    - Some ability to update structure, fault position, and facies boundaries (e.g. shales)

Discussion:
105 models have been used. all had same behavior? The ensemble didn't collapse.
If model corrupted it couldn't get to right answer.

Speaker # 2: Vidar Hepsø, Statoil/NTNU; Thomas Østerlie, NTNU

Open innovation of subsurface software

- Background
    - Significant investments on research and development within the subsurface domain
    - Limited impact within operation subsurface communities

- Question
    - How can technology platforms be used to foster open innovation within the subsurface domain?

- Research approach
    - Study innovation processes within the subsurface domain

- Closed innovation principles
    - The smart people in the field work for us
    - To profit from R&D we must discover, develop and ship it ourselves
    - If we discover it ourselves, we go to market first
    - If we are the first to commercialize an innovation, we will win
    - If we create the most and best ideas in the industry, we will win
    - We should control our IP so that our competitors don't profit from our ideas
- Open innovation principles
    - Not all the smart people work for us
    - External R&D can create value; internal R&D is needed to claim a portion of that value
    - We don't have to originate the research in order to profit from it
    - Building a better business model is better than getting to market first
    - If we make the best use of both internal and external ideas, we will win
    - We should profit from others' use of our IP and vice versa

- 'Innovation', pragmatic definition:

- Any technique or technology contributing towards increasing production volumes

- Use of production data in practice
- Data-driven innovation cycle
- Example: Sand monitoring
  - Challenge #1: Technology adoption
  - Challenge #2: Data utilization
    - Data administration
    - Dual materiality

- Open innovation, open source

Discussion:

People in research and production are in different world and it makes sometimes the circle missed. For example for QC of data you need people from production in research.

How universities can address their role in development plans?

The role of universities and research institutes in such a platform is still asked.

Panel Session

Panel Speakers: Rob Arts, TNO, David Echeverria Ciaurri, IBM, Vidar Hepsø, Statoil, Lars Høier, Statoil, Pallav Sarma, Chevron

Panel Speakers

- The perspective of Norne field is great and rather than some similar previous cases, it is challenging and creative for this kind of studies.
- It is really hard to compare different results to choose one as the best, or to choose a method of these.
- The most important and valuable point is to find where differences between different studies and methods happened.
- The seismic data have not been widely used at least in some sessions it is considerable.
- Of course, it must be mentioned that based on the characteristics of Norne field, the use of seismic is a little typical.
- Also, fluid contacts in this model are typical.
- Uncertainties on horizons are interesting and of course, more uncertainties exist which must be considered.
- Is a more quantitative work going through more inversions of uncertainties is necessary? Or more robust?

- It seems necessary to know that in benchmark studies which methods are implemented.
- All related data of Norne field are not released and it seems for a better job more data especially production data, are necessary.
- This field was more complicated than previous similar cases, and fewer participants were present.
- It is hard to get so many conclusions based on different methods used.
- How much advance can be gained by automatic or semiautomatic history matching in terms of time, etc?

- Why some people prefer synthetic data?
- Quality Checking of data is an issue specifically in Norne field.
- What's the best method for handling and managing the data of Norne field? For example, by a student association, or etc?
- All methods, more or less, converge to good results but applying the same methods in real reservoir cases will often or maybe always result in worse conditions and results. It is then far from global minimum and you need to work a little different there. How can we come up with good results there?
- These data belonged to the first Norne field data release and hopefully, the next data release will be considered for the next benchmark study.
- It is advantageous for Statoil to release the Norne field data and see the efforts, from a different point of view, on this field. Specially, it is valuable to see the efforts for EOR in Norne field and particularly E-segment in which a considerable residual oil is left.
- The association of data with particular software makes it difficult to be applied in other softwares.
- In some companies people can share their ideas with other employees, even if it is not a completely open innovation, and comment on those to select more realistic and productive ideas for further researches.
- When these methods come to real cases, more realistic (less computations) are essential to be able to apply them to real field cases. This must be considered in methodologies.
- The workshop is a success because the objective was not to look for a winner but to experience working with real data.

Audiences

- When a commercial company person present something about Norne field it will be completely different compared to a presentation by research or university person. So, the idea is so nice to evaluate these, too.
- Most of the efforts have been in production matching; it seems that production forecast is not considered so much while it is also important.

- It is more helpful to state the input data for each study to be able to compare and evaluate different results and studies based on that input data.
- There are not so many geologists present in this workshop if any! It seems that more geologists have to be involved in such a workshop and study.
- The conferences with similar titles but different participants (only reservoir engineers or seismic engineers or geologists) will result in different environment and discussions made based on their expertise. Do reservoir students need more seismic and geology education for multidisciplinary works?
- Companies cannot spend as much time as universities in this kind of study.
- Can 4D seismic help to evaluate the impact of initial oil in place on compaction drive in, for example, carbonate reservoirs?
- It seems to be a better idea to separate history matching from optimization in competitive studies to be able to work on more precise objectives.
- Reservoirs are not generally homogeneous. So, understanding the limitations is so important.

Closing Remarks

- A single conclusion for Norne-field has not been achieved but bringing all these ideas was valuable.
- Based on the decision of share-holders beyond Statoil, the next workshop can be planned in few years.