The National IOR Centre of Norway

# Data assimilation using 4-D seismic data

Project 2.7.6 (TNO)

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# Data assimilation using 4-D seismic data

IOR Centre Theme 2, Task 2.7.6
Final report

## Executive summary

History matching using data assimilation, the use of 4D data, and production optimization are key research areas of The National IOR Centre of Norway. This project entitled “Data assimilation using 4D seismic data” demonstrated methodologies for front-detection based history matching on seismic monitoring field data and therefore delivers to the category of Monitoring tools and history matching in the IOR Centre roadmap. More specifically it delivers to the milestones 6 and 9 according to the roadmap, which is aiming at improved monitoring and history matching using 4D seismic data.

In this 2-year project an existing methodology, consisting of an ensemble based data assimilation technique for history matching to 4D seismic data, has been further developed to become applicable to a field case. The project activities involved, amongst others, model and data preparation, development of distance parametrization and tracking of complex water fronts, enhancements of ensemble based data assimilation techniques, 4D seismic data inversion, and demonstration of the workflow on synthetic cases and a segment of the Norne field case. During the project regular interaction and discussions took place with the IOR Centre Task 7 leader and with other researchers on 4D seismic data within the Centre. Furthermore, results obtained with the workflow were disseminated via conferences, journal papers, workshops and other events.

## Project background

4D seismic data provides abundant information about dynamic changes in the reservoir which are vital for improving reservoir monitoring and management. However, quantitative use of 4D seismic is still challenging. This project aimed to find an efficient way to incorporate 4D seismic data into a history matching process with a focus on real field data and to contribute to an increase in the reservoir’s oil recovery. For this purpose, state-of-the-art data conditioning and statistical methods are required to better define the oil-water-contact and thereby improving history matching performance.

TNO is the Netherlands Organisation for Applied Scientific Research. It has as its mission to connect people and knowledge to create innovations that boost the sustainable competitive strength of industry and well-being of society. TNO is active on the social themes Industry, Healthy Living, Defence, Safety & Security, Urbanisation and Energy, and employs more than 2500 staff members spread over several locations in The Netherlands, as well as three foreign offices (Qatar, Aruba and Singapore). The TNO Geo Energy department in Utrecht, which hosts all applied geoscientific research activities, cooperates as foreign partner in the National IOR Center mainly via this completed 2-year PostDoc project.

TNO has earlier implemented and tested the use of a workflow methodology where the 4D seismic data are interpreted as information about the changes in the waterfront during oil production. This interpretation of the changes in the waterfront has then been used for history matching using ensemble based methods. This ensemble-based history matching workflow methodology had promising results on synthetic fields, but experience with real field cases was very limited. By demonstration on a real field case from the Norwegian sector a knowledge gap would be fulfilled on proper application of data conditioning, monitoring and inversion methods. Hence, this project for the National IOR Centre was an opportunity to fill this knowledge gap and was having as main objective the further development and application to a field case of ensemble based data assimilation techniques for history matching to 4D seismic data. To this 2-year project a post-doc was assigned who worked daily together with senior TNO research staff, and via regular meetings as well with 4D seismic data researchers at IRIS. The project finished in May 2017.

In the next section of this report the project activities and results obtained are briefly discussed and linked to dissemination of those results at various events and in different publications. All these disseminations are listed in the last section of this report.

## Project and results discussion

To achieve the project's main objective, the Norne field was taken as our working field case based on its multiple high-quality seismic surveys and public access. From then on, the research was carried out in two directions. On the one hand, efforts were made to improve the applicability of the TNO workflow in real-field seismic history-matching cases by extending it to be able to deal with reservoir models defined on generic corner-point grids and to be more robust to the models with complex saturation-front patterns. These improvements were verified by a series of numerical experiments on synthetic realistically complex test cases. The research results have been presented at international conferences and then submitted to related academic journals. On the other hand, observations of front positions were acquired via an inversion of the Norne AVO seismic data set. These achievements mainly based on geophysical expertise, and based on own internal TNO research budget, have been presented at the conference of IOR Norway 2017. In a last step for the project TNO has done a final demonstration of the improved methodology with the obtained real field data and which has also been presented on this recent IOR conference.

To fill the knowledge gap on proper field application of data assimilation, monitoring and inversion methods on 4D seismic data, the following main activities (work packages) have been employed for this project (after the post-doc first completed a literature review on state-of-the-art and an introduction to the existing TNO software for ensemble based history matching):

**Work package 1**: History matching for Norne field case with production data only

In WP1 uncertainty in porosity, permeability, transmissibility multipliers and endpoints of saturation functions was first parameterized based on the provided Norne dataset and various publications. An initial ensemble of model realizations representing the uncertainty was generated with the help of a Petrel workflow. A simple rock physics model was constructed for simulation of certain seismic attributes, and various small enhancements were made to the existing TNO history matching

workflow. Some potential challenges were identified through initial experimenting, like ensemble collapse due to substantial number of data (localization-like methods that could become essential), difficulties in matching of water production, and complex water front patterns.

Publications and presentations from this WP are listed in the Results Dissemination section below as item [5].

**Work package 2** Improve the distance parameterization for corner-point gridded reservoir models

The existing distance computation method for regular grids was modified to be applicable in generic corner point grids as are usually employed with real field models. An extended abstract was written on this work and a poster was presented at ECMOR 2016.

Publications and presentations from this WP are listed as items [1] and [7].

**Work package 3** Modification of ensemble-based history matching workflow methodology

Test runs on synthetic 2D channel model and on the Norne model identified a problem with the pre-existing TNO workflow. This led to the development of a more robust fast marching method for models with complex saturation-front patterns by use of distance concepts from the field of image processing. The resulting methodology was compared to alternative approaches proposed in the literature. This work has led to a journal publication.

Related to this, possible ways to alleviate the sampling and ranking issues of ensemble-based methods were investigated. The application of localization methods was tested in a history matching experiment with production data of the Norne field.

Publications and presentations from this WP are listed as items [2], [3], [8], [9] and [10].

**Work package 4** Comparative study of other similar approaches for 4D seismic HM.

This led to a presentation at the EnKF workshop listed as item [6] in the Results Dissemination section.

**Work package 5** Norne 4D seismic interpretation and inversion

In this WP, work was performed on the enhancement of the inversion workflow for AVO data and demonstration for inversion for oil-water front positions in 4D seismic data including seismic time shifts. The workflow was applied to the Norne dataset and resulted in consistent identification of pressure and saturation fronts, further enhanced using advanced image processing. This image enhancement processing de-noised the 3D pressure and saturation datasets in order to produce more coherent volumes and fronts of pressure and saturation. The increased coherence allows for more stable front distance tracking.

Please note that the activities for this work package have been performed on own internal TNO research budget.

Publications and presentations from this WP are listed as items [11] and [13].

**Work package 6** Field case study of Norne using production and 4D seismic data

The combined improved seismic inversion, front identification and ensemble-based history matching workflow was applied to the Norne field data with focus on the G segment for validation of results, such as observed water fronts. This work was presented at the SIAM conference on Computational Issues in the Geosciences held in Erlangen, 2017, item [12] below.

During the project activities there have been frequent meetings between the TNO team, the IOR Centre Task 7 leader and a research team at IRIS that is also working on 4D data. The cooperation has given TNO the opportunity to discuss and develop new ideas and improve the applicability of the methodology to field cases. Benefits for the IOR Centre were that results obtained could be used in other research projects and shared with the other Centre partners.

The main outcome of the project concerns the demonstration on a field case of a methodology facilitating the incorporation of time-lapse seismic data into history matching workflows through a combination of ensemble-based data-assimilation methods and a distance parameterization of flood fronts derived from time-lapse seismic anomalies. This main project outcome has been accomplished via the following project results:

- methodology for better distance parameterization and saturation front tracking on corner-point grid models,
- ensemble-based history matching workflow methodology appropriate for using 4D seismic data for realistic reservoir models,
- comparison of the methodology with other methods for seismic history matching,
- synthetic and field models/data appropriate for demonstration of several relevant aspects of workflow methodology,
- results of application of the methodology to the Norne field case.

Any near-future application of the developed workflow methodology to field cases will be of direct benefit to an operator and other partners of the assets because of the expected improvements in the quality of the reservoir models, as quantified by the match to historic data, the uncertainty in model parameters, and the robustness of model forecasts.

By Q2 2017 this main project as contribution out of TNO to the Norwegian IOR Centre has ceased. Currently TNO is discussing with main partner IRIS what further smaller activities could contribute to the Centre's research activities. These activities of TNO will be bounded by the remaining funding as part of the cooperation agreement between TNO and the Centre.

## Results dissemination

Outcomes of this project have been reflected in papers and extended abstracts, have been presented and discussed via posters and presentations. All this dissemination is found in the sequel of this section.

### Papers, extended abstracts

1. Zhang, Yanhui; Leeuwenburgh, O.
   Ensemble-based seismic history matching with distance Parameterization for complex grids.

   ECMOR XV - Proceedings of 15th European Conference on the Mathematics of Oil Recovery, Amsterdam, Netherlands, 29 August – 1 September 2016.

   European Association of Geoscientists and Engineers 2016

   ISBN 978-94-6282-193-4.

2. Zhang, Yanhui; Leeuwenburgh, O.
   Image-oriented distance parameterization for ensemble-based seismic history matching.

   Computational Geosciences (2017) 21:713–731, DOI: 10.1007/s10596-017-9652-1, http://rdcu.be/rWIP

3. Zhang, Yanhui; Leeuwenburgh, Olwijn; Carpentier, Stefan; Steeghs, Philippe.
   4D seismic history matching of the Norne field model using ensemble-based methods with distance parameterization

   19th European Symposium on Improved Oil Recovery 2017 / IOR Norway 2017, Stavanger, Norway, 24 April - 27 April 2017

   European Association of Geoscientists and Engineers 2017

   ISBN 978-94-6282-209-2.

## Presentations, posters

4. Zhang, Yanhui
   Ensemble-based reservoir history matching for complex geology and seismic data.

   ISAPP symposium 2015; 11 November 2015 - 12 November 2015

5. Zhang, Yanhui; Leeuwenburgh, Olwijn; Steeghs, Philippe; Carpentier, Stefan.
   4D seismic history matching with distance parameterization for synthetic Norne field model.

   Workshop on 4D seismic and history matching (in connection to IOR Norway 2016); 28 April 2016

6. Zhang, Yanhui; Leeuwenburgh, Olwijn.
   Comparative study of ensemble-based seismic history matching using image-oriented parameterizations.

   11th international EnKF workshop; 20 June 2016 – 22 June 2016

7. Zhang, Yanhui; Leeuwenburgh, O.
   Ensemble-based Seismic History Matching with Distance Parameterization for complex grids.

   ECMOR XV-15th European Conference on the Mathematics of Oil Recovery, Amsterdam, Netherlands, 29th August-1 September. EAGE 2016; 29 August 2016 – 1 September 2016

8. Zhang, Yanhui; Leeuwenburgh, Olwijn; Carpentier, Stefan; Steeghs, Philippe.
   Efficient seismic history matching using ensemble-based methods with distance parameterization

   Meeting with Statoil on 4D Seismic history matching January 31, 2017, Bergen, Norway

9. Zhang, Yanhui; Leeuwenburgh, Olwijn; Carpentier, Stefan; Steeghs, Philippe.
   Efficient seismic history matching using ensemble-based methods with distance parameterization

   Given at weekly Production Engineering meeting, Delft University of Technology, February 8, 2017

10. Zhang, Yanhui; Leeuwenburgh, Olwijn; Carpentier, Stefan; Steeghs, Philippe.
    4D seismic history matching of Norne field model using ensemble-based methods with distance parameterization

First EAGE Workshop Practical Reservoir Monitoring, Amsterdam, the Netherlands, 6 March - 9 March 2017

11. Zhang, Yanhui; Leeuwenburgh, Olwijn; Carpentier, Stefan; Steeghs, Philippe.
4D seismic history matching of the Norne field model using ensemble-based methods with distance parameterization

    19th European Symposium on Improved Oil Recovery 2017 / IOR Norway 2017, Stavanger, Norway, 24 April - 27 April 2017

12. Zhang, Yanhui; Leeuwenburgh, Olwijn.
An ensemble-based framework for assimilation of image-type data – application to seismic history matching, presented at the SIAM GS 2017 Conference, Erlangen, 11 September - 14 September 2017.

## Additional dissemination

Further dissemination has been performed for activities related to this project, but for which own internal TNO research budget has been used. This dissemination concerns:

13. Carpentier, Stefan; Steeghs, Philippe; Zhang, Yanhui; Leeuwenburgh, Olwijn.
Data Conditioning of 4D Seismic Time-lapse Data for Improved Inversion of Reservoir Pressure and Saturation

    Poster presentation, 19th European Symposium on Improved Oil Recovery 2017 / IOR Norway 2017, Stavanger, Norway, 24 April - 27 April 2017

14. Carpentier, Stefan; Steeghs, Philippe; Zhang, Yanhui; Leeuwenburgh, Olwijn.
Data Conditioning of 4D Seismic Time-lapse Data for Improved Inversion of Reservoir Pressure and Saturation

    19th European Symposium on Improved Oil Recovery 2017 / IOR Norway 2017, Stavanger, Norway, 24 April - 27 April 2017

    European Association of Geoscientists and Engineers 2017

    ISBN 978-94-6282-209-2.