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Multi-data reservoir history matching for enhanced reservoir forecasting and uncertainty quantification

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ABSTRACT

Reservoir simulations and history matching are critical for fine-tuning reservoir production strategies, improving understanding of the subsurface formation, and forecasting remaining reserves. Production data have long been incorporated for adjusting reservoir parameters. However, the sparse spatial sampling of this data set has posed a significant challenge for efficiently reducing uncertainty of reservoir parameters. Seismic, electromagnetic, gravity and InSAR techniques have found widespread applications in enhancing exploration for oil and gas and monitoring reservoirs. These data have however been interpreted and analyzed mostly separately, rarely exploiting the synergy effects that could result from combining them. We present a multi-data ensemble Kalman filter-based history matching framework for the simultaneous incorporation of various reservoir data such as seismic, electromagnetics, gravimetry and InSAR for best possible characterization of the reservoir formation. We apply an ensemble-based sensitivity method to evaluate the impact of each observation on the estimated reservoir parameters. Numerical experiments for different test cases demonstrate considerable matching enhancements when integrating all data sets in the history matching process. Results from the sensitivity analysis further suggest that electromagnetic data exhibit the strongest impact on the matching enhancements due to their strong differentiation between water fronts and hydrocarbons in the test cases.

1. Introduction

Reservoir history matching plays a significant role in improving formation characterization and understanding. Recently, it has assumed an even more critical role in optimizing reservoir development strategies and increasing recovery rates to overcome the shortfalls of existing reservoirs that are depleting at unprecedented rates. With reservoir models becoming more complex in response to the demand for greater accuracy and more details, the number of parameters and observations has risen substantially. Ensemble Kalman based filtering (EnKF) techniques have found widespread applications in reservoir history matching as they provide an efficient reservoir state and parameter estimation framework and are capable of incorporating large and various data sets (Oliver and Chen, 2011; Katterbauer et al., 2014a). Gu and Oliver (2005) presented a PUNQ-S3 reservoir model history matching study using the EnKF in which they incorporated production data, such as water cut, for the estimation of reservoir parameters. The results exhibit satisfactory performance as compared to traditional techniques and are obtained with reasonable computational requirements. In another work by Krymskaya et al. (2009) an iterative variant of the EnKF was applied for enhancing filtering performance and overcome poor specification of a priori information.

While the focus was on history matching production data, the sparse nature of these data has posed a significant challenge to obtain reliable estimates of reservoir state parameters and to enhance its forecasting skills. Advances in seismic imaging, especially with the development of 4D seismic, have led to the incorporation of seismic data into the reservoir history matching process focusing on tracking water front's (Sedighi-Dehkordi and Stephen, 2010; Kazemi et al., 2011; Leeuwenburgh et al., 2011; Oliver and Chen, 2011). Furthermore, significant work has been conducted on quantifying the uncertainty in the seismic data and seismic inversion process (Osypov et al., 2013; Fomel and Landa, 2014). Electromagnetic (EM) techniques have also found growing interest for enhancing reservoir characterization with several field studies being conducted (Marsala et al., 2007, 2011, 2013). Integration of these data for reservoir history matching purposes was successfully demonstrated by Katterbauer et al. (2014a, 2014b), leading to enhanced history matches and characterization of the reservoir formation.

More recently, gravimetric techniques have regained attention for monitoring hydrocarbon reservoirs with new developments achieving measurement accuracy in the micro Gal range, thus enabling the detection of mass re-distributions within the subsurface (Alnes et al.,

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2008; Glegola et al., 2012a). Several synthetic and field studies have demonstrated the feasibility of 4D gravimetry to monitor reservoir mass distributions induced by water–gas displacements (Hare et al., 1999; Van Gelderen et al., 1999; Zumberge et al., 2012). Glegola et al. (2012a, 2012b) demonstrated their applicability for monitoring the water influx into gas fields. They have also suggested a good complementarity between production and gravity data.

Time-lapse interferometric synthetic aperture radar (InSAR) is now increasingly utilized in the context of reservoir monitoring, relating the surface deformation to pressure changes in the reservoir. Du et al. (2010) utilized a simplified micromechanics approach for specifying the subsurface properties for two synthetic test cases based on the Krechba test field case. While several studies have been conducted for inverting surface deformations into reservoir compositional changes (Lecampion et al., 2011; del Conte et al., 2013; Tamburini et al., 2013), there has been only limited research on using InSAR data for reservoir history matching (Katterbauer et al., 2014c).

The growing availability of different geophysical data for reservoir monitoring purposes has prompted researchers to consider combining these data for achieving greater enhancements in the history matching process. The synergy effects were successfully demonstrated for EM and seismic data by Katterbauer et al. (2014d), for Gravimetry, EM and seismic inversion by Colombo and Stefano (2007) as well as in several other studies (Gao et al., 2010; Katterbauer et al., 2014a).

The combination of different data sets demonstrated considerable improvements in reservoir characterization and forecasts as compared to the integration of single geophysical data sets. Determining the impact of each observational data set on the parameter estimates is quintessential for the optimal selection of the different data sets, understanding the correlation between the estimated parameters and the data, and avoiding the allocation of additional resources for conducting surveys for data sets whose impact is rather marginal. Evaluating the impact of the different data sets is typically conducted via a sensitivity analysis. A frequently utilized approach is to use the adjoint of the forward model for determining the sensitivity of the parameter changes with respect to the individual observation changes (Daescu and Todling, 2010; Todling, 2013). While the adjoint model may be an efficient method to determine sensitivities, coding the adjoint model requires important human and computational efforts, and may not even be possible in certain situations. To avoid the implementation of the adjoint, Liu and Kalnay (2008) presented an ensemble-based sensitivity method to calculate observation impacts on the forecast error reduction. The results were examined using a Lorenz 40-variable model and it was shown that the ensemble-based estimated sensitivities are anti-correlated with the observation error, and that the method qualitatively agrees with the results of computationally much more expensive data-denial experiments.

In this work, a multi-data EnKF-based history matching framework is presented to simultaneously incorporate production, seismic, EM, gravity and InSAR data. We conduct different history matching experiments of realistic reservoir formations to evaluate the contribution of each of the data sets on the final EnKF solutions and estimates. The results indicate considerable improvements in the history matching and forecasting quality. They also suggest that EM and seismic techniques have the highest impact on the parameter estimates for the tested cases. The framework provides a platform for the integration of multiple observation data, quantify their impact, and enhance history matches and forecasts.

2. History matching methodology

The developed framework is presented in Fig. 1 and integrates a reservoir simulator together with 4D seismic and electromagnetic survey modules that are complemented by time lapse gravity and

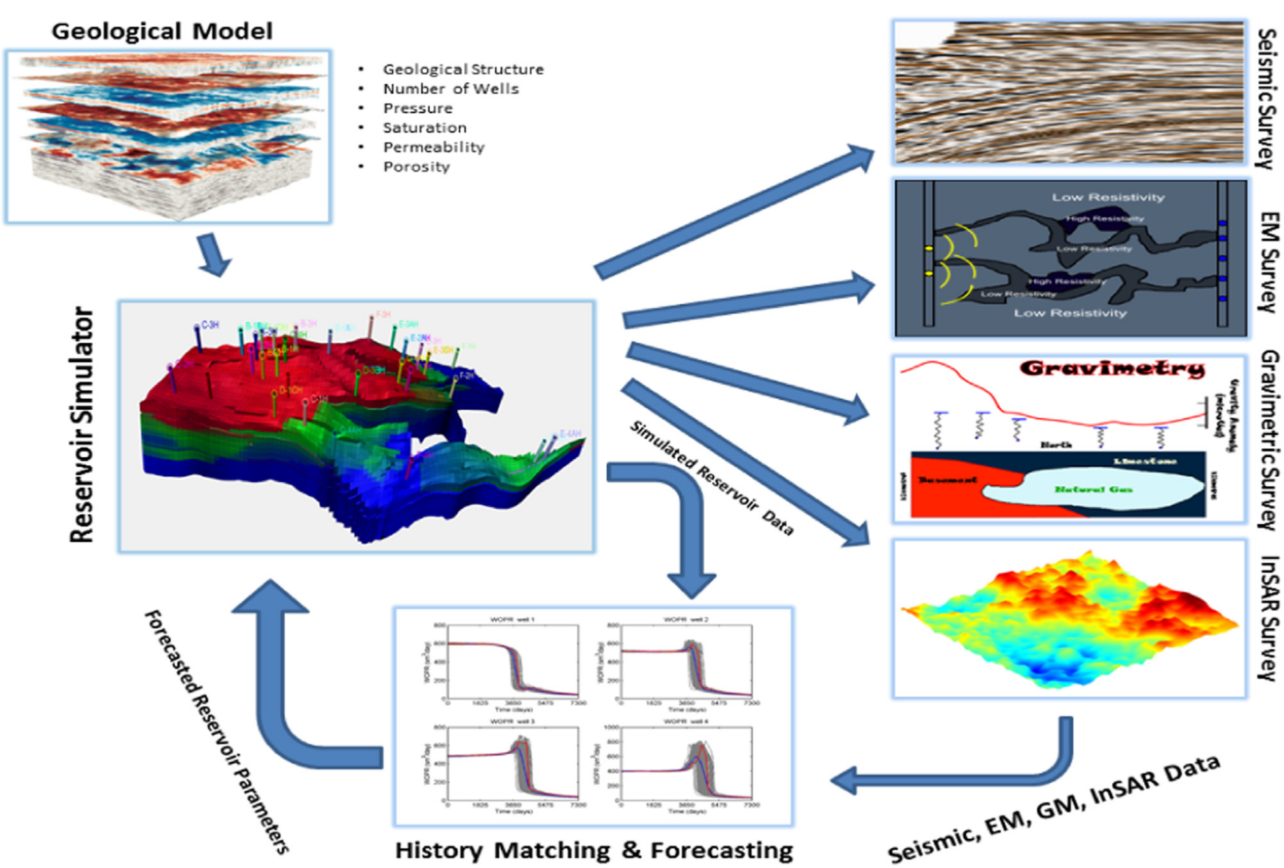

Fig. 1. Flowchart representation of the Multi-Data history matching framework.