Illumination-consistent modeling of time-lapse seismic data

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Abstract

This paper explores an alternative approach to 3D and 4D seismic modeling based on the PSDM simulator technique introduced by Lecomte et al. (2003), Lecomte (2004), and presented in more detail in Lecomte (2008). The method is both computationally efficient, allowing quick, repeatable, multi-scenario analysis, and allows the integration of illumination constraints from the survey and overburden. The PSDM simulator is a rapid and cost efficient alternative for realistic simulation of seismic data which goes far beyond classic 1D trace modeling and allows comprehensive sensitivity analyses by forward modeling.

The technique will be demonstrated on both synthetic models and on real data from the Norne field offshore mid-Norway. This paper will focus on the integration of survey data, overburden properties, rock properties and fluid simulator data into the 3D and 4D seismic modeling schemes, and discuss their impact on the seismic responses.

Introduction

Mapping the changes in the fluid and pressure distributions of a reservoir during production is a major objective in 4D seismic data analysis, as seismic data is the primary source of information about the changes taking place within the reservoir volume during production away from well control.

Seismic modeling can be used as a guide for interpreting seismic changes during production, e.g. whether they are consistent with producing hydrocarbons or pressure changes, or a combination of both. However, in most 4D projects a simple 1D seismic modeling approach is used, disregarding the illumination and sampling characteristics imposed on the reservoir response as the seismic waves are transmitted by a pattern of sources, modified by the overburden structures, reflected in the reservoir and recorded by another pattern of receivers.

It is documented that the combination of these influences will cause uneven sampling of the subsurface target and may in some situations cause “false” amplitudes in the seismic data (e.g. Laurain et al., 2004). Also the horizontal resolution characteristics are frequently ignored in the 1D approach. The complete 3D characteristics of the survey and overburden can be incorporated in FD approaches but the computing challenges for such methods in 3D and 4D field studies are huge.

In this paper we use an alternative approach to 3D and 4D elastic and seismic modeling based on a PSDM simulator technique introduced by Lecomte et al. (2003), Lecomte (2004), and presented in more detail in Lecomte (2008). The method is both computationally efficient and allows the integration of constraints from the survey and overburden properties in terms of both illumination and resolution. The technique will be demonstrated on data from the Norne field offshore mid-Norway. An overview of a typical modeling workflow can be found in Gjøystdal et al. (2007).

Illumination maps

Before modeling the 4D response an illumination analysis is performed to investigate the seismic sampling characteristics, the offset-angle dependencies and whether “false amplitudes” generated through the survey-overburden interaction are significant. A common approach to quantifying illumination properties is to generate illumination maps by ray tracing. In Figure 1 are the principles behind generation of illumination maps shown. For every pair of shot and receiver the reflection point on the target horizon and its associated properties is modeled, including its position and the corresponding offset, angles, amplitude coefficients, etc. By dividing the target horizon into bin cells, the illumination properties of each bin cell can be quantified.

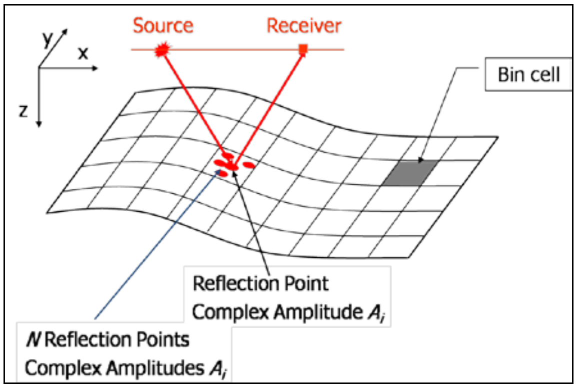

Figure 1. Principle for generation of illumination maps using ray tracing events.

The major 4D surveys on Norne are near accurately repeated surveys using a layout with 6 streamers with length of 3.2 km and separation of 50 meters, see Figure 2.

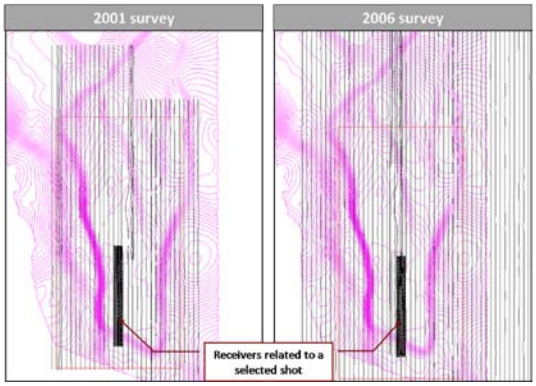

Figure 2. Shot positions for the 2001 and 2006 Norne surveys.

Figure 3 shows the hit maps (fold at target) associated with the 2001 and 2006 surveys over the Norne field. Other illumination maps may be maximum horizontal distance between CMP and CRP points, average incidence angle and Simulated Migration Amplitude. Looking at the illumination results, the sampling of the main reservoir plateau shows some systematic stripes of uneven fold. However, most of the target is well sampled except the steep flanks almost parallel to the shot direction.

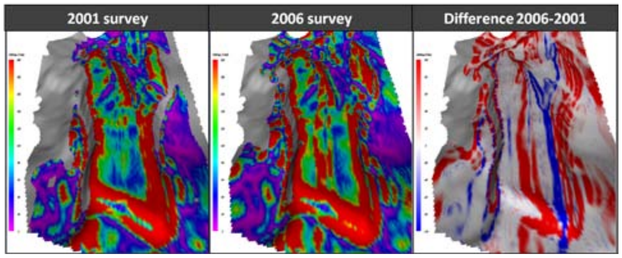

Figure 3. Maps describing the illumination properties of the target horzon of the Norne field, sorted according to the full, near and far offset stacks.

Illumination vectors

Another quantity that is useful for characterizing the illumination properties at a subsurface target is the so-called illumination vector, which can be calculated from ray tracing according to Figure 4.

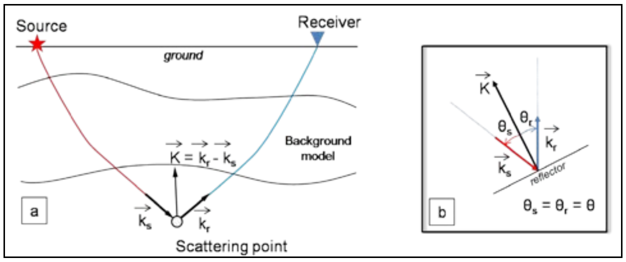

Figure 4. Definition of the illumination vector by ray tracing.

It is defined as the difference between the incoming and departing wavenumber at a scattering point. Each shot-receiver pair will give one vector and a survey will consequently define a collection of vectors. An important feature of the illumination vector is that only dips perpendicular to the vector will contribute to the selected shot and receiver. In 3D, each vector can be associated with an azimuth direction and a dip angle allowing the survey representation shown in Figure 5. This means that a horizontal reflector will only be mapped if illumination vectors exist in the centre of the diagram.

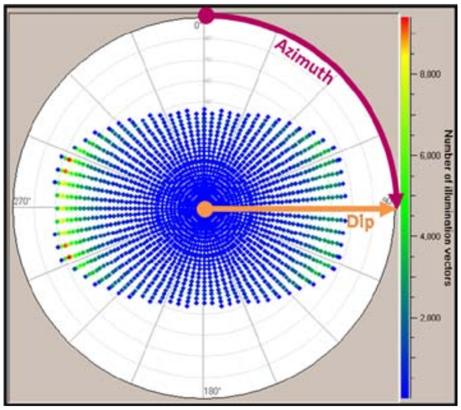

Figure 5. Plotting of illumination vectors at a location on a subsurface target for a specific survey.

In Figure 6 are illumination vectors shown for different types of marine surface seismic surveys, ranging from a 2D single streamer survey to a complete 3D multi-streamer survey. Notice the increased crossline coverage obtained by adding more streamers and more shot lines.

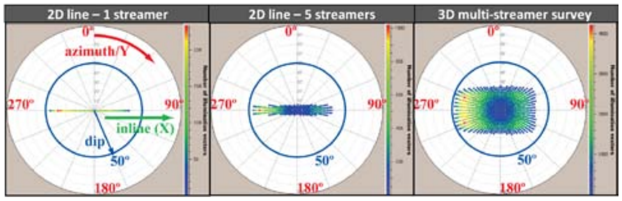

Figure 6. Illumination vector associated with differet types of seismic surveys acquired in the 90º azimuth direction.

The illumination-consistent PSDM simulator

A common approach to seismic time-lapse modeling is to create a vertical pseudo-well at the selected locations and perform the modeling by a simple convolution. By systematically repeating the modeling over an area a 3D seismic volume can be created. However, the modeling is still 1D and there is no way of including survey-overburden constraints in terms of illumination and resolution.

Through the use of a 3D PSDM simulator (SimPLI – Simulated Prestack Local Imaging) we demonstrate a more realistic result can be obtained by integrating illumination vectors as a constraint in the modeling. The SimPLI concept efficiently estimates PSDM seismic amplitudes without the need to predict and process synthetic seismic gathers. The method can be regarded as a generalized 3D convolution technique working in the depth domain constrained by illumination and resolution effects of the acquisition. As such, it goes beyond classic

1D trace modeling. The method consists basically of combining a detailed reflectivity model of the target with an overburden-survey-wavelet filter (SimPLI filter) derived from the illumination vectors and the wavelet. The method allows direct calculation of any combination of both full and partial offset and angle stacks for a variety of surveys and overburden models. For more details about the method and the calculation of the illumination vectors, SimPLI filter and the PSDM simulator we refer to Lecomte (2008).

Examples

The first example is a zero-offset PSDM section from a 2D line with an overburden structure containing a high-velocity layer, see Figure 7. Notice the variability of the illumination vectors across the structure and the connection between the illumination gap and dimming of the amplitude as the target dip no longer is covered by the illumination vectors (circled area). The example shows that there is a consistent link between missing data and damped amplitude.

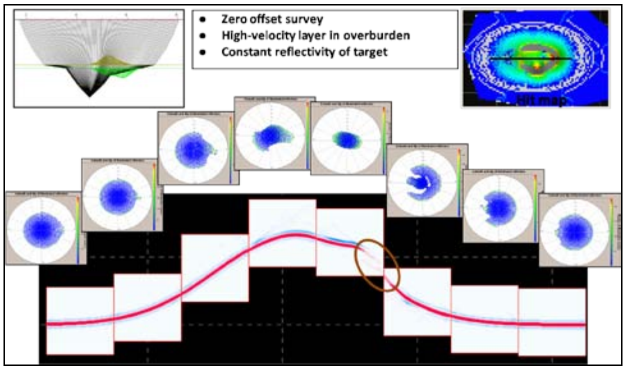

Figure 7. Prediction of a zero-offset 2D PSDM section for a single reflector with constant reflectivity in the presence of overburden structures.

The second example uses the SEG/EAGE salt model as overburden structure and shows the zero-offset PSDM response of a block structure under and to the side of the salt body, see Figure 8. Notice how the near perfect seismic image from the side of the salt becomes disturbed when the structure is located under the salt.

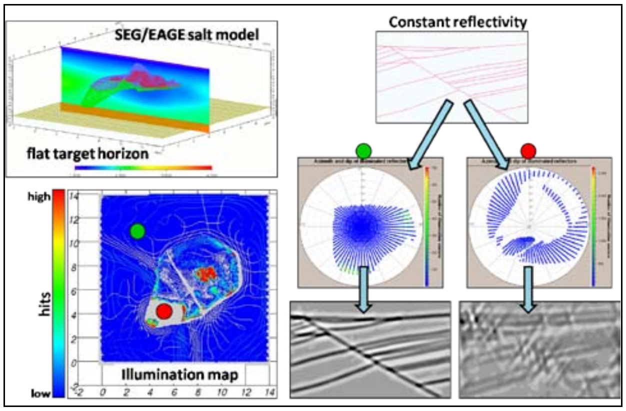

Figure 8. Prediction of zero-offset 2D PSDM sections for a block structure with constant reflectivity on the side (green dot) and under (red dot) a salt overburden.

The third example assumes a simple overburden and shows the illumination vectors and corresponding seismic sections for different types of seismic surveys, see Figure 9. The results show how the ability to map small-scale features within the interface clearly depends on the survey strategy implemented. Of primary importance is that a 1D approximation creates an image that only mimics the structure shown in the reflectivity, though broadened by the seismic wavelet. However, the other cases all include the illumination constraints of the survey and therefore parts of the structure are rightfully absent from the image. Looking within these, note how the central fault is well mapped in the OBS and WAZ surveys, but is missing in the marine and VSP surveys.

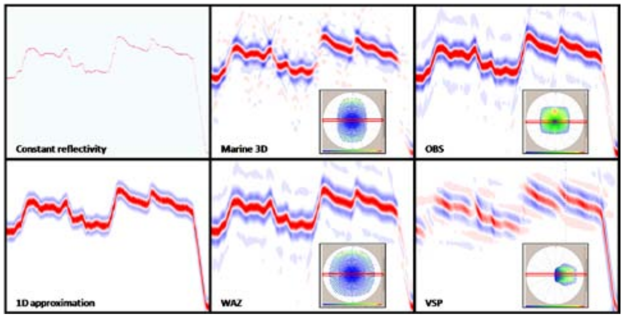

Figure 9. Predicted seismic PSDM response for a constant reflectivity target assuming different seismic survey configurations. The scenarios include a 1D approach, a marine 3D multi-streamer survey, an ocean bottom survey (OBS), a wide-azimuth survey (WAZ) and a well-seismic survey (VSP).

The final example is from the Norne field offshore Norway. We refer to Osdal et al. (2006) for more information about the Norne field and how the 4D seismic data are applied to optimize production on Norne. The major data elements used are shown in Figure 10 together with the location of the modeled crossline.

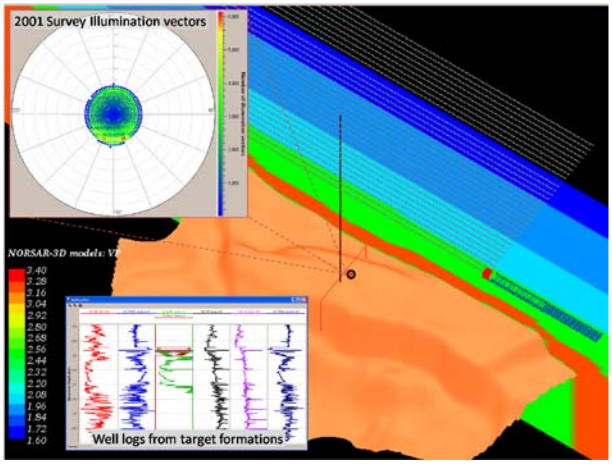

Figure 10. Overview of some data elements from the Norne field including the survey, a calibration well and the location of the presented crossline and its associated illumination vectors derived from the 2001 survey.

The available data include survey data and an overburden model for generating the illumination vectors and well log data for constraining the rock physics. Rock physics models are essential for realistic prediction of elastic properties based on the geological model and in this case the model properties were calibrated using well log data.

In 4D analyses the focus is put on the differences between a baseline and a monitor survey. Figure 11 shows an overview of the 2001 geological properties for a crossline and the differences in dynamic geological properties after 5 years of production.

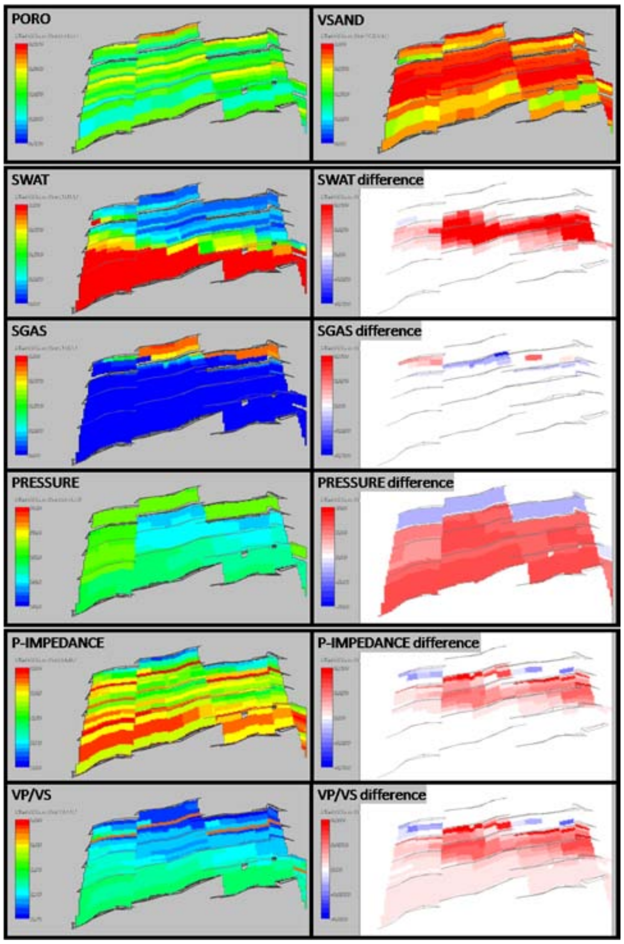

Figure 11. Comparison of geological and elastic properties along a crossline of the Norne field as extracted from a fluid simulator model. and the elastic properties were predicted using a rock physics model calibrated by well log data. Predicted properties in 2001 and predicted changes after 5 years of production (denoted difference in figure).

In Figure 12 are the modelled and observed 2001 seismic properties and corresponding time-lapse changes shown. Two synthetic seismic versions are provided, assuming either the SimPLI filter to be derived from the 2001 survey or using a filter corresponding to perfect illumination (i.e. 1D approach). Again the 1D response is a rather sharp wavelet-smoothed image of the elastic model, disregarding the illumination constraints of the surveys. Using a proper SimPLI filter provides more realistic synthetic seismic data in particular when regarding the lateral continuity of the reflectors.

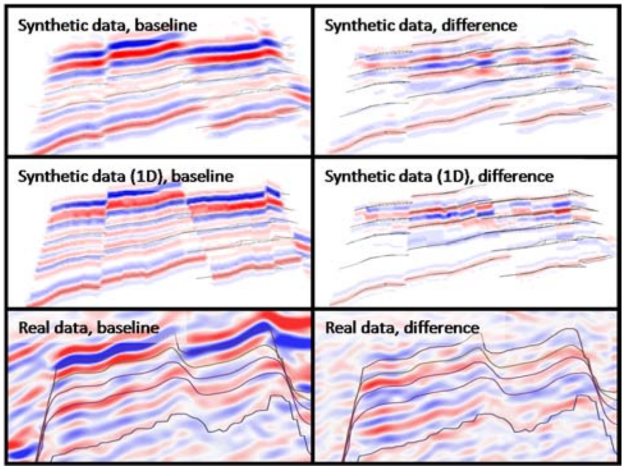

Figure 12. Comparison of seismic properties along a crossline of the Norne field. Predicted properties in 2001 (left column) and predicted changes after 5 years of production (right column). Note that the vertical coordinate of the synthetic data is depth whereas traveltime is used for the real data.

In Figure 13 is a comparison between the seismic responses obtained from different coverage of illumination vectors. Notice how improved coverage of vectors will improve the sharpness of both the seismic response and the seismic differences. This allows the direct evaluation of resolution requirements and benefits associated with different types of seismic surveys.

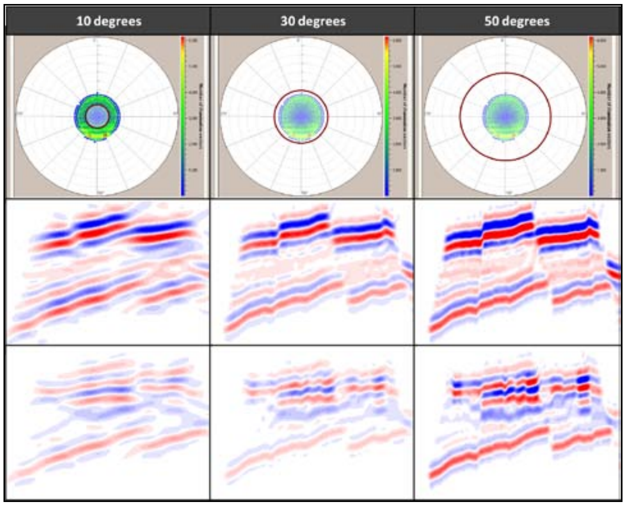

Figure 13. Effect of varying the azimuth and dip coverage of the illumination vectors on a seismic section. Top row shows the illumination vector coverage as a circle superimposed on the illumination vectors of the 2001 survey, middle row shows the baseline seismic properties, bottom row shows the differences after 5 years of production.

Conclusions

The illumination vector is shown to be a powerful concept for describing the illumination properties at a subsurface target. They do not only describe the azimuth and dip ranges that can be recovered using a specific survey, but may also be used to investigate the constraints imposed on the expected seismic response.

An illumination-consistent PSDM simulator is proven to be a valuable tool for calculating the synthetic seismic response from complex reservoir geometries. Using model data taken from the Norne field we have shown that the SimPLI approach, where PSDM seismic amplitudes that include 3D illumination and resolution effects are used, is superior to a 1D approach where these constraints are ignored. What is more, the methodology behind SimPLI and the implementation of the technology means that the rapid evaluation of different survey configurations can be easily achieved.

The workflow presented here has shown that more realistic 4D signals are obtained from the PSDM simulator compared to the 1D approximation. This is so even in the Norne case with its geologically simple overburden. It is right to assume that as the overburden increases in complexity, the value of a survey and overburden consistent modeling technique also increases. As the SimPLI method includes the resolution and illumination of the overburden it can provide more accurate seismic simulations thus leading to the generation of a better history match within the reservoir model.

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References

H. Gjøystdal, Å. Drottning, I. Lecomte, and M. Branston, Quantitative model-assisted seismic interpretation, First Break, March 2007.

R. Laurain, V. Vinje, and C. Strand, Simulated migration amplitude for improving amplitude estimates in seismic illumination studies, The Leading Edge, pp. 240-245, March 2004.

I. Lecomte, H. Gjøystdal and Å. Drottning, Simulated Prestack Local Imaging: a robust and efficient interpretation tool to control illumination, resolution, and time-lapse properties of reservoirs, 73rd SEG Annual Meeting, Dallas, U.S.A., October 26-31, 2003.

I. Lecomte, Simulating Prestack Depth Migrated Sections, 66th EAGE Conference and Exhibition, Paris, June 2004.

I. Lecomte, Resolution and illumination analyses in PSDM: A ray-based approach, The Leading Edge, pp. 650-663, 2008.

B. Osdal, O. Husby, H. A. Aronsen, N. Chen and T. Alsos, Mapping the fluid front and pressure buildup using 4D data on Norne Field, The Leading Edge, pp. 1134-1141, 2006.