# Direct Modelling of Reservoir Properties from Seismic using PDF Transforms

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## Summary

We show how the concepts of Feynman Path Integration can be used to estimate disparate reservoir properties directly from input partial-angle stacks. The vehicles for this are probability density transforms (PDFs) which represent the seismic reflection data in a probability space. Comparing this mapping at well locations enables the establishment of a relationship between the transform elements and reservoir properties described by the log curves. This procedure facilitates the fast estimation of reservoir properties and provides excellent initial models for seismic inversions.

## Introduction

Our method closely follows the concepts of Bayesian inference which combines prior information and newly available evidence to make probabilistic assessments of hypotheses. Prior information can be in the form of well curves and geologic models although here we utilize a Uniform distribution. These ideas were first employed in estimating geophysical facies using the results of seismic inversions as inputs (Pendrel et al., 2006). This was done by computing per-facies, per-layer probability density functions (PDFs) in multi-dimensional cross-plot space. Integration over the PDFs centred at the inversion values gives the probabilities of occurrence of each of the possible facies. The facies models, thus obtained, can be used to create elastic models to improve seismic inversions with superior, data-driven low frequency models (Pendrel et al., 2022, Pendrel and Schouten, 2020).

Here we follow the principle of Feynman Path Integration (Feynman, 1948) which proposes that solutions to physical problems can be obtained from the sum of all possible answers, each weighted by their respective probabilities of occurrence. In the present context, the means of the PDFs represent the solutions and the weights are their probabilities.

## Method

We closely follow the method in Pendrel and Schouten (2023a, 2023b) but with an improved strategy for PDF design. Following our previous work, we define PDFs which cover the input seismic partial-stack space and thereby transform the seismic data to a probability domain. Previously, we defined 10 PDFs with geophysical meaning, representing, gas, sands, shales, etc. Now, we increase the number of PDFs to 30 and locate them on a regular grid in the seismic input space without regard for any possible geophysical meaning. We only require that these *PDF elements*, cover the entire input space where data points exist. They are still defined on a geologic layer basis. The probabilities for each of the PDF elements are computed across the project using Bayesian inference. The procedure is completely analogous to Bayesian facies estimation except that, in this case, the PDF elements do not necessarily represent particular geophysical facies. Prior conditioning of the seismic can be done such as alignment, zero-phasing, quadrature rotation and signal-to-noise enhancement. Zero phasing followed by a 90 deg. rotation to align peaks and troughs with their corresponding geologic layers gives optimal results. This can easily be accomplished by extracting the relative components of a set of post-stack inversions.

The PDF element means and their associated probabilities across the project can now be used to estimate reservoir properties corresponding to well log curves. To do this, their probabilities are recorded as probability log curves at the well locations. The association of the PDF element probability curves with reservoir property curves at the wells allows the relationship between PDF element means and property values to be explored and reservoir property values to be determined. This is done by creating a set of new *property PDFs*. Each property PDF is associated with a PDF element and its mean represents a reservoir property value. The reservoir property to be modelled becomes the weighted average of the property PDF means, the weights being the corresponding PDF element probabilities.

The property PDF standard deviations are used to estimate uncertainty in the models. Sets of solutions are obtained by adding and subtracting standard deviations to each of the N property PDF means. This results in $3^N$ different models. Uncertainties are represented by the standard deviations in the model sets at each 3D project sample. We restrict N to the six most-probable property PDFs to make the estimation tractable.

It is important to recognize the assumptions inherent in this procedure. We require stationarity of both the property PDF means and their standard deviations. The latter is needed for the uncertainty estimations. Structural models with sufficient layers can usually be designed to achieve this.

## Results

We illustrate the procedure using a Gulf of Mexico data set. This contains two vertically-stacked middle Pliocene deltaic systems. They average about 400 ft. in thickness and are separated by about 500 ft. Within the play area are delta slope deformation, slump-induced turbidites and thin mouth-bed deposits. In our study, the upper and lower *Green* horizons define two gas-charged sandstone reservoirs. Over-pressuring can occur in certain areas.

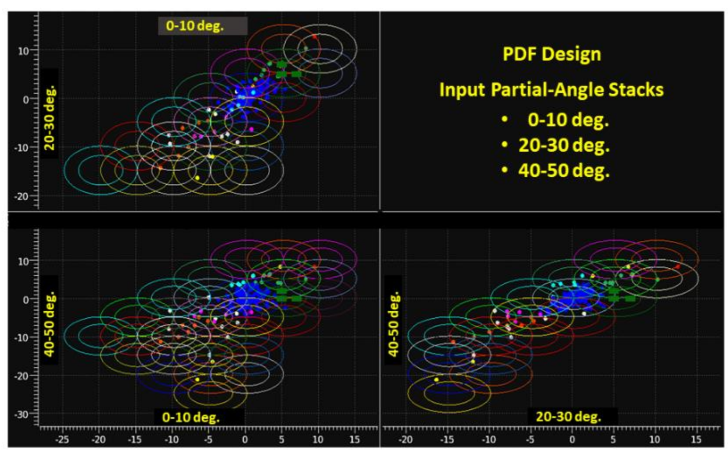


Figure 1: The figure shows the PDF element design for the upper Green layer from the three partial-angle stacks. Thirty PDF elements have been constructed. Their first two standard deviations are shown.

The input data consisted of three partial-angle stacks: 0-10 deg., 20-30 deg. and 40-50 deg. Partial-stack alignment was done. Wavelet removal and phase correction was accomplished by extracting the relative (seismic band) results from post-stack inversions applied separately to the Near, Mid and Far partial stacks.

Figure 1 shows the PDF elements in the upper Green layer for 30 PDF elements designed from the partial stacks. Data away from the well locations were incorporated to verify the PDF element design. Note that the PDF elements are defined on a regular grid with equal standard deviations.

In Figure 2, are the first and second most-probable PDF elements from Bayesian inference. Probabilities of all the PDF elements were used in the final modelling. For each PDF element, reservoir property PDFs were designed, specific to the target reservoir property. An example is shown for Vp/Vs estimation in the Upper Green. The property PDF means are associated with Vp/Vs values although their probabilities of occurrence remain the same as in Figure 2. The property PDFs are well distributed along the Vp/Vs axis, indicating that Vp/Vs can be considered a good candidate for modelling. The property PDF standard deviations were used to estimate uncertainty. The final Vp/Vs model with logs overlaid is shown in Figure 4 (left) along with the Vp/Vs standard deviations determined by the method described above (right). Agreement with the logs is qualitatively good. The process is essentially self-trending, gathering trend information from the wells collectively. Otherwise, the process is effectively blind to the wells, making them available for quality control.

By this method, we have computed models for P Impedance, Vp/Vs, Density, Vclay, water saturation, effective porosity and net-to-gross (Vernik et al., 2002). We have also used the P Impedance, Vp/Vs and Density models to compute synthetic gathers for comparison to the seismic. The results are shown in Figure 5 where correlations average about 0.75. Improved results might be obtained from denser PDF gridding. We have also noticed that some areas of poorer S/N are associated with input seismic data that has extended beyond the coverage of the PDFs. Using more PDF elements should improve this.

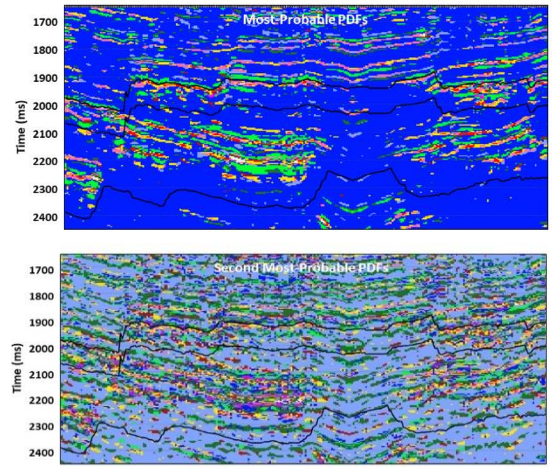


Figure 2: Most-probable (upper) and second most-probable (lower) PDF elements from Bayesian inference. Similar data exist for the other 28 PDFs. The probabilities of all PDF elements were used in the property modelling.

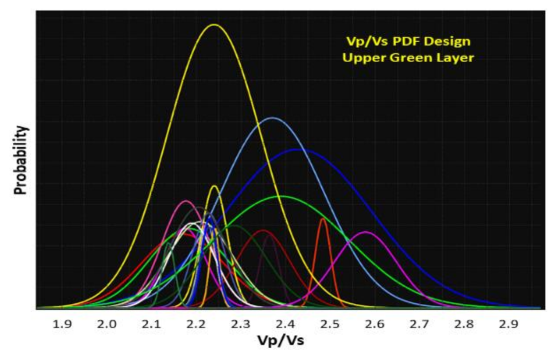


Figure 3: The property PDF design for Vp/Vs estimation in the upper Green layer is shown. PDF histograms for the log data have been omitted for clarity. The property PDF scales are plotted proportional to each of their supports.

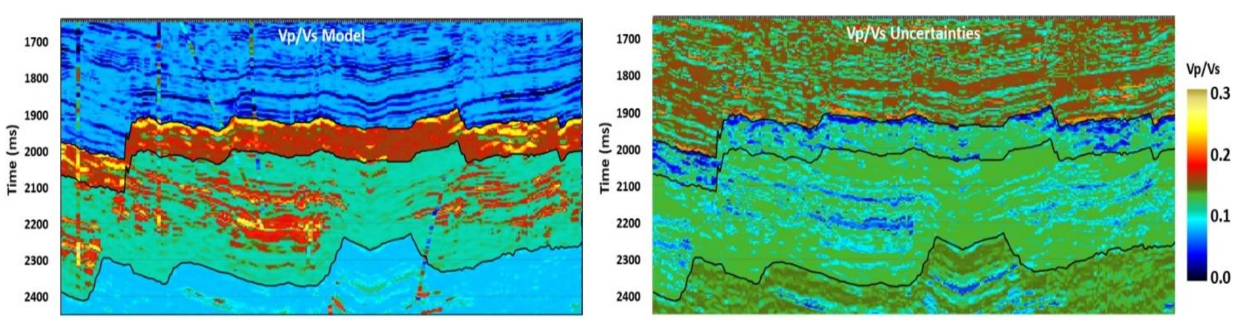


Figure 4: The left panel shows the modelled Vp/Vs with five filtered Vp/Vs logs overlaid. The right panel is the standard deviation of Vp/Vs. Note the variability in standard deviation across the figure.

## Conclusions

We have demonstrated how PDF transforms of seismic partial-angle stacks can be used with well logs to model various reservoir properties. The method follows the concepts of Feynman Path Integration, using Bayesian inference to compute PDF element probabilities for all possible solutions. Alternate solutions created from property PDF standard deviations have been used to estimate property uncertainties.

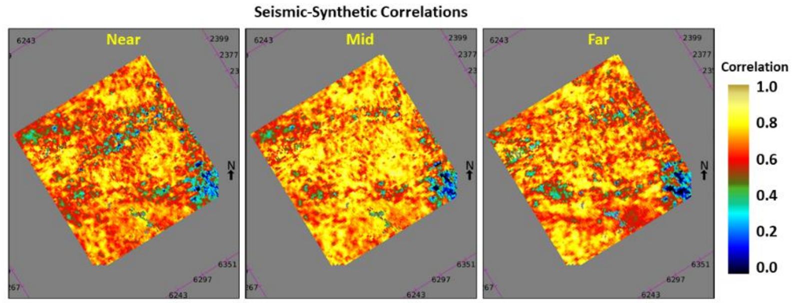


Figure 5: Correlations between the input seismic and the synthetics from a model made from estimated P Impedance, Vp/Vs and Density are shown for the Near Mid and Far, partial-angle stacks from left to right.

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