The Road Ahead in Seismic Processing

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Summary

The next generation seismic processing system will comprise a chain of unified algorithms, from preprocessing to reservoir characterization. All these algorithms are formulated in terms of a closed-loop estimation problem, showing a great similarity with each other. A critical module in each algorithm is forward modeling, allowing feedback between output and input ('closing the loop'). For this purpose a new wavefield modeling concept is proposed that uses for each algorithm a different choice of parameterization. Characteristic properties of the proposed closed-loop processing system are full wavefield, low complexity, high degree of automation and relatively little maintenance.

Introduction

In the past the seismic discipline was much less integrated than we observe today. History shows that the different specializations in seismic processing developed their own type of algorithm in relative isolation. It explains why the total processing system has become very diverse and complex. This is one of the main reasons that, nowadays, processing quality is difficult to assess and processing systems are cumbersome to maintain.

It is proposed to leave the heritage of the past behind us and make a new start, using the immense processing knowledge and experience that has been stored in today's organizations. I will make a plea for a new processing system that will offer the industry significantly better processing quality, combined with less effort to operate and with less expenses to maintain.

In traditional seismic processing we have little information about the inconsistency between output and input: processing has largely been implemented as an 'open loop process'. Taking into account that more information in the seismic data will be utilized in the future (think at multiple scattering and wave conversion), a simple open loop approach is not acceptable anymore. By taking the open-loop processing result as input to a forward modeling algorithm, we are able to close the loop by generating simulated measurements in the feedback path. Next, iterative minimization of the difference between simulated and real measurements allows us to optimize the processing output: each processing step is formulated as a closed-loop estimation process. The basic computational diagram for each step is shown in Figure 1.

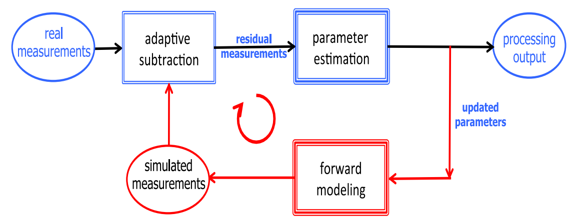

Figure 1: Seismic processing is formulated as a closed-loop estimation process, meaning that output and input are connected via a feedback loop with a forward modeling module that transforms the (sub)surface parameters into simulated measurements.

Today, finite difference modeling is most popular but solutions are not very flexible with respect to the choice of parameters as well as the choice of the wavefield space. In addition, high performance finite difference modeling of broadband seismic data is expensive if elastic wavefields need be generated over and over again in an iterative processing loop. In the closed-loop processing system finite difference modeling (based on the differential equation for seismic wavefields) is replaced by finite summation modeling (based on the integral equation for seismic wavefields). This counter approach enables us to replace the usual velocity-density description of the subsurface by an alternative description in terms of parameters that require a minimum of prior knowledge about the physical wavefield processes at each particular stage. Using this variable-parameter concept of modeling, full freedom is given to the seismic measurements to reveal their information. It will be shown that the proposed wavefield modeling algorithm fits much better the requirements for stepwise full wavefield processing than finite difference alternatives.

In the presentation I will explain how the collection of unified algorithms in the new processing system will look like. I focus on the marine system and will discuss the following principal subsystems: (1) deblending and interpolation (DBL^+), (2) surface-related multiple estimation ($SRME^+$), (3) full wavefield migration (FWM), (4) joint migration inversion (JMI) and (5) seismic inversion for elastic reservoir parameters (JMI-res). At the end of the closed-loop processing chain, a post-processing module transforms the seismic parameters into geological properties (STG-res). This module is applied in reservoir

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areas only and may be considered as an example of 'big data technology' in geosciences.

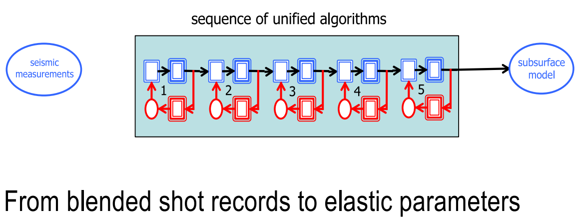


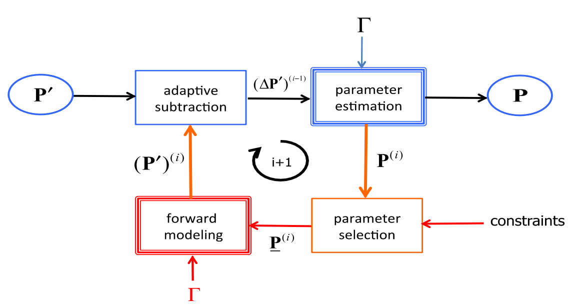
Figure 2: Computational diagram, showing the five closed-loop processing steps. The output describes the subsurface in terms of elastic parameters.

Algorithmic modules

In the proposed processing chain I distinguish five closed-loop algorithms (see Figure 2):

1. *Deblending and Interpolation (DBL$^+$)*

Blended input $\mathbf{P}'$ is transformed into deblended output $\mathbf{P}$. Figure 3 shows that the iterative algorithm computes the deblended shot records such that the difference between the modeled blended data and the measured blended data is below a user-specified threshold. Note that the modeling module transforms deblended into blended shot records.



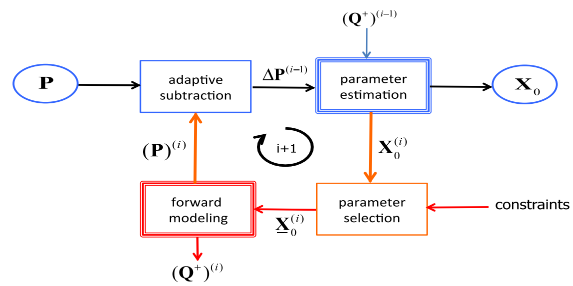
Estimate samples of $\mathbf{P}$ such that:

$$\|\Delta\mathbf{P}'\|^2 = (\mathbf{P}' - \mathbf{P}\,\Gamma)^H \Lambda\, (\mathbf{P}' - \mathbf{P}\,\Gamma) = \textit{minimum}$$

Figure 3: Computational diagram, showing how to deblend seismic shot records (DBL$^+$).

2.*Surface-related multiple estimation (SRME$^+$)*

Deblended shot records $\mathbf{P}$ are transformed into subsurface inpulse responses $\mathbf{X}_0$, representing the deconvolved shot records without surface multiples. Figure 4 shows that the iterative algorithm computes the deconvolved, demultipled shot records such that the difference between the modeled data and the measured data is below a user-specified threshold. Note that the modeling module transforms impulse responses $\mathbf{X}_0$ into shot records $\mathbf{P}$. Note also that $\mathbf{Q}^+$ represents the total downgoing wavefield at the surface.



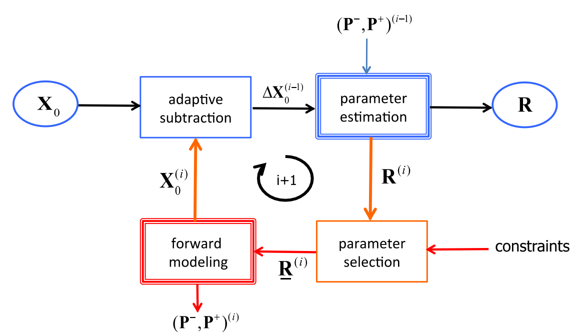
Estimate samples of $\mathbf{X}_0$ such that:

$$\|\Delta\mathbf{P}\|^2 = (\mathbf{P} - \mathbf{X}_0\mathbf{Q}^+)^H \Lambda\, (\mathbf{P} - \mathbf{X}_0\mathbf{Q}^+) = \textit{minimum}$$

Figure 4: Computational diagram, showing how to estimate deconvolved shot records without surface related multiples (SRME$^+$).

3.*Full wavefield Migration (FWM)*

Output of SRME is transformed into a reflectivity image $\mathbf{R}$, using both primaries and multiples, and assuming that the migration velocity distribution is known. Figure 5 shows that the iterative algorithm computes the reflectivity image such that the difference between the modeled data and the measured data is below a user-specified threshold. Note that the forward modeling module transforms reflectivity $\mathbf{R}$ into impulse responses $\mathbf{X}_0$.



Estimate samples of $\mathbf{R}$ such that:

$$\|\Delta\mathbf{X}_0\|^2 = \left(\mathbf{X}_0 - \sum_m \mathbf{W}^-\mathbf{R}\mathbf{P}\right)^H \Lambda \left(\mathbf{X}_0 - \sum_m \mathbf{W}^-\mathbf{R}\mathbf{P}\right) = \textit{minimum}$$

Figure 5: Computational diagram, showing how to utilize both primaries and multiples in seismic migration (FWM).

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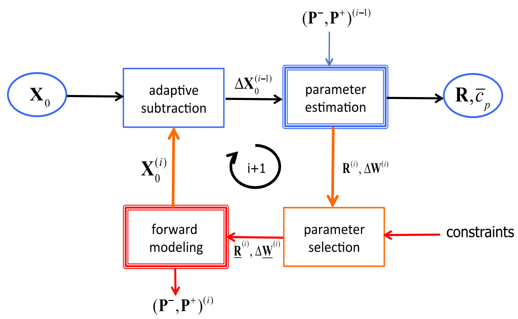
4.*Joint Migration Inversion (JMI)*
Output of SRME is transformed into flectivity image $\mathbf{R}$ as well as a migration velocity distribution, using primaries and multiples. Figure 6 shows that the iterative algorithm computes the reflectivity image and the differential propagation operator $\Delta\mathbf{W}$ such that the difference between the modeled data and the measured data is below a given threshold. Note that the forward modeling module transforms reflectivity into shot records, using the updated propagation operator $\mathbf{W}_0 + \Delta\mathbf{W}$. Note also that the velocity distribution $\mathbf{C}_p$ is estimated from $\Delta\mathbf{W}$ in the last iteration.

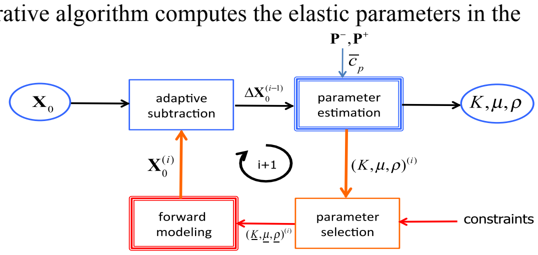


Estimate samples of $\mathbf{R}$ *and* $\Delta\mathbf{W}$ such that:

$$\|\Delta \mathbf{X}_0\|^2 = \left(\mathbf{X}_0 - \sum_m \mathbf{W}_0^-(\mathbf{RP} + j\Delta\mathbf{WQ})\right)^H \Lambda \left(\mathbf{X}_0 - \sum_m \mathbf{W}_0^-(\mathbf{RP} + j\Delta\mathbf{WQ})\right) = \textit{minimum}$$

Figure 6: Computational diagram, showing how to combine migration and velocity estimation (JMI).

5.*Joint Migration Inversion for the characterization of reservoirs (JMI-res)*
Wavefields and velocities from JMI are used to estimate elastic reservoir parameters. Figure 7 shows that the iterative algorithm computes the elastic parameters in the reservoir area such that the difference between the modeled data and the measured data is below a given threshold. Note that the forward modeling module transforms elastic parameters into impulse responses $\mathbf{X}_0$, a very suitable task for finite difference algorithms. Note also that in Figure 7 the quantity β represents the elastic parameter matrix.



Estimate in each gridpoint K,μ,ρ such that:

$$\|\Delta \mathbf{X}_0\|^2 = \left(\mathbf{X}_0 - \sum_m \mathbf{G}^- \beta \mathbf{P}\right)^H \Lambda \left(\mathbf{X}_0 - \sum_m \mathbf{G}^- \beta \mathbf{P}\right) = \textit{minimum}$$

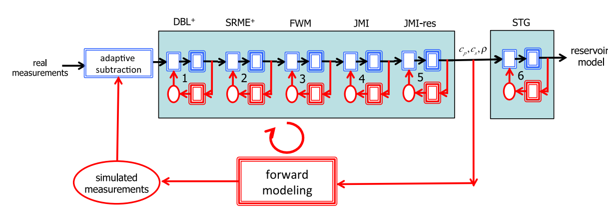
Figure 7: Computational diagram, showing how to utilize multiples in the estimation of the detailed elastic parameters of a reservoir (JMI-res) by making use of the JMI output (wavefields and velocities).

Example

During the presentation the above five processing steps are illustrated with an integrated data example: from blended shot records to elastic parameters.

Closing the macro loop

If all five closed-loop processing steps have been carried out, the total processing chain may be closed by going back to the beginning of the chain, see Figure 8. In this macro feedback loop the elastic finite difference modeling algorithm is an option to be used, transforming the elastic parameters (output of the step 5) into blended shot records (input of step 1). The difference can be used for the next macro iteration. This iteration may be focused on the converted S-waves. But it may also be used in 4D processing, where the real measurements are data from the new time lapse. In addition, in a post-processing module the elastic parameters are transformed into geological properties (see Figure 8).



- From blended shot records to reservoir model
- Subsurface parameters change along the processing chain

Figure 8: Computational diagram, showing the five closed-loop processing steps in a macro loop. A post-processing module – seismic to geology (STG) – transforms the elastic parameters into geological properties.

Towards an holistic view

Finally, Figure 9 provides an overview of the data that is used in the closed-loop seismic system: from blended samples to geological properties. It is important to realize that in the proposed processing system the parameterization of the subsurface is different in each step, including more

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information of the subsurface when we move along the chain. In this way the obtained uniqueness of the solution is beyond current capability (compare with Google Search).

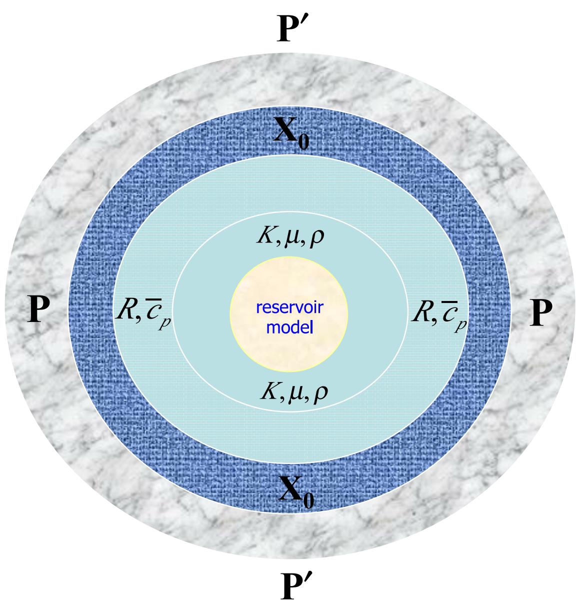

Figure 9: The total picture, showing that the parameterization along the proposed processing chain is utilizing step-by-step more subsurface knowledge.

Conclusions

It is proposed to formulate each step in the seismic processing chain as a closed-loop parameter estimation problem. The consequence of this unified formulation is that all processing algorithms show great similarity: they contain a feedback path that connects the output with the input via a forward modeling module ('closing the loop'). In each processing step the difference between the real and simulated measurements is used to steer the iterations of the estimation process.

Each processing step uses its own parametric description of the subsurface: from wavefield samples at the surface in the first step to elastic parameters of the subsurface in the last step. When moving along the processing chain, the subsurface is described with an increasing amount of subsurface knowledge. In addition, in the iterations of all estimation processes the large parameters are addressed first.

The double hierarchical parametric approach (hierarchical in parameter type and parameter size) aims at eliminating the notorious nonlinear problems, generally referred to as crosstalk and cycle skipping. For the proposed processing system the hierarchy is of particular importance because full wavefield processing is applied, meaning that complex multiple scattering is considered as signal.

Optionally, the total seismic processing chain may be closed by installing a macro feedback path between the end and the beginning of the chain. Along this macro path forward modeling (here, the elastic finite difference algorithm is an option) transforms the elastic description of the subsurface into blended shot records that are compared with the measured blended shot records. The difference is input to a second move along the processing chain, focusing on aspects like mode conversion. But, even more important, the measured blended shot records may be the data of the next time lapse. This approach may revolutionize 4D processing.

The proposed unified architecture has interesting potential advantages for the industry: (1) improvements in one processing module may immediately be 'copied' into the other modules (cross-innovation), (2) residuals and uncertainties will provide objective information on the performance of the processes along the chain (quality control), (3) system updates will be significantly simplified due to the universality of the processing modules (maintenance), (4) far-reaching automation of the human intensive processes are close at hand (productivity).

At the end of the closed-loop processing chain the elastic parameters are transformed into geological properties of the (potential) reservoir: post-processing module.

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EDITED REFERENCES

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REFERENCES

None