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Name: Tomohide Ishiyama
Company: Delft University of Technology
Job title: PhD Researcher
Address: Stevinweg 1, 2628 CN Delft, the Netherlands
Email: t.ishiyama@tudelft.nl

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Title: Dispersive multi-modal mud-roll estimation and removal using feedback-loop approach

Author(s): Tomohide Ishiyama and Gerrit Blacquiere

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Abstract

In a shallow water environment, mud-rolls are often dominant and appear as a prevailing coherent linear noise in OBC seismic data. Their complex properties make the noise removal notably challenging in seismic processing. To address the challenges, we propose a method of dispersive multi-modal mud-roll estimation and removal, using the feedback-loop approach with a sparse inversion of 3D Radon transform. In this paper, we illustrate the proposed method, and will show some real data examples in our presentation at ADIPEC 2013 to demonstrate the virtues.

Introduction

In a shallow water environment like the Gulf region in the Middle East, mud-rolls are often dominant and appear as a prevailing coherent linear noise in OBC seismic data. Compared to the primary signal, they are present with higher amplitude, lower frequency and lower apparent velocity. They are dispersive, i.e., different frequencies propagate with different phase velocities, and multi-modal, i.e., each frequency propagates with several phase velocities simultaneously, or different modes exist all together. In addition, their characteristics are spatially variable, i.e., their basis properties change from one shot to another across the whole seismic survey area. Furthermore, they are usually aliased due to a large spatial sampling interval. These complex properties make the noise removal to obtain high data quality with respect to S/N, resolution and prestack amplitude fidelity a challenging step in seismic processing.
Conventionally, seismic processing is implemented as one-way process, or open-loop process, in which information about the inconsistency between output and input is not taken into account. Recently, the so-called feedback-loop process has been introduced, see, e.g., Verschuur et al. (2012) for data reconstruction, Lopez and Verschuur (2012) for multiple removal and primary estimation, Davydenko et al. (2012) for full wavefield migration, and Berkhout (2012) for joint migration inversion. The feedback-loop is described by an inversion problem of its own model parameters in each

processing. It contains a feedback-path which connects output with input via a forward modeling module and closes the loop itself, making it possible to evaluate the residual between the forward modeled data and the input measurements, to update the model parameters, and to obtain an optimal solution after several iterations of the procedure (Figure 1).
To address the challenges of mud-rolls and fully adopt the recent advances in seismic processing, we propose a method of dispersive multi-modal mud-roll estimation and removal, using the feedback-loop approach with a sparse inversion of 3D Radon transform.

Expression of Mud-rolls

For the feedback-loop approach, mud-rolls are expressed in such a way that they can be forward modeled based on it.
Mud-rolls N can be formulated as:

$$N(\vec{r},\omega)=\sum_{m}A_m(\vec{r},\omega)e^{-j\varphi_m(\vec{r},\omega)}, \tag{1}$$

$$A_m(\vec{r},\omega)=e^{-\alpha_m(\omega)|\vec{r}|}\frac{1}{\sqrt{|\vec{r}|}}A^S(\omega), \tag{2}$$

$$\varphi_m(\vec{r},\omega)=\omega\frac{|\vec{r}|}{|\overrightarrow{v_m}(\omega)|}+\varphi^S(\omega), \tag{3}$$

where *m* is the number of modes, and $\vec{r}$ is the receiver location relative to the source location. A_m is the amplitude term, φ_m is the phase term, α_m is the intrinsic attenuation constant, and $\overrightarrow{v_m}$ is the velocity. A^S and φ^S are the amplitude and the phase term of the source signature at the source location, respectively. The frequency dependent modal velocity $\overrightarrow{v_m}$ represents the basis mud-roll properties: dispersion and multi-modes. Therefore, mud-roll components in the velocity-frequency (*v-f*) domain, or the slowness-frequency (*p-f* or Radon) domain where the slowness is just an inverse of the velocity, well explain the mud-roll events in the input measurements.
The *p-f* domain exists with Radon transform based on a decomposition of linear events with their slowness. The Radon transform brings mud-rolls from the original *x-t* domain to the *p-f* domain where mud-roll and other components are well distinguished in terms of their amplitude difference and areal separation. Sparsity constraint makes the distinguishability more robust. Additional constraints like amplitude thresholding and areal muting make it possible that only the mud-roll components are extracted in the *p-f* domain. Note that each sample of the components in the *p-f* domain contains not only the phase φ_m but also the amplitude A_m information. Therefore, mud-rolls are fully restored from the extracted components by the inverse Radon transform.

Method of Mud-roll Estimation and Removal

The proposed feedback-loop is described as an inversion problem of mud-roll model parameters, and shown in Figure 1. In this feedback-loop, mud-rolls are estimated such that the forward modeled mud-rolls should match the input ones. The essence of the loop is to extract mud-roll components under certain constraints in the *p-f* domain in such a way that the residual between the forward modeled mud-rolls and the input ones should be minimized.
Making use of a 3D matrix notation in the *x-f* domain, this concept can be described for each monochromatic component as:

$$(\mathbf{P}+\mathbf{N}) = \mathbf{P}+\mathbf{N}(= \mathbf{A}^{-1}\mathbf{L}^{H}(\mathbf{P}+\mathbf{N})), \tag{4}$$

$$\mathbf{J} = \sum_{\omega} \left\| (\mathbf{P}+\mathbf{N}) - \mathbf{N} \right\|^{2}, \tag{5}$$

where $(\mathbf{P}+\mathbf{N})$ is the input measurements, $\mathbf{P}$ is the primaries, and $\mathbf{N}$ is the mud-rolls. $\mathbf{A}$ is the amplitude normalization operator to enhance the phase information, and $\mathbf{L}$ is the 3D linear Radon operator. The hat symbol ^ is used to indicate "estimated", the tilde symbol ~ to indicate the *p-f* domain, and the superscript *H* to denote conjugate transposition. The equation (4) is for the forward modeling, which simply describes that the input measurements $(\mathbf{P}+\mathbf{N})$ are explained by the estimated primaries $\mathbf{P}$ and mud-rolls $\mathbf{N}$, and the mud-rolls are expressed in the *p-f* domain. The equation (5) is for the objective function, where $\mathbf{N}$ is the mud-roll model parameters to be updated by minimizing the function $\mathbf{J}$.

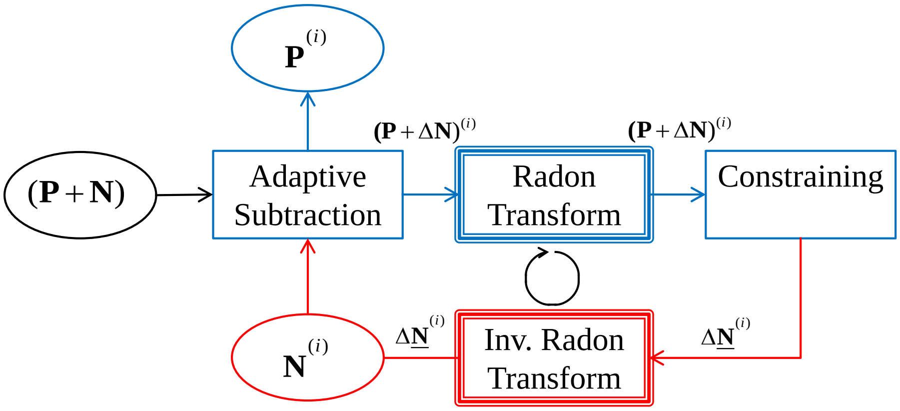

Figure 1: The proposed feedback-loop diagram.

The loop itself can be described for each iteration as:

$$(\mathbf{P}+\Delta\mathbf{N})^{(i)} = (\mathbf{P}+\mathbf{N}) - \mathbf{N}^{(i-1)}, \tag{6}$$

$$\begin{aligned} \Delta\underline{\mathbf{N}}^{(i)} &= \mathbf{A}^{-1}\mathbf{L}^{H}\mathbf{T}\mathbf{L}\mathbf{A}(\mathbf{P}+\Delta\mathbf{N})^{(i)} \\ &= \mathbf{A}^{-1}\mathbf{L}^{H}\mathbf{T}(\mathbf{P}+\Delta\mathbf{N})^{(i)} \\ &= \mathbf{A}^{-1}\mathbf{L}^{H}\Delta\underline{\mathbf{N}}^{(i)} \qquad , \end{aligned} \tag{7}$$

$$\mathbf{N}^{(i)} = \mathbf{N}^{(i-1)} + \alpha^{(i)}\Delta\underline{\mathbf{N}}^{(i)}, \tag{8}$$

$$\alpha^{(i)} = \frac{\sum_{\omega} \mathrm{Re}\{((\mathbf{P}+\Delta\mathbf{N})^{(i-1)})^{H}\,\Delta\underline{\mathbf{N}}^{(i)}\}}{\sum_{\omega} (\Delta\underline{\mathbf{N}}^{(i)})^{H}\,\Delta\underline{\mathbf{N}}^{(i)}}, \tag{9}$$

$$\begin{aligned} \mathbf{P}^{(i)} &= (\mathbf{P}+\mathbf{N}) - \mathbf{N}^{(i)} \\ &= (\mathbf{P}+\Delta\mathbf{N})^{(i+1)} \ , \end{aligned} \tag{10}$$

where $\mathbf{T}$ is the constraining operator like amplitude thresholding and areal muting in the *p-f* domain, and α is the adaptive scale from a steepest descent algorithm in the original *x-t* domain. The underbar _ is used to indicate "extracted". For each iteration, the residual $(\mathbf{P}+\Delta\mathbf{N})^{(i)}$ is transformed into the *p-f* domain; constrained to enhance the mud-roll components $\Delta\underline{\mathbf{N}}^{(i)}$ in this domain; inverse transformed (i.e., forward modeled) to the original *x-t* domain; and the mud-roll model parameters $\mathbf{N}^{(i)}$ and the residual $\mathbf{P}^{(i)}$ are updated in this original domain. This procedure is iterated until it has reached to a stopping criterion or a maximum number of iterations. Consequently, the residual is expected to contain only the resulting primaries.

Examples

We will show real data examples in our presentation at ADIPEC 2013.

Conclusions and Remarks

We proposed a method of dispersive multi-modal mud-roll estimation and removal. The essence of the method is:

- This method fully addresses the basis mud-roll properties: dispersion and multi-modes.
- This method is fully data-driven and data-adaptive. This makes the method practicable for any receiver component type of seismic data, thus, not only for hydrophone and vertical geophone data but also for horizontal geophone data.
- This method is implemented in any geometry domains, such as 3D common shot gathers, 3D common receiver gathers and cross-spread gathers. This offers flexibility in choosing a suitable geometry domain with a smaller spatial sampling interval. Furthermore, the method automatically takes into account the spatial variability of mud-roll characteristics by estimating mud-rolls in each gather, like shot by shot, receiver by receiver, or cross-spread by cross spread.
- This method is implemented for both regularly and irregularly undersampled seismic data. This offers possibility in relaxing the spatial sampling interval without degrading the resulting data quality with respect to mud-roll removal.

The proposed method is targeting the mud-rolls which are often dominant in OBC seismic data in a shallow water environment. It should be noted that recent advances in 3D OBC seismic acquisition, like single point receivers and a large amount of equipment, make the method more effective because of the proper sampling of mud-roll wavefields without negative array effects.

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