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AVP-preserving Estimation of Reservoir Impulse Responses

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Summary

Estimating the reservoir properties from surface seismic data for a target below a complex overburden is a challenging problem. One of the approaches is to apply reservoir-oriented local inversion schemes on the redatumed local reflection response. In this paper, we propose a process to estimate the reservoir impulse responses (redatumed reflection response) in a complex overburden setting for realistic data with angle-dependent or angle vs ray parameter (AVP) characteristics. The impulse responses are estimated using Joint Migration Inversion (JMI) followed by sparsity constrained Proximity Transformation. It comprises a full wavefield approach in the sense that it correctly accounts for all internal multiples and transmission effects. As a result, the estimated impulse responses are free of interference related to internal multiples in the overburden. The process involves a noval procedure to estimate the propagation velocity model using the flexibility in the JMI parameterization. We finally show that this proposed JMI redatuming provides a much more reliable local reflection response, compared to standard redatuming based on time reversal of recorded data.

Introduction

Estimating deep subsurface reservoir properties from surface seismic data is a challenging task. This challenge becomes even larger when a target area is situated below a complex overburden. One familiar approach is to obtain the wavefields at the target depth level via redatuming (Wapenaar et al., 1992; Schuster and Zhou, 2006) and apply localized inversion schemes such as target-oriented nonlinear full waveform inversion (Gisolf and van den Berg, 2010). The major bottleneck for the success of any target-oriented inversion scheme is the accuracy of the input dataset, i.e. the redatumed wavefields at the target depth level. A standard redatuming approach (Beryhill, 1984), based on time reversal of recorded surface seismic data, fails to explain complex propagation (transmission) and scattering effects (internal multiples) as a result of strong overburden heterogeneities, apart from the fact that it requires the correct pre-estimated velocity model.

Joint Migration Inversion (JMI) (Berkhout, 2014b; Staal, 2015) is a noval data-driven approach to estimate the up- and downgoing wavefields within the subsurface along with the subsurface propagation velocity and reflectivity image. JMI is similar to data-driven Marchenko redatuming (van der Neut and Herrmann, 2013; Wapenaar et al., 2014) in the sense that it also constructs up- and downgoing waves in the medium. But unlike Marchenko redatuming, JMI does not rely on dense source sampling and can update errors in the background velocity field. On the other hand, it relies on a forward modeling engine that includes all propagation and scattering effects. The resulting up- and downgoing wavefields at the target depth can then be used to estimate the impulse responses (redatumed reflection response) from the target area via Proximity Transformation (Garg and Verschuur, 2016). These impulse responses are free from spurious events related to the internal multiples in the overburden.

The full wavefield approach to estimate the impulse responses was demonstrated by Garg and Verschuur (2016) using the notorious "inverse-crime" scenario where we used Full Wavefield Modeling (FWMod) (Berkhout, 2014a) to both model and invert the data with scalar reflectivity. Here, we go one step ahead and use acoustic finite-difference (FD) modeled data as input and estimate the impulse responses at the target depth level using the proposed approach. Here, we also demonstrate the flexibility in the JMI implementation in the sense that we can get the propagation velocity model using only scalar-reflectivity JMI for data with angle-dependent reflectivity or AVP characteristics. We also show the comparison and the advantages of the impulse responses estimated via JMI redatuming over standard redatuming.

Theory

Joint Migration Inversion (JMI) is a fully data-driven and operator-based inversion algorithm, which estimates reflectivity image of the subsurface with automatic velocity update, while also estimating the up- and downgoing wavefields at each subsurface depth level. The general JMI flowchart is depicted in fig. 1a. It iteratively minimizes the difference between the observed and the modeled data in a least-squares sense. This minimization can be summarized as follows:

$$J = \sum_{j}\sum_{\omega} \left|\left| \vec{P}^{-}_{j,obs}(z_0) - \vec{P}^{-}_{j,mod}(z_0) \right|\right|_2^2, \tag{1}$$

where $\vec{P}^{-}_{j,obs}$ and $\vec{P}^{-}_{j,mod}$ represent shot j of the observed and modeled data, respectively, and the subscript 2 of the residual refers to the L2 norm. The main strength of JMI is in its forward modeling engine, called Full Wavefield Modeling (FWMod). In FWMod, the seismic reflection response is explained in terms of two sets of operators, the scattering operator (**R**) and the wave propagation operator (**W**). **R** encodes the amplitude changes due to the reflection coefficients and **W** explains the phase changes due to the propagation velocities. This kind of parameterization reduces the non-linearity in the inversion process. In FWMod, the data is modeled iteratively and recursively for the given velocity model and reflectivity image, while it also includes all multiples and transmission effects.

The up- and downgoing wavefields at any subsurface depth level z_d can be related as follows:

$$\vec{P}^{-}(z_d; z_0) = \mathbf{X}(z_d, z_d)\vec{P}^{+}(z_d; z_0), \tag{2}$$

$\vec{P}^{-}(z_d; z_0)$ and $\vec{P}^{-}(z_d; z_0)$ represents the up- and downgoing wavefields at datum level z_d while $\mathbf{X}$ represents the impulse responses from the area below z_d. The impulse responses at the target level are estimated via Proximity Transformation, which is a least-squares inversion process applied to eq. 2 with sparsity and reciprocity constraints (Garg and Verschuur, 2016).

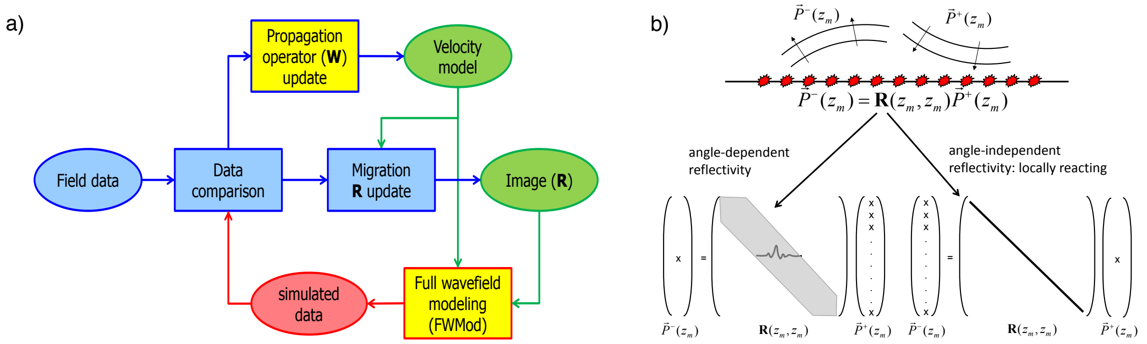

***Figure 1** a) JMI implementation flowchart. b) Reflectivity operator (**R**) as a spatial convolution operator.*

Methodology

In FWMod, the reflectivity operator matrix (**R**) at each depth level acts as the spatial convolution operator that scatters the incoming wavefield to the outgoing wavefield based on certain directivity (fig. 1b). In principle, **R** at any depth level will either be a banded matrix or a diagonal matrix, based on our assumption of angle-dependent reflection characteristics present or not in the input data, respectively (fig. 1b). For any real data or FD modeled data (with velocity variations), there will always be angle-dependent reflection characteristics present. Ideally, we should consider simultaneous estimation of angle-dependent **R** and the velocity in JMI. However, then we are at the risk of running into null spaces due to over-parameterization, while it is also more expensive. The more realistic approach demands us to apply JMI in steps while making use of the flexibility in FWMod parameterization.

First, we apply a quick run of JMI on the input data assuming scalar R. Although, we get a somewhat wrong velocity and reflectivity, we do get modeled data with angle-independent reflection characteristics, as in this case, FWMod will only be able to explain the angle-independent part of data. We use this modeled data as a reference data and generate an amplitude scaling function w.r.t. the original input data. Using this scaling function, we make a scaled-input data that will have minimized angle-dependency. Next, scalar-R JMI will explain this scaled-input data and estimate correct propogation velocity model and structural image. As a final step, we fix the velocity and apply JMI to the original input data, only with angle-dependent **R** update, to explain the angle-dependent part of input data. Actually, this final step is full wavefield Migration with angle-dependent **R** (Davydenko and Verschuur, 2017). From the final output, the up- and downgoing wavefields at the target depth are extracted as input for Proximity Transformation (Garg and Verschuur, 2016).

Numerical Example

The subsurface model for this example with strong overburden is shown in fig. 2a,b. The input data is modeled using acoustic FD modeling for the acquisition geometry defined by sources and receivers at $40m$ and $20m$ intervals, respectively, and with a Ricker wavelet of peak frequency 20 hz as source. In fig. 2c,d we can see the AVO (or AVP) effects present in the data. The initial reflectivity and velocity model for inversion process are taken as zero and a simple linear vertical gradient, respectively. Using the approach explained in the previous section, we first generate the reference data via scalar-R JMI (fig. 3a) and then the scaled-input data (fig. 3c). Using this scaled-input data, we are able to estimate the propagation velocity model (fig. 3d) again via scalar-R JMI. Finally, to explain angle-dependent characteristics in the input data and to get the up- and downgoing wavefields at $z_d = 680m$, we go for JMI with angle-dependent **R** with fixed velocity. The final estimated wavefields are shown in fig. 4. The residual (fig. 4c) at large offsets is due to some unexplained post-critical events, whereas the limited offsets in upgoing wavefield (fig. 4e) are a result of limited illumination at target depth (z_d) due to the overburden. The up- and downgoing wavefields at z_d (fig. 4d,e) are used to estimate impulse responses via Proximity Transformation, as shown in fig. 5a. We can clearly see 3 sharp reflections corresponding to the target, free of overburden internal multiples interference. On contrary, the impulse responses estimated via standard redatuming (fig. 5b), using the JMI estimated velocity model, are dominated by spurious events related to internal multiples in the overburden. The comparison becomes more clear in the tau-p domain. Note that for the standard redatuming we have the luxury of a good velocity model from JMI, otherwise results may have phase inaccuracies too. Thus, the JMI output can serve as accurate input to local inversion schemes.

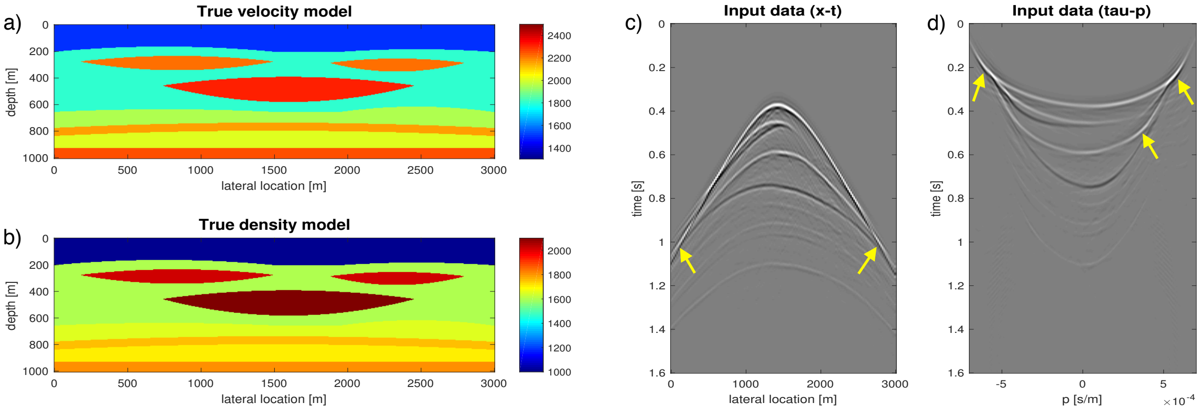

Figure 2 *a) Velocity and b) density model used to generate the acoustic FD modeled input data. Shot record at position* $x = 1480m$ *in c) x-t domain and d) tau-p domain. Yellow arrows indicate the AVO (or AVP) characteristics in the input data.*

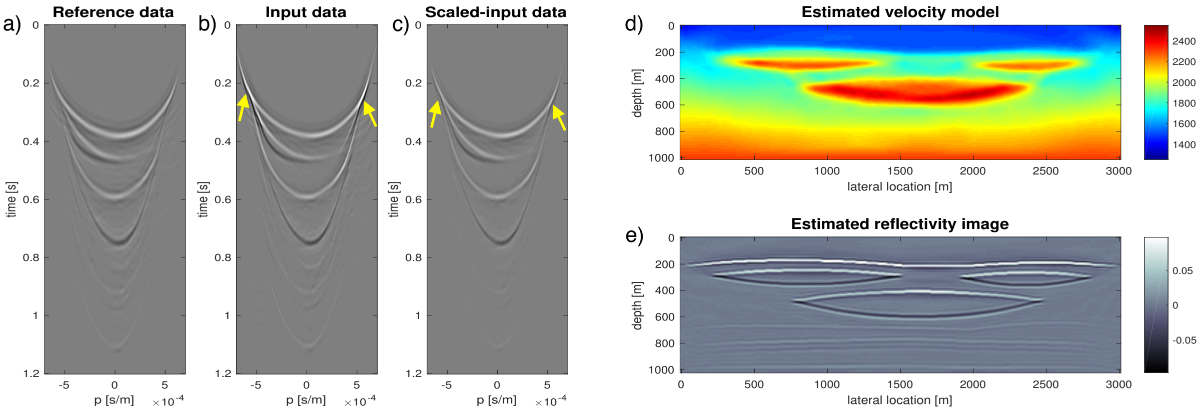

Figure 3 *a) Reference data used to scale b) the input data amplitudes in order to generate c) scaled-input data for shot record at position* $x = 1480m$*. All panels are in the tau-p domain. d) Estimated velocity model using scaled-input data via scalar-R JMI. e) Estimated structural or scalar reflectivity image.*

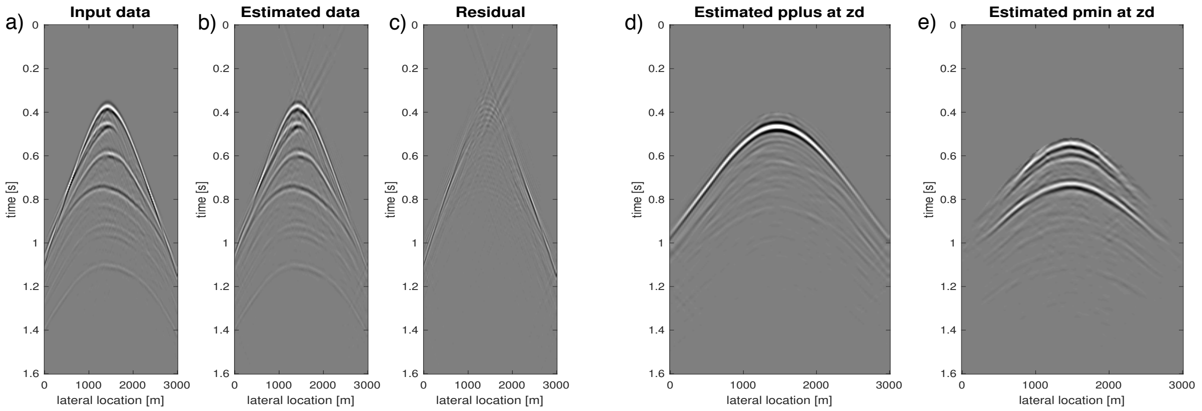

Figure 4 *a) Input data, b) estimated data and c) their residual. d) Down- and e) upgoing wavefields at* $z_d = 680m$*. All wavefields are at position* $x = 1480m$ *after JMI, including the angle-dependent* ***R*** *step.*

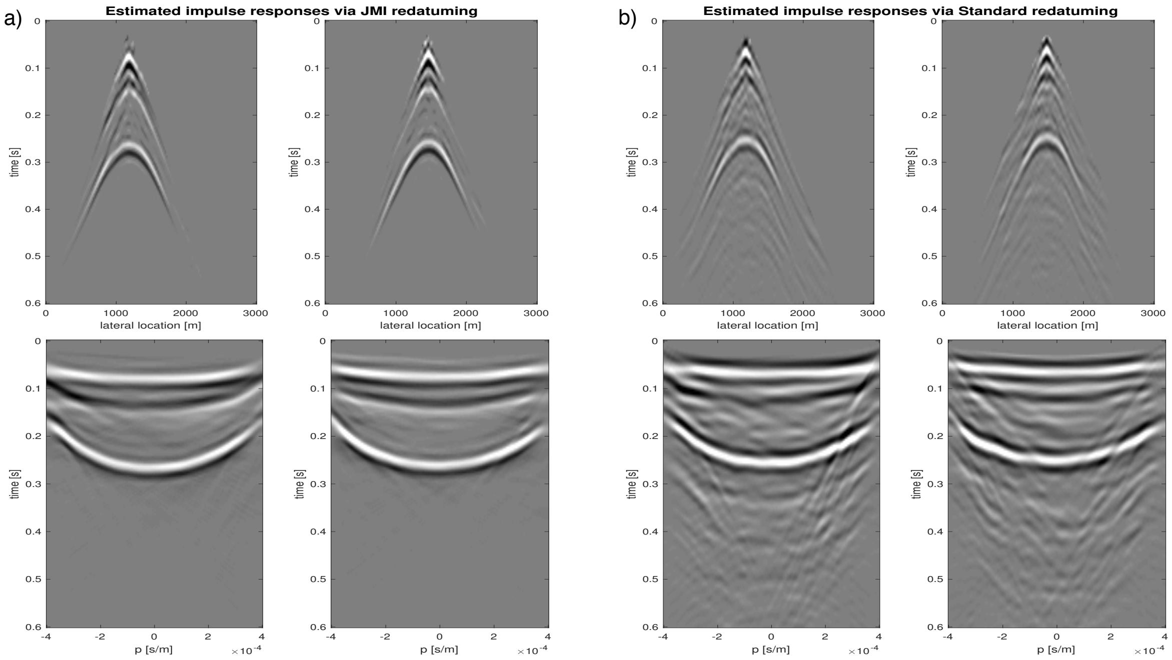

Figure 5 *Comparison of estimated impulse responses at* $z_d = 680m$ *via a) JMI redatuming and b) standard redatuming at positions* $x = 1200m$ *and* $x = 1480m$ *in x-t (above) and tau-p domains (below).*

Conclusions

In this paper we demonstrate the target-related impulse response estimation for realistic input data with angle-dependent reflectivity or AVP characteristics. Moreover, we handle the internal multiples from the overburden correctly using the JMI process. At the same time, we also estimate the propagation velocity model as the integral step of the process, using the flexibility in JMI parameterization (scalar or angle-dependent **R**), starting from a very simple velocity model. Finally, we also show the inherent internal multiples interference in standard redatuming, apart from the need of a correct pre-estimated velocity model.

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