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### **► To cite this version:**

Fandy Adji Fachtony, Romain Brossier, Bastien Dupuy, Ludovic Métivier, Anouar Romdhane. 4D FWI with Short Offset Data: a Reflection Oriented Approach. 84th EAGE Annual Conference & Exhibition, Jun 2023, Vienne, Austria. pp.1-5, <10.3997/2214-4609.202310427>. <hal-04278858>

**HAL Id: hal-04278858**

**<https://hal.science/hal-04278858v1>**

Submitted on 10 Nov 2023

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# 4D FWI with short offset data: a reflection oriented approach

F. A. Fachtony<sup>1</sup>, R. Brossier<sup>1</sup>, B. Dupuy<sup>3</sup>, L. Métivier<sup>1,2</sup> & A. Romdhane<sup>3</sup>

<sup>1</sup> Univ. Grenoble Alpes, ISTerre, F-38058 Grenoble, France

<sup>2</sup> CNRS, Univ. Grenoble Alpes, LJK, F-38058 Grenoble, France

<sup>3</sup> SINTEF Industry, Applied Geosciences Department, S.P. Andersens veg 15A, 7031 Trondheim, Norway

January 13, 2023

## Main objectives

To present an integrated 4D FWI workflow based on the combination of reflection based “joint full waveform inversion” and simultaneous time lapse strategy for short offset data.

## New aspects covered

The integrated workflow incorporates a hierarchical approach utilizing both reflection based “joint full waveform inversion” and simultaneous time-lapse strategy. Here, the hierarchical approach consists of 4D macromodel estimation based on combination of JFWI and simultaneous time lapse strategy, and followed by high resolution 4D model estimation based on simultaneous time lapse inversion.

## **Summary (250 words)**

The use of full waveform inversion (FWI) is still at a relatively experimental stage for time lapse applications. Time lapse changes from seismic data can be estimated from simple subtraction between two different models obtained by FWI, baseline and monitor respectively. However, a simple subtraction between two inverted FWI models suffers from artifacts due to the non-linearity and ill-posedness of the underlying inverse problem. In addition, most of the available time lapse data are vintage data set, which have limited offset characteristics, implying that the deeper part cannot be sampled by diving waves and are only constrained by reflections. Such data-set already bring inherent challenges for conventional FWI, let alone time lapse FWI application. To tackle these challenges, an integrated hierarchical workflow based on combination of joint diving and reflection waves FWI (JFWI) and simultaneous time lapse strategy is introduced. JFWI mitigates the lack of diving wave penetration on short offset, while simultaneous time lapse strategy ensures coupling between baseline and monitor, therefore minimizing the presence of 4D artifacts. As an integrated hierarchical workflow, starting with crude initial model, the combined JFWI and simultaneous time lapse strategy is able to infer relevant 4D macro model. Followed by subsequent simultaneous time lapse FWI, high resolution 4D models can be estimated. In this context, we show how this integrated hierarchical workflow is able to better estimates the 4D changes compared to the direct implementation of simultaneous time lapse FWI without the JFWI step.

## 4D FWI with short offset data: a reflection oriented approach

### Introduction

Full waveform inversion (FWI) has become a standard tool for exploration seismic to deliver high resolution seismic images of the subsurface. When it comes to track the temporal evolution of the subsurface elastic properties, the use of FWI is still at a relatively experimental stage. The temporal evolution of the subsurface can be approximated by simple subtraction between two different models obtained by FWI, baseline and monitor respectively. However, a simple subtraction between two reconstructed FWI models suffers from artifacts due to the non-linearity and ill-posedness of the underlying inverse problem.

Several strategies have been introduced to improve such a crude workflow. One way is to invert the baseline data and utilize the reconstructed baseline model on a sequential inversion for the monitor data (Asnaashari et al., 2015). Another possibility is to perform a Double Difference Waveform Inversion (DDWI): the difference between two data-set is minimized, namely the synthetic data difference and observed data difference (Watanabe et al., 2004). Direct data subtraction however implicitly constrains on the need of repeatable seismic acquisitions, which is difficult to ensure in practice. Zhou and Lumley (2021) propose to mitigate these difficulties with central difference strategies by averaging the results from two sequential inversion, forward (baseline to monitor), and reverse (monitor to baseline). Alternatively, Maharramov and Biondi (2015) introduce a joint formulation of the baseline and monitor data misfit function to couple the inversion and introduce total variation regularization to suppress oscillatory artifacts in the model difference.

For most of time lapse applications, most of the available data sets are vintage seismic data which are mainly acquired with limited offset geometry. For FWI applications, limited offset implies the following limitation: the diving waves cannot sample the deep part of the model. Consequently, FWI is limited to high wavenumber perturbations (migration isochrone) at depth, which mainly contribute to the creation of interfaces rather than updating the background model. One possibility to circumvent this difficulty while relying on finite-frequency full waveform modeling approaches is to use Reflection oriented Waveform Inversion (RWI). RWI subtracts the migration isochorones from the gradient and uses only its rabbit ears (low wavenumber component) to update the model beyond the depth sampled by diving waves (Xu et al., 2012). Combining information from diving and reflected waves, Joint FWI (JFWI) uses both wave types to update the low wavenumber component of the model (Zhou et al., 2015).

In this work, we want to assess the interest of integrating the JFWI workflow for 4D FWI in the context of short offset data. As for 4D strategy, we choose to utilize the simultaneous time lapse FWI (STFWI) proposed by Maharramov and Biondi (2015) to enforce inversion coupling between data set. In a hierarchical manner, we combine the JFWI workflow with a simultaneous 4D approach which we call simultaneous time lapse JFWI (STJFWI) to infer reflection based 4D macromodel. Then we follow with the STFWI utilizing models obtained from STJFWI to infer high resolution 4D model. We compare this 4D hierarchical workflow with a direct implementation of STFWI without STJFWI step. From the 2D synthetic experiment we present, it appears that the combination of STJFWI followed by STFWI is more amenable to provide reliable 4D changes from short offset data in a context of gas charged sediments.

### Methodology

#### Joint-FWI

We recall here the basic principle of JFWI. We rely on the recent implementation proposed in Provenzano et al. (2022), which makes use of a  $V_p - I_p$  parameterization, a specific preconditioner for the  $I_p$  reconstruction, and a pseudo-time formulation for the impedance reconstruction. We recall the main ingredients in the following. The misfit function writes

$$C_{JFWI}(V_P, I_P) = \frac{1}{2} \|W^{div}(d_{cal}(V_P, I_0) - d^{div})\|_{L_2}^2 + \frac{1}{2} \|W^{refl}(d_{cal}(V_P, I_P) - d^{refl})\|_{L_2}^2, \quad (1)$$

where  $d_{cal}(V_P, I_0)$  is simulated based on the background velocity model  $V_P$  and a smooth impedance model  $I_0$  (typically derived from the initial model  $V_P$  through a Gardner's law), while the second term  $d_{cal}(V_P, I_P)$  is simulated using the background velocity model  $V_P$  plus the impedance model  $I_P$ .  $W^{div}$  and  $W^{refl}$  are data weighting operator to select and balance the contribution between early arrivals and reflections respectively. During the inversion, diving and reflected waves contribute to the background velocity  $V_P$  updates, while for  $I_P$  updates only reflected waves are taken into account.

We minimize  $C_{JFWI}$  using a variable projection approach. The gradient of  $C_{JFWI}$  with respect to  $V_P$  can be written in form as (Zhou et al., 2015)

$$\begin{aligned} \nabla_{V_P} C_{JFWI} = & u_0(V_P, I_0) \star \lambda_0^{div}(V_P, I_0) \text{ (banana-donuts)} \\ & + \delta u(V_P, I_P) \star \lambda_0^{refl}(V_P, I_0) + u_0(V_P, I_0) \star \delta \lambda^{refl}(V_P, I_P) \text{ (rabbit ears)}, \end{aligned} \quad (2)$$

where  $u_0(V_P, I_0)$  and  $\lambda_0^{div}(V_P, I_0)$  denotes the incident wavefield and adjoint wavefield with the diving wave residuals as adjoint source propagating in the medium  $(V_P, I_0)$ ,  $\delta u(V_P, I_P)$  is the scattering component of the incident wavefield due to the presence of  $I_P$ ,  $\lambda_0^{refl}(V_P, I_0)$  denotes the adjoint wavefield with the reflection data residuals as the adjoint source inside the medium  $(V_P, I_0)$ , and  $\delta \lambda^{refl}(V_P, I_P)$  is the scattering component of the adjoint wavefield due to the presence of  $I_P$ . The  $\star$  denotes the zero lag cross-correlation.

The gradient construction in (2) needs a reflectivity  $I_P$  which we compute through Impedance Waveform Inversion (IPWI). This consists in minimizing  $C_{JFWI}$  with respect to the impedance  $I_P$ . The gradient with respect to  $I_P$  can be written as

$$\nabla_{I_P} C_{JFWI} = u_0(V_P, I_P) \star \lambda_0^{refl}(V_P, I_P) \text{ (migration isochrones)}. \quad (3)$$

Provenzano et al. (2022) reformulated the JFWI in pseudo-time domain, following Plessix (2013); Brossier et al. (2015). We can write the relationship between pseudo-time ( $\tau$ ) and depth ( $z$ ) with the function of velocity as follows:

$$\tau(z) = \int_0^z dz' / V_0^z(z'), \quad z(\tau) = \int_0^\tau V_0^t(\tau') d\tau'. \quad (4)$$

The depth domain  $V_P^z, I_P^z$  model is transformed to the pseudo-time domain  $\tau$ , discretized using  $\Delta\tau = \Delta z / V_{0,max}$  and reaching  $\tau_{max} = z_{max} / V_{P,min}$ , where  $V_{P,max}$  and  $V_{P,min}$  are the maximum and minimum values of  $V_P$  respectively. The gradient in eq. 2 is still computed in depth domain, but then reformulated from depth domain to pseudo-time domain using the chain rule Plessix (2013) as follows

$$\nabla_{\tau(i)} C_{JFWI} = \nabla_{z(i)} C_{JFWI} - \int_{z_i}^{z_{max}} \frac{dV_P^z}{dz} \frac{1}{V_P(z)} \nabla_z C_{JFWI} dz. \quad (5)$$

At each iteration, after  $V_P$  is updated in the pseudo-time ( $\tau$ ) domain, the  $V_P^\tau, I_P^\tau$  model is transformed back to the depth ( $z$ ) domain. By fixing  $I_P$  in pseudo-time rather than in depth domain, we mitigate the velocity-depth ambiguity. Then, by transforming back to the depth domain with updated velocity, we move the reflectors towards correct position while preserving zero offset travel times. We present the theory for the least-squares misfit function but that as for FWI any kind of misfit function can be used. To better handle potential cycle skipping issue, as what is done in Provenzano et al. (2022) we choose a Graph-Space Optimal Transport misfit function (Métivier et al., 2019).

#### Combination of Joint-FWI with 4D FWI

We review here the formulation of the simultaneous approach proposed by Maharramov and Biondi (2015). We integrate the JFWI misfit function formulation to joint formulation of baseline and monitor data as follow.

$$\begin{aligned} f(V_{P,base}, I_{P,base}, V_{P,mon}, I_{P,mon}) = & C_{JFWI}(V_{P,base}, I_{P,base}) \\ & + C_{JFWI}(V_{P,mon}, I_{P,mon}) + \frac{\alpha}{2} \|\nabla(V_{P,mon} - V_{P,base} - \Delta V^{Prior})\|_1. \end{aligned} \quad (6)$$

Within STJFWI framework, we perform JFWI on baseline and monitor data simultaneously, while enforcing total variation regularization based on the model difference controlled by the hyper parameter  $\alpha$ . In practice, one can utilize either the same or different initial models for each dataset to do simultaneous inversion as the formulation gives us flexibility related to the initial model choice. Meanwhile, current implementation of the impedance building is performed independently and not coupled unlike the velocity model inversion. The impedance information obtained from independent IPWI inversion are used as prior reflectors input for STJFWI.

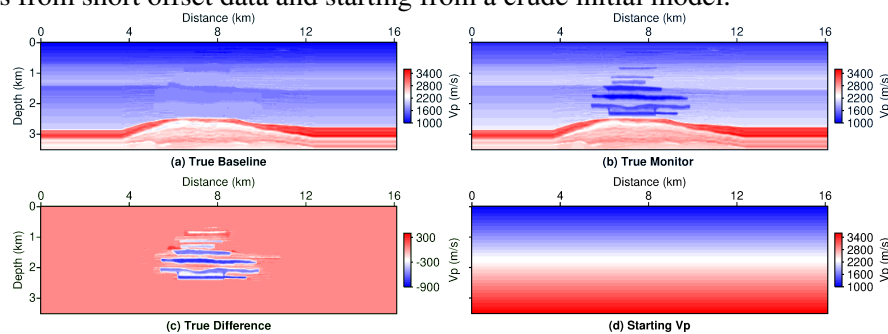
#### Numerical examples

To test the feasibility of the proposed workflow, we consider a 2D synthetic example based on a North Sea model (Fig. 1), mimicking the case of an oil and gas field with a gas cloud anomaly, the model contains a multi-layered low-velocity zone (LVZ) and a deeper high velocity anticline (HVA). 128 shots are simulated at 110 m spacing, recorded by a 229 channels streamer with group interval of 25 m and maximum offset of 5700 m. The source signature is a zero-phase Ricker with central frequency equal to 6.25 Hz. The starting model is 1D as in Figure 1, and it consists of a 70 m depth water layer ( $V_p=1500$

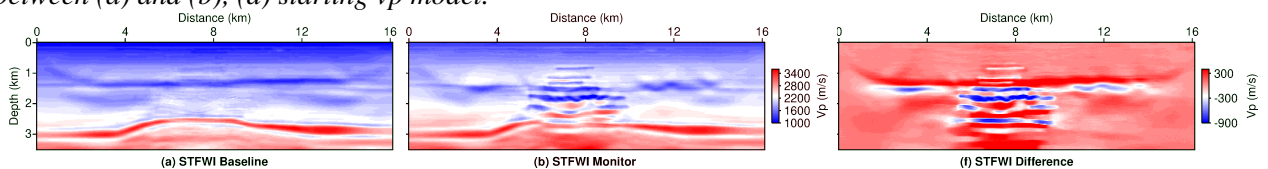
m/s) and a subsurface in which  $V_p$  increases linearly with depth.

We perform three inversions under simultaneous time lapse strategy. First, we illustrate how STFWI performs in Figure 2. Simultaneously inverting 4D data directly with the starting model in Figure 1d shows an improper reconstruction of the gas cloud anomaly and the baseline model, resulting in ambiguous 4D differences (Fig. 2c). Next, as part of the hierarchical workflow, performing STJFWI is able to promote tomographic models which contain gas cloud anomaly reasonably well (Fig. 3a-c) while maintaining minimal presence of 4D artifacts and honoring the smooth-blocky component of the gas cloud anomaly. Finally, taking the results from STJFWI as an initial model, a subsequent run of STFWI able to reconstruct the gas cloud anomaly quite accurately (Fig. 4), resulting well separated 4D differences with minimal 4D artifacts. In this second stage, the initial model for the baseline and monitor data are the final models obtained after the first STJFWI stage.

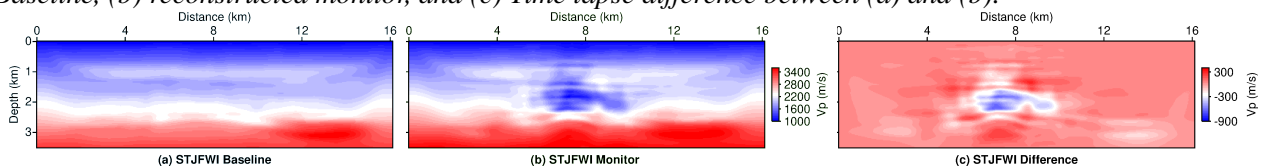
The improvement compared to the direct implementation of STFWI can be linked to the better constraint on density/impedance as passive information during JFWI especially in high contrast case as in gas cloud anomaly. In 4D context, this passive information helps to drive the 4D changes update between baseline and monitor where high contrast impedance is expected. Especially if we start with the same smooth initial, it is going to be biased. As an integrated 4D workflow, it is essential to build initial models which have some prior information of the 4D anomaly then construct the following high resolution 4D models from it. In addition, simultaneously inverting baseline and monitor data at each step of the workflow ensures a coupling during the inversion which minimize the 4D artifacts caused by convergence issue. All in all, integrated workflow of STJFWI and STFWI appears as a good strategy to recover high resolution 4D anomalies from short offset data and starting from a crude initial model.



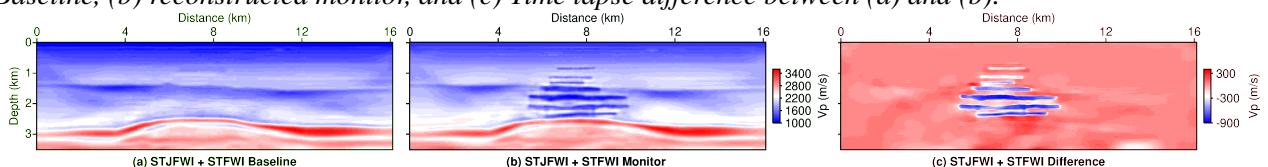
**Figure 1**  $V_p$  models, (a) true baseline  $v_p$  model, (b) true monitor  $v_p$  model, (c) true time lapse difference between (a) and (b), (d) starting  $v_p$  model.



**Figure 2** Simultaneous time lapse FWI starting from 1D initial model in Figure 1d. (a) Reconstructed Baseline, (b) reconstructed monitor, and (c) Time lapse difference between (a) and (b).



**Figure 3** Simultaneous time lapse JFWI starting from 1D initial model in Figure 1d. (a) Reconstructed Baseline, (b) reconstructed monitor, and (c) Time lapse difference between (a) and (b).



**Figure 4** Simultaneous time lapse FWI with initial model from simultaneous JFWI results in Figure 3a and 3b respectively (STJFWI + STFWI). (a) Reconstructed Baseline, (b) reconstructed monitor, and (c) Time lapse difference between (a) and (b).

## Conclusions

In this work we have integrated the reflection based JFWI workflow in the 4D FWI context for short offset data. We implement an integrated hierarchical strategy of STJFWI and STFWI to infer 4D models under the full wavefield method framework. We observe that STJFWI, combined effort of JFWI and simultaneous time lapse inversion is able to promote 4D macro model changes from reflections with minimal 4D artifacts serving as good initial model for a subsequent run of STFWI. The results show very well reconstructed 4D anomaly and minimal 4D artifacts, which is a significant improvement compared with a direct implementation of STFWI without the STJFWI step.

## Acknowledgements

This study was partially funded by the SEISCOPE consortium (<http://seiscope2.osug.fr>), sponsored by AKERBP, CGG, EXXON-MOBIL, GEOLINKS, JGI, PETROBRAS, SHELL, SINOPEC and TOTALENERGIES, and by the NCCS consortium (<https://www.sintef.no/projectweb/nccs/>). This study was granted access to the HPC resources provided by the GRICAD infrastructure (<https://gricad.univ-grenoble-alpes.fr>), Cray Marketing Partner Network (<https://partners.cray.com>) and IDRIS/TGCC under the allocation 046091 made by GENCI.

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