IPTC-18189-MS

Optimization Driven Model-Space Approach for Gas Clouds Using Full Waveform Inversion

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This paper was prepared for presentation at the International Petroleum Technology Conference held in Kuala Lumpur, Malaysia, 10–12 December 2014.

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Abstract

Exact quantitative information from seismogram based on full-wavefield modeling with non-linear wave equation method enhanced by computational cost and time over-burden, conventional full waveform inversion (FWI) method is a very challenging. Due to the limited accuracy, lack of adequate and accurate initial velocity model, and the approximate modeling of the wave-physics complexity, local minima does not prevent towards the convergence of misfit function. An alternative simultaneous-source encoding inversion technique is proposed. With the use of proposed algorithm, successfully recoverd the true geological information though inversion, however, the use of simultaneous source introduces the crosstalk artifacts which are efficient at higher frequencies and minimum at low frequencies, which we can clearly see in the model fit at top but it has minimal effect on whole dataset. However, we successfully recovered the true geological structure.

Introduction

Efficient computation of high capability in subsurface imaging, full-waveform inversion remains an elusive area of research. Full waveform inversion is based on the minimization of the misfit between observed and estimate data after each optimization to achieve satisfactory results with reduced misfit (Tarantola, 1984; 1986). The estimation of misfit and gradient are linearly dependant on each seismic source in the acquired data with a band-limited wavelet (like, a Ricker wavelet). Computational complexity of wavefield is proportional to the size of model and acquisition geometry, which simulate the over burden costs and time. Computational cost of full waveform inversion is a major issue to estimate the true velocity model for large-scale problem such as gas clouds, where the wave are attenuated and acoustic velocity decrease drastically with time. In the Malaysian (Malay) basin, the geophysical challenges are numerous, like imaging thin sands, imaging below gas clouds and below carbonates, understanding wave propogation in effective media. Gas clouds problems are very dominant in Malay basin and its challenges are well explained by Ghosh et al., (2010). An example of such imaging problem in East Malaysia production field, where in one part there is no gas leakage and perfect imaging (Figure

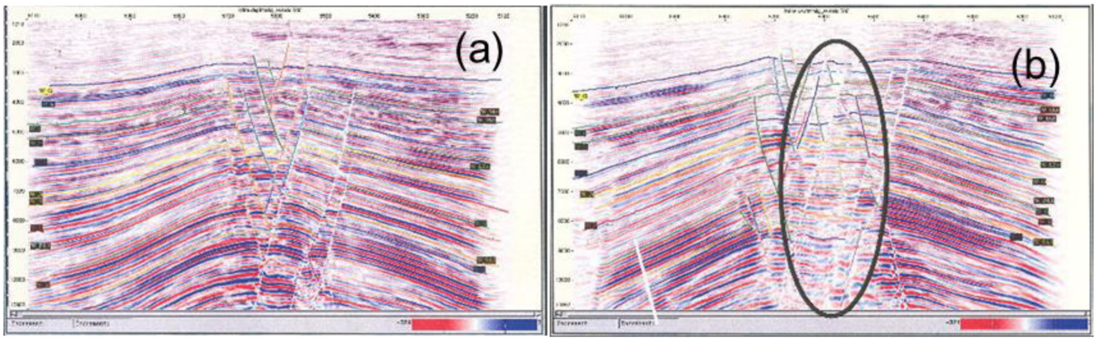

Figure 1—Gas Masking Effect in Malay basin: (a) perfecting imaging with no shallow gas cloud (b) Poor imaging with gas leakage due to poor sealing of Hydrocarbon Reservoir

1a), where as in another part of the same field with similar structural play (Figure 1b) is a serious "Seal" breach in gas leakage resulting *P*-wave masking.

Use of OBC shear wave approach to solve the wipeout issue,

1. Considering *P*-wave attenuation, using Q Migration (Reilly et al., 2008)
2. Equivalent solution as 1) but using Scattering theory (Ghazali, 2011)
3. Full waveform inversion improving P image

They manifest most commonly as a vertical "chimney" below where the seismic *P*-wave energy is wiped out making the reflectors with strong internal short period multiples and non-hyperbolic moveout, the probable possible causes are,

a. Multiple scattering wavefield due to complicated faulting.
b. Wells are difficult to penetrate in gas clouds due to poor seismic imaging and lack of true geological knowledge.
c. Few attentation was made using 2D acoustic full waveform inversion to image gas cloud (Prieux et al., 2009)

The simultaneous source encoding approach has been proposed to reduce the computational burden in time-domain (Boonyasiriwat et al., 2009; Krebs et al., 2009) and also implemented in the frequency-domain (Herrmann et al., 2009). In simultaneous approach, individual shots gathers into super-shots gathers (Romero et al., 2000). Based on signal-to-noise ratio (S/N), Schuster et al., (2011) conclude that the number of migration iterations should be the number of shot gathers in a super-shot gather. Here, we consider the low frequency model to remove the effect of cycle skipping and crosstalk noise, which affect the gradient misfit and degrades the inversion results during convergence to get local minima. Moreover, due to incoherent behavior of crosstalk, it cancels after each iteration. Batch sampling method (van Leeuwen and Herrmann, 2013) is an alternative technique to reduce the computational cost, but this method used randomly selected sources at each iteration. The proposed simultaneous source algorithm successfully recovered the original geological information.

Full waveform Inversion

We used misfit function for full waveform inversion as

$$\varphi(m) = max\left[\frac{1}{NR}\sum_{k=1}^{NR}\frac{\varphi_k^{NR}(m)}{\sigma_k^{NR}}\right] \tag{1}$$

$$\varphi_k(m) = \|A(m)u_k - d_k\|^2 \tag{2}$$

Where *A(m)* assign for modelling parameter, *m* denote the model parameter, u_i is the source at *i*-th point, d_i the corresponding short record and *NR* the total number of sources used to estimate the misfit.

The misfit ϕ gives a measure of closeness of the observed and estimated with respect to standard deviation. The partial derivatives of estimated data with respect to model parameters show that estimated data are affected by source and shot. The misfit $\phi(m)$ gives equal importance to $\phi(m)/\sigma$ for each source and shot.

Simultaneous source encoding

Simultaneous source is a summing encoded source into supershots:

$$\tilde{d} = \sum_{k=1}^{NR} \omega_k d_k \tag{3}$$

Where $\tilde{d}$denote the corresponding data generate by above equation. The random weighting vector $w = (\omega_1, \omega_2. \ldots\ldots \omega_k)^t$; such that $M\{ww^t\} = 1/N$ (van Leeuwen and Herrmann (2013). The corresponding supershot $(\tilde{l})$and adjoint wavefields $(\tilde{m})$) is given by

$$\tilde{l} = \sum_{k=1}^{NR} \omega_k l_k \quad \text{and} \quad \tilde{m} = \sum_{k=1}^{NR} \omega_k m_k \tag{4}$$

Previously, such encoding with random weights has been considered for full waveform inversion (van Leeuwen et al., 2011). Then the encoded misfit is given by

$$\breve{\varphi}(m) = max\left[\frac{1}{NR}\sum_{k=1}^{NR}\frac{\breve{\varphi}_k^{NR}(m)}{\sigma_k^{NR}}\right] \tag{5}$$

$$\breve{\varphi}_k(m) = \left\|A(m)\breve{u}_k - \breve{d}_k\right\|^2 \tag{6}$$

Here, we can comes to new misfit, which is average misfit,

$$\varphi(m) = M\{\breve{\varphi}(m)\} \tag{7}$$

Optimization method

Now, we have the misfit to be in the form,

$$\varphi(m) = max\left[\frac{1}{NR}\sum_{k=1}^{NR}\frac{\varphi_k^{NR}(m)}{\sigma_k^{NR}}\right] \tag{8}$$

where, $\varphi_k^{NR}$is the misfit for a simultaneous source. The appropriate optimization method we chosen here,

$$m_{k+1} = m_k + \propto_k (-\nabla q[m]_k) \tag{9}$$

where $\propto_k$ an appropriately chosen using line search method and $(-\nabla q[m]_k)$is the steepest-decent method. During optimization, convergence rate is an important property which provide us rate of decay of the misfit at each iteration.

Algorithm for Simultaneous Full waveform inversion

Output estimate for the model $\boldsymbol{m}$ and $\boldsymbol{m_0}$
assign the frequency band
for $i_{band} = N$
do
while iteration to convergence or not
build supershots
generate wavefields from supershots
calculate wavefield residuals and misfit function
compute updated misfit and gradient at every frequency band as define
check convergence limit
estimate back propagate residual
end for
if iter =1 then
compute diagonal Hessian
end if
scale gradient vector using Hessian
compute step length using line search method
update model: $m_{k+1} = m_k - \propto_k \nabla q[m]_k$
end while
end for

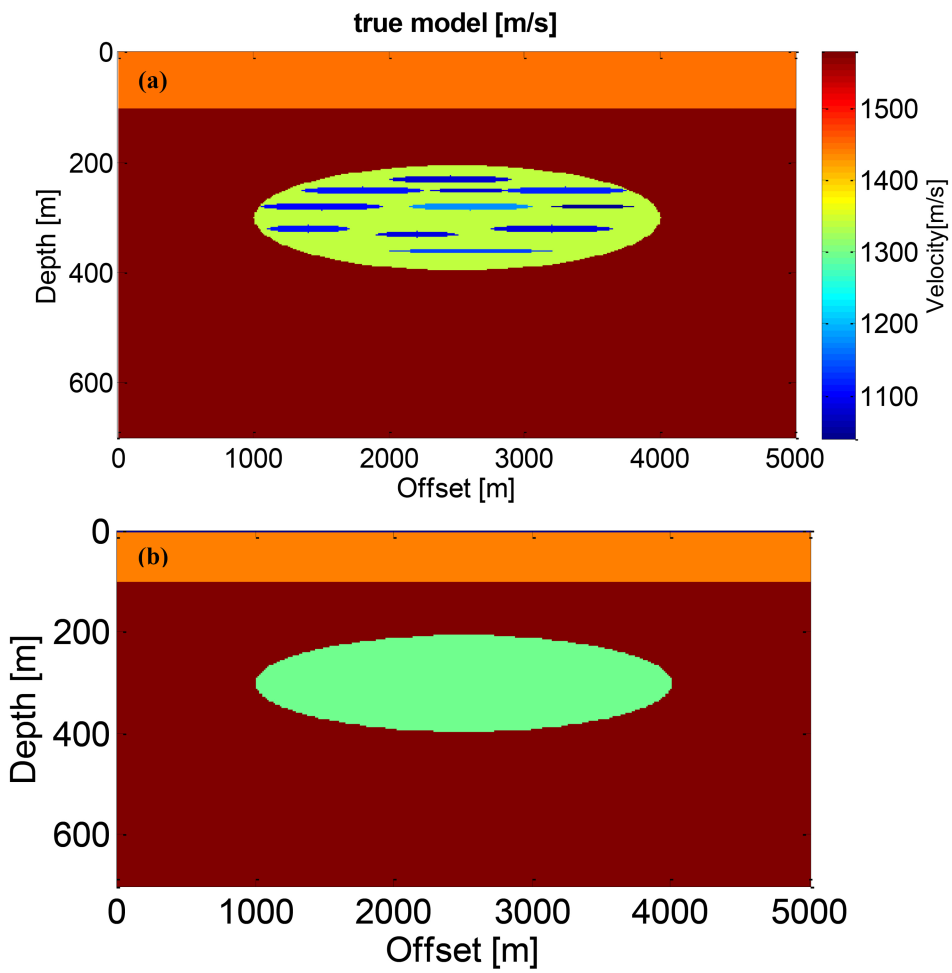

Figure 2—(a) true velocity model for gas cloud model study, encrypt with Gaussian anomalies with low velocity, (b) the initial velocity model used for gas cloud full wave-form inversion, color bar is common for both figures (a, b). Please note that the color bar is same for both figures.

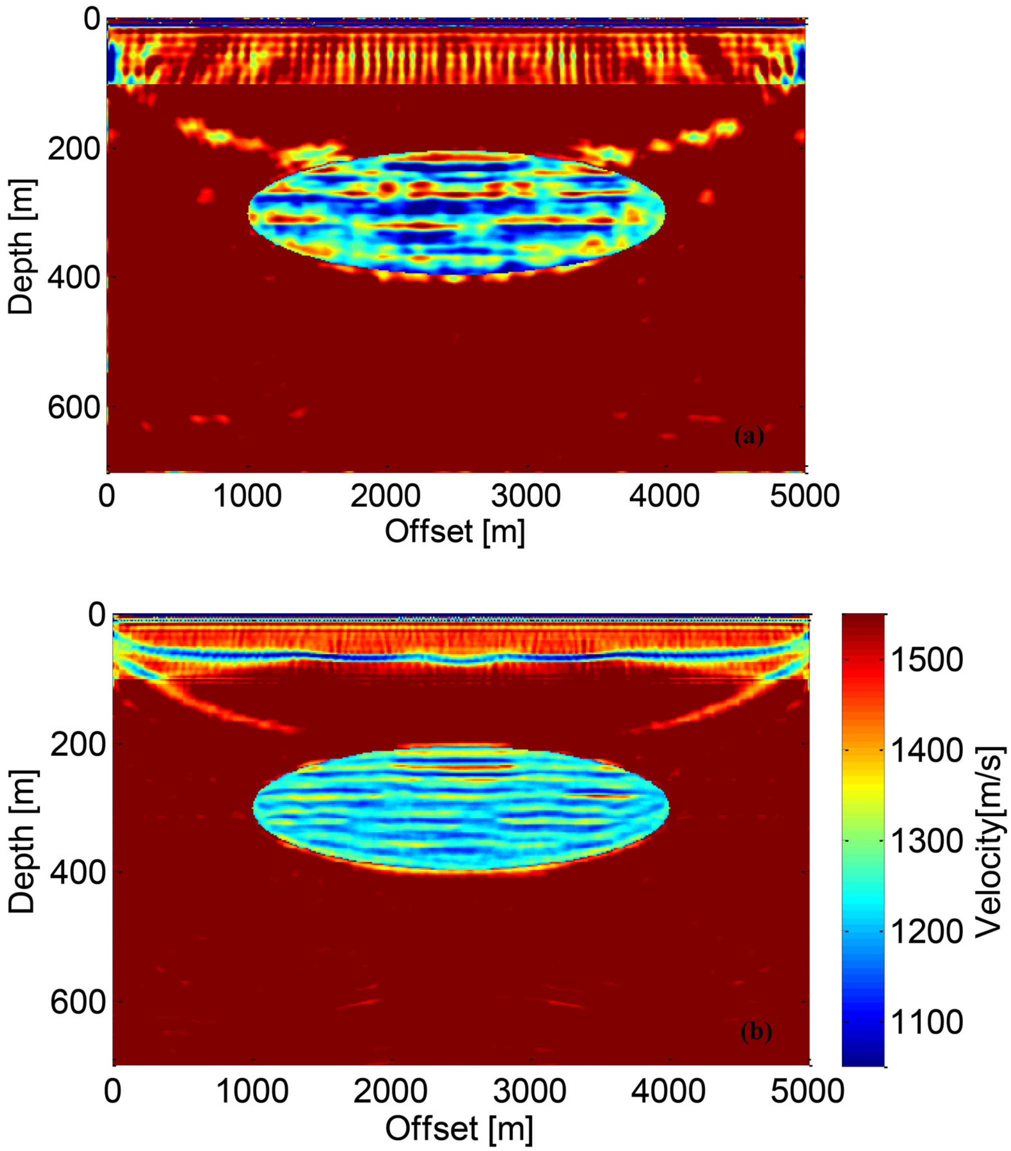

Figure 3—(a) Full waveform inversion using conventional method, (b) full waveform inversion result using simultaneous source encoding. Both results performed at same frequency (10 Hz). Please note that the color bar is same for both figures.

Numerical Example: Offshore Malay basin

The numerical example is based on the synthetic model for gas cloud (Figure 1), which is close representative of gas clouds problem in Malay Basin (Malaysia) (Ghazali, 2011, Ghosh et al., 2010). The main aims are the gas cloud in sediment layer in shallow part of Malay basin. Gas clouds are easily found in Malay Basin and it is a very challenging issue to identify the hydrocarbon trap. In Gas cloud, P-wave velocities are very low whereas the signature of S-wave is much weaker.

To implement the above proposed algorithm, we consider a shallow gas cloud model as 5-km long offset and 0.7-km deep with P-wave velocities lower as we find in Malay basin. We used source as Ricker wavelet with a 10-Hz central frequency. For initial velocity model, we smooth and average laterally the reference velocity model (Figure 2b) which is consistent with the true velocity model (Figure 2a). Good smooth initital velocity model is very important to ensure convergence to minima and closed to global minima. Synthetic data were generated with 125 shots (with 40m interval) at 50-m depth and with 250 receivers at lateral positions (with 20m interval) at 20-m depth. The misfit (nonlinear) relation between

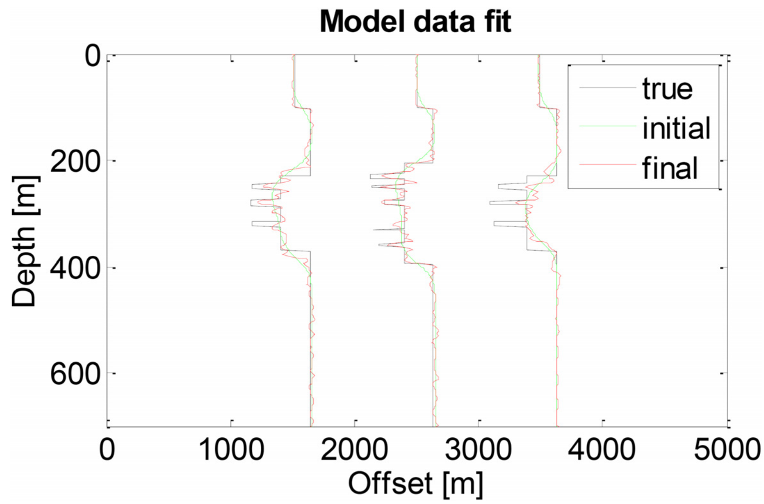

Figure 4—misfit plot with simultaneous source (red color)

the model parameters and the data is mitigated by performing the inversion from low to high frequency data.

The optimization is solved with L-BFGS (Nocedal, 1980), which is a quasi-Newton optimization method for approximating the inverse of the Hessian matrix without computing the Hessian matrix. Data is inverted in 5 separate frequency band [1.5, 2.5], [2.5, 3.5], [4, 6], [7, 9], [10, 12] with 12 iterations per frequency band. The diagonal of the Hessian matrix (Shin et al., 2001) is used as an initial guess for L-BFGS algorithm. Observed and modeled have been both produced by in frequency domain.

Discussion and Conclusions

In order to evaluate the full waveform inversion results from simultaneous source encoding, we first did the conventional FWI using least square penalty by inverting all the individual shots.

Observed and modelled data have been produced by both the conventional and simultaneous source encoding in frequency domain with same setup of grid parameters.

During inversion, we applied both random phase technique and without random phase technique to know the effect of crosstalk noise affect that arises from the interference of sources in the inverted model. These artifacts arise from the interference among the sources of the supershots (Berkhout and Blacquire, 2011). Moreover the crosstalk noise is directly proponational to the supershots and inversely proponation to the reconstruction of the imporved image. To cmpare the quality and robustness of the inverted model, we compute $Q = \log_{10}[||m||^2/||m - m_0||^2||]$, where m_0 and m are the true and inverted velocity model, respectively. A high value of Q corresponds to more accurate model i.e. inverted model is closed to true model. Here, we estimated the quality factor of the reconstructed velocity model as Q=73.95 and compare with the Q eatimated in table 3 by Anagaw et al., (2014). The resulting acoustic simultaneous full waveform inversion and conventional full waveform inversion results after 12 iterations are shown in figure 3a-3b and their corresponding misfit is ploted as figure 4. One could notice that results from without simultaneous source encoding, we clearly see the crosstalk signature in inversion result, which affect the final inversion result and the quality of the image is decreases. Meanwhile, when we applied simultaneous source encoding technique with random phase, we can see the better results with minimum effect of crosstalk noise; however, crosstalk noise is more efficient with high frequencies and less sensitive to low frequencies. Here, we can conclude that, even at low frequency, presence of the crosstalk effect is clearly seen at top of the model, however, it has been completely removed at around the gas cloud and a clear model could be seen. Although, one important thing is that the resolution of the image is still low, but it describes the subsurface structure very well.

Acknowledgements

The authors would like to thanks Universiti Teknologi PETRONAS (UTP) for financial support and permission to publish this research. This research was carried out as part of PETRONAS Research project.

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