Joint full-waveform inversion of time-lapse seismic data sets

SEP Report 152, pages 19-28

Musa Maharramov and Biondo Biondi

Stanford Exploration Project

June 3, 2014

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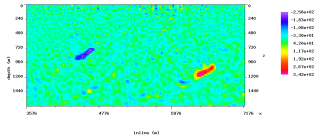
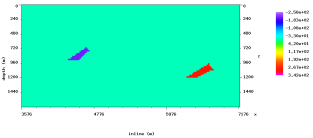
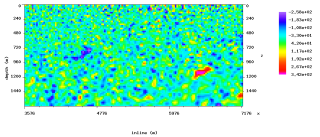






Outline

- Motivation and Objectives
- Existing methods
- NEW: Joint 4D FWI
- Clean synthetic tests
- Random noise synthetic tests
- Different survey parameters
- Conclusions and perspectives
- Acknowledgements
- Q&A

Motivation: improved reservoir monitoring

- Depends on successful tracking of fluid movement
- Conversion of time shifts $\Rightarrow$ impedance changes
- Requires manual interpretation
- More automated approaches based on, e.g., WE image-difference tomography (Albertin et al., 2006)
- 4D FWI (Routh et al., 2012)
- Goal: design robust 4D FWI less sensitive to repeatability issues

Full-waveform inversion

Find a model $\mathbf{m}$ that minimizes misfit between misfit between the true $\mathbf{D}$ and synthetic $\mathbf{u}(\mathbf{m})$ data (Lailly, 1983; Tarantola, 1984)

$$\|\mathbf{W}_d \left[\mathbf{D} - \mathbf{u}(\mathbf{m})\right]\|^2 \;\rightarrow\; \min, \tag{1}$$

with optional model regularization

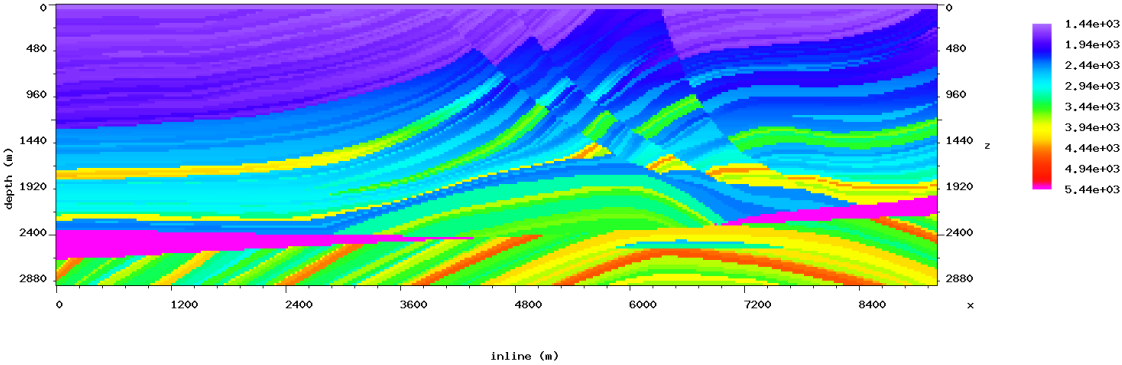
$$+\beta \|\mathbf{RW}(\mathbf{m} - \mathbf{m}^{\mathrm{P}})\|^2, \tag{2}$$

where

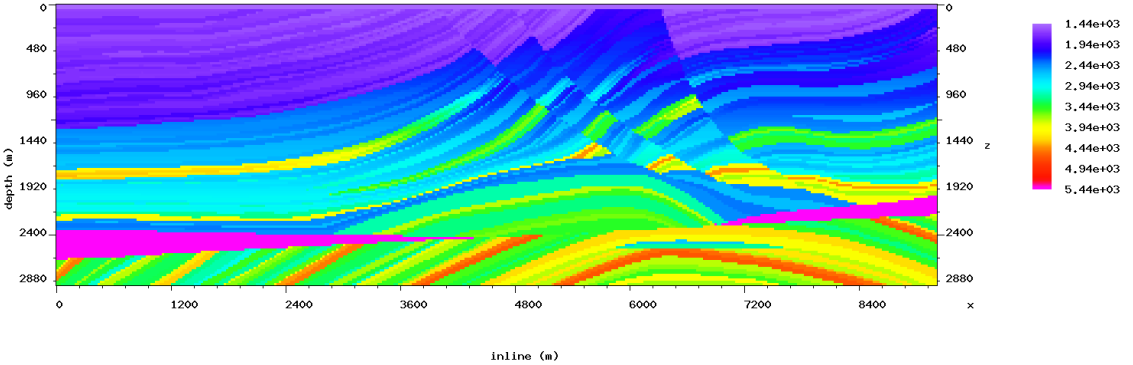
$$\begin{aligned} m(\mathbf{x})\frac{\partial^2 u(\mathbf{x},t)}{\partial t^2} &= \Delta u(\mathbf{x},t) + f(\mathbf{x},t), \\ u(\mathbf{x},t=0) &= \frac{\partial u(\mathbf{x},t=0)}{\partial t} = 0, \end{aligned} \tag{3}$$

$\mathbf{W}_d$ and $\mathbf{W}$ are data and model weighting operators, and $\mathbf{R}$ is a model regularization operator.

“Marmousi” model: true baseline

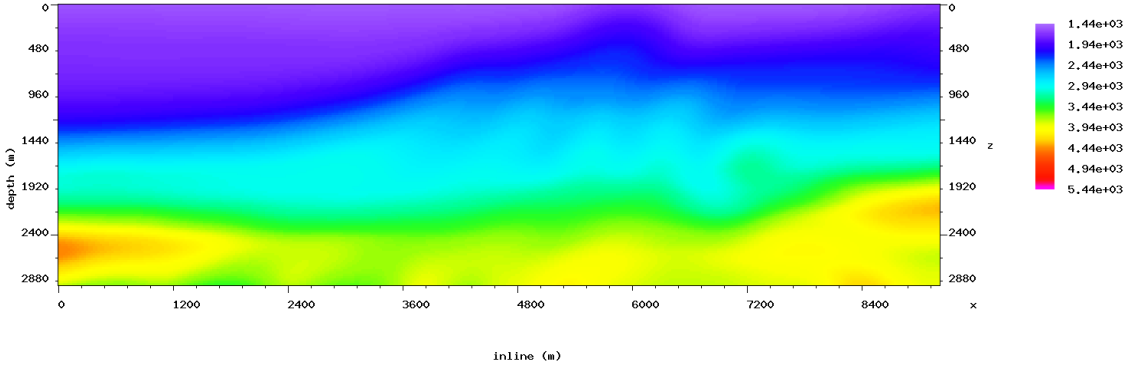


Modified "Marmousi": true monitor

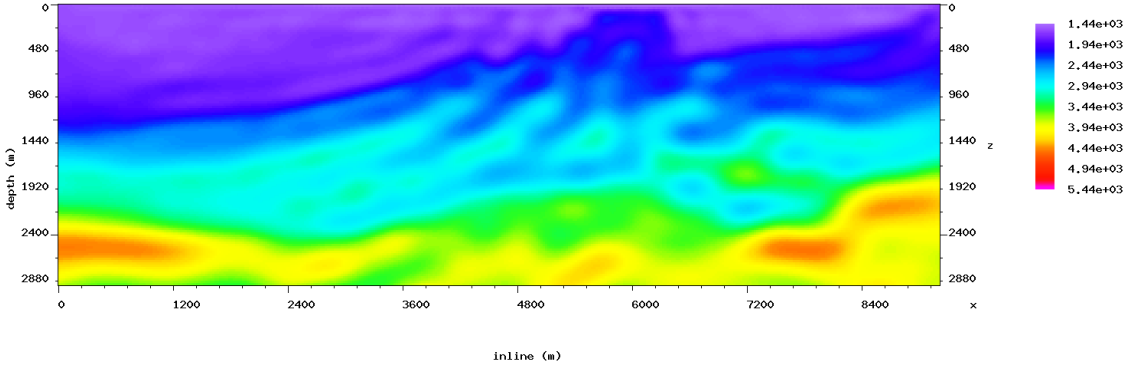


Baseline inversion from clean synthetic

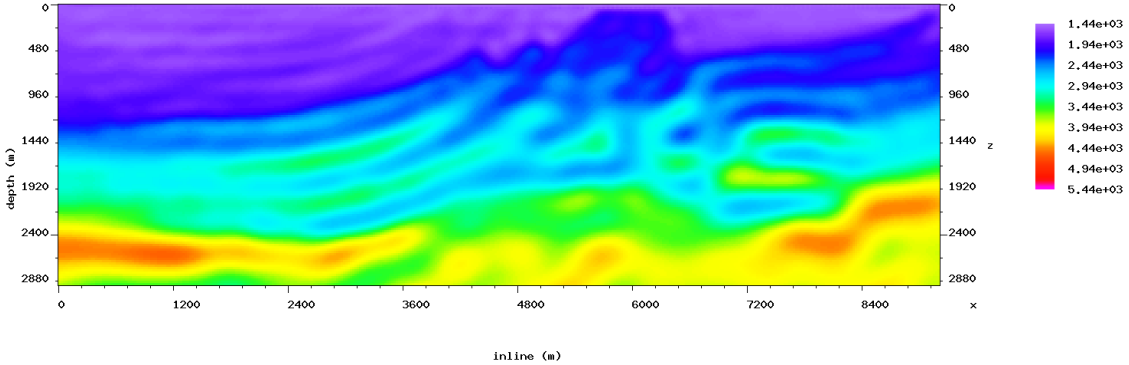
Baseline inversion, starting model



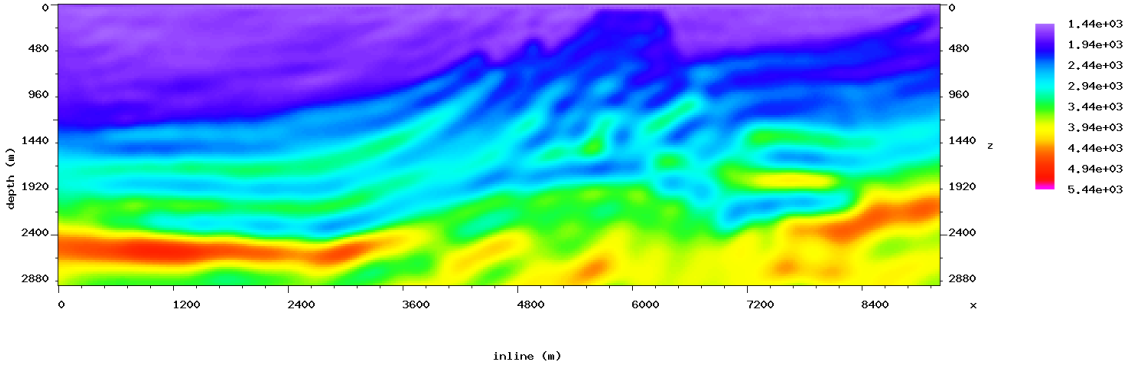
Baseline inversion, 3.0Hz



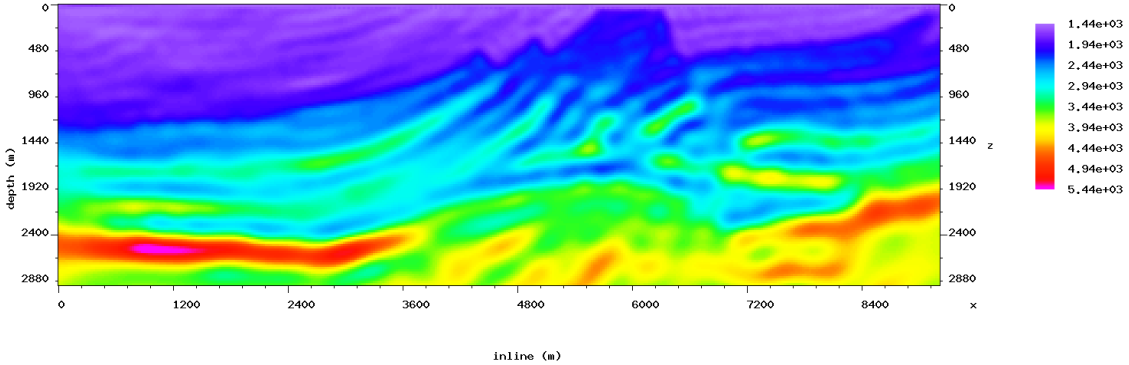
Baseline inversion, 3.6Hz



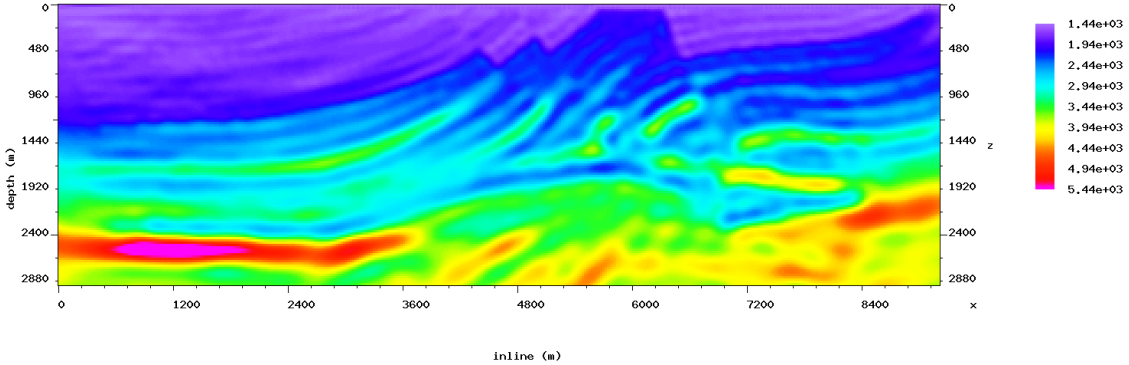
Baseline inversion, 4.3Hz



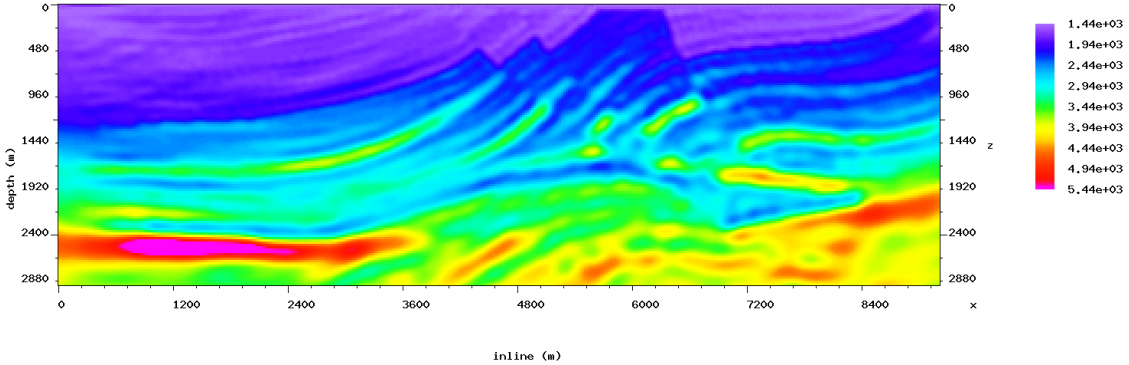
Baseline inversion, 5.1Hz



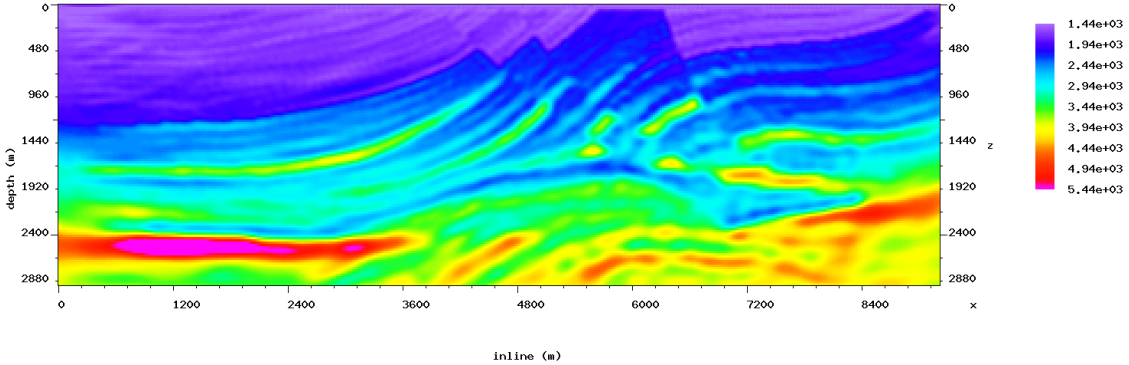
Baseline inversion, 6.2Hz



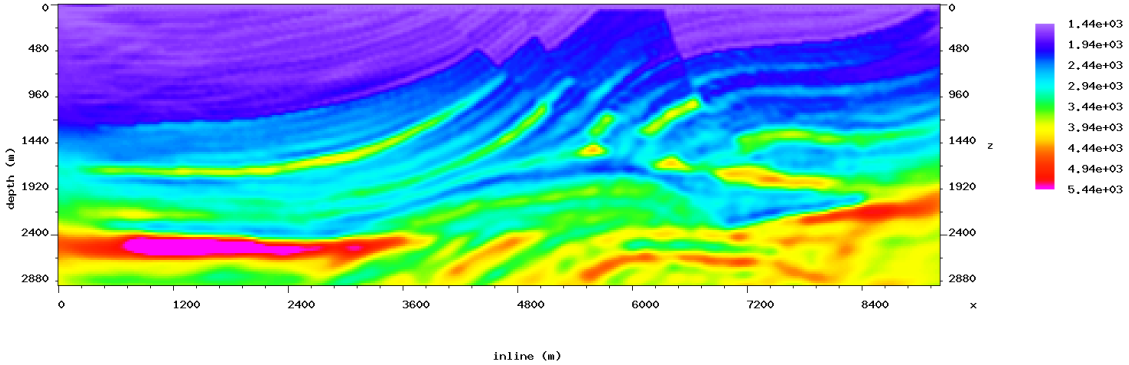
Baseline inversion, 7.5Hz



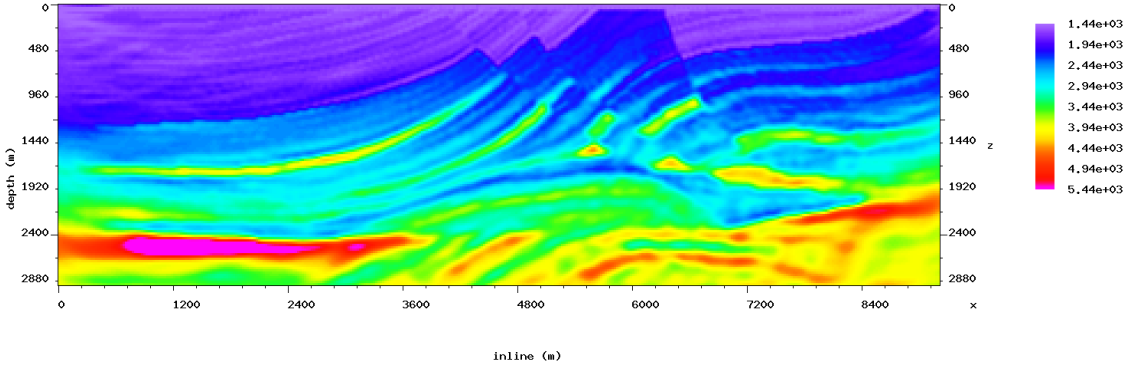
Baseline inversion, 9.0Hz



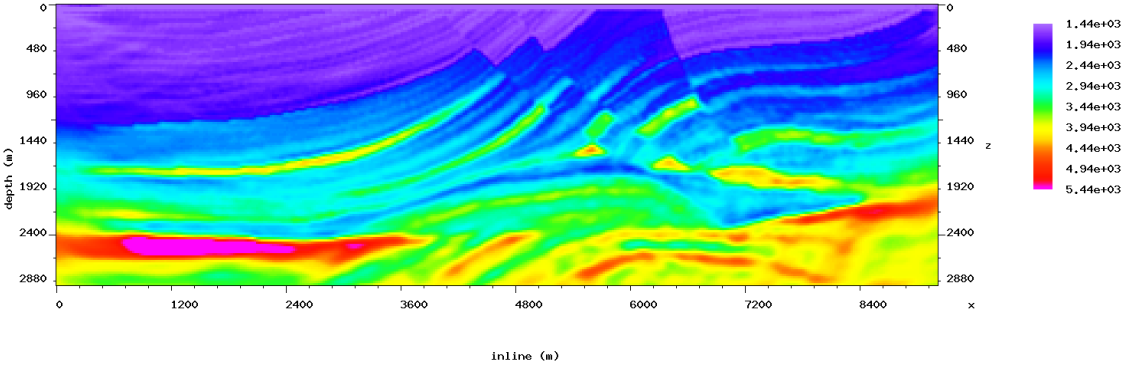
Baseline inversion, 10.8Hz



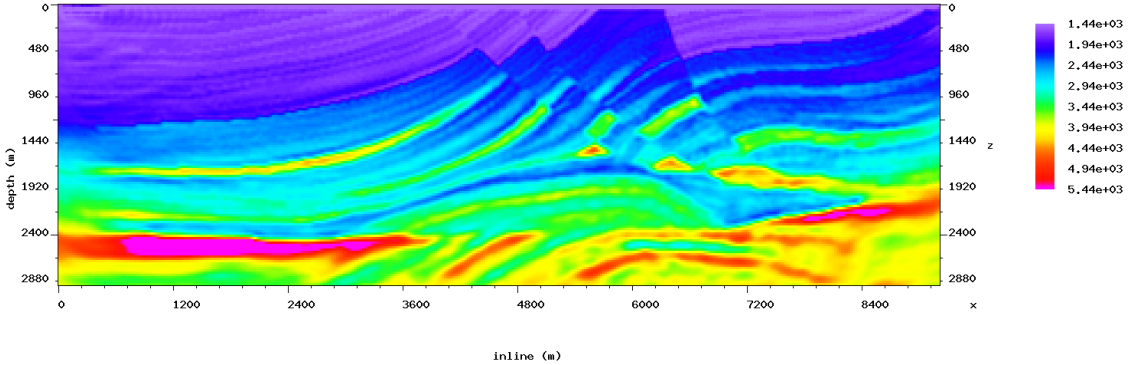
Baseline inversion, 12.8Hz



Baseline inversion, 15.5Hz

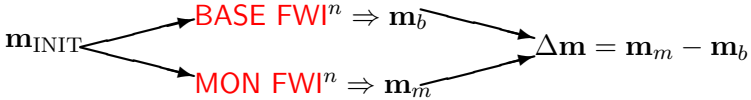


Baseline inversion, second cycle, 15.5Hz

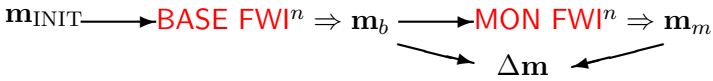


Existing 4D FWI methods

- *Parallel Difference* FWI (iterated) (Miller et al., 2007)



- *Sequential Difference* FWI (iterated) (Oldenborger et al., 2007)



- *Double Difference* (Watanabe et al., 2004)

$$\| \left(\mathbf{M}^s_m \mathbf{u}_m - \mathbf{M}^s_b \mathbf{u}_b\right) - \left(\mathbf{M}_m \mathbf{D}_m - \mathbf{M}_b \mathbf{D}_b\right) \| \ \rightarrow \ \min, \tag{4}$$

where $\mathbf{M}^s_{m,b}, \mathbf{M}_{m,b}$ denote equalization operators for synthetic and field data.

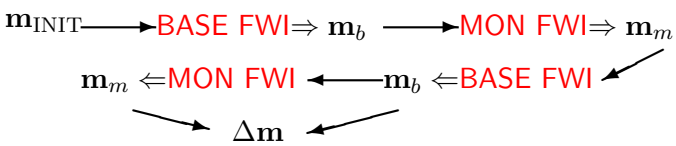
Joint 4D FWI: simultaneous inversion and cross-updating

- NEW: *Simultaneous FWI* of baseline and monitor with *difference regularization*:

$$\sum_{i=1}^{2} \alpha_i \|\mathbf{W}_d^i \left[\mathbf{D}_i - \mathbf{u}(\mathbf{m}_i)\right]\|^2 + \tag{5}$$

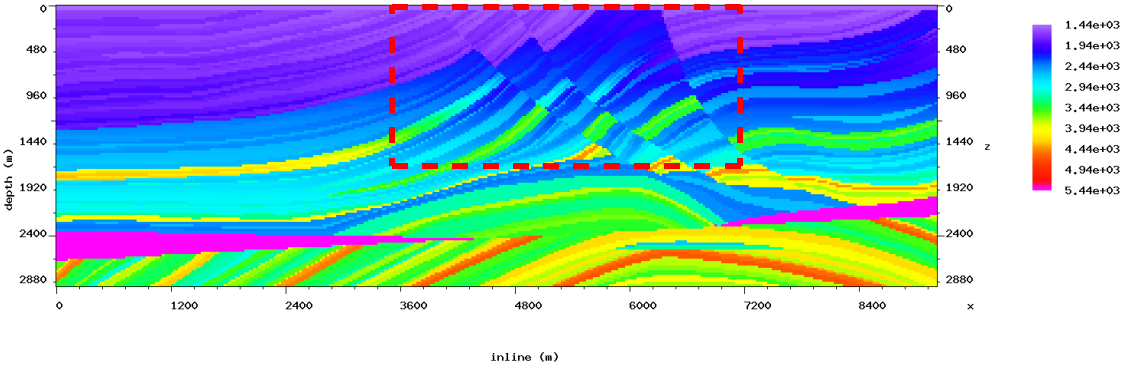
$$+ \alpha \|\mathbf{RW}(\mathbf{m}_2 - \mathbf{m}_1 - \Delta\mathbf{m}^{\mathrm{P}})\|^2. \tag{6}$$

- NEW: *Cross-updating* Approximation to the Simultaneous FWI:

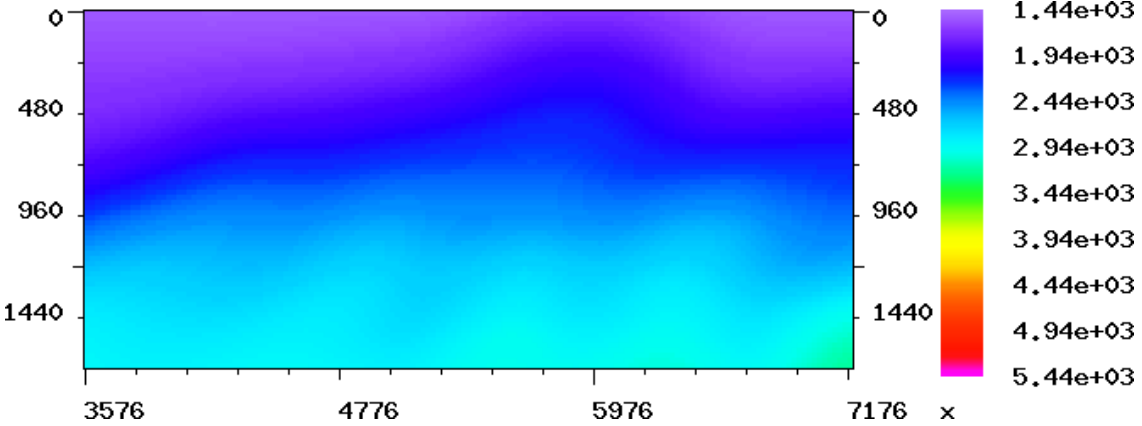


The effect of random noise on FWI

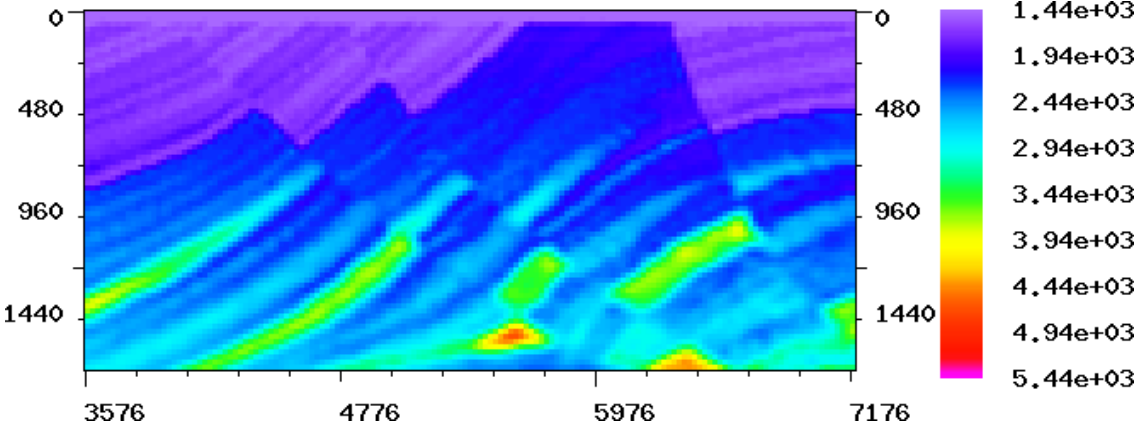
Target area


0
480
960
1440
1920
2400
2880
depth (m)
0
1200
2400
3600
4800
6000
7200
8400
x
inline (m)
z
1.44e+03
1.94e+03
2.44e+03
2.94e+03
3.44e+03
3.94e+03
4.44e+03
4.94e+03
5.44e+03

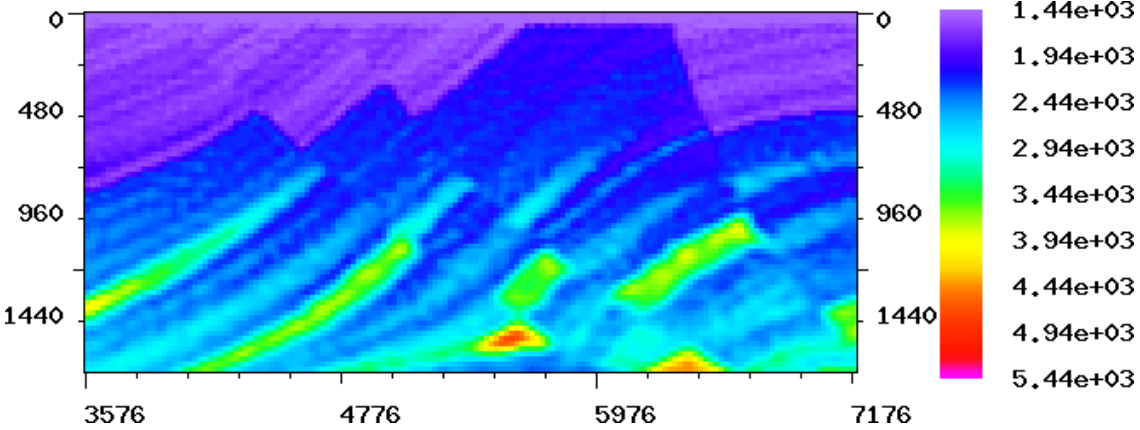
Starting model target baseline



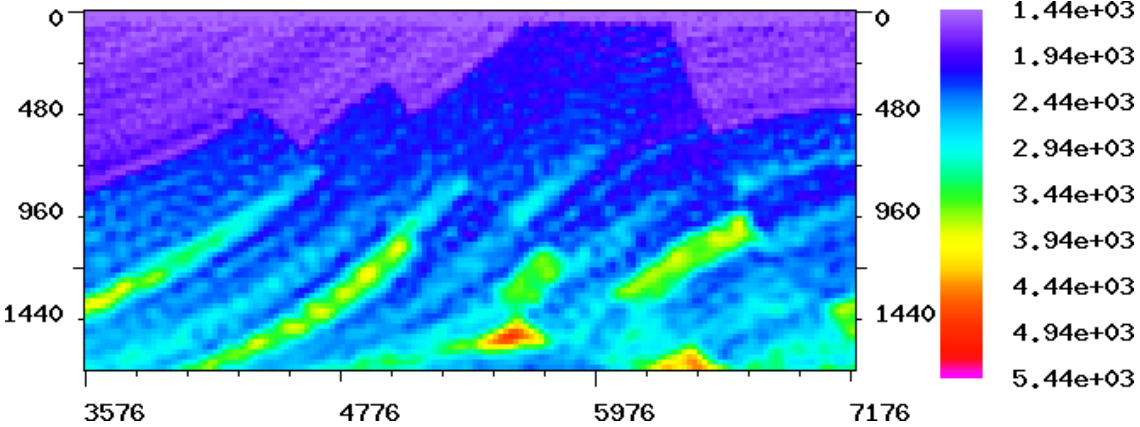
Target baseline reconstructed from clean synthetic



Target baseline reconstructed from 14 dB synthetic

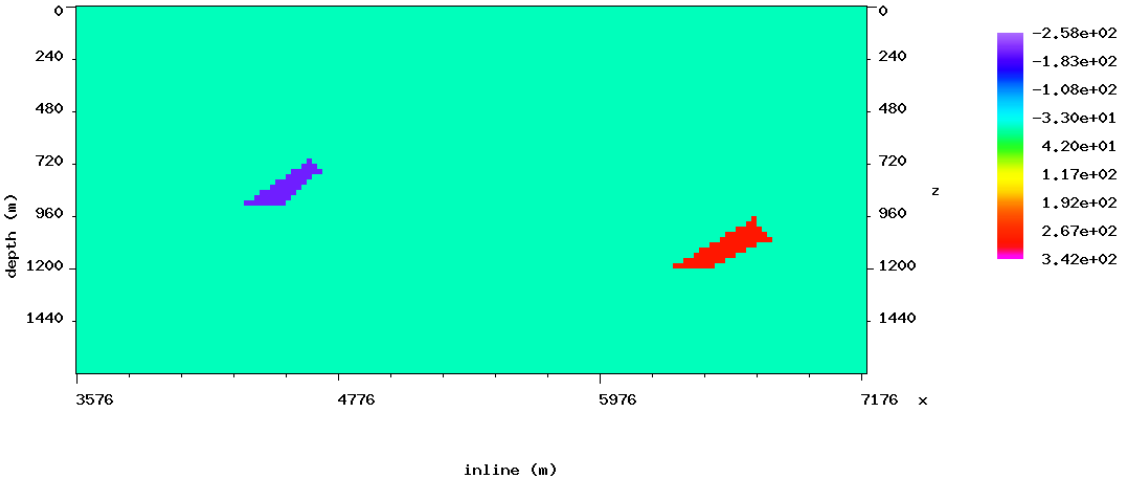


Target baseline reconstructed from 7 dB synthetic

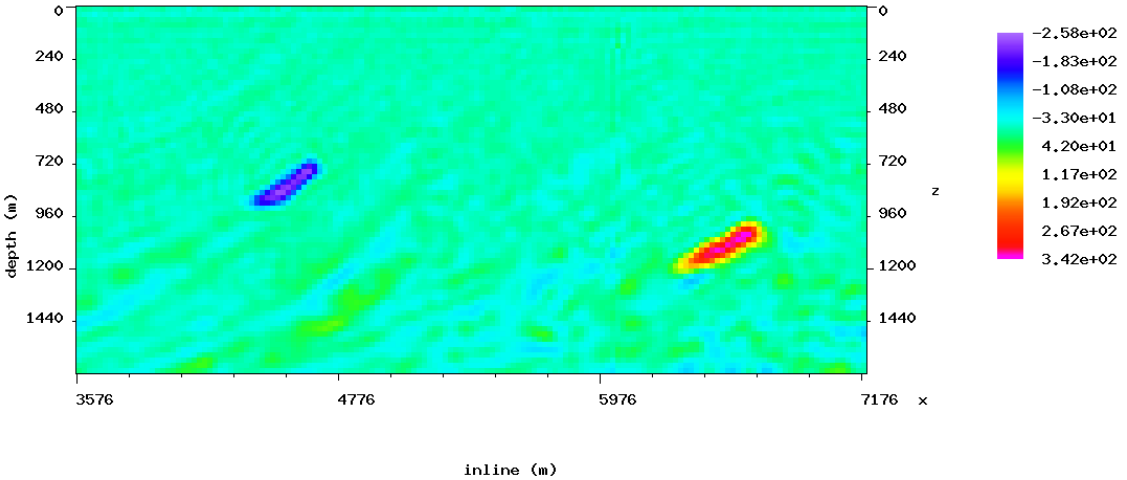


Clean synthetic

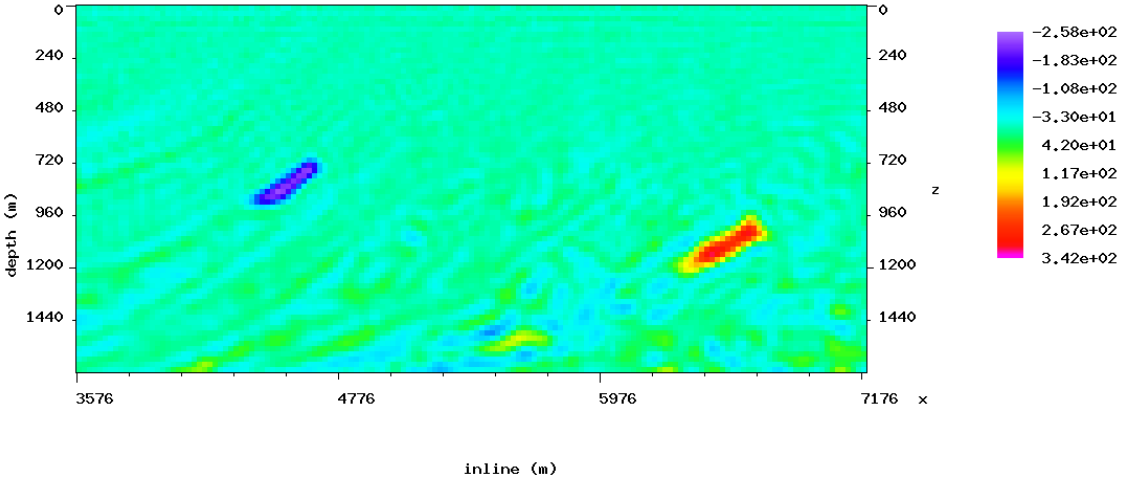
True difference



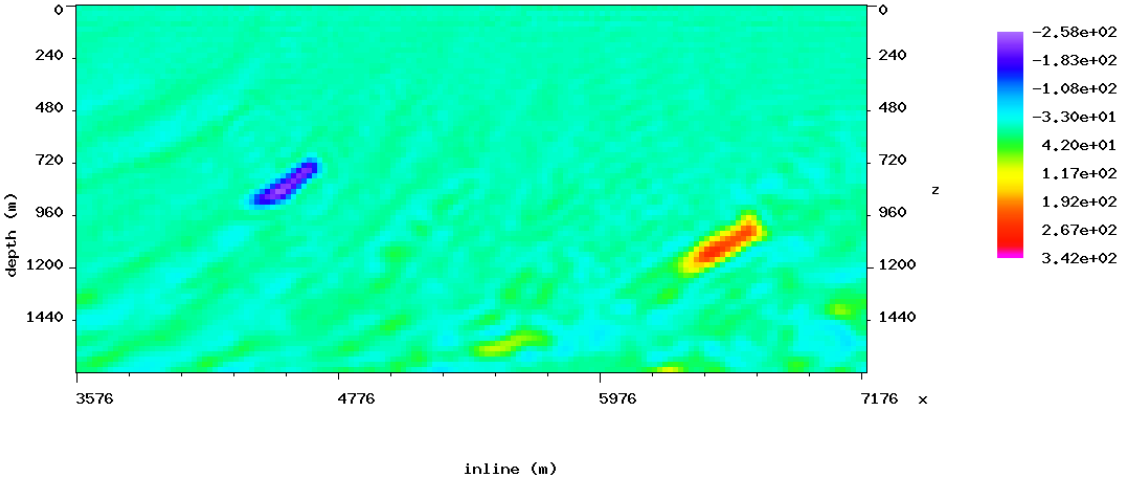
Parallel difference, clean synthetic



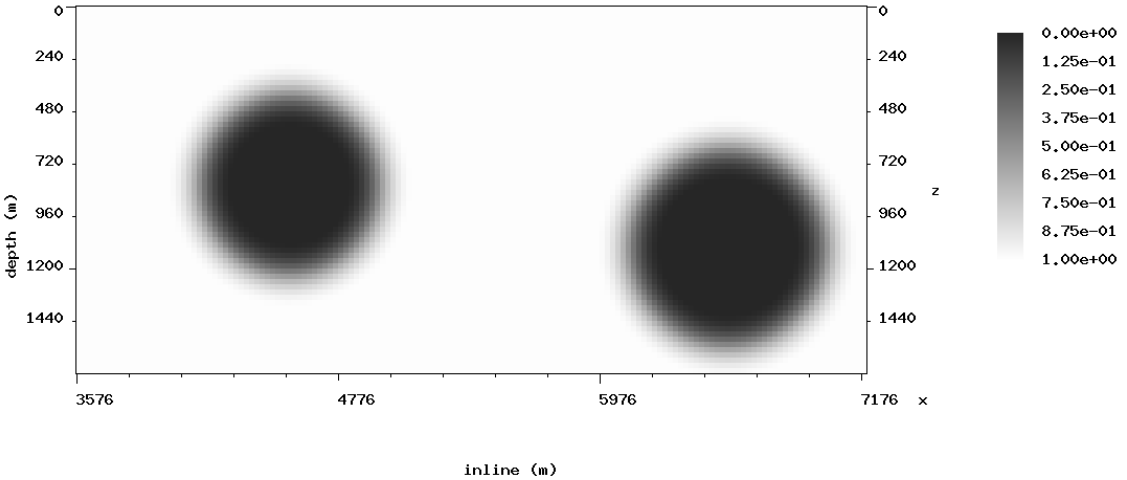
Sequential difference, clean synthetic



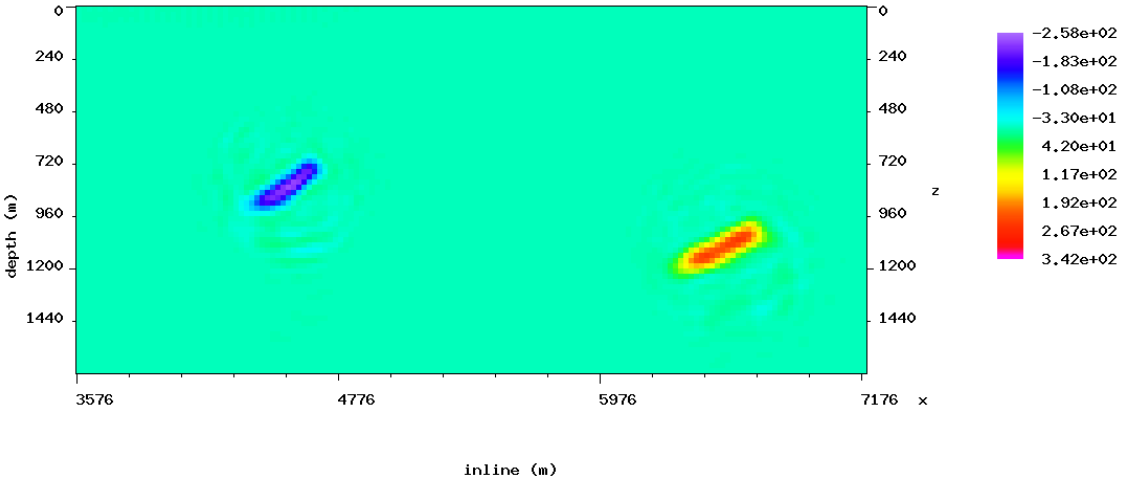
Cross-updating, clean synthetic



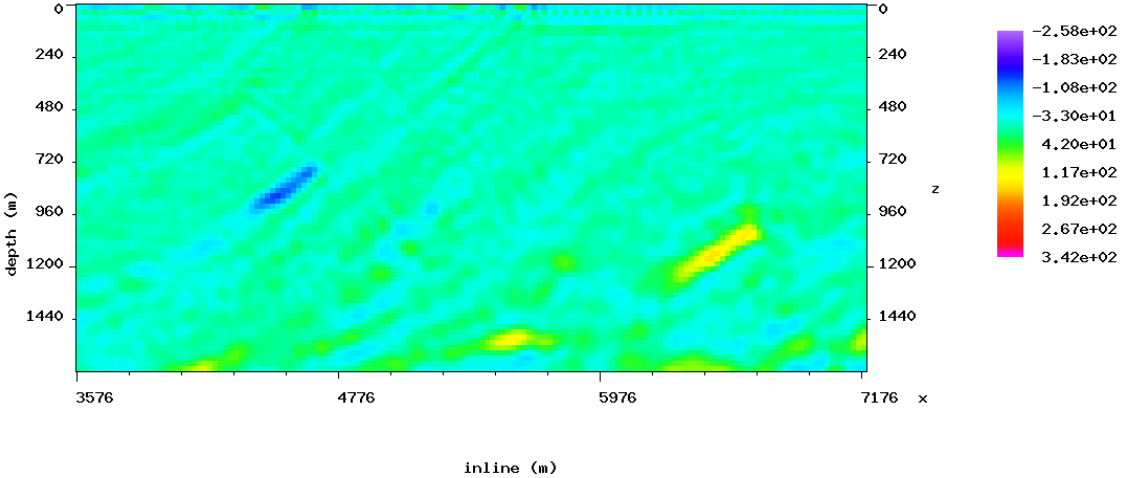
Targeting/weighting operator W for *simultaneous* FWI



Targeted simultaneous, clean synthetic

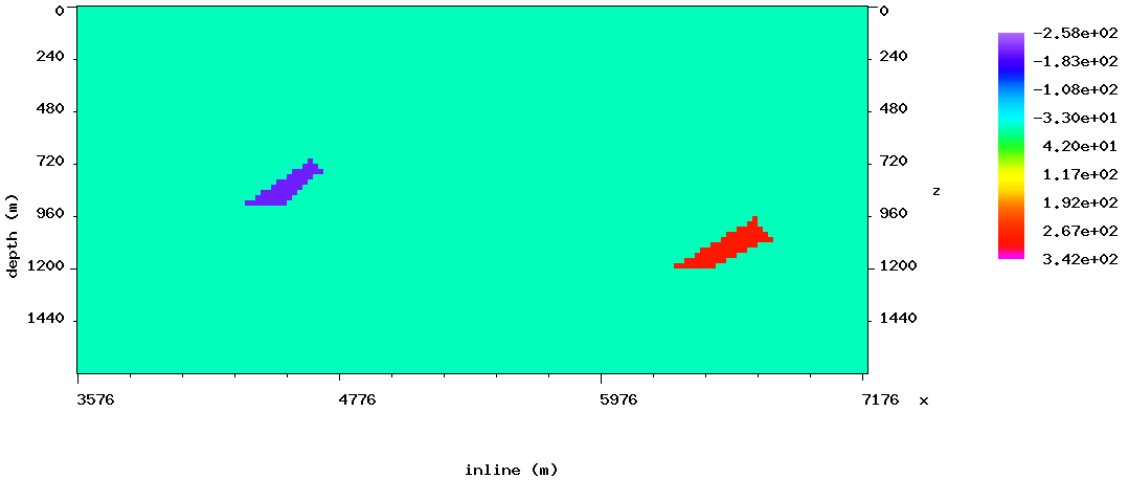


Double difference, clean synthetic

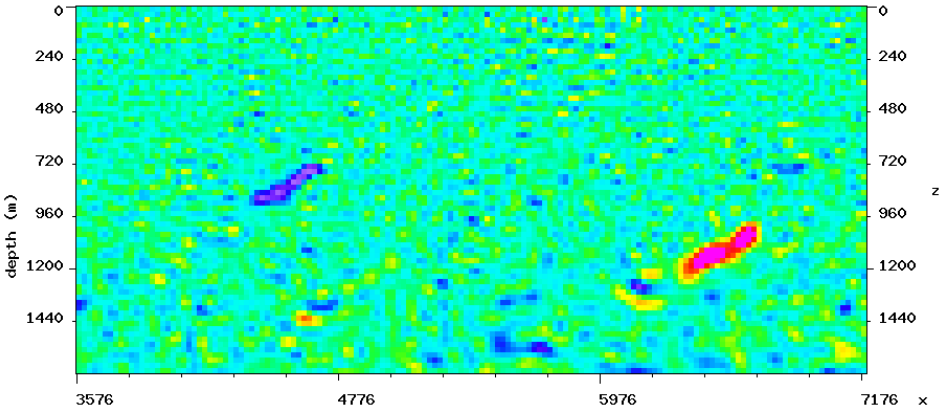


14 dB SNR synthetic (same acquisition parameters)

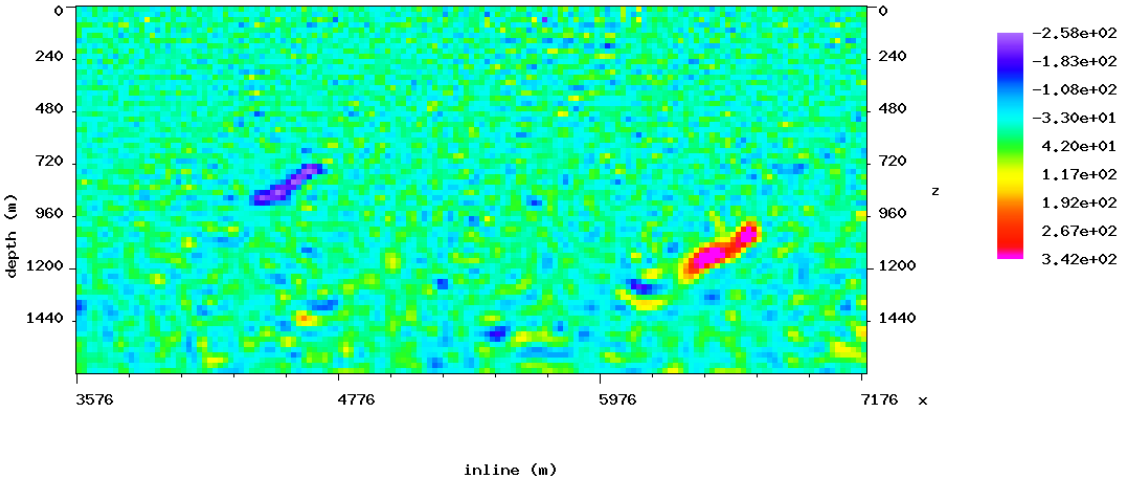
True difference



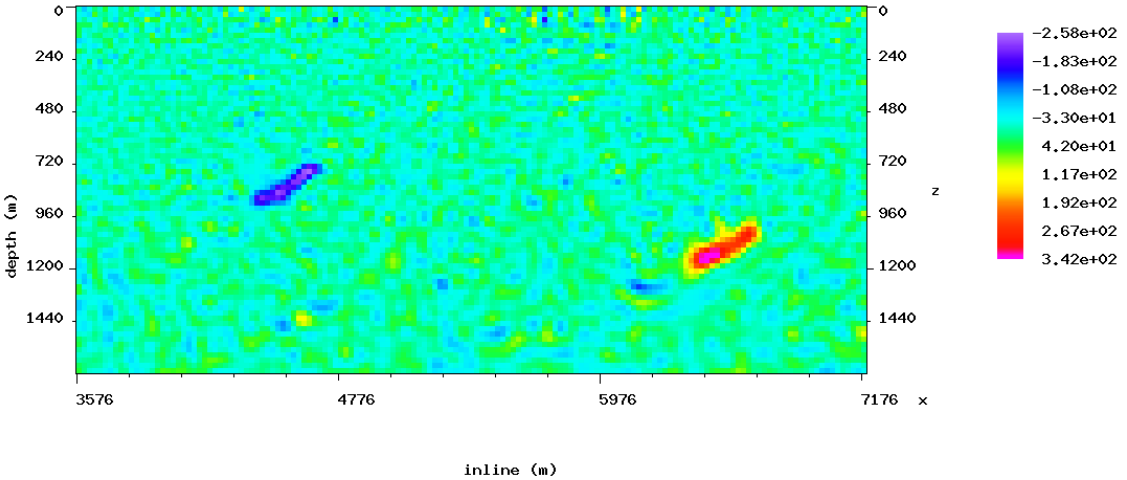
Parallel difference, 14 dB synthetic



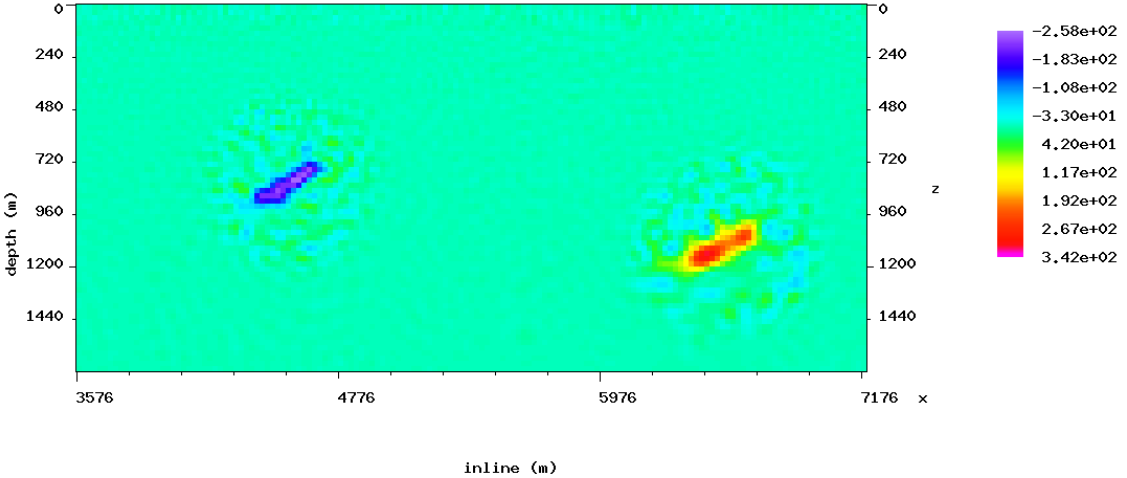
Sequential difference, 14 dB synthetic



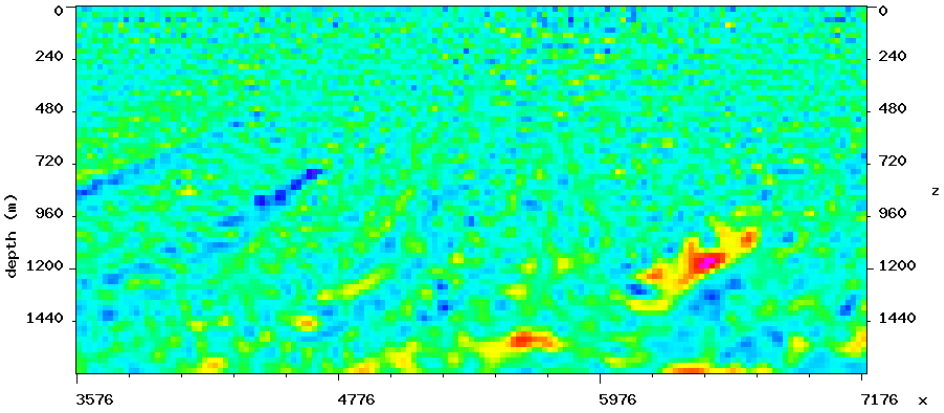
Cross-updating, 14 dB synthetic



Targeted simultaneous, 14 dB synthetic



Double difference, 14 dB synthetic



Sequential difference suppresses

$$\delta \mathbf{m}_b \in \text{null} \left(\frac{dF}{d\mathbf{m}}(\mathbf{m}_m) \right) \tag{7}$$

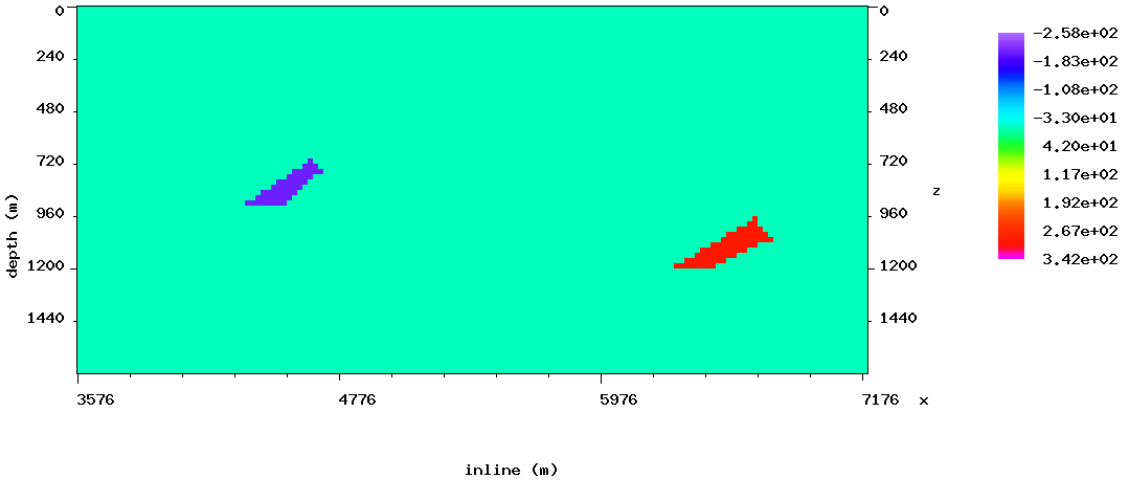
by propagating it into the monitor model, but still suffers from

$$\delta \mathbf{m}_m \in \text{null} \left(\frac{dF}{d\mathbf{m}}(\mathbf{m}_b) \right). \tag{8}$$

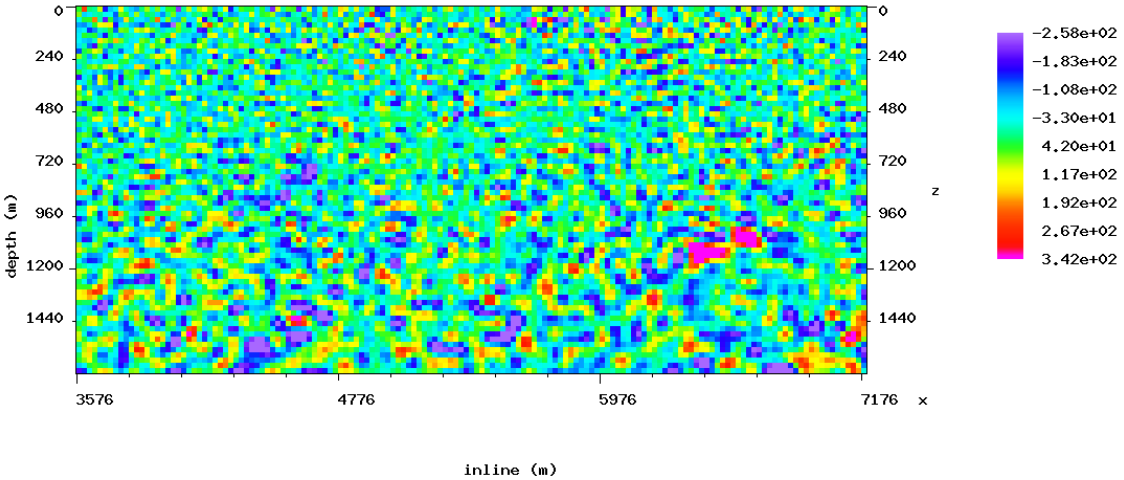
Joint FWI propagates $\delta \mathbf{m}_{m,b}$ into *both* models, canceling them in the diffference.

7 dB SNR synthetic (same acquisition parameters)

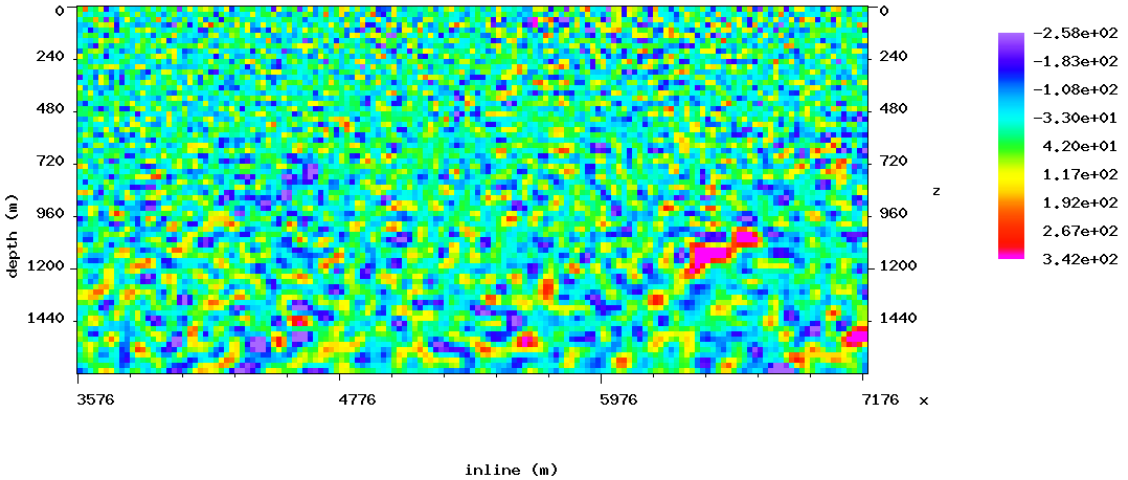
True difference



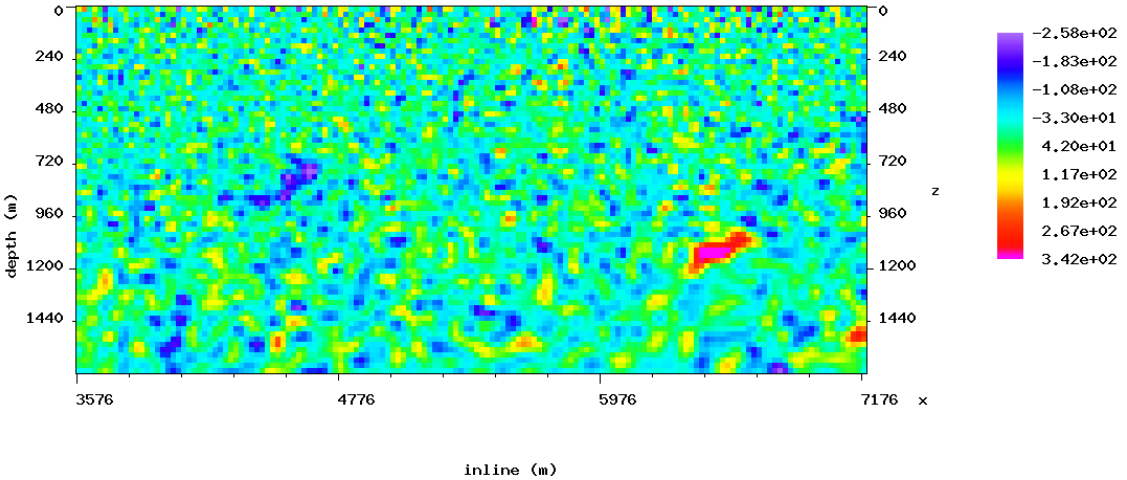
Parallel difference, 7 dB synthetic



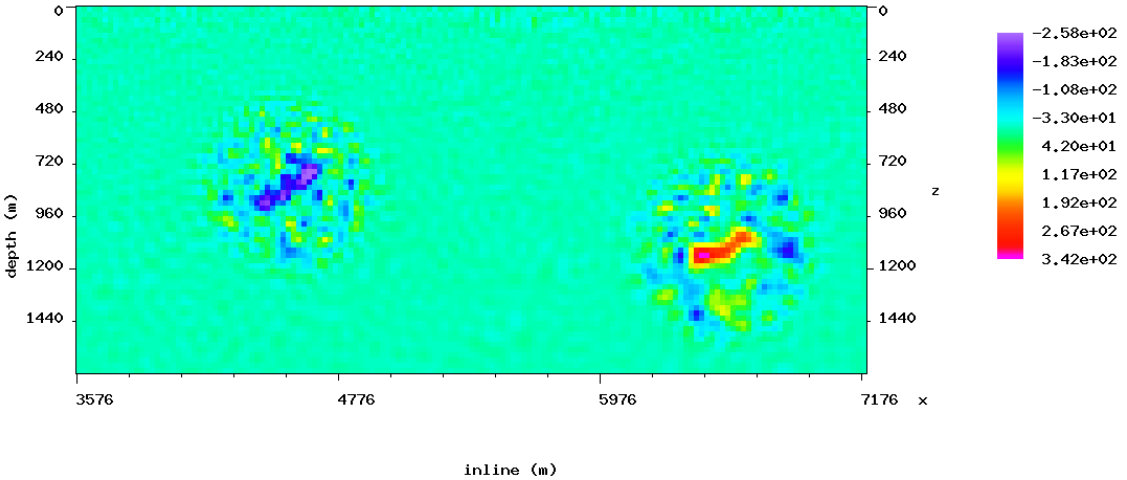
Sequential difference, 7 dB synthetic



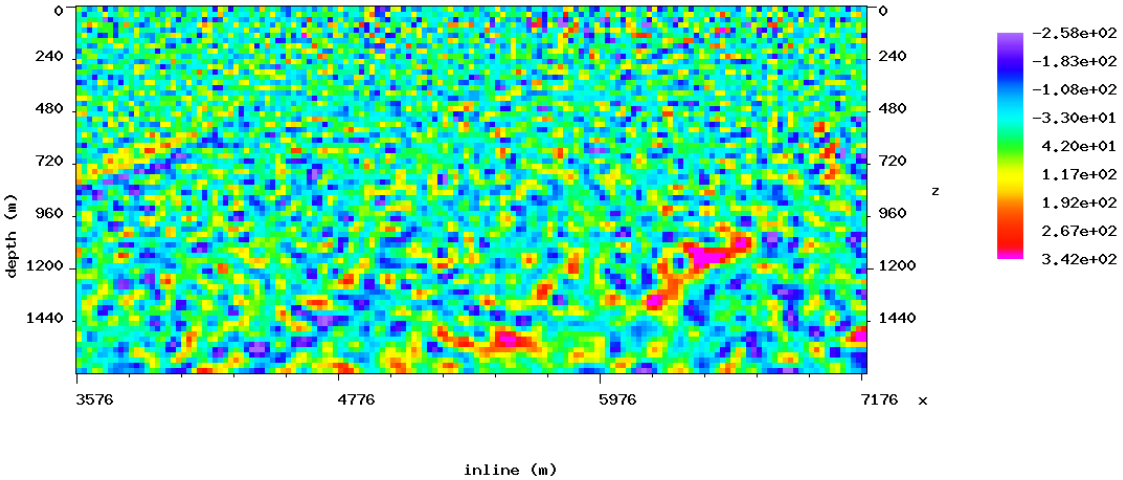
Cross-updating, 7 dB synthetic



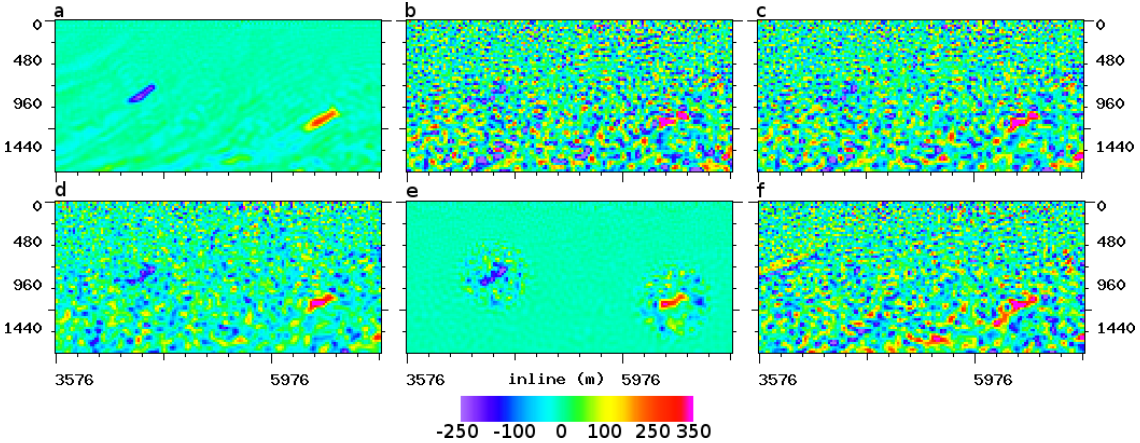
Targeted simultaneous, 7 dB synthetic



Double difference, 7 dB synthetic



Robustness of 4D FWI



(a) X-update different acquisition pars; (b) pardiff random noise; (c) seqdiff random noise; (d) X-update random noise; (e) simultaneous inversion random noise; (f) double-diff random noise

Conclusions and perspectives

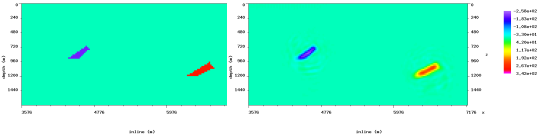
1. Both X-updating and simultaneous 4DFWI perform well on noisy synthetic data.
2. Double differencing with "data regularization" Zheng et al. (2011), Raknes et al. (2013) is sensitive to repeatability.
3. 4D FWI implemented in the `CESLib` Fortran 2003/2008 object-oriented library (Maharramov, 2014, SEP 152 pp 361-366).

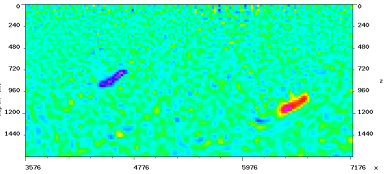
Next steps:

1. Use geomechanical priors.
2. Test simultaneous 4DFWI with $\mathbf{W}$ from geomechanical and rock physics constraints.
3. Application to field data.

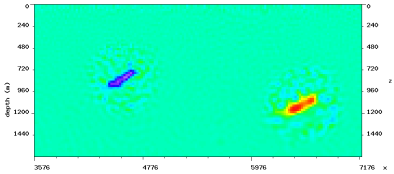
Acknowledgements

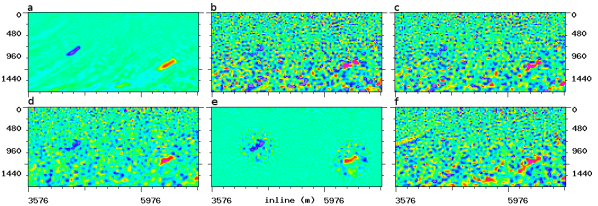
The authors thank **Stewart Levin** for a number of useful discussions, and the sponsors of Stanford Exploration Project for their support.





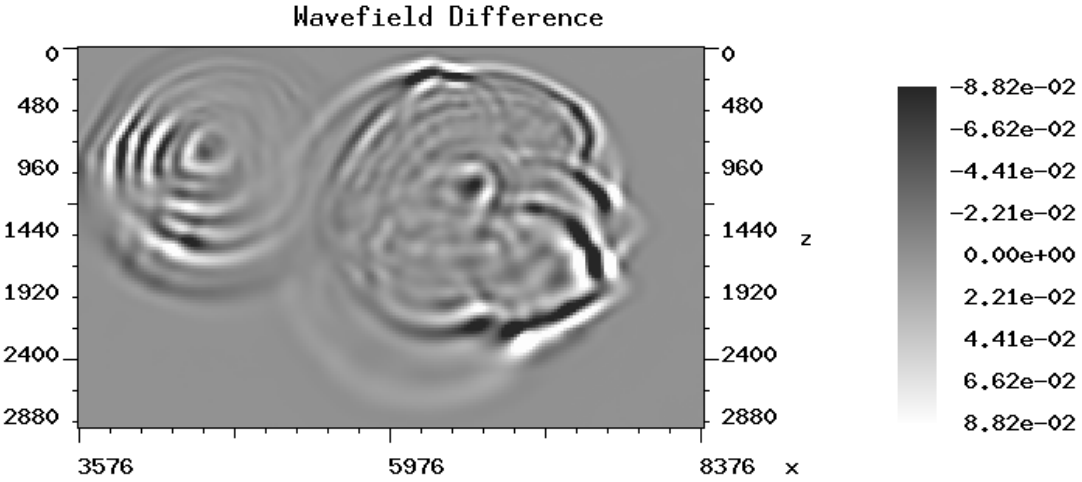
Q&A



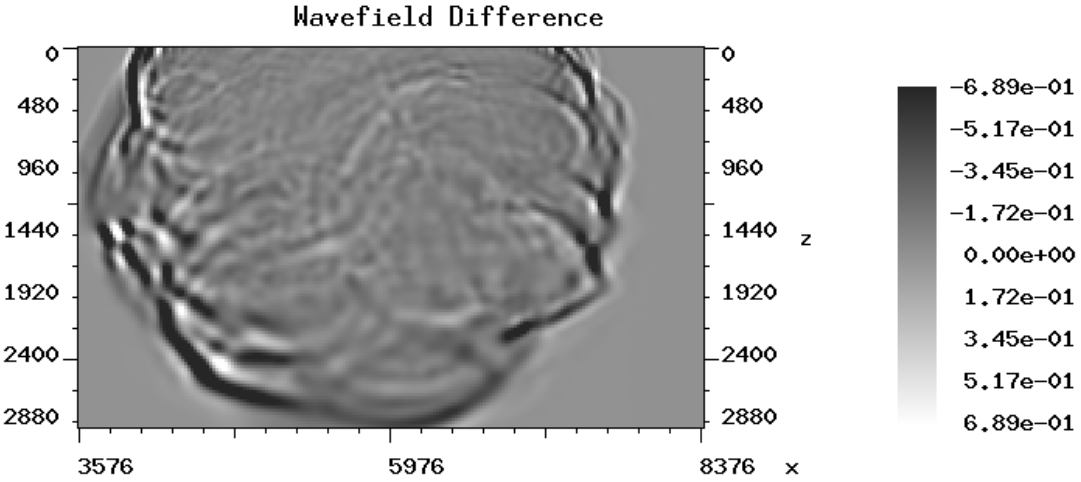


Different survey acquisition parameters

Data difference, same survey parameters



Data difference, different surveys



Cross-updating, different surveys, clean synthetic