Salt Reconstruction in Full-Waveform Inversion

A parametric level-set approach

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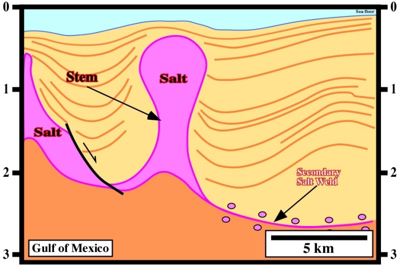
SIAM GS-17, Erlangen, Germany

September 14, 2017

NWO Applied and Engineering Sciences
Universiteit Utrecht

Motivation



	velocity [km/s]	density [g/cm^3]
water	1.5	1
layers	1.8-3.5	1.5-2
Salt	**4.6**	**2.1-2.2**
Anhydrite	4-4.2	2.9-3
Basalt	4.5	2.7-3.1

salt-bodies are important for hydrocarbon exploration!

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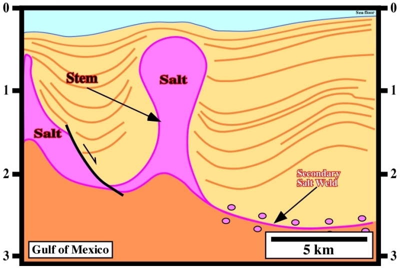

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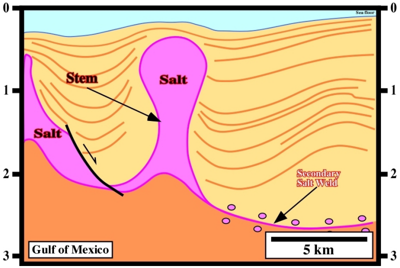

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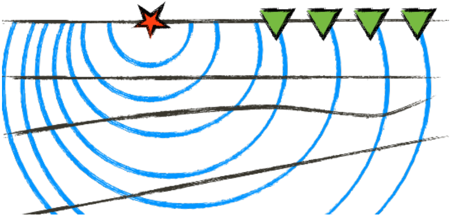
salt-bodies are important for hydrocarbon exploration!

- cost of drilling **2 to 12M USD** per well [DoE, 2016]
- significant **dry hole** costs (30% upwards failure chance)

Outline

Seismic experiment

A controlled explosion (dynamite or airgun)



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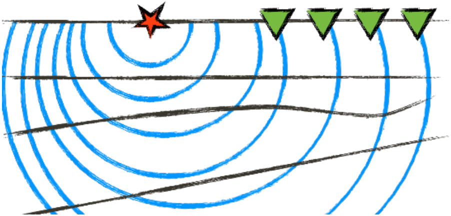

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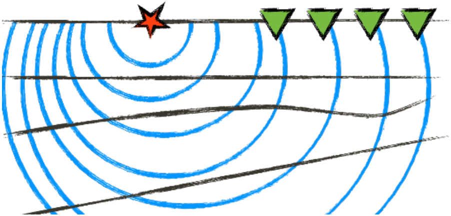

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- Frequency space - a scalar Helmholtz equation:

$$\underbrace{\left(\omega^2 m(\mathbf{x}) + \nabla^2\right)}_{A(\mathbf{m})} u(\omega, \mathbf{x}) = q(\omega, \mathbf{x})$$

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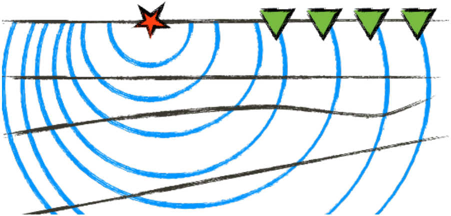

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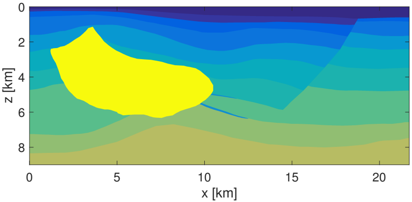
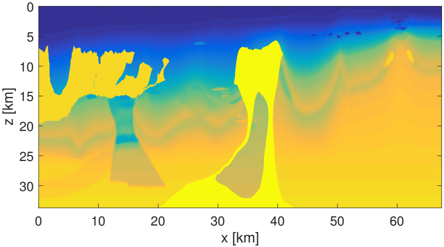
- ill-posed problem, no unique solution, heavily depends on $\mathbf{m}^0$
  [Santosa and Symes, 1989, Bunks et al., 1995,
  van Leeuwen and Herrmann, 2015, Bharadwaj et al., 2016]

Earth models



2D Hess VTI Model



BP 2004 Model

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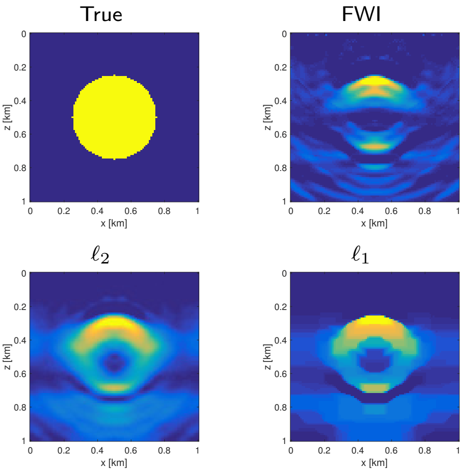
- Total-variation(ℓ_1) [Rudin et al., 1992]

$$g(\mathbf{m}) = \|\nabla\mathbf{m}\|_1$$

An example

- salt(v=4000m/s) in a constant sediment(v=2500m/s) - Camembert model
- Data generated for $[5, 8, 10, 15]$ Hz, Gaussian noise with 50 dB SNR



Outline

Classical approach

- Represent shape by level-set function

$$m(\mathbf{x}) = \begin{cases} m_1 & \text{if } x \in \Omega \\ m_0(\mathbf{x}) & \text{otherwise} \end{cases} \qquad \Longrightarrow \qquad \begin{cases} \phi(\mathbf{x}) \geq 0 & \text{if } x \in \Omega \\ \phi(\mathbf{x}) < 0 & \text{otherwise} \end{cases}$$

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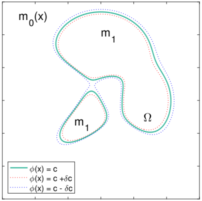

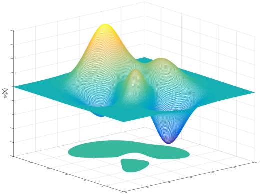

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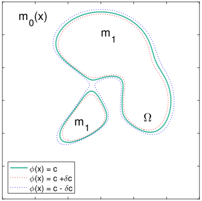
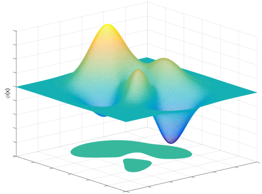




- Hamilton-Jacobi equation [Osher and Sethian, 1988]

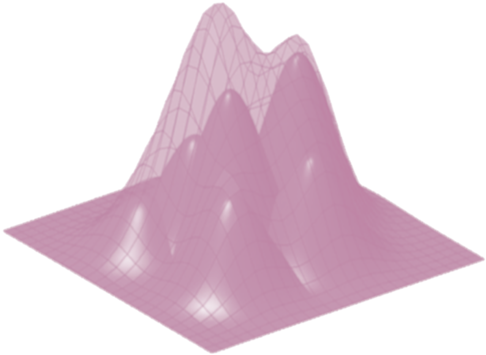
$$\dot{\phi} = v|\nabla\phi|$$

choice for v: gradient - ∇f [Burger, 2001, Dorn and Lesselier, 2006]

Parametric level-set method

- Represent level-set in lower-dimensional space [Aghasi et al., 2011]:

$$\phi(\mathbf{x}) = \sum_{i=1}^{m} \alpha_i \Psi(\|\mathbf{x} - \boldsymbol{\chi}_i\|)$$



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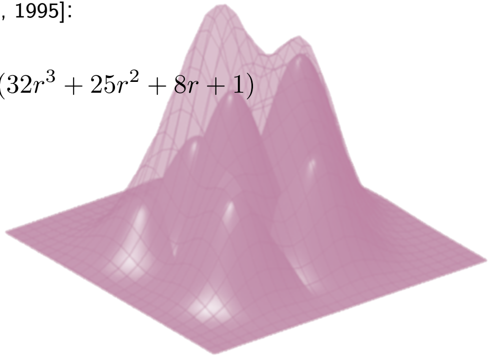

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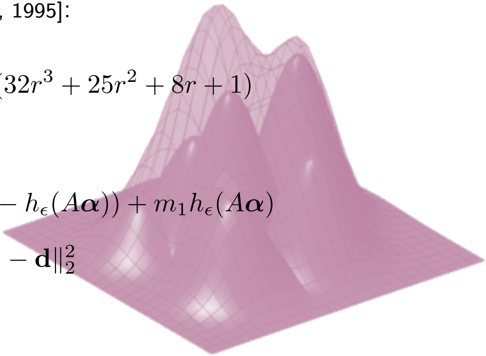

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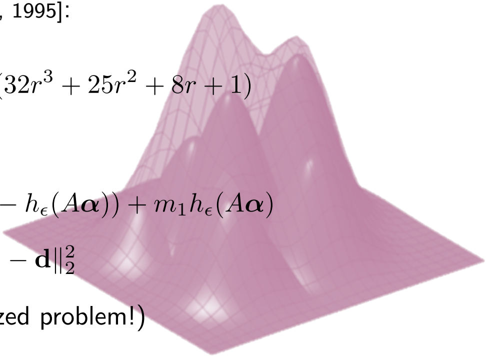
(lower dimensional and regularized problem!)



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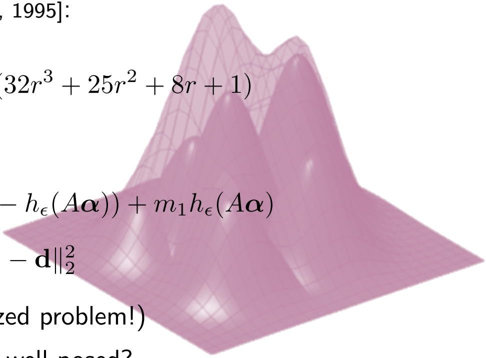

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- Open Question: Is this problem well-posed?

Revisiting an example

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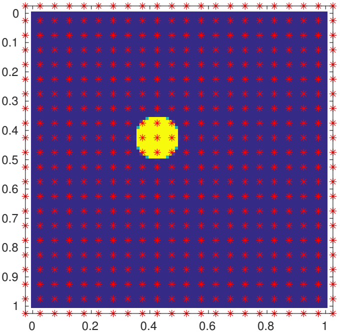

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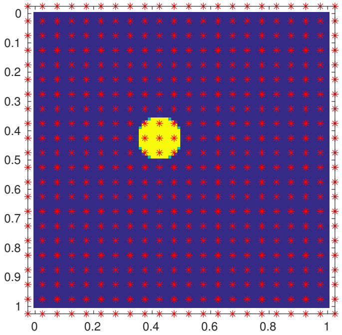
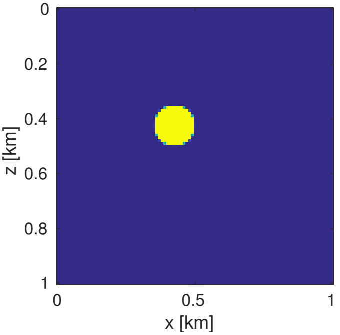
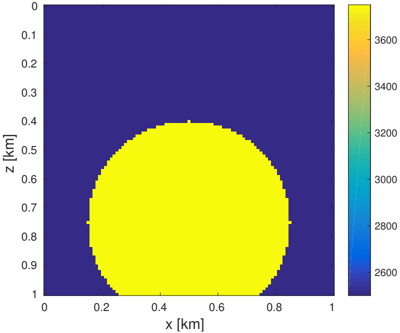


Level-set Evolution



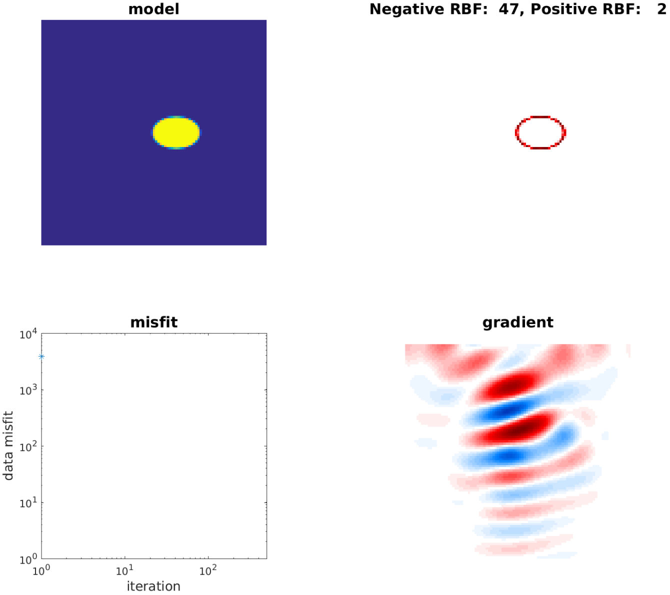
A more challenging example

Shifted camembert model (Resolution: 101 $\times$ 101 pixels)



- data generated for $[5, 6, 7, 8]$ Hz. (Gaussian noise of 50 dB SNR)
- RBF grid: 7 $\times$ 7 (dimensions reduced by ≈ 200 times)

A more challenging example



Outline

An inverse problem

$$
\begin{aligned}
\text{minimize}_{\boldsymbol{\alpha},\mathbf{m}_0} \quad & \frac{1}{2}\|F\big(B(\boldsymbol{\alpha},\mathbf{m}_0)\big)-\mathbf{d}\|_2^2 \\
\text{subject to} \quad & l \le \mathbf{m}_0 \le u
\end{aligned}
$$

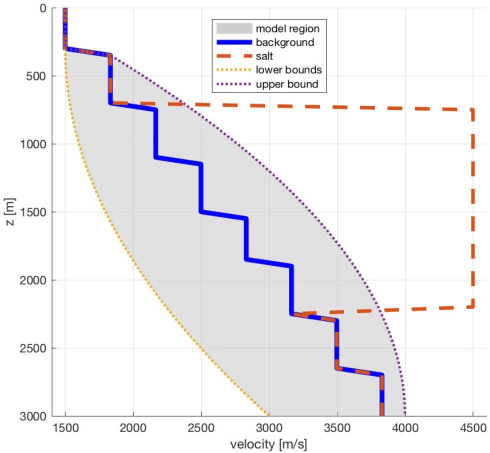
where, $\quad B(\boldsymbol{\alpha},\mathbf{m}_0) = \mathbf{m_0} \odot (\mathbf{1} - h_\epsilon(A\boldsymbol{\alpha})) + m_1 h_\epsilon(A\boldsymbol{\alpha})$

Simultaneous updates

Gauss-Newton updates:

$$\begin{bmatrix} \boldsymbol{\alpha}^{k+1} \\ \mathbf{m}_0^{k+1} \end{bmatrix} \leftarrow \begin{bmatrix} \boldsymbol{\alpha}^{k} \\ \mathbf{m}_0^{k} \end{bmatrix} - \gamma_k \begin{bmatrix} \widetilde{H}_{\boldsymbol{\alpha}} & 0 \\ 0 & \widetilde{H}_{\mathbf{m}_0} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{g}_{\boldsymbol{\alpha}} \\ \mathbf{g}_{\mathbf{m}_0} \end{bmatrix}$$

constraining sediment



box constraints are handled using proximal operator [Parikh et al., 2014]

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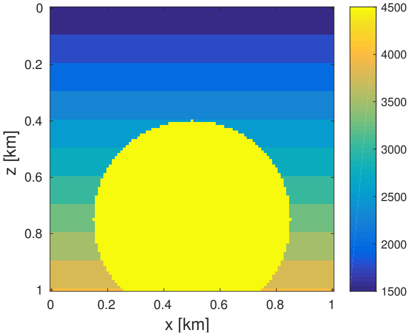
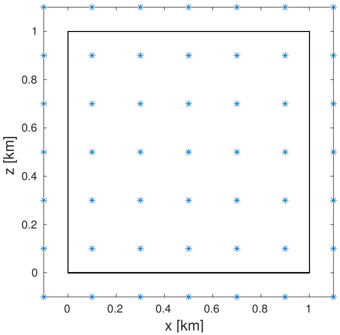
Experiment details





Experiment details

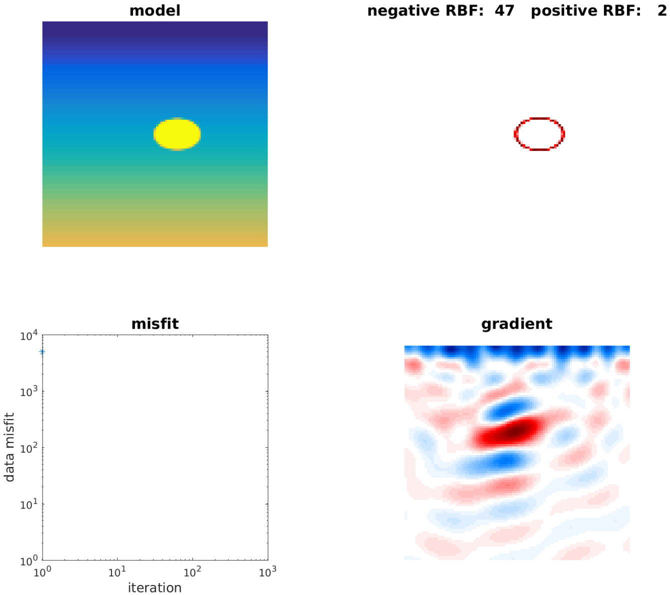
- shifted Camembert (101 $\times$ 101 pixels) model with sediment layers
- Reflection Expt: 6 sources (200m apart) and 21 receivers (50m apart)
- frequencies: $[3, 4.67, 6.33, 8]$ Hz
- surface multiples off! absorbing boundary conditions (all four sides)
- Source: Ricker wavelet with peak freq of 10 Hz and 0 phase shift

- No inverse crime! Data generated using different code.
- Source Estimation at every iterate (only scalar).

- RBF grid: 7 $\times$ 7

- WAVEFORM toolbox from SLIM [Da Silva and Herrmann, 2016].

Preliminary results



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Future Roadmap:

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- Proposed method has a potential to extract the salt in complex sediment structure (on the assumption of known salt velocity)
- Low frequencies play an important role in salt reconstruction!

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- testing the framework on real 2D marine data
  (data provided by Shell/NAM)

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Thanks!

Read:

- A. Kadu, T. van Leeuwen and W. A. Mulder Salt Reconstruction in Full-Waveform Inversion With a Parametric Level-Set Method. *IEEE Transactions on Computational Imaging* 3.2 (2017): 305-315.
- A. Kadu, T. van Leeuwen and W. A. Mulder Parametric level-set full-waveform inversion in the presence of salt bodies. In *SEG Technical Program Expanded Abstracts* 2017 (pp. 1518-1522).

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Special Thanks to:

Eldad Haber, Felix Herrmann, Bas Peters, Rajiv Kumar and SLIM group at UBC