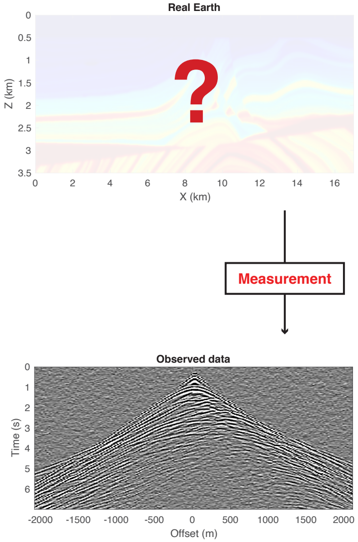
Full waveform inversion

where are we on this long journey to make speak each piece of seismic trace?

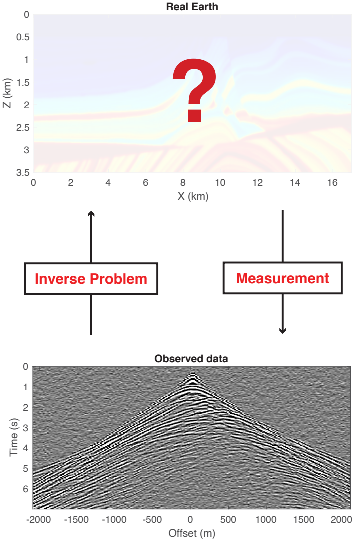
R. Brossier[1] and many others from SEISCOPE[1,2]

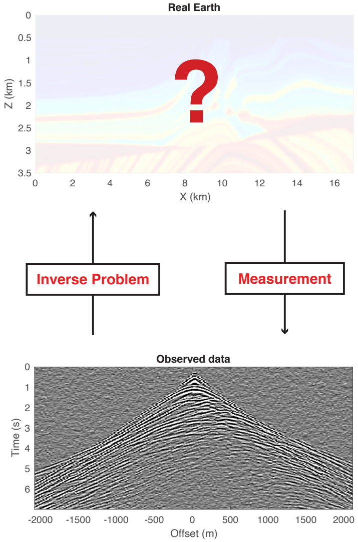
November 1st 2021 - FORCE Impressions of FWI

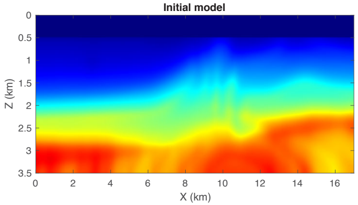
[1] Univ. Grenoble Alpes, CNRS, ISTerre Grenoble, France
[2] Univ. Grenoble Alpes, CNRS, LJK, Grenoble, France
http://seiscope2.osug.fr


Real Earth
Z (km)
X (km)
?
Measurement
Observed data
Time (s)
Offset (m)

Full Waveform Inversion's principle

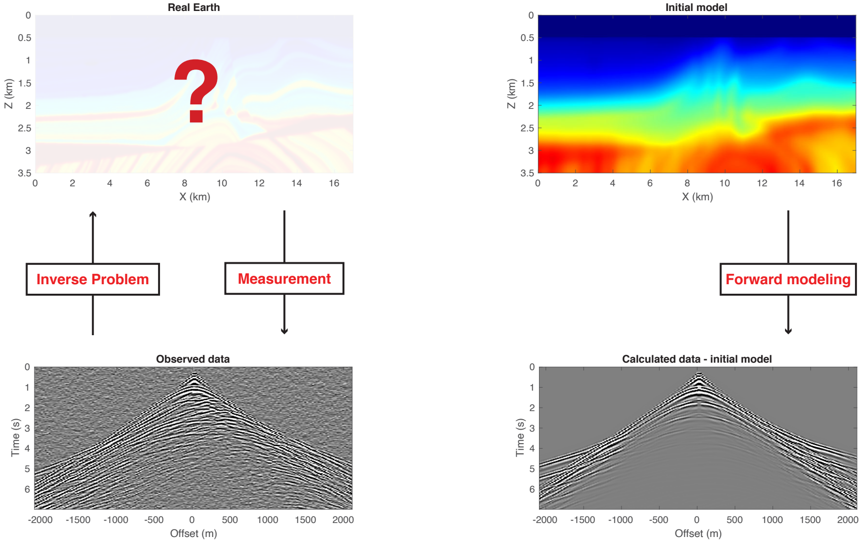



Real Earth
Z (km)
X (km)
Inverse Problem
Measurement
Observed data
Time (s)
Offset (m)

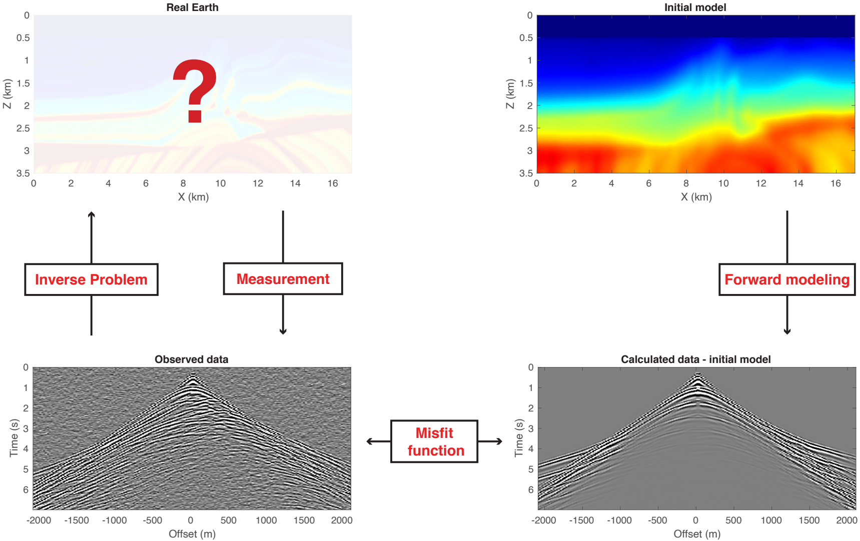

Initial model
Z (km)
X (km)

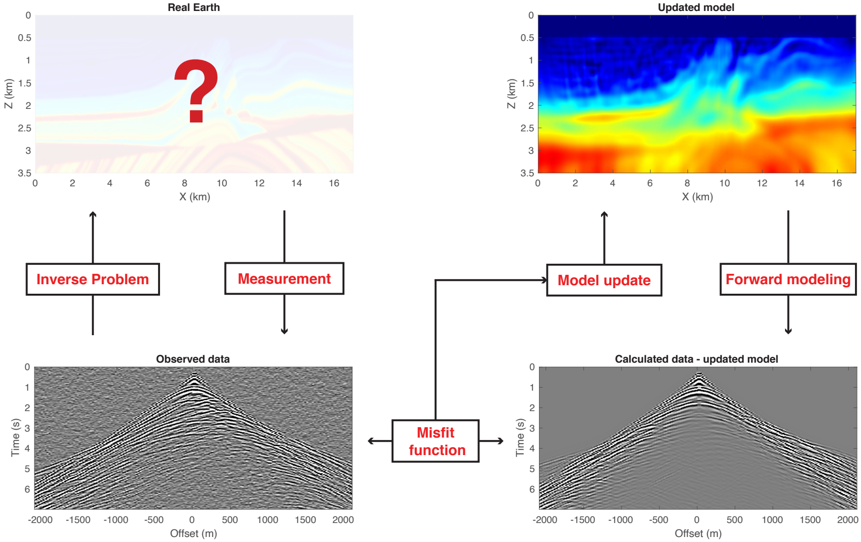
Full Waveform Inversion's principle

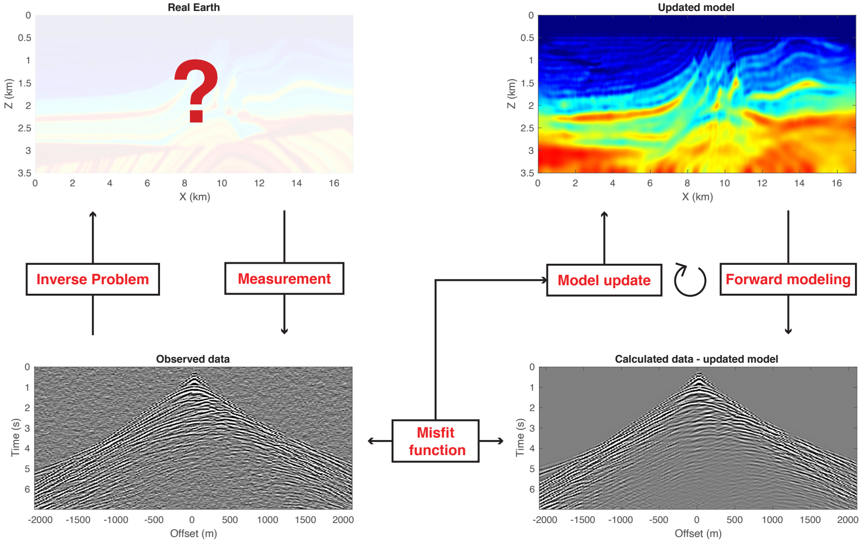
SEISCOPE



Full Waveform Inversion's principle




Real Earth
?
Z (km)
X (km)
Updated model
Z (km)
X (km)
Inverse Problem
Measurement
Model update
Forward modeling
Observed data
Time (s)
Offset (m)
Misfit function
Calculated data - updated model
Time (s)
Offset (m)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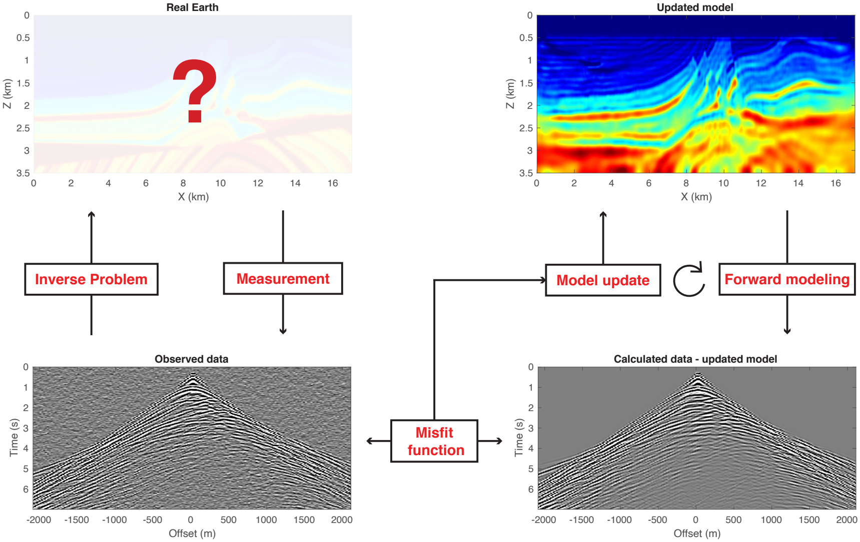
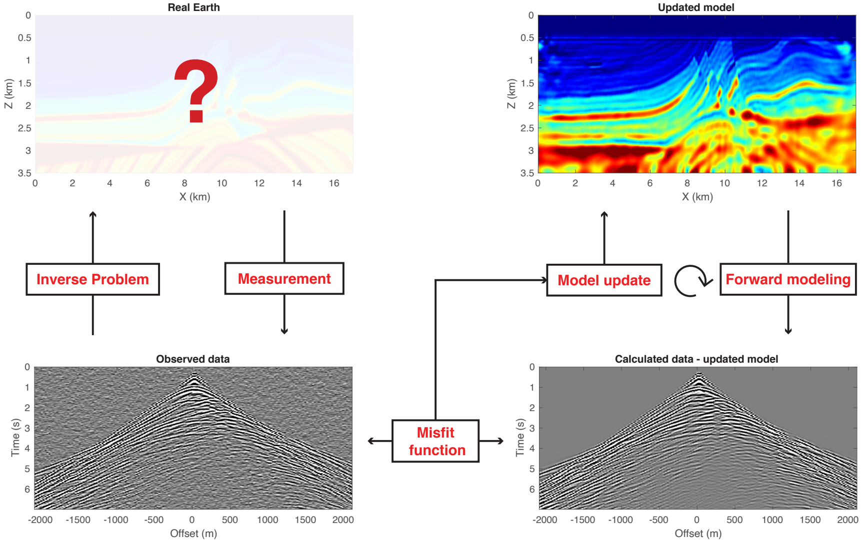
Full Waveform Inversion's principle

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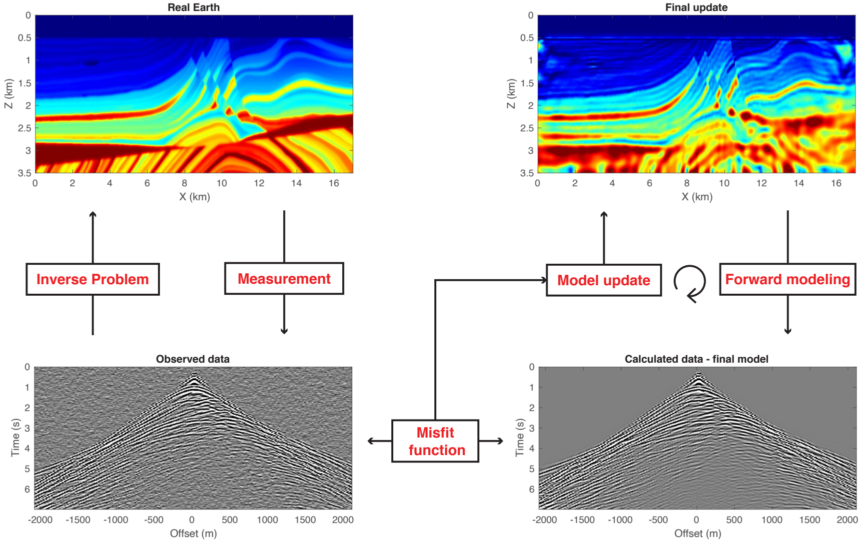
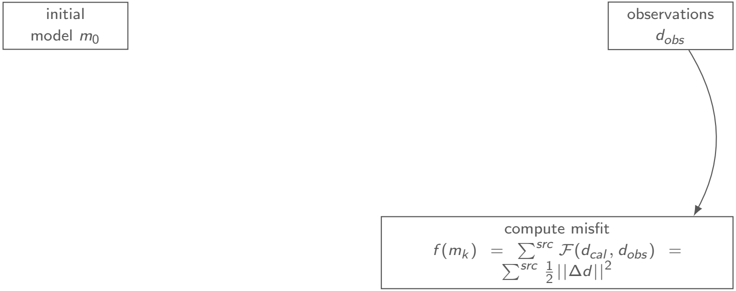


Global Scheme of FWI

initial model m_0

observations d_{obs}

Global Scheme of FWI



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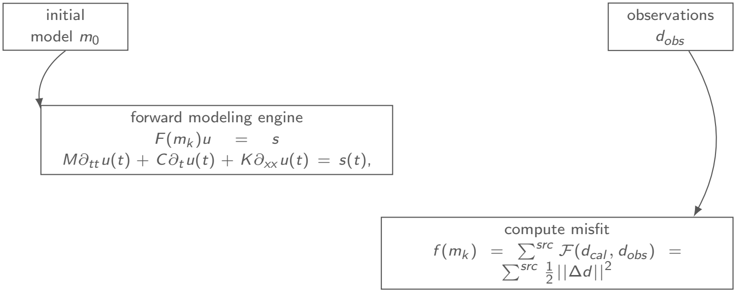

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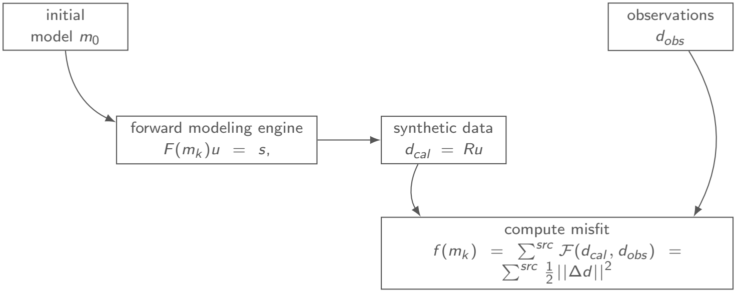

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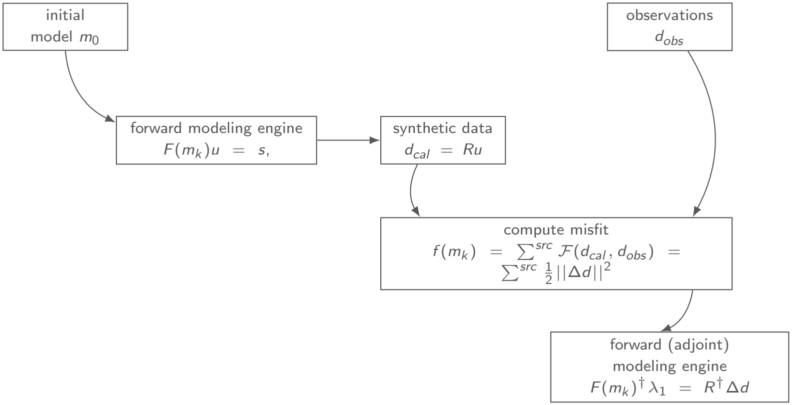

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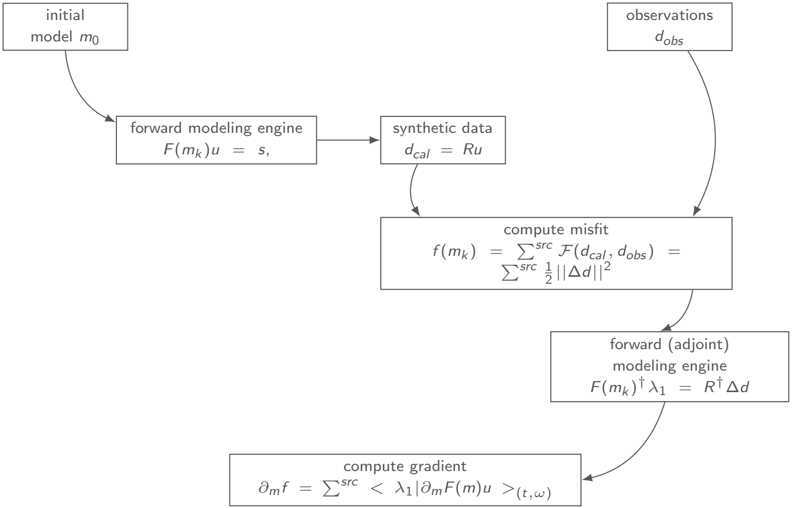

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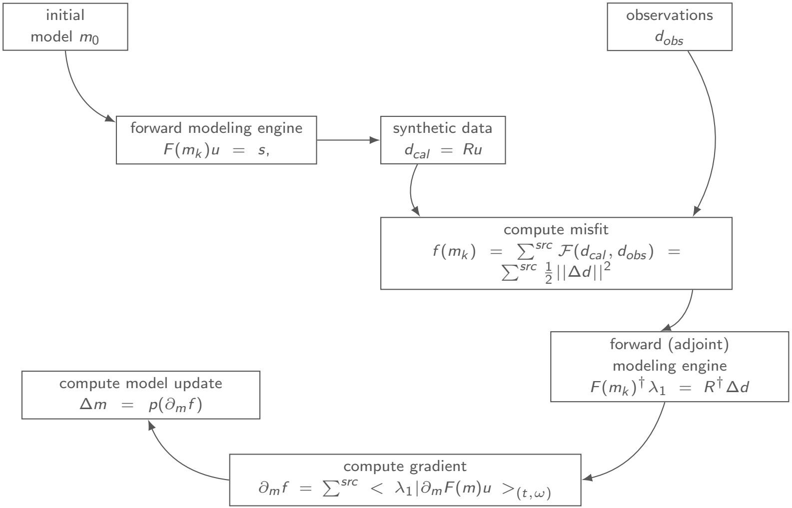

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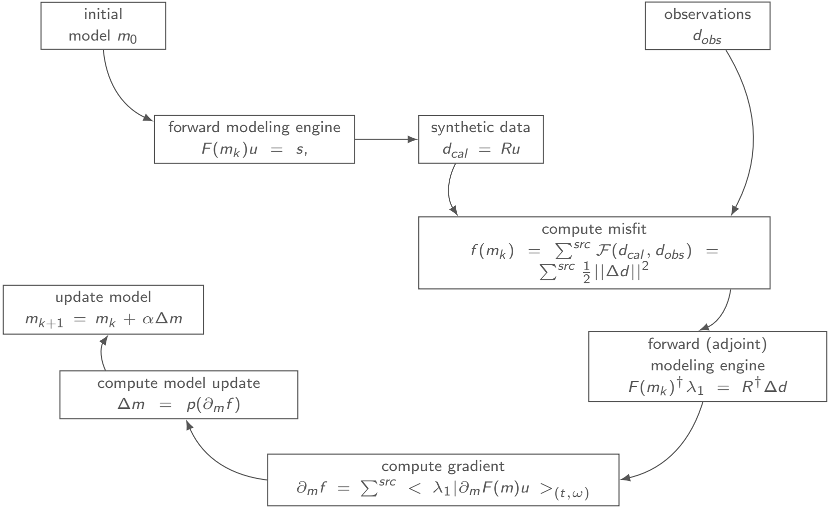

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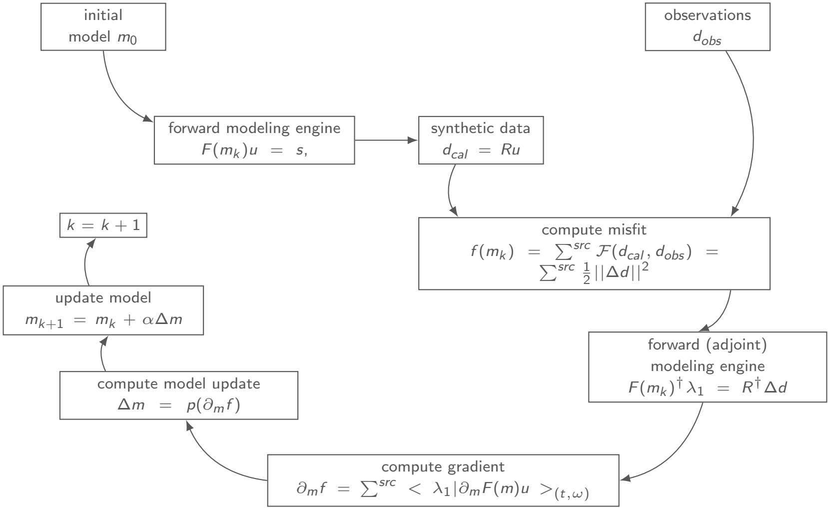

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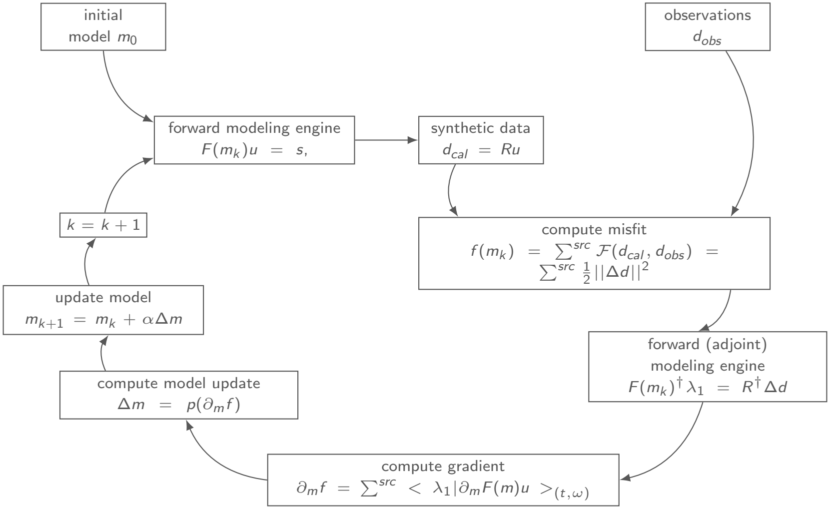
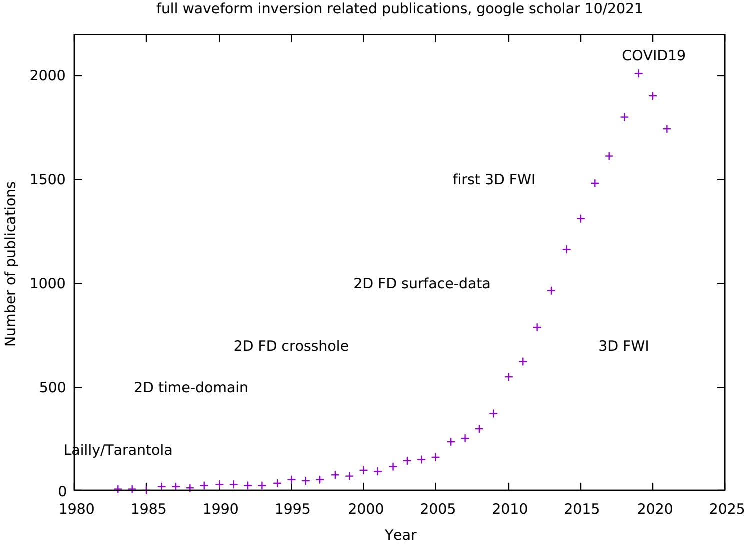
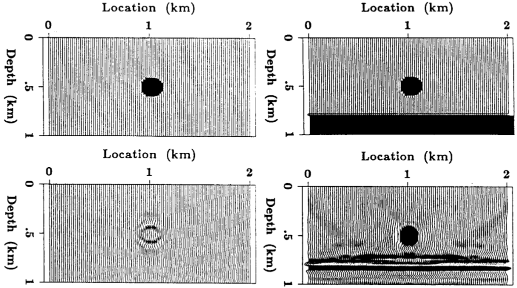


Interest in the literature

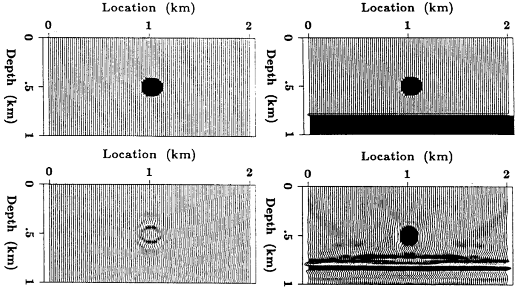


- data type
- cycle-skipping
- multi-parameters sensitivity and non-linearity
- FWI with reflections
- computational cost
- high frequency FWI



Mora (1989)

- In the 80's: short-offset data only → FWI as a non-linear migration



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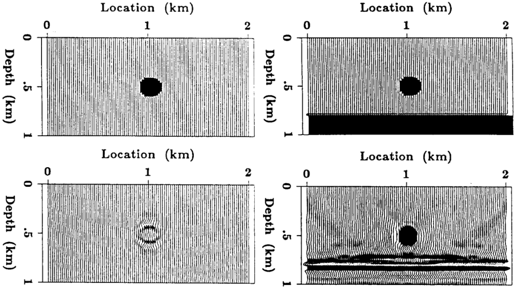

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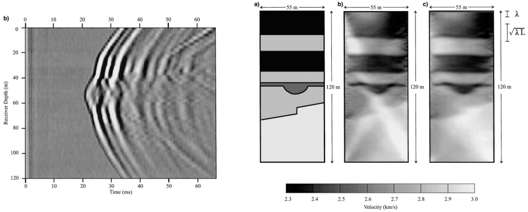


Pratt (1999)

- In the 80's: short-offset data only → FWI as a non-linear migration, but already seen the interest of "transmissions"
- In the 90's: reinvestigation of FWI in the 90's by Pratt's group, for cross-well data (in 2D frequency-domain) → success thanks to transmissions (and cheaper HPC cost)

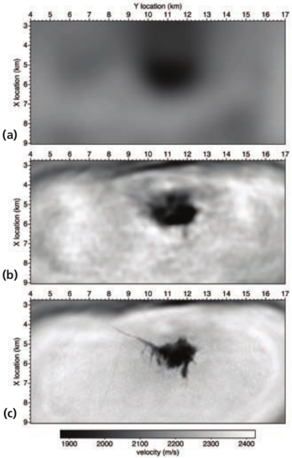
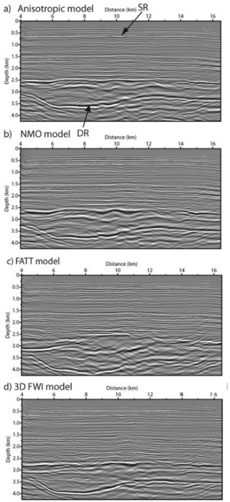


Figure 4 *Evolution of a depth slice at 1050 m below sea level over the course of FWI: (a) the 2007 starting model; (b) after using only the lowest frequency of 3.5 Hz; and (c) after six frequencies from 3.5 to 7.0 Hz were used.*

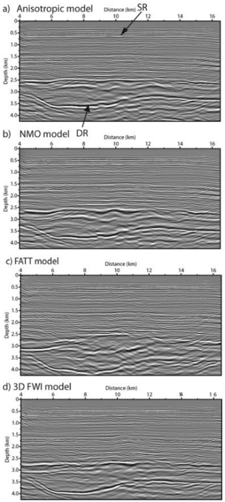
Sirgue et al. (2010)

- In the 2000's: first 2D and 3D applications from long-offset surface data (reflections and transmission)

Reflection and diving waves: requirement of anisotropy



Prieux et al. (2011)



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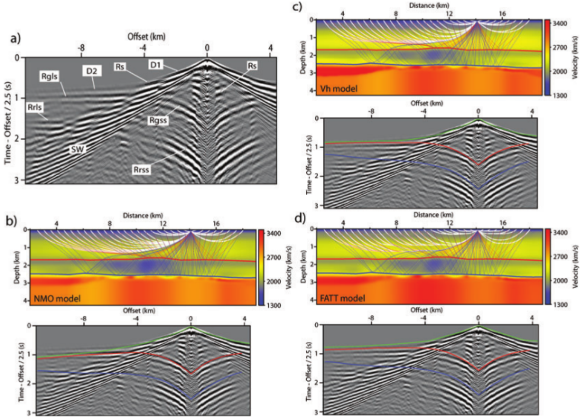
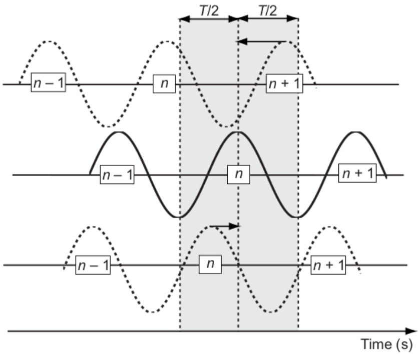
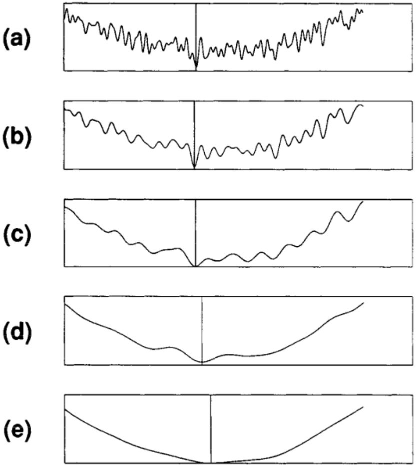


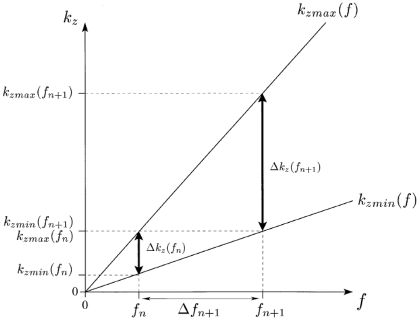
all waves-types needs to be fit: anisotropy is compulsary to account all propagation directions

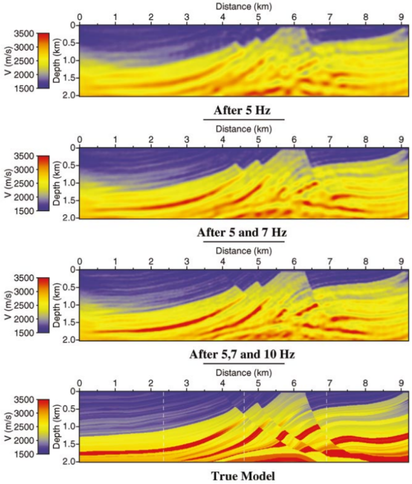


Virieux and Operto (2009)

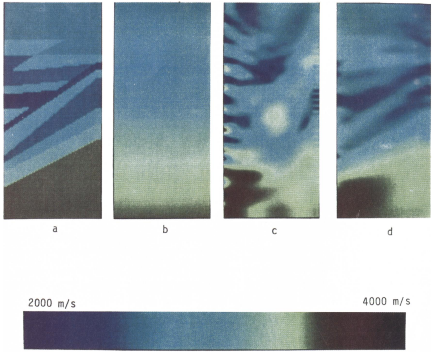


Bunks et al. (1995)





Sirgue and Pratt (2004)

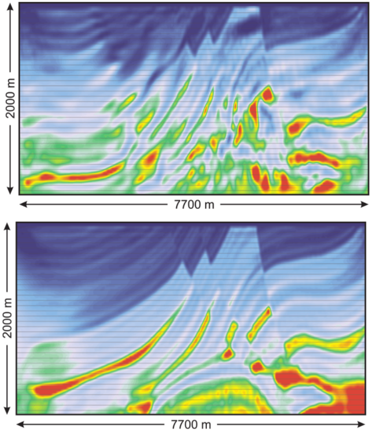


WET from Luo and Schuster (1991)

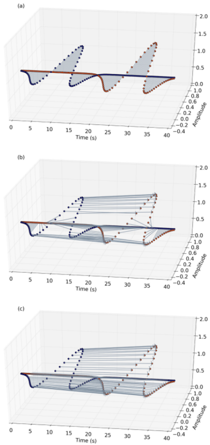
but also Tape et al. (2009); Fichtner et al. (2008) in seismology, or dynamic-time warping (Ma and Hale, 2013)

More recently in the industry: Adjustive FWI (Schlumberger), Time Lag FWI (CGG), Travel Time FWI (TGS)

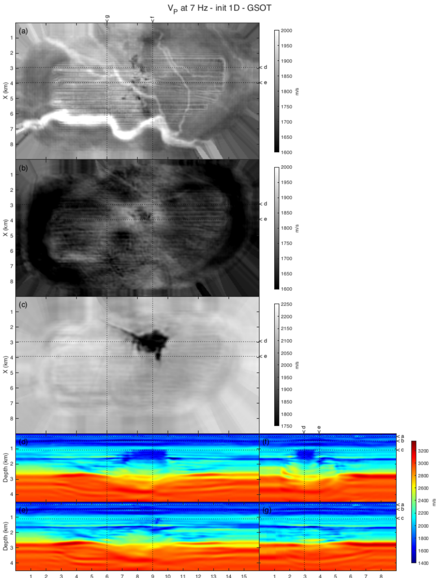
Cycle-skipping: misfit functions



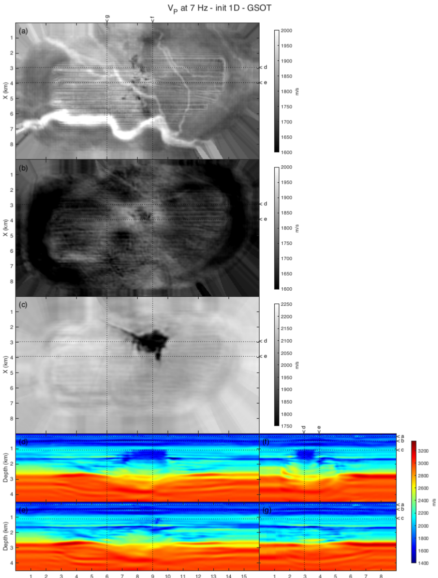
Adaptive Waveform Inversion from Warner and Guasch (2016)



Graph-Space Optimal Transport from Métivier et al. (2018, 2019)



Graph-Space OT applied to 3D OBC data from the Valhall field (Pladys et al, sub), from 1D initial model



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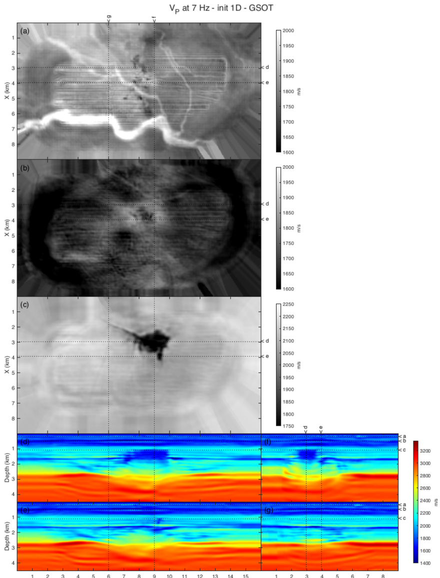
- despite all those efforts, as well as model extention approaches (WRI, source-extention, WEMVA-based approaches), is cycle-skipping behind us?



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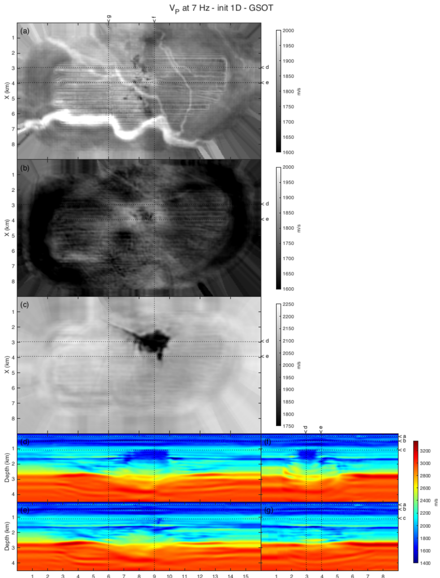
- maybe for P-wave (with 'identification)?



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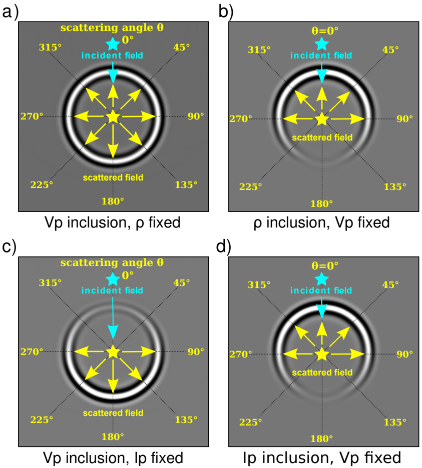
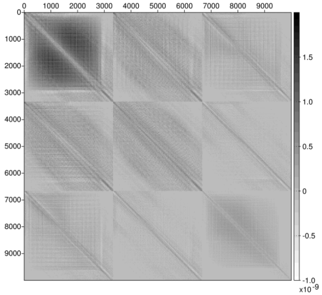
- what about very complex targets? surface-waves? multiples?

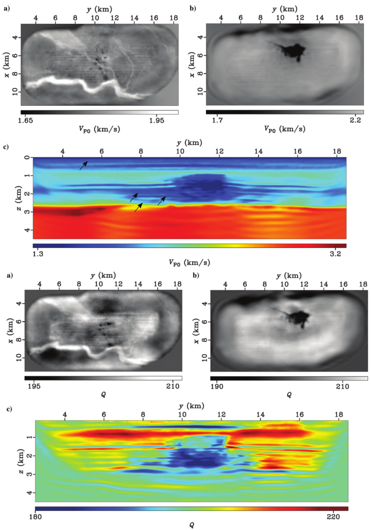


radiation patterns from Zhou et al. (2015)



3 parameters Hessian matrix from Métivier et al. (2015)

Multi-parameter FWI: exploiting amplitudes



Kamath et al. (2021)

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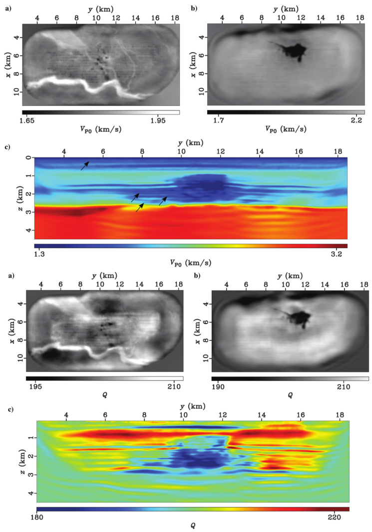

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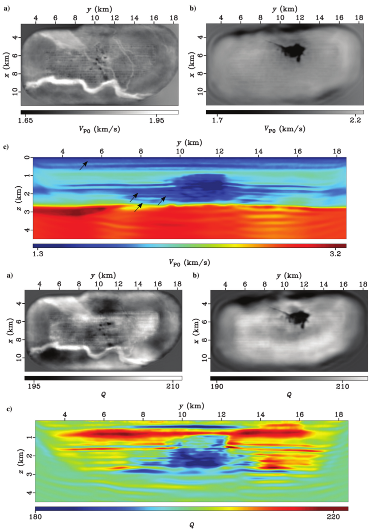

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- Multi-componant data (OBS, OBC) should allow to go beyond V_P only. Do we have numerical optimization do perform multi-parameter inversion (Hessian) ?

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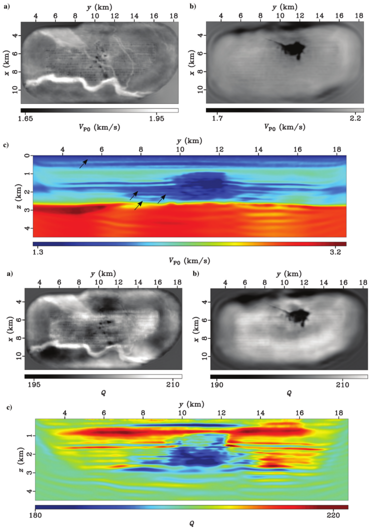

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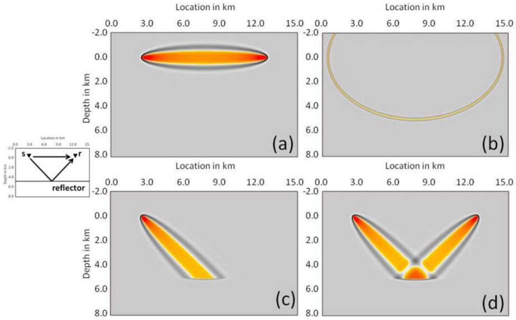
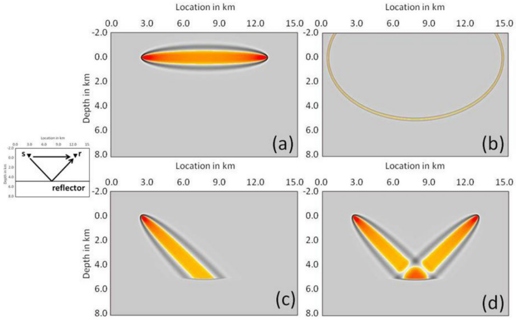
- Multi-componant data (OBS, OBC) should allow to go beyond V_P only. Do we have numerical optimization do perform multi-parameter inversion (Hessian) ?
- high-frequency should also more info on multiple parameters down to the reservoir scale.

Exploiting reflections for low-K



RWI from Xu et al. (2012),
inspired by the MBTT (Chavent et al., 1994)



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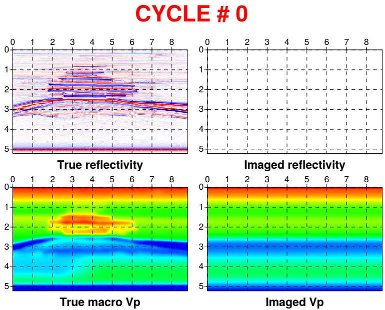
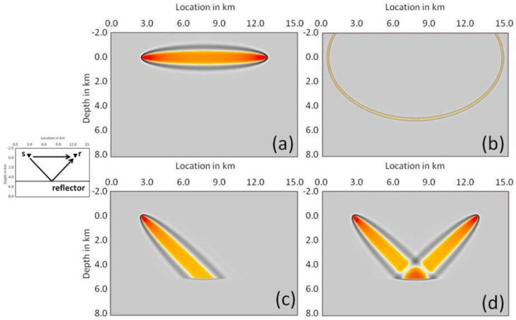


Joint FWI from Zhou et al. (2015) that combines RWI and diving-waves FWI



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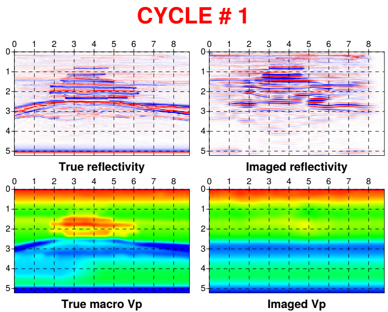

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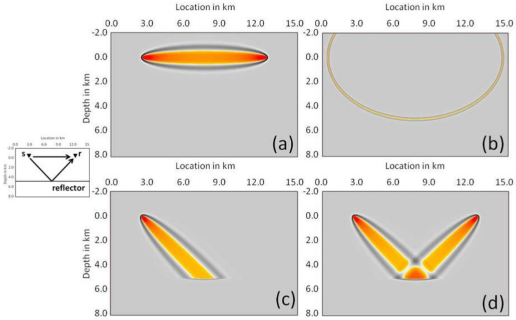

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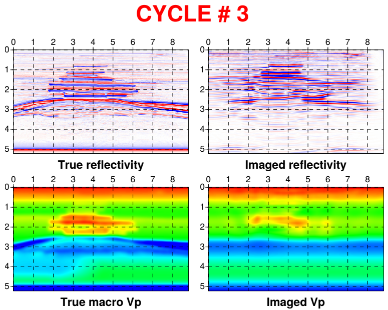

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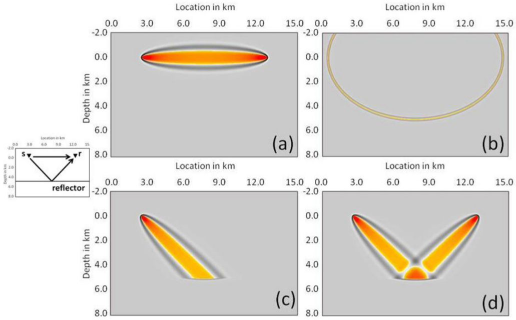

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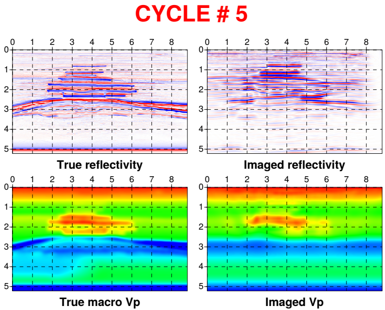

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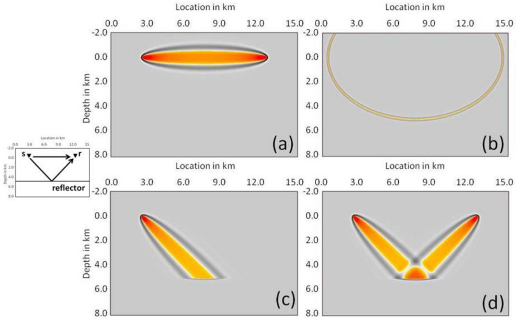

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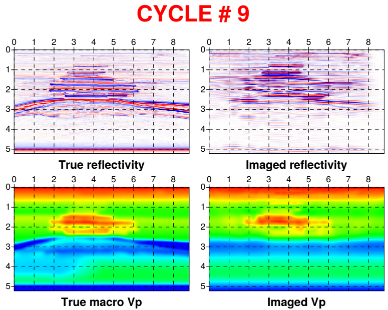

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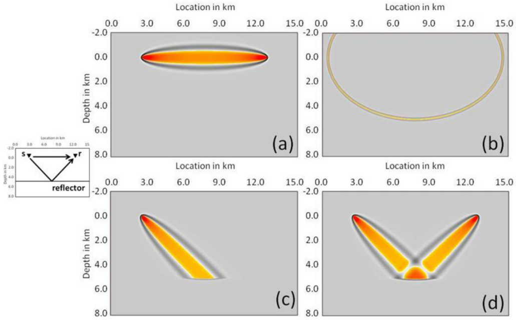

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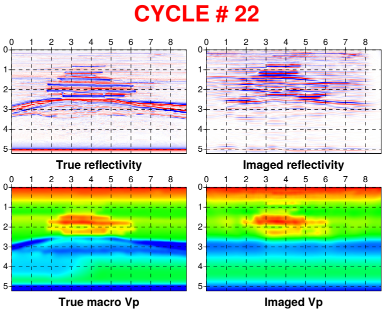

Joint FWI from Zhou et al. (2015) that combines RWI and diving-waves FWI

- limitation of 3D modeling at early times
  $\rightarrow$ most early applications in 2D

HPC Challenges

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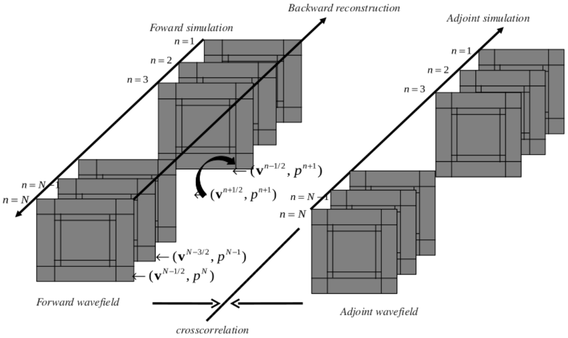
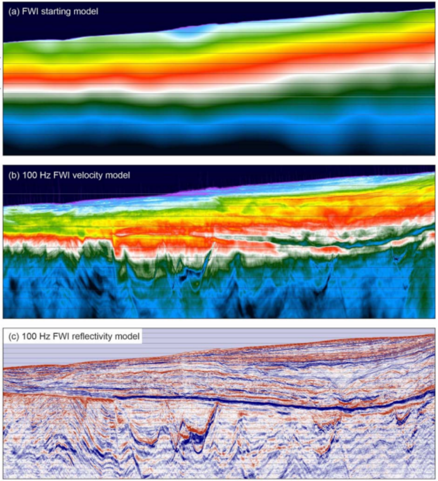
- imaging condition challenges for the correlation of both fields(Symes, 2007; Anderson et al., 2012; Yang et al., 2016; Komatitsch et al., 2016; Robertsson et al., 2021, among others)



Yang et al. (2016)

Current trend: push FWI to (very) high frequency



Warner et al. (2021)

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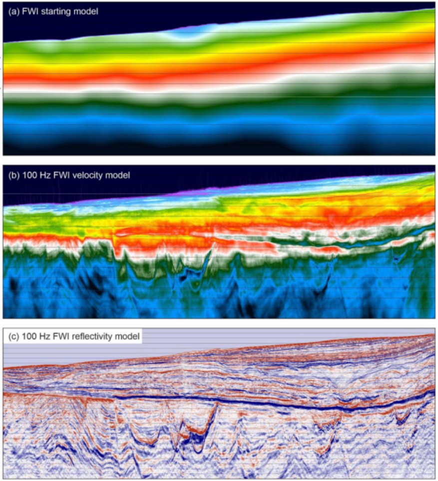

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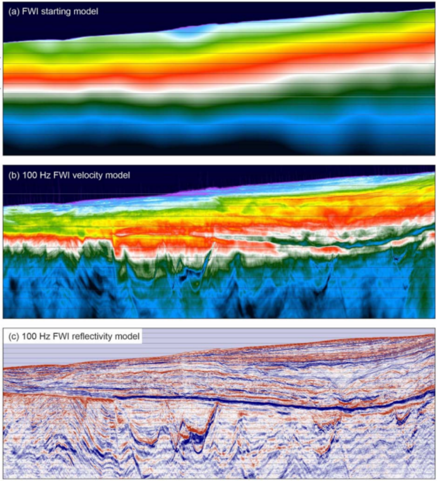

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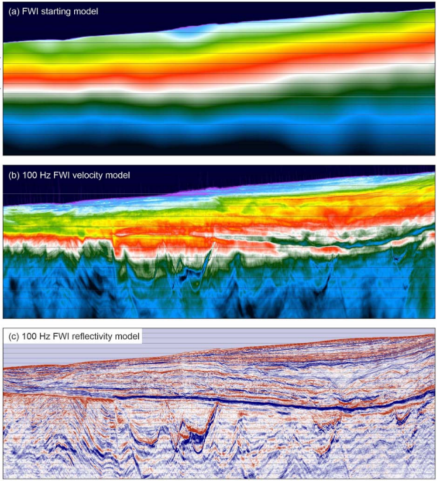

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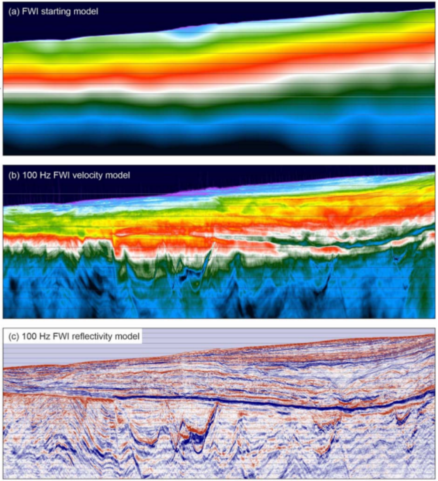

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- is homogeneization theory required when reconstructing velocity model on several octaves?

What about uncertainties?

- Curse of dimensionality in 3D... but RJMCMC seems appealing in low frequency (Sen and Biswas, 2017)

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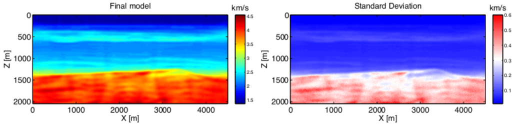
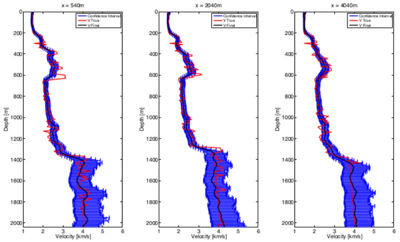
- Probing the Hessian... with it cost

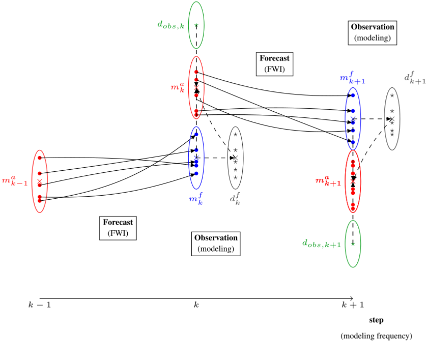


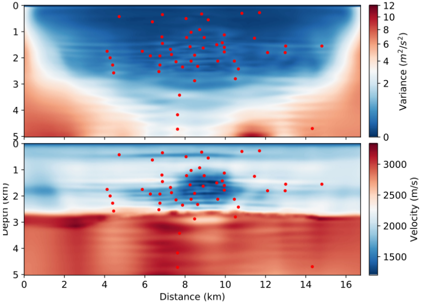
(a) Final model (b) Standard Deviation

Figure 3 *Final model and standard deviation.*



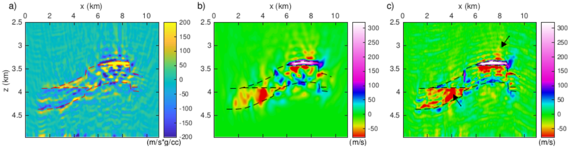
Fang et al. (2014, 2018)





Thurin et al. (2019)

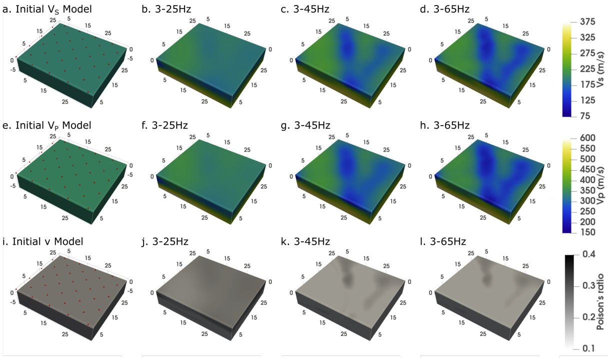
- 4D FWI for monitoring: field monitoring, CCS, H2, ...



Zhou & Lumley (2021)

Other challenging perspectives for FWI

- 4D FWI for monitoring: field monitoring, CCS, H2, ...
- near-surface characterization/surface waves (wind turbine foundation?)



Irnaka et al. (sub)

- 4D FWI for monitoring: field monitoring, CCS, H2, ...
- near-surface characterization/surface waves (wind turbine foundation?)
- sparse/cheap acquisitions? from ambiant noise?

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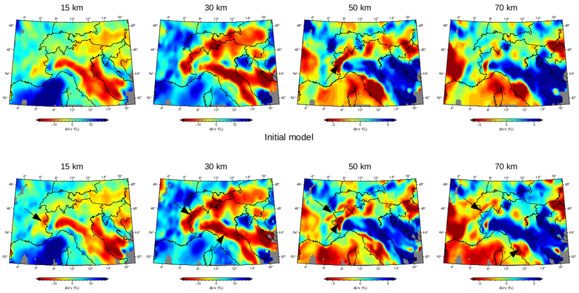

Nouibat et al (in prep)

Acknowledgments

Thanks for the invitation and your attention

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- H2020 Enerxico project and French ANR HIWAI project
- CIMENT infrastructure (*https://ciment.ujf-grenoble.fr*) and CINES/IDRIS/TGCC (allocation 046091 made by GENCI) computing centers

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