Tomographic inversion with CRS attributes: data extraction and preconditioning

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Overview

Introduction

Velocity determination with 3D CRS attributes

Attribute preconditioning and extraction

Synthetic data example

Conclusions

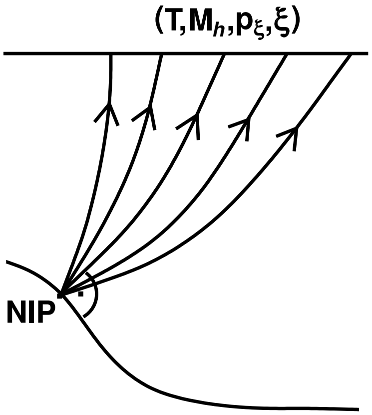
Acknowledgments

Introduction

Construction of a background/migration velocity model is one of the key aims of seismic imaging schemes.

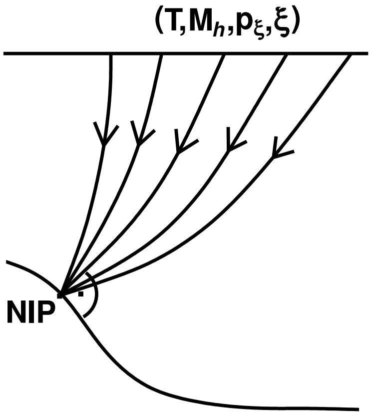
- Problems with conventional reflection tomography: identifying and picking events in the prestack data
- 3D velocity models for depth imaging
- Tomographic approach based on CRS stack results
- Advantages:
  - picking in simulated ZO volume of high S/N ratio
  - pick locations independent of each other
  - very few picks required

NIP waves and velocities



CRS attributes $\mathbf{M}_h$ and $\mathbf{p}_\xi$ at (t_0, ξ) describe second-order traveltime approximation of emerging NIP wave.

NIP waves and velocities



In consistent velocity models, NIP waves focus at zero traveltime.

Tomography with CRS attributes

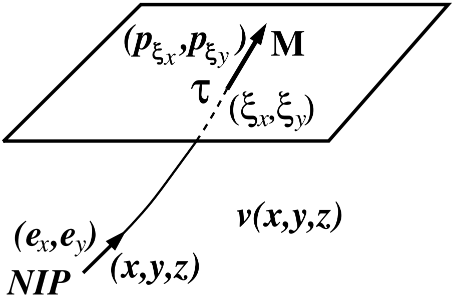
Find a velocity model in which all considered NIP waves, described by kinematic wavefield attributes, are correctly modeled.

For tomographic inversion in 3D, one azimuth ϕ of $\mathbf{M}_h$ is required: M_ϕ.

For multi-azimuth data the full Matrix $\mathbf{M}_h$ is to be preferred.

3D tomography with CRS attributes

Data and model components



Data:
$(\tau, M_{11}, M_{12}, M_{22},$
$p_{\xi_x}, p_{\xi_y}, \xi_x, \xi_y)_i$

$\tau = t_0/2$

Model:
$(x, y, z, e_x, e_y)_i, v_{jkl}$

v_{jkl}: B-spline coefficients

Inversion procedure

- nonlinear least-squares problem:
  - iterative solution, local linearization
  - τ, p_{ξ_x}, p_{ξ_y}, ξ_x, ξ_y from kinematic ray tracing
  - $\mathbf{M}_h = \mathbf{D}\,\mathbf{B}^{-1}$ from dynamic ray-tracing: $\mathbf{T} = \begin{pmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{pmatrix}$ propagator matrix in Cartesian coordinates
- model update $\Delta\mathbf{m}$: least-squares solution of
  $$\mathbf{F}\Delta\mathbf{m} = \Delta\mathbf{d}$$
- calculation of Fréchet derivatives (matrix $\mathbf{F}$): ray perturbation theory

Regularization/additional constraints

Regularization:

- minimization of second derivatives of velocity (spatially dependent)

Additional constraints:

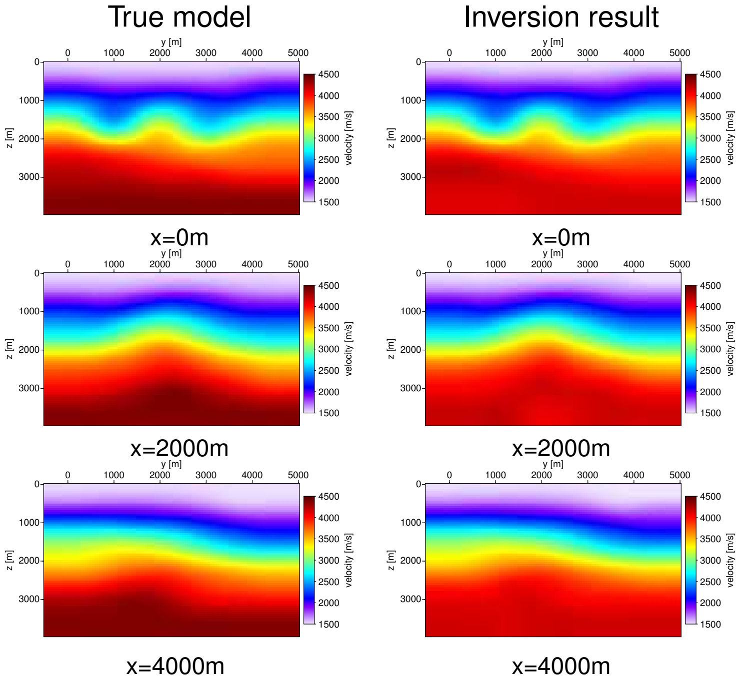
- $v(x, y, z)$ values at arbitrary locations (x, y, z)
- force velocity structure to follow local reflector structure

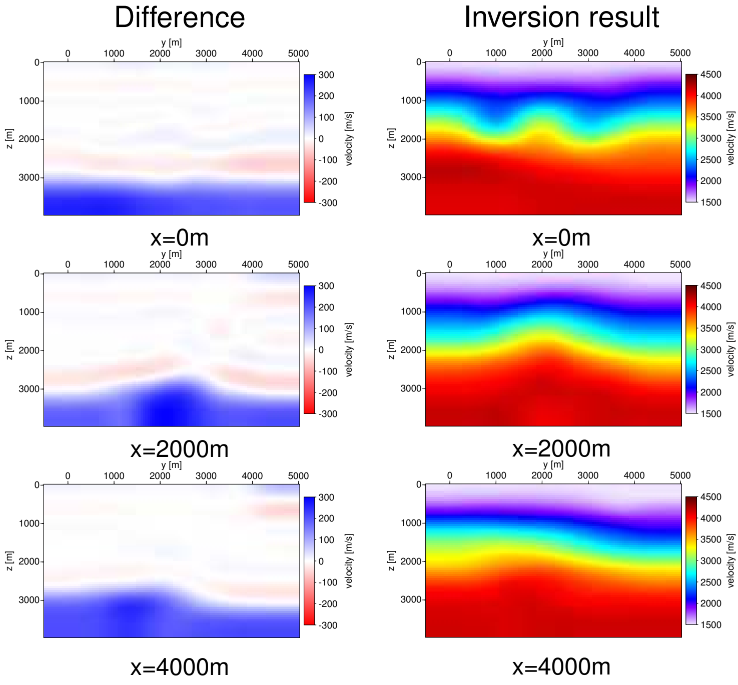
Synthetic example: forward modeled attributes

Model description:

- $9 \times 9 \times 9 = 729$ B-spline knots
- horizontal spacing: 500 m
- vertical spacing: 400 m

- 1008 NIP-locations used to model the input data
- initial ray direction follows local velocity gradient


True model
Inversion result
y [m]
0
1000
2000
3000
4000
5000
z [m]
velocity [m/s]
1500
2000
2500
3000
3500
4000
4500
x=0m
x=2000m
x=4000m


Difference
Inversion result
y [m]
0 1000 2000 3000 4000 5000
z [m]
0 1000 2000 3000
velocity [m/s]
300 200 100 0 -100 -200 -300
4500 4000 3500 3000 2500 2000 1500
x=0m
x=2000m
x=4000m

Motivation

CRS attributes have characteristic features:

- they should be constant along the wavelet
- they should vary smoothly along the event

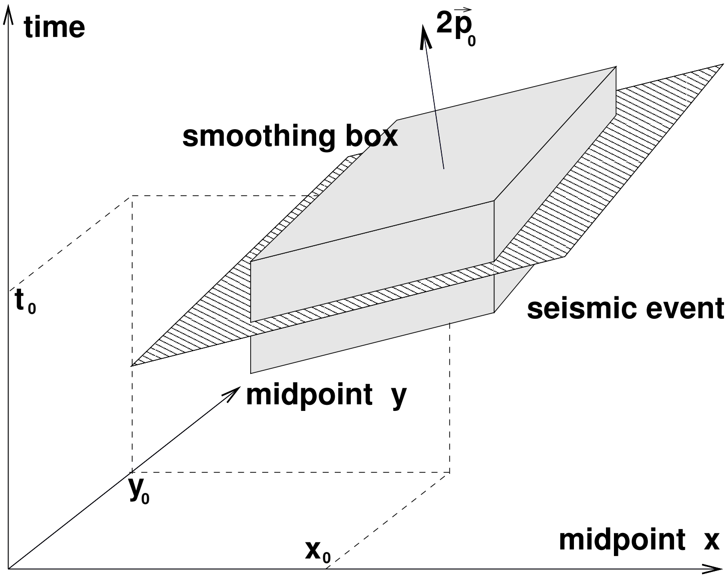
However, in practice

- unphysical fluctuations
- outliers
- possibly not locally coherent

Thus

- event-consistent smoothing
- identification of valid pick locations

The event-aligned volume



Event-consistent smoothing

For each zero-offset sample and CRS-parameter

- align smoothing volume with reflection event using first traveltime derivatives
- reject samples below user-defined coherence threshold
- reject samples with dip difference beyond user-defined threshold
  - ➥ avoid mixing of events
- apply combined filter:
  - median filter ➥ remove outliers
  - averaging ➥ remove fluctuations
- assign result to zero-offset sample

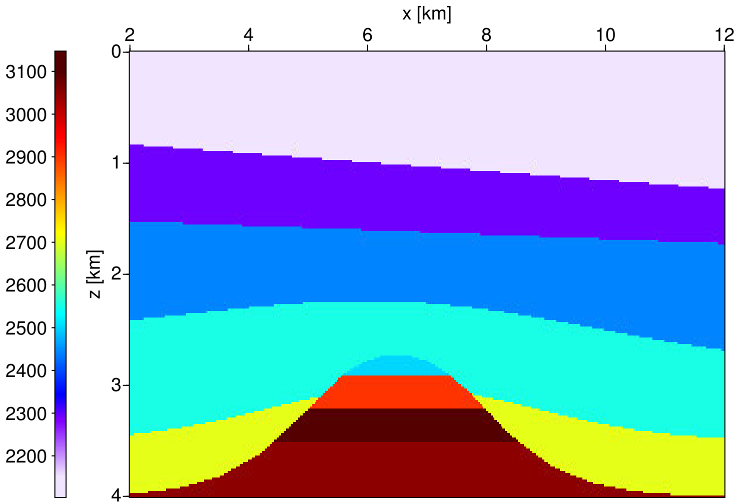
Automated attribute extraction

For each selected trace

- search (next) coherence maximum
- get nearest maximum of stack envelope
- align volume with reflection event using first traveltime derivatives
- reject pick if user-defined percentage of all samples inside the volume
  - is below a given coherence threshold or
  - has a dip difference exceeding a given threshold
- or if amplitude is below a user-defined threshold

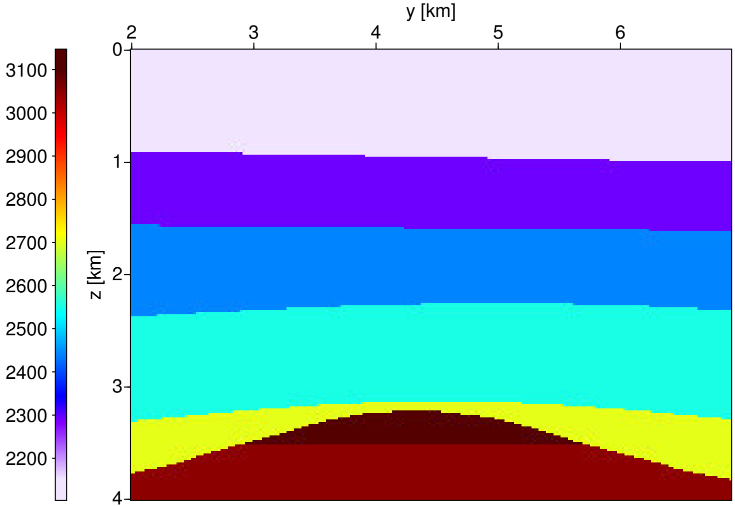
  ➥ prefer high-energy events
- continue on selected trace

Synthetic data example



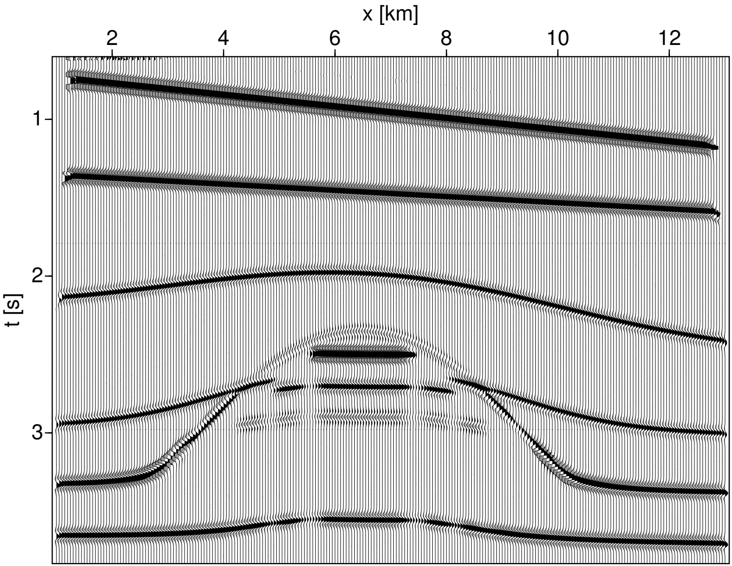
interval velocity [m/s] model at $y = 5000\,\mathrm{m}$

Synthetic data example



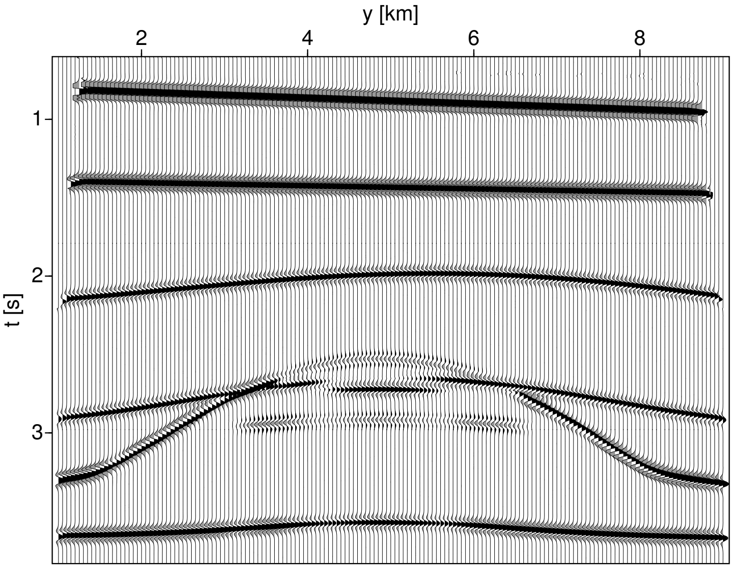
interval velocity [m/s] model at $x = 5000\,\mathrm{m}$

CRS-stacked volume



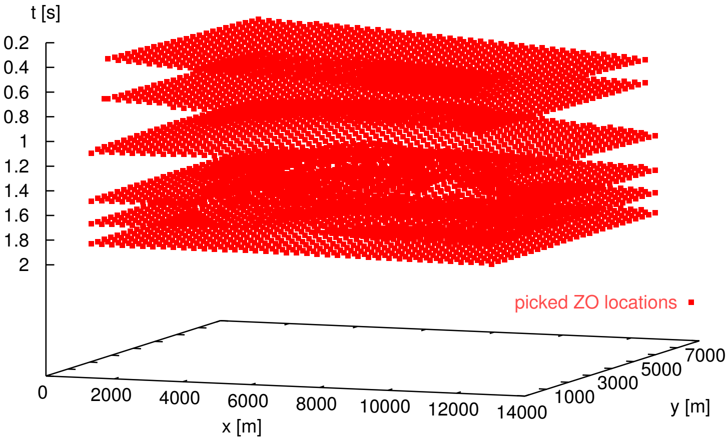
inline section at $y = 5000\,\mathrm{m}$

CRS-stacked volume



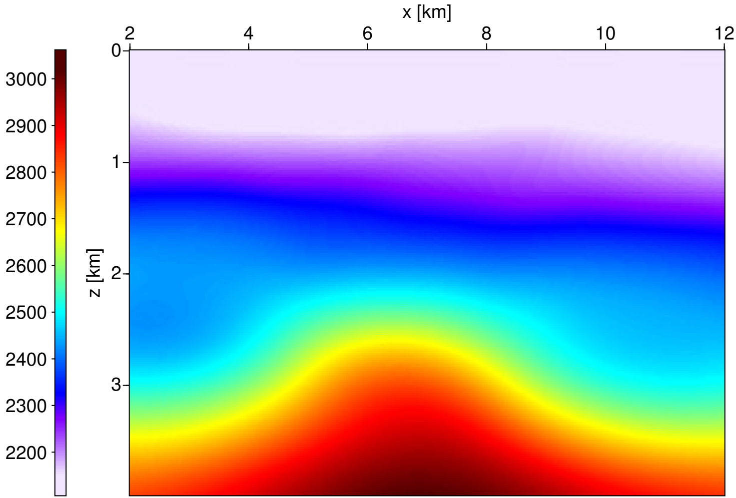
crossline section at $x = 5000\,\mathrm{m}$

Automatically picked ZO locations



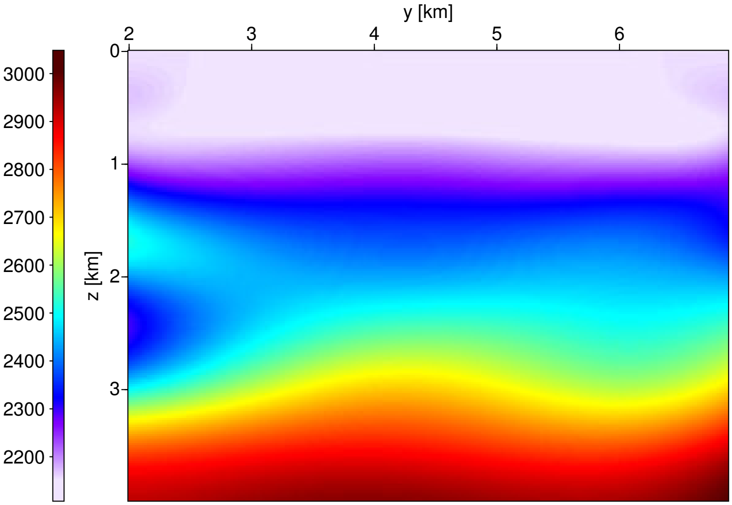
p and **M** available for all picks

Inversion result (1)



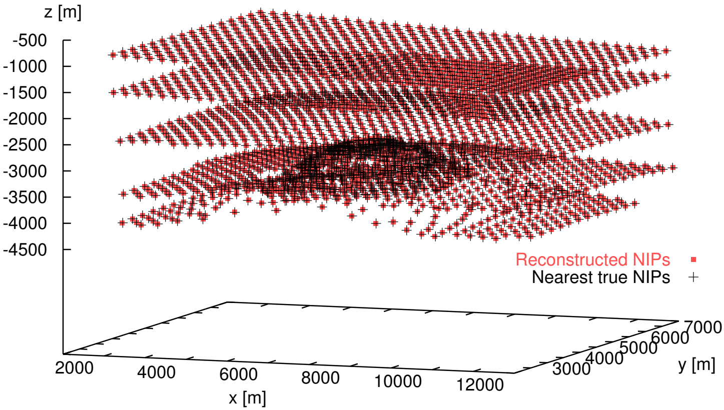
reconstructed velocity [m/s] model at $y = 5000\,\mathrm{m}$

Inversion result (1)



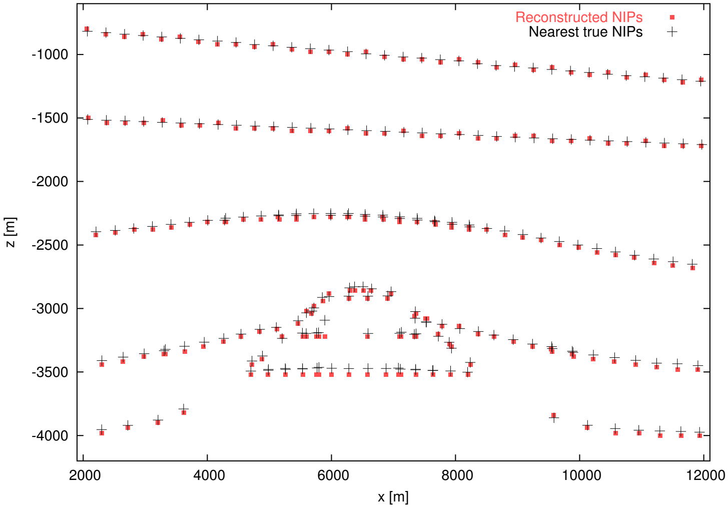
reconstructed velocity [m/s] model at $x = 5000\,\mathrm{m}$

Inversion result (2)



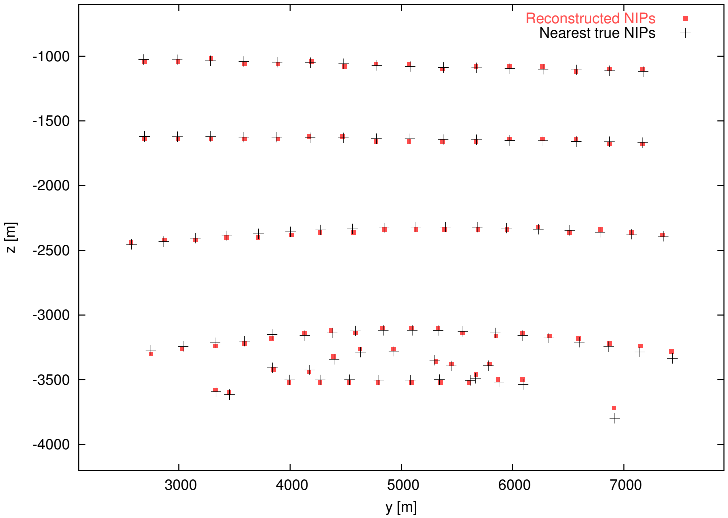
full 3D view

Inversion result (2)



inline view at $4000 < y < 4300\,\text{m}$

Inversion result (2)



crossline view at $8000 < x < 8300\,\mathrm{m}$

Conclusions

- 3D tomographic inversion based on CRS attributes
- Advantages:
  - very few picks are required
  - automated smoothing of attributes
  - automated picking in ZO volume
  - no assumptions about reflector continuity
  - smooth velocity model (ideal for ray tracing)
- Limitations:
  - smooth velocity description must be valid
  - limited lateral variation within CRS apertures (approximately hyperbolic traveltimes)

Acknowledgments

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Contributors:
Miriam Spinner: model building, acquisition design, and forward-modelling with NORSAR
Nils-Alexander Müller: 3D CRS stack processing