Near-surface velocity estimation by residual statics constrained early-arrival waveform inversion

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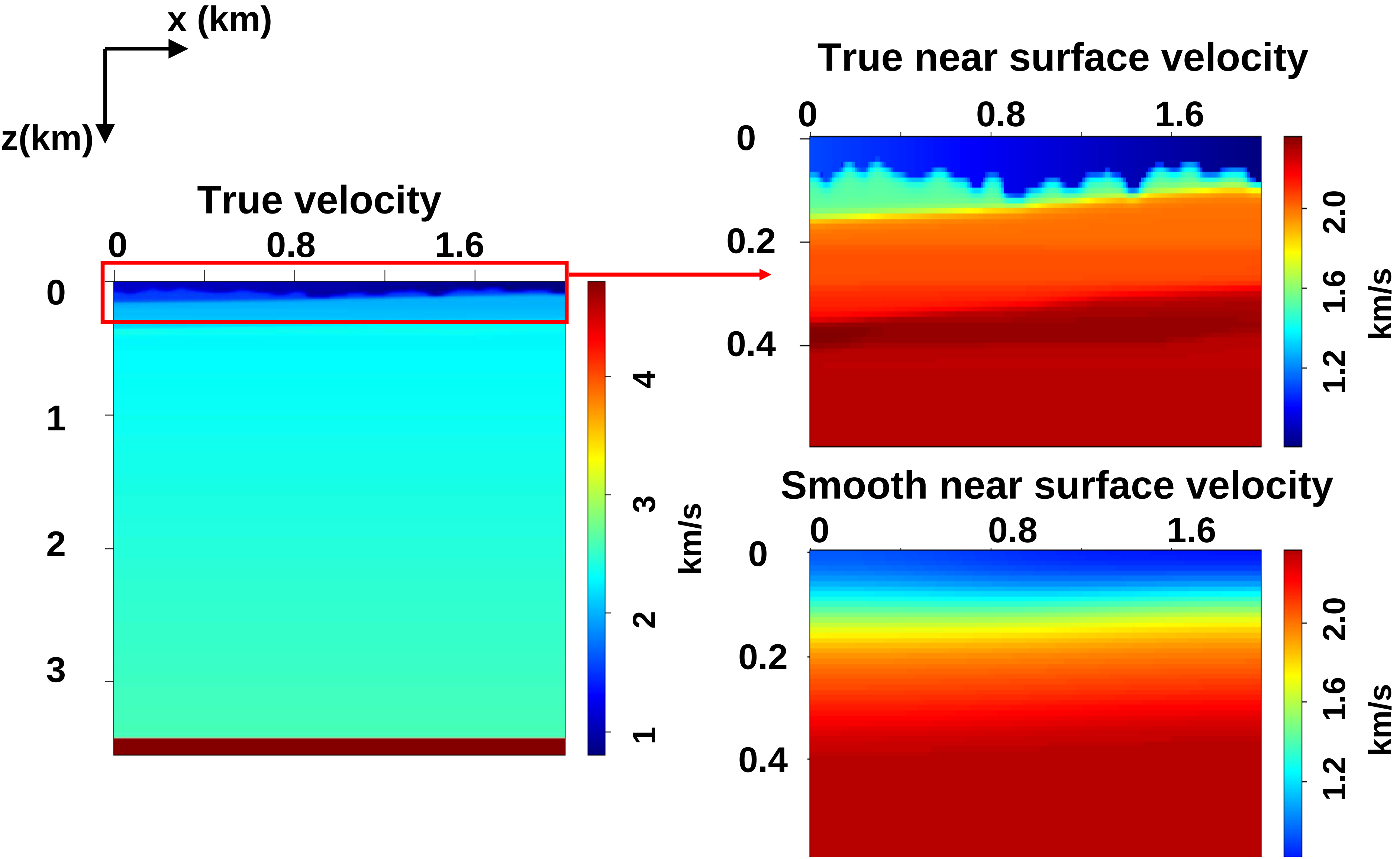
Goal: Obtain high resolution subsurface image

Choices:

1. Conventional processing

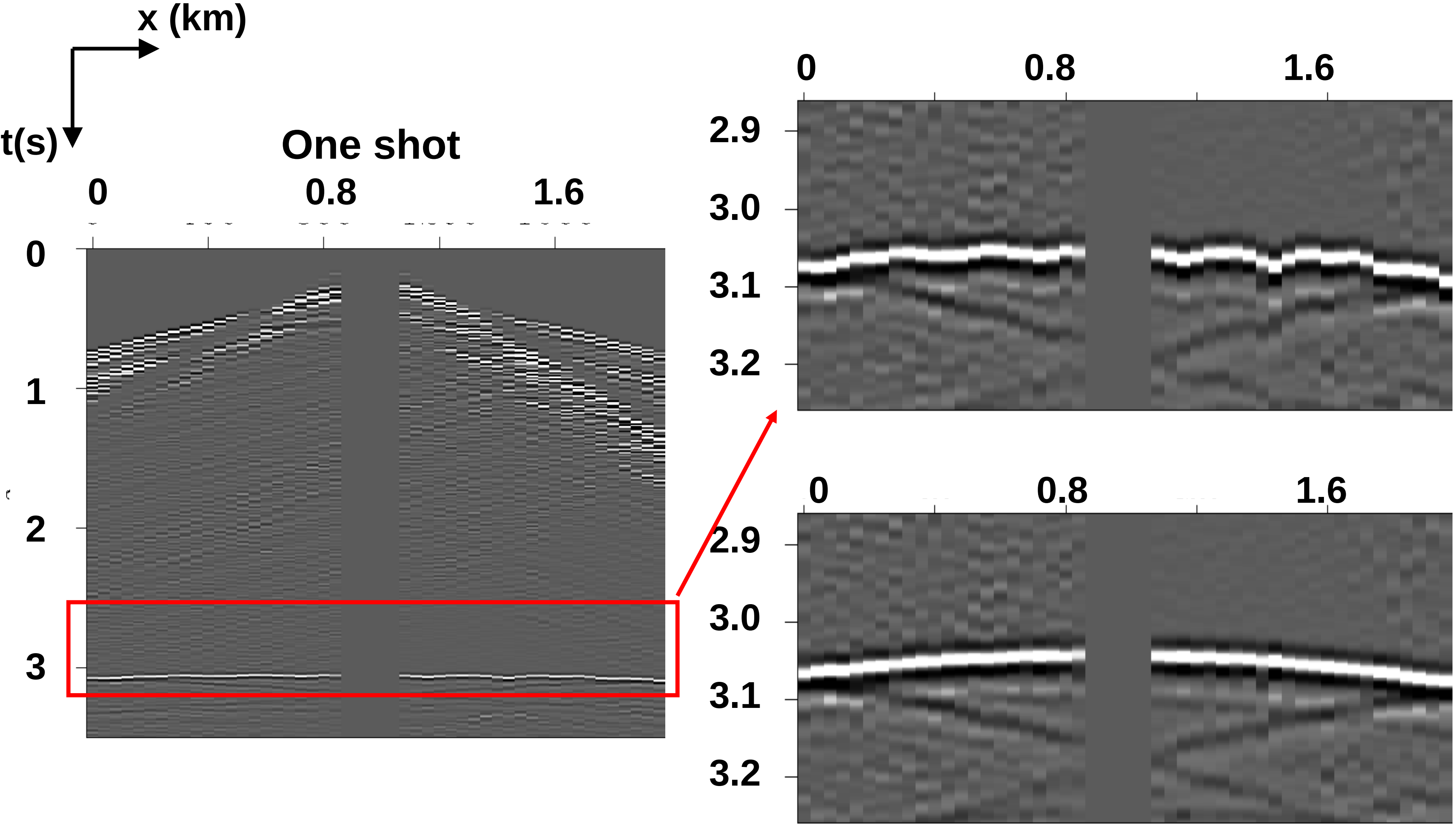
   residual statics corrections + migration with smooth near surface velocity

2. Migration with high resolution near surface velocity


True velocity

True near surface velocity

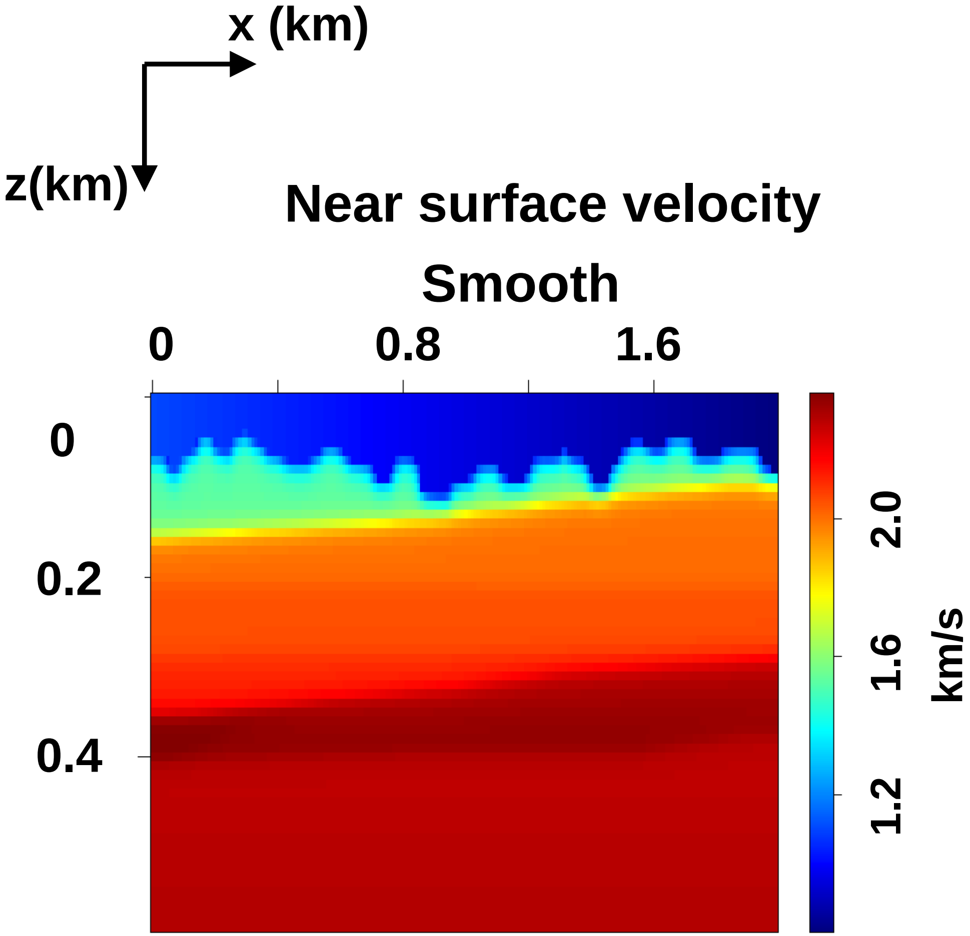
Smooth near surface velocity



Residual statics corrections by
stack power maximization (Shuki and Jon, 1985)

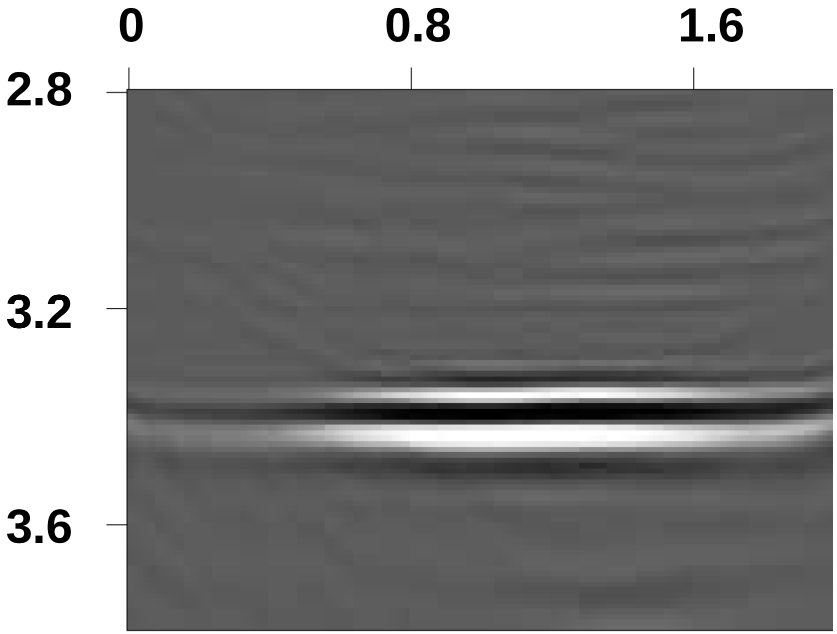
Near surface velocity

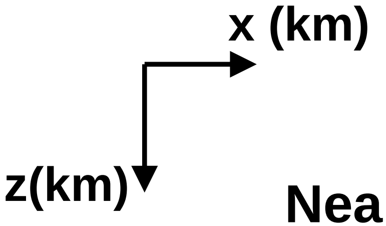
Smooth

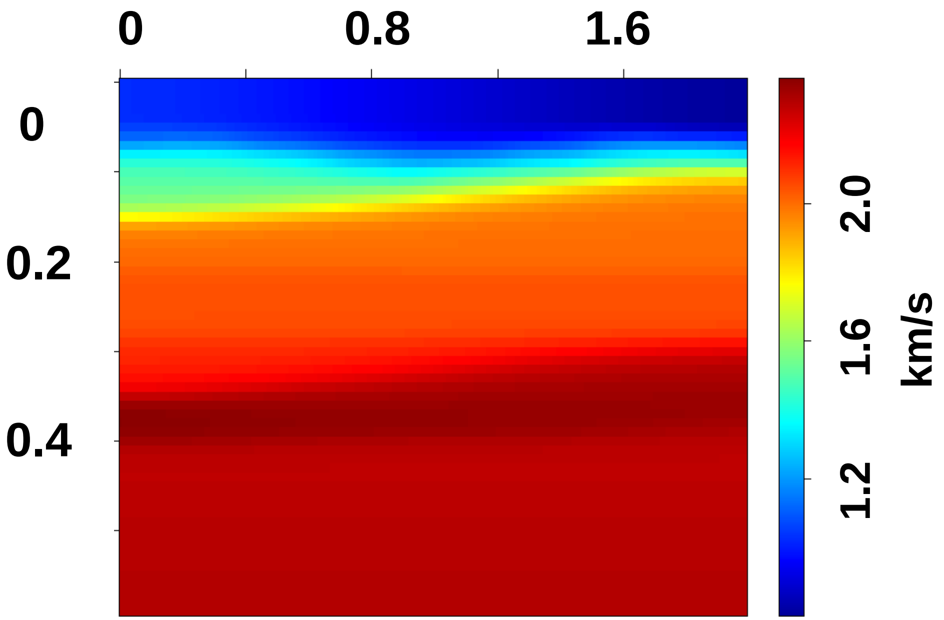


Migrated image

Conventional

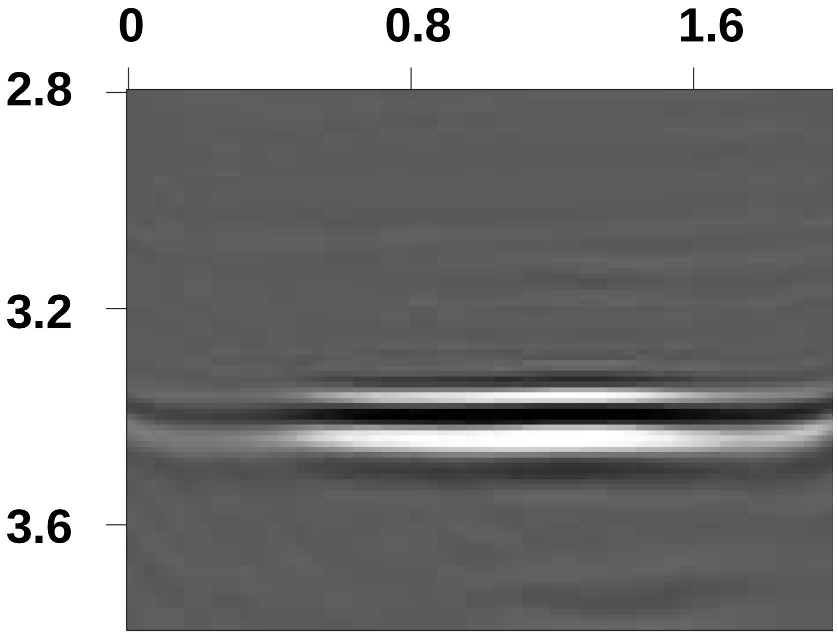






Near surface velocity

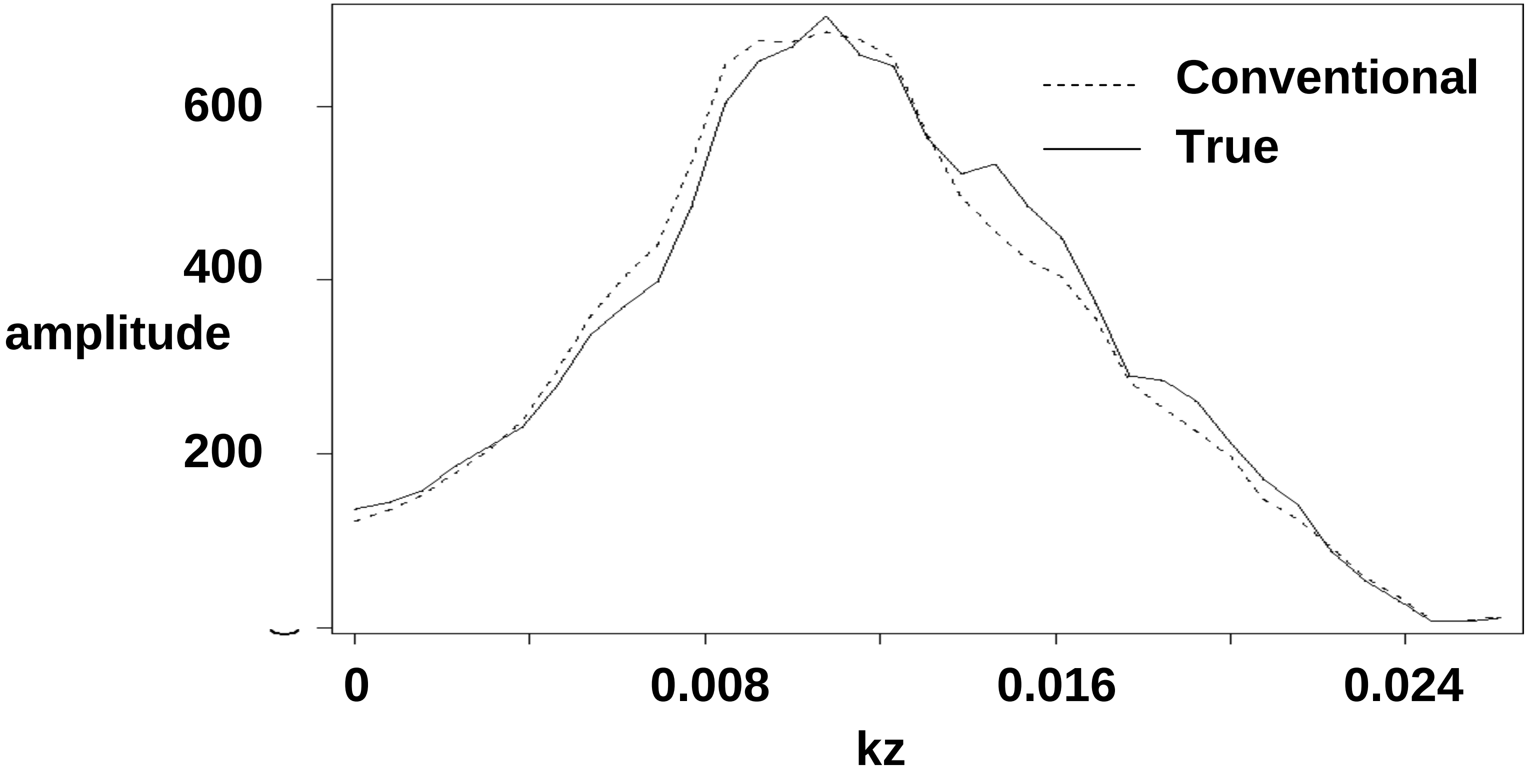
True



Migrated image

True

Normalized image spectrum



Conventional processing produces a lower resolution image

Outline

- Waveform inversion: problem with land data and solution
- Theory
- Example
- Conclusion
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What is waveform inversion:

Non-linear iterative estimation of velocity by matching recorded wave field

(Tarantola, 1984; Pratt and Hicks, 1998)

Advantage:

Higher resolution of estimated velocity compared with ray-based tomography

Problem1:

Non-linearity

Recorded data is a non-linear function of velocity

More data → more non-linearity

Proposed Solution:

Matching early-arrivals rather than the entire recorded wavefield

Problem2:

Data sparsity

Sparse data in both in-line and cross-line direction

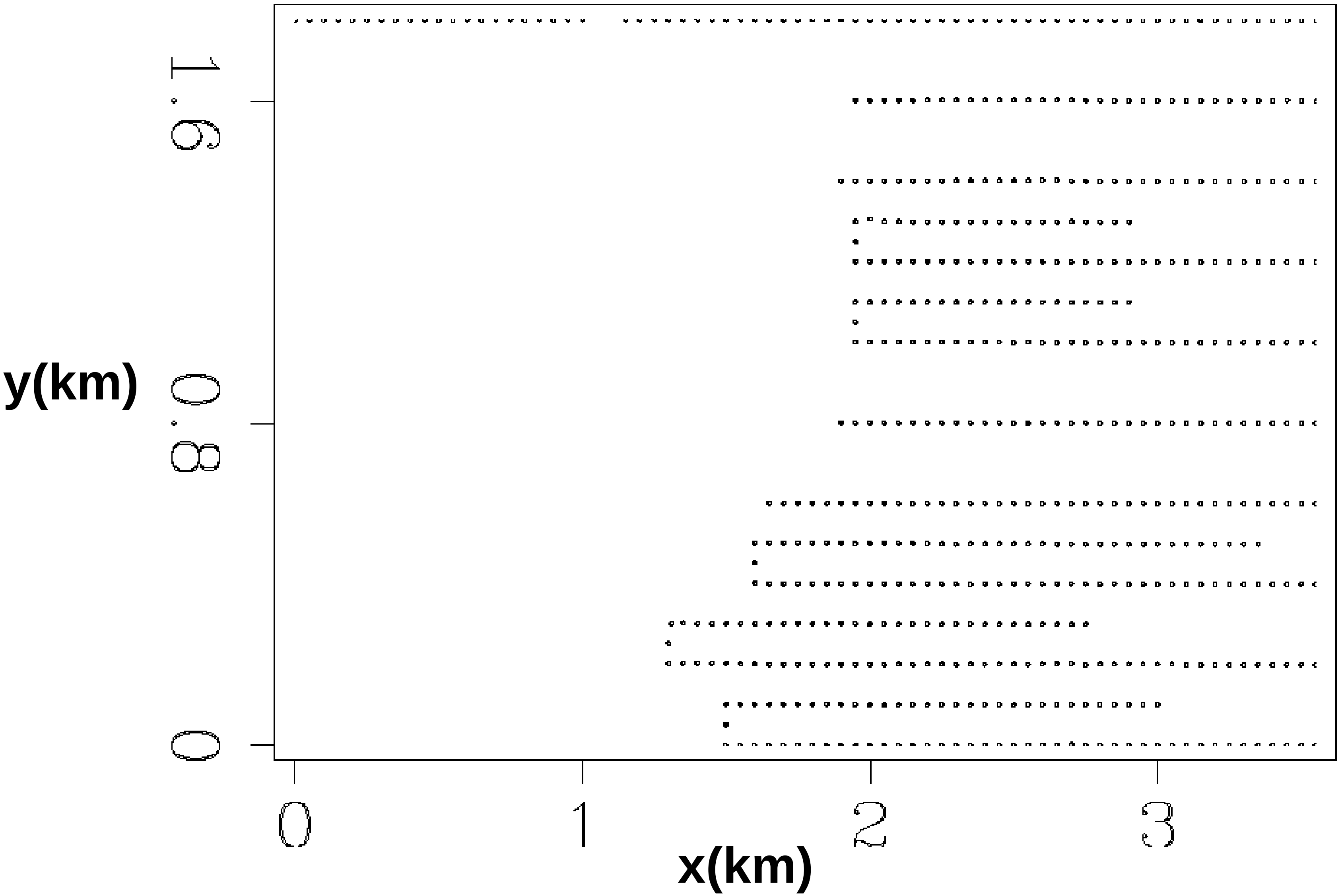
Interpolation does not help

Proposed Solution:

Using RRSD

(Receiver Residual Statics Difference constraints)

Receiver location from ecopetrol dataset



Problem3:

Data amplitude

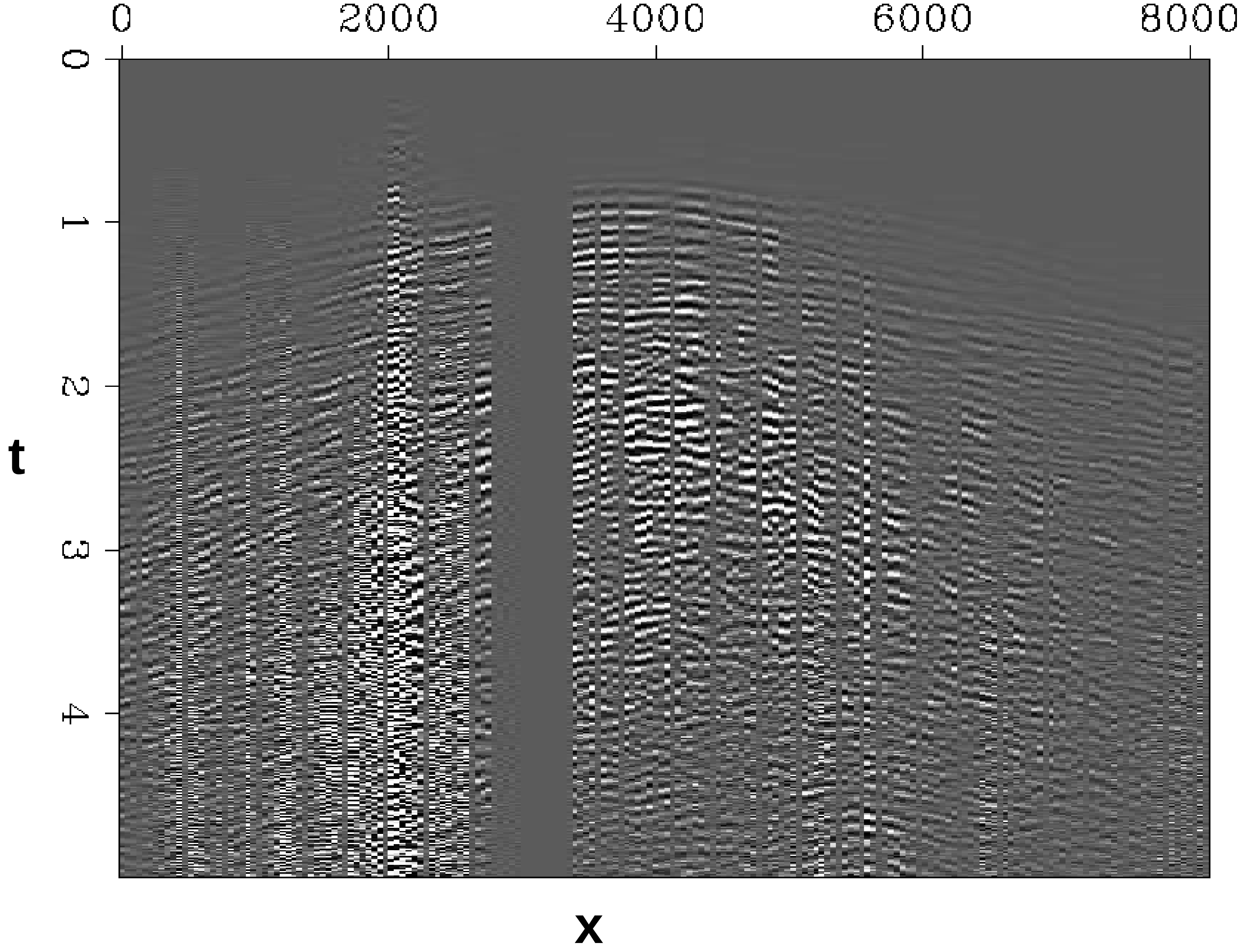
Receiver coupling and/or preprocessing

Proposed Solution:

New objective function

(less sensitive to amplitude)

typical land shot gather from Saudi Aramco



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Defining RRSD (Receiver residual statics difference)

- statics shift between adjacent traces (in the same shot) that maximize the cross-correlation of the the two traces (after NMO)

$$f(\Delta\tau_{\mathrm{measure}}) = f(\Delta\tau_{\mathrm{measure}}(\mathbf{r},\mathbf{s})) = \max\left(f(\Delta\tau)\right)$$

where

$$f(\Delta\tau) = \int d(t+\Delta\tau,\mathbf{r},\mathbf{s})\,d(t,\mathbf{r}+1,\mathbf{s})\,d\mathrm{t}$$

$$\tau \in (-T, T)$$

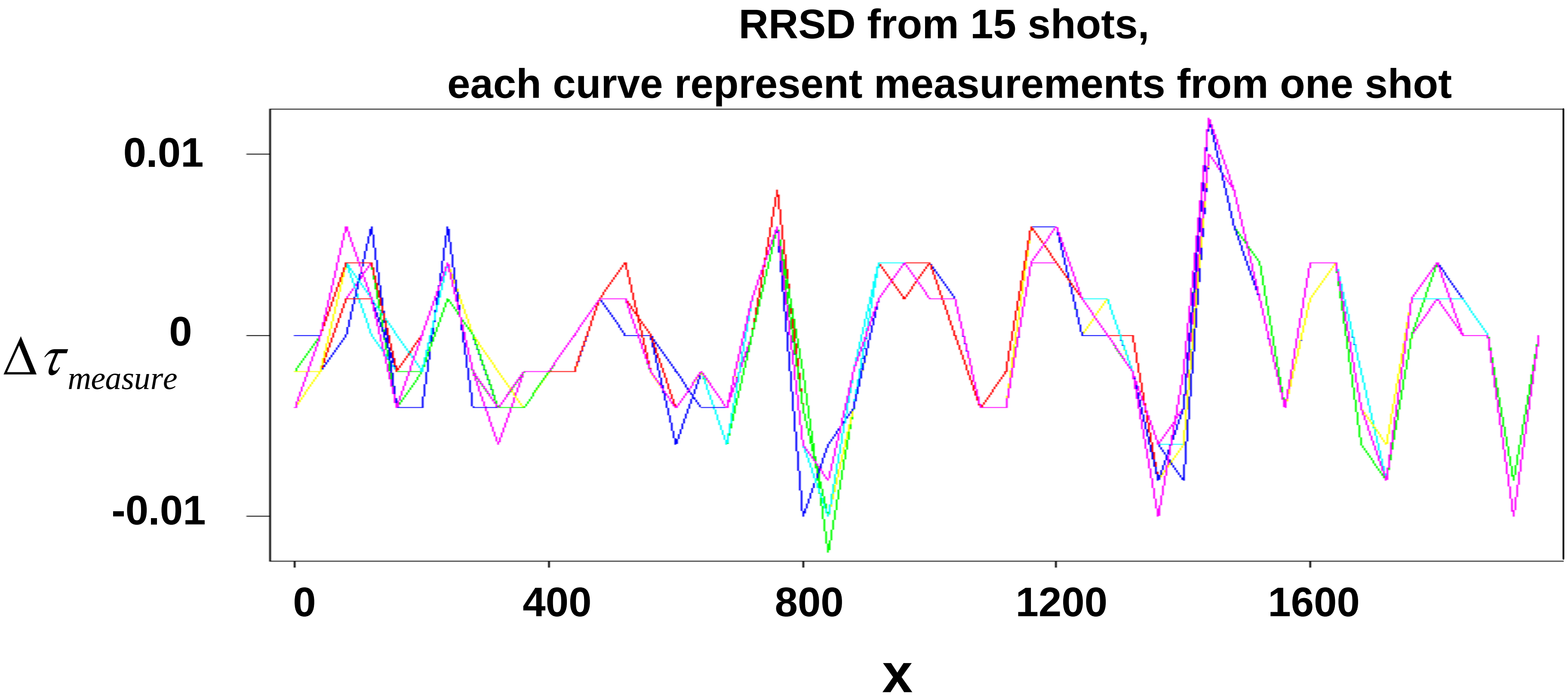
d	**Reflection data after NMO**	$\mathbf{r}$	**Receiver location**
T	**Predefined constant**	$\mathbf{s}$	**Source location**

Difference between conventional residual statics and RRSD :

(Receiver residual statics difference)

- Calculated in shot-receiver space rather than midpoint-offset space
- Is a function of both receiver and source location
- Reflects traveltime difference between ***adjacent*** receiver locations
- Can be connected with near-surface velocity assuming vertical traveling path in near surface for deep reflection events.

RRSD from synthetic example (Receiver residual statics difference)



Connecting RRSD with velocity via modeled surface consistent RRSD

$$\min\left(\sum_{\mathbf{r},\mathbf{s}}\left(\vartriangle\tau_{\mathrm{measure}}(\mathbf{r},\mathbf{s})-\vartriangle\tau_{\mathrm{cal}}(\mathbf{r})\right)^2\right)$$

where

$$\Delta\tau_{\mathrm{cal}}(\mathbf{r})=\int_0^{z_1}dz\left(\frac{1}{v(\mathbf{r},z)}-\frac{1}{v(\mathbf{r}+1,z)}\right)\qquad(1)$$

v	**Near surface velocity**	$\mathbf{r}$	**Receiver location**
$\Delta\tau$	**RRSD**	$\mathbf{s}$	**Source location**

Problem formulation using RRSD

$$\min\left(\sum_{\mathbf{r},\mathbf{s}}\left\|\mathbf{W_e}\mathbf{F_{bp}}\left(\mathbf{d_{obs}}(\mathbf{r},\mathbf{s},t)-\mathbf{d_{cal}}(\mathbf{r},\mathbf{s},t)\right)\right\|^2+\varepsilon^2\sum_{\mathbf{r},\mathbf{s}}\left(\triangle\tau_{\mathrm{measure}}(\mathbf{r},\mathbf{s})-\triangle\tau_{\mathrm{cal}}(\mathbf{r})\right)^2\right)$$

$\mathbf{d_{obs}}$	**Observed wave field**
$\mathbf{d_{cal}}$	**Calculated wave field**
$\mathbf{W_e}$	**Matrix that window out early arrivals**
$\mathbf{F_{bp}}$	**Bandpass filter**
$\triangle\tau$	**RRSD**
v	**Near surface velocity field**
$\mathbf{r}$	**Receiver location**
$\mathbf{s}$	**Source location**
ε	**Weighting coefficient**

Problem formulation using RRSD

$$\min\left(\boxed{\sum_{\mathbf{r},\mathbf{s}}\left\|\mathbf{W}_{\mathbf{e}}\mathbf{F}_{\mathbf{bp}}\left(\mathbf{d}_{\mathbf{obs}}(\mathbf{r},\mathbf{s},t)-\mathbf{d}_{\mathbf{cal}}(\mathbf{r},\mathbf{s},t)\right)\right\|^{2}}+\varepsilon^{2}\sum_{\mathbf{r},\mathbf{s}}\left(\triangle\tau_{\mathrm{measure}}(\mathbf{r},\mathbf{s})-\triangle\tau_{\mathrm{cal}}(\mathbf{r})\right)^{2}\right)$$

Early arrival waveform inversion fitting goal

$\mathbf{d}_{\mathbf{obs}}$	**Observed wave field**
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Problem formulation using RRSD

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RRSD fitting goal

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Problem formulation using RRSD

$$\min\left(\boxed{\sum_{\mathbf{r},\mathbf{s}}\left\|\mathbf{W}_{\mathbf{e}}\mathbf{F}_{\mathbf{bp}}\left(\mathbf{d}_{\mathbf{obs}}(\mathbf{r},\mathbf{s},t)-\mathbf{d}_{\mathbf{cal}}(\mathbf{r},\mathbf{s},t)\right)\right\|^{2}}+\varepsilon^{2}\sum_{\mathbf{r},\mathbf{s}}\left(\triangle\tau_{\mathrm{measure}}(\mathbf{r},\mathbf{s})-\triangle\tau_{\mathrm{cal}}(\mathbf{r})\right)^{2}\right)$$

Early arrival waveform inversion only

$\mathbf{d}_{\mathbf{obs}}$	**Observed wave field**	v	**Near surface velocity field**
$\mathbf{d}_{\mathbf{cal}}$	**Calculated wave field**	$\mathbf{r}$	**Receiver location**
$\mathbf{W}_{\mathbf{e}}$	**Matrix that window out early arrivals**	$\mathbf{s}$	**Source location**
$\mathbf{F}_{\mathbf{bp}}$	**Bandpass filter**	ε	**Weighting coefficient**
$\triangle\tau$	**RRSD**		

Problem formulation using RRSD

$$\min\left(\underbrace{\boxed{\sum_{\mathbf{r},\mathbf{s}}\left\|\mathbf{W}_{\mathbf{e}}\mathbf{F}_{\mathbf{bp}}\left(\mathbf{d}_{\mathbf{obs}}(\mathbf{r},\mathbf{s},t)-\mathbf{d}_{\mathbf{cal}}(\mathbf{r},\mathbf{s},t)\right)\right\|^{2}}}_{\text{Step 2}}+\underbrace{\boxed{\varepsilon^{2}\sum_{\mathbf{r},\mathbf{s}}\left(\vartriangle\tau_{\mathrm{measure}}(\mathbf{r},\mathbf{s})-\vartriangle\tau_{\mathrm{cal}}(\mathbf{r})\right)^{2}}}_{\text{Step 1}}\right)$$

$\mathbf{d}_{\mathbf{obs}}$	**Observed wave field**	v	**Near surface velocity field**
$\mathbf{d}_{\mathbf{cal}}$	**Calculated wave field**	$\mathbf{r}$	**Receiver location**
$\mathbf{W}_{\mathbf{e}}$	**Matrix that window out early arrivals**	$\mathbf{s}$	**Source location**
$\mathbf{F}_{\mathbf{bp}}$	**Bandpass filter**	ε	**Weighting coefficient**
$\vartriangle\tau$	**RRSD**		

Problem formulation using RRSD

$$\min\left(\sum_{\mathbf{r},\mathbf{s}}\left\|\mathbf{W}_{\mathbf{e}}\mathbf{F}_{\mathbf{bp}}\left(\mathbf{d}_{\mathbf{obs}}(\mathbf{r},\mathbf{s},t)-\mathbf{d}_{\mathbf{cal}}(\mathbf{r},\mathbf{s},t)\right)\right\|^{2}+\varepsilon^{2}\sum_{\mathbf{r},\mathbf{s}}\left(\triangle\tau_{\mathrm{measure}}(\mathbf{r},\mathbf{s})-\triangle\tau_{\mathrm{cal}}(\mathbf{r})\right)^{2}\right)$$

Joint inversion

$\mathbf{d}_{\mathbf{obs}}$	**Observed wave field**	v	**Near surface velocity field**
$\mathbf{d}_{\mathbf{cal}}$	**Calculated wave field**	$\mathbf{r}$	**Receiver location**
$\mathbf{W}_{\mathbf{e}}$	**Matrix that window out early arrivals**	$\mathbf{s}$	**Source location**
$\mathbf{F}_{\mathbf{bp}}$	**Bandpass filter**	ε	**Weighting coefficient**
$\triangle\tau$	**RRSD**		

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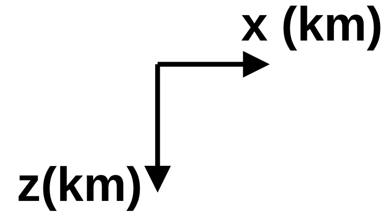
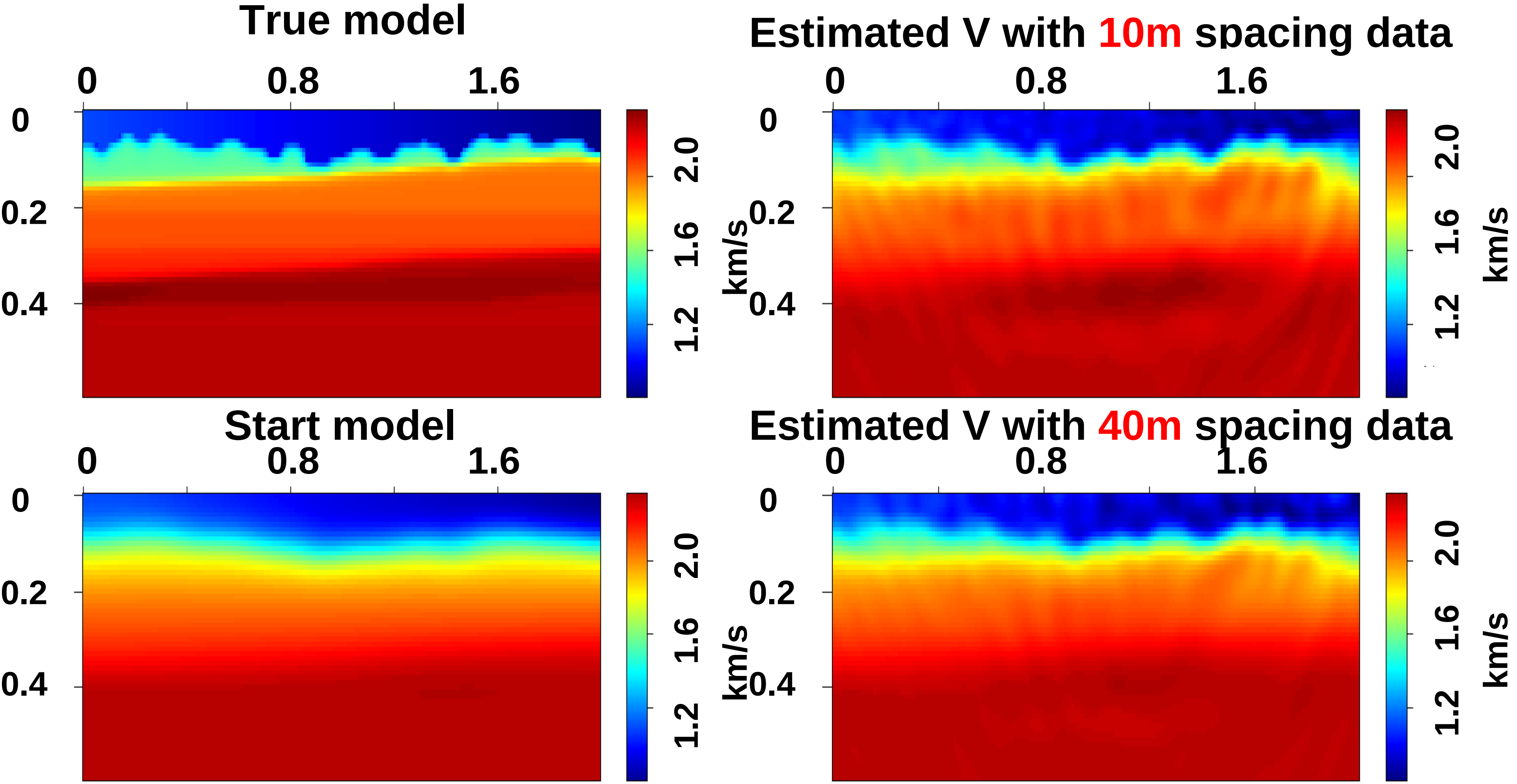
Data spatial density effect



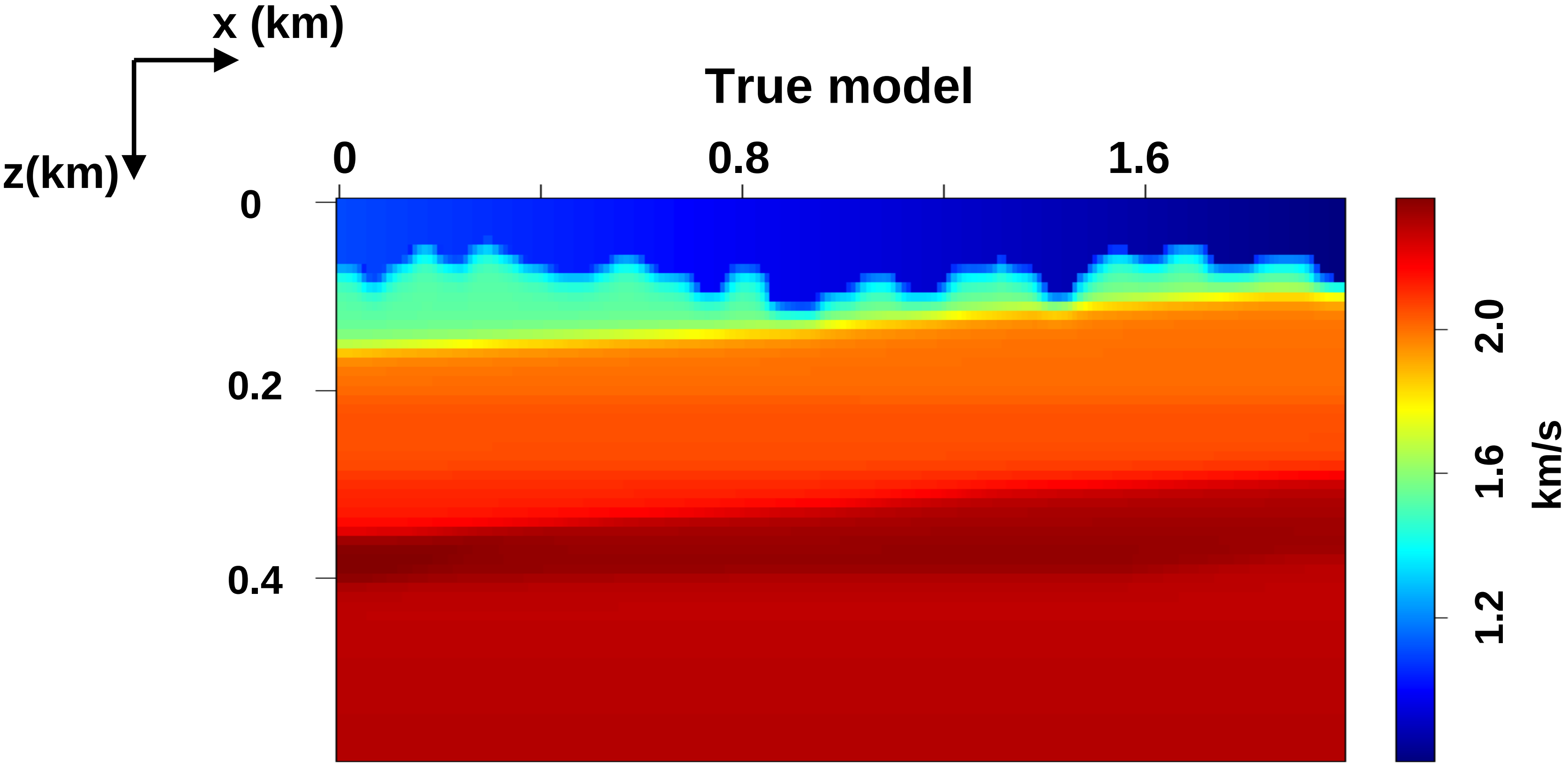

True model

Estimated V with 10m spacing data

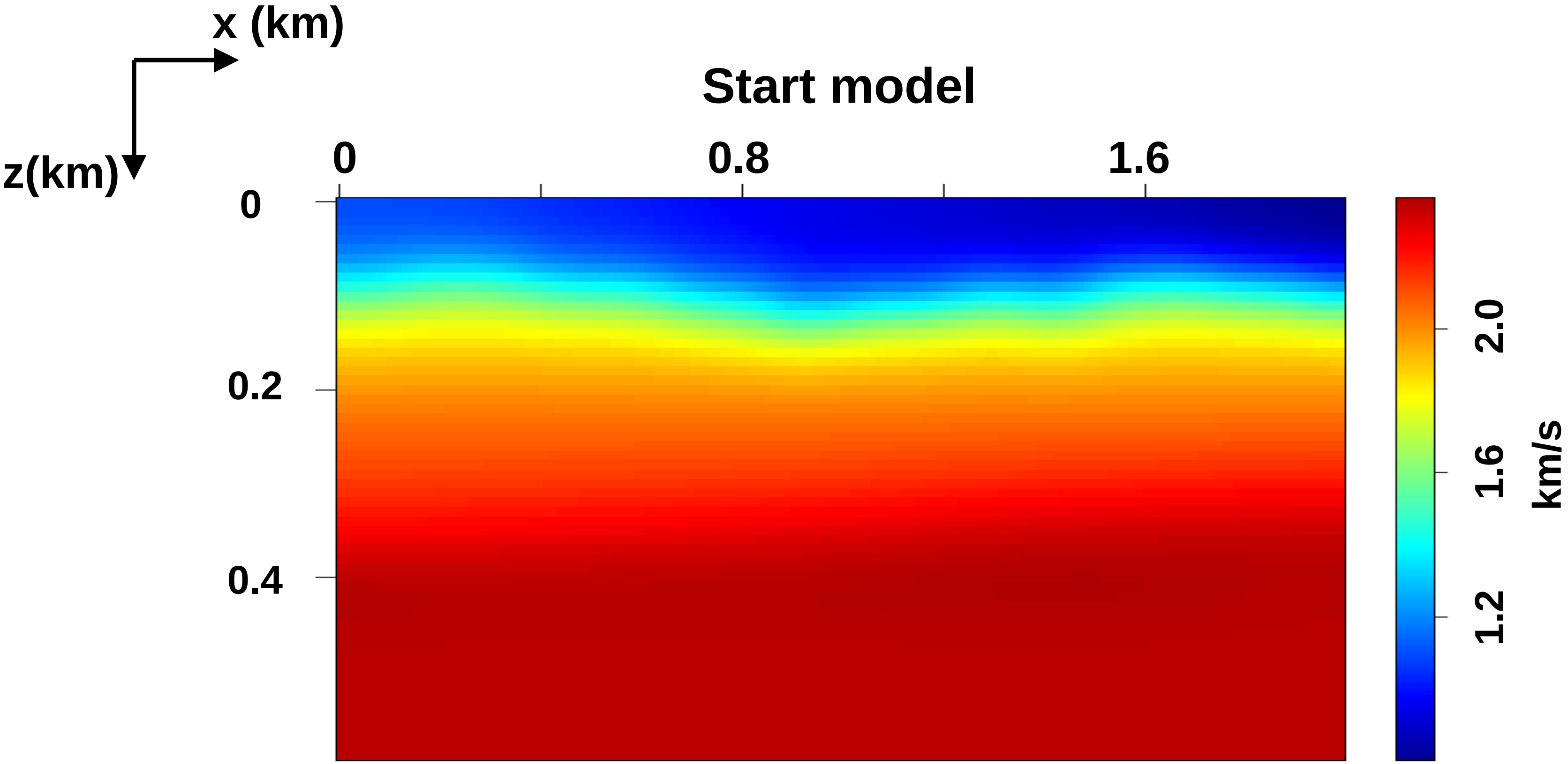
Start model

Estimated V with 40m spacing data

Data spatial density effect

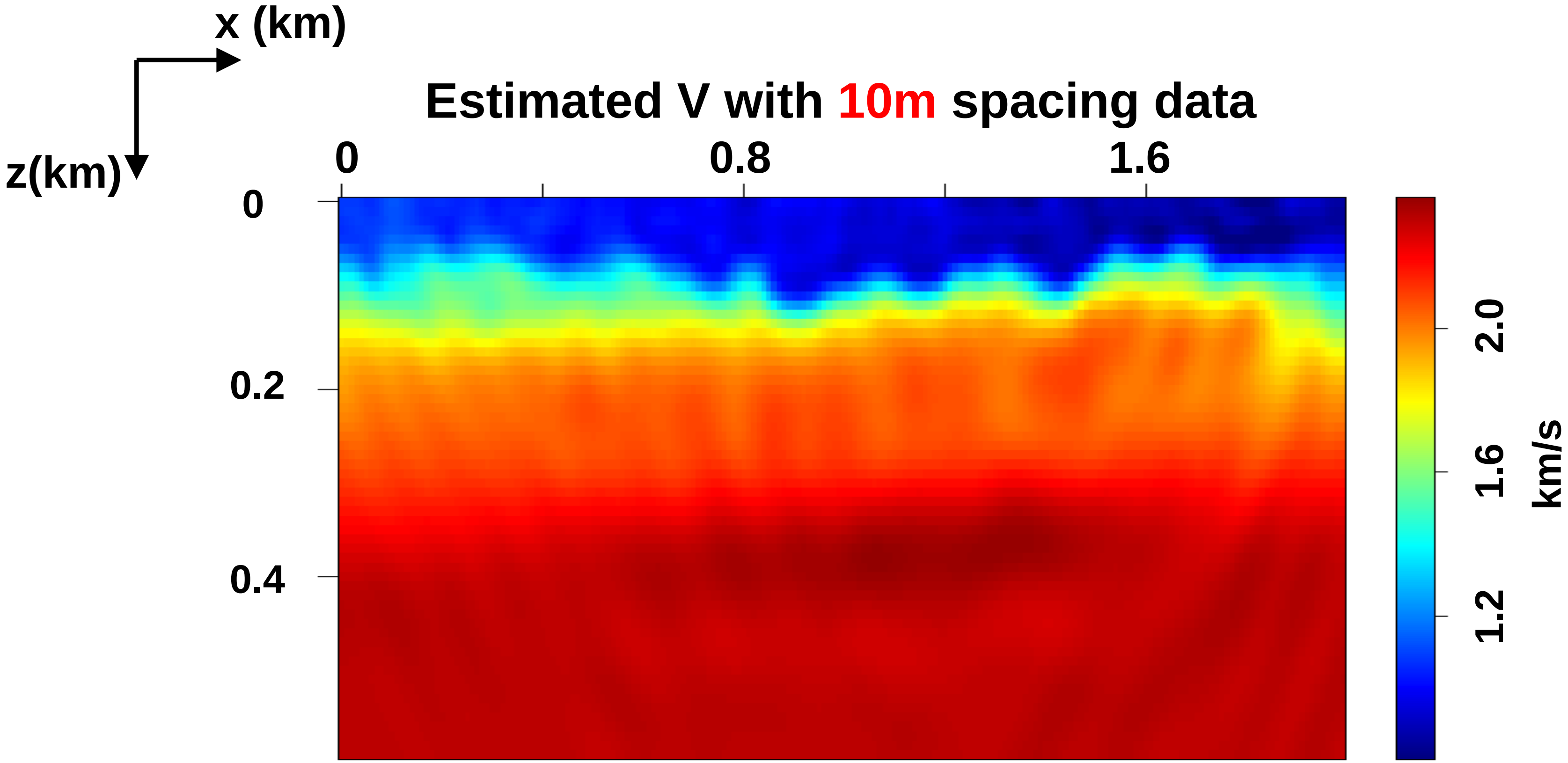

True model

Data spatial density effect

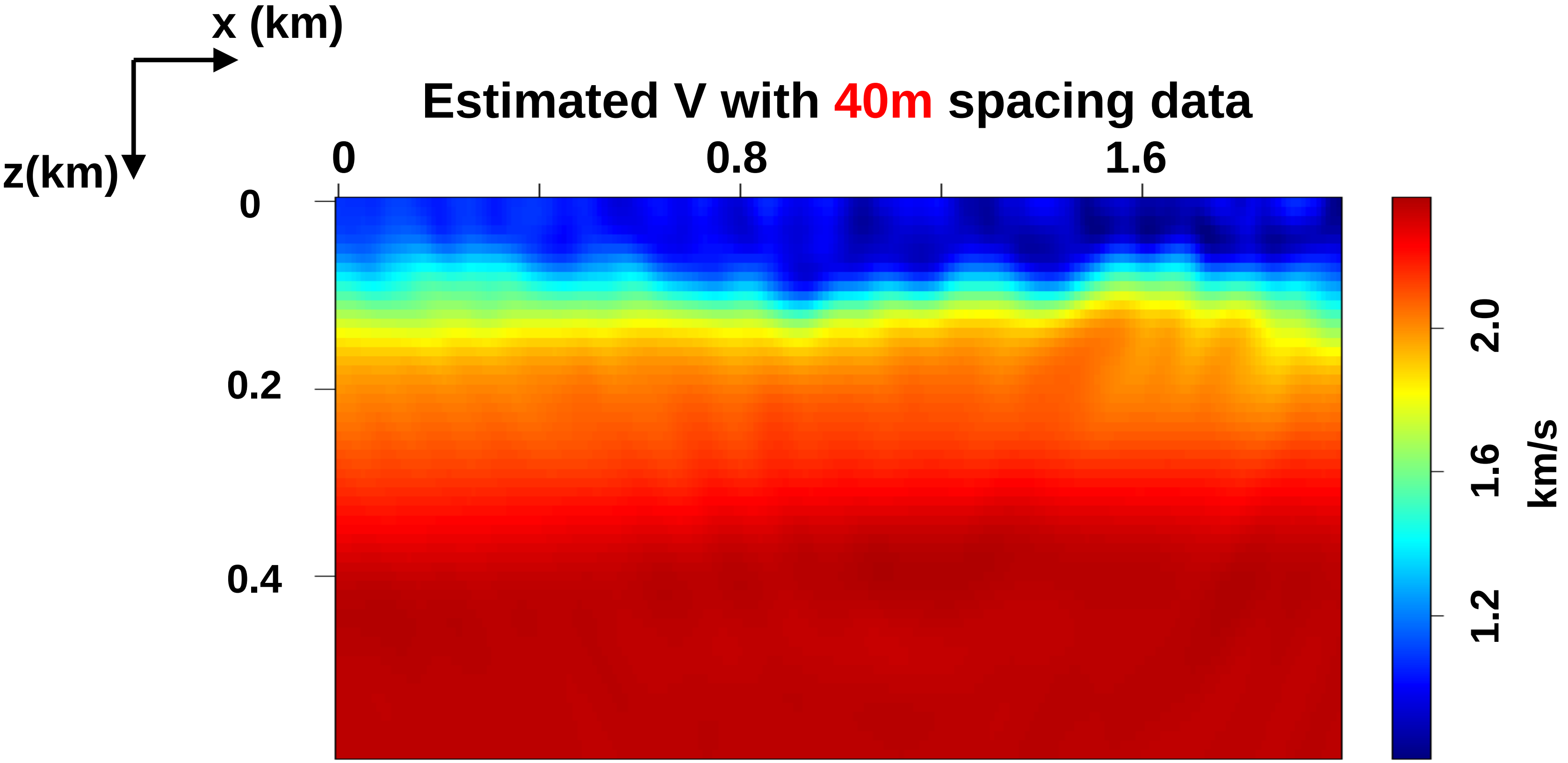


Start model

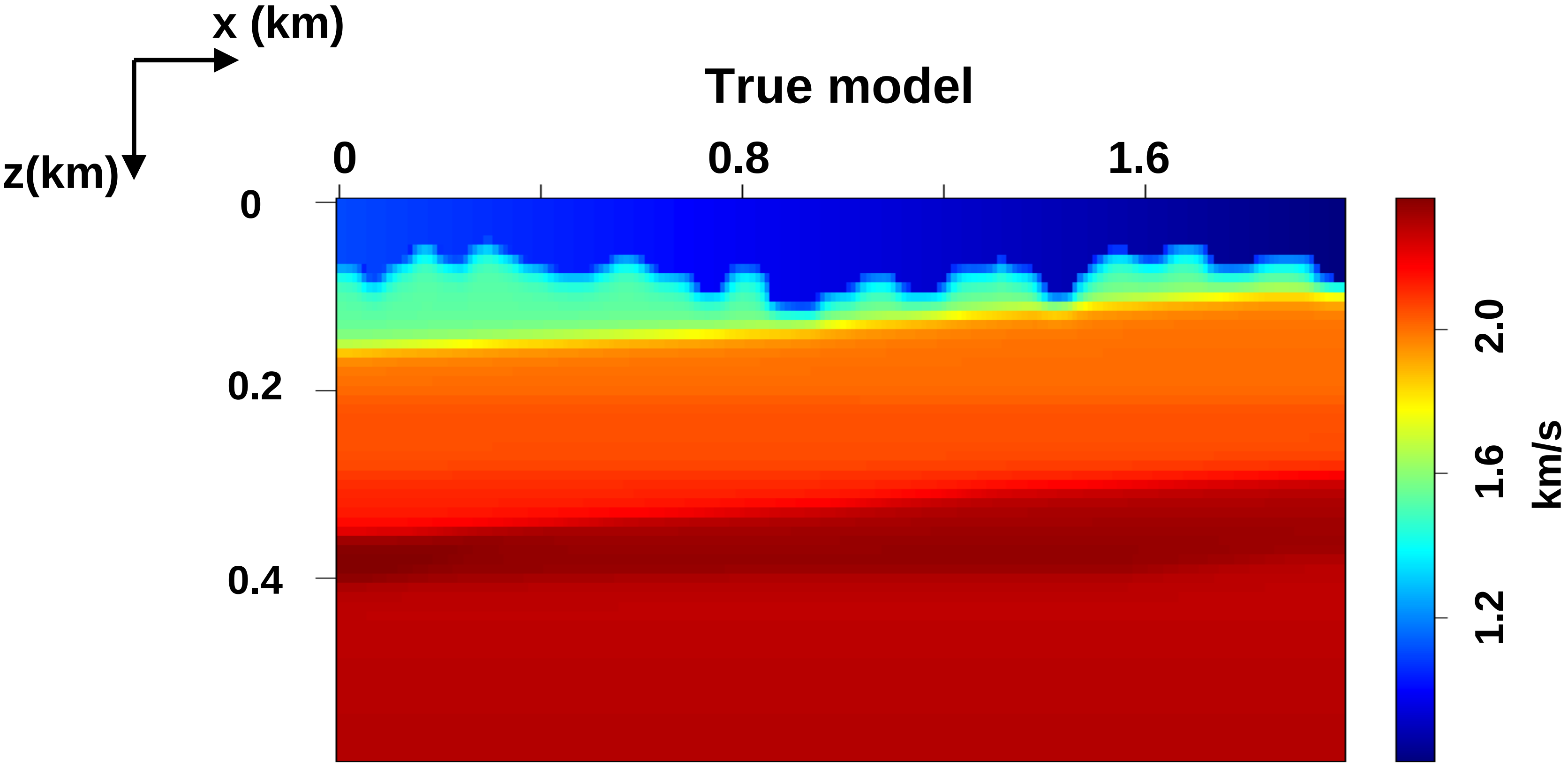
Data spatial density effect



Data spatial density effect


Estimated V with 40m spacing data

Data spatial density effect



Inversion with different RRSD constraints:

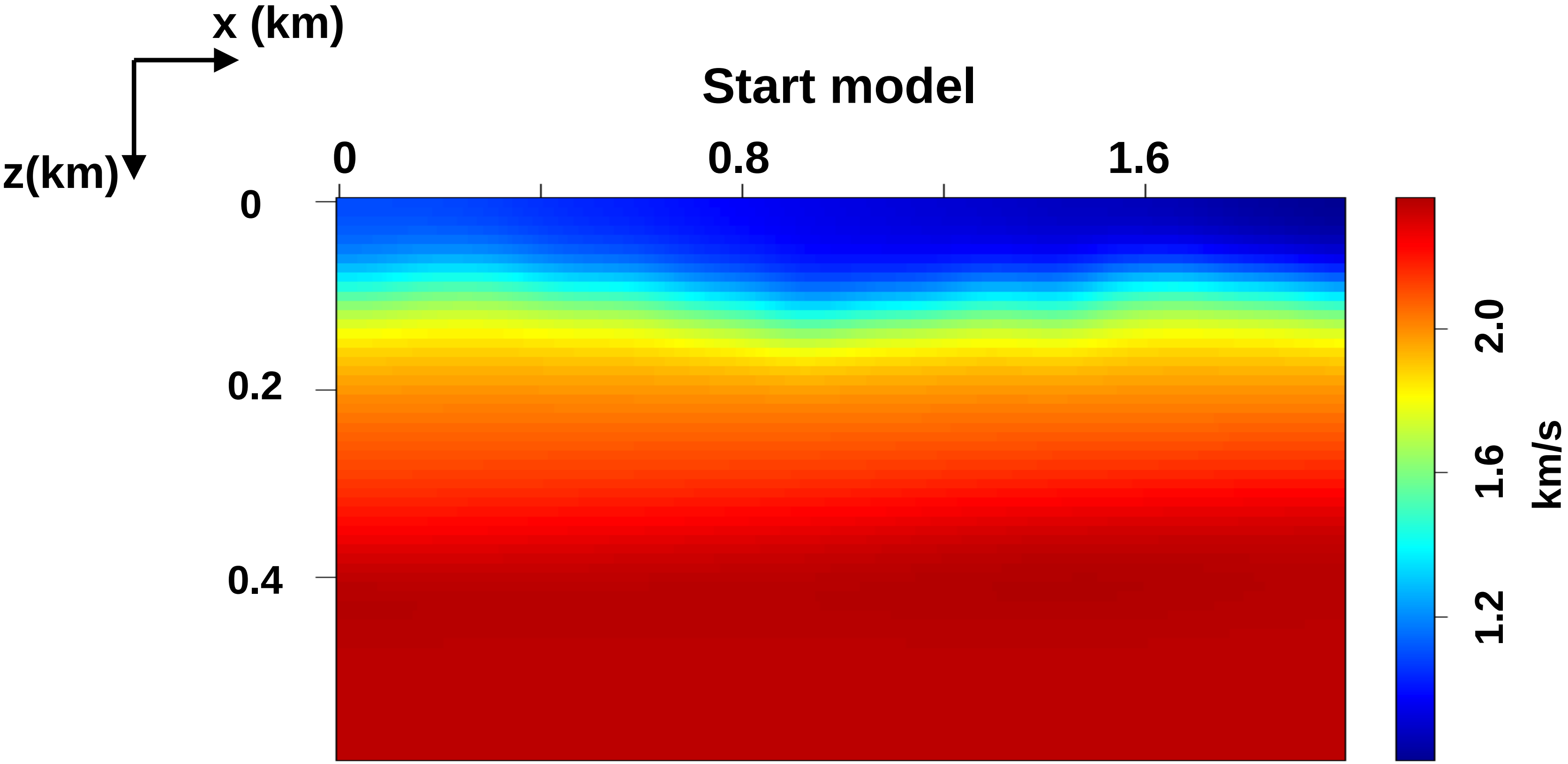
Three different experiments:

- Early arrival waveform inversion alone

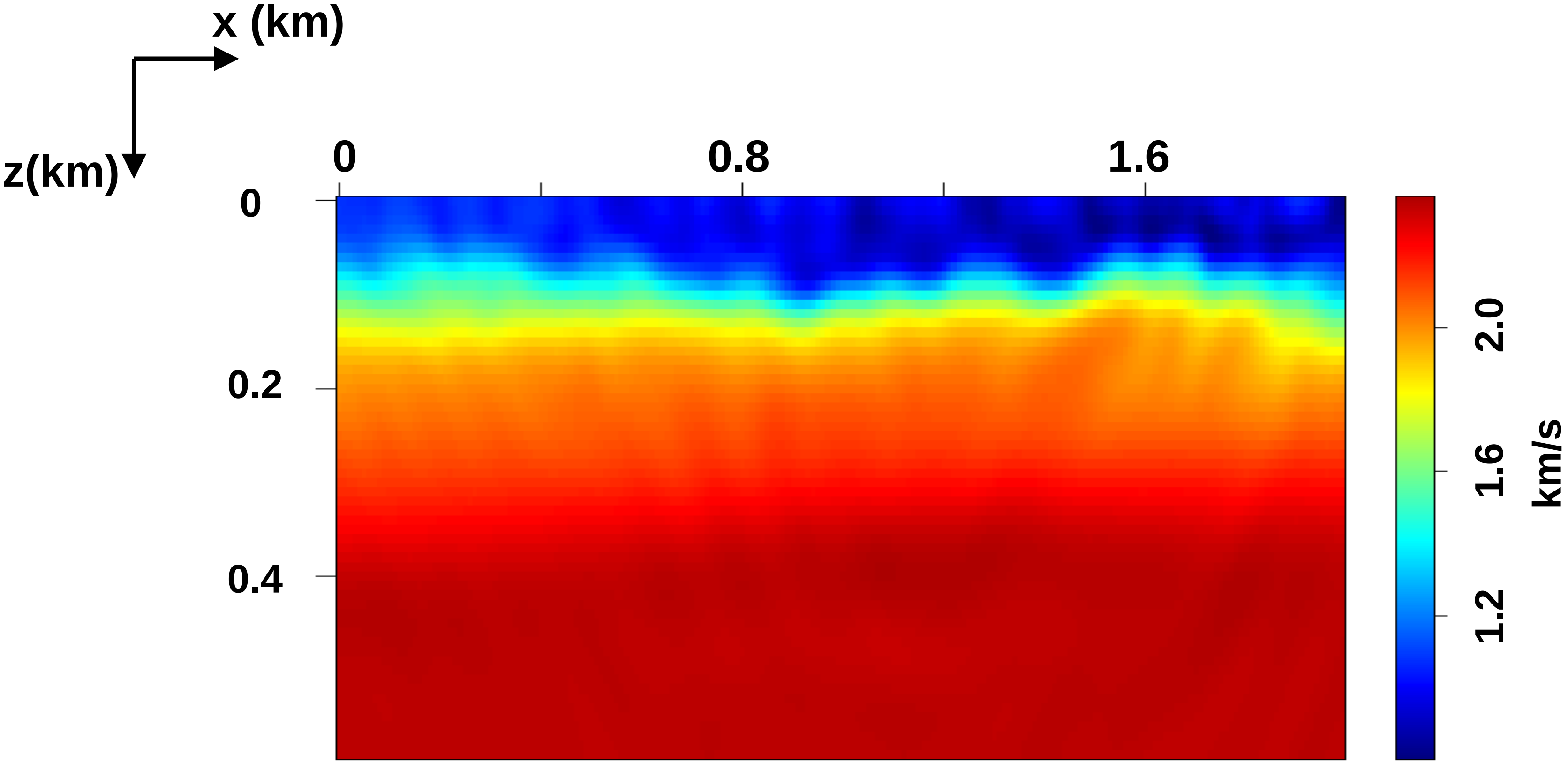
- Two step approach

- Joint inversion

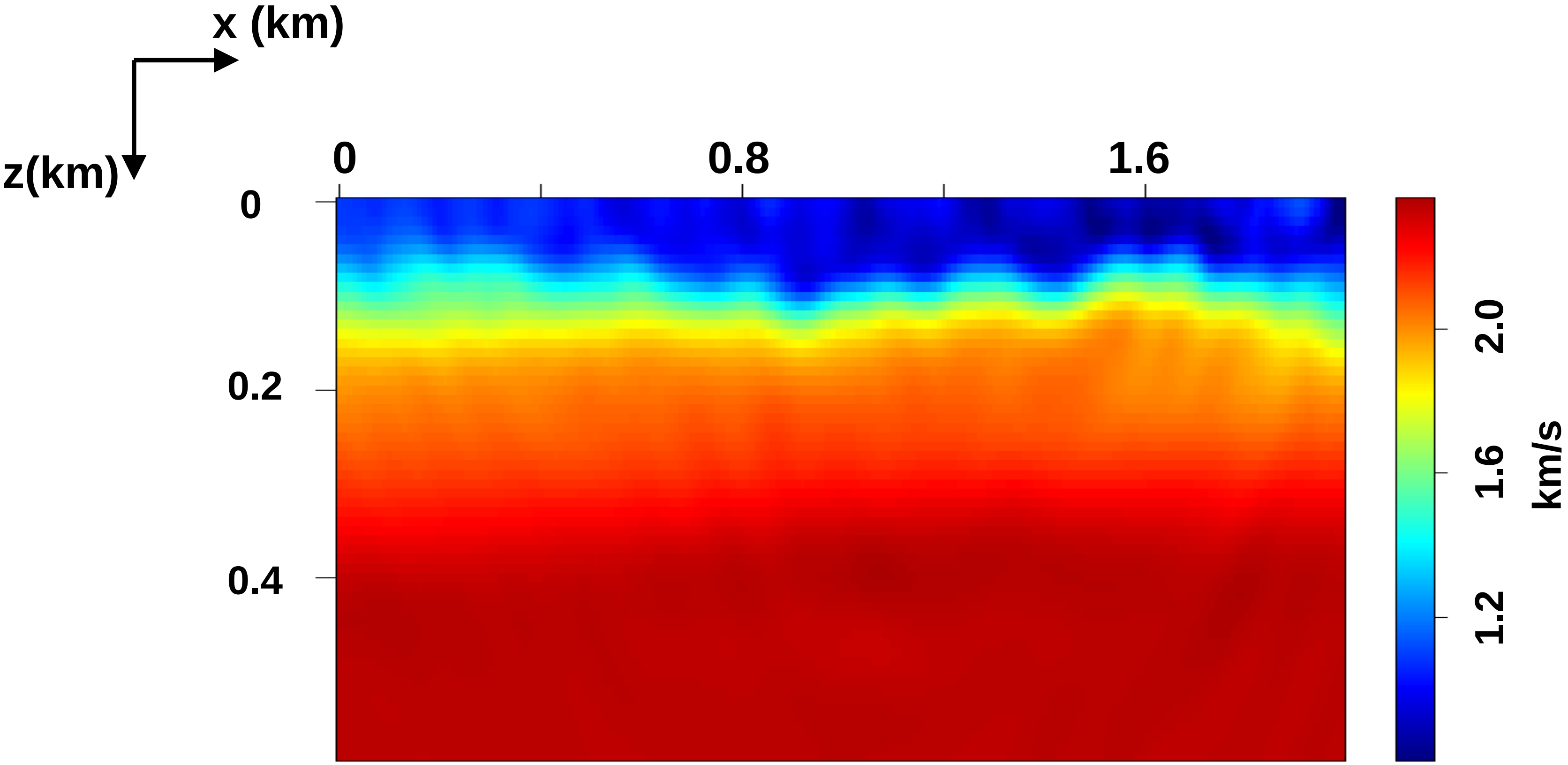
Inversion with different RRSD constraints:



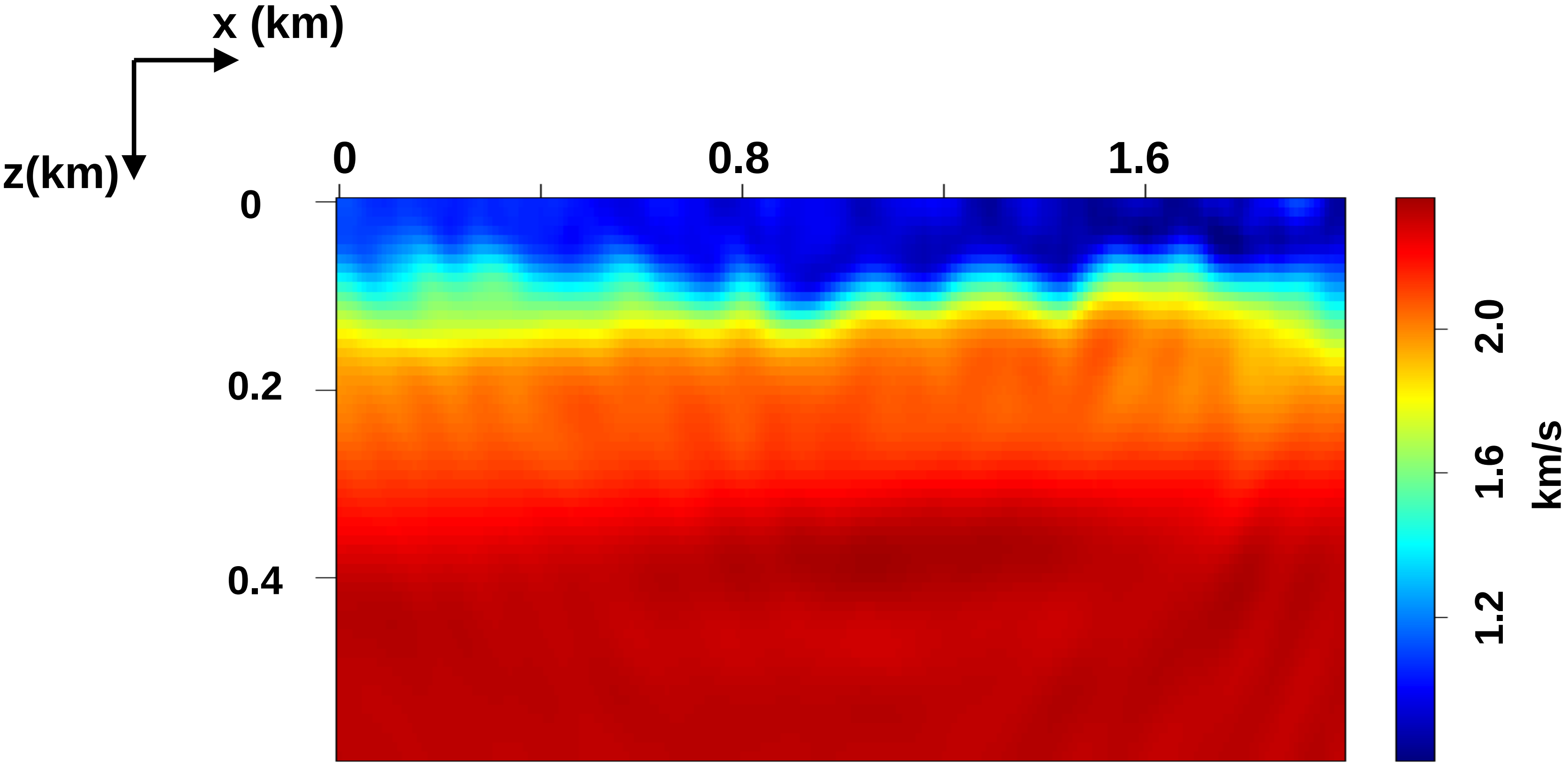
Inversion without RRSD constraints:



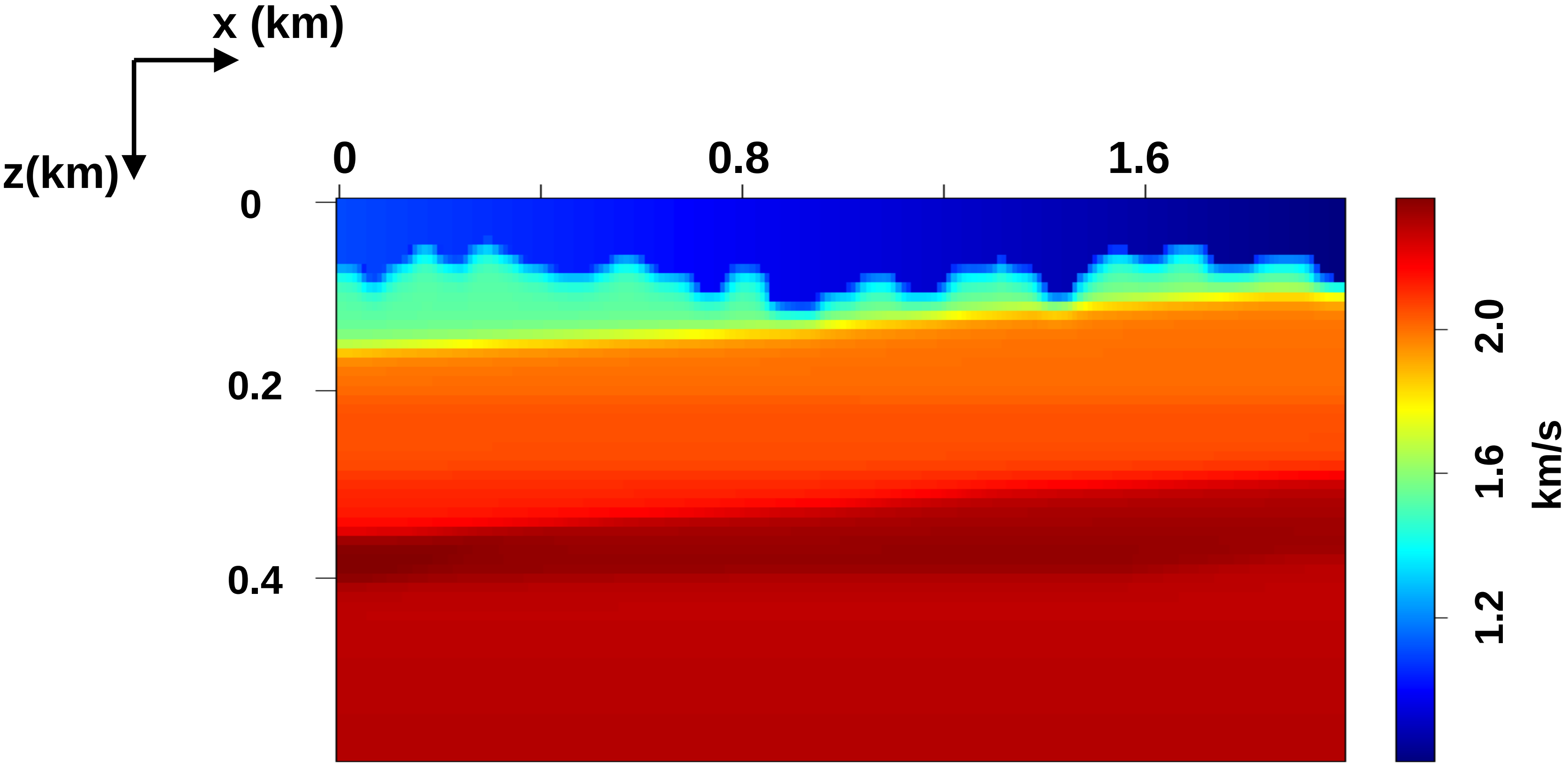
Inversion with two-step approach:



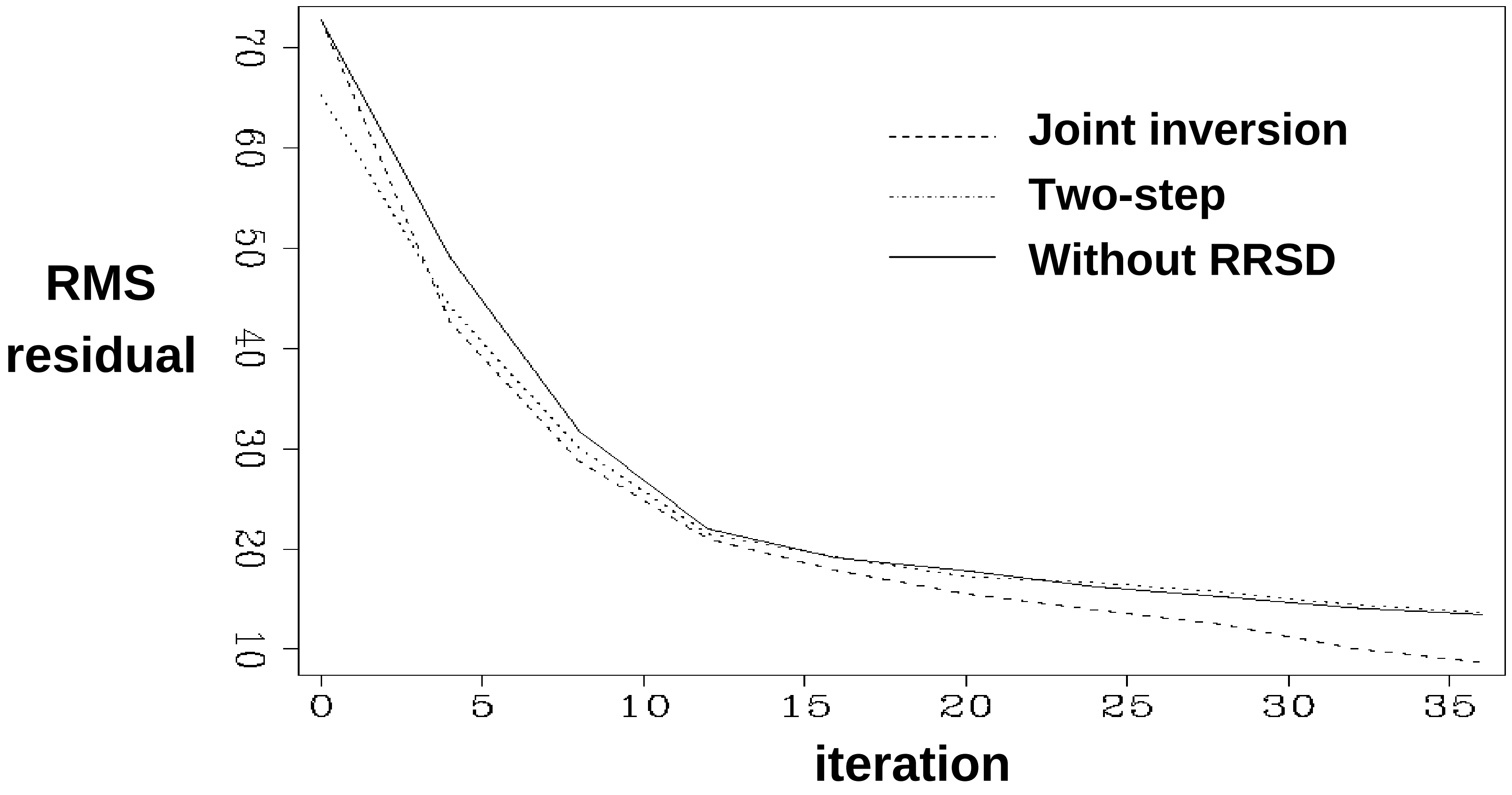
Inversion with joint inversion:



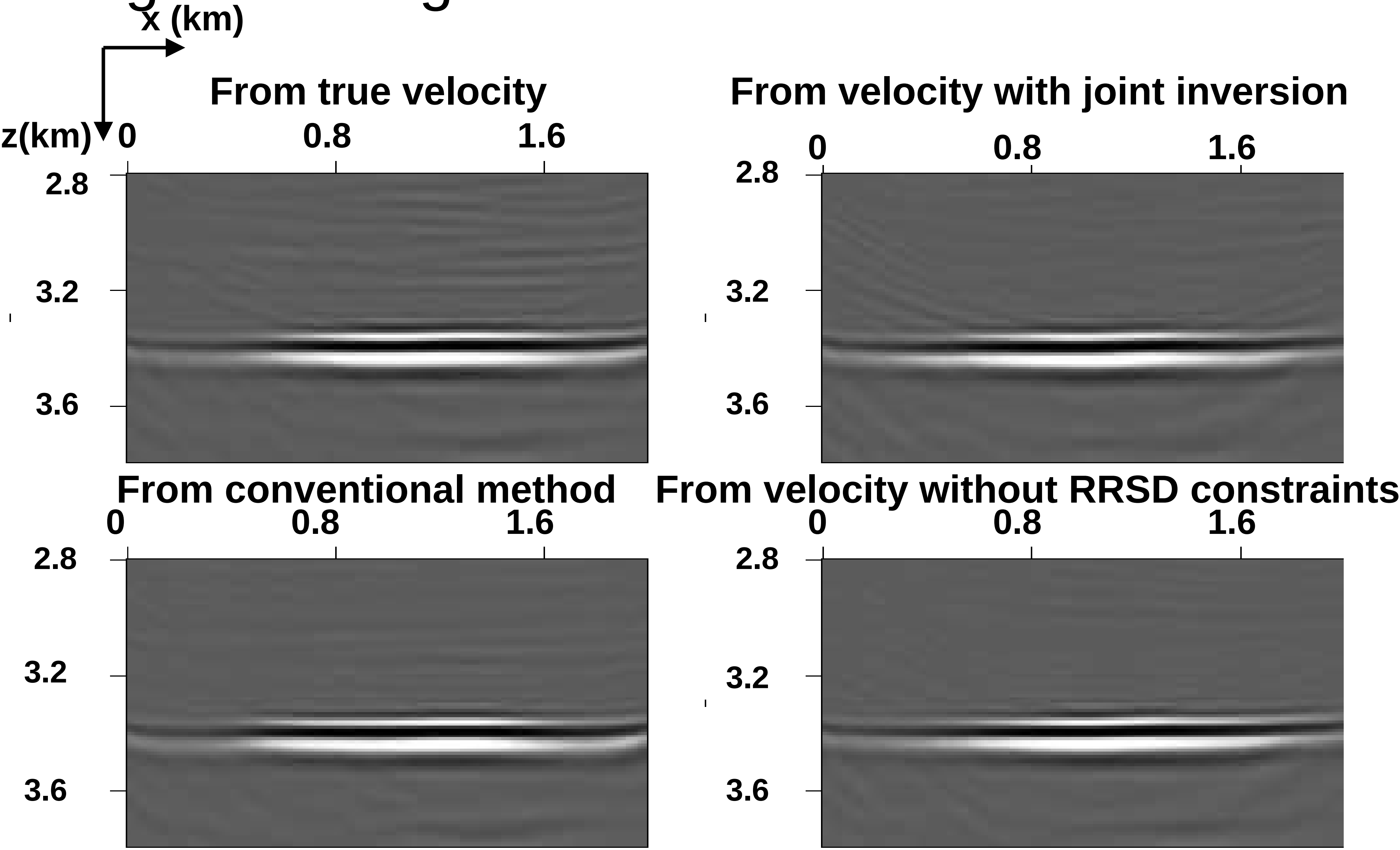
True model:



Inversion with different RRSD constraints: RMS residual of wavefield



Migrated images :



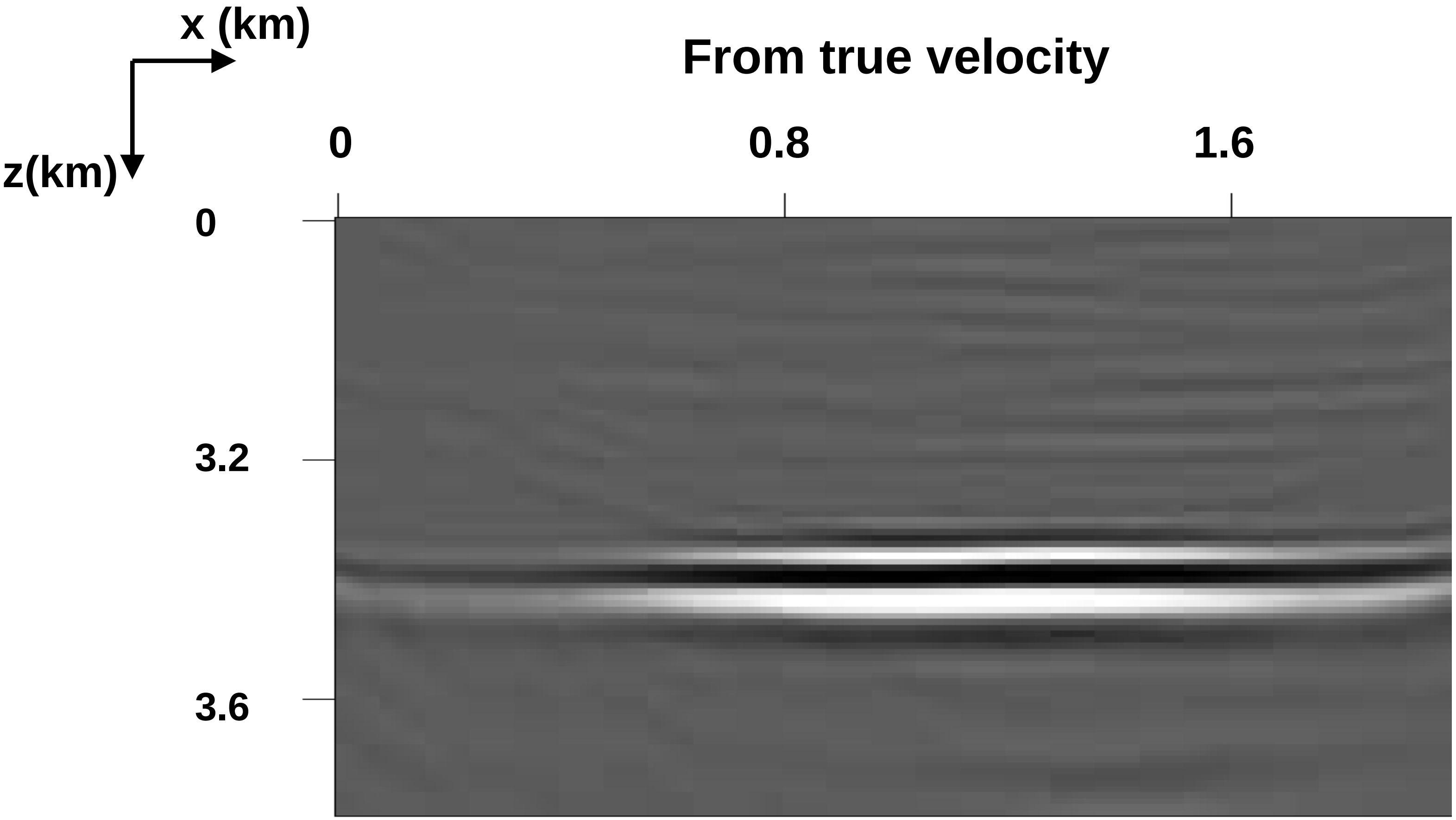
From true velocity

From velocity with joint inversion

From conventional method

From velocity without RRSD constraints

Migrated images :



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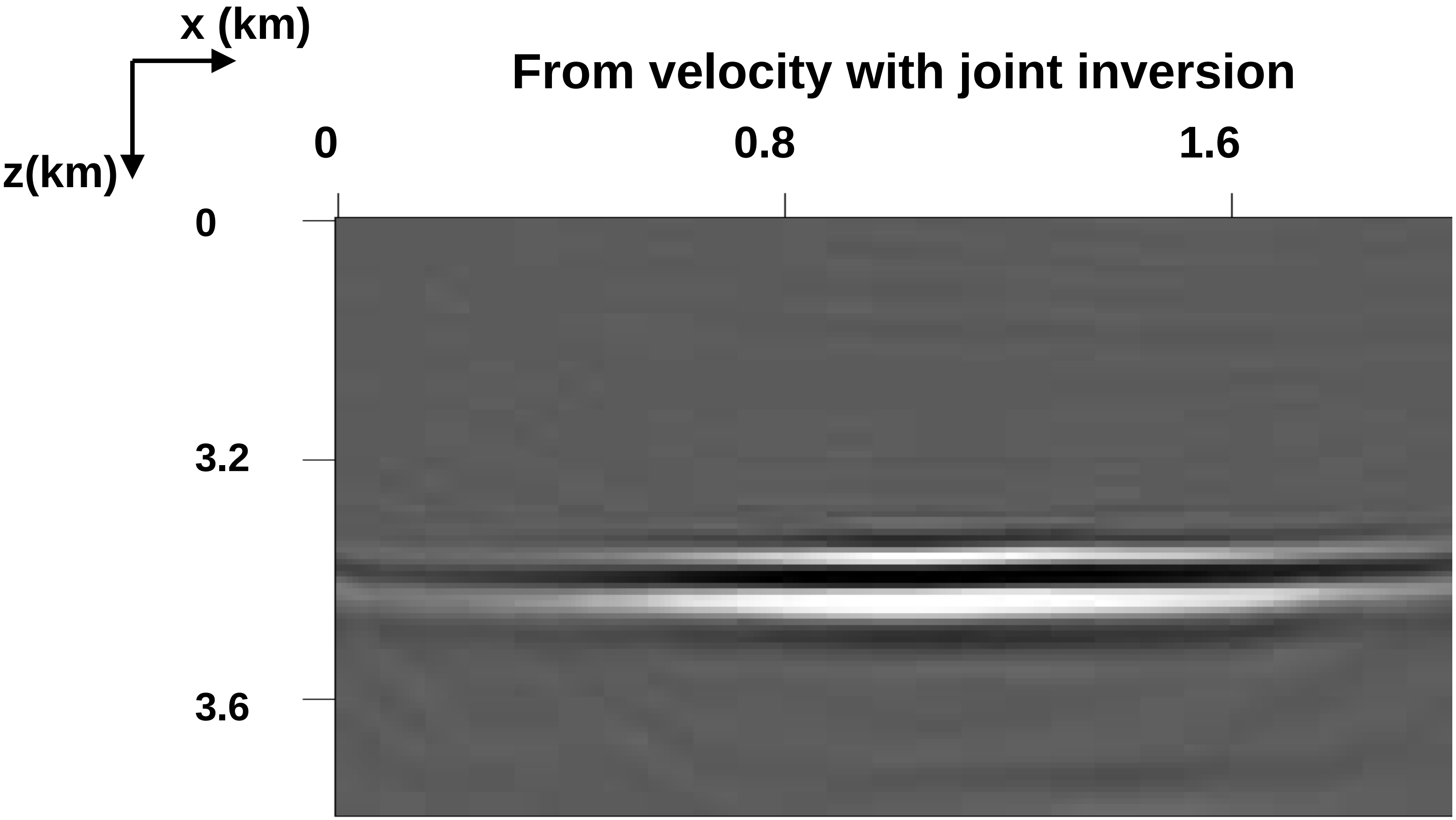

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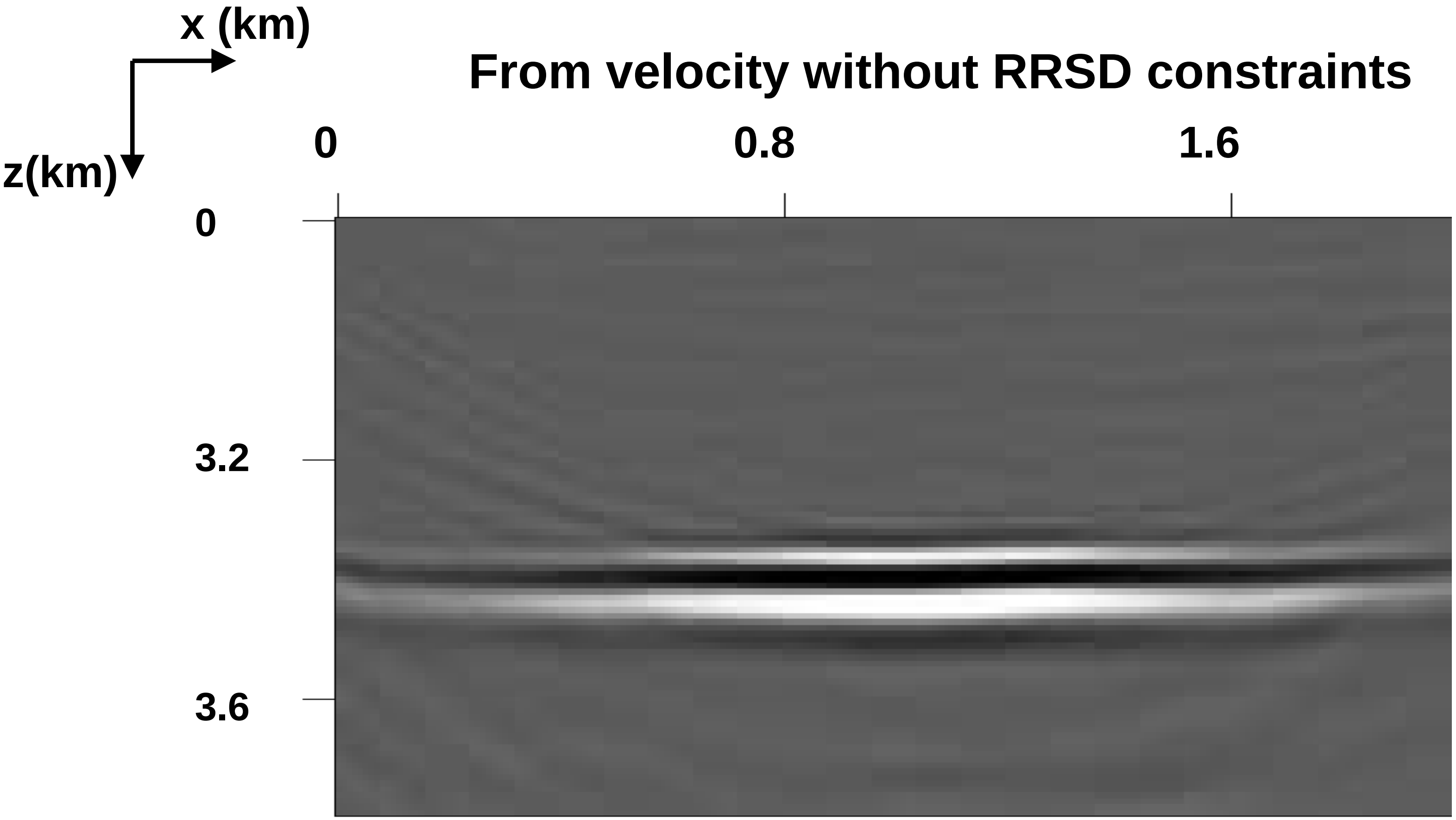

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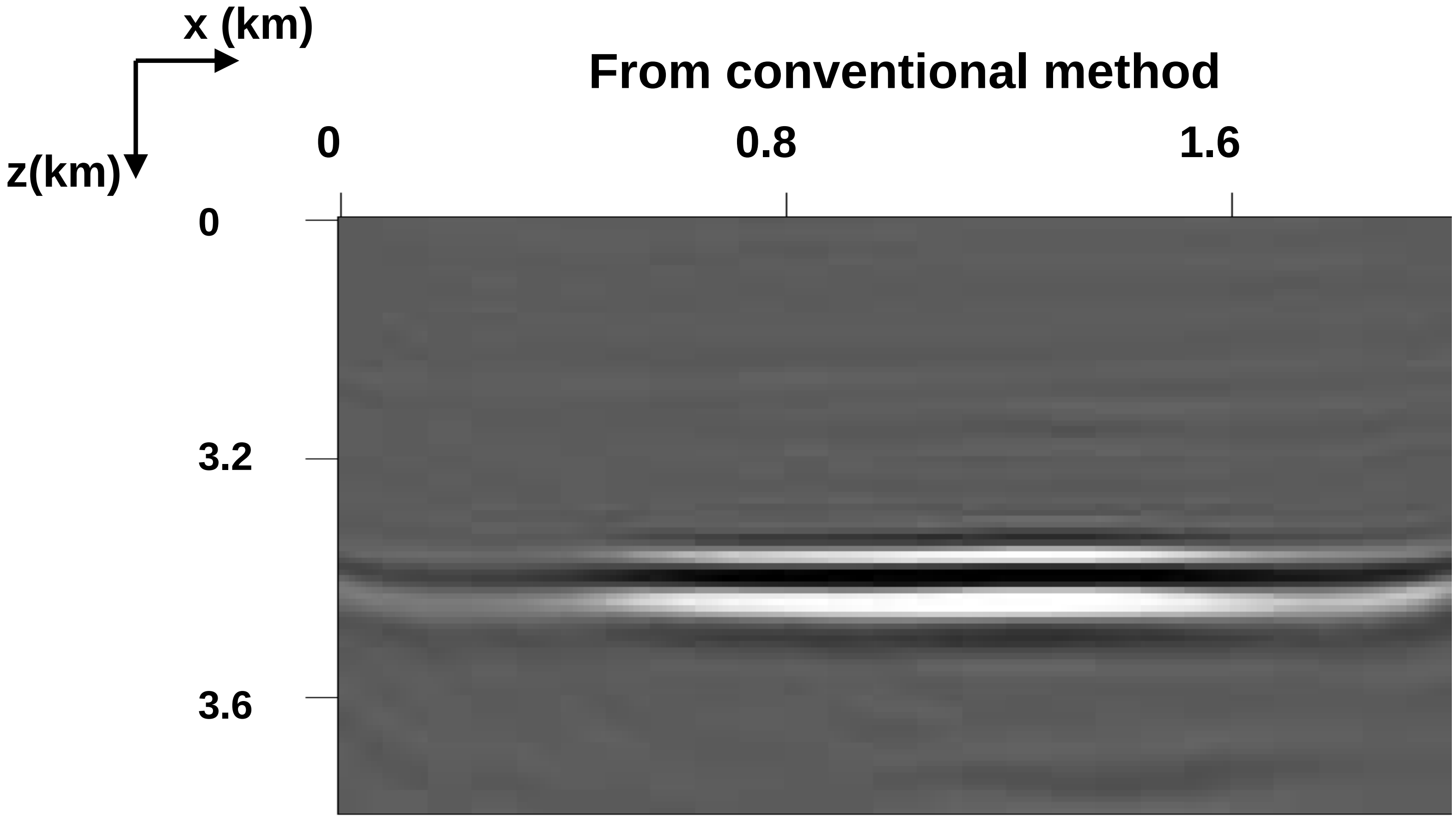

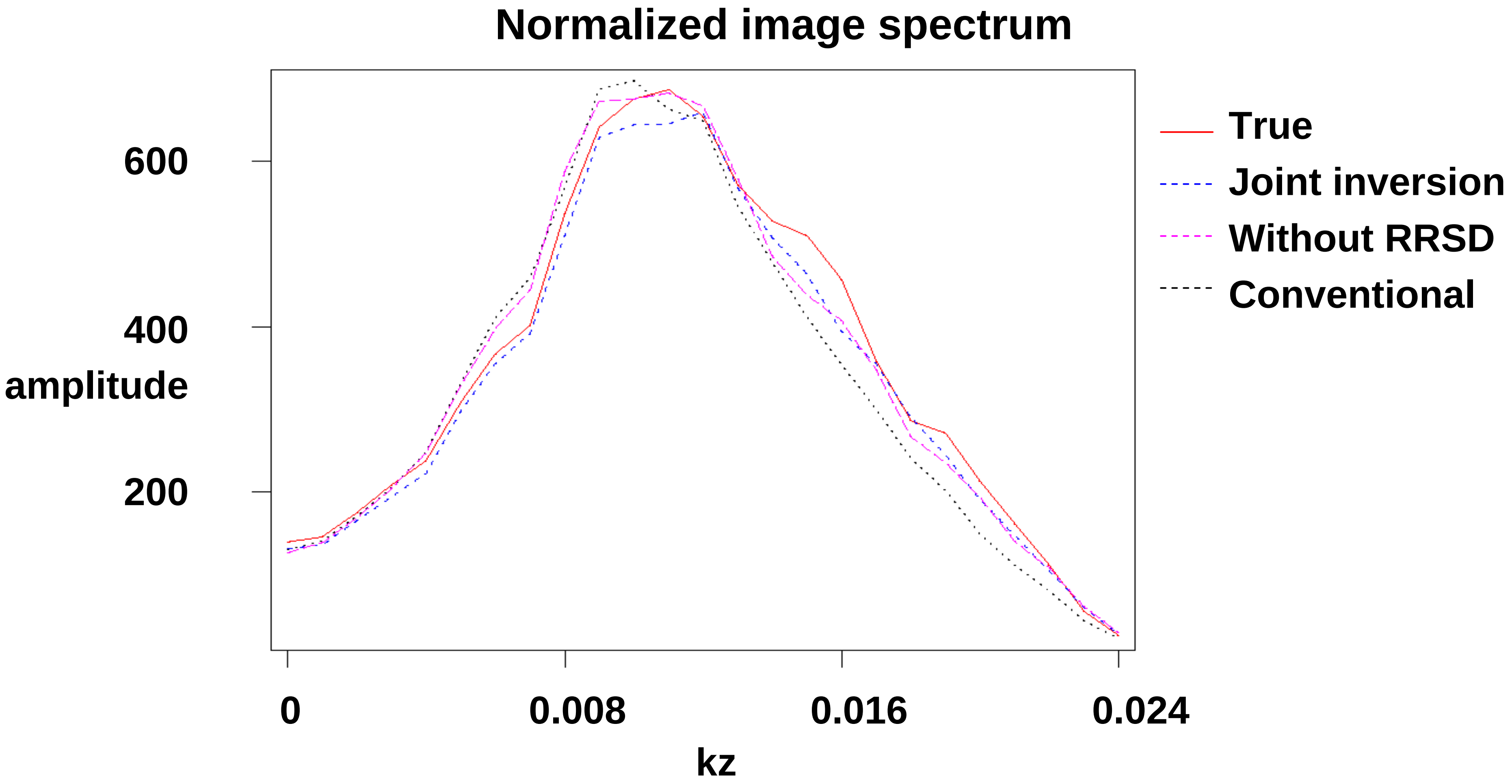
Normalized image spectrum
600
400
200
amplitude
0
0.008
0.016
0.024
kz
True
Joint inversion
Without RRSD
Conventional

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- Conventional processing produces a lower resolution image

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- Early-arrival waveform inversion can provide high resolution velocity estimation if data are dense enough

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- Early-arrival waveform inversion can provide high resolution velocity estimation if data are dense enough
- RRSD constraints can increase the resolution of estimated velocity when data are not spatially dense enough

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- Test algorithm on more complex examples
- Devise new objective function that is less sensitive to amplitude
- Speedup algorithm by parallelizing on GPUs (single GPU version up and running)

Acknowledgments

- Biondo, Bob, Shuki, Antoine, Jon for useful discussions, Bob for numerous debugging suggestions
- Other SEP members for various suggestions