M-OSRP
Misson - Oriented Seismic Research Program
Solve The Right Problem

The first multi-dimensional ISS internal-multiple-elimination method: A new toolbox option for removing internal multiples that interfere with primaries, without damaging the primary, and without any knowledge of, and need for, subsurface information

Yanglei Zou, Chao Ma and Arthur B. Weglein

June 5, 2018

ISS internal multiple attenuation algorithm

Araújo et al. (1994),Weglein et al. (1997),Weglein et al. (2003)

$$
\begin{aligned}
b_3(k_g, k_s, q_g + q_s) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \mathrm{d}k_1 \, \mathrm{e}^{-\mathrm{i}q_1(\epsilon_g - \epsilon_s)} \, \mathrm{d}k_2 \, \mathrm{e}^{\mathrm{i}q_2(\epsilon_g - \epsilon_s)} \\
\times \int_{-\infty}^{\infty} \mathrm{d}z_1 \, \mathrm{e}^{\mathrm{i}(q_g + q_1)z_1} b_1(k_g, k_1, z_1) \int_{-\infty}^{z_1} \mathrm{d}z_2 \, \mathrm{e}^{\mathrm{i}(-q_1 - q_2)z_2} b_1(k_1, k_2, z_2) \\
\times \int_{z_2}^{\infty} \mathrm{d}z_3 \, \mathrm{e}^{\mathrm{i}(q_2 + q_s)z_3} b_1(k_2, k_s, z_3),
\end{aligned}
$$

It is the only internal multiple removal method that does not require subsurface information.

Partial list of those applying ISS internal multiple attenuation algorithm from M-OSRP

services companies

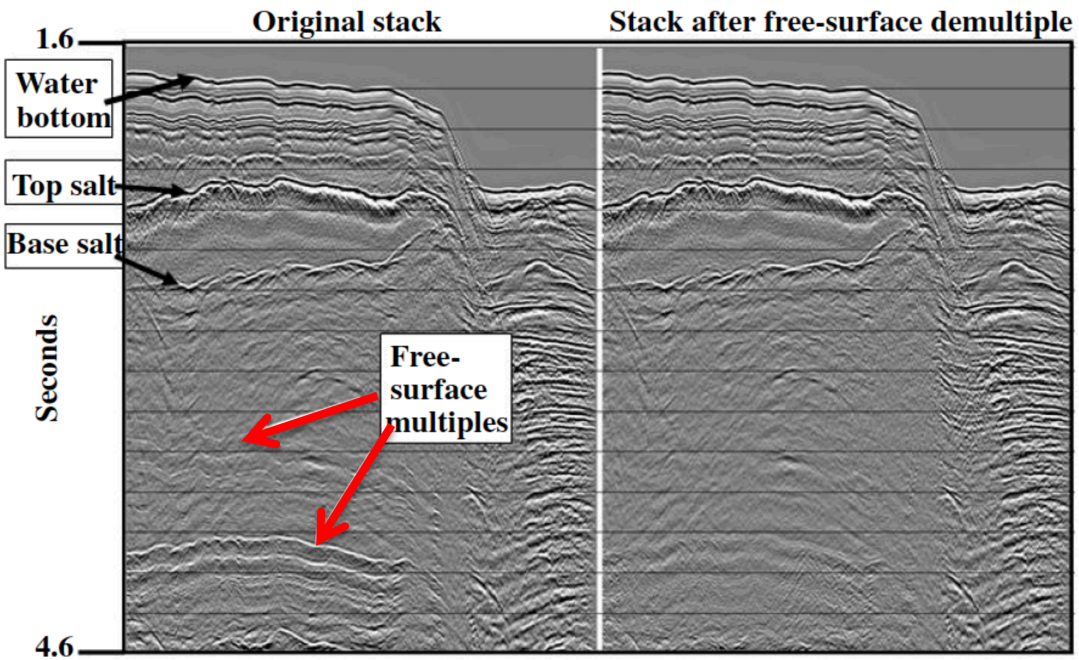
- Dragoset,2013 (Schlumberger)
- Frederico Xavier de Melo et al.,2013 (Schlumberger)
- Griffiths et al., 2013 (CGG)
- Hegge et al.,2013(PGS)
- Hung and Wang, 2014 (CGG)

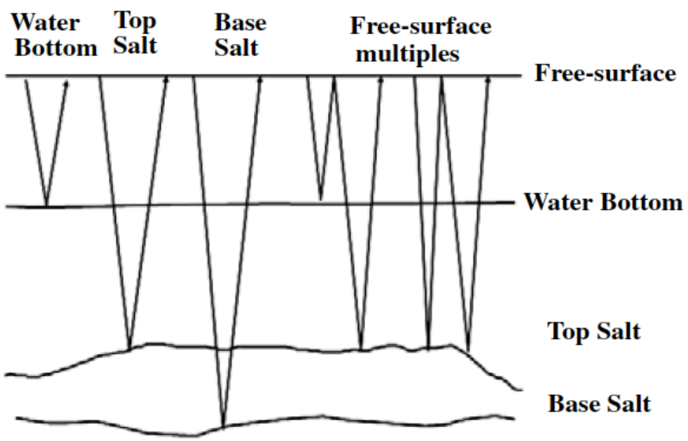
petroleum companies

- Matson et al., 2000 (ARCO) first marine field data test
- Yi Luo et al., 2010 (Aramco) first on-shore field data test
- Qiang Fu et al., 2010 (Aramco/UH)
- Degang Jin et al., 2013 (CNPC)
- Ferreira et al., 2013(Petrobras)
- Goodway (Apache) and Mackidd (Encana), 2013
- Kelamis et al.,2013 (Aramco)

ISS free surface multiple elimination from M-OSRP

Matson et al. (2000),Weglein et al.(2003)





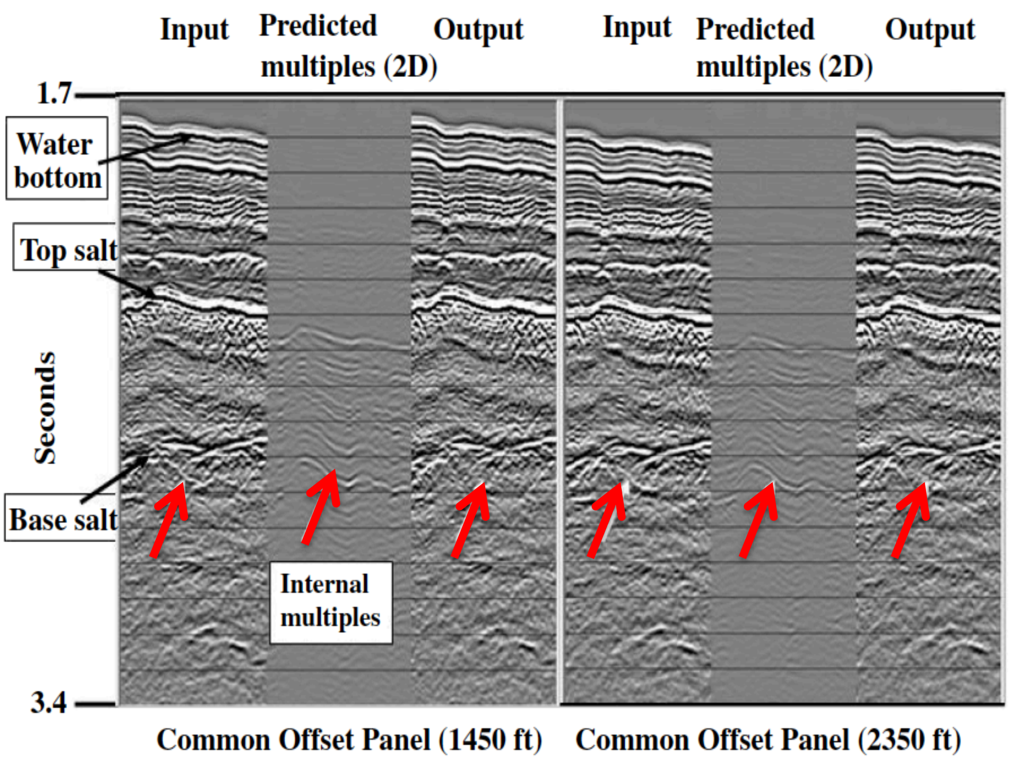
The left panel is a stack of a field data set from the Gulf of Mexico. The right panel is the result of inverse-scattering free-surface multiple removal. Data are courtesy of WesternGeco. *Matson et al. (2000),Weglein et al.(2003)*

A cartoon illustrating the events that are used by the algorithm to predict free-surface multiples. *Weglein et al.*(2003)

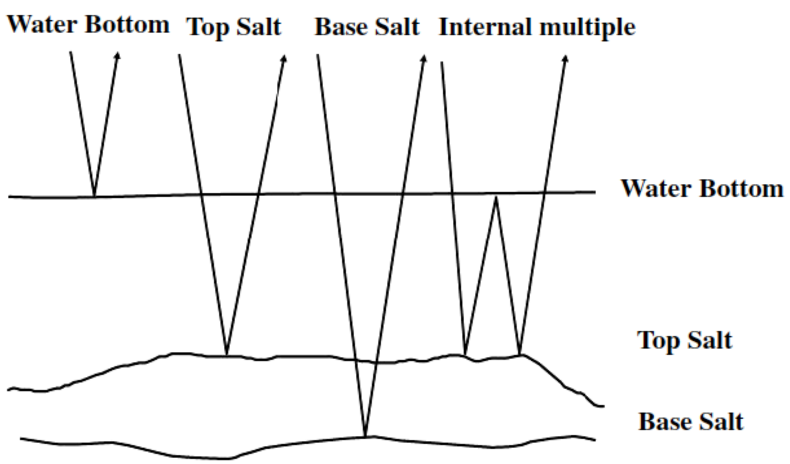
(The first marine field data test for ISS free-surface multiple elimination is Carvalho et al, Nonlinear Inverse Scattering For Multiple Suppression: Application to Real Data, 1992)

ISS internal multiple attenuation from M-OSRP

Matson et al. (2000),Weglein et al.(2003)



An example of inverse-scattering internal multiple attenuation from the Gulf of Mexico. Data are courtesy of WesternGeco. *Matson et al. (2000),Weglein et al.(2003)*



A cartoon illustrating the events that are used by the algorithm to predict a subsalt internal multiple. *Weglein et al.*(2003)

"The encouraging results from the internal multiple attenuation algorithm were run in a reasonable time frame." -*Matson et al. (2000)*

On-shore ISS internal multiple algorithm from M-OSRP

Frederico Xavier de Melo et al.,2013 (Schlumberger)

Cascaded internal multiple attenuation with inverse scattering series: Western Canada case study

Frederico Xavier de Melo, Murad Idris, Zhiming James Wu, Clement Kostov, Schlumberger*

Summary

This work shows a cascaded internal multiple attenuation workflow based on top-down inverse scattering series (ISS) predictions followed by adaptive subtraction. The ISS multiple modeling is purely data driven and does not assume a priori subsurface information such as velocity field and known generating horizons.

3D marine ISS internal multiple algorithm from M-OSRP

M. Wang and B. Hung(CGG)

We E102 06

3D Inverse Scattering Series Method for Internal Multiple Attenuation

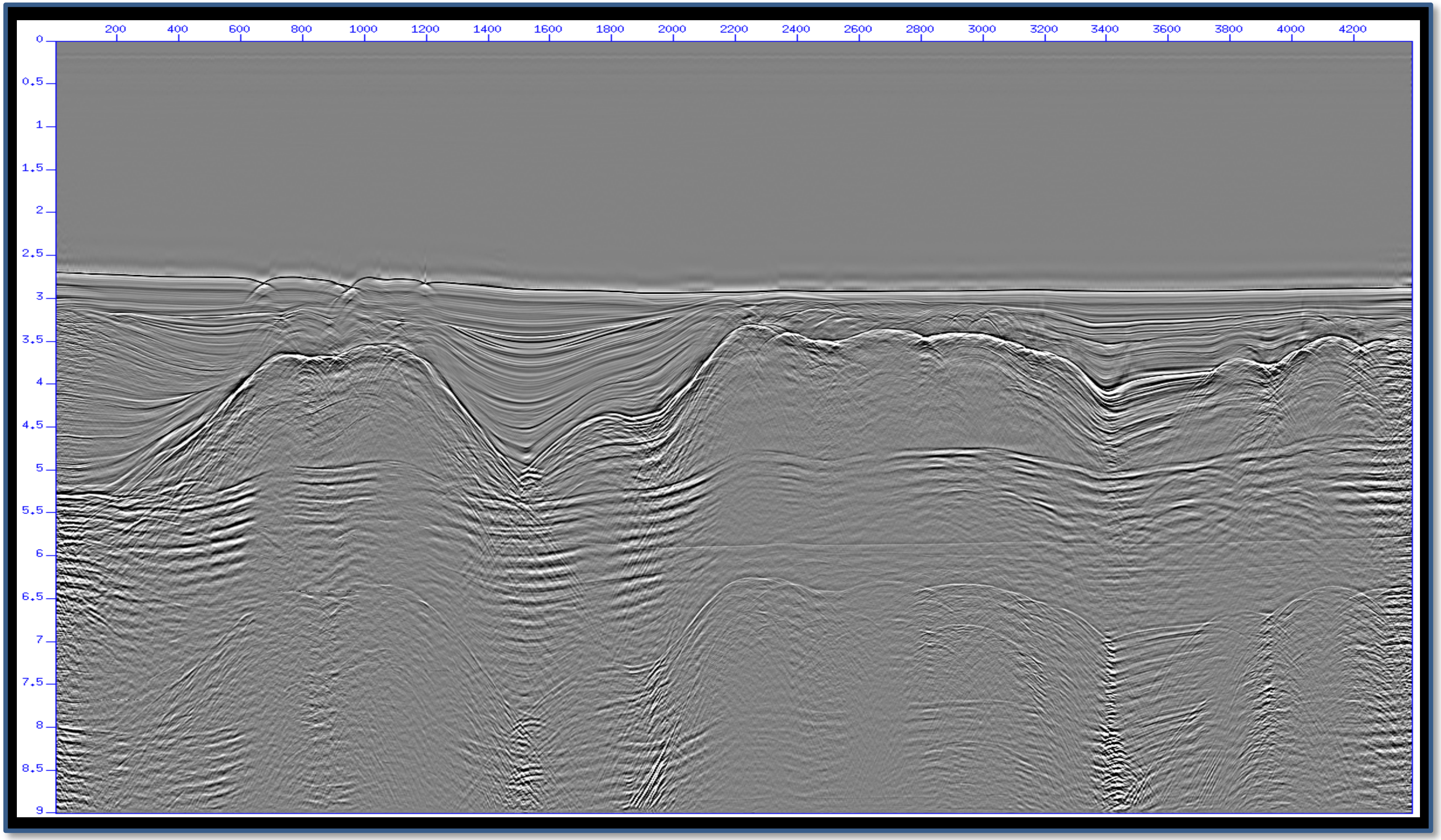
M. Wang* (CGG) & B. Hung (CGG)

SUMMARY

In this paper, we show the first application of the 3D inverse scattering series (ISS) method for internal multiple attenuation. The ISS method is a data-driven approach that can predict all internal multiples without any prior knowledge of subsurface information. We discuss the implementation of the true-azimuth 3D ISS based method which is suitable for conventional streamer data. We apply the approach on a synthetic example as well as data acquired from the Santos Basin, offshore Brazil. The results show that the 3D prediction and subtraction method outperforms the 2D method as it takes into account out-of-plane multiple contributions.

2D marine ISS free surface and internal multiple algorithms from M-OSRP *Andre S. Ferreira (Petrobras)*

- Free surface multiple removal
  - Stack before free surface multiple removal



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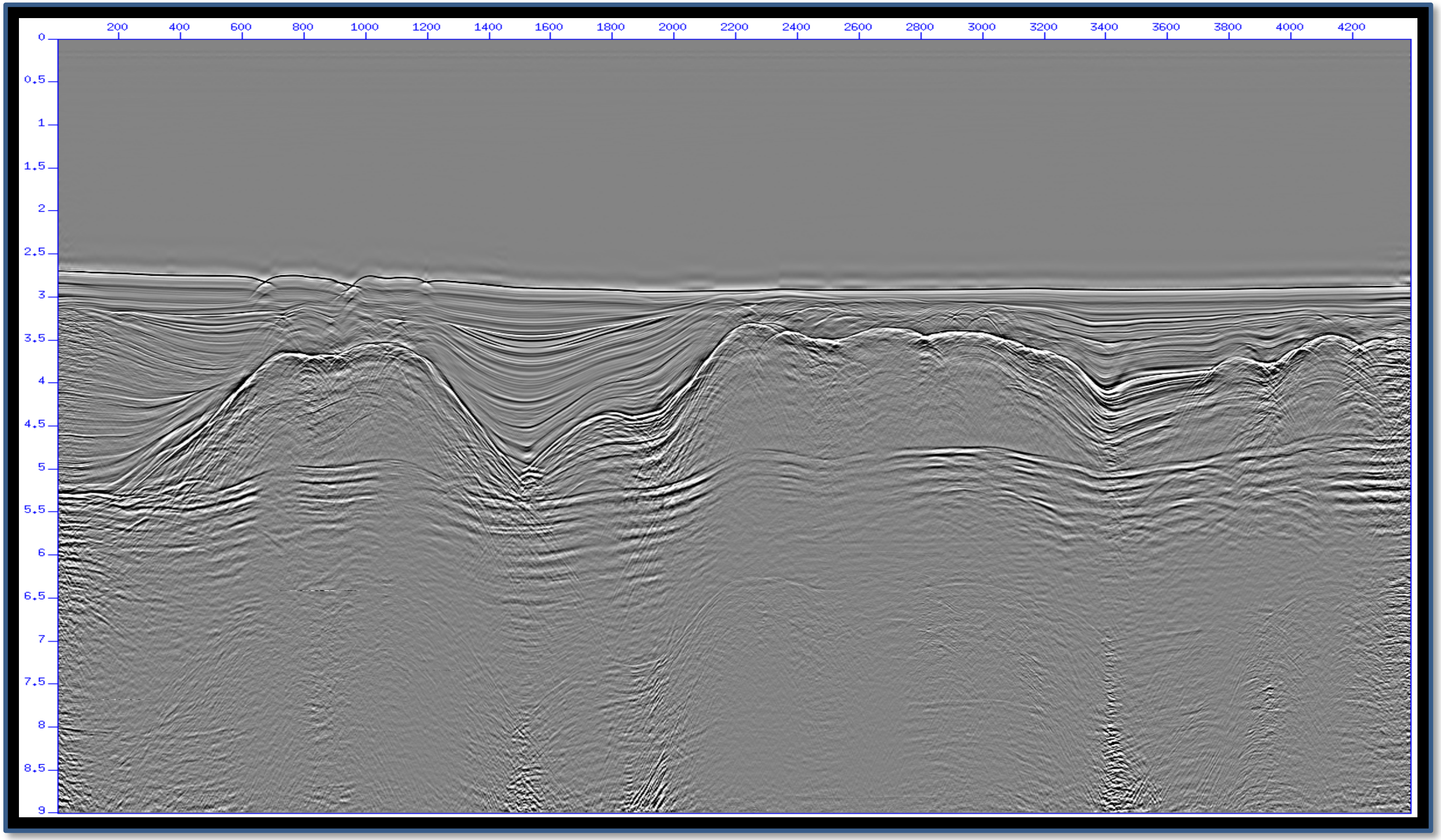
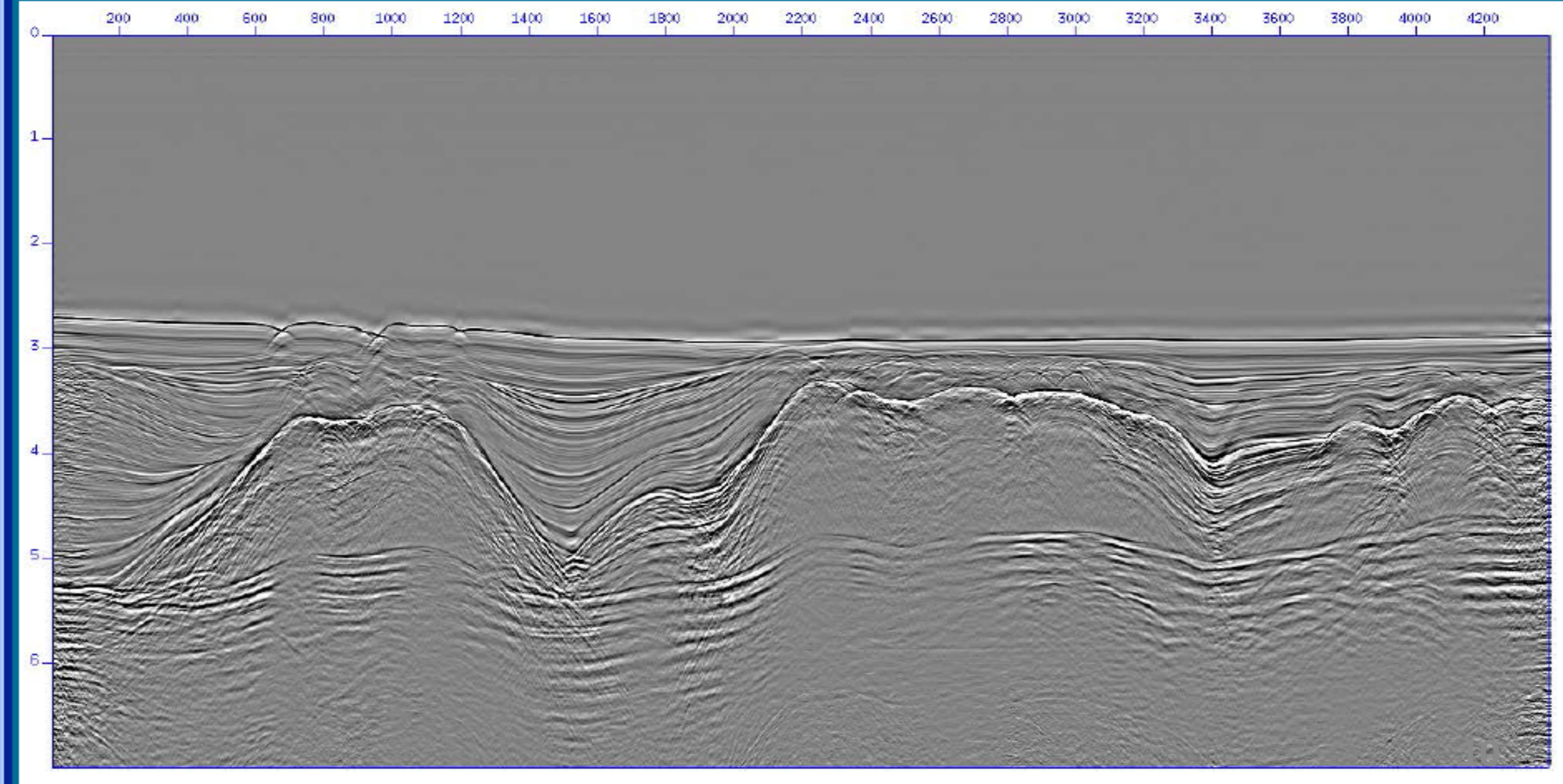


2D marine ISS free surface and internal multiple algorithms from M-OSRP *Andre S. Ferreira (Petrobras)*

Multiple attenuation

- Internal multiple attenuation results (stacked sections)



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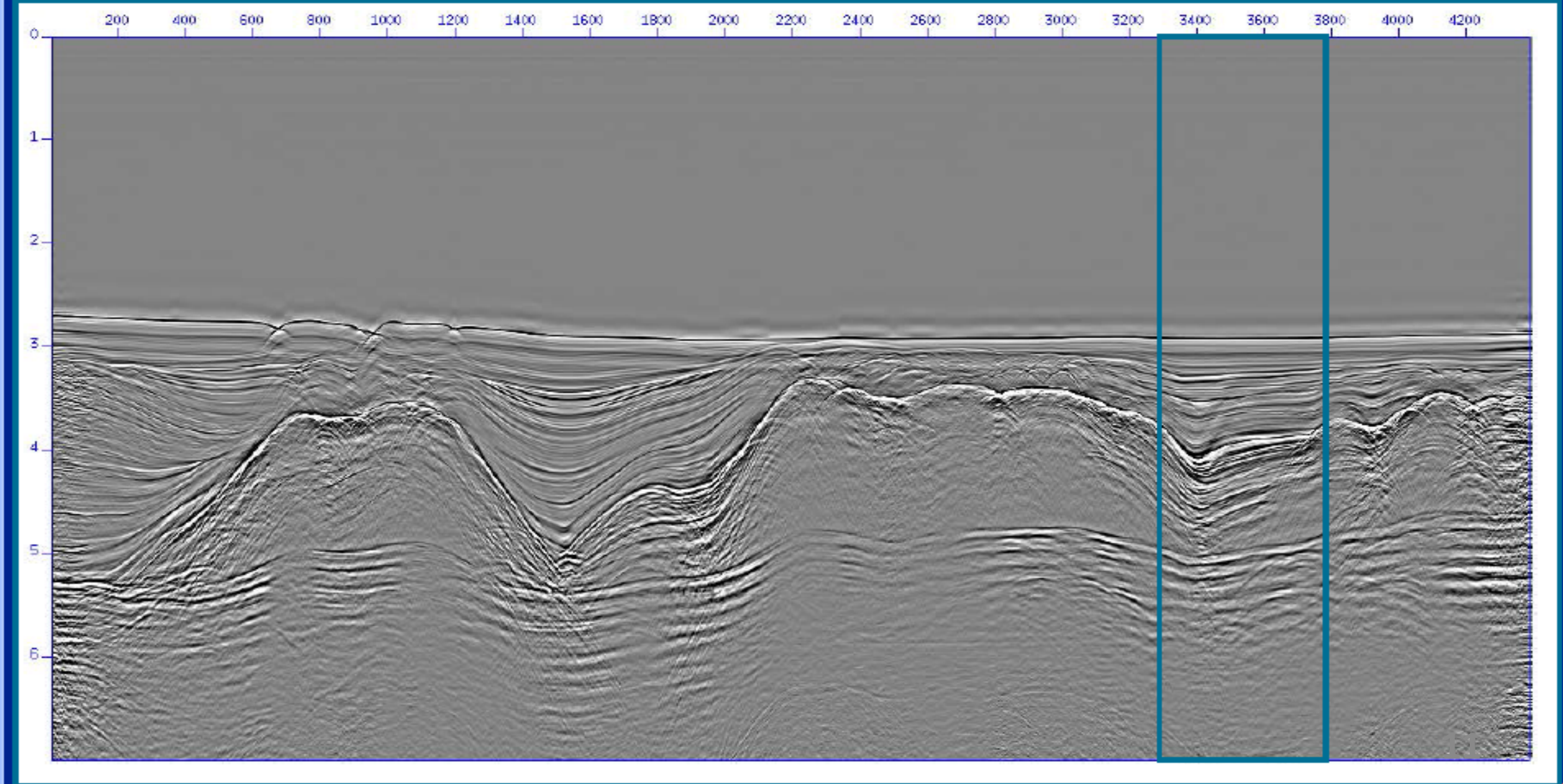

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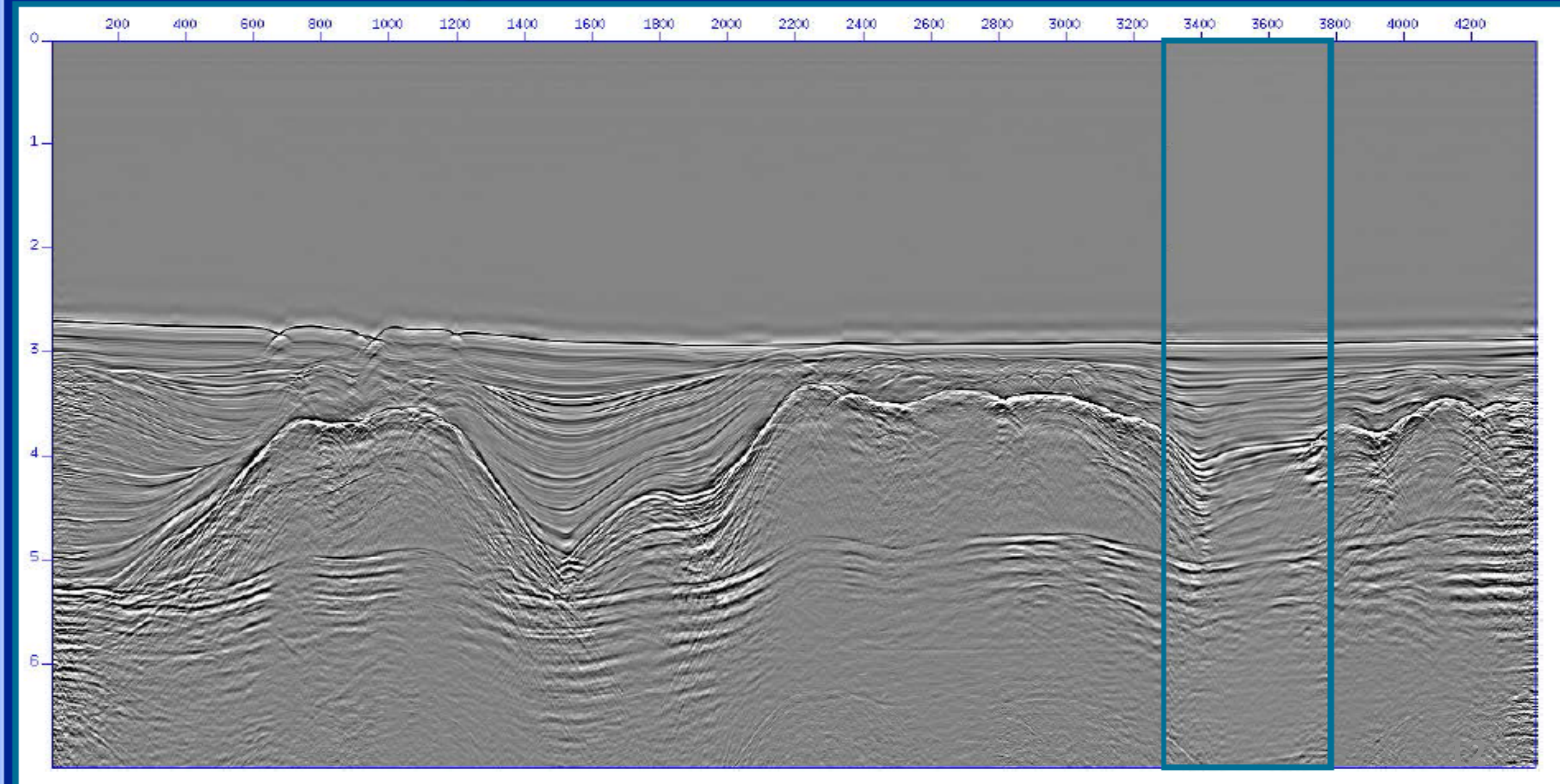


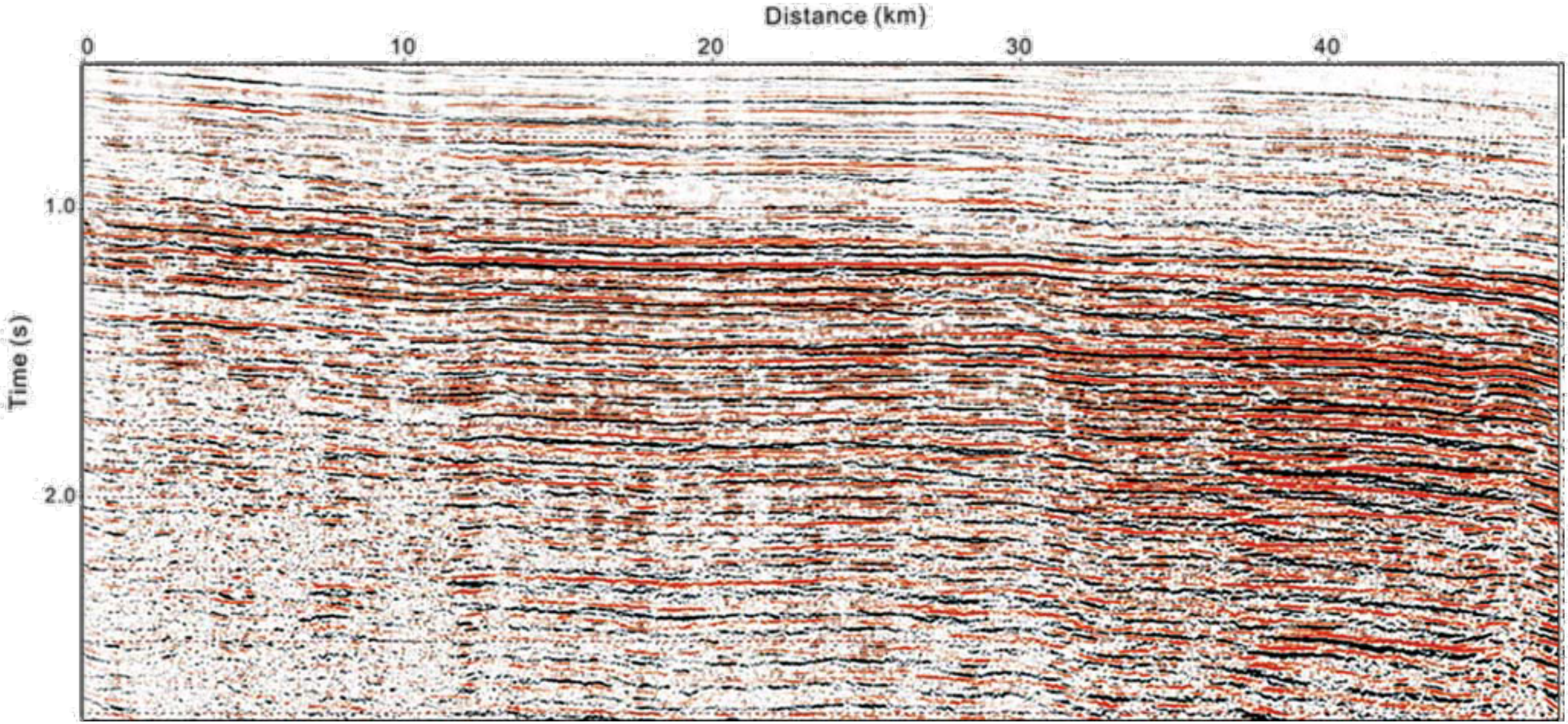
2D marine ISS free surface and internal multiple algorithms from M-OSRP ***Andre S. Ferreira (Petrobras)***

Conclusions

- ISS methods were able to attenuate both free surface and internal multiples in a very complex situation
  - No a priori information about the dataset is necessary
  - No other tested method was able to attenuate the sequence of internal multiples below the salt layers
  - High computer cost (internal multiples)
  - Adaptive subtraction requirement

Yi Luo et al.,(Aramco) Qiang Fu et al., (Aramco/UH)

1D land field data test

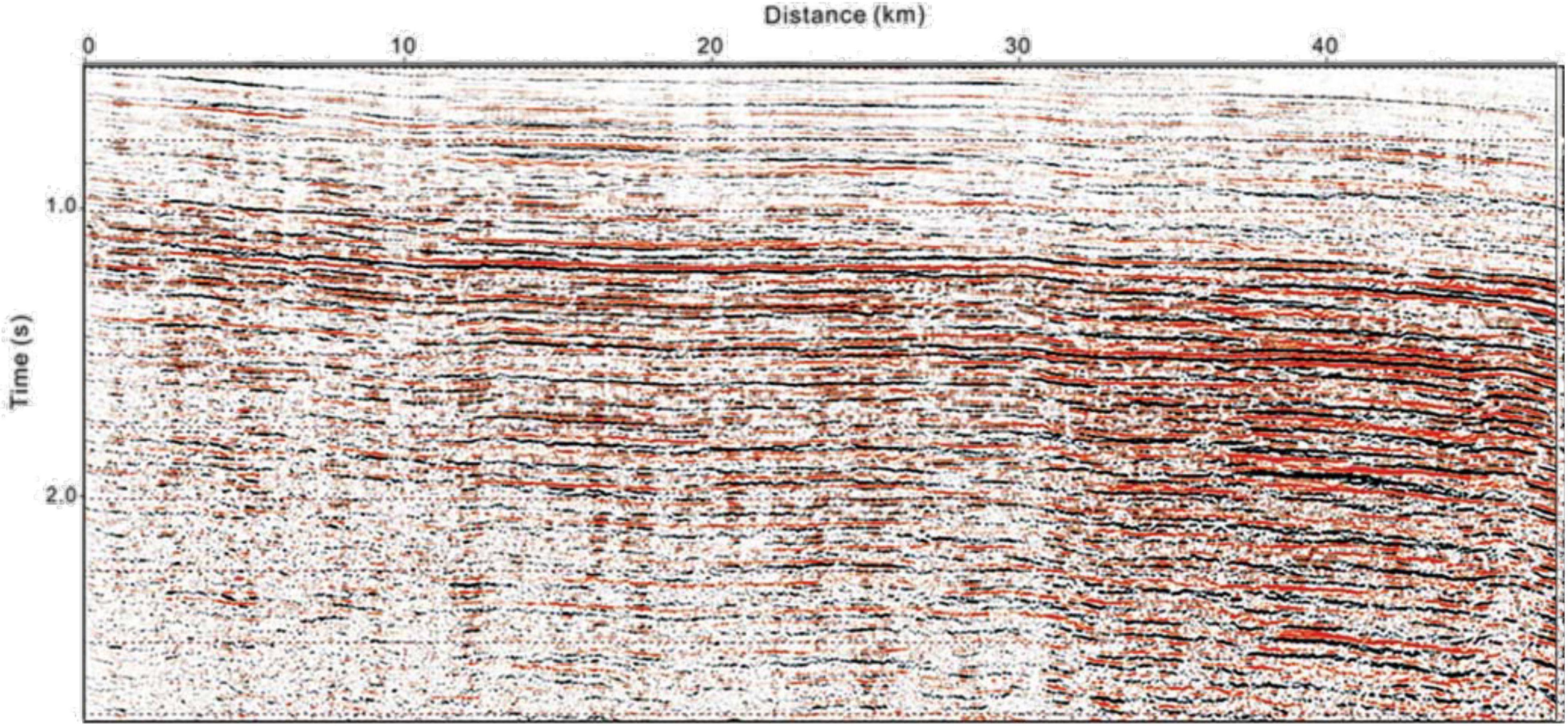


Stack section from a land data set from Saudi Arabia

On-shore ISS internal multiple algorithm from M-OSRP

Yi Luo et al.,(Aramco) Qiang Fu et al., (Aramco/UH)

1D land field data test

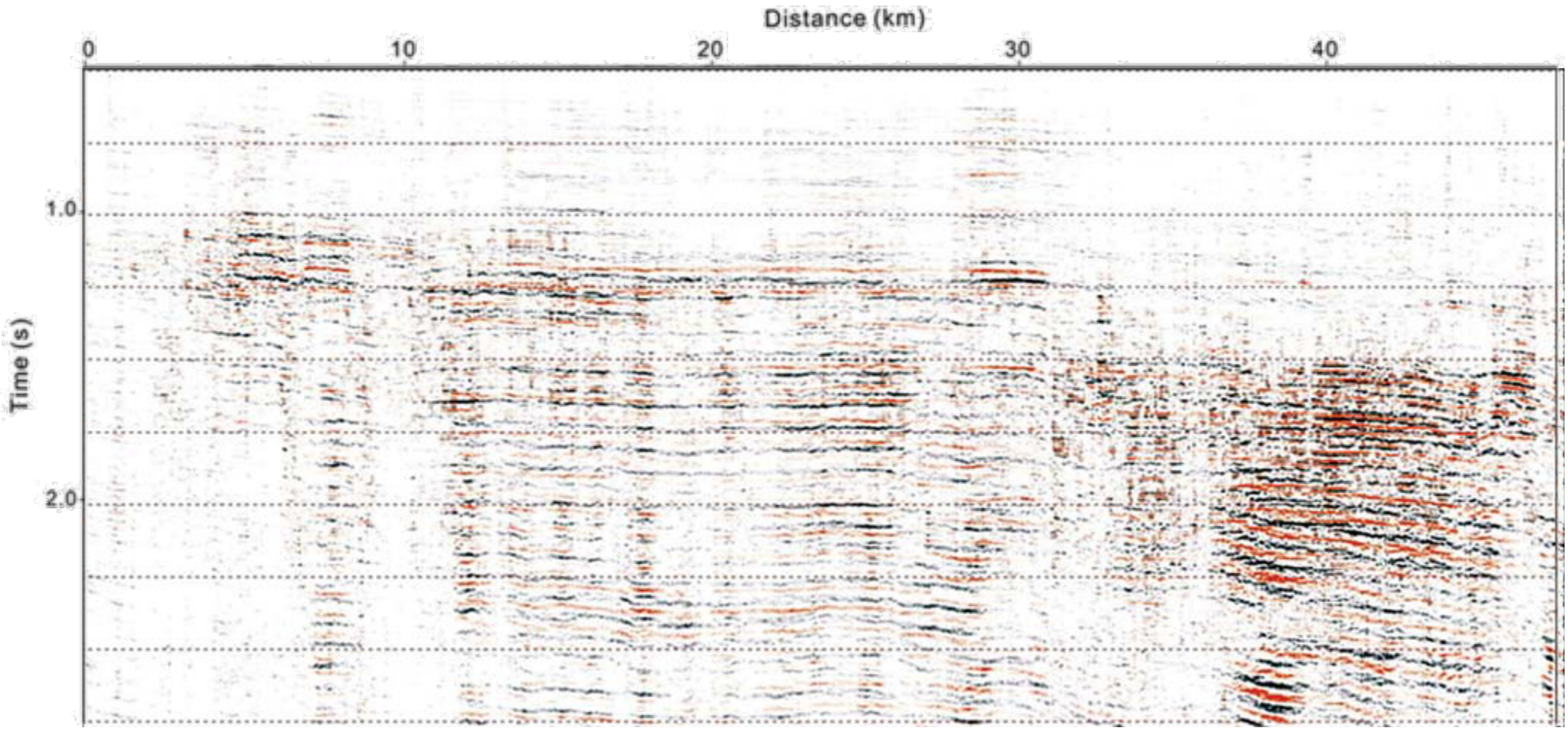


Same data after ISS internal multiple attenuation

On-shore ISS internal multiple algorithm from M-OSRP

Yi Luo et al.,(Aramco) Qiang Fu et al., (Aramco/UH)

1D land field data test



ISS algorithm estimated internal multiples

On-shore ISS internal multiple algorithm from M-OSRP

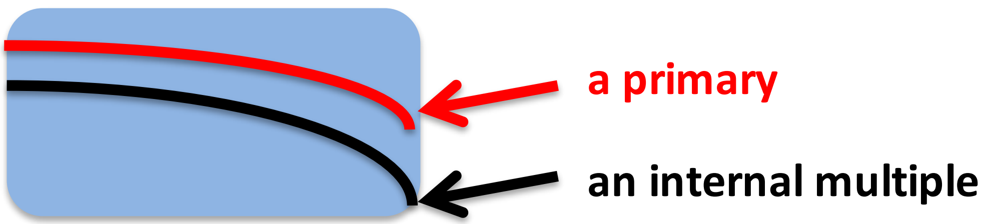
Yi Luo et al.,(Aramco) Qiang Fu et al., (Aramco/UH)

"Their (ISS internal multiple algorithm) performance was demonstrated with complex synthetic and challenging land field datasets with encouraging results, where other internal multiple suppression methods were unable to demonstrate similar effectiveness."

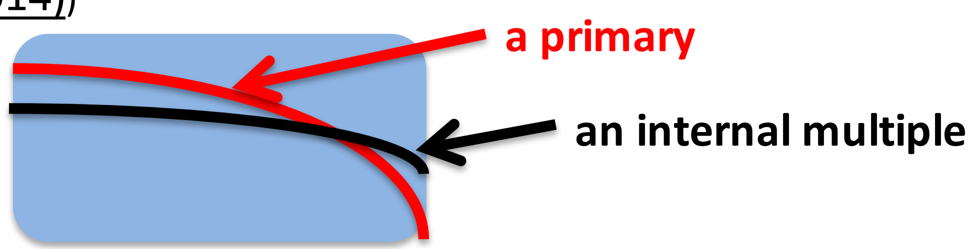
- Yi Luo, Panos G. Kelamis, Qiang Fu, Shoudong Huo, and Ghada Sindi, Saudi Aramco; Shih-Ying Hsu and Arthur B. Weglein, U. of Houston, "The inverse scattering series approach toward the elimination of land internal multiples." Aug 2011, TLE

ISS internal multiple elimination from M-OSRP

- **When primaries and internal multiples are separated:**
  ISS Internal-multiple attenuation + adaptive subtraction



- **When internal multiples are proximal to or interfering with primaries:**
  internal-multiple **elimination** algorithm is needed (three-pronged strategy *Weglein*(2014))



The three-pronged strategy *Weglein*(2014)

1. Pre-requisites for on-shore application;

2. Beyond ISS internal multiple attenuation;
   a) Removing artifacts/spurious events
   b) Internal multiple elimination

3. New adaptive subtraction criteria.

ISS internal multiple elimination

- The ISS has a promise of achieving seismic data processing tasks **without any subsurface information.**

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- **Distinct subseries** can be isolated from the overall series to achieving different seismic data processing tasks.

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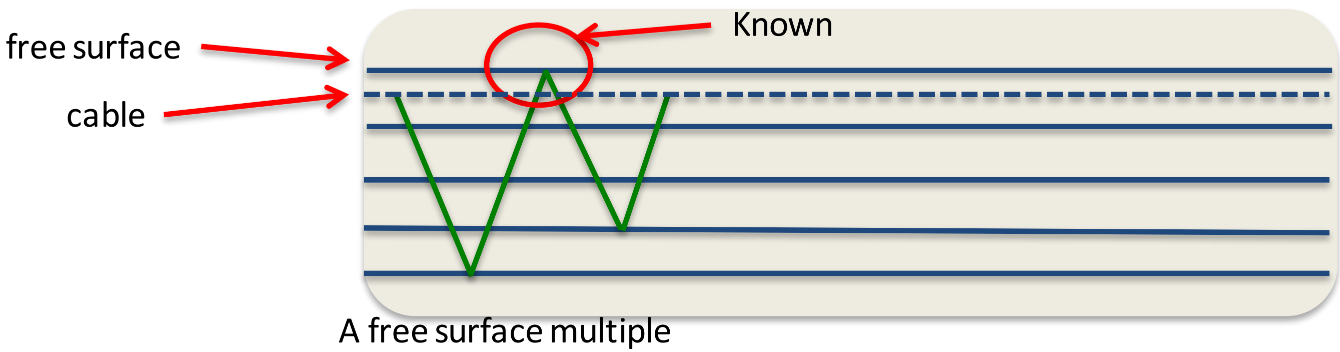
- Subseries associated with removing multiples are:
  - ISS free surface multiple **elimination** subseries
  - ISS internal multiple **elimination** subseries

(For ISS methods, we assume we know all the information above cable and do not know any information below the cable.)

ISS internal multiple elimination



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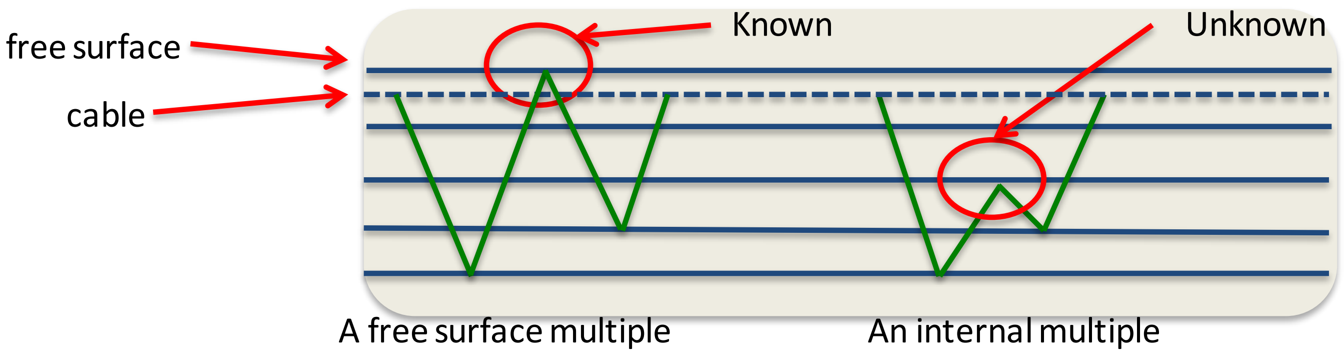

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ISS internal multiple elimination

- proposed the initial idea and expressed the attenuation factor using reflection coefficients

  Weglein and Matson(1998)

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- first elimination algorithm for first-order internal multiples generated by the shallowest reflector (1D normal incidence)

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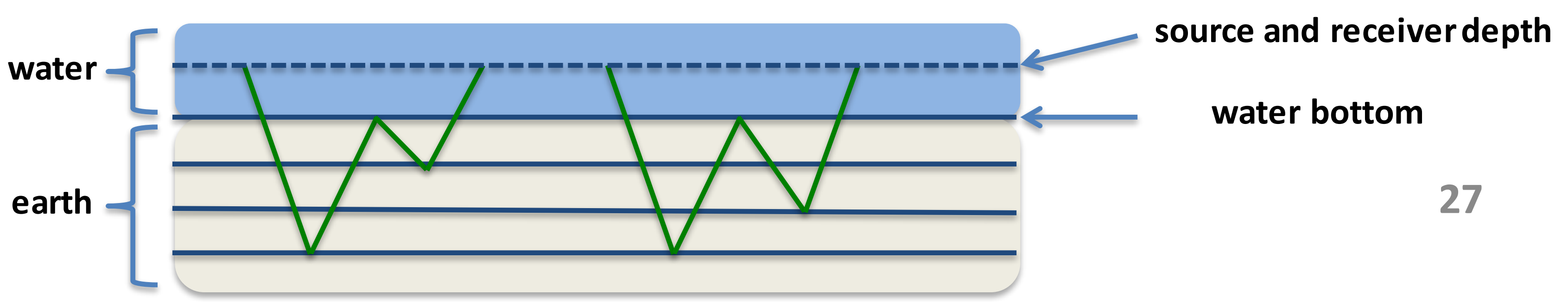

internal multiples generated by the shallowest reflector

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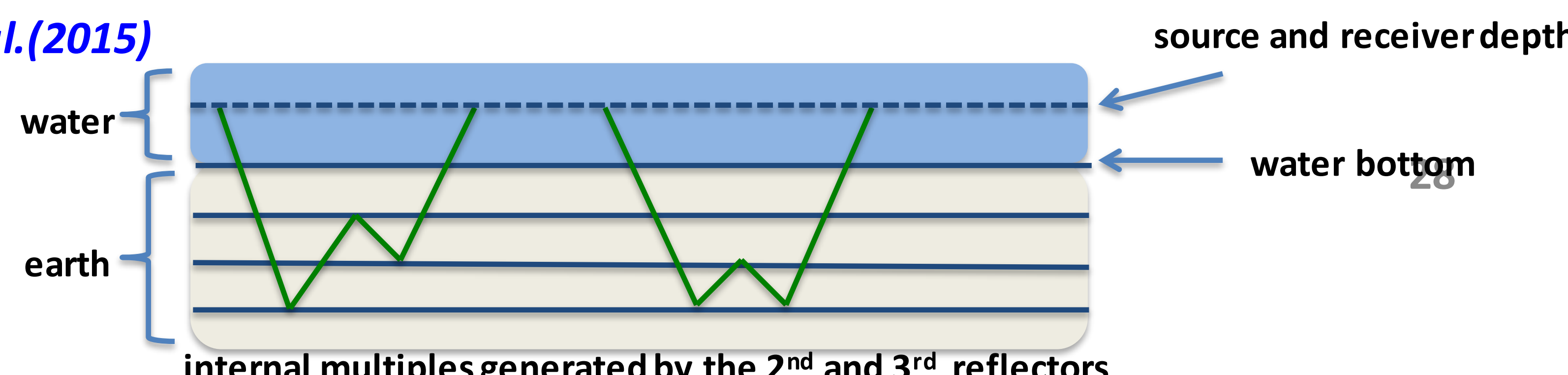

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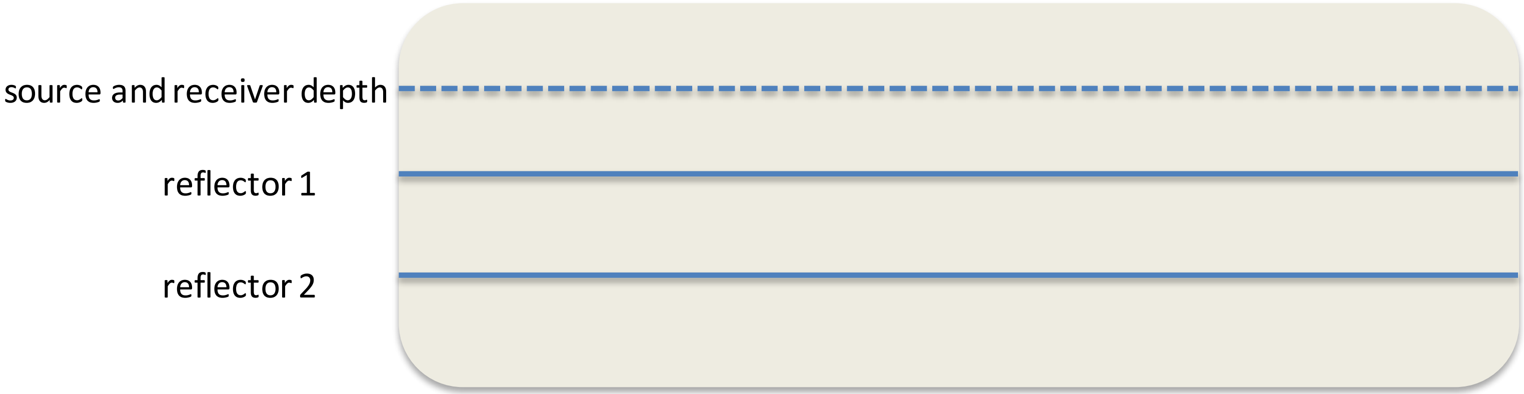
- first elimination algorithm for first-order internal multiples generated by all (shallowest and deeper) reflectors for a multi-dimensional acoustic subsurface

  Zou and Ma(2017)

ISS internal multiple elimination

- accommodation of the topography of the acquisition surface
- adequate data collected for 2D and 3D application
- reference wave removed
- source signature and radiation pattern removed
- source and receiver deghosting
- free surface multiple removed
- The ISS internal multiple **attenuation** algorithm is **model-type independent.**
- The ISS internal multiple **elimination** algorithm (at this point) contains the **model-type independent** ISS internal multiple **attenuation** algorithm, the part that beyond attenuation is **model-type dependent.** An acoustic relationship is assumed. The elimination algorithm has been tested on elastic earth model and shows encouraging results. We will develop a more complete ISS internal multiple elimination algorithm with consideration of elastic/anelastic effects.
- In this presentation, we focus on the first-order internal multiples. The current method can be extended to remove higher order internal multiples.

ISS internal multiple attenuation
(a simplest 1D normal incidence example)



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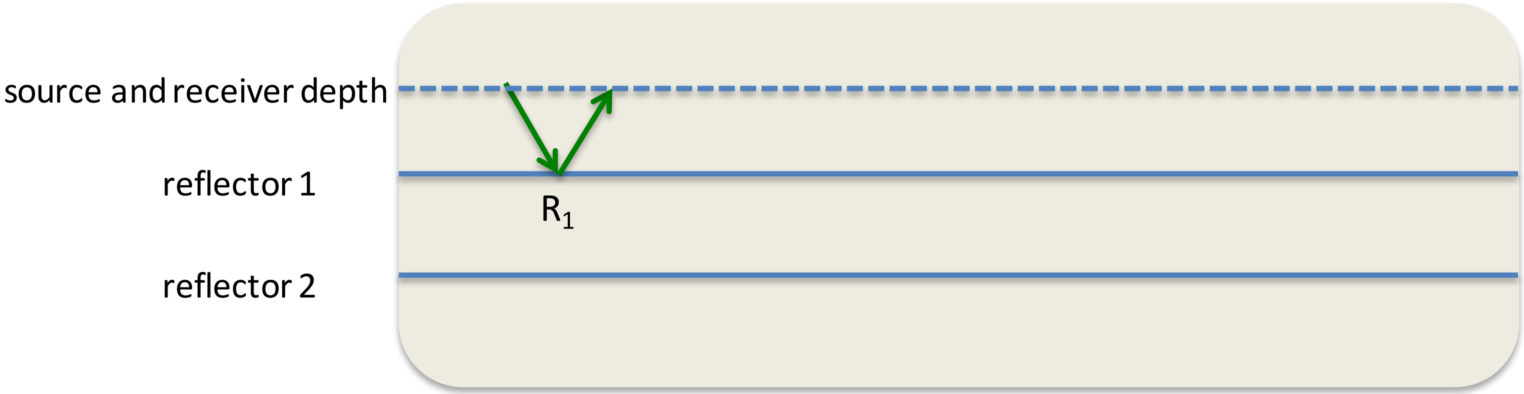

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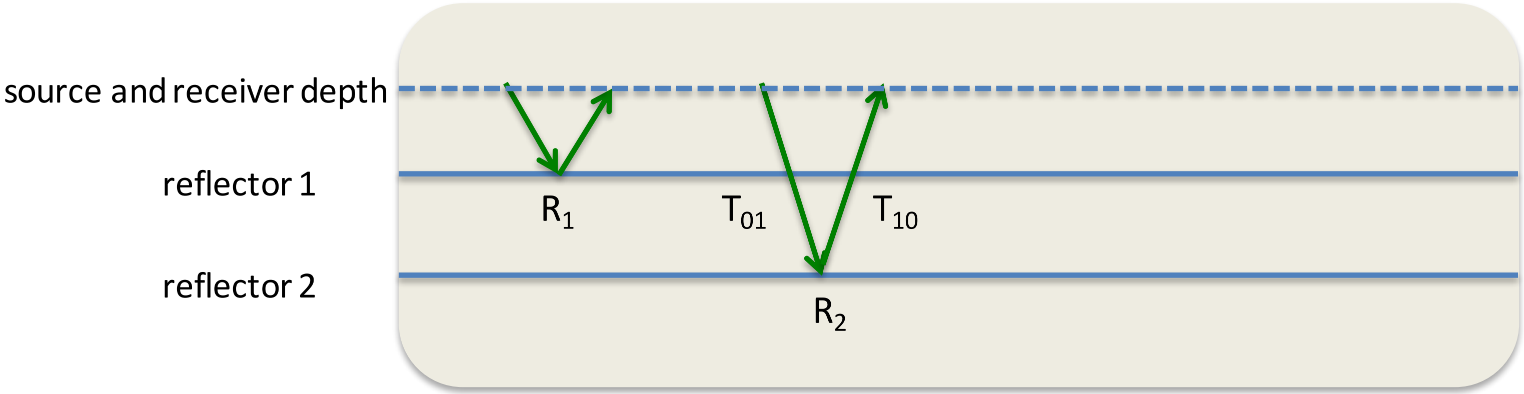

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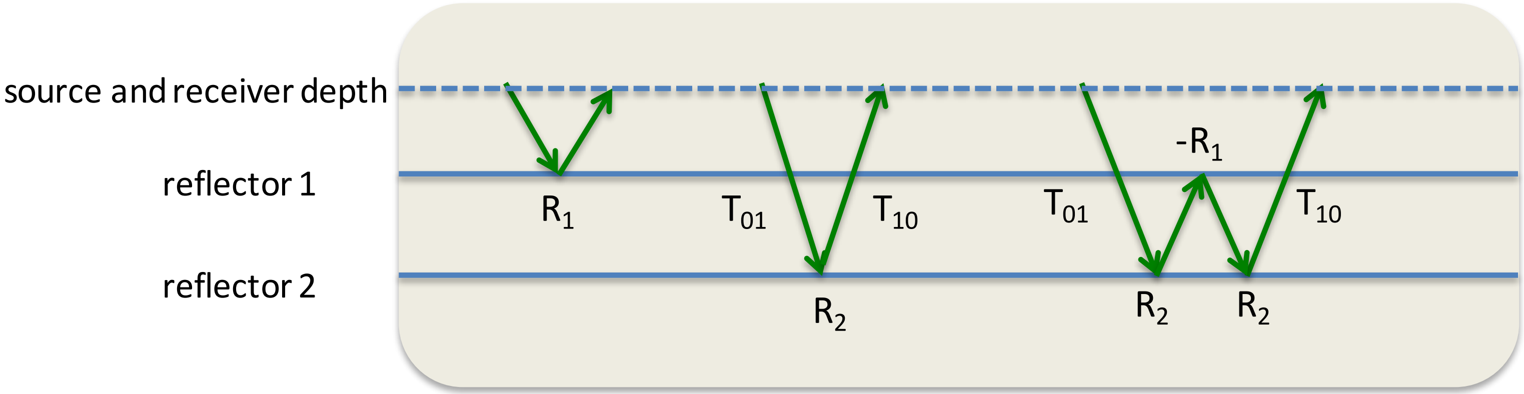

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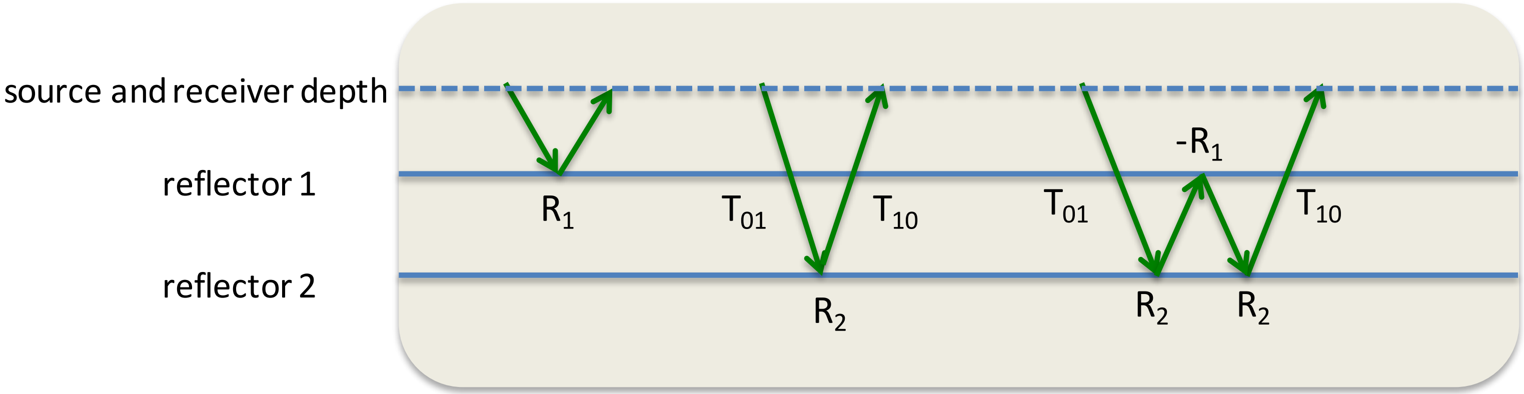
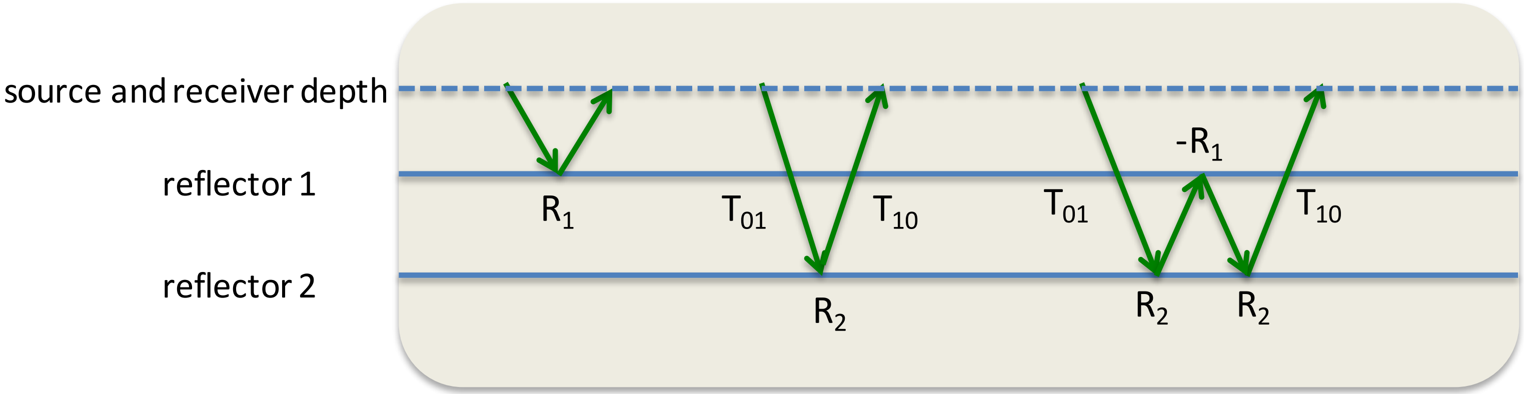


The first primary arrival time: t_1
The second primary arrival time: t_2
first primary arrival time: $2t_2$-t_1

ISS internal multiple attenuation
(a simplest 1D normal incidence example)



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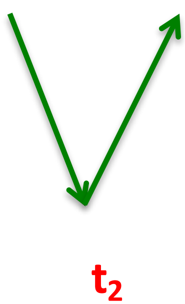

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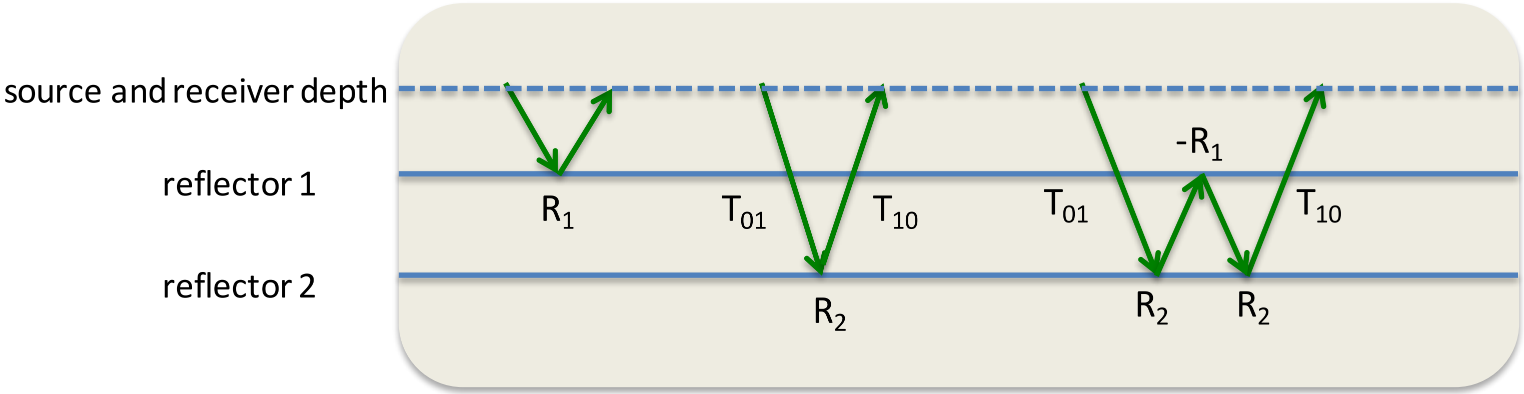

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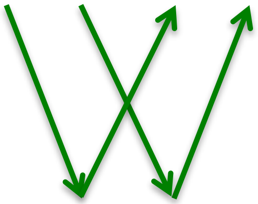

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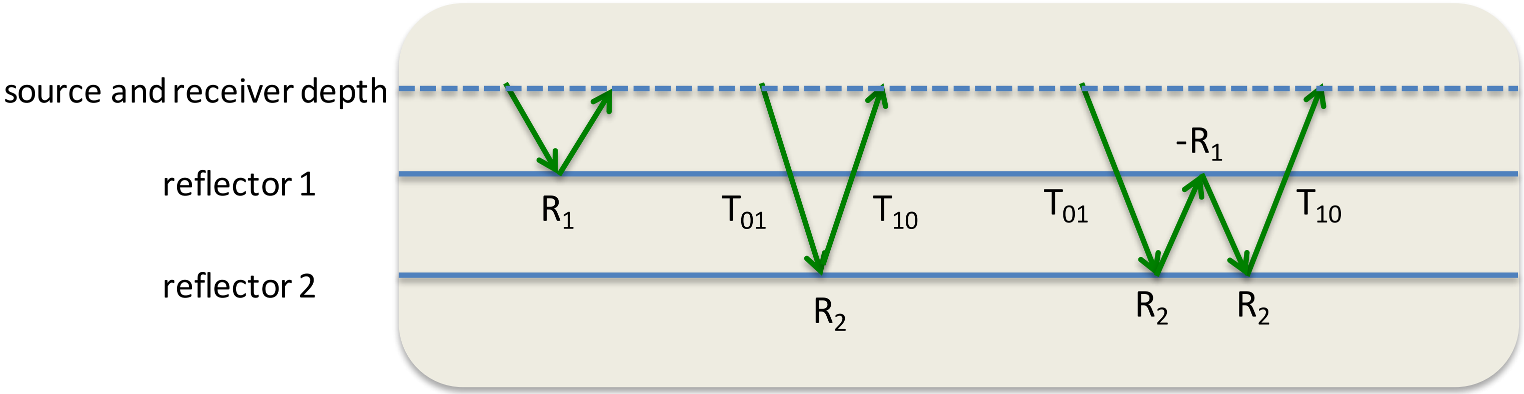

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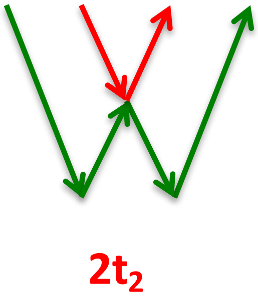

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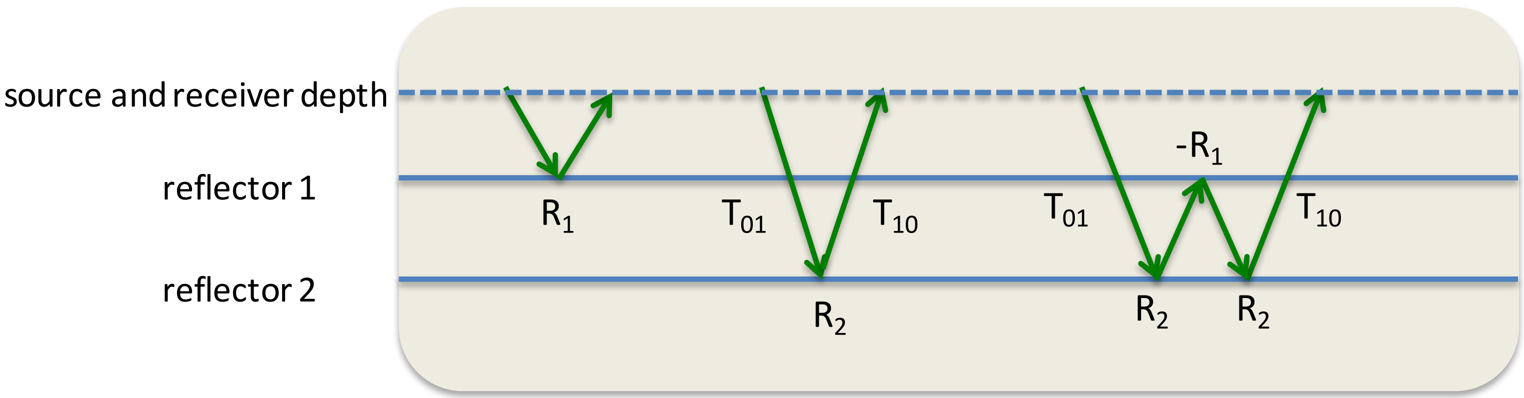

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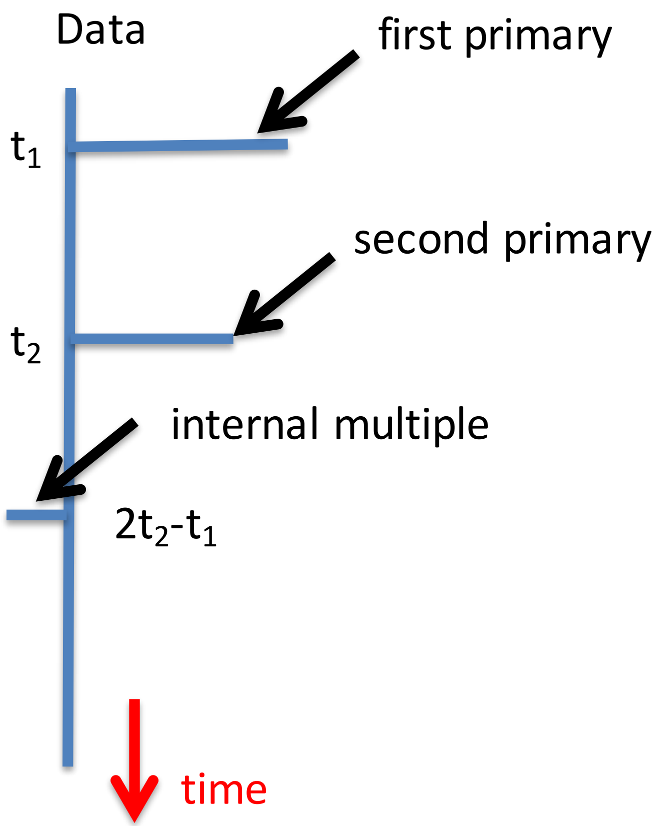

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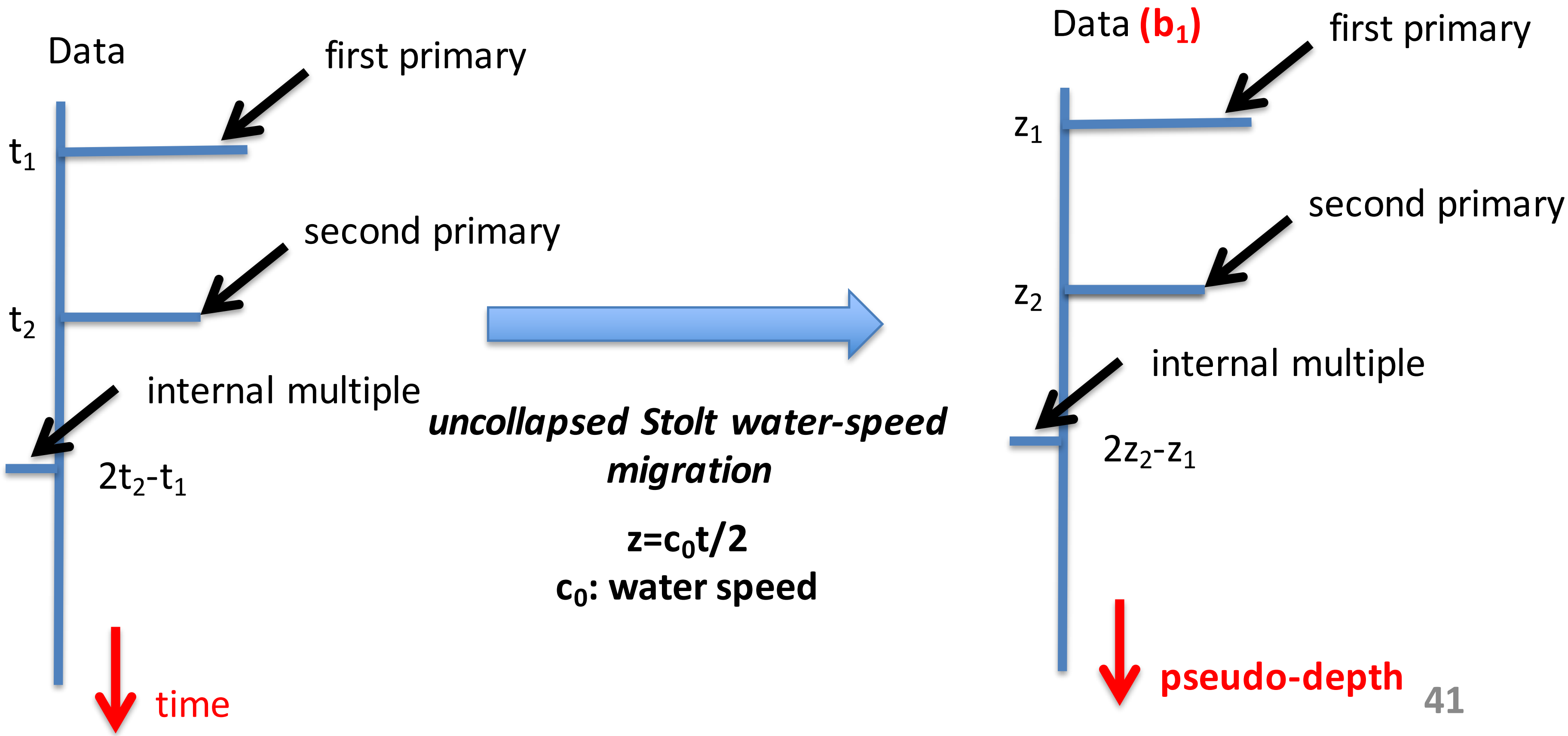
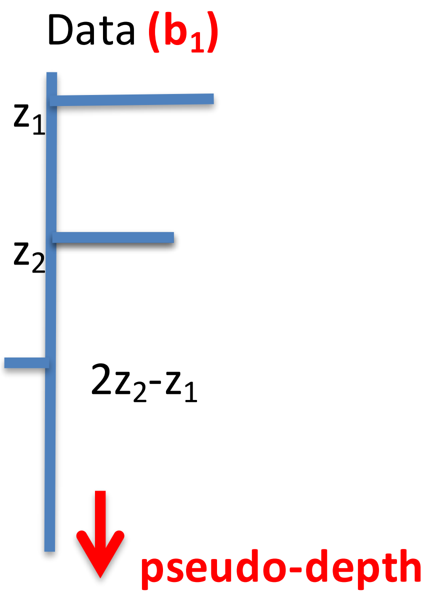
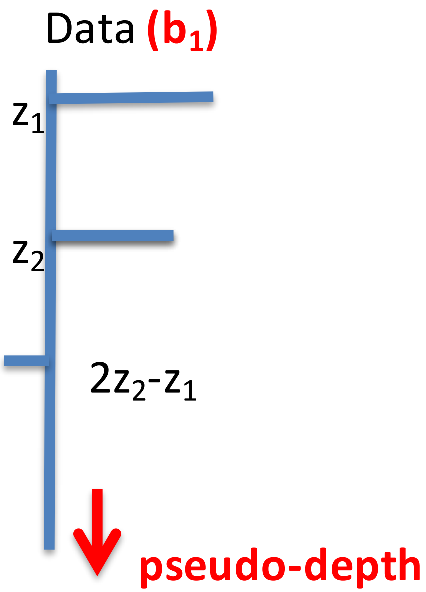


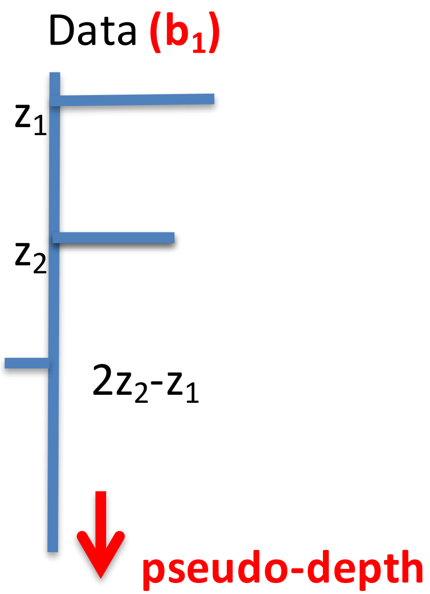
ISS internal multiple attenuation
(a simplest 1D normal incidence example)

ISS internal multiple attenuation algorithm (1D normal incidence)

$$b_3^{IM}(k) = \int_{-\infty}^{\infty} dz e^{ikz} b_1(z) \int_{-\infty}^{z-\varepsilon_2} dz' e^{-ikz'} b_1(z') \int_{z'+\varepsilon_1}^{\infty} dz'' e^{ikz''} b_1(z'')$$







ISS internal multiple attenuation
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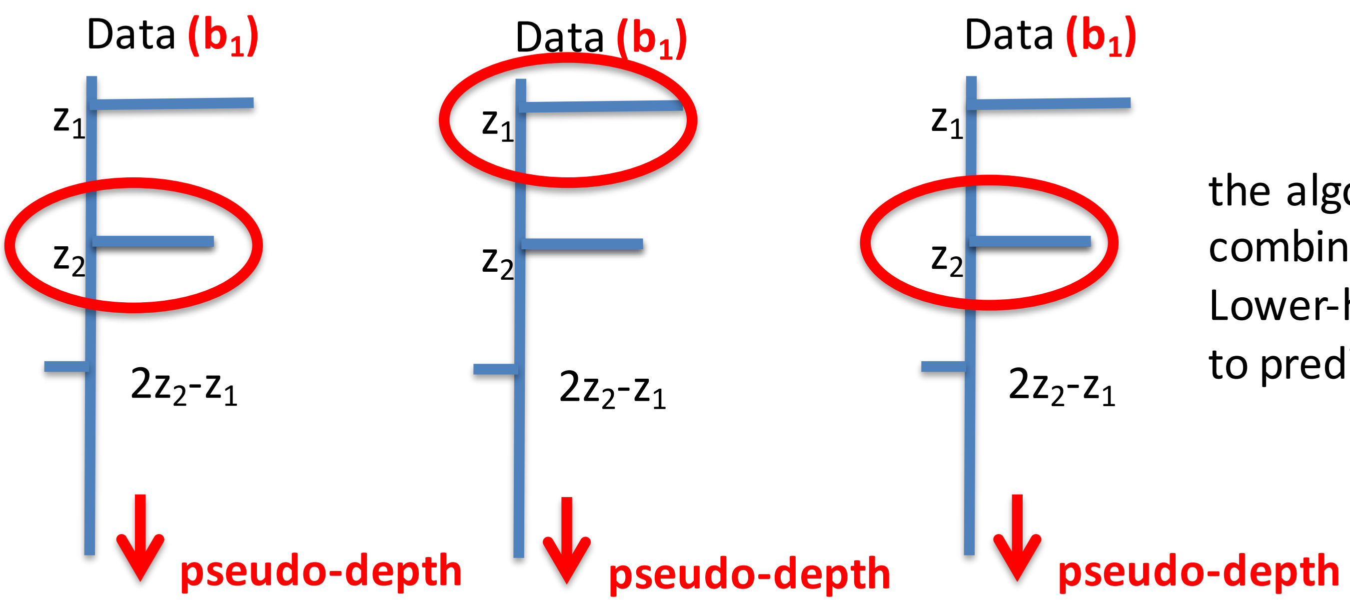

the algorithm automatically combines subevents that satisfy Lower-higher-lower relationship to predict internal multiples

ISS internal multiple attenuation
(a simplest 1D normal incidence example)

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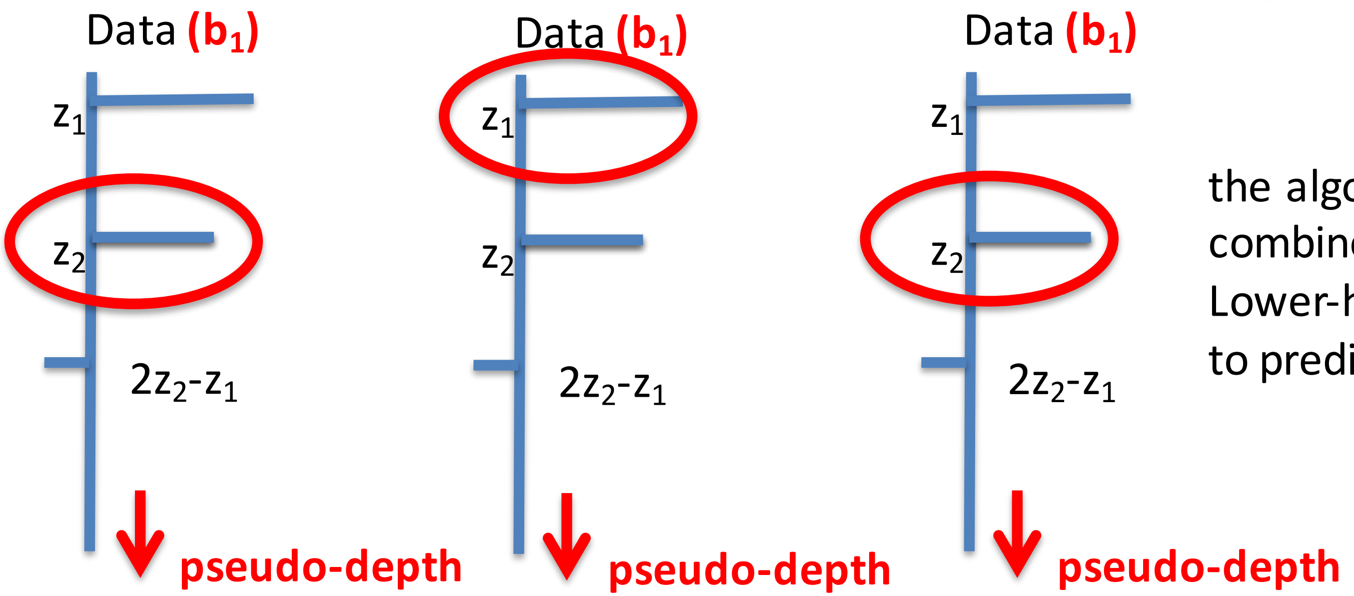

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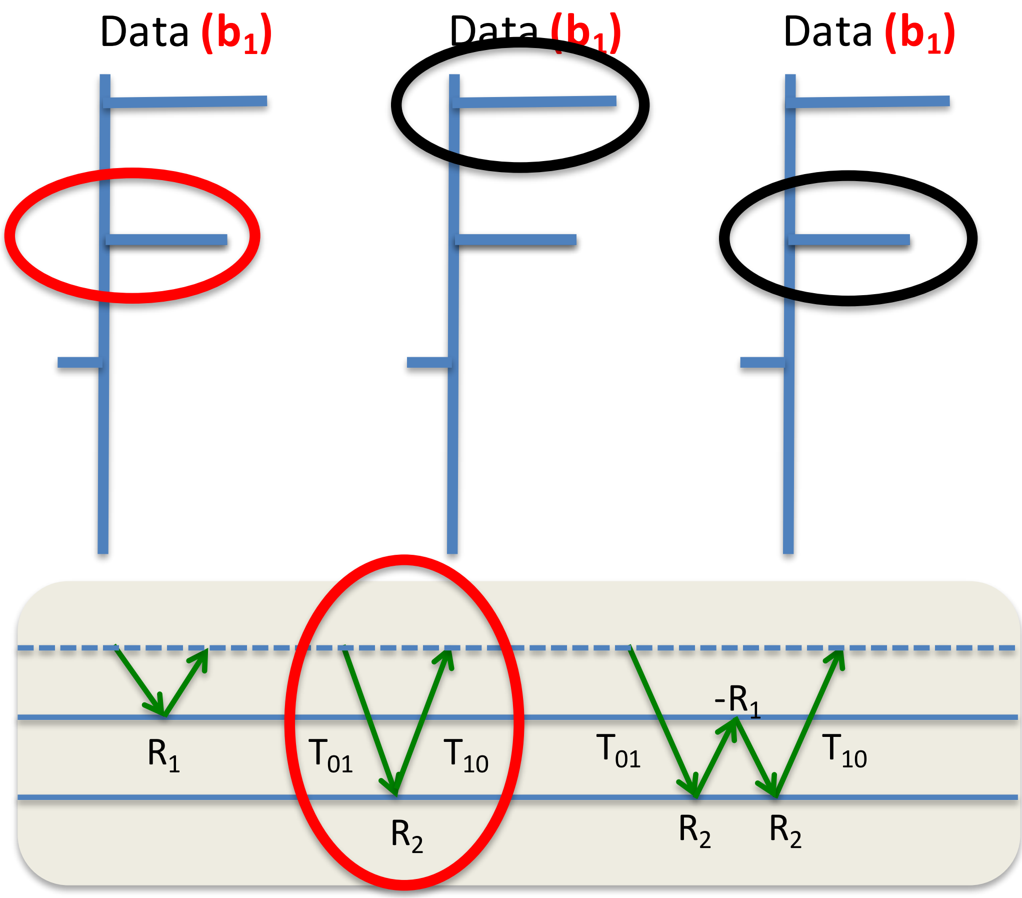
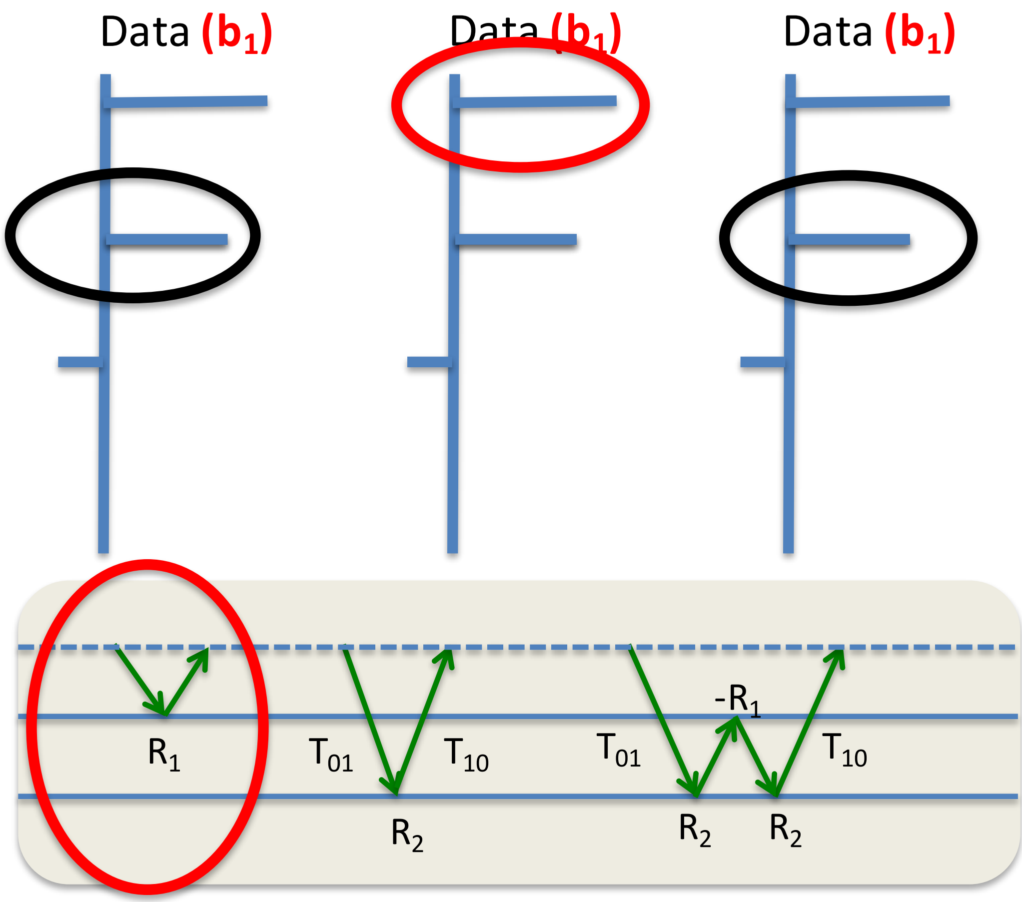


The first subevent is a second primary:
arrival time: t_2
amplitude: $T_{01}R_2T_{10}$

ISS internal multiple attenuation
(a simplest 1D normal incidence example)



The first subevent is a second primary:
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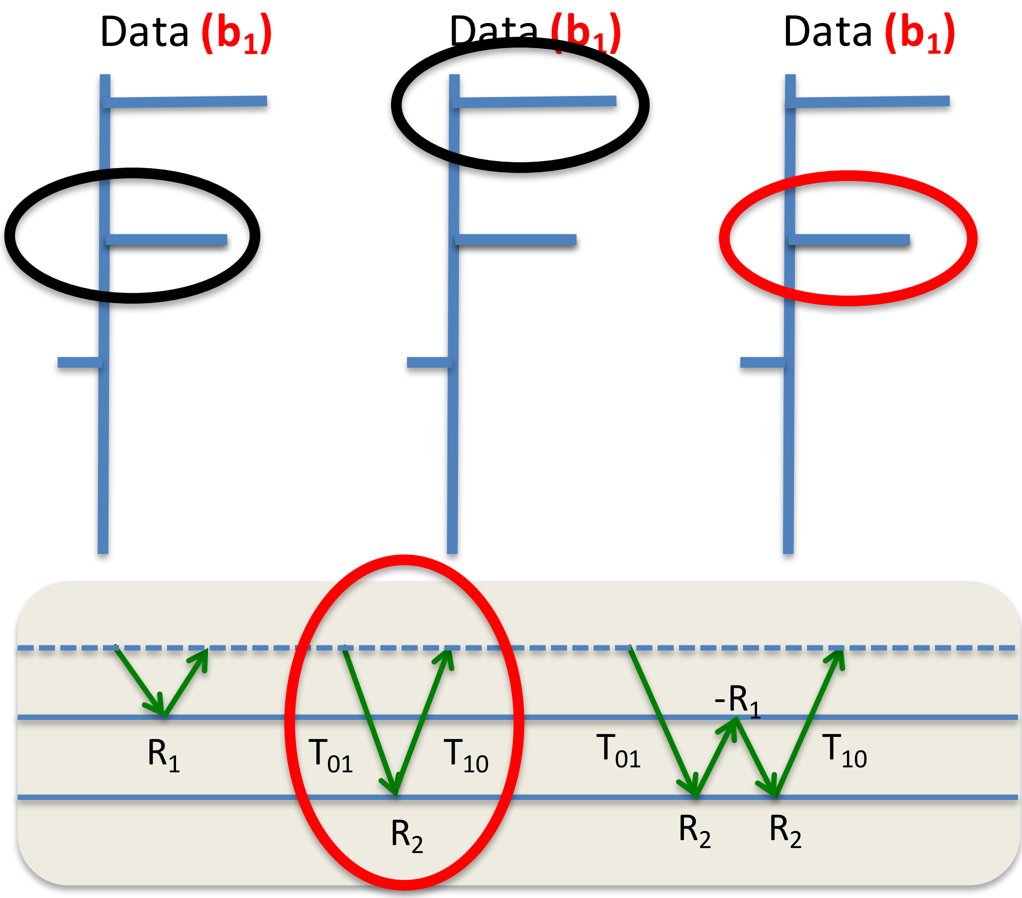
amplitude: $T_{01}R_2T_{10}$

The second subevent is a first primary:
arrival time: t_1
amplitude: R_1

ISS internal multiple attenuation
(a simplest 1D normal incidence example)

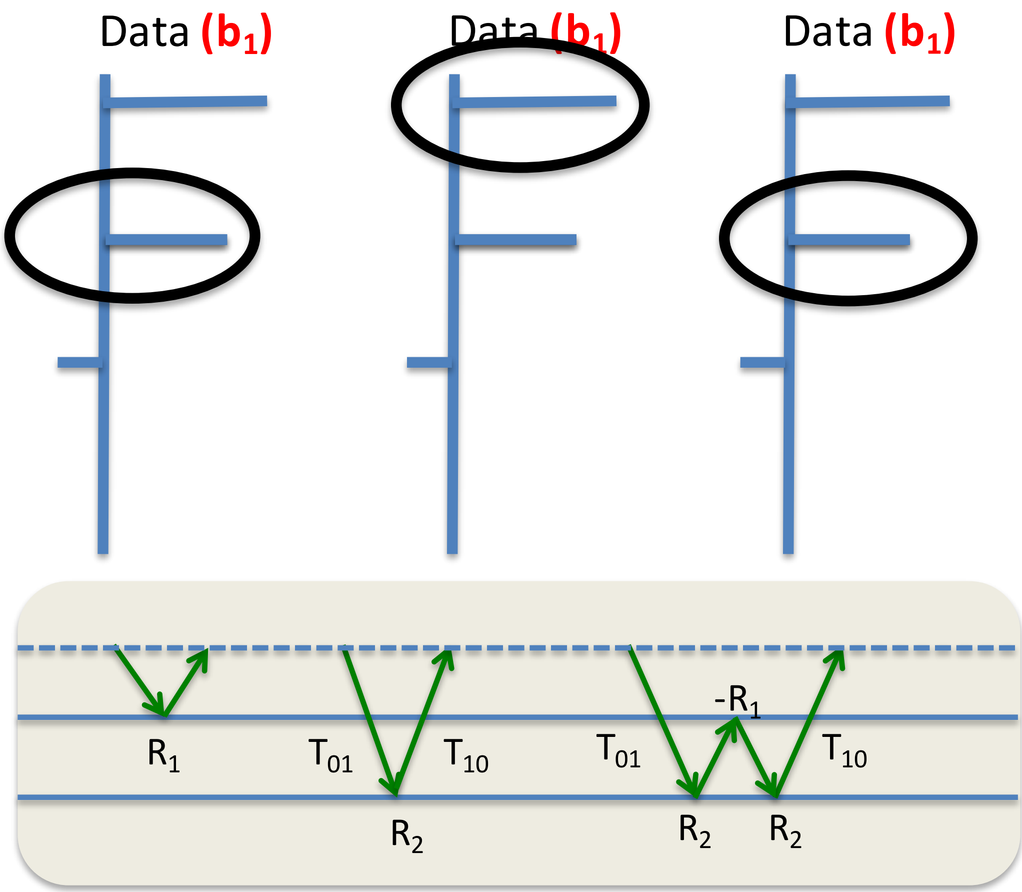


The first subevent is a second primary:
arrival time: t_2
amplitude: $T_{01}R_2T_{10}$

The second subevent is a first primary:
arrival time: t_1
amplitude: R_1

The third subevent is a second primary:
arrival time: t_2
amplitude: $T_{01}R_2T_{10}$

ISS internal multiple attenuation (a simplest 1D normal incidence example)



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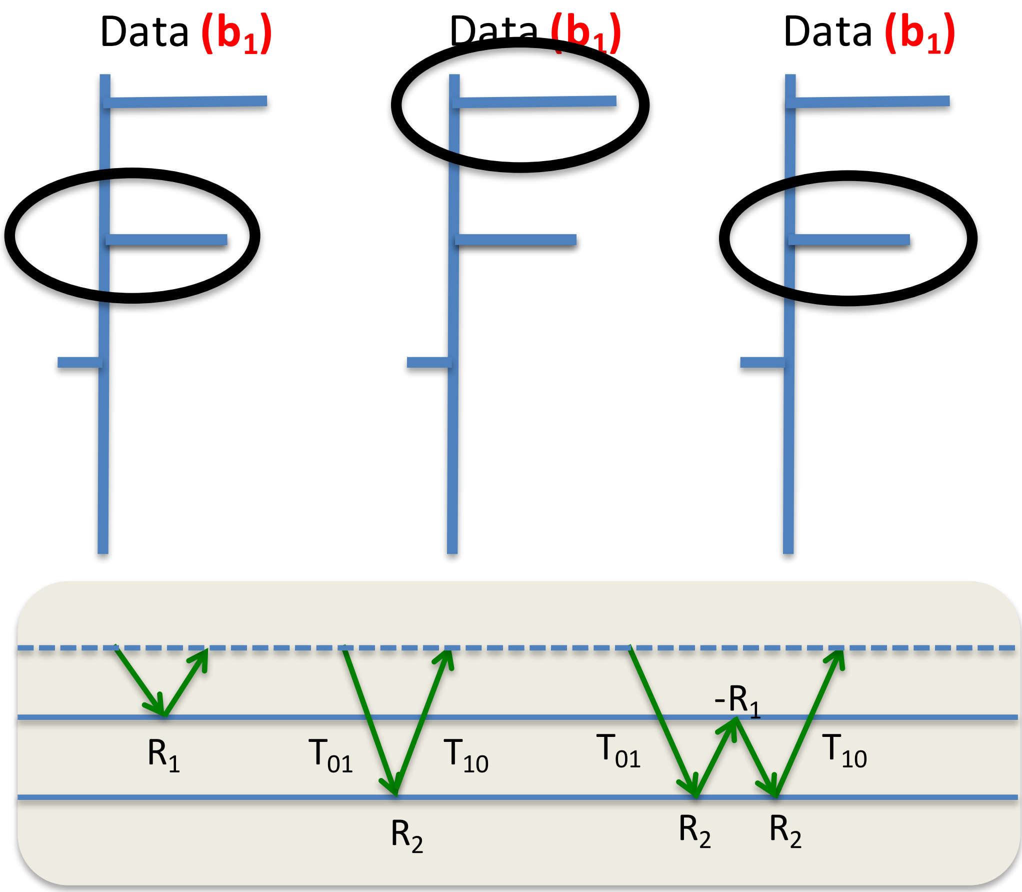
amplitude: R_1

The third subevent is a second primary:
arrival time: t_2
amplitude: $T_{01}R_2T_{10}$

The predicted internal multiple:
arrival time: $2t_2-t_1$
amplitude: $T_{01}R_2T_{10}R_1T_{01}R_2T_{10}$

ISS internal multiple attenuation
(a simplest 1D normal incidence example)



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arrival time: $2t_2-t_1$
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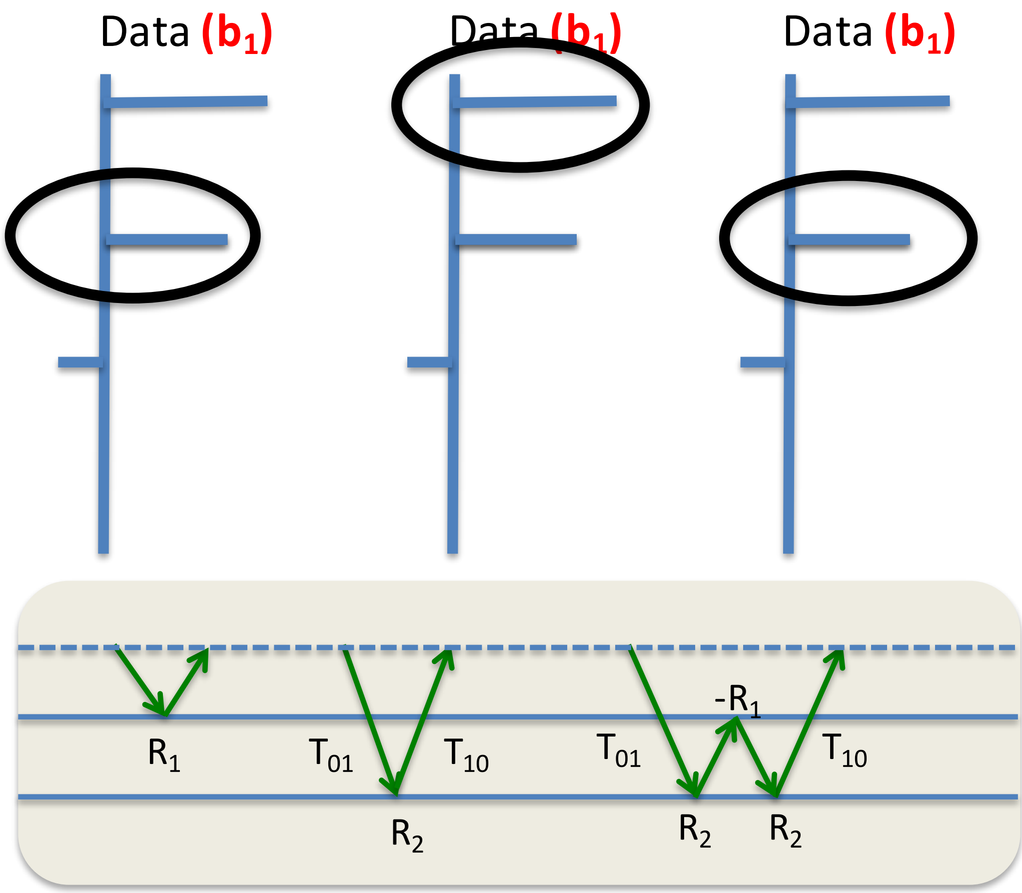
The actual internal multiple:
arrival time: $2t_2-t_1$
amplitude: $-T_{01}R_2R_1R_2T_{10}$

ISS internal multiple attenuation
(a simplest 1D normal incidence example)



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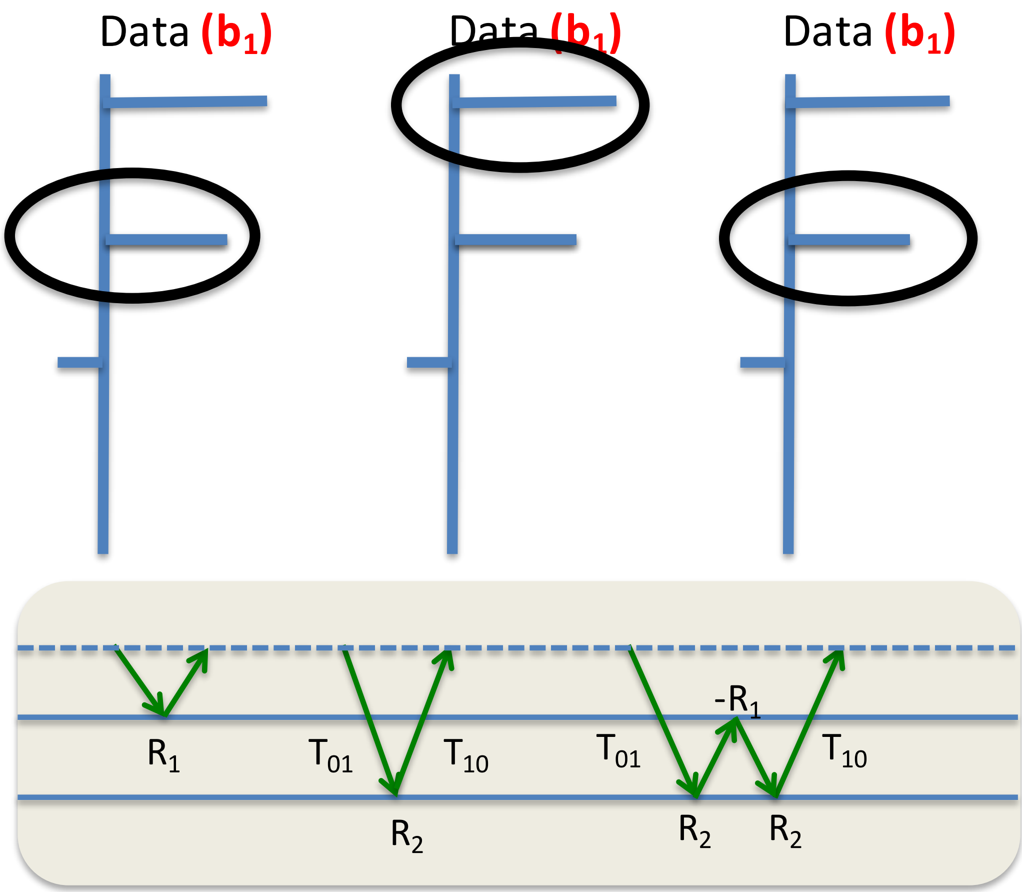
The actual internal multiple:
arrival time: $2t_2-t_1$
amplitude: $-T_{01}R_2R_1R_2T_{10}$

predicted multiple has correct arrival time

ISS internal multiple attenuation
(a simplest 1D normal incidence example)



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The predicted internal multiple:
arrival time: $2t_2-t_1$
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The actual internal multiple:
arrival time: $2t_2-t_1$
amplitude: $-T_{01}R_2R_1R_2T_{10}$

predicted multiple has more Ts in its amplitude

ISS internal multiple elimination for internal multiples generated from the shallowest reflector

- proposed the initial idea and expressed the attenuation factor using reflection coefficients
  Weglein and Matson(1998)

$$elimination = \frac{attenuation}{T_{01}T_{10}} = \frac{attenuation}{1 - R_1^2}$$

$$= attenuation + attenuation \times R_1^2 + attenuation \times R_1^4 + \cdots$$

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- following Weglein and Matson's analysis, terms are identified from the series to remove the attenuation factor for the shallowest reflector
  Herrera et al.(2012)

R_1 ⟶ data(b_1)

R_1^2, R_1^4... ⟶ even powers of Data(b_1)

Multi-Dimensional ISS internal multiple elimination for internal multiples generated from all reflectors

- proposed the first ISS internal multiple elimination algorithm for all reflectors, first for 1D and 1D with offset then for multi-dimensional subsurface

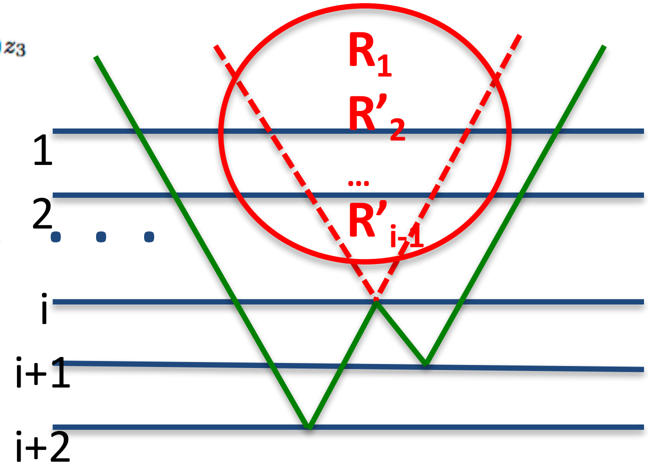
Zou et al.(2015) Zou et. al (2017)

$$
\begin{aligned}
elimination =& \frac{attenuation}{AF_i} \\
=& \frac{attenuation}{(1-R_i^2)(1-R_1^2-R_2'R_2-\cdots-R_{i-1}'R_{i-1})^2} \\
=& attenuation(1+R_i^2+R_i^4+\cdots)(1+(R_1^2+R_2'R_2+\cdots+R_{i-1}'R_{i-1})+\cdots)^2 \\
=& attenuation(1+R_i^2+R_i^4+\cdots+(R_1^2+R_2'R_2+\cdots+R_{i-1}'R_{i-1})+\cdots) \\
=& attenuation + attenuation \times R_i'^2 + attenuation \times R_i'^4 \\
& +\cdots+ attenuation \times (R_1^2+R_2'R_2+\cdots+R_{i-1}'R_{i-1})+\cdots
\end{aligned}
$$

Multi-Dimensional ISS internal multiple elimination for internal multiples generated from all reflectors

$$elimination = \frac{attenuation}{AF_i} = attenuation + attenuation \times R_i'^2 + attenuation \times R_i'^4$$
$$+ \cdots + attenuation \times (R_1^2 + R_2' R_2 + \cdots + R_{i-1}' R_{i-1}) + \cdots$$

$$b_E(k_s, k_g, q_g + q_s) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} dk_1 dk_2 \int_{-\infty}^{+\infty} dz_1 b_1(k_g, k_1, z_1) e^{i(q_g+q_1)z_1}$$
$$\times \int_{-\infty}^{z_1-\varepsilon} dz_2 F(k_1, k_2, z_2) e^{-i(q_1+q_2)z_2} \int_{z_2+\varepsilon}^{+\infty} dz_3 b_1(k_2, k_s, z_3) e^{i(q_2+q_s)z_3}$$



$$F(k_1, k_2, z) = \int_{-\infty}^{+\infty} d(q_1 + q_2) e^{-i(q_1+q_2)z} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} dk' dk'' \int_{-\infty}^{+\infty} dz' b_1(k_1, k', z') e^{i(q_1+q')z'}$$
$$\times \int_{-\infty}^{z'-\varepsilon} dz'' b_1(k', k'', z'') e^{-i(q'+q'')z''} \int_{z''-\varepsilon}^{z''+\varepsilon} dz''' g(k'', k_2, z''') e^{i(q''+q_2)z'''}$$

$$g(k_1, k_2, z) = \int_{-\infty}^{+\infty} d(q_1 + q_2) e^{-i(q_1+q_2)z} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} dk' dk'' \int_{-\infty}^{+\infty} dz' b_1(k_1, k', z') e^{i(q_1+q')z'}$$
$$\times \int_{-\infty}^{z'-\varepsilon} dz'' b_1(k', k'', z'') e^{-i(q'+q'')z''} \int_{z''-\varepsilon}^{z''+\varepsilon} dz''' g(k'', k_2, z''') e^{i(q''+q_2)z'''}$$

Multi-Dimensional ISS internal multiple elimination for internal multiples generated from all reflectors

$$elimination = \frac{attenuation}{AF_i} = attenuation + attenuation \times R_i'^2 + attenuation \times R_i'^4$$

$$+ \cdots + attenuation \times (R_1^2 + R_2' R_2 + \cdots + R_{i-1}' R_{i-1}) + \cdots$$

$$b_E(k_s, k_g, q_g + q_s) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} dk_1 dk_2 \int_{-\infty}^{+\infty} dz_1 b_1(k_g, k_1, z_1) e^{i(q_g+q_1)z_1}$$

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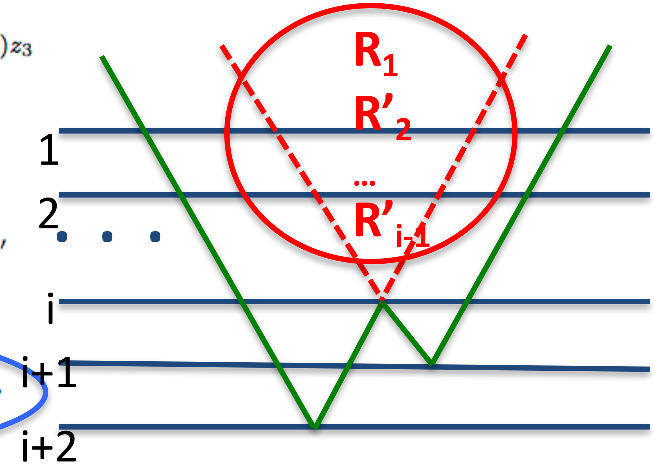
$$F(k_1, k_2, z) = \int_{-\infty}^{+\infty} d(q_1 + q_2) e^{-i(q_1+q_2)z} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} dk' dk'' \int_{-\infty}^{+\infty} dz' b_1(k_1, k', z') e^{i(q_1+q')z'}$$

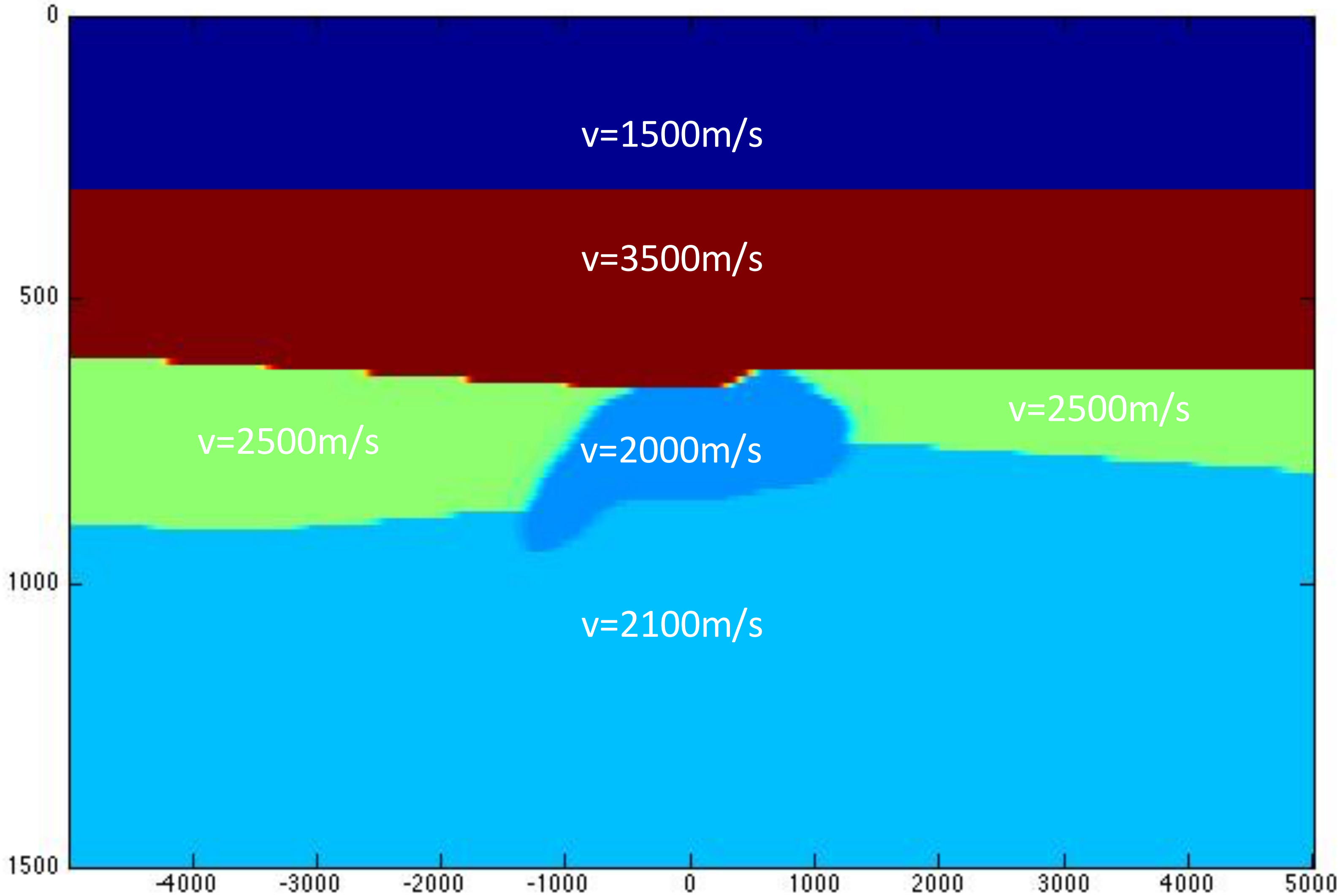
$$\times \int_{-\infty}^{z'-\varepsilon} dz'' b_1(k', k'', z'') e^{-i(q'+q'')z''} \int_{z''-\varepsilon}^{z''+\varepsilon} dz''' g(k'', k_2, z''') e^{i(q''+q_2)z'''}$$



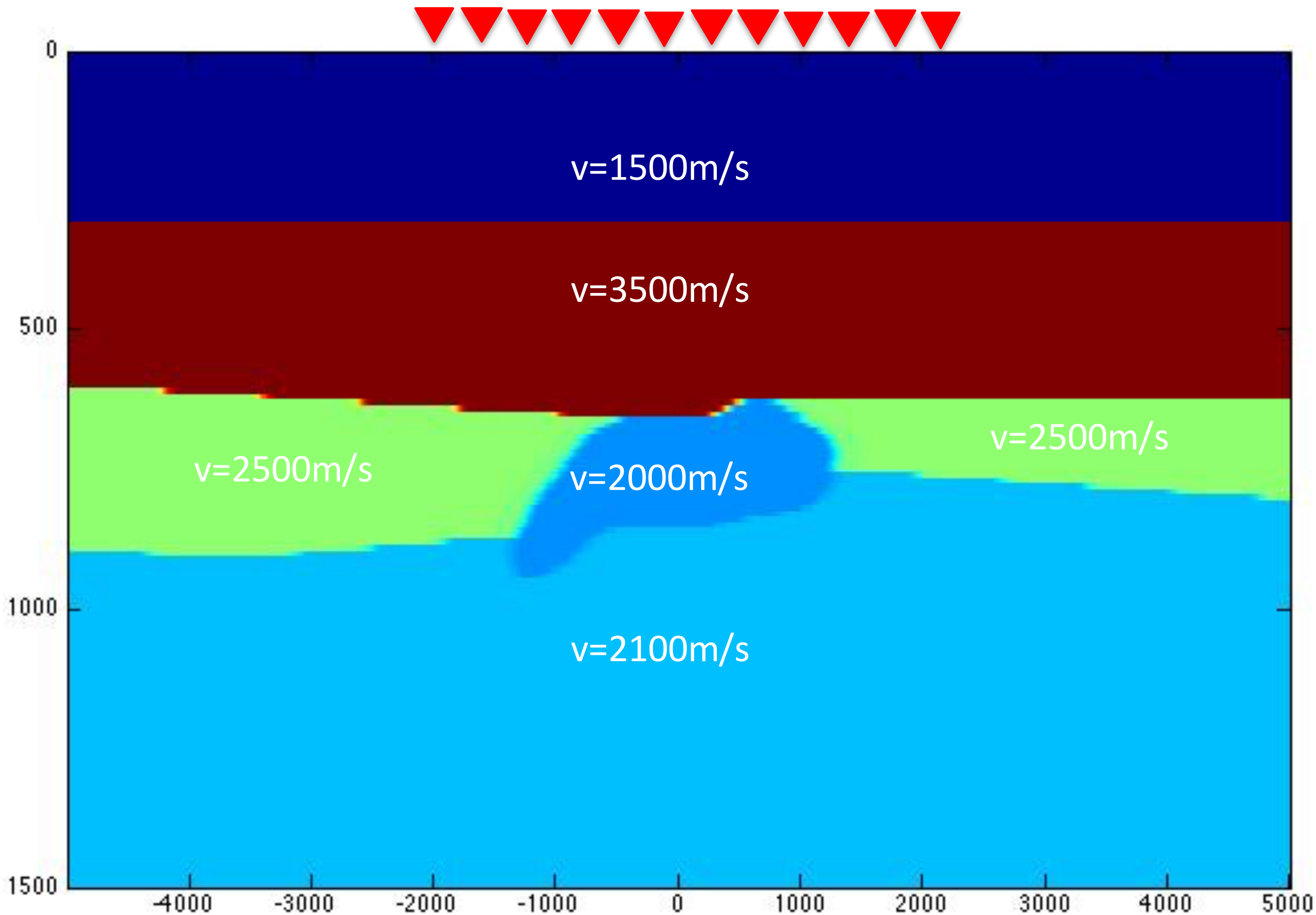
$$\int_{-\infty}^{z'-\varepsilon} dz'' b_1(k', k'', z'') e^{-i(q'+q'')z''} \int_{z''-\varepsilon}^{z''+\varepsilon} dz''' g(k'', k_2, z''') e^{i(q''+q_2)z'''}$$

Multi-Dimensional ISS internal multiple elimination (numerical test)

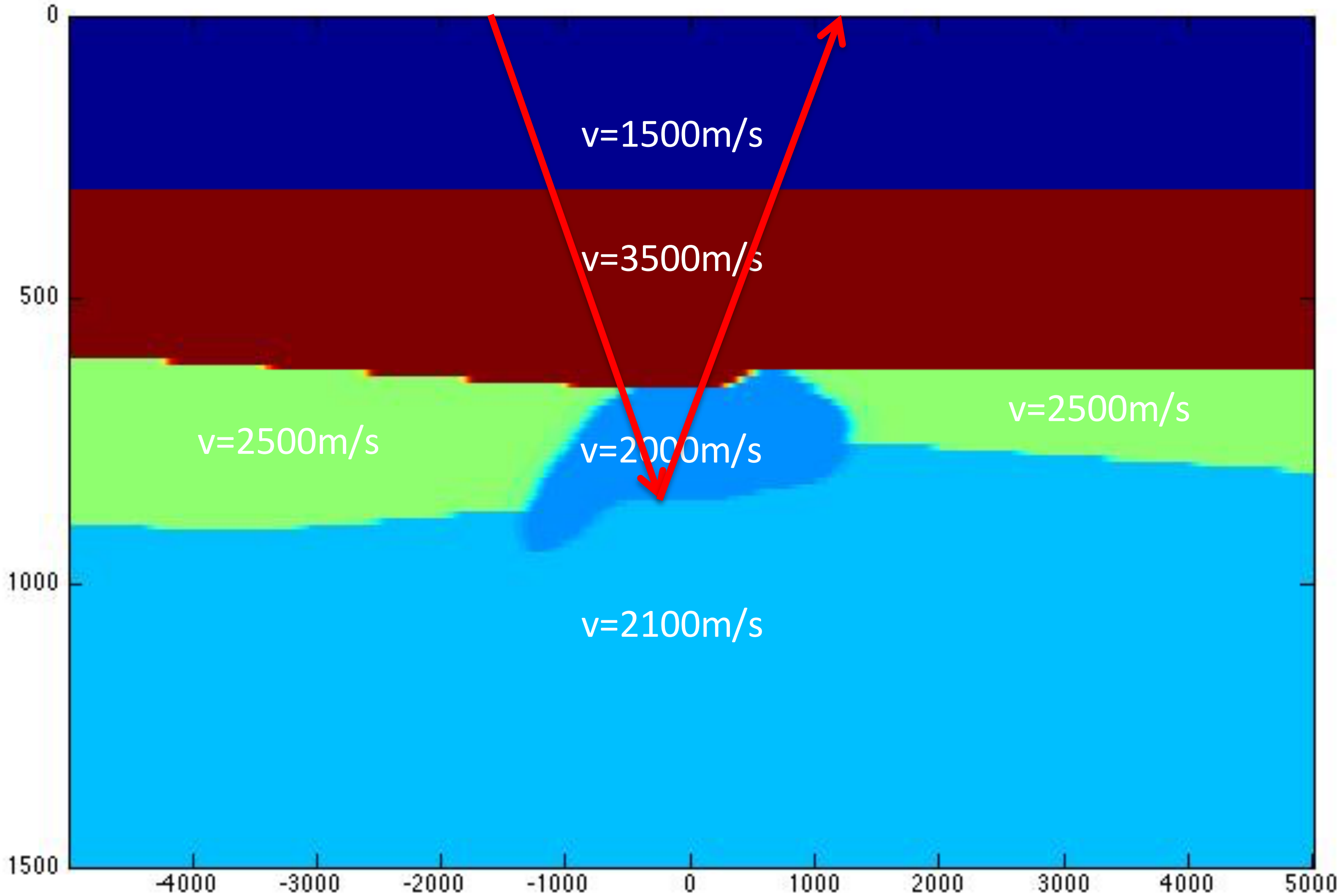
127 sources,127 receivers, 2seconds



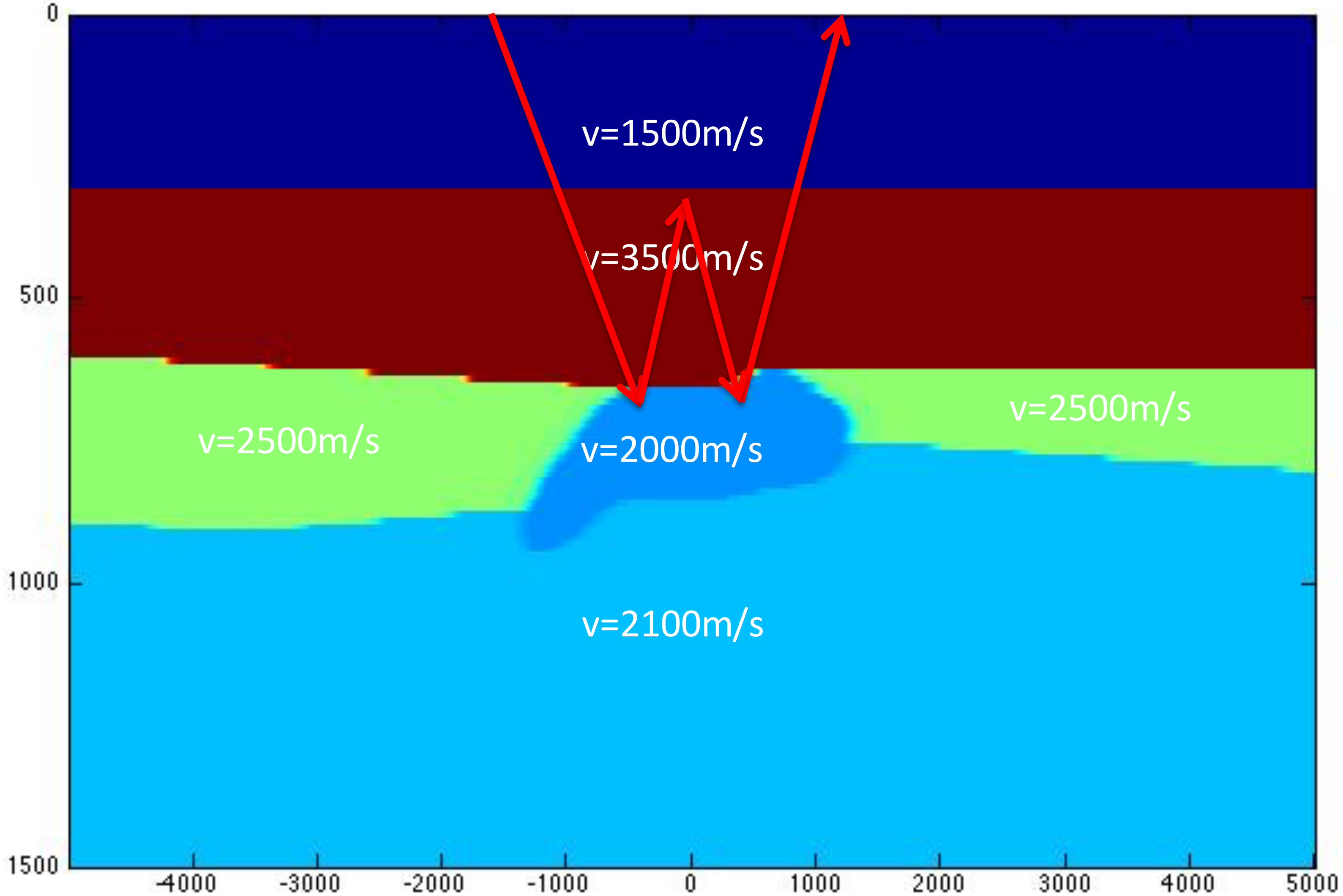
Multi-Dimensional ISS internal multiple elimination (numerical test)



Multi-Dimensional ISS internal multiple elimination
(numerical test)

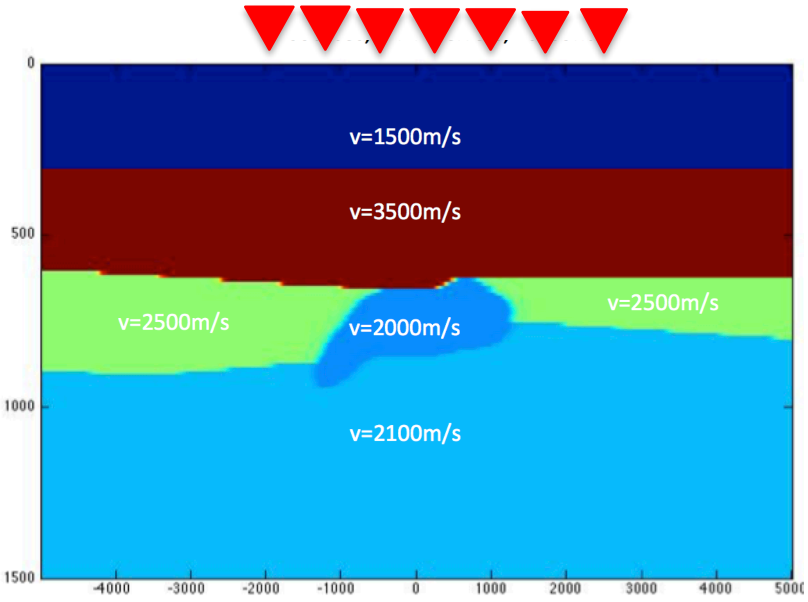


Multi-Dimensional ISS internal multiple elimination (numerical test)

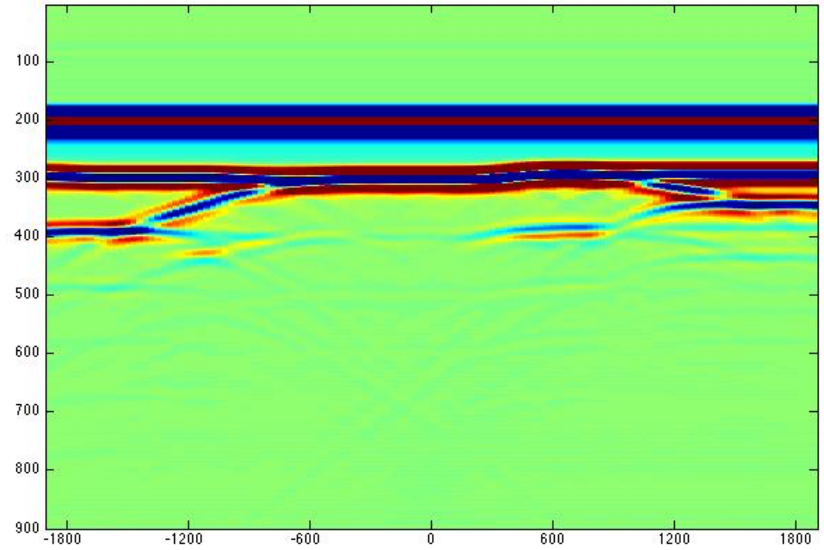


Multi-Dimensional ISS internal multiple elimination (numerical test)

model

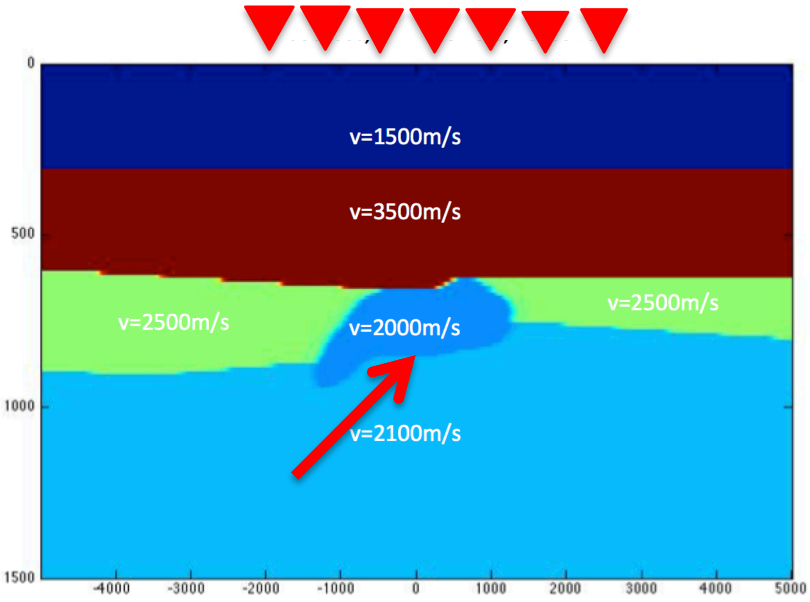


data (0-offset traces)

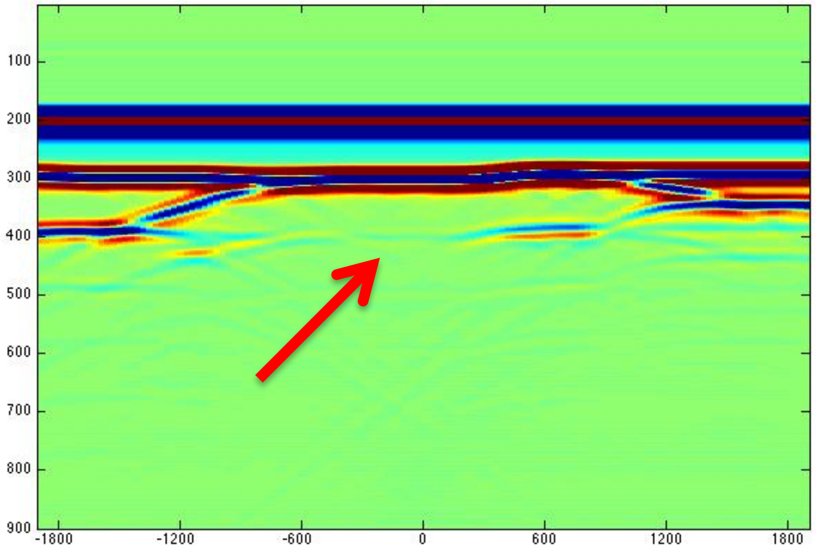


Multi-Dimensional ISS internal multiple elimination (numerical test)

model

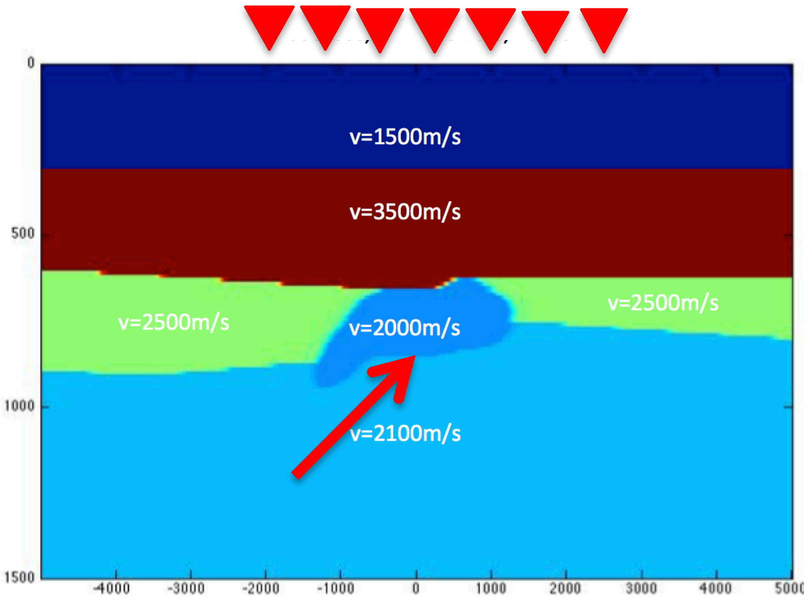


data (0-offset traces)

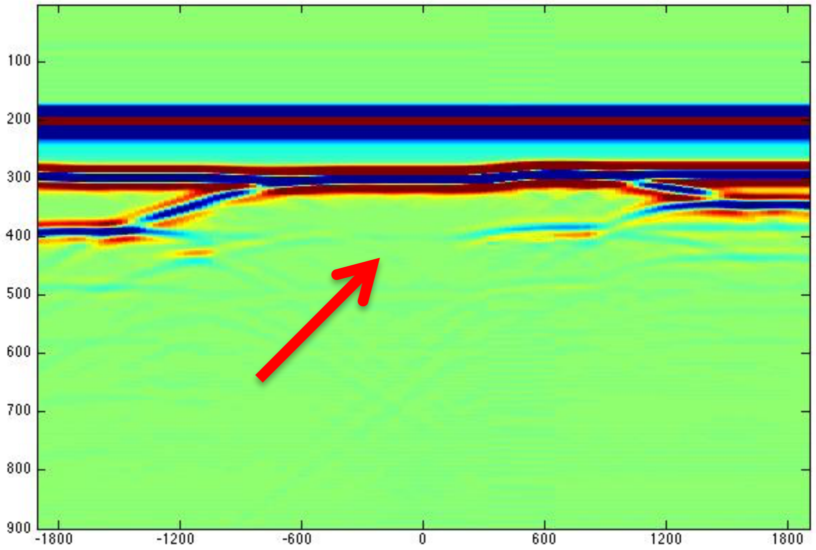


Multi-Dimensional ISS internal multiple elimination
(numerical test)

model

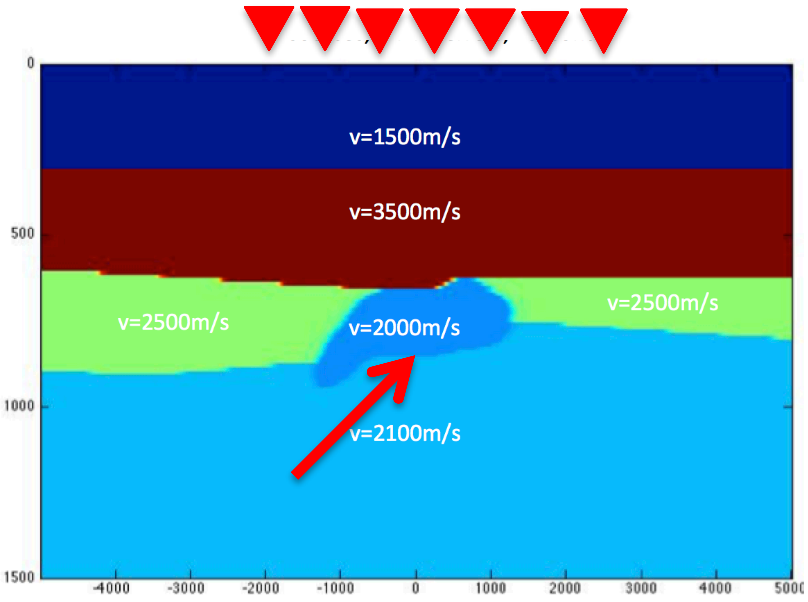


after internal multiple attenuation + energy minimization adaptive subtraction (0-offset traces)

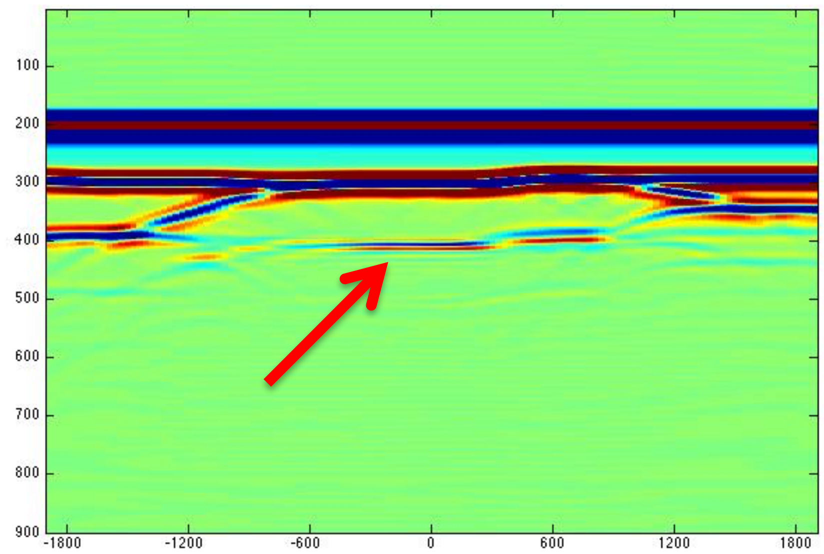


Multi-Dimensional ISS internal multiple elimination
(numerical test)

model



after internal multiple elimination (0-offset traces)



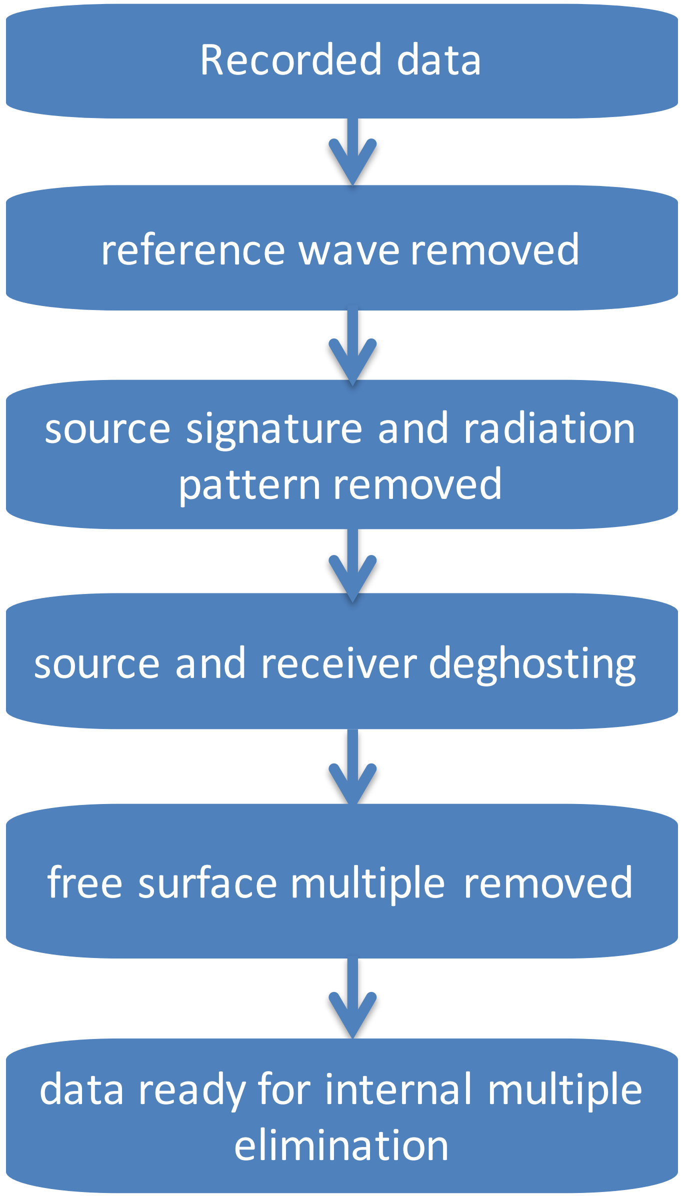
Multi-Dimensional ISS internal multiple elimination (computational requirements)

- The ISS internal-multiple attenuation and elimination algorithms are compute-intensive.
- The ISS internal-multiple elimination algorithm needs tens or hundreds more compute power than the ISS internal-multiple attenuation algorithm. (Perrone 2007, Fu et al. 2014)
- In our 2D numerical example, we use a 2D data with 127 shot gathers with each shot gather containing 127 traces and each trace containing 1000 time samples. It takes an 8-core workstation about 1 day to finish computing the elimination algorithm.

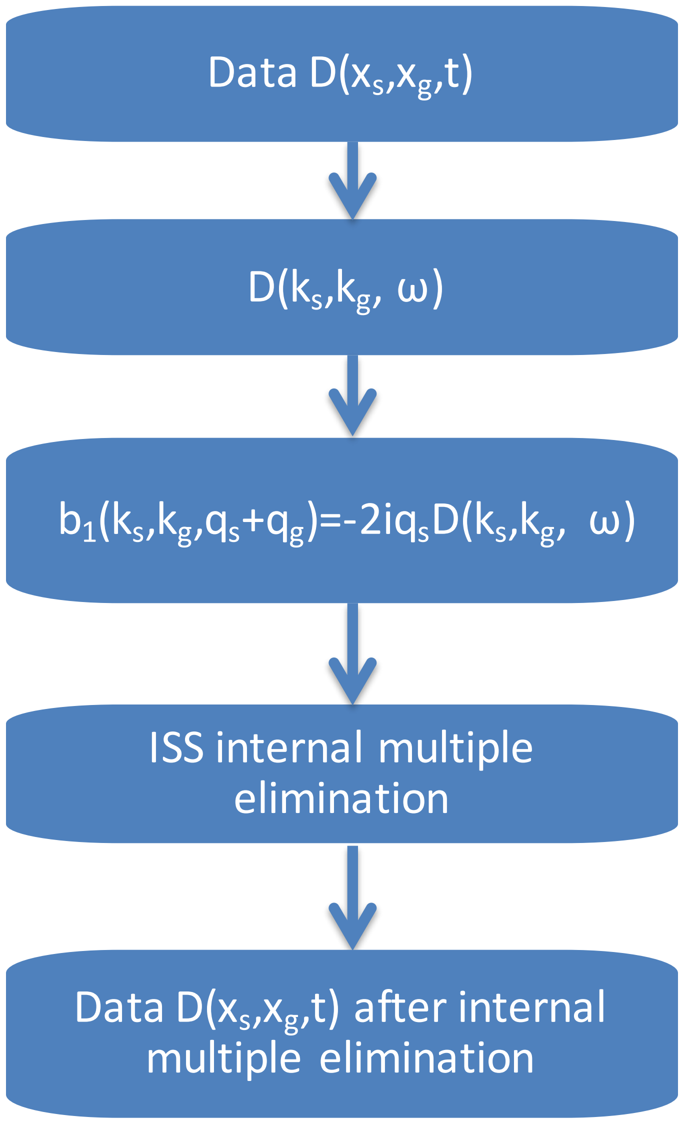
ISS internal multiple elimination

- accommodation of the topography of the acquisition surface
- adequate data collected for 2D and 3D application
- reference wave removed
- source signature and radiation pattern removed
- source and receiver deghosting
- free surface multiple removed
- The ISS internal multiple **attenuation** algorithm is **model-type independent.**
- The ISS internal multiple **elimination** algorithm (at this point) contains the **model-type independent** ISS internal multiple **attenuation** algorithm, the part that beyond attenuation is **model-type dependent.** An acoustic relationship is assumed. The elimination algorithm has been tested on elastic earth model and shows encouraging results. We will develop a more complete ISS internal multiple elimination algorithm with consideration of elastic/anelastic effects.
- In this presentation, we focus on the first-order internal multiples. The current method can be extended to remove higher order internal multiples.

Multi-Dimensional ISS internal multiple elimination (pre-requisites)



Multi-Dimensional ISS internal multiple elimination (flow chart)



Multi-Dimensional ISS internal multiple elimination (future plan and conclusion)

- The ISS internal-multiple elimination algorithm is a part of the three-pronged strategy that is a direct response to current seismic processing and interpretation challenge **when primaries and internal multiples are proximal to and/or interfere with each other** in both on-shore and off-shore plays.

- This ISS internal-multiple-elimination algorithm is **more effective and more compute-intensive** than the current most capable ISS attenuation-plus-adaptive subtraction method. We provide it as **a new capability in the multiple-removal toolbox and a new option** for circumstances when this type of capability is called for, indicated and necessary.

- We will develop a more complete ISS internal multiple elimination algorithm that includes consideration of elastic/anelastic effects.

- We are interested in **field data** to test the ISS internal multiple elimination algorithm where there is interfering primary and internal multiple and there is well control.