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

Multiple removal and prerequisite satisfaction: Current status and future plans

James D. Mayhan* and Arthur B. Weglein

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2. Show results of satisfying the prerequisites for ISS free-surface-multiple and internal-multiple algorithms with synthetic data corresponding to offshore plays
   — For ISS to reach its full potential and deliver its promise, its prerequisites must be met
3. Motivate onshore methods for satisfying ISS prerequisites

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What's the problem?

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- As exploration for hydrocarbons has moved into areas with increasingly complex geology, there are more instances in which multiples are proximal to or even overlap the primaries.
- Hence, demultiple algorithms are challenged to remove multiples without damaging proximal primaries.

A solution to add to your seismic toolbox

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- In particular, the ISS free-surface-multiple algorithm can accurately predict the phase (time) and amplitude of free-surface multiples, if its prerequisites (source signature and deghosted data) are satisfied (Carvalho et al., 1992; Weglein et al., 1997, 2003).

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- In particular, the ISS free-surface-multiple algorithm can accurately predict the phase (time) and amplitude of free-surface multiples, if its prerequisites (source signature and deghosted data) are satisfied (Carvalho et al., 1992; Weglein et al., 1997, 2003).
- This has been demonstrated on marine field data (Carvalho, 1992; Carvalho et al., 1992; Carvalho and Weglein, 1994; Weglein et al., 2003; Ferreira, 2011).

A solution to add to your seismic toolbox

- The current ISS internal-multiple algorithm can predict the exact phase (time) and an approximate amplitude of all internal multiples, at once, automatically, and without subsurface information (Araújo et al., 1994; Weglein et al., 2003).

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- This has been demonstrated on marine field data (Matson et al., 1999; Terenghi et al., 2011; Ferreira, 2011; Weglein, 2013; Goodway and Mackidd, 2013; Kelamis and Yi Luo, 2013; Ferreira et al., 2013; Dragoset, 2013; Brookes and Jenner, 2013; Griffiths et al., 2013; Hegge et al., 2013).

A solution to add to your seismic toolbox

- Those ISS properties are what all other current demultiple methods (*e.g.*, Feedback-loop methods, modeling and subtraction of multiples, and filter methods) do not possess and cannot deliver (Weglein, 1999; Weglein and Dragoset, 2005; Qiang Fu et al., 2010; Yi Luo et al., 2011; Weglein et al., 2011; Ferreira, 2011; Kelamis et al., 2013).

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- Details concerning the ISS free-surface-multiple and internal-multiple algorithms were covered in Dr. Weglein's tutorial.

But the ISS demultiple algorithms have prerequisites

- The prerequisites for ISS demultiple algorithms can be met by Green's-theorem-based algorithms (Weglein and Secrest, 1990; Weglein et al., 2002; Jingfeng Zhang and Weglein, 2005, 2006; Jingfeng Zhang, 2007).

But the ISS demultiple algorithms have prerequisites

- The prerequisites for ISS demultiple algorithms can be met by Green's-theorem-based algorithms (Weglein and Secrest, 1990; Weglein et al., 2002; Jingfeng Zhang and Weglein, 2005, 2006; Jingfeng Zhang, 2007).
- Background on Green's-theorem-based algorithms was covered in Dr. Weglein's tutorial.

- But why use Green's theorem for deghosting instead of the ISS?

- But why use Green's theorem for deghosting instead of the ISS?
- The ISS equation linear in data is $D = G_0 V G_0$, where D is the measured data (after removing the reference wave), G_0 is a known analytic Green's function, and V is the difference between the actual medium and the reference medium.

- We can deghost by replacing G_0 with the direct-wave Green's function, G_0^d (Carvalho, 1992):

$$G_0^d G_0^{-1} D G_0^{-1} G_0^d = G_0^d \underbrace{G_0^{-1} G_0}_{=I} V \underbrace{G_0 G_0^{-1}}_{=I} G_0^d$$

$$D' = G_0^d V G_0^d$$

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- However, G_0^{-1} can be unstable (near ghost notches) if we don't know the exact depth of the towed cable.
- No similar inverse function appears when using Green's theorem, provides a more stable deghosting algorithm.
- This fact motivates us to find Green's-theorem-type methods for onshore.

- Discussions of Green's-theorem deghosting in Weglein et al. (2013a,b).

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- The ability of Green's theorem to meet prerequisites has been tested on SEAM and field data (Mayhan and Weglein, 2013a; Mayhan, 2013).

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- The ability of Green's theorem to meet prerequisites has been tested on SEAM and field data (Mayhan and Weglein, 2013a; Mayhan, 2013).
- We show examples in Figures 1 - 4 that will follow.

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Green's-theorem deghosting

- Links to the current interest in broadband seismic
- Used to satisfy ISS prerequisites

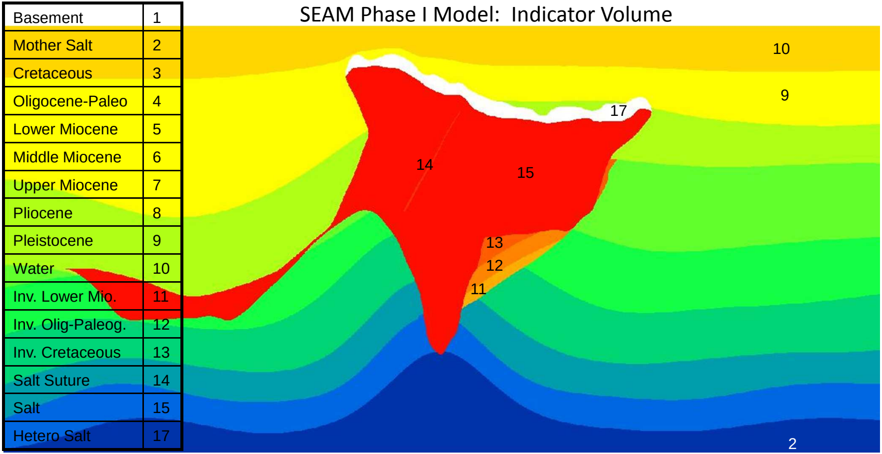


Figure 1: *SEAM deep-water Gulf of Mexico model: inline section from the middle of the model. Layers 3-8 lie sequentially between layers 2 and 9. Layer 1 isn't shown. Figure courtesy of SEAM.*

Figure 2: *SEAM data, example shot (131373), recorded data at 17 m. Tested while an intern at PGS.*

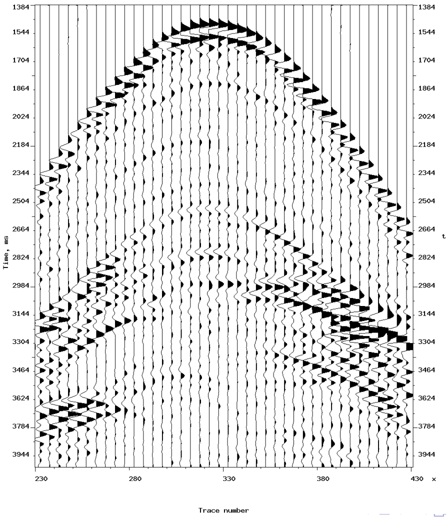
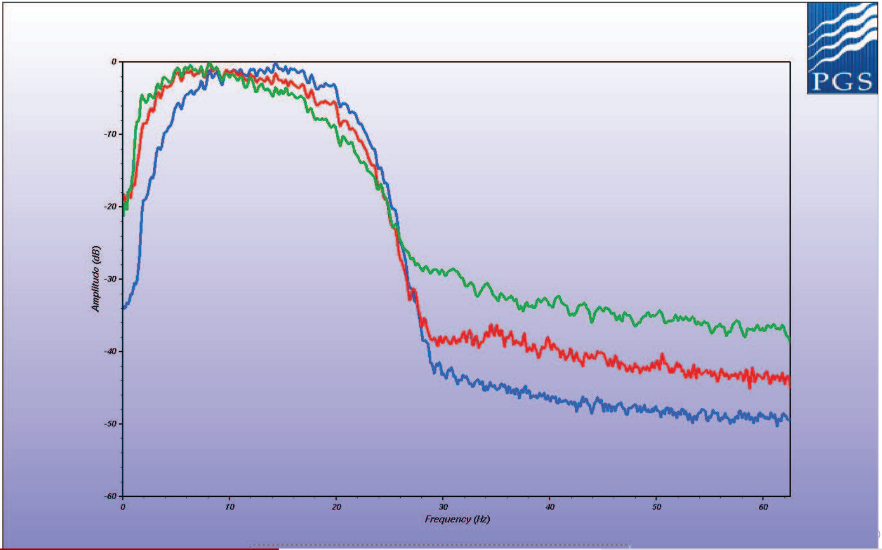


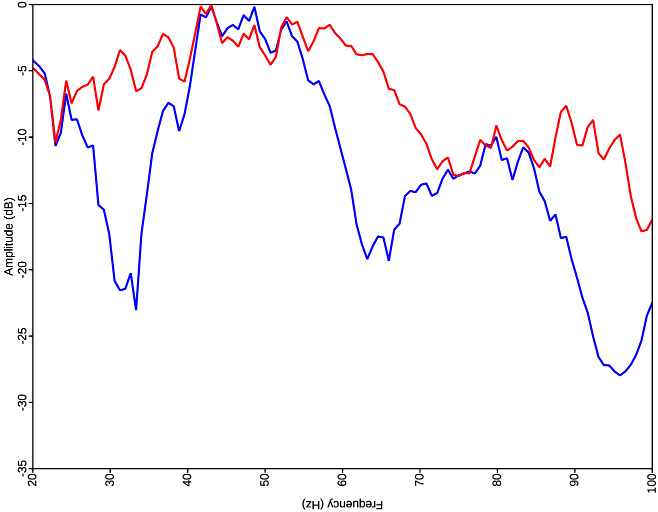
Figure 3: *Green's-theorem deghosting on SEAM data: blue=input, red=R deghosted, green=S&R deghosted*



Caption for Figure 3 on previous slide (from Mayhan and Weglein, 2013b)

- SEAM data, shot 131373, frequency spectra: blue=P at 17 m, red=receiver deghosted at 10 m using Green's theorem, green=source and receiver deghosted at 10 m using Green's theorem.
- Vertical axis=amplitude (dB), horizontal axis=frequency (Hz).
- The first source notch is at 44 Hz, which lies above the source frequency range (1–30 Hz).
- Note the shift of the spectrum towards lower frequencies (which may be of interest to FWI).

Figure 4: *Green's-theorem deghosting on field data: blue=input, red=R deghosted*

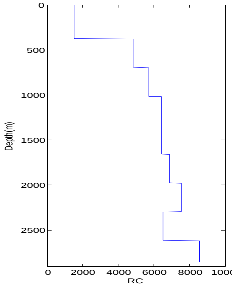


Caption for Figure 4 on previous slide (from Mayhan et al., 2011)

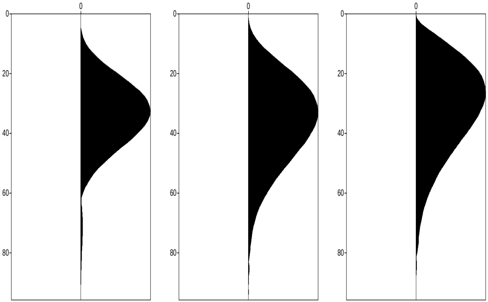
- 2D field data, shot 841, frequency spectra: blue=P at 25 m, red=receiver deghosted at the air-water boundary using Green's theorem.
- Vertical axis=amplitude (dB), horizontal axis=frequency (Hz).
- The receiver notches around 30 Hz, 60 Hz, and 90 Hz have been filled in.
- Input data courtesy of PGS.

- Zhiqiang (Justin) Wang (now at PGS) tested Green's-theorem deghosting while an intern at Total (shown in next slide)

Some of Zhiqiang Wang's deghosting results



(a) *Velocity model (provided by Total)*



(b) *Spectrum plots of the wavelets*

Figure 5: *In (b), the left panel is before deghosting, the middle panel is receiver deghosted, and the right panel is source and receiver deghosted. Both receiver deghosting and source deghosting recover more low-frequency information. (Zhiqiang Wang et al., 2012)*

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- When the prerequisites are satisfied, the prediction of multiples improves.

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- We show examples in Figures 6-13 that will follow.

- The ISS free-surface-multiple algorithm has the following form (in 2D) (Carvalho, 1992):

$$D'(k_g, k_s, \omega) = \sum_{n=1}^{\infty} D'_n(k_g, k_s, \omega), \text{ where} \tag{1}$$

$$D'_n(k_g, k_s, \omega) = \frac{1}{i\pi\rho_0 A(\omega)} \int_{-\infty}^{\infty} dk\, q \exp\left(iq(\epsilon_g + \epsilon_s)\right) \times D'_1(k_g, k, \omega) D'_{n-1}(k, k_s, \omega). \tag{2}$$

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- Summing terms D'_1 through D'_n removes free-surface multiples of orders 1 through $n-1$ — and alters higher order multiples.

Define variables in equations 1 and 2 (previous slide)

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- $A(\omega)$ is frequency spectrum of point isotropic source
- ϵ_g, ϵ_s are (fixed) receiver and source depths below the free surface
- Obliquity factor, q, is given by $q = sgn(\omega)\sqrt{\omega^2/c_0^2 - k^2}$

- Equation 2 (with the integral) requires only the source signature $A(\omega)$ and data $D'_1(k_g, k, \omega)$ (deghosted and wavelet deconvolved) as its input.

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- The free-surface multiples are predicted order-by-order and are summed (equation 1) to give the free-surface-demultipled (and deghosted) data.

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- For a more detailed discussion, please see Section 5.4 of Weglein et al. (2003).

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- The free-surface multiples are predicted order-by-order and are summed (equation 1) to give the free-surface-demultipled (and deghosted) data.
- For a more detailed discussion, please see Section 5.4 of Weglein et al. (2003).
- Equation 2 can be modified to accommodate an extended source with a radiation pattern (Jinlong Yang et al., 2013).

Model used for testing free-surface-multiple algorithm

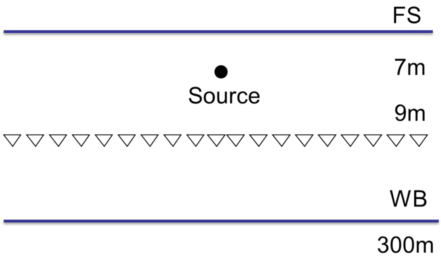
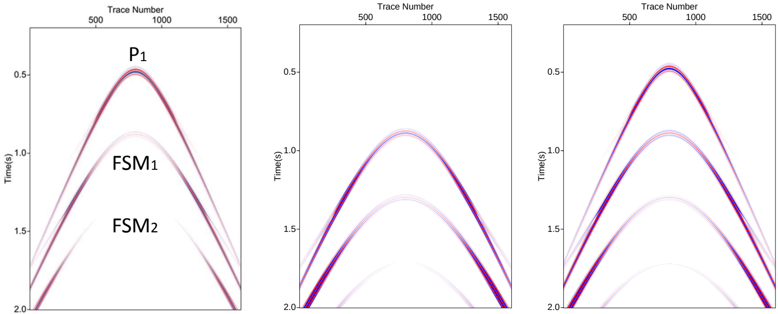


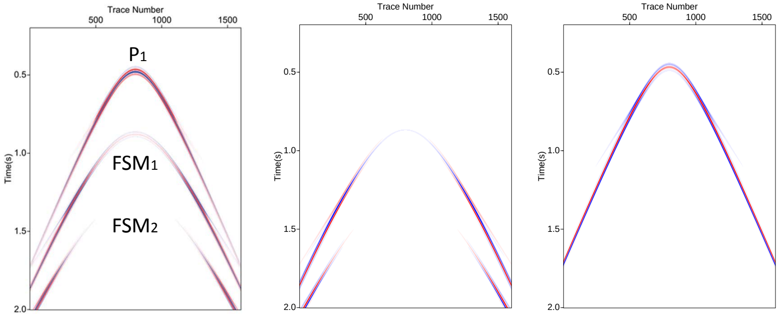
Figure 6: *Model used for Figures 7 - 10 that will follow (Jinlong Yang et al., 2012).*

Figure 7: *Free-surface-multiple elimination* ==*without*== *prior removal of ghosts (Jinlong Yang reported in Lin Tang et al., 2013)*



(a) *Input data* (b) *ISS FSM prediction* (c) *After a simple (non-adaptive) subtraction*

Figure 8: *Free-surface-multiple elimination* *with* *prior removal of ghosts (Jinlong Yang reported in Lin Tang et al., 2013)*

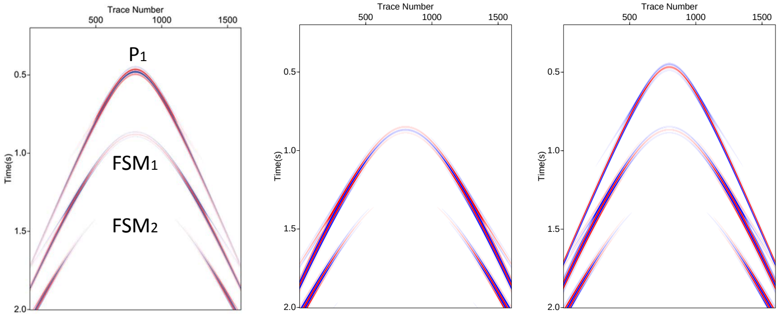


(a) *Input data*

(b) *ISS FSM prediction*

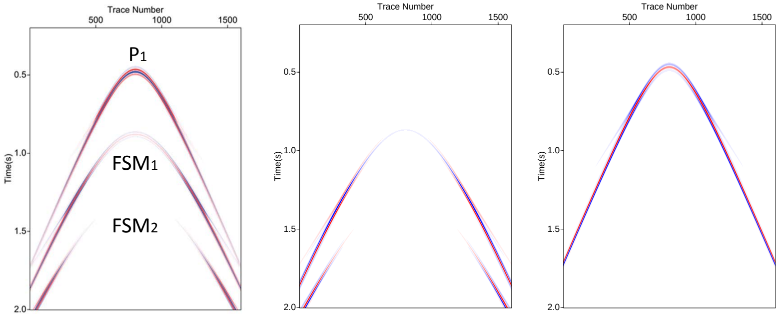
(c) *After a simple (non-adaptive) subtraction*

Figure 9: *ISS free-surface-multiple elimination* *without* *source wavelet deconvolution (Jinlong Yang et al., 2012).*



(a) *Input data* (b) *ISS FSM prediction* (c) *After a simple (non-adaptive) subtraction*

Figure 10: *ISS free-surface-multiple elimination with source wavelet deconvolution (Jinlong Yang et al., 2012).*



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ISS free-surface-multiple algorithm assumes

1. Carvalho's obliquity factor, q, given (in 2D) by
   $q = sgn(\omega)\sqrt{\omega^2/c_0^2 - k^2}$
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1. Carvalho's obliquity factor, q, given (in 2D) by $q = sgn(\omega)\sqrt{\omega^2/c_0^2 - k^2}$ — Not available in methods from other consortia
2. Wavelet removed
3. Receiver and source ghosts removed

Taking a first order equation and expecting adaptive subtraction to correct is overuse of adaptive subtraction — Make prediction as strong as possible

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The ISS internal-multiple algorithm has the following form (in 2D) (Araújo et al., 1994; Weglein et al., 2003; Terenghi et al., 2011):

$$
\begin{aligned}
& b_{3IM}(k_g, k_s, \omega) \\
=& \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} dk_1 \exp\left(iq_1(z_g - z_s)\right) \int_{-\infty}^{\infty} dk_2 \exp\left(iq_2(z_g - z_s)\right) \\
\times & \int_{-\infty}^{\infty} dz_1 b_1(k_g, k_1, z_1) \exp\left(i(q_g + q_1)z_1\right) \\
\times & \int_{-\infty}^{z_1-\varepsilon} dz_2 b_1(k_1, k_2, z_2) \exp\left(-i(q_1 + q_2)z_2\right) \\
\times & \int_{z_2+\varepsilon}^{\infty} dz_3 b_1(k_2, k_s, z_3) \exp\left(i(q_2 + q_s)z_3\right)
\end{aligned} \tag{3}
$$

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- $b_1(k_g, k_s, z)$ corresponds to effective incident plane-wave data in the pseudodepth domain

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- $b_1(k_g, k_s, z)$ corresponds to effective incident plane-wave data in the pseudodepth domain
- For a more detailed discussion please see Section 6 of Weglein et al. (2003).

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- A new ISS algorithm is being developed to eliminate (rather than attenuate) internal multiples (Yanglei Zou and Weglein, 2014a,b).

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- A new ISS algorithm is being developed to eliminate (rather than attenuate) internal multiples (Yanglei Zou and Weglein, 2014a,b).
- As in the free-surface-multiple case, equation 3 can be modified to accommodate an extended source with a radiation pattern (Jinlong Yang et al., 2014).

Model used for testing internal-multiple algorithm

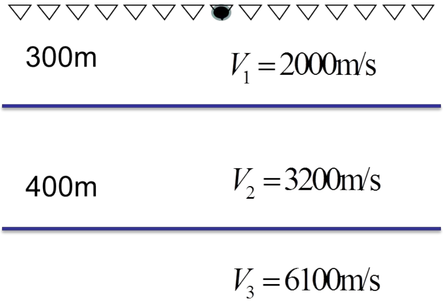
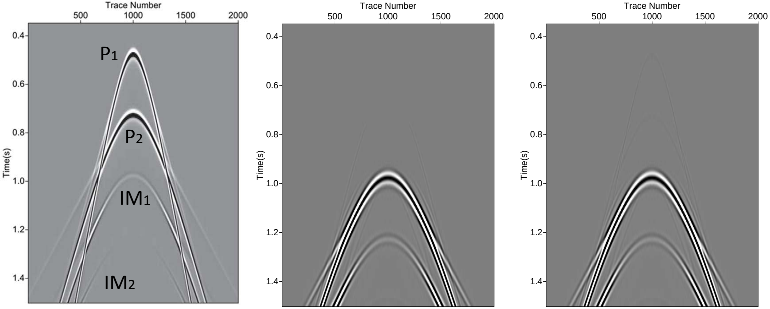


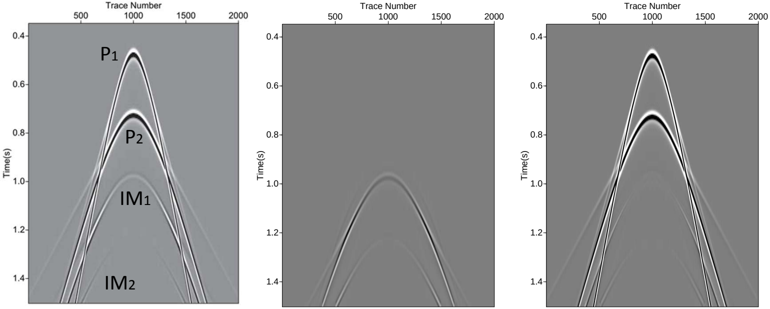
Figure 11: *Model used for Figures 12 and 13 that will follow. (Jinlong Yang et al., 2013, 2014b).*

Figure 12: *ISS internal-multiple attenuation* ***without*** *source wavelet deconvolution (Jinlong Yang et al., 2014a,b).*



(a) *Input data* (b) *ISS IM prediction* (c) *After a simple (non-adaptive) subtraction*

Figure 13: *ISS internal-multiple attenuation with source wavelet deconvolution (Jinlong Yang et al., 2014a).*



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ISS internal-multiple algorithm assumes

1. Same as free-surface-multiple algorithm plus free-surface multiples removed

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- Use of Green's theorem to satisfy ISS prerequisites, as is currently performed for marine seismic data, is discussed in Jing Wu et al. (2014b), and a method for finding the reference velocity in the near surface is discussed in Lin Tang's presentation.

[1] Rayleigh waves, *i.e.*, longitudinal and transverse waves that travel near the surface

- Use of Green's theorem to satisfy ISS prerequisites, as is currently performed for marine seismic data, is discussed in Jing Wu et al. (2014b), and a method for finding the reference velocity in the near surface is discussed in Lin Tang's presentation.
- Use of Green's theorem to remove ground roll[1] is discussed in Jing Wu's first presentation.

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Revisiting the purposes of this talk:

1. We show ISS prerequisites are achievable on synthetic and field data

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1. We show ISS prerequisites are achievable on synthetic and field data
2. We show the impact of preprocessing on ISS multiple removal

Revisiting the purposes of this talk:

1. We show ISS prerequisites are achievable on synthetic and field data
2. We show the impact of preprocessing on ISS multiple removal
3. We want the same for onshore

Revisiting the purposes of this talk:

- In complex geology, adaptive subtraction can't fix everything we leave out

Revisiting the purposes of this talk:

- In complex geology, adaptive subtraction can't fix everything we leave out
- Prerequisites matter more because we're after multiple elimination

Revisiting the purposes of this talk:

- In complex geology, adaptive subtraction can't fix everything we leave out
- Prerequisites matter more because we're after multiple elimination
- Successes in marine are motivating us to do the same on land

Code currently available on sponsors-only portion of mosrp.uh.edu:

- Modeling
  — Cagniard-de Hoop forward modeling (1D acoustic earth, line source)
  — Finite-difference forward modeling (2D acoustic earth, line source)

Code currently available on sponsors-only portion of mosrp.uh.edu:

- Modeling
  — Cagniard-de Hoop forward modeling (1D acoustic earth, line source)
  — Finite-difference forward modeling (2D acoustic earth, line source)
- Preprocessing
  — Green's-theorem marine-data preprocessing (2D or 3D data sets)

Code currently available on sponsors-only portion of mosrp.uh.edu:

- Multiple removal
  — ISS free-surface-multiple elimination (3D data sets)
  — ISS internal-multiple attenuation (1.5D, 2D, or 3D data sets, including limited aperture version)

Code currently available on sponsors-only portion of mosrp.uh.edu:

- Multiple removal
  — ISS free-surface-multiple elimination (3D data sets)
  — ISS internal-multiple attenuation (1.5D, 2D, or 3D data sets, including limited aperture version)
- Adaptive subtraction

To access the code

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- Code listed in reverse chronological order (most recent code first)
- Code has documentation, assumes working knowledge of Linux, Seismic Unix, MPI, C, Fortran

New MOSRP_SU Collection of Seismic Data Processing Codes Based on Seismic Unix

Download Code: MOSRP_SU_20120708.tar.gz (43 MB)

MOSRP_SU is a software package based on and fully consistent with CWP/SU, composed of a variety of programs developed at M-OSRP.

The current release features:

- A revised and improved version of the Green's theorem marine-data preprocessing codes. The code was rewritten (1) to make it more like M-OSRP's demultiple code (which decreases run time and corrects a bug uncovered in testing at PGS) and (2) to add the "double Dirichlet" Green's function (which enables source-side deghosting when over/under sources are not available).

  Like Release 1, Release 2 uses Green's theorem and measurements of P and its normal derivative to deghost P. It is assumed these are measured by a dual-sensor cable or dual (over/under) streamers. Release 2 includes the Green's theorem code, two files containing analytic test data (P and its normal derivative), and user documentation.
- Two new implementations of the leading order ISS internal multiple attenuation algorithm. The first applies to a horizontally layered earth and the second to an earth with lateral variations. Thanks to full control on the algorithm's aperture and capability to accommodate 3-dimensional aperture and dip, the cost of computations can be tightly proportioned to the characteristics of each particular application. Additionally, useful approximated internal multiple predictions can be achieved using a fraction of the computer effort required for the full computation.

Following talks will cover:

- How back out onshore reference properties (Lin Tang)

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- How back out onshore reference properties (Lin Tang)
- How predict onshore reference wave (Jing Wu)
- The importance of collecting the right data onshore (Qiang Fu)

- We thank the M-OSRP sponsors for their encouragement and support.

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