Addressing on-shore challenges: A method to remove the need to know, estimate or determine near surface properties for seismic preprocessing and processing methods: Part I, basic concept and initial examples

Arthur B. Weglein[*]

ABSTRACT

The current inability to provide adequate information about the overburden above a target has been and remains an open and very serious issue for seismic preprocessing and processing. There are current methods for preprocessing based on Green's theorem, and for processing that derive from the inverse scattering series (ISS), that do not need or require subsurface information. That is, they do not require any information starting at some depth below where sources and receivers reside (that is, beneath the measurement surfaces). However, they do require information at, and immediately beneath, the measurement surface (MS) (and the latter defines the "near surface"). For on-shore and OBS applications, the need for near-surface information (often hard to define, let alone to determine) is a major hurdle, a largely unsolved problem, open issue and challenge. In this paper, we introduce a new concept and method for seismic processing that removes the need to know, estimate or to determine both subsurface and near surface properties. We illustrate the idea with an example where there is both a localized heterogeneous change in velocity at the earth's surface, and a separate heterogeneity in velocity at depth in the subsurface, and both start out and remain unknown while providing a successful processing result. The localized velocity heterogeneity at the earth's surface represents the ultimate near surface property change. The localized heterogeneity in velocity at depth represents a change in velocity in the subsurface.

INTRODUCTION:

There is an extensive literature on the evolution and development of direct processing methods that do not need to know, estimate or to determine subsurface information. [please see, e.g., Weglein, 2019b]

As an introduction, we suggest the reference below of a recent key-note address presented at the 2019 SEG/KOC workshop on Multiples in Kuwait "A New Perspective on Removing and Using Multiples" [please see Weglein, 2019a]

In addition, Weglein et al. (2020) provides an invited presentation for the 2020 EAGE Workshop on Multiples with a succinct perspective on the topic of removing free surface and internal multiples.

The Green's theorem methods for preprocessing — and the ISS methods for multiple removal, Q compensation, depth imaging and amplitude analysis are each able to perform their specific task directly and without subsurface information to be known, estimated or determined. The ISS methods for removing free surface and internal multiples represent the high water mark of current multiple removal capability. They remove all multiples, and can automatically accommodate specular and non-specular reflectors, including curved reflectors and pinchouts without subsurface information or any knowledge of the generators of the multiples. They are the only methods with that set of capabilities (Weglein et al., 2020). The key word here (for the purposes of this paper) is <u>sub</u>surface, and by subsurface is meant starting at some depth <u>beneath</u> the surface(s) where the sources and receivers reside (that is, the measurement surface(s)). The latter implies (and assumes) that medium properties are known at and to some small depth beneath the measurement surface.

That near-surface information requirement is not a problem for towed streamer marine acquisition and processing. However, it is a major issue and challenge for on-shore and OBS plays.

CHALLENGES FOR ON-SHORE SURVEYS

Weglein (2013) proposed a three-pronged strategy for addressing on-shore challenges. One of those three relates to finding a way to (either determine or) avoid the need for near surface information.

All current methods for predicting ground roll and reflection data are filtering techniques that can remove ground roll while damaging reflection data. There is recent significant progress in predicting the reference wave (that includes the ground roll) and reflection data (without filtering or damaging either), e.g., without needing or determining subsurface properties, but requiring near surface information [Wu and Weglein, 2015b]. Similarly, Zhang and Weglein (2006) and Matson and Weglein (1996) provide methods for onshore and OBC deghosting and demultiple, respectively, and did not require subsurface information but (once again) required near-surface information.

This paper is the first step in a new research initiative to extend the original Green's theorem preprocessing and ISS processing methods to allow them to be applied to on-shore and OBS plays, without needing to know, estimate or determine *<u>both</u>* subsurface and *<u>near surface</u>* properties.

The model we will employ (to illustrate the new concept and method) will have two localized heterogeneities in velocity, one located at depth, in the subsurface, and the second located at the earth's surface where the source and receiver will be made to reside. We will show that the original Green's theorem preprocessing method [for separately predicting the reference and the scattered wave, P_0 and P_s, respectively] (Weglein and Secrest, 1990; Wu and Weglein, 2017) can be extended to allow for an unknown velocity at depth <u>and</u> an unknown velocity at the earth's surface.

As we noted above, for on-shore applications [Wu and We-

---

[*] M-OSRP/Physics Dept./UH

glein, 2015b] the reference wavefield prediction of P_0 will include the ground roll. Although we apply the idea of how to make this extension to the specific goal of separately predicting P_0 and P_s, the concept is general, and can be applied to deghosting (Weglein et al., 2002; Zhang and Weglein, 2005, 2006; Zhang, 2007; Mayhan and Weglein, 2013; Zhang and Weglein, 2016, 2017; Wu and Weglein, 2014, 2015a,b, 2016, 2017) and to multiple removal (Carvalho et al., 1992; Araújo et al., 1994; Weglein et al., 1997, 2003, 2007; Matson and Weglein, 1996; Amundsen and Zhou, 2013; Sun and Innanen, 2019; Zou et al., 2019; Ma et al., 2019) and imaging (Weglein et al., 2016) and migration-inversion (e.g., Stolt and Weglein, 1985, 2012; Zhang, 2006; Liang, 2013; Li, 2011).

THEORY/BACKGROUND

The first step in the seismic processing chain is predicting P_0 and P_s. In this paper we apply the new method to that task.

We will keep the derivation as simple (and accessible) as possible. Let's consider a one dimensional heterogeneous acoustic medium that satisfies

$$\left[\frac{d^2}{dx^2}+\frac{\omega^2}{c^2(x)}\right]P(x,\omega)=A_s\delta(x-x_s) \tag{1}$$

where $c(x)$ is the heterogeneous velocity configuration and the energy source is $A_s\delta(x-x_s)$. A_s is a constant, and ω is the temporal frequency.

In equation (1) we now characterize the velocity configuration $c(x)$ in terms of a constant reference velocity c_0 and a perturbation $\alpha(x)$ defined as follows

$$\frac{1}{c^2(x)}=\frac{1}{c_0^2}(1-\alpha(x)). \tag{2}$$

Equation (1) becomes

$$\left[\frac{d^2}{dx^2}+\frac{\omega^2}{c_0^2}\right]P(x,\omega)=\frac{\omega^2}{c_0^2}\alpha(x)P(x,\omega)+A_s\delta(x-x_s) \tag{3}$$

and with $\rho(x,\omega)$ defined as

$$\rho(x,\omega)\equiv k^2\alpha(x)P(x,\omega)+A_s\delta(x-x_s) \tag{4}$$

and ($k\equiv\omega/c_0$), equation (3) becomes

$$\left(\frac{d^2}{dx^2}+k^2\right)P(x,\omega)=\rho(x,\omega). \tag{5}$$

The associated Green's function for equation 5 is

$$\left(\frac{d^2}{dx^2}+k^2\right)G_0(x,x',\omega)=\delta(x-x'). \tag{6}$$

The subscript on G indicates that it relates to c_0. The causal solution of (6) G_0^+ is

$$G_0^+(x,x',\omega)=\frac{e^{+ik|x-x'|}}{2ik}. \tag{7}$$

The P_0,P_s prediction for the marine case (Figure 1) is detailed in Weglein and Secrest (1990) including the case of an air-water boundary [the free surface], and for an acoustic and elastic subsurface. That theory assumed (and required) that the energy source resided above, and the earth resided beneath, the measurement surface where the receivers were located. That required the passive source [e.g., $k^2\alpha P$] of the scattered field to be beneath the (receiver) MS.

However, for on-shore plays (see e.g., Figure 2) those assumptions are violated: the source resides on the receiver measurement surface and the earth begins at the receiver measurement surface, as well.

In papers and theses that address either on-shore or OBS P_0,P_s prediction (e.g. Wu and Weglein, 2014, 2015a,b, 2016, 2017) or multiple removal (Matson and Weglein, 1996) in order to keep the unknown earth [e.g. 'α'] to begin in the subsurface beneath the measurement surface, the near surface and on the receiver MS properties were assumed to be known. Those near-surface properties then had to be included in the reference medium. That's the problem; and that's exactly what this paper is addressing.

The key result (in 1D) for the P_0,P_s prediction follows from Weglein and Secrest (1990). For the example of Figure 3 we have:

$$\begin{aligned}P_0(x,\omega)&=\int_{-\infty}^{a}\rho(x',\omega)G_0^+(x,x',\omega)\,dx'\\&=|_{x'=a}^{\infty}\{P(x',\omega)\frac{d}{dx'}G_0^+(x,x',\omega)\\&\quad-G_0^+(x,x',\omega)\frac{d}{dx'}P(x',\omega)\}\end{aligned} \tag{8a}$$

valid for $x>a$, and

$$\begin{aligned}P_s(x,\omega)&=\int_{a}^{\infty}\rho(x',\omega)G_0^+(x,x',\omega)\,dx'\\&=+|_{x'=\infty}^{a}[P(x',\omega)\frac{d}{dx'}G_0^+(x,x',\omega)\\&\quad-G_0^+(x,x',\omega)\frac{d}{dx'}P(x',\omega)]\end{aligned} \tag{8b}$$

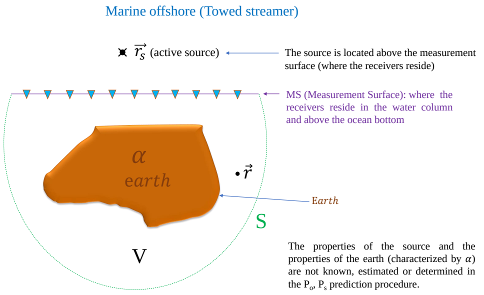
for $x<a$.

In the example illustrated in Figure 3 we will show how to extend the above method so that the unknown earth can extend up to the receiver measurement surface, and the active source can reside on the receiver measurement surface, as well.

In this way we have removed the need for both the reference medium to agree with the actual medium at and beneath the receiver MS, and for the source to be above the receiver MS. Hence, the properties of both the active source on the earth's surface and the near-surface and subsurface properties need not be known, estimated or determined.

EXAMPLE WITH TWO LOCALIZED HETEROGENEITIES

We consider the prediction of P_0 and P_s for the case of two localized heterogeneous velocities at x_1 and x_2. The mea-

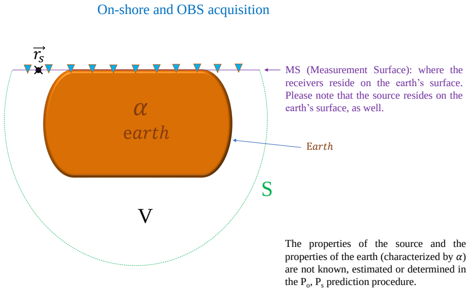


The source is located above the measurement surface (where the receivers reside)

MS (Measurement Surface): where the receivers reside in the water column and above the ocean bottom

The properties of the source and the properties of the earth (characterized by α) are not known, estimated or determined in the P_o, P_s prediction procedure.

Figure 1: *Towed streamer (marine geometry)*



MS (Measurement Surface): where the receivers reside on the earth's surface. Please note that the source resides on the earth's surface, as well.

The properties of the source and the properties of the earth (characterized by α) are not known, estimated or determined in the P_o, P_s prediction procedure.

Figure 2: *On-shore geometry (Land and OBS)*

surement surface is at x='a', and we first assume both heterogeneities are deeper than 'a', and the source is shallower than 'a'. The output point, x, (where P_0 and P_s are predicted) is (at first) beneath the measurement surface where P_0 is predicted. The prediction at the output point $'x'$, doesn't require any knowledge about the three sources above or below the measurement surface. We demonstrate that first. Then we arrange for x_s, x_1 and the output point x to all be on the measurement surface — and show that the wave prediction doesn't require knowledge of the energy source, the velocity heterogeneity on the earth's surface, and the velocity heterogeneity at depth.

For this example we choose

$$\alpha(x) = \lambda_1 \delta(x - x_1) + \lambda_2 \delta(x - x_2)$$

(please see Figure 3) and we find

$$\begin{aligned} P(x,\omega) = A\frac{e^{ik|x-x_s|}}{2ik} &+ \frac{k^2\lambda_1}{2ik}e^{ik|x-x_1|}P(x_1,\omega) \\ &+ \frac{k^2\lambda_2}{2ik}e^{ik|x-x_2|}P(x_2,\omega) \end{aligned} \tag{9}$$

using

$$P(x,\omega) = \int_{-\infty}^{\infty} G_0^+(x,x',\omega)\rho(x',\omega)\,dx'$$

$-\infty < x < \infty$.

As in Weglein and Secrest (1990) the right hand side of (8a), is the part of the field in $a < x < \infty$ due to the sources <u>outside</u> that interval, i.e. due to sources at $-\infty < x < a$, that is, P_0.

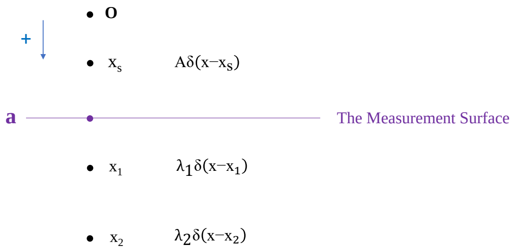


Figure 3: <u>allowing for two heterogeneities one at, and one beneath the earth's surface</u>: (1) a source at x_s is at first above and then at the earth's surface $x_s = a$, (2) a heterogeneity in velocity at x_1 located at first beneath and then at the earth's surface, (at $x_1 = a$) and (3) a different heterogeneity in velocity located in the subsurface beneath the earth's surface at $x = x_2$.

[The $x' = \pm\infty$ contribution in (8a) and (8b) will vanish with an entry (and then removal) of a small imaginary component of velocity.]

We compute P_0 from 8a for the example in Figure 3

$$\begin{aligned} P_0(x,\omega) &= -|_{x'=a}(PG_0' - G_0P') \\ &= \left[\frac{Ae^{ik|a-x_s|}}{2ik}\frac{1}{2}sgn(a-x)e^{ik|x-a|}\right. \\ &\quad + \frac{k\lambda_1}{2i}e^{ik|a-x_1|}B\frac{1}{2}sgn(a-x)e^{ik|x-a|} \\ &\quad \left. + \frac{k\lambda_2}{2i}e^{ik|a-x_2|}C\cdot\frac{1}{2}sgn(a-x)e^{ik|x-a|}\right] \\ &\quad - \left[\frac{Ae^{ik|a-x_s|}}{2ik}ik\,sgn(a-x_s)\cdot\frac{e^{ik|x-a|}}{2ik}\right. \\ &\quad + \frac{k\lambda_1}{2i}e^{ik|a-x_1|}ik\,sgn(a-x_1)B\frac{e^{ik|x-a|}}{2ik} \\ &\quad \left. + \frac{k\lambda_2}{2i}e^{ik|a-x_2|}ik\,sgn(a-x_2)C\frac{e^{ik|x-a|}}{2ik}\right] \end{aligned} \tag{10}$$

for $x > a$ where $\left[\textcircled{1}\right]_{\textcircled{1}} = B$

$\left[\textcircled{1}'\right]_{\textcircled{1}'} = C$ where

$$\{\textcircled{1}\}_{\textcircled{1}}$$

$$= \left\{\left[\frac{k\lambda_2}{2i}\left[-\frac{Ae^{ik|x_1-x_s|}}{2ik} + \frac{Ae^{ik|x_2-x_s|}}{2ik}\right] + \frac{A}{2ik}e^{ik|x_1-x_s|}\right]\right\} \Big/ \left\{1 - \frac{k(\lambda_1+\lambda_2)}{2i}\right\}$$

$$\{\textcircled{1}'\}_{\textcircled{1}'}$$

$$= \left\{\left[\frac{k\lambda_1}{2i}\left[-\frac{Ae^{ik|x_2-x_s|}}{2ik} + \frac{Ae^{ik|x_1-x_s|}}{2ik}\right] + \frac{A}{2ik}e^{ik|x_2-x_s|}\right]\right\} \Big/ \left\{1 - \frac{k(\lambda_1+\lambda_2)}{2i}\right\}$$

The signs in (10) are determined by the relative locations of x_s, a, x_1, and x_2.

In Figure (3) we have

$$\begin{aligned} x &> a & sgn(a-x) &= - \\ x_1 &> a & sgn(x_1-a) &= + \\ x_2 &> a & sgn(x_2-a) &= + \\ x_s &< a & sgn(a-x_s) &= +. \end{aligned}$$

That is with $x_s < a$, $x_1 > a$, $x_2 > a$, $x > a$ the result is becomes

$$\begin{aligned} & \frac{Ae^{ik(a-x_s)}}{2ik}e^{ik(x-a)}\frac{1}{2}\overbrace{sgn(a-x)}^{-} \\ & +\frac{k\lambda_1}{2i}e^{ik(x_1-a)}Be^{ik(x-a)}\frac{1}{2}\overbrace{sgn(a-x)}^{-} \\ & +\frac{k\lambda_2}{2i}e^{ik(x_2-a)}Ce^{ik(x-a)}\cdot\frac{1}{2}\overbrace{sgn(a-x)}^{-} \\ & -\frac{Ae^{ik(a-x_s)}}{2ik}ik\overbrace{sgn(a-x_s)}^{+}\frac{e^{ik(x-a)}}{2ik} \\ & -\frac{k\lambda_1}{2i}e^{ik(x_1-a)}ik\overbrace{sgn(a-x_1)}^{-}B\frac{e^{ik(x-a)}}{2ik} \\ & -\frac{k\lambda_2}{2i}e^{ik(x_2-a)}ik\overbrace{sgn(a-x_2)}^{-}C\frac{e^{ik(x-a)}}{2ik} \\ & = -\frac{A}{2}\frac{e^{ik(x-x_s)}}{2ik} \\ & -\frac{A}{2}\frac{e^{ik(x-x_s)}}{2ik} \end{aligned}$$

$$\therefore\ PG' - GP = -\frac{Ae^{ik(x-x_s)}}{2ik}$$

for $x > a$ and

$$\begin{aligned} -|_{x'=a}PG' - GP' &= \frac{Ae^{ik(x-x_s)}}{2ik} \\ &= \frac{Ae^{ik|x-x_s|}}{2ik} \end{aligned}$$

and is (as expected) the portion of the field inside $x > a$ due to the source outside $a < x < \infty$, i.e., due to x_s which is located at $x < a$. The right hand side of [10] predicts P_0.

P_0 AND P_S PREDICTION FOR ON-SHORE AND OBS APPLICATION

P_0 and P_s can be predicted at the receiver MS with the energy source at the receiver MS and with no known or determined subsurface and near-surface properties by an informed and purposeful choice of signs in 8a, 8b and 10. For example in [10] we now choose $sgn(a-x_1)$ when $x_1 = a$, $sgn(0)$, to be $\ominus$, the $sgn(a-x_s)$ when $x_s = a$ to be $\oplus$ and $sgn(a-x)$ to be negative $\ominus$ when $x = a$ then we can predict P_0 the portion of the field due to a source at the measurement surface $x_s = a$ at $x = a$. Both the heterogeneity at x_1 [when placed at the receiver MS that is on the earth's surface, $x_1 = a$] and the localized heterogeneity at x_2 for $x_2 > a$ do not need to be known, estimated or determined.

If we define the sign of zero for sign (x-a) to be positive, when x=a, the prediction from the right hand side of equation 8a, (10) will be P_0, the reference field, when the outpoint x is at the receiver measurement surface, a. And if we define sign (x-a) at x=a to be negative at $x = a$, then equation 8a will predict $-P_s$, the negative of the scattered field at x=a. Similarly if we define the sign of zero, for sign $(x_s - a)$ to be negative, the x_s surface at $x_s = a$ will be part of the region shallower than $x_s = a$. And in the same way if we define sign of zero when $x_1 = a$, that is the sign $(x_1 - a)$ to be positive, then the heterogeneity at the earth's surface is part of the volume beneath the surface of the earth, which starts out and remains unknown. This allows the separate prediction of the reference wave (including the ground roll) and the reflection data (P_s) as in Wu and Weglein (2014, 2015a,b, 2016, 2017), for measurements on the surface of the earth to be achieved without any knowledge of the source and both subsurface and near surface properties.

All subsequent processing for deghosting, free surface and internal multiple removal, Q compensation, depth imaging and inversion, can be extended in a similar way.

While ISS processing methods have no need to know, estimate or to determine subsurface properties, they do require and assume that the earlier steps in the processing chain be carried out effectively. The development of new onshore preprocessing and processing methods that do not need near surface information would be an important advance towards satisfying that assumption and requirement.

CONCLUSION

The new advance in this paper allows the energy source, the earth's surface and the output point, x, to all reside on the surface where receivers reside and to predict P_0 and P_s at the receiver measurement surface without damaging either. That prediction is without needing to know, estimate or to determine the property of the energy source or the near surface or subsurface properties of the earth. The method illustrated here can be used for all preprocessing and processing objectives.

ACKNOWLEDGMENT

We thank the M-OSRP sponsors for their encouragement and support. We thank Jing Wu, Jim Mayhan and Chao Ma for useful discussions. We thank Jim Mayhan for help and assist with this manuscript and Hasan Salehi Najafabadi for the excellent drafting of the figures.

REFERENCES

Amundsen, L., and H. Zhou, 2013, Low-frequency seismic deghosting: Geophysics, **78**, WA15–WA20.

Araújo, F. V., A. B. Weglein, P. M. Carvalho, and R. H. Stolt, 1994, Inverse scattering series for multiple attenuation: An example with surface and internal multiples: 64th Annual International Meeting, SEG, Expanded Abstracts, 1039–1041.

Carvalho, P. M., A. B. Weglein, and R. H. Stolt, 1992, Nonlinear inverse scattering for multiple suppression: Application to real data. Part I: 62nd Annual International Meeting, SEG, Expanded Abstracts, 1093–1095.

Li, X., 2011, I.- Multi-parameter depth imaging using the inverse scattering series; II.- Multi-component direct nonlinear inversion for elastic earth properties using the inverse scattering series: PhD thesis, University of Houston.

Liang, H., 2013, Addressing several key outstanding issues and extending the capability of the inverse scattering subseries for internal multiple attenuation, depth imaging, and parameter estimation: PhD thesis, University of Houston.

Ma, C., Q. Fu, and A. B. Weglein, 2019, Comparison of the Inverse Scattering Series (ISS) Free-Surface Multiple-Elimination (FSME) algorithm, and the industry-standard SRME: Defining the circumstances where each method is the appropriate tool-box choice: Geophysics, **84**, S459–S478.

Matson, K., and A. B. Weglein, 1996, Removal of elastic interface multiples from land and ocean bottom data using inverse scattering: 66th Annual International Meeting, SEG, Expanded Abstracts, 1526–1530.

Mayhan, J. D., and A. B. Weglein, 2013, First application of Green's theorem-derived source and receiver deghosting on deep-water Gulf of Mexico synthetic (SEAM) and field data: Geophysics, **78**, WA77–WA89.

Stolt, R. H., and A. B. Weglein, 1985, Migration and inversion of seismic data: Geophysics, **50**, 2458–2472.

———, 2012, Seismic imaging and inversion: Application of linear inverse theory: Cambridge University Press.

Sun, J., and K. A. Innanen, 2019, A plane-wave formulation of elastic multicomponent inverse scattering series internal multiple prediction: Geophysics, **84**, V255–V269.

Weglein, A., 2019a, A new perspective on removing and using multiples: They have the same exact goal, imaging primaries: Recent advances in multiple removal, a key-note address for the SEG/KOC Workshop, Dec. 3-5, 2019 in Kuwait: `https://youtu.be/sD89_418h1A`.

Weglein, A., J. Mayhan, Y. Zou, Q. Fu, F. Liu, J. Wu, C. Ma, X. Lin, and R. Stolt, 2016, The first migration method that is equally effective for all acquired frequencies for imaging and inverting at the target and reservoir: 86th Annual International Meeting, SEG, Expanded Abstracts, 4266–4272.

Weglein, A. B., 2013, Multiple attenuation: Recent advances and the road ahead (2013). Invited presentation given at the SEG Convention special session on Recent Advances and the Road Ahead, Houston, Texas.

———, 2019b, Arthur Weglein is on Facebook.: `https://m.facebook.com/story.php?story_fbid=2350596735209811&id=100007785225589`.

Weglein, A. B., L. Amundsen, F. Liu, K. Innanen, B. Nita, J. Zhang, A. Ramirez, and E. Otnes, 2007, Inverse scattering sub-series direct removal of multiples and depth imaging and inversion of primaries without subsurface information: strategy and recent advances: 77th Annual International Meeting, SEG, Expanded Abstracts, 2456–2460.

Weglein, A. B., F. V. Araújo, P. M. Carvalho, R. H. Stolt, K. H. Matson, R. T. Coates, D. Corrigan, D. J. Foster, S. A. Shaw, and H. Zhang, 2003, Inverse scattering series and seismic exploration: Inverse Problems, **19**, R27–R83.

Weglein, A. B., F. A. Gasparotto, P. M. Carvalho, and R. H. Stolt, 1997, An inverse-scattering series method for attenuating multiples in seismic reflection data: Geophysics, **62**, 1975–1989.

Weglein, A. B., and B. G. Secrest, 1990, Wavelet estimation for a multidimensional acoustic or elastic earth: Geophysics, **55**, 902–913.

Weglein, A. B., S. A. Shaw, K. H. Matson, J. L. Sheiman, R. H. Stolt, T. H. Tan, A. Osen, G. P. Correa, K. A. Innanen, Z. Guo, and J. Zhang, 2002, New approaches to deghosting towed-streamer and ocean-bottom pressure measurements: 72nd Annual International Meeting, SEG, Expanded Abstracts, 2114–2117.

Weglein, A. B., J. Wu, and F. X. de Melo, 2020, Multiples: towards a toolbox perspective on assumptions, challenges and options (an Invited Presentation): `http://www.mosrp.uh.edu/content/07-news/m-osrp-news-2020-eage-workshop-on-multiples-invited-talk/EAGE_Workshop_on_Multiples_2020_Arthur_Weglein_Jing_Wu_and_Fred_Melo_Invited_Presentation_Expanded_Abstract_w_Title.pdf`.

Wu, J., and A. Weglein, 2016, Green's theorem-based onshore preprocessing: A reduced data requirement assuming a vacuum/earth model for the air/earth interface and the evaluation of the usefulness of that assumption: 86th Annual International Meeting, SEG, Expanded Abstracts, 4685–4689.

Wu, J., and A. B. Weglein, 2014, Elastic Green's theorem preprocessing for on-shore internal multiple attenuation: Theory and initial synthetic data tests: 84th Annual International Meeting, SEG, Expanded Abstracts, 4299–4304.

———, 2015a, Preprocessing in displacement space for on-shore seismic processing: removing ground roll and ghosts without damaging the reflection data: 85th Annual International Meeting, SEG, Expanded Abstracts, 4626–4630.

———, 2015b, Preprocessing in the PS space for on-shore seismic processing: removing ground roll and ghosts without damaging the reflection data: 85th Annual International Meeting, SEG, Expanded Abstracts, 4740–4744.

———, 2017, A new method for deghosting data collected on a depth-variable acquisition surface by combining Green's theorem wave separation followed by a Stolt extended Claerbout III wave prediction for oneway propagating waves: 87th Annual International Meeting, SEG, Expanded Abstracts, 4859–4864.

Zhang, H., 2006, Direct non-linear acoustic and elastic inversion: Towards fundamentally new comprehensive and realistic target identification: PhD thesis, University of Houston.

Zhang, J., 2007, Wave theory based data preparation for inverse scattering multiple removal, depth imaging and parameter estimation: analysis and numerical tests of Green's theorem deghosting theory: PhD thesis, University of Houston.

Zhang, J., and A. B. Weglein, 2005, Extinction theorem deghosting method using towed streamer pressure data: analysis of the receiver array effect on deghosting and subsequent free surface multiple removal: 75th Annual International Meeting, SEG, Expanded Abstracts, 2095–2098.

———, 2006, Application of extinction theorem deghosting method on ocean bottom data: 76th Annual International Meeting, SEG, Expanded Abstracts, 2674–2678.

Zhang, Z., and A. Weglein, 2016, 2D Green's theorem receiver deghosting in the (x-omega) domain using a depth-variable cable towards on-shore and ocean-bottom application with variable topography: 86th Annual International Meeting, SEG, Expanded Abstracts, 4735–4740.

Zhang, Z., and A. B. Weglein, 2017, 3D source and receiver deghosting in the space-frequency domain using a depth-variable measurement surface: an initial off-shore synthetic data study with anticipated on-shore and ocean bottom application: Presented at the 87th Annual International Meeting, SEG, Expanded Abstracts.

Zou, Y., C. Ma, and A. B. Weglein, 2019, A new multidimensional method that eliminates internal multiples that interfere with primaries, without damaging the primary, without knowledge of subsurface properties, for offshore and onshore conventional and unconventional plays: 89th Annual International Meeting, SEG, Expanded Abstracts, 4525–4529.