

# Multiple attenuation: recent progress and a plan to address open, prioritized and pressing issues and challenges

Arthur B. Weglein, M-OSRP, Physics Department, University of Houston

## Summary

This paper provides: (1) a brief overview of the current status of multiple attenuation in the petroleum industry; (2) recent progress for marine and on-shore plays; (3) open issues and pressing challenges and (4) a plan, and a schedule of delivery, of fundamental new capability to address these open issues and challenges.

## Introduction

The demand for new and improved capability in removing multiples is driven by the portfolio of the petroleum industry and by current and anticipated future exploration trends. For example, the industry moved to deep water roughly 30 years ago. With that move, highly effective multiple-removal methods that were being applied industry-wide suddenly bumped up against their assumptions, when applied to deep water plays, and failed. (As an example, deconvolution is based on 1D and on statistical assumptions, the latter not satisfied in deep water.)

Since then, the overall industry trend to explore in progressively more complex and remote areas, with ill-defined and difficult-to-estimate subsurface properties and increasingly complex plays, is a constant that motivates the search for capabilities that will not require subsurface information. Methods that require various forms of subsurface information include, *e.g.*, F-K, Radon, and Feedback demultiple methods.

The inverse scattering series provides the opportunity to achieve all processing objectives directly and without subsurface information. The current inverse-scattering-series (ISS) internal-multiple-attenuation algorithm has a unique capability to predict the exact phase (time) and approximate amplitude of all internal multiples, at once, automatically, and without subsurface information. These properties separate the ISS internal-multiple-attenuation algorithm from all other methods, and make it the high-water mark of current internal-multiple effectiveness. That is, those ISS properties and strengths are what all other current demultiple methods (*e.g.*, Feedback loop methods, modeling and subtracting multiples, and filter methods) do not possess and cannot deliver (Weglein and Dragoset, 2005).

Carvalho (1992), Carvalho and Weglein (1994), Araújo (1994), Araújo et al. (1994), Weglein et al. (1997), and Weglein et al. (2003) developed ISS free-surface-multiple elimination algorithms and internal-multiple attenuation algorithms. Field-data applications demonstrated their effectiveness. Several marine and onshore data examples

are noted below.

However, at every period in the history of E&P, the arrival of new capability to address the latest set of challenges has encouraged industry to explore in more difficult circumstances — situations never previously imagined, let alone considered, and beyond current capability to accommodate. That will once again demand a new and fundamentally higher level of capability and effectiveness. In this article, we describe how that's the state of affairs for multiple attenuation today.

The petroleum industry's current worldwide portfolio of both conventional and unconventional onshore plays, and of increasingly complex offshore plays — with new and unforeseen challenges — has returned and rejuvenated an interest in multiple removal (and a demand for substantially increased effectiveness). Multiple removal has come back to center stage, both for our petroleum-industry sponsors and concomitantly as a key and fundamental research project for the Mission-Oriented Seismic Research Program (M-OSRP).

## Marine

Early marine field-data examples of the promise and delivery of ISS free-surface-multiple and internal-multiple algorithms can be found in the above-cited papers, SEG Abstracts, theses, and, *e.g.*, in Matson et al. (1999) and the Mississippi Canyon data tests in Weglein et al. (2003) pages R69 and R70.

Those algorithms were recently employed on data from offshore Brazil, and the results were reported in Ferreira (2011) (see Figure 1). One of the conclusions in those field-data tests at Petrobras was that “no other method was able to show similar effectiveness in attenuating the internal multiples generated by the salt layers.”

## Onshore

Fu et al. (2010a), Terenghi et al. (2011), and Luo et al. (2011) describe the motivation, evaluation, and comparison of different approaches to the removal of internal multiples on complex synthetic and onshore data. Fu et al. (2010a) concluded that “Their (ISS internal multiple algorithm) performance was demonstrated with complex synthetic and challenging land field data sets with encouraging results, where other internal multiple suppression methods were unable to demonstrate similar effectiveness.”

Goodway (2013), Mackidd (2013), and Griffiths et al.

(2013) were among those that came to the same conclusion. A recent paper by Kelamis et al. (2013) presented at the International Petroleum Technology Conference in Beijing, China was entitled “Strategies of Land Internal Multiple Elimination based on Inverse Scattering Series.”

### Good news

At the 2013 post-convention SEG Internal Multiple Workshop (Thursday, September 26, 2013) it was positive and encouraging to see nine of the eleven presentations describe and exemplify the industry-wide impact and stand-alone capability (for complex offshore and onshore plays) of the inverse-scattering-series (ISS) internal-multiple-attenuator. ISS internal-multiple attenuation has become fully mainstream within the petroleum industry.

### Challenge we face

With all this “good news”, what could be the problem? Industry’s portfolio/trend and focus today (and for the foreseeable future) makes it clear that a large and significant gap exists between the current challenge for the removal of free-surface multiples and internal multiples and the collective capabilities of the world-wide seismic exploration community (including, of course, M-OSRP). The specific issues are that: (1) the multiple generators and the subsurface properties are ill-defined and increasingly complex and (2) too often the multiple is proximal to or interfering with the primaries. The latter serious and significant issue can occur in many marine circumstances (*e.g.*, in the North Sea) and frequently occurs with onshore plays. That type of challenge of removing multiples proximal to, and/or overlapping with, primaries (without damaging primaries) is well beyond the collective capability of the petroleum industry, service companies and academic research groups and consortia to effectively address. It is not an issue that new and more complete data collection and acquisition will by itself address. We simply don’t have the theory and fundamental concepts in place today that are needed for algorithm development, implementation and application. That’s the basic reason we are unable to address the level of challenge we currently face worldwide in the petroleum industry. That’s the bottom line. To adequately address the current industry challenge, we will need to be able to predict exactly the phase and amplitude of all internal multiples and surgically remove (eliminate) the multiples at all offsets, directly, and without subsurface information, and without damaging primaries. No one today is able to provide that for marine applications, let alone for the frequently more challenging onshore plays.

There is a need for new basic concepts and fundamental theory development that must begin with a frank and forthright recognition of the problem, its economic moment and significance, and the current technical gap. New concepts and algorithms will need to be produced, and

then will be followed by addressing the practical application, implementation and compute issues.

### The plan

At the 2013 SEG International Conference (Recent Advances and the Road Ahead Session), we proposed and described a three-pronged strategy (please see the links below) that M-OSRP will pursue as a direct response to that challenge. It will have the potential to provide the necessary step-change increase in capability, and thereby to respond effectively to this current and pressing problem. The level and scale of the challenge and the dividend that will derive from addressing it, motivates and galvanizes our efforts. Multiple removal has returned from being viewed as a relatively mature subject and project that helped M-OSRP “pay the rent” and is back to occupying center stage as a major research project and focus within M-OSRP.

The three-pronged strategy to respond to the current open issues and pressing challenges in removing multiples is as follows:

- (1) Develop the ISS prerequisites for predicting the reference wave field (wavelet and radiation pattern) and producing de-ghosted data (in particular, for on-shore and ocean bottom acquisition) that are direct and do not require subsurface information;
- (2) Develop internal-multiple-elimination algorithms from the inverse scattering series;
- (3) Develop a replacement for the energy-minimization criteria for adaptive subtraction, that derives from, and always aligns with and serves, the inverse-scattering-series free-surface and internal-multiple algorithms.

This three-pronged strategy represents a consistent and aligned processing chain, with one single objective: providing a direct and practical solution to the removal of all multiples, without requiring any subsurface information, and without damaging primaries.

The plan is first to progress and deliver items (2) and (3) for marine applications (since item (1) is in relatively good shape for marine application), and simultaneously to progress item (1) for onshore plays. Then, we will return to onshore exploration with the full suite of (1), (2) and (3) ingredients in place. Our plan is to deliver in stages, with offshore delivery coming before onshore delivery.

### Recent progress on the three-pronged plan to address current open issues and challenges

In discussing the second of the three prongs, that is, the upgrade of the ISS internal multiple attenuator, we need to begin with a review of its strengths and limitations. The first order ISS internal multiple attenuator always attenuates all internal multiples of first order from all reflectors at once, directly and without subsurface information, automatically and without interpretive intervention. That’s a tremendous strength, and is a constant and holds independent of the circumstances and

complexity of the geology and the play. The primaries in the reflection data that enters the algorithm provides that delivery, without our requiring the primaries to be identified or in any way separated. The other events in the reflection data, that is, the internal multiples, when they enter the first order ISS internal multiple algorithm will alter and prep the higher order internal multiples and thereby assist and cooperate with higher order ISS internal multiple attenuation terms, to attenuate higher order internal multiples. That's a benefit and definite asset, and it's always in action and completely automatic. However, there is a downside, a limitation. There are cases when internal multiples that enter the first order attenuator can predict spurious or false events. That is a well-understood shortcoming of the leading order term, when taken in isolation, but is not an issue for the entire ISS internal multiple capability. It is anticipated by the ISS and higher order ISS internal multiple terms exist to precisely remove that issue of spurious event prediction, and taken together with the first order term, no longer experiences spurious event prediction. Chao Ma and Hong Liang provided those higher order terms and tests with complex multiple generators show the effectiveness of their spurious removal higher order ISS internal multiple attenuation algorithms (Liang et al., 2013; Ma and Weglein, 2013, 2014a,b). In a similar way, there are higher order ISS internal multiple terms that provide the elimination of internal multiples when taken together with the leading order attenuator term. Yanglei Zou has produced a general elimination algorithm for first order internal multiples in a 1D acoustic or elastic earth. Please see Zou and Weglein (2013), Zou and Weglein (2014a), Zou and Weglein (2014b), and Zou and Weglein (2014c).

The first tests that evaluated the ability of the ISS attenuator to perform in inelastic media showed it maintained its effectiveness in a medium where waves are attenuated and experiencing Q absorption, without any need or interest in knowing the absorptive mechanism (Wu and Weglein, 2014a). An outlined initial strategy for eliminating internal multiples in an inelastic medium is also described.

There are times, for example, in pre-salt plays in the North Sea, the deep water Gulf of Mexico, offshore Brazil and the Red Sea where the strategy and algorithms to eliminate internal multiples in an absorptive inelastic medium will be called for and necessary. There are other circumstances, for example, in certain on-shore and off-shore plays where elastic internal multiple elimination will be sufficient.

Jing Wu et al. (Wu and Weglein, 2014b) has contributed to extending off-shore Green's theorem preprocessing for wavelet estimation and deghosting to the on-shore elastic wave-field separation, in preparation for on-shore ISS internal multiple attenuation/elimination. Mayhan et al. (Mayhan et al., 2012; Mayhan and Weglein, 2013) has demonstrated the ability of Green's theorem marine preprocessing to be effective with SEAM data and marine field data. He reviewed and summarized the im-

port of that preprocessing on subsequent multiple removal (Zhang, 2007; Wang et al., 2012; Yang et al., 2013; Tang et al., 2013) that motives the on-shore extension. Jinlong Yang extended the ISS free surface and internal multiple algorithms to accommodate a source signature and radiation pattern (Yang et al., 2013; Yang and Weglein, 2014). Shih-Ying Hsu (Hsu et al., 2011) described the relative insensitivity of the ISS internal multiple attenuator to the near surface reference velocity. Lin Tang (Tang and Weglein, 2014) presented a method to use an invariance of Green's theorem preprocessing to back out the reference medium properties. Qiang Fu has contributed the first published results on applying the ISS internal multiple attenuator to field data from Saudi Aramco and Encana (Fu et al., 2010b; Fu and Weglein, 2014). Fang Liu (Liu and Weglein, 2013; Liu et al., 2011) has pioneered: (1) new wave equation migration methods for RTM and (2) ISS direct depth imaging without a velocity model, with viability demonstrated on the Kristin North Sea field data.

Below please find links for the SEG abstracts/posters/presentations and slides that relate to this communication.

<http://mosrp.uh.edu/events/event-news/seg-annual-meeting-2013>

<http://mosrp.uh.edu/news/seg-annual-meeting-2013>

<http://mosrp.uh.edu/>

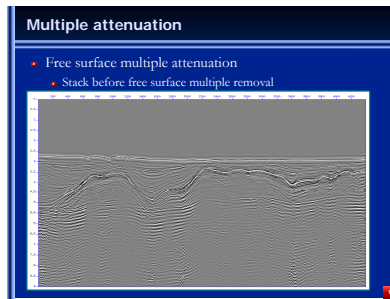
<http://arthurweglein.com>

## Summary

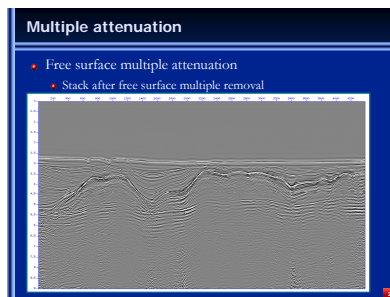
Today, the ISS internal-multiple attenuator combined with an energy-minimization adaptive subtraction is the most capable method for removing internal multiples. However, the current ISS attenuator-plus-adaptive-subtraction method will fail under the pressing and prioritized challenge of removing internal multiples that are proximal to and/or interfering with primaries. In this note, we describe a three-pronged strategy for providing an effective response to this pressing and prioritized challenge while retaining and adding to the strengths of the current ISS internal-multiple attenuator.

## Acknowledgments

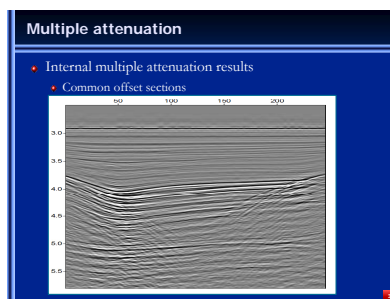
We thank the M-OSRP sponsors for their constant encouragement and strong support. We thank Dr. Jim D. Mayhan for his assistance in preparing this Abstract.



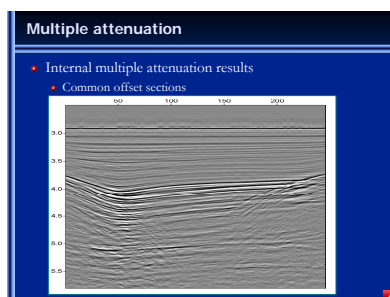
(a)



(b)



(c)



(d)

Fig. 1: Stack before (a) and after (b) free-surface-multiple removal; common offset sections before (c) and after (d) internal-multiple attenuation (Ferreira, 2011).

## References

- Araújo, F. V., 1994, Linear and non-linear methods derived from scattering theory: backscattering tomography and internal-multiple attenuation.: PhD thesis, Universidade Federal da Bahia, Brazil. (In Portuguese).
- 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, Society of Exploration Geophysicists, 1039–1041.
- Carvalho, P., and A. Weglein, 1994, Wavelet estimation for surface multiple attenuation using a simulated annealing algorithm: 64th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists, 1481–1484.
- Carvalho, P. M., 1992, Free-surface multiple reflection elimination method based on nonlinear inversion of seismic data: PhD thesis, Universidade Federal da Bahia. (In Portuguese).
- Ferreira, A., 2011, Internal multiple removal in offshore Brazil seismic data using the inverse scattering series: Master's thesis, University of Houston.
- Fu, Q., Y. Luo, P. G. Kelamis, S. Huo, G. Sindi, S.-Y. Hsu, and A. B. Weglein, 2010a, The inverse scattering series approach towards the elimination of land internal multiples: 80th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists, 3456–3461.
- , 2010b, The inverse scattering series approach towards the elimination of land internal multiples: 80th Annual International Meeting, SEG, Expanded Abstracts.
- Fu, Q., and A. B. Weglein, 2014, Inverse scattering series internal multiple attenuation on encana data: 84th Annual International Meeting, SEG, Expanded Abstracts. (Submitted).
- Goodway, W., 2013, Preliminary results of synthetic and land internal multiple removal by inverse scattering. Presentation at the Post SEG Convention Workshop on Internal Multiples.
- Griffiths, M., A. Pica, and B. Hung, 2013, Internal multiple removal solutions for multiple environments. Presentation at the Post SEG Convention Workshop on Internal Multiples.
- Hsu, S.-Y., P. Terenghi, and A. B. Weglein, 2011, The properties of the inverse scattering series internal multiple attenuation algorithm: Analysis and evaluation on synthetic data with lateral variations, choosing reference velocity and examining its sensitivity to near surface properties: M-OSRP 2010-2011 Annual Report, 16–28.
- Kelamis, P. G., Y. Luo, and A. B. Weglein, 2013, Strategies of land internal multiple elimination based on inverse scattering series: Technical Session 21: Recent Development in Seismic Imaging/Processing, International Petroleum Technology Conference, Beijing, China, 26-28 March 2013, Society of Exploration Geophysicists, 1–4.
- Liang, H., C. Ma, and A. B. Weglein, 2013, General theory for accommodating primaries and multiples in internal multiple algorithm: Analysis and numerical tests: 83rd Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists, 4178–4183.
- Liu, F., X. Li, and A. B. Weglein, 2011, Addressing innate data limitations in ISS imaging algorithms: distinct data regularization methods to address different types of data limitations, to facilitate and allow specific ISS imaging steps and goals: 2010 M-OSRP Annual Report, 50–81.
- Liu, F., and A. B. Weglein, 2013, The first *wave theory* RTM, examples with a layered medium, predicting the source and receiver at depth and then imaging, providing the correct location and reflection amplitude at every depth location, and where the data includes primaries and all internal multiples: 2012 M-OSRP Annual Report, 284–335.
- Luo, Y., P. G. Kelamis, Q. Fu, S. Huo, G. Sindi, S.-Y. Hsu, and A. B. Weglein, 2011, Elimination of land internal multiples based on the inverse scattering series: The Leading Edge, **30**, 884–889.
- Ma, C., and A. B. Weglein, 2013, One-dimensional analytic analysis of the effects of including internal multiples as part of input into the leading-order inverse scattering series (ISS) internal-multiple attenuation algorithm: comparison between free-surface and internal-multiple cases: M-OSRP 2012-2013 Annual Report, 123–145.
- , 2014a, Including higher-order inverse scattering series (ISS) terms to address a serious shortcoming/problem of the ISS internal-multiple attenuator: exemplifying the problem and its resolution: Presented at the 84th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists. (Submitted).
- , 2014b, Inverse scattering series (ISS) leading-order internal-multiple-attenuation algorithm and higher-order modification to accommodate primaries and internal multiples as input: 1-D normal incident test on interfering events, and extension to multi-D: Presented at the M-OSRP 2013-2014 Annual Report.
- Mackidd, D., 2013, Multiples... the elephant in the room. Presentation at the Post SEG Convention Workshop on Internal Multiples.
- Matson, K., D. Corrigan, A. Weglein, C.-Y. Young, and P. Carvalho, 1999, Inverse scattering internal multiple attenuation: Results from complex synthetic and field data examples: 69th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists, 1060–1063.
- 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.

- Mayhan, J. D., A. B. Weglein, and P. Terenghi, 2012, First application of Green's theorem derived source and receiver deghosting on deep water Gulf of Mexico synthetic (SEAM) and field data: 82nd Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists, 1–5.
- Tang, L., J. D. Mayhan, J. Yang, and A. B. Weglein, 2013, Using Green's theorem to satisfy data requirements of multiple removal methods: The impact of acquisition design: 83rd Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists, 4392–4396.
- Tang, L., and A. B. Weglein, 2014, Predicting reference medium properties from invariances in Green's theorem reference wave prediction: towards an on-shore near surface medium and reference wave prediction: Presented at the 84th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists. (Submitted).
- Terenghi, P., S.-Y. Hsu, A. B. Weglein, and X. Li, 2011, Exemplifying the specific properties of the inverse scattering series internal-multiple attenuation method that reside behind its capability for complex onshore and marine multiples: *The Leading Edge*, **30**, 876–882.
- Wang, Z., A. B. Weglein, J. D. Mayhan, P. Terenghi, and C. Rivera, 2012, Green's theorem derived deghosting: fundamental analysis, numerical test results, and impact on ISS free-surface multiple elimination: 82nd Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists, 1–5.
- 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., and W. Dragoset, eds., 2005, Multiple attenuation: SEG. SEG Geophysics Reprint Series, No. 23.
- 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.
- Wu, J., and A. B. Weglein, 2014a, The first test and evaluation of the ISS internal multiple attenuation algorithm for the attenuating medium: Presented at the 84th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists. (Submitted).
- , 2014b, Green's theorem based wavefield separation application on elastic/land: Presented at the 84th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists. (Submitted).
- Yang, J., J. D. Mayhan, L. Tang, and A. B. Weglein, 2013, Accommodating the source (and receiver) array in free-surface multiple elimination algorithm: Impact on interfering or proximal primaries and multiples: 83rd Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists, 4184–4189.
- Yang, J., and A. B. Weglein, 2014, Incorporating source wavelet and radiation pattern into the ISS internal multiple attenuation algorithm: Presented at the 84th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists. (Submitted).
- 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.
- Zou, Y., and A. B. Weglein, 2013, A new method to eliminate first order internal multiples for a normal incidence plane wave on a 1d earth: SEG Technical Program Expanded Abstracts, 4136–4140.
- , 2014a, An algorithm for the elimination of all first-order internal multiples from all reflectors: 1D normal incidence and 1D pre-stack algorithm, discussion and numerical tests: Presented at the M-OSRP 2013-2014 Annual Report.
- , 2014b, The pre-stack 1D ISS internal multiple elimination algorithm for all reflectors Part I: strengths and limitations: Presented at the 84th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists. (Submitted).
- , 2014c, The pre-stack 1D ISS internal multiple elimination algorithm for all reflectors Part II: addressing the limitations: Presented at the 84th Annual International Meeting, SEG, Expanded Abstracts, Society of Exploration Geophysicists. (Submitted).