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SEG|KOC Workshop on Advances in Land & Shallow Marine Multiple Attenuation and Imaging, scheduled on 28-30 November 2023 in Kuwait City, Kuwait.

A Keynote Address: Recent Advances and Open Issues in Multiple Attenuation and Imaging, including Land and Shallow Marine

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Nov 28-30, 2023

Express my appreciation to Dr. Adel El-Emam of KOC for the invitation to participate and present this Keynote address.

- This presentation can be viewed as an executive summary of a longer and detailed presentation “A Perspective on Advances and Open Issues in Seismic Exploration (2024)” that is located in the same link where this presentation resides

- The events in seismic reflection data are catalogued as either primary or multiple
- We start with a new perspective and understanding of the role that primaries and multiples play in seismic processing and exploration
- We then focus on specific prioritized obstacles to effectiveness for land and shallow water.
- Let's begin

- Migration is the method used to locate structure (reflectors) in the subsurface.
- Migration-inversion (M-I) is a two step procedure that first locates where any property has changed (M) and then determines the actual properties that have changed, and the amplitude of those changes (M-I). (Stolt and Weglein (1985), (2012))

There is a new and most effective method of migration and migration-inversion that we label Stolt-Claerbout III migration (SCIII) for continuous and discontinuous media

The SCIII migration formula for continuous and discontinuous media

$$D(x_g, z_g, x_s, z_s, \omega) = \iint \left[D \frac{\partial G_0^{DD}}{\partial n} - G_0^{DD} \frac{\partial D}{\partial n} \right] dS_g dS_s$$

where G_0^{DD} satisfies both Dirichlet and Neumann boundary conditions on the lower surface of the finite migration volume
Weglein et al (2016), SEG Abstract, "The first migration method that is equally effective for all acquired frequencies for imaging and inverting at the target and reservoir"

SCIII is the only migration method that can image and invert:

(1) without artifacts above and beneath top salt
(2) specular or diffractive targets
(3) can automatically image and invert for R or V and then changes in v_p, v_s and ρ

(4) can image and invert targets without high frequency approximations — e.g. no geometric optics R.C. — no one way wave assumptions in a smooth velocity model

(5) maximal amplitude and resolution capability, no compromise in illumination

(6) the only migration method that can accommodate a discontinuous velocity model — and hence can provide a definitive response to the role of primaries and multiples in migration and inversion

Migration

RTM doesn't satisfy any one of those properties and characteristics — let alone all of them.
RTM and Kirchhoff have serious imaging, resolution, illumination and inversion issues compared to SCIII.

Migration

Another important fact is that if one used a Stolt-Claerbout III migration with an accurate discontinuous velocity model, then multiples would not cause any problems, and would not need to be removed. [Weglein et al 2016 SEG Abstract]

Migration

- However, <u>if you use a smooth velocity</u> to migrate data <u>from a discontinuous medium</u>, every multiple will produce a false image, and every multiple must be removed.
- Since our most capable velocity analysis methods today can at best produce a smooth velocity, all multiples must be removed before migration.

Multiples must be removed in all seismic processing methods, that is in all direct and indirect seismic processing methods.

The former, the direct methods include all classic wave equation migration methods (that require an adequate velocity model) and the inverse scattering isolated task subseries for depth imaging (that do not need to know, estimate or to determine a velocity model).

Indirect methods, including all model matching methods like AVO and FWI- require all multiples to be removed either initially or at some point within the process.

Migration

Of course, the latter conclusion about velocity analysis includes FWI where a smooth velocity is the stretch goal today.
Therefore methods (like FWI) that at best produce a smooth velocity model—result in all multiples needing to be removed.

What about the use of multiples to enhance imaging?

The removal of multiples and the use of multiples (to enhance imaging) have the same exact goal: the imaging of primaries, recorded and unrecorded primaries, respectively.

What about the use of multiples to enhance imaging?

- Nobody is migrating multiples—the phrase "migrating multiples" has no meaning.
- However, at times a recorded multiple can be used to find an approximate image of an unrecorded primary subevent of the recorded multiple.

What about the use of multiples to enhance imaging? (continued)

To predict a multiple, you need to have recorded all of its subevents; hence, if you can predict a multiple its useless. If you cannot predict a multiple, because you have not recorded all its subevents, then it might be useful. Hence, predicted multiples are useless, and useful multiples cannot be predicted.

What about the use of multiples to enhance imaging? (continued)

What if the unrecorded subevent of the recorded multiple, is not an unrecorded primary — but an unrecorded multiple.
That unrecorded multiple will be treated as an unrecorded primary and will result in an artifact.

What about the use of multiples to enhance imaging? (continued)

Since we are confined to a smooth migration velocity, recorded multiples must be removed to image recorded primaries, and unrecorded multiples must be removed to find an approximate image of an unrecorded primary.

Up to now we explained "why" multiples must always be removed in all seismic processing methods

With that established: Now we describe "how" to remove multiples

What is the current toolbox of multiple removal capability?

An overview of methods: How to remove multiples?

JOURNAL OF SEISMIC EXPLORATION **31**, 15-28 (2022) 15

MULTIPLE REMOVAL: AN OVERVIEW AND PERSPECTIVE OF CURRENT CAPABILITY, ALGORITHMIC ASSUMPTIONS AND OPEN ISSUES

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An overview of methods


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ABSTRACT
Weglein, A.B., Wu, J., Xavier de Melo, F., Etgen, J.T. and Mayhan, J.D., 2022. Multiple removal: an overview and perspective of current capability, algorithmic assumptions and open issues. *Journal of Seismic Exploration*, 31: 15-28.

This is the second paper of a two-paper set - the first describes in detail why multiples must be removed at some point within all seismic processing methods-and there are absolutely no exceptions. With that 'why' issue established and in place, this second paper then proceeds to address the 'how' aspect, and therein provides a tool-box perspective on overall industry collective capability. All seismic methods make assumptions, and have prerequisites - and, requiring subsurface information has become an increasing difficult assumption to satisfy. The latter challenge is largely due to the industry trend to deep water and more complex offshore and on-shore plays. That reality motivated the development of multiple removal methods that did not require subsurface information. The distinct inverse scattering subseries for removing free surface and internal multiples are the only multiple removal methods that require absolutely no subsurface information.

This paper provides a guide and perspective for making a well-informed cost-effective choice within the toolbox. No method is the cost-effective choice under all circumstances - and under certain situations a less effective and less costly choice might do a reasonable job. The development of more effective, and sometimes more costly, options provide the opportunity to pay more to receive more, when that heightened capability is necessary and needed. It is necessary to know what are the assumptions and prerequisites behind every multiple removal method, within the toolbox, in order to: (1) make an informed cost-effective choice, among tool-box options, and (2) to define open issues and challenges. There is a truism, that today's reasonable assumption will be tomorrow's impediment to effectiveness and obstruction to progress. The multiple removal toolbox is always a work in progress - and no method has been, or ever will be, the last and final word.

KEY WORDS: overview, multiples, primaries, multiple removal, tool box, cost-effective options, on-shore, off-shore, progress and open issues.

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An overview of methods

The published paper Feb. 2022, JSE, co-authored with John Etgen of BP and Fred Melo and Jing Wu of Schlumberger and Jim Mayhan of M-OSRP provides a timely overview and describes when each option within the multiple removal toolbox might be the well-informed cost-effective choice — along with open issues and challenges.

Multiples: an overview of methods

One of several conclusions of that recent overview paper (cited above) is that the most effective method for removing internal multiples is the inverse scattering internal multiple eliminator (ISS IME). Yanglei Zou et al, (2019)

An overview of methods

A new multidimensional method that eliminates internal multiples that interfere with primaries, without damaging the primary, without knowledge of subsurface properties, for off-shore and on-shore conventional and unconventional plays

Yanglei Zou, Chao Ma, and Arthur B. Weglein, M-OSRP/Physics Dept./University of Houston

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SUMMARY

Multiple removal is a longstanding problem in exploration seismology. Many methods have been developed including: stacking, FK filter, Radon transform, deconvolution and Feedback loop. They make statistical assumptions, assume move-out differences, or require knowledge of the subsurface and the generators of the multiples (e.g., Foster and Mosher, 1992; Verschuur et al., 1992; Berkhout and Verschuur, 1997; Jakubowicz, 1998; Robinson and Treitel, 2008; Wu and Wang, 2011; Meles et al., 2015; da Costa Filho et al., 2017; Lomas and Curtis, 2019). As the industry moved to deep water and more complex on-shore and off-shore plays, these methods bumped up against their assumptions. The Inverse Scattering Series (ISS) internal-multiple-attenuation algorithm (Araújo et al., 1994, Weglein et al., 1997 and Weglein et al., 2003) made none of the assumptions of previous methods (listed above) and stands alone, and is unique in its effectiveness when the subsurface and generators are complicated and unknown. It is the only multi-dimensional internal-multiple-removal method that can predict all internal multiples with exact arrival time and approximate amplitude without requiring any subsurface information. When internal multiples and primaries are isolated, the ISS internal-multiple-attenuation algorithm is usually combined with an energy-minimization adaptive subtraction to remove internal multiples. For isolated internal multiples, the ISS attenuator combined with energy-minimization adaptive subtraction is successful and effective. However, when internal multiples are proximal to and/or interfering with primaries or other events, the criteria behind energy-minimization adaptive subtraction can fail (e.g., the energy can increase rather than decrease when a multiple is removed from a destructively interfering primary and multiple). With interfering events, energy-minimization adaptive subtraction can lead to damaging the target primary, which is the worst possible outcome. In this paper, we provide the first multi-dimensional ISS internal-multiple-elimination algorithm that can predict both the correct time and amplitude of internal multiples. This is an important part of a three-pronged strategy proposed by Weglein at the 2013 SEG International Conference (Weglein 2014). Herrera and Weglein (2012) proposed a 1D ISS internal-multiple-elimination algorithm for all first-order internal-multiples generated at the shallowest reflector. Y. Zou and Weglein (2014) then went further and developed and illustrated an elimination algorithm that can eliminate all first-order internal multiples generated by all reflectors for a 1D earth. In this paper we provide the first multidimensional ISS internal-multiple-elimination method that can remove internal multiples interfering with primaries, without subsurface information, and without damaging the primary. We also compare the ISS elimination result with ISS attenuation plus energy-minimization adaptive subtraction for an interfering primary and internal multiple. 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. That can frequently occur in offshore and onshore conventional and unconventional plays. We are exploring methods to reduce the computational cost of these ISS attenuation and elimination algorithms, without compromising effectiveness.

INTRODUCTION

The ISS (Inverse-Scattering-Series) allows all seismic processing objectives, e.g., free-surface-multiple removal and internal-multiple removal, depth imaging, non-linear amplitude analysis and Q compensation to be achieved directly in terms of data, without any need for, or determination of subsurface properties (e.g., Weglein et al., 2012; Zhang and Weglein, 2009a,b; Zou and Weglein, 2018). The ISS internal-multiple attenuation algorithm is the only method today that can predict the correct time and approximate amplitude for all first-order internal multiples generated from all reflectors, at once, without any subsurface information. If the multiple to be removed is isolated from other events, then the energy minimization adaptive subtraction can fill the gap between the attenuation algorithm and the amplitude of the internal multiples. However primary and multiple events can often interfere with each other in both on-shore and off-shore seismic plays. In these cases, the criteria of energy minimization adaptive subtraction can fail and eliminating internal multiples is beyond the current capability of the petroleum industry.

For dealing with this challenging problem, Weglein (2013) proposed a three-pronged strategy:

1. For on-shore applications, predicting ground roll and reflection data: all current methods are filtering techniques that remove ground roll while damaging reflection data. The latter is harmful for all subsequent processing goals (e.g., multiple removal, imaging and inversion). Recent significant progress in predicting ground roll and reflection data (without filtering or damaging either), e.g., Wu and Weglein (2015) without needing or determining subsurface properties, but requiring near surface information. Similarly, Matson (1997) and Matson and Weglein (1996), Zhang and Weglein (2006) provide methods for on-shore and OBC demultiple and deghosting, respectively, and did not require subsurface information but required near-surface information. A new and general method (Weglein, 2019) for seismic preprocessing and processing, not only doesn't require

Multiples: an overview of methods

There are three properties that only this internal multiple (ISS IME) method possesses: (1) it predicts the exact amplitude and phase of the internal multiple at all offsets; (2) there is no subsurface information known, estimated or determined, no interpreter intervention, and (3) it is one unchanged algorithm for every earth model type;

Multiples: an overview of methods

(4) ISS IME contains a water speed Stolt-Claerbout III migration, and unlike Kirchhoff and RTM it can automatically accommodate multiple generators that are planar curved, and point scatterer diffractive pinch outs; (5) there is no need for an adaptive step since it predicts the exact phase and amplitude of the internal multiple at every offset — and the criteria behind energy minimization adaptive subtraction can fail with interfering or proximal events.

Multiples: an overview of methods

(6) the key lower higher lower relationship is correct and in vertical time, not total time (the latter is erroneous (and deleterious) and called upon in Marchenko methods).

Multiples: an overview of methods

No other multiple removal method (e.g., Radon, Jakubowicz, or Marchenko) satisfies one let alone all these beneficial properties — and that explains why ISS IME is currently the most effective internal multiple removal method.

Multiples: an overview of methods

The inverse scattering internal multiple attenuator (ISS IMA) predicts the exact time and approximate amplitude of all internal multiples — and hence ISS IMA often calls upon an adaptive step to remove the internal multiple.

Multiples: an overview of methods

The inverse scattering free surface eliminator (ISS FSME) and the inverse scattering internal multiple eliminator (ISS IME) are the most effective methods for removing free surface and internal multiples, respectively.

Multiples: an overview of methods

See e.g., Chao Ma et al 2018 for a direct comparison between ISS FSME and SRME, and Chao Ma et al (2020) for a comparison of internal multiple methods.

Multiples: an overview of methods

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Comparison of the inverse scattering series free-surface multiple elimination (ISS FSME) algorithm with the industry-standard surface-related multiple elimination (SRME): Defining the circumstances in which each method is the appropriate toolbox choice

Chao Ma[1], Qiang Fu[1], and Arthur B. Weglein[1]

ABSTRACT

The industry-standard surface-related multiple elimination (SRME) method provides an approximate predictor of the amplitude and phase of free-surface multiples. This approximate predictor then calls upon an energy-minimization adaptive subtraction step to bridge the difference between the SRME prediction and the actual free-surface multiple. For free-surface multiples that are proximal to other events, the criteria behind energy-minimization adaptive subtraction can be invalid. When applied under these circumstances, a proximal primary can often be damaged. To reduce the dependence on the adaptive process, a more accurate free-surface multiple prediction is required. The inverse scattering series (ISS) free-surface multiple elimination (FSME) method predicts free-surface multiples with accurate time and accurate amplitude of free-surface multiples for a multidimensional earth, directly and without any subsurface information. To quantify these differences, a comparison with analytic data was carried out, confirming that when a free-surface multiple interferes with a primary, applying SRME with adaptive subtraction can and will damage the primary, whereas ISS free-surface elimination will precisely remove the free-surface multiple without damaging the interfering primary. On the other hand, if the free-surface multiple is isolated, then SRME with adaptive subtraction can be a cost-effective toolbox choice. SRME and ISS FSME each have an important and distinct role to play in the seismic toolbox, and each method is the indicated choice under different circumstances.

INTRODUCTION

In the beginning of the paper, it is useful to remind ourselves of the definitions of seismic events based on their travel histories (Weglein et al., 2003). For instance, Figure 1 shows different types of seismic events in marine seismic exploration. In marine seismic exploration, reference waves are *first* defined as waves that travel directly from source to receiver and waves that first travel up to the air-water boundary and then to the receiver. These two types of waves did not experience the subsurface. All other events have experienced the subsurface. *Then*, among the waves that did experience the subsurface, ghost events are defined as the seismic events that begin their propagation histories by traveling up from the source to the air-water boundary (source ghosts) or end their histories by traveling down from the air-water boundary to the receiver (receiver ghosts) or both (source and receiver ghosts). After that, events that begin their history going downward from the source and end their history upward at the receiver are divided into primary and multiple events. Primary events are defined as the events that experience only one upward reflection during their propagation history, whereas multiple events are defined as the events that experience multiple reflections during their propagation history. Multiple events are further divided into free-surface multiples and internal multiples depending on the location of downward reflection between two consecutive upward reflections.

Multiples that have at least one downward reflection at the air-water (for offshore exploration) or air-land (for onshore exploration) surface are called free-surface multiples, whereas multiples that have all of their downward reflections below the air-water or air-land surface are called internal multiples (Weglein et al., 1997).

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Multiples: an overview of methods

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Analysis and application of data-driven approaches for internal-multiple elimination

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SUMMARY

Imaging artifacts caused by strong internal multiples can interfere with primary images, affecting structural interpretation and amplitude analysis. In such cases, internal multiples are often attenuated in either data domain or in the image domain. In this abstract, we study three data-driven approaches: Jakubowicz, Inverse Scattering Series (ISS) and Marchenko for internal-multiple removal and analyze their performances. Each method has its unique advantages due to the differences among them. This knowledge, in turn, helps users to choose the appropriate method. Following the analysis, we show field data applications of these methods on towed steamer data.

INTRODUCTION

Although the use of multiples to help subsurface imaging (e.g., Lu et al, 2011) has gained a lot of interest and developments in recent years, multiple removal remains an essential step in seismic data processing for velocity model building and imaging primaries. Many multiple-removal methods have been developed based on the assumption that primaries and multiple have different characteristics. For example, multiples can be attenuated based on the difference in Radon transformed space. These methods are often an effective and appropriate choice when the assumptions are satisfied. Wave-equations based methods are another set of methods used to attenuate multiples by first predicting multiple models using wave equations and then adaptively subtracting the models from the data. Methods using wave equations for predicting multiple models fall into two categories: (1) multiples are forward modeled with the subsurface information, and (2) multiples are predicted by data-driven approaches without the subsurface information.

Among the data-driven approaches, Surface-Related Multiple Elimination (SRME) (Berkhout, 1985; Verschuur and Berkhou, 1992) and ISS Free-surface multiple elimination (Carvalho et al. 1991 and Weglein et al. 1997) algorithms were developed for surface-related multiples. Araujo et al. (1994) and Weglein et al. (1997) developed the ISS internal multiple removal algorithm. Jakubowicz (1998) extended the approach of SRME to predict and remove internal multiples. Most recently, van der Neut and Wapenaar (2016) proposed a Marchenko-based internal multiple removal algorithm.

In this abstract, we study and compare three data-driven approaches (Jakubowicz, ISS and Marchenko) for internal multiple removal and analyze their similarities and differences. These data-driven approaches for internal-multiple removal share the idea of combining events in the data to predict an internal-multiple model. However, they differentiate from each other by each method's unique way to select and combine the events. In the following two sections, we first study those similarities and differences, understand each method's unique advantages and disadvantages, and then we share some field data applications.

METHOD

Like the data-driven approaches for predicting surface-related multiples, internal multiples can be predicted by combining different reflections in the data domain, but it involves convolving two outer events and cross-correlating the middle event (see Figure 1). Different ways of selecting the events that are convolved and cross-correlated distinguish the different methods we discuss in this abstract.

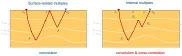

Figure 1: Illustration of the general idea of using data-driven approaches for predicting surface-related (convolution) and internal multiples (convolution and cross-correlation) by combining events in the data.

In the Jakubowicz (1998) method, to predict an internal multiple, an internal-multiple generator (the reflector at which the downward reflection occurs) is identified first. Then, the input data are separated into two parts: one part contains the reflection corresponding to the generator, the other part contains all the reflections below the generator. The two parts are combined to predict the internal multiples as follows:

$$M_j(x_s,x_g,\omega) = -\sum_{x',x} P_{i_{(>j)}}(x_s,x,\omega)P_j^*(x,x',\omega)P_{i_{(>j)}}(x',x_g,\omega), \quad (1)$$

where, P_j is the reflection corresponding to the j-th generator (* means the complex conjugate in the frequency domain), $P_{i_{(>j)}}$ are the reflections below the j-th generator with travel times larger than the travel time of the reflection in P_j. M_j is the predicted internal-multiple model reflected downward at the j-th generator for a source at x_s and a receiver at x_g. To

Multiples: an overview of methods

The ISS methods are often the well-informed cost-effective choice under the most complicated and daunting circumstances, with rapidly varying multiple generators (and for interfering and proximal events). Further detail and analysis can be found in the video presentations and publications in the links below.

http://www.mosrp.uh.edu/people/faculty/arthur-weglein

What are prioritized open issues for land and shallow water multiple removal?

And what are some of the approaches that could address these open issues on multiple removal and imaging and inversion?

What are prioritized open issues for land and shallow water multiple removal? (continued)

Onshore challenges begin with the complex ill-defined near surface issues where identifying the model type and medium properties are a major obstacle and largely unsolved problem.

What are prioritized open issues for land and shallow water multiple removal? (continued)

A new embryonic seismic processing method has been developed that removes the need for near surface and subsurface information to be known, estimated, or determined (Weglein, 2024). Early tests are encouraging.

Responding to on-shore challenges: (1) A method to remove the need to know, estimate or determine near surface information for seismic preprocessing and processing methods and (2) a response to the multiples generated by near-surface subresolution reflectors: Part I, the basic concept and first examples

Arthur B. Weglein
Jan 2024

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, that do not need or require subsurface information. That is, they do not require any information about the earth 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 (and the latter defines the "near surface"). For on-shore and OBS applications, the need for near-surface information (information that is 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 preprocessing and processing that removes the need to know, estimate or to determine both subsurface and near surface properties. We introduce the concept with the first step in the seismic processing chain, namely, the separation of the reference wave (that would include the direct wave and ground-roll for on-shore application) and the recorded scattered wavefield (the data that has experienced the subsurface and near surface). We use an analytic data example to demonstrate how the method works and we point out how it would be applied in practice. This paper introduces a new concept and method. It will be followed by both more complicated synthetic and field data examples within this paper's objective and to the next steps in the processing chain (for example, for deghosting, multiple removal and imaging and inversion). In addition, a response to the issue of multiples generated by subresolution reflectors (often in the near surface) is proposed. This paper responds to two currently intractable on-shore exploration problems: the need for near-surface information and subresolution multiples.

1

Ground roll issues

Jing Wu et al (2015) present a new method to separately predict ground roll and reflection data without filtering and harming either one.

Ground roll issues

Preprocessing in displacement space for on-shore seismic processing: removing ground roll and ghosts without damaging the reflection data

Jing Wu and Arthur B. Weglein, M-OSRP, University of Houston

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SUMMARY

This paper derives an elastic Green's theorem wave separation method for on-shore data in displacement space. Applying the algorithm presented in this paper only once, both the reference waves (including the direct wave and the surface wave) and the ghosts can be effectively removed. The method is tested on a layered elastic earth model. The results indicate its effectiveness for reducing the ground roll and ghosts at the same time, and without harming the up-going reflections, in preparation for on-shore processing.

INTRODUCTION

On-shore seismic exploration and processing seeks to use reflection data (the scattered wavefield) to make inferences about the subsurface. The measured total wavefield consists of the reflection data and the reference wave that contains the direct wave and the surface wave/ground roll; hence, one prerequisite is to separate the reference wave and scattered wave. Filtering methods are typically employed to remove the reference wave, particularly the ground roll. That can be at the expense of damaging reflection data when ground roll is interfering with the scattered wavefield.

In addition, for buried sources and receivers, not only up-going waves are in the reflection data but also ghosts, whose existence can cause notches in the spectrum. Thus, removing the ghosts from the reflection data is another prerequisite. In this study, we will assume the source is located slightly above the air/earth surface (could be infinitely close, or on the air/earth surface), and the receivers are slightly beneath the air/earth surface. Therefore, there are receiver ghosts but no source ghosts in our study.

As a flexible and useful tool, Green's theorem provides a method to satisfy both prerequisites; i.e., removing the reference wave without damaging the reflection data and removing the ghosts from the reflection data without destroying the up-going reflected data. The distinct advantages of applying the method based on Green's theorem in off-shore plays have been demonstrated by Weglein et al. (2002); Zhang (2007); Mayhan et al. (2011); Mayhan and Weglein (2013); Tang et al. (2013); Yang et al. (2013).

Basically, wave separation from Green's theorem has a model of the world that consists of the **reference medium** and the **sources**. The choice of reference medium is arbitrary, and the choice of reference will determine what the sources have to be to arrange for the reference medium and sources together to correspond to the actual medium and experiment (Weglein et al., 2003). For on-shore plays, Green's theorem wave separation method is applicable for data either in displacement space (Pao and Varatharajulu, 1976; Weglein and Secrest, 1990) or in the PS space (Wu and Weglein, 2014). In this paper, for data in displacement space, we choose a homogeneous elastic whole space as the reference, then both the reference wave and receiver ghosts can be removed in one step while applying the elastic Green's theorem wave separation algorithm. In a companion paper (Wu and Weglein, 2015b), and for data in the PS space, the reference medium is chosen to be composed of two homogenous half-spaces, an air/acoustic half-space over an elastic half-space, then Green's theorem method can extinguish the reference wave (including the ground roll) without harming the reflection data. After obtaining the reflection data, Green's theorem provides a reflection data deghosting algorithm with a choice of a whole-space homogenous elastic reference (Wu and Weglein, 2015b).

DESCRIPTION OF THE MODEL: REFERENCE MEDIUM + SOURCES

As shown in Figure 1, the model consists of an air half-space and an elastic-earth half-space. Receivers are buried in the earth, and the active source in the form of a vertical force is applied on the free surface (F.S.). Therefore, ghosts exist at the receiver side only. The measurement surface (M.S.) can be infinitely close to the free surface, like on-surface acquisition, or several meters below the free surface, like buried-receiver acquisition; however, the receivers are coupled with the elastic medium in both situations.

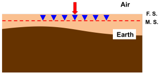

Figure 1: A generic model describing the land experiment

In this paper, we will assume that the portion of earth along the measurement surface is homogeneous and known. Within this assumption, we choose the reference medium to be a homogenous elastic whole space, as shown in Figure 2, whose property agrees with the actual earth along the measurement surface.

There are three sources acting on the homogeneous reference medium that is described in Figure 2. As shown in Figure 3, one is the active source (or the vertical force S_1) and the other two are passive sources (or the perturbations S_2 and S_3) on two sides of the measurement surface, respectively. S_1 produces the direct waves. S_2 produces the ground roll; it also produces

Shallow water challenge

Among major shallow water issues, is the fact that the nearest phone to the source can be in the postcritical regime. That is a major impediment to multiple removal methods that depend on recorded subevents.

Shallow water challenge

To arrange for those required subevents there is typically an extrapolation to nearer offsets when the nearest phone is in the precritical region; that is often successful. However, extrapolation methods will fail when the nearest phone is postcritical region and the sought after data is precritical.

Shallow water challenge

One approach for addressing this challenge can be found in the 2001 M-OSRP Annual Report by Mrinal Sen, Paul Stoffa (UTIG) and A. Weglein (M-OSRP) present a method for predicting precritical data from postcritical data.

Shallow water challenge: a response

Research Project Report

Title: Prediction of pre-critical seismograms from post-critical traces

Principal Investigator: Mrinal Sen
Co-principal Investigators: Arthur Weglein and Paul Stoffa

Arthur B. Weglein

2001 M-OSRP Annual Technical Review and Report for Sponsors

Final report submitted to BP on January 5, 2001

Attention:
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Near surface subresolution multiple generators

A frequent challenge in land seismic processing is a series of subresolution internal multiple generators at the near surface.

Near surface subresolution multiple generators

Those subresolution multiple generators produce a chain of troublesome multiples that cannot currently be removed. That is a prioritized challenge that within all conventional thinking does not have an effective response — or even an embryonic concept or theory

Near surface subresolution multiple generators

We propose the following response:
(1) apply the ISS Q compensation algorithm [Zou and Weglein (2018)] to boost the high frequency content of the recorded data, and hence the resolution of currently subresolution multiple generators.

Near surface subresolution multiple generators

JOURNAL OF SEISMIC EXPLORATION 27, 593-608 (2018) 593

ISS *Q* COMPENSATION WITHOUT KNOWING, ESTIMATING OR DETERMINING *Q* AND WITHOUT USING OR NEEDING LOW AND ZERO FREQUENCY DATA

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Near surface subresolution multiple generators

JOURNAL OF SEISMIC EXPLORATION 27, 593-608 (2018) 593

ISS *Q* COMPENSATION WITHOUT KNOWING, ESTIMATING OR DETERMINING *Q* AND WITHOUT USING OR NEEDING LOW AND ZERO FREQUENCY DATA

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ABSTRACT

Zou, Y. and Weglein, A.B., 2018. ISS *Q* compensation without knowing, estimating or determining *Q* and without using or needing low and zero frequency data. *Journal of Seismic Exploration*, 27: 593-608.

Developing new and more effective methods to achieve *Q* compensation is of priority in seismic processing and exploration. We propose a new approach for *Q* compensation as an isolated task subseries of the inverse scattering series (ISS). This inverse scattering subseries achieves *Q* compensation without needing to know, estimate or to determine *Q*. The method avoids the pitfall of an earlier ISS method by not needing or using low frequency data and in particular not needing zero frequency data. This paper provides two contributions (1) It develops a reformulated inverse scattering series (ISS) *Q* compensation method without knowing or estimating *Q* and (most importantly) without needing zero frequency data (2) It avoids a division by zero in the subsequent reformulated algorithm by adding a small imaginary term to k_z (adding a small amount of friction in the reference medium).

In this paper, we test the *Q* compensation algorithm in a two-reflector model and have obtained encouraging results. This advance in ISS *Q* compensation also has immediate significant and positive consequence for all amplitude analysis (that currently require low and zero frequency data) including ISS depth imaging, ISS direct parameter inversion, traditional iterative AVO and model matching FWI. In addition, the ISS *Q* compensation without knowing or estimating *Q* method can be transferred for electromagnetic applications where conductivity plays the role of *Q*, and a conductivity map can be output.

Once the *Q* compensated data is available we could use that data together with the original data to estimate *Q*. Alternatively, the anelastic equation and data could input the original data and ISS inverted for elastic and *Q* parameters.

Near surface subresolution multiple generators

(2) apply the high water mark of internal multiple removal the ISS IME algorithm with its water speed SCIII migration to maximize the ability to locate and delineate multiple generators and remove the multiples they generate

Near surface subresolution multiple generators

A new multidimensional method that eliminates internal multiples that interfere with primaries, without damaging the primary, without knowledge of subsurface properties, for offshore and on-shore conventional and unconventional plays

Yanglei Zou, Chao Ma, and Arthur B. Weglein, M-OSRP/Physics Dept./University of Houston

Near surface subresolution multiple generators

A new multidimensional method that eliminates internal multiples that interfere with primaries, without damaging the primary, without knowledge of subsurface properties, for off-shore and on-shore conventional and unconventional plays

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SUMMARY

Multiple removal is a longstanding problem in exploration seismology. Many methods have been developed including: stacking, FK filter, Radon transform, deconvolution and Feedback loop. They make statistical assumptions, assume move-out differences, or require knowledge of the subsurface and the generators of the multiples (e.g., Foster and Mosher, 1992; Verschuur et al., 1992; Berkhout and Verschuur, 1997; Jakubowicz, 1998; Robinson and Treitel, 2008; Wu and Wang, 2011; Meles et al., 2015; da Costa Filho et al., 2017; Lomas and Curtis, 2019). As the industry moved to deep water and more complex on-shore and off-shore plays, these methods bumped up against their assumptions. The Inverse Scattering Series (ISS) internal-multiple-attenuation algorithm (Araújo et al., 1994, Weglein et al., 1997 and Weglein et al., 2003) made none of the assumptions of previous methods (listed above) and stands alone, and is unique in its effectiveness when the subsurface and generators are complicated and unknown. It is the only multi-dimensional internal-multiple-removal method that can predict all internal multiples with exact arrival time and approximate amplitude without requiring any subsurface information. When internal multiples and primaries are isolated, the ISS internal-multiple-attenuation algorithm is usually combined with an energy-minimization adaptive subtraction to remove internal multiples. For isolated internal multiples, the ISS attenuator combined with energy-minimization adaptive subtraction is successful and effective. However, when internal multiples are proximal to and/or interfering with primaries or other events, the criteria behind energy-minimization adaptive subtraction can fail (e.g., the energy can increase rather than decrease when a multiple is removed from a destructively interfering primary and multiple). With interfering events, energy-minimization adaptive subtraction can lead to damaging the target primary, which is the worst possible outcome. In this paper, we provide the first multi-dimensional ISS internal-multiple-elimination algorithm that can predict both the correct time and amplitude of internal multiples. This is an important part of a three-pronged strategy proposed by Weglein at the 2013 SEG International Conference (Weglein 2014). Herrera and Weglein (2012) proposed a 1D ISS internal-multiple-elimination algorithm for all first-order internal-multiples generated at the shallowest reflector. Y. Zou and Weglein (2014) then went further and developed and illustrated an elimination algorithm that can eliminate all first-order internal multiples generated by all reflectors for a 1D earth. In this paper we provide the first multidimensional ISS internal-multiple-elimination method that can remove internal multiples interfering with primaries, without subsurface information, and without damaging the primary. We also compare the ISS elimination result with ISS attenuation plus energy-minimization adaptive subtraction for an interfering primary and internal multiple. 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. That can frequently occur in offshore and onshore conventional and unconventional plays. We are exploring methods to reduce the computational cost of these ISS attenuation and elimination algorithms, without compromising effectiveness.

INTRODUCTION

The ISS (Inverse-Scattering-Series) allows all seismic processing objectives, e.g., free-surface-multiple removal and internal-multiple removal, depth imaging, non-linear amplitude analysis and Q compensation to be achieved directly in terms of data, without any need for, or determination of subsurface properties (e.g., Weglein et al., 2012; Zhang and Weglein, 2009a,b; Zou and Weglein, 2018). The ISS internal-multiple attenuation algorithm is the only method today that can predict the correct time and approximate amplitude for all first-order internal multiples generated from all reflectors, at once, without any subsurface information. If the multiple to be removed is isolated from other events, then the energy minimization adaptive subtraction can fill the gap between the attenuation algorithm and the amplitude of the internal multiples. However primary and multiple events can often interfere with each other in both on-shore and off-shore seismic plays. In these cases, the criteria of energy minimization adaptive subtraction can fail and eliminating internal multiples is beyond the current capability of the petroleum industry.

For dealing with this challenging problem, Weglein (2013) proposed a three-pronged strategy:

1. For on-shore applications, predicting ground roll and reflection data: all current methods are filtering techniques that remove ground roll while damaging reflection data. The latter is harmful for all subsequent processing goals (e.g., multiple removal, imaging and inversion). Recent significant progress in predicting ground roll and reflection data (without filtering or damaging either), e.g., Wu and Weglein (2015) without needing or determining subsurface properties, but requiring near surface information. Similarly, Matson (1997) and Matson and Weglein (1996), Zhang and Weglein (2006) provide methods for on-shore and OBC demultiple and deghosting, respectively, and did not require subsurface information but required near-surface information. A new and general method (Weglein, 2019) for seismic

Near surface subresolution multiple generators

(3) use SCIII migration with heterogeneous and discontinuous medium to (avoid high frequency approximations) and have the benefit of all frequency components in the source wave field.

Near surface subresolution multiple generators

A wedge resolution comparison between RTM and the first migration method that is equally effective at all frequencies at the target: tests and analysis with both conventional and broadband data

Yanglei Zou, Qiang Fu, and Arthur B. Weglein, M-OSRP/Physics Dept./University of Houston

Near surface subresolution multiple generators

A wedge resolution comparison between RTM and the first migration method that is equally effective at all frequencies at the target: tests and analysis with both conventional and broadband data

Yanglei Zou, Qiang Fu, and Arthur B. Weglein, M-OSRP/Physics Dept./University of Houston

SUMMARY

Acquiring lower-frequency seismic data is an industry-wide interest. There are industry reports that (1) when comparing the new and more expensively acquired broad-band lower-frequency data with conventional recorded data, taken over a same region, these two data sets have the expected difference in frequency spectrum and appearance, but (2) they often provide less than the hoped for difference in structural resolution improvement or added benefit for amplitude analysis at the target and reservoir. In Weglein et al. (2016) and Q. Fu et al. (2017), they demonstrate that all current migration and migration-inversion methods make high-resolution asymptotic assumptions. Consequently, in the process of migration, they lose or discount the information in the newly acquired lowest-frequency components in the broadband data. The new Stolt extended Claerbout III migration for heterogeneous media (Weglein et al. 2016) addresses this problem as the first migration method that is equally effective at all frequencies at the target and reservoir. That allows the broadband lower frequency data to provide full benefit for improving structural resolution and amplitude analysis. Q. Fu et al. (2017) provide the first quantification of the difference and impact on resolution for RTM (CII) and Stolt extended CIII. In this paper, we continue to study and quantify these differences in the migration resolution using a wedge model and define the added resolution value provided by the new Stolt extended CIII migration for heterogeneous medium. The side lobes of the images of upper and lower reflectors produce an interference that determines resolution. The migration method with a greater reduction of side lobes will be the migration with a greater ability to resolve two reflectors with a same bandwidth in the data, conventional or band limited.

INTRODUCTION

Migration methods that use wave theory for seismic imaging have two components: (1) a wave-propagation concept and (2) an imaging condition. Today all migration methods make a high-frequency approximation in (1) or (2) or both (1) and (2). Our new migration method, Stolt extended CIII for heterogeneous media is the first migration method that makes no high-frequency approximation in both components (1) and (2), for a heterogeneous medium, and is equally effective at all frequencies at the target and/or the reservoir. Weglein (2016) provides a detailed development of this new migration method.

For the imaging principle component, a good start is Jon Claerbout's 1971 landmark contribution (Claerbout, 1971) where three imaging principles are described. The first is the exploding-reflector model for stacked or zero-offset data, which we call Claerbout imaging principle I (CI). The second is time-space Claerbout imaging principle II (CII). Waves propagate down from the source, are incident on the reflector, and the reflector generates a reflected upgoing wave. According to CII, the reflector exists at the location in space where the wave that is downward propagating from the source and the upwave from the reflector are at the same time and space. All RTM methods are based on RTM (CII) imaging principle and we after refer to RTM in this paper as RTM (CII). The third is Claerbout imaging principle III (CIII), which starts with surface source and receiver data and predicts what a source and receiver would record inside the earth. CIII then arranges the predicted source and receiver to be coincident and asks for $t = 0$. If the predicted coincident source and receiver experiment at depth is proximal to a reflector one gets a non-zero result at time equals zero. Stolt and his colleagues provided several major extensions of CIII and we refer to that category of imaging principles/methods as Stolt extended CIII.

RTM (CII) and Stolt extended CIII are of central industry interest today, since we currently process pre-stacked data. RTM (CII) and Stolt extended CIII will produce different results for a separated source and receiver located in a homogeneous half space above a single horizontal reflector. That difference forms a central and key message of this paper.

CII can be expressed in the form

$$I(\vec{x}) = \sum_{\vec{x}_s}\sum_{\omega} S'(\vec{x}_s,\vec{x},\omega)R(\vec{x}_s,\vec{x},\omega), \tag{1}$$

where R is the reflection data (for a shot record), run backwards, and S' is the complex conjugate of the source wavefield.

A realization of CIII is Stolt FK migration (Stolt, 1978)

$$\begin{aligned} M^{stolt}(x,z) = {} & \frac{1}{(2\pi)^3}\iiint d\omega dx_g dx_s dk_{sx} \\ & \times \exp(-i(k_{sz}z + k_{sx}(x-x_s))) \\ & \times \int dk_{gx}\exp(-i(k_{gz}z + k_{gx}(x-x_s))) \\ & \times \int dt \exp(i\omega t)D(x_g,x_s,t). \end{aligned} \tag{2}$$

The weighted sum of recorded data, summed over receivers, basically predicts the receiver experiment at depth, for a source on the surface. The sum over sources predicts the source in the subsurface. Then the predicted source and receiver experiment is output for a coincident source and receiver, and at time equals zero; it defines a Stolt extended CIII image. Each step (integral) in this Stolt extended CIII has a specific physically interpretable purpose towards the Stolt extended CIII image.

RTM IS A HIGH-FREQUENCY APPROXIMATION

Today all migration methods assume a high-frequency approx-

Overview

In the 1980's the methods for migration were conceptually and practically more advanced compared to methods for removing multiples. Now that situation is reversed

Overview: In 1985

- migration: multiD and needed the velocity model
- multiples: one-D methods, with statistical assumptions or filtering methods that needed a velocity model

Overview: In 2023

- migration (SCIII): multi-D and need the velocity model
- multiples (ISS): multi-D and with no subsurface information known, estimated or determined

Overview: In 2043 we predict

- migration (ISS direct depth imaging): multi-D and no need for subsurface information to be known, estimated or determined
- multiples (ISS removal of free surface and internal multiples): multi-D and with no need for subsurface information to be known, estimated or determined

Overview

migration needs to catch-up with multiple removal

JOURNAL OF SEISMIC EXPLORATION **21**, 1-28 (2012) 1

INVERSE SCATTERING SERIES DIRECT DEPTH IMAGING WITHOUT THE VELOCITY MODEL: FIRST FIELD DATA EXAMPLES

ARTHUR B. WEGLEIN[1], FANG LIU[1], XU LI[1], PAOLO TERENGHI[1], ED KRAGH[2], JAMES D. MAYHAN[1], ZHIQIANG WANG[1], JOACHIM MISPEL[3], LASSE AMUNDSEN[3], HONG LIANG[1], LIN TANG[1] and SHIH-YING HSU[1]

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JOURNAL OF SEISMIC EXPLORATION **21**, 1-28 (2012)

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ABSTRACT

Weglein, A.B., Liu, F., Li, X., Terenghi, P., Kragh, E., Mayhan, J.D., Wang, Z., Mispel, J., Amundsen, L., Liang, H., Tang, L. and Hsu, S.-Y., 2012. Inverse scattering series direct depth imaging without the velocity model: First field data examples. *Journal of Seismic Exploration*, 21: 1-28.

In Weglein et al. (2010) an update and status report were provided on the progress on the inverse scattering series (ISS) direct depth imaging without the velocity model. In that article, results on synthetics with sufficient realism indicated that field data tests were warranted. This paper documents those first field data tests. These first early tests are encouraging and indicate that ISS direct depth imaging on field data is possible. Each member of a set of three distinct data or algorithmic conditions and requirements are identified and shown to be necessary for inverse scattering direct depth imaging, without a velocity model, to be effective and to produce the accurate structural configuration of reflectors and interfaces in the subsurface. Taken together, that set represents both necessary and sufficient conditions. In addition, for ISS imaging, the CIG flatness condition is a necessary and sufficient indication that an accurate depth image has been reached. The latter property is in contrast to conventional velocity dependent imaging methods where common image gather (CIG) flatness is a necessary but not a sufficient condition that a correct depth image has been achieved. The next steps, and open issues, on the road between viable and providing relevant and differential added value to the seismic tool-box are described and discussed.

KEY WORDS: imaging, migration, inverse scattering series, field data, velocity, CIG flatness.

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Summary

- The inverse scattering free surface eliminator (ISS FSME) and the inverse scattering internal multiple eliminator (ISS IME) are the most effective methods for removing free surface and internal multiples, respectively.
- See e.g., Chao Ma et al 2018 for a direct comparison between ISS FSME and SRME, and Chao Ma et al (2020) for a comparison of internal multiple methods.

Summary

This Presentation has described the current state of multiple removal and imaging, and the open issues and challenges to all marine and onshore seismic processing.

Summary

We addressed specific prioritized obstacles to effectiveness for land and shallow water. Lastly new embryonic concepts, and methods that can begin to address these multiple removal and imaging and inversion challenges were suggested and described.

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