Multiple removal: open issues, pressing challenges and recent progress towards providing the next and higher level of required capability

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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 to address those high priority challenges and recent progress towards that goal.

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 statistical assumptions, when applied to deep water plays, and failed.

Since then, the overall industry trend to explore in progressively more complex and remote areas, with ill-defined and difficult-to-estimate subsurface properties motivates the search for capabilities that will not require subsurface information. Methods for multiple removal that require various forms of subsurface information include, *e.g.*, stacking, F-K and Radon filters, 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 (*e.g.*, Hung et al. (2014); Kelamis et al. (2013a); Luo et al. (2011); Ferreira (2011)).

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 yet 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). We will see why multiple removal interest (and research) has come back to center stage for the petroleum-industry.

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.

For example, those algorithms were 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. (2010), 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. (2010) 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), Goodway and Mackidd (2013), and Griffiths et al. (2013) were among those that came to the same conclusion. A paper by Kelamis et al. (2013b) presented at the Inter-

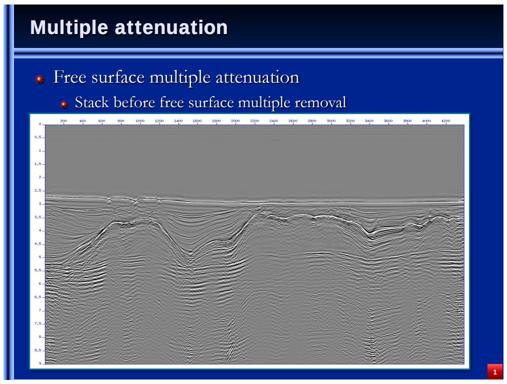

Figure 1a: Before free-surface-multiple removal.

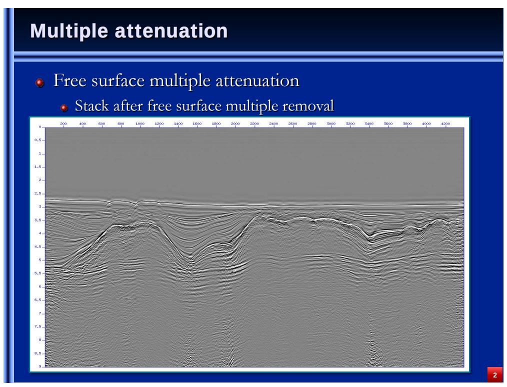

Figure 1b: After free-surface-multiple removal.

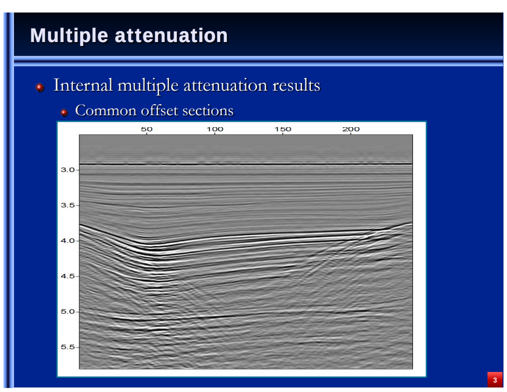

Figure 1c: Common offset sections before internal-multiple attenuation.

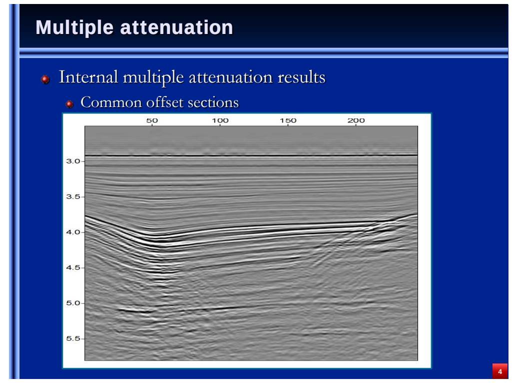

Figure 1d: Common offset sections after internal-multiple attenuation.

national Petroleum Technology Conference in Beijing, China was entitled "Strategies of Land Internal Multiple Elimination based on Inverse Scattering Series."

THE GOOD NEWS

At the 2013 post-convention SEG Internal Multiple Workshop (Thursday, September 26, 2013) it was 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.

THE OUTSTANDING OPEN ISSUES AND THE HIGH PRIORITY CHALLENGES 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, Duquet et al. (2013)) 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, be able to 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 reason we are unable to address that challenge faced today in the world-wide petroleum industry. To adequately address the current industry challenge (proximal and interfering multiples and primaries), 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 is able to provide that newer and necessary capability today 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, theory and algorithms will need to be produced, and then will be followed by addressing the practical application, implementation and compute issues.

A PROPOSED 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. 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 fundamental research project.

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 deghosted 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 relatively mature 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 progress in stages, with offshore delivery coming before onshore delivery.

RECENT PROGRESS ON A 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, 2015a,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), and Zou and Weglein (2014b, 2015a,b).

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, 2014b). Our strategy includes eliminating internal multiples in an inelastic medium without knowing the absorptive/dispersive properties of the subsurface.

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.

Progress to report within our plan and strategy to provide a next generation of multiple removal capability includes: Jing Wu et al. (Wu and Weglein, 2014a, 2015c,d,a,b) 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. That paper reviewed and summarized the impact 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). 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. Xinglu Lin (Lin and Weglein, 2015a,b) demontrates the importance of including a 3D source in internal multiple algorithm (independent of the dimension of the subsurface). 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., 2010; 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. The latter advances in depth imaging depend on an effective removal of multiples to be able to deliver their promise and impact.

CONCLUSIONS

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. We have documented recent progress within that strategy to deliver the next generation of required multiple removal. To achieve that goal without requiring subsurface information requires Green's theorem wave separation methods for preprocessing, and mining the Inverse Scattering Series for increased effectiveness and predictive capability.

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