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 preprocessing and processing, not only doesn't require

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subsurface information, but in addition, removes the need for near surface information, as well. The latter is of extremely high moment and priority for on-shore conventional and unconventional plays, and OBS, where the inability to determine near surface properties is one of the most daunting tasks and challenges in world-wide petroleum exploration and production.

2. Develop internal-multiple elimination algorithms from ISS.
3. Develop a new criteria for adaptive subtraction that derives from and always aligns with the ISS elimination algorithm.

The ISS internal multiple attenuator requires no subsurface information and is the same exact unchanged algorithm independent of the earth model type (Weglein et al., 2003). However, there are two well-understood limitations of this ISS internal-multiple attenuation algorithm

1. It may generate spurious events due to internal multiples treated as sub-events.
2. It is an attenuation algorithm not an elimination algorithm.

The complete removal of internal multiples requires a sub-series of the ISS. The ISS internal multiple attenuator is the leading order term in that subseries. The two items listed above are accommodated by higher order terms. Ma et al. (2012), Liang et al. (2012), and Ma and Weglein (2014) provided those higher order terms for spurious event removal.

In a similar way, there are higher order ISS internal multiple terms that provide the elimination of internal multiples. The initial idea is provided by Weglein and Matson (1998) in which the attenuation factor, the difference between attenuation and elimination, is first analyzed and examined. Ramírez (2007) further discussed, examined and analyzed this topic. Herrera et al. (2012) then proposed an algorithm for internal multiple elimination for all first order internal multiples generated at the shallowest reflector. Zou and Weglein (2014) then developed a new algorithm that can eliminate all first order internal multiples for all reflectors for a 1D earth. In this paper, we further extend the previous 1D elimination algorithm and provide the first ISS multi-dimensional elimination method for all first order internal multiples. The new elimination algorithm retains the benefits of the attenuation algorithm, including not requiring any subsurface information and removes all first-order internal multiples from all subsurface reflectors (flat, dipping, curved, diffractive, pinchout) at once.

THE ISS INTERNAL-MULTIPLE ATTENUATION ALGORITHM AND THE INITIAL IDEA FOR INTERNAL MULTIPLE ELIMINATION

The ISS internal-multiple attenuation algorithm was first presented by Araújo et al. (1994) and Weglein et al. (1997). The 1D normal incidence version of the algorithm is equation (1) (The 2D version is given in Araújo et al. (1994), Weglein et al. (1997) and Weglein et al. (2003) and the 3D version is a straightforward extension.),

$$b_3(k) = \int_{-\infty}^{\infty} dz e^{ikz} b_1(z) \int_{-\infty}^{z-\varepsilon_2} dz' e^{-ikz'} b_1(z') \times \int_{z'+\varepsilon_1}^{\infty} dz'' e^{ikz''} b_1(z''). \tag{1}$$

$b_1(z)$ is the constant velocity Stolt migration of the data due to a 1D normal incidence spike plane wave. ε_1 and ε_2 are two small positive numbers. $b_3^{IM}(k)$ is the predicted internal multiples in the vertical wavenumber domain. This algorithm can predict the correct time and approximate amplitude of all first-order internal multiples at once without any subsurface information.

When compared with the actual internal multiple, the prediction has extra factors of the transmission coefficients down to the location where the internal multiple has its downward reflection.

The difference between attenuation and elimination is called "the attenuation factor," AF. Weglein and Matson (1998) studied the attenuation factor and provide the initial idea and algorithm to remove the attenuation factor using only reflection data to achieve the elimination, without subsurface information.

We can remove the attenuation factor using the data (which contains reflection coefficients) without any subsurface information. For example, to remove AF_1 (due to a single multiple generator) in the prediction, we have

$$elimination = \frac{attenuation}{AF_1} = \frac{attenuation}{T_{0,1}T_{1,0}} = \frac{attenuation}{1-R_1^2} \tag{2}$$

$$= attenuation + attenuation \times R_1^2 + attenuation \times R_1^4 + \ldots$$

where the first term is the attenuation algorithm, the term $attenuation \times R_1^2$ corresponds to the first higher order term towards elimination and so on. A detailed discussion can be found in Weglein and Matson (1998) and Ramírez (2007) and Ramírez and Weglein (2008).

THE FIRST INVERSE-SCATTERING-SERIES INTERNAL MULTIPLE ELIMINATION METHOD FOR A MULTI-DIMENSIONAL SUBSURFACE

The multi-D Inverse-Scattering-Series contains a multi-D internal-multiple elimination sub-series. We identify an Inverse-Scattering-Series internal multiple elimination subseries, that can eliminate all first-order internal multiples for all reflectors (including flat, dipping, curved, diffractive, pinchouts) for a multi–dimensional subsurface. Below please find the 2D version of a

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higher order term in the elimination algorithm.

$$b_E(k_s,k_g,q_g+q_s) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} dk_1 dk_2 \int_{-\infty}^{+\infty} dz_1 b_1(k_g,k_1,z_1) e^{i(q_g+q_1)z_1} \times \int_{-\infty}^{z_1-\varepsilon} dz_2 F(k_1,k_2,z_2) e^{-i(q_1+q_2)z_2} \int_{z_2+\varepsilon}^{+\infty} dz_3 b_1(k_2,k_s,z_3) e^{i(q_2+q_s)z_3} \quad (3)$$

$$F(k_1,k_2,z) = \int_{-\infty}^{+\infty} d(q_1+q_2) e^{-i(q_1+q_2)z} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} dk' dk'' \int_{-\infty}^{+\infty} dz' b_1(k_1,k',z') e^{i(q_1+q')z'} \times \int_{z'-\varepsilon}^{z'+\varepsilon} dz'' g(k',k'',z'') e^{-i(q'+q'')z''} \int_{z''-\varepsilon}^{z''+\varepsilon} dz''' g(k'',k_2,z''') e^{i(q''+q_2)z'''} \quad (4)$$

$$g(k_1,k_2,z) = \int_{-\infty}^{+\infty} d(q_1+q_2) e^{-i(q_1+q_2)z} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} dk' dk'' \int_{-\infty}^{+\infty} dz' b_1(k_1,k',z') e^{i(q_1+q')z'} \times \int_{z'-\varepsilon}^{z'+\varepsilon} dz'' b_1(k',k'',z'') e^{-i(q'+q'')z''} \int_{z''-\varepsilon}^{z''+\varepsilon} dz''' g(k'',k_2,z''') e^{i(q''+q_2)z'''} \quad (5)$$

Similar to the extension in the previous work in Zou and Weglein (2014) , $F(k_1,k_2,z)$ and $g(k_1,k_2,z)$ are two intermediate functions. Combining all of these higher order terms provides the elimination algorithm for a 2D earth. The elimination algorithm for a 3D earth is a straightforward extension.The complete subseries is given in Zou et al. (2016).

SYNTHETIC DATA EXAMPLE

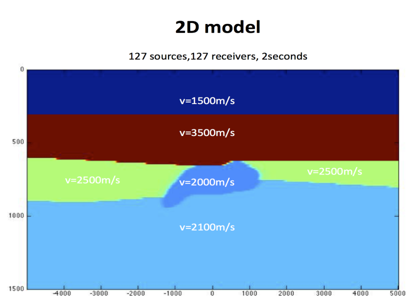

Figure 1: 2D Model

Figure 1 shows the 2D model, the data is generated by a finite difference method. There is a oblong shaped structure [meant to imitate salt] in the middle of the model. The salt body is designed so that the primary from its lower boundary is negatively interfering with an internal multiple between the water bottom and top salt. In this synthetic data, there are 127 shot gathers, each shot gather contains 127 receivers. The source and receiver interval is 30 meters and time interval 0.002s.

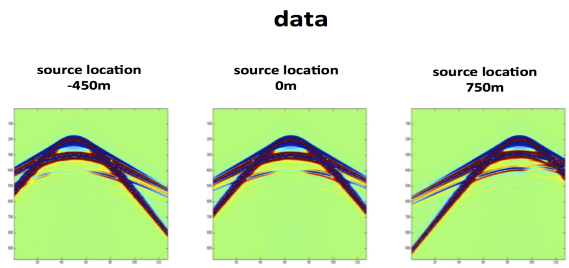

Figure 2: pre-stack data

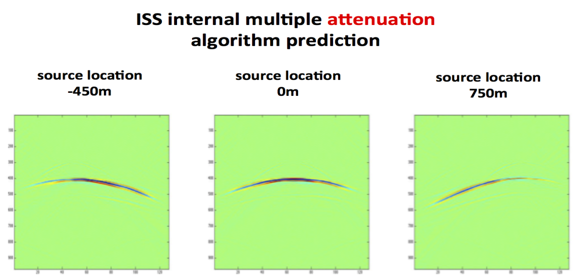

Figure 3: ISS internal multiple attenuation algorithm prediction

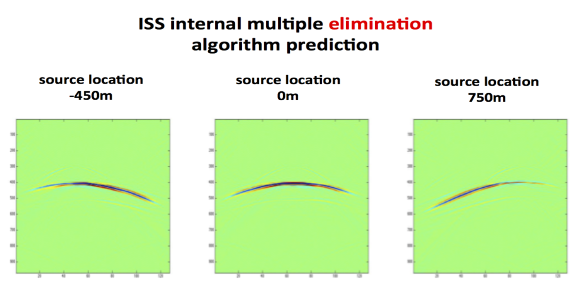

Figure 4: ISS internal multiple elimination algorithm prediction

Figure 2 shows three shot gathers of the input data with source at -450m, 0m, 750m respectively. Figure 3 shows three shot gathers of the ISS attenuation algorithm prediction with source at -450m, 0m, 750m respectively. Figure 4 shows three shot gathers of the ISS elimination algorithm prediction with source at -450m, 0m, 750m respectively. From these figures we can see the strongest internal multiple interferes with the base salt primary in the data, especially at small offset.

In order to clearly see the result, we show the zero offset trace

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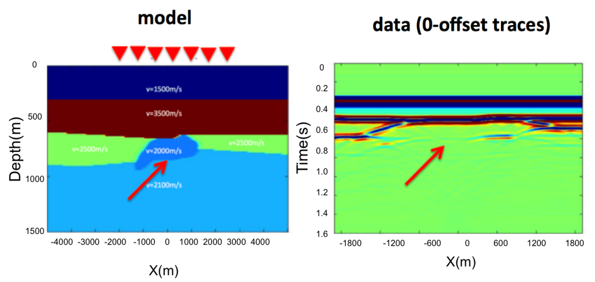

Figure 5: Zero offset traces of data. Note the interfering internal multiple and base salt primary.

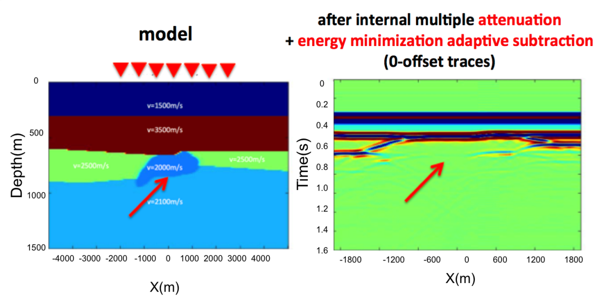

Figure 6: Zero offset traces after ISS internal-multiple attenuation and energy minimization adaptive subtraction. Note the damaged base salt primary.

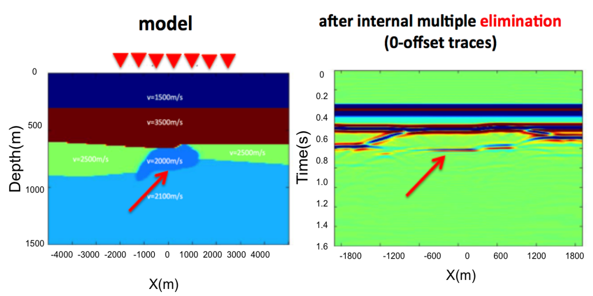

Figure 7: Zero offset traces after ISS internal-multiple elimination. Note the preserved base salt primary.

results. Figure 5 shows the zero offset traces of the input data. Compared to the model, we can see clearly that the lower boundary of the salt body is almost invisible because the primary generated by the salt's lower boundary is negatively interfering with the internal multiple. Figure 6 shows the zero offset trace results after ISS internal-multiple attenuation and adaptive subtraction. We can see the lower boundary of the salt shape is still not visible. The criteria behind the energy minimization adaptive subtraction fails, that is, the primary energy after subtraction is larger than the energy of the interfering events. Figure 7 shows the 0-offset trace results after internal-multiple elimination. The lower boundary of the salt model is recovered in the result. It demonstrates that the elimination algorithm can predict both correct time and amplitude and can eliminate internal multiples without damaging a proximal or interfering primary.

CONCLUSION

The ISS multi-dimensional internal-multiple-elimination algorithm that removes internal multiples (while accommodating primaries and internal multiples as sub-events) is one part of the three-pronged strategy that is a direct response to a current seismic processing and interpretation challenge when primaries and internal multiples are proximal to and/or interfere with each other in both on-shore and off-shore plays. This new algorithm addresses the shortcomings of the current most capable internal-multiple-removal method (ISS internal-multiple-attenuation algorithm plus adaptive subtraction). Meanwhile, this elimination algorithm retains the stand-alone benefits of the ISS internal-multiple-attenuation algorithm that can predict all internal multiples at once and requiring no subsurface information (in contrast to stripping and Feedback loop methods that remove multiples layer by layer and require subsurface information). This ISS internal-multiple-elimination algorithm is more effective and more compute-intensive than the current best internal-multiple-removal method. Within the three-pronged strategy, our plans include developing an alternative adaptive-subtraction criteria for internal-multiple elimination derived from, and always aligned with the ISS elimination algorithm. That would be analogous to the new adaptive criteria for free-surface-multiple removal proposed by Weglein (2012), as a replacement for the energy-minimization criteria for adaptive subtraction. In this paper, we provide this new multi-dimensional internal-multiple-elimination method as a new internal-multiple-removal capability in the multiple-removal toolbox that can remove internal multiples that interfere with primaries without subsurface information and without damaging the primary. This new tool-box option is called for in many off-shore and on-shore plays (e.g., the Middle-East, the North Sea, offshore Brazil and Australia, and the Permian Basin).

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