A new and comprehensive perspective on the role of primaries and multiples in seismic data processing for structure determination and amplitude analysis

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SUMMARY

In this paper, we provide a new and comprehensive perspective on primaries and multiples, that encompasses both removing multiples and using multiples. We describe the original motivation and objectives behind these two initiatives, viewed almost always as "remove multiples versus use multiples". The premise behind that "versus" phrasing implies a competing and adversarial relationship.

A contribution in this paper is placing these two activities and interests within a single comprehensive framework and platform that demonstrates their complementary rather than adversarial nature and relationship.

They are in fact after the same single exact goal, that is, to image primaries: both recorded primaries and unrecorded primaries. There are circumstances where a recorded multiple can be used to find an approximate image of an unrecorded subevent primary of the recorded multiple.

All direct methods for imaging and inversion require only primaries as input. To image recorded primaries recorded multiples must be removed. To use a recorded multiple to find an approximate image of an unrecorded primary requires that unrecorded multiples be removed. All multiples, recorded multiples and unrecorded multiples need to be removed. Not removing those recorded and unrecorded multiples will produce imaging artifacts and false and misleading images, when seeking to image recorded and unrecorded primaries, respectively.

Multiple removal and using multiples have a single and exactly identical goal and objective: imaging primaries, recorded primaries and unrecorded primaries.

DIRECT AND INDIRECT METHODS FOR STRUCTURAL DETERMINATION AND AMPLITUDE ANALYSIS

Inverse methods are either direct or indirect (see the definition and examples of direct and indirect inversion in e.g., Weglein, 2017, 2013). Direct methods provide assurance and confidence that we are solving the problem of interest. In addition, and equally important, they communicate whether the problem of interest is the problem that we (the seismic industry) need to be interested in. When a direct solution doesn't result in an improved drill success rate, we know that the problem we have chosen to solve is not the right problem — since the solution is direct and cannot be the issue. On the other hand with an indirect method, if the result is not an improved drill success rate, then the issue can be either the chosen problem, or the particular choice within the plethora of indirect solution methods, or both. The inverse scattering series (ISS) is the only direct inversion method for a multidimensional subsurface.

For indirect methods that either: (1) solve a forward problem in an inverse sense, like AVO or (2) are model matching methods like, e.g., FWI, where for the latter any data can be model matched. In indirect model matching methods the data plays a passive role while the modeling and matching and searching is where the action resides.

The direct ISS method for determining earth material properties, defines both the precise data required and the algorithms that directly output earth mechanical properties. For an elastic model of the subsurface the required data is a matrix of multicomponent data, and a complete set of shot records, with only primaries. With indirect methods any data can be matched: one trace, one or several shot records, one component, multicomponent data, with primaries only or primaries and multiples, pressure, displacement, spatial derivatives of these quantities, and stress or only just multiples. Direct and indirect parameter inversion have been compared with analytic data (Yang, 2014; Yang and Weglein, 2014; Weglein, 2017). The direct ISS method has more rapid convergence and a broader region of convergence. The difference in effectiveness increases as subsurface circumstances become more realistic and complex and in particular with band-limited noisy data.

There are two categories of direct methods for imaging and inversion: (1) those that require subsurface information, and (2) those that do not require subsurface information. Stolt CIII imaging (Weglein et al., 2016; Zou et al., 2017), the current high water mark of migration and migration-inversion capability requires recorded primaries. For Stolt CIII structural determination a smooth velocity model will suffice, for reflector location. For more ambitious objectives beyond structural determination, such as amplitude analysis for target identification, ALL elastic and inelastic subsurface properties need to be provided above the target. For all migration methods, e.g., Stolt CIII and CII RTM or Kirchhoff, all multiples must first be removed, to avoid false and misleading images from multiples, before imaging and inverting primaries.

There are isolated task ISS subseries that perform free surface multiple removal, then internal multiple removal, followed by distinct subseries that migrate and invert primaries, and perform Q compensation directly and without subsurface elastic or inelastic information. The ISS is the only direct inversion methodology for a multidimensional subsurface, it doesn't require subsurface information and multiples are removed prior to performing the tasks of structural determination and amplitude analysis, the latter inputting only primaries. If ISS depth imaging and inversion subseries needed multiples it would not have distinct ISS subseries that remove free surface and internal multiples. The only direct inversion method for a multidimensional subsurface treats multiples as coherent noise that needs to be removed.

Hence, all direct imaging and inversion methods call for an adequate set of primaries, and require as a prerequisite that all multiples be removed.

We suggest that it would be worthwhile for those developing e.g., interferometry and Marchenko methods, to demonstrate their added value relative to the current high water mark of imaging and inversion methods that either require or do not require subsurface information, respectively.

The most effective migration concepts, Stolt CIII migration needs recorded primaries (Weglein et al., 2016; Zou et al., 2017). The use of multiples to provide an approximate image of an unrecorded primary, cannot produce a Stolt CIII image of the unrecorded primary, instead it provides a weaker and approximate RTM CII imaging result. In direct imaging and inversion methods multiples are always needing to be removed. That reality drives and defines the need and priority of effective multiple removal. We review and exemplify the recent advances in that arena, and open issues and challenges that need to be addressed.

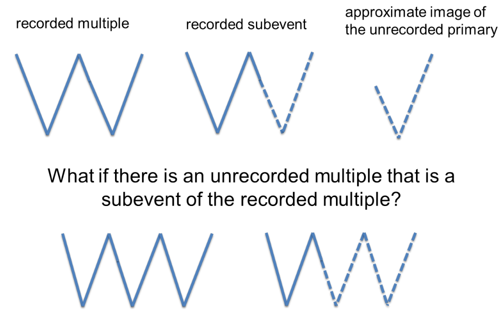

Figure 1: *Using a recorded multiple to find an approximate image of an unrecorded primary of the multiple: illustrate the need to remove unrecorded multiples. A solid line (___) is a recorded event, and a dashed line (− − −) connotes an unrecorded event.*

A NEW AND COMPREHENSIVE PERSPECTIVE ON THE ROLE OF PRIMARIES AND MULTIPLES IN SEISMIC PROCESSING FOR STRUCTURAL DETERMINATION AND AMPLITUDE ANALYSIS

A major activity within M-OSRP has been and remains the development and delivery of fundamentally new and more effective methods for removing free surface and internal multiples, for offshore and on-shore plays, without damaging proximal or interfering events. That is, removing multiples that interfere with target or reservoir identifying primaries, without damaging the primaries. More effective multiple removal remains an active and priority seismic research topic, with open issues to address, and where advances and the next generation of deliverables will have a further significant positive impact on drilling success rates for locating and developing reservoirs.

We recognize that there is considerable attention and communication these days on "using multiples".

In the note below and in the executive summary video `http://mosrp.uh.edu/news/executive-summary-progress-2017` we present a new perspective on the removal and using of multiples.

All direct methods for imaging and inversion require a complete set of primaries. However due to limits in acquisition some primaries are recorded and others are not recorded. Primaries are therefore classified as either recorded primaries or unrecorded primaries.

To image recorded primaries, with a smooth velocity model, recorded multiples need first to be removed. If not removed, each multiple will always produce a false and misleading structural image. A method to find an approximate image of an unrecorded primary uses a recorded multiple and a recorded subevent of the multiple to find an approximate image of an unrecorded primary that is a subevent of the recorded multiple (Valenciano et al., 2014; Shan, 2003; Liu et al., 2011; Lu et al., 2011; Muijs et al., 2007). However we assume that the unrecorded subevent of the recorded multiple is an unrecorded primary. Any unrecorded multiple that is a subevent of the recorded multiple must be removed to avoid it producing a false and misleading structural image.

Hence, to image recorded primaries recorded multiples must first be removed, and to find an approximate image of an unrecorded primary requires unrecorded multiples to be removed. The very use of multiples speaks to the primacy of primaries. A multiple is only useful if it contains as a subevent an unrecorded primary. A multiple that has all of its subevents recorded has absolutely no use or value. All primaries are useful — and there is no substitute for a complete set of recorded primaries. Multiples can at times be useful but are not in any sense the "new primary".

The recorded multiple event that can be used (at times) to find an approximate image of an unrecorded primary, must as an event be removed in order to image recorded primaries.

Basically: (1) to image recorded primaries, with a smooth velocity model, recorded multiples must be removed and (2) for unrecorded primaries, to use a recorded multiple and a recorded subevent of the multiple to find an approximate image of an unrecorded primary subevent of the recorded multiple, any unrecorded multiple that is a subevent of the recorded multiple must be removed.

The key point is that it's primaries, both recorded and unrecorded primaries that we seek and require, and removing and using multiples are not adversarial, they serve the same single purpose and objective: the imaging of primaries.

What use is a multiple where all primary sub-events of the multiple have been recorded. The answer: absolutely no use or value, none whatsoever — the only interest for us in such a multiple is (as always) to remove that recorded multiple to avoid producing false, misleading and injurious images when migrating recorded primaries.

Hence multiples are NOT now rehabilitated events on equal footing with recorded primaries. They are NOT the new primaries and multiples are NEVER migrated (That idea and thought of "migrating multiples" has no meaning, Please see Weglein,

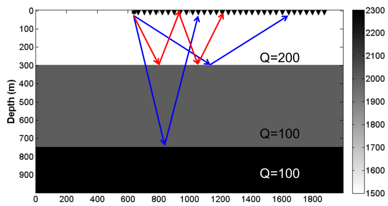

Figure 2: *model used to generated synthetic data. Two primaries (Blue) and one free-surface multiple (Red) are generated.*

2016). For those pursuing the use of multiples, it is suggested to inform us as to how unrecorded multiples will be removed.

The use of multiples is worthwhile to pursue, and to develop and deliver. Their value directly depends on the lack of adequate recorded primaries. However, there is no substitute for recorded primaries for the extraction of complex structural information and subsequent amplitude analysis.

MULTIPLES: A BRIEF HISTORIC OVERVIEW

Multiple removal has a long history in seismic exploration. Among early and effective methods for removing multiples are CMP stacking, deconvolution, and FK and Radon filtering. However, as the industry trend moved to deep water and ever more complex offshore and on-shore plays, the assumptions behind those methods could not be satisfied and these methods were unable to be effective and failed. Methods that sought to avoid those limiting assumptions include SRME (Berkhout, 1985; Verschuur and Berkhout, 1997) for free surface multiples and the distinct inverse scattering subseries (ISS) for removing free surface (Carvalho et al., 1992; Weglein et al., 1997) and internal multiples (Araújo et al., 1994; Weglein et al., 1997). SRME did not require subsurface information but only predicted the approximate time and amplitude of first order free surface multiples at all offsets. The ISS free surface multiple removal algorithm does not require subsurface information and predicts the exact time and exact amplitude of all orders of free surface multiples at all offsets. A quantitative comparison of SRME and the ISS Free Surface Multiple Elimination (FSME) algorithm can be found in Ma et al. (2018a,b), Figure 2 and 3. That analysis helps to define when SRME and ISS free surface elimination are the appropriate and indicated choice within the free-surface multiple removal seismic toolbox.

The result shows SRME + adaptive subtraction can be the effective and appropriate choice to remove isolated free-surface multiples, whereas the ISS FSME is effective and the appropriate choice to surgically remove free-surface multiple that interfere with primaries or other events, and without damaging primaries.

For internal multiples, only the ISS internal multiple algorithms require no subsurface information — and is currently the only toolbox option for offshore and on-shore plays where subsurface information is either unavailable or unreliable. The ISS internal multiple attenuation algorithm predicts the precise time and approximate amplitude of all orders of internal multiples.

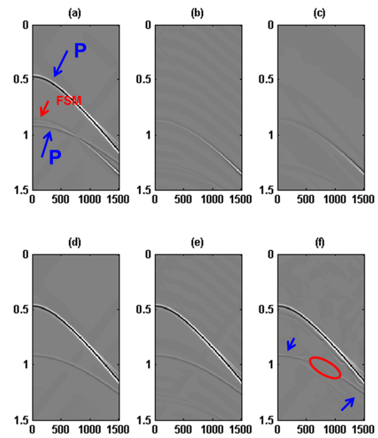

Figure 3: *(a) Input data generated using model shown in Figure 2. Two primaries are pointed by the blue arrows, one free-surface multiple is pointed by the red arrow. (b) ISS free-surface multiple prediction (c) SRME free-surface multiple prediction (d) Actual primaries in the data (e) Result after ISS FSME (f) Result after SRME + Adaptive subtraction. The free-surface multiple is interfering with the recorded primary. The SRME + Adaptive damages the primary that interferes with the free surface multiple. The ISS free-surface algorithm effectively removes the free surface multiple without damaging the primary.*

THE CURRENT HIGH WATER MARK OF FREE SURFACE AND INTERNAL MULTIPLE REMOVAL

The ISS free surface multiple elimination algorithm (see e.g., Carvalho et al., 1992; Weglein et al., 1997, 2003) predicts both the exact time and amplitude of all orders of free surface multiples at all offsets. It is effective with either isolated and interfering free surface multiples. The ISS internal multiple algorithm attenuates internal multiples — and often will be applied along with an energy minimization adaptive subtraction, to remove an internal multiple that is not proximal to other events. To remove an internal multiple that is proximal to or interferes with other events (cannot rely on energy minimization, since the energy minimization criteria itself can fail), we need a more capable prediction, to surgically remove the multiple without damaging a nearby or interfering event. ISS internal multiple elimination had its origins in Weglein and Matson (1998), discussion in Ramírez and Weglein (2005), and an initial algorithm development in Herrera and Weglein (2013) and a fuller development and multidimensional algorithm in Zou et al. (2018). The latter elimination algorithm is based on an acoustic medium, and the effectiveness under different circumstances for acoustic, elastic and an-elastic media is demon-

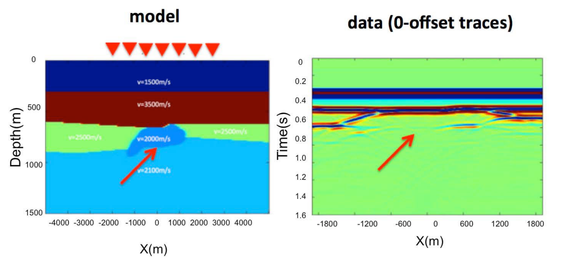

Figure 4: *The model and zero offset traces of data. The base salt is almost invisible because the primary generated by the base salt is negatively interfering with an internal multiple.*

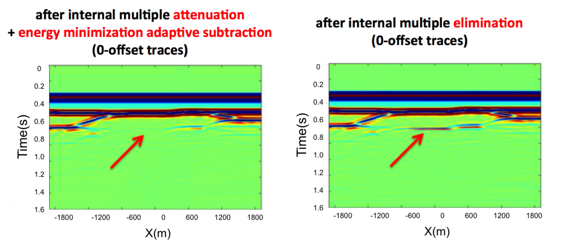

Figure 5: *Zero offset traces after ISS internal-multiple attenuation and energy minimization adaptive subtraction. The base salt is still not visible. The criteria of the energy minimization adaptive subtraction fails, that is, the energy after subtraction is larger than the energy of the interfering events. The base salt is recovered using the ISS internal multiple elimination algorithm. 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.*

strated in Wu and Weglein (2017) and Zou et al. (2018); Fu et al. (2018).

The left part of the Figure 4 shows the 2D model. The data is generated by the finite difference method. The model is designed so that the base salt primary is negatively interfering with an internal multiple.

We can see clearly that the base salt is almost invisible because the primary from base salt is negatively interfering with the internal multiple. Figure 5 (right hand side) shows the results after internal-multiple elimination. The base salt is recovered. It demonstrates that the elimination algorithm can predict both the correct time and amplitude and can eliminate internal multiples without damaging an interfering or proximal primary.

The only direct inverse methods for parameter estimation — the parameter estimation subseries of the inverse scattering series, pioneered by Zhang (2006); Li (2011); Liang (2013) (Please see Weglein et al., 2016) specify the data required and the algorithms, and the required data are a complete set of shot records with multi-component primaries.

In contrast, with model matching methods like FWI there is no guide, no underlying theory or conceptual platform — one trace, many traces, multi-component traces, and horizontal and vertical derivatives of displacement and pressure, and stress measurements and gravity data — in fact, absolutely any data can be chosen to be model matched, including only one trace, or traces with only multiples. It seems reasonable that adding more data and data types would provide more constraints to search algorithms that might benefit and assist the parameter identification objective — however while including free surface multiples with primaries is often viewed as helpful, with added constraints for the modeling to match, the addition of internal multiples seems in practice to be "too full" model matching with too many complicated constraints. It seems that model matching with only primaries is viewed as not "full" enough, with primaries and free surface multiples that feels just right and perfectly full, and with the addition of internal multiples, apparently a little "too full". We are back to the lack of an underlying theory and framework.

In the history of useful methods and contributions that seek to accommodate limited data acquisition, like DMO, and 2D and 2.5D processing with asymptotic techniques in the cross line direction, that eventually data acquisition advances to provide the data necessary to reach processing and interpretation goals — and methods that seek to accommodate limited data become less interesting and less relevant.

CONCLUSION

The confusion over 'using' multiples is not a harmless misunderstanding — without consequences — because if multiples were in fact the new signal and the equivalent of primaries then we should no longer remove multiples, no more than we remove primaries — that's the danger that derives from a misinformed premise and conclusion.

Multiple removal and using multiples have one single exact goal: imaging primaries, recorded and unrecorded primaries. To be effective at reaching that objective recorded and unrecorded multiples must be removed. Since recorded primaries have the greatest potential (via Stolt CIII migration and migration-inversion and ISS depth imaging and inversion) for delivering structure and amplitude analysis, the removal of recorded multiples has the concomitant highest priority and impact.

There are two main obstacles: lack of adequate or complete acquisition of primaries, and when recorded primaries interfere with multiples, free surface and internal multiples.

Multiple removal is a permanent issue, whereas multiple usage is transient, and the latter will eventually be replaced by a more complete recording of primaries.

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