Primary-preserving multiple attenuation for broadband data

Ronan Sablon, Jean-Michel Deprey, and Celine Lacombe (CGG)*

Summary

Multiple attenuation is a key step in broadband marine processing which can be challenging for primary and low frequency preservation. Many multiple modeling and adaptive subtraction tools have been developed to address specific problems, depending on water depth and data complexity. The way to combine them has become complicated: common practice is to apply several de-multiple methods sequentially. However, this approach, while attractive for its flexibility and apparent simplicity, may lead to cumulative mistakes and ultimately harm primary event continuity and low frequencies, to the detriment of overall quality and further inversion work. This paper proposes an optimized multiple attenuation methodology and new quality controls (QCs) based on correlations and pseudo-impedance.

Introduction

Numerous multiple modeling and adaptive subtraction tools are now available to address problems linked to water depth, geometry, offset range, or data complexity: each tool has a specific application domain, with strengths and limitations. Combining various methods is often necessary, so that a standard de-multiple flow may consist of applying various different steps in succession. However, beyond the individual parameterization of these tools, the way different methods are combined is critical. The larger the number of steps, the greater the risk of accumulating unrecoverable errors or creating uncertainties and instabilities in the final results. Standard de-multiple processing could also be inadequate for broadband data, because separation between primaries and multiples is most difficult at low frequencies. In the following, we define a de-multiple flow which avoids cumulative mistakes to obtain stable and robust results.

What about standard cascaded de-multiple?

The data set we use for testing is from a 2D variable-depth streamer acquisition offshore Australia, which crosses three wells. Reference results were obtained with a standard cascaded de-multiple sequence applied directly after pre-migration receiver de-ghosting (Poole, 2013).
The cascaded sequence (Figure 1 left) includes a model-based surface-related multiple modeling (SRMM) with a first adaptive subtraction, followed by a convolutional surface-related multiple estimation (SRME) with a second adaptive subtraction, and lastly, Radon de-multiple to handle the remaining multiples on mid to far offsets.

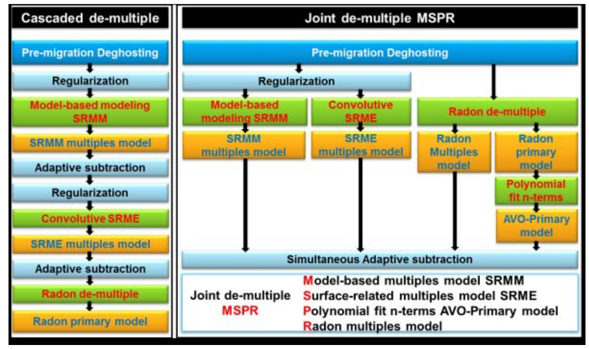

Figure 1: Comparison between a standard cascaded demultiple flow and a joint de-multiple sequence MSPR.

Surface-related multiple modeling by SRMM uses the seismic reflectivity of the shallow section to predict any order of multiples (Pica et al., 2005). SRME is a method generating a multiple model by convolution of traces (Verschuur, 2006). SRMM and SRME modelling methods are well known to be complementary and are generally applied consecutively in a marine processing sequence (each with its own adaptive subtraction), but in more complex cases may be applied together with a simultaneous adaptive subtraction.
Figure 2 shows the results of two different de-multiple flows on an angle gather of 0-60 degrees at a well location, with their respective differences from the input and the corresponding synthetic generated from the well log. Examples of data leakage which can occur with such a cascaded sequence are illustrated on Figures 2 B and D, e.g.:
- continuity breaks in offset/angle (around 15 degrees in this case) due to, for example, a window effect in adaptive subtraction.
- low frequency primary (below 10 Hz) damage on all useable angles at reservoir level (pink rectangle), also visible spatially on stacks or pseudo-impedance sections (Figures 5 B and D, and 3 B and D, respectively).
This damage to primary amplitude observed here makes the data set unreliable for amplitude-versus-offset (AVO) and pre-stack inversion work.
Although simple in appearance, the cascaded flow involves many steps (two adaptive subtractions among others), which increases the risk of unrecoverable error (loss of primary amplitude). The order used for the flow can vary and therefore may lead to differing results.
Moving away from the cascaded method and reducing the number of steps could be achieved by using simultaneous adaptive subtraction, the solution already chosen for complex de-multiple cases. This method should be simpler and also more robust in terms of primary preservation.

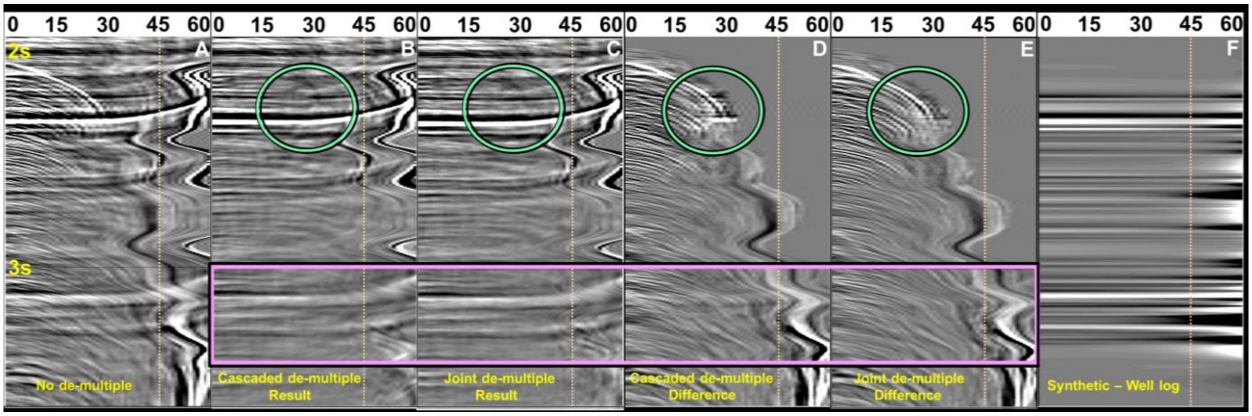

Figure 2: Angle gathers 0-60 degrees (non-migrated). A: after pre-mig deghosting; B and D: result and difference with cascaded demultiple; C and E: result and difference with joint demultiple MSPR; F: synthetic angle gather from well log (gas reservoir at 3200–3400 ms); the green circle and pink rectangle (reservoir level gas) illustrate examples of localized and low frequency data leakages with cascaded flow, well preserved with joint de-multiple MSPR.

Joint de-multiple with primary preservation

Since no multiple model will ever be perfect, an efficient way to benefit from respective strengths and overcome weaknesses is to use several of them simultaneously. We propose to combine the two multiple models SRMM and SRME with a pass of Radon de-multiple, both for multiple modeling and to generate a guide for a primary model.

AVO-driven primary model

With a sufficiently accurate velocity trend, the Radon de-multiple method is very efficient in discriminating primaries from multiples on mid to far offsets, and thus the Radon multiple model naturally complements the two other multiple models, SRMM and SRME, which both take care of near to mid offsets. The Radon method also enables the generation of a primary model. However, this model, and particularly the quality of its low frequencies, strongly depends on the Radon parameterization. For low frequency preservation, we propose the generation of a primary model with mild Radon parameters. This model is further stabilized with an additional n-terms polynomial fit (in the example shown here, 2-terms, as for an AVO fit) applied on a defined useable angle range, typically 0-40 degrees (Johansen et al., 1995). This stabilization makes the primary model less sensitive to the chosen Radon parameters. The second main weakness of the Radon method is a poor primary/multiple separation on the near offsets (especially for shallow water depths). Such an n-term polynomial fit takes advantage of data redundancy along offsets/angles to effectively reject residual multiples that are still contaminating near offsets.

Joint de-multiple method

In this joint de-multiple method, called here **MSPR,** the four complementary models, namely **M**odel-based multiple model SRMM, **S**urface-related convolutional multiple model SRME, AVO-driven **P**rimary model and **R**adon multiple model, work together in one pass of simultaneous adaptive subtraction, including a least-square global adaptation followed by a local subtraction (Figure 1 right). Figure 2 shows a comparison of results between a cascaded de-multiple flow (B and D) and a parallel MSPR sequence (C and E). For comparison purposes, both flows use exactly the same adaptation parameters. Continuities in offset/angle and low frequencies are well preserved with the MSPR sequence (green circles and pink rectangles in Figure 2).

Benefits: quality & efficiency

MSPR de-multiple presents several advantages to avoid or significantly reduce possible data leakages:

- the complementary nature of the different multiple models is fully taken into account.
- primaries, especially at low frequencies, are better preserved by adding a primary model to the adaption. This is particularly the case here where the multiple-to-primary amplitude ratio is low, as adaptive subtraction tends to be controlled by stronger amplitudes. Also, correlation between primaries and multiples increases as frequencies decrease. Imposing a model of primaries in the adaptation helps to better discriminate primaries and multiples at low frequencies.
- the simultaneous use of complementary models allows the adaptation to be constrained efficiently, making the process more robust and stable.

The efficiency of this method is also interesting in terms of computation time: Each multiple estimation (SRME, SRMM and Radon) can be performed in parallel. There are also gains in pre-conditioning, with only one regularization required, and in the adaptation part, as simultaneous global/local adaptive subtraction of n different models is faster than n consecutive processes.

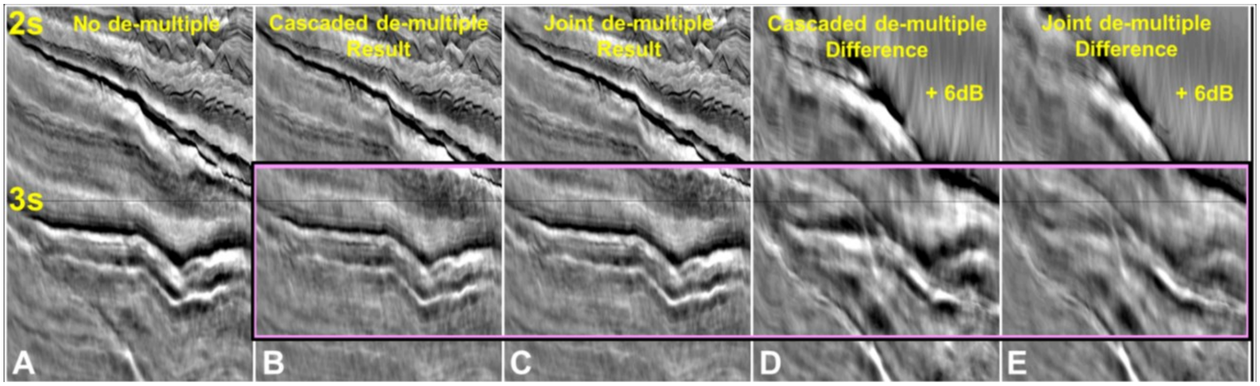

Figure 3: PSTM stacks converted to pseudo-impedance (with low-cut filter at 1.5 Hz); A: no demultiple. B and D: with cascaded de-multiple flow, result and difference; C and E: with joint de-multiple MSPR, result and difference (+ 6dB gain applied on differences). The pink rectangle highlights the reservoir level. Low frequency continuity is better preserved using the joint de-multiple flow MSPR.

Introducing new QC tools

How to QC low frequencies?

The quality of de-multiple results for low frequencies (below 10 Hz) can be difficult to assess visually. Therefore, a conversion to the pseudo-impedance domain (Yang et al., 2015; Jarfargandomi et al., 2015) can help to focus the QC on the 0-10 Hz frequency band (Figure 3). The differences clearly show some primary leakage for the cascaded flow and better primary preservation for the MSPR flow.

How to QC pre-stack event continuity?

The quality of a de-multiple sequence is classically assessed by looking at the energy removed by the process, where any primary leakage will become visible, together with auto-correlations. Comparison of well synthetics (if available) with seismic may also be useful (Figure 2F). However, the QC of a de-multiple sequence on a whole survey remains subjective, often relying on user interpretation.

Firstly, de-multiple QC should be focused on the angle range that will be used later for inversion work: typically 0-40 degrees. We propose a new kind of QC, fast and volumetric, based on event continuity in pre-stack gathers. Pre-stack traces are compared to a limited angle stack of 10-40 degrees (i.e., excluding the near offsets and therefore possible residual multiples) and using the maximum correlation over sliding time windows. The frequencies analyzed (here about 10 Hz) depend on the length of the chosen time window (lower frequencies could be analyzed with larger windows). Correlations are normalized, and allow detection of sudden changes in the shape of events (lack of continuity with offset) compared to the stack. On the angle gather example (Figure 4), an increase of correlation is indicated by consecutive colors: white, blue, red, and yellow. Low correlation values can be related to noise, residual ghosts, non-flatness of residual moveout (on angle range 45-60 degrees) and of course, multiples and primary data leakage. On the differences, selecting only the negative correlation is useful to easily detect anomalies related to residual multiples and/or primary data leakage (anomalies shown in red on Figures 4 D and E).

How to QC spatial continuities (on stack)?

A volumetric QC can be obtained by stacking the correlation gathers over the useable angle range for inversion, typically 0-40 degrees (Figure 5). Correlation stacks help detect anomalies on a volume before looking at them in detail on gathers. Differences of correlation stacks before and after de-multiple can be used to illustrate improvements in gather continuity (Figure 5 D and E). Red to yellow colors indicate areas of continuity improvement.

Here, for example, joint de-multiple MSPR results show globally better correlation values and fewer anomalies than the cascaded flow, which indicates a better preservation of primary continuity both in offset/angle and spatially.

Conclusions

Broadband data reveal shortcomings in standard de-multiple processing, especially in low frequencies. Applying different de-multiple methods sequentially increases the risk of cumulative errors, which could be detrimental to the overall quality for inversion. A joint de-multiple sequence, combining complementary multiple models with an AVO-driven primary model in a simultaneous adaptive subtraction, allows a better primary and low frequency preservation, and improves event continuity both in the offset/angle domain and spatially.

The improvement in the de-multiple sequence has been assessed using correlation-based pre-stack event continuity measurements and pseudo-impedance for the low frequencies. These approaches allow a better detectability of potential issues than standard QCs.

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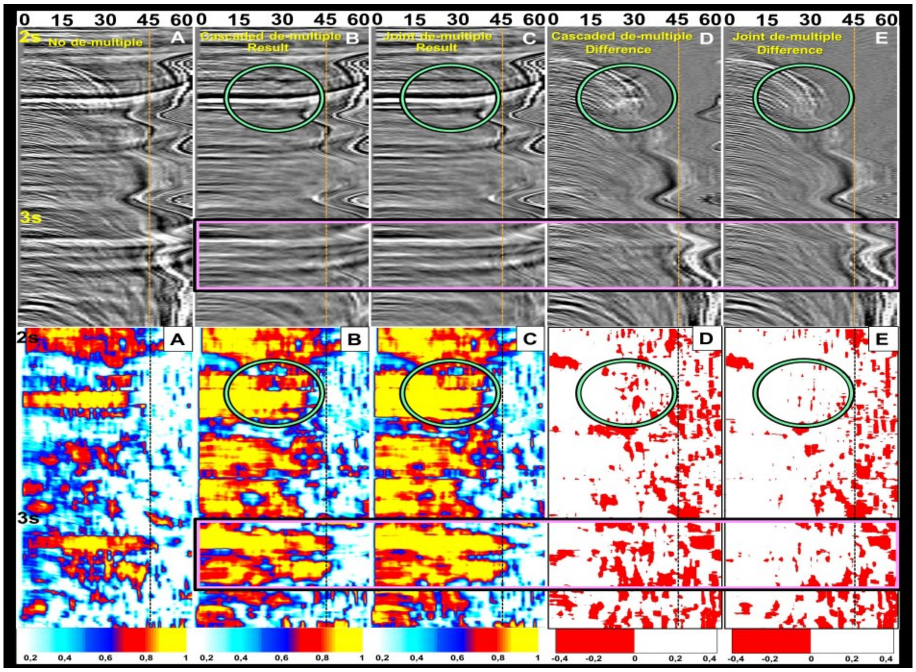

Figure 4: PSTM angle gathers (degrees) at well location (top) and corresponding correlation gathers (bottom). A: no de-multiple. B and D: with cascaded de-multiple, result and difference (anomalies in red); C and E: with joint demultiple MSPR, result and difference. The green circle and pink rectangle (reservoir level) illustrate examples of localized and low frequency data leakages with cascaded flow, well preserved with joint de-multiple MSPR.

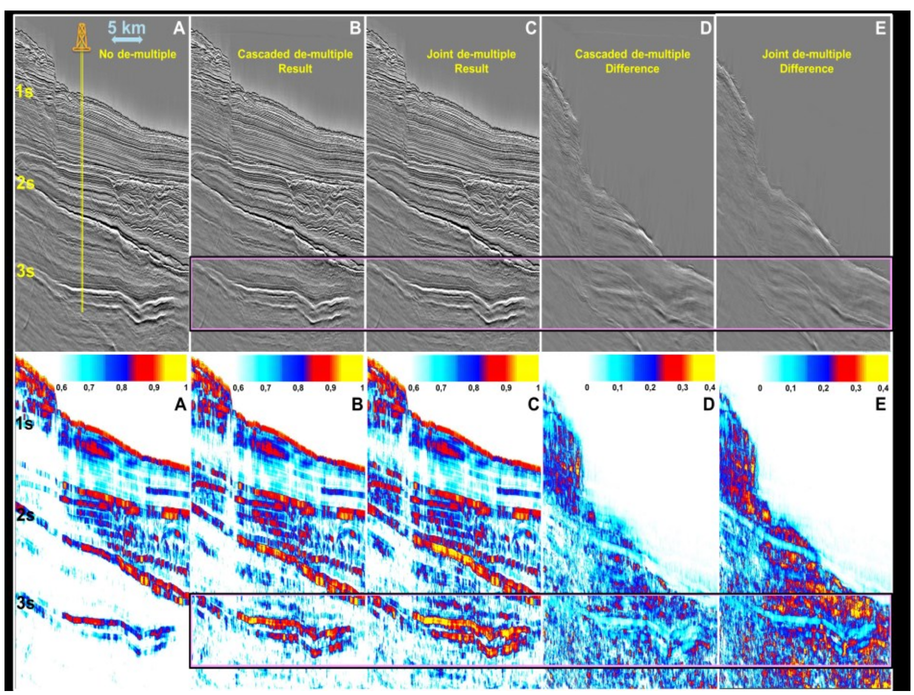

Figure 5: PSTM stacks (top) and corresponding correlations stacks (bottom). A: no-demultiple. B and D: with cascaded de-multiple flow, result and difference. C and E: with joint de-multiple MSPR, result and difference. The pink rectangle shows the reservoir level. The level of correlation allows to evaluate the quality of the de-multiple results; here, it is globally better with the joint de-multiple sequence MSPR.

EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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