Reverse Time Migration in the presence of known sharp interfaces

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SUMMARY

We propose using the forward propagated source wave to create synthetic receiver data on the surfaces of the computational domain where real receiver data is not available as a means of exploiting known information about reflector locations in Reverse Time Migration. The inclusion of synthetic boundary data can make true amplitude imaging possible, and reduce the artifacts associated with the inclusion of multiples. Here, we describe the new method, present synthetic examples, and propose an appropriate imaging condition.

INTRODUCTION

When the locations of some reflectors in the imaging domain are known, such as the location of the sea floor, this information can be exploited to improve the migrated image. The conventional Reverse Time Migration (RTM) method does not do this effectively, however. We present a simple modification to rectify this. The improvements are particularly important for facilitating true amplitude imaging and imaging with multiples.

We begin by describing the structure of the RTM algorithm, focusing in particular on the aspects that will be relevant to the description of the proposed modification. We then discuss the limitations of the algorithm that have lead to this proposal of a modification. This is followed by a presentation of the new method, and by synthetic examples. To correctly image with multiples, the conventional imaging condition must also be modified. The fourth section proposes an appropriate imaging condition.

Reverse Time Migration

Reverse Time Migration (Baysal et al. (1983)) consists of two stages. The first numerically propagates an approximation of the source wave forward in time, saving information in such a way that this wavefield can be later regenerated at each time step. One way in which this can be achieved is to save the boundaries and final state of the wavefield; strategy 4 in Dussaud et al. (2008). Using the final state as the initial condition, and the saved boundaries to reintroduce energy that left the domain during forward propagation, the source wavefield can be propagated backward in time to regenerate earlier time steps. The second step propagates the recorded data, typically from receivers at the surface, backward in time. Transparent boundary conditions are imposed through the use of a PML so that energy reaching domain boundaries is not reflected. An image of the reflectors is created by applying an imaging condition, typically a zero lag cross correlation between the source and data wavefields.

Limitations of conventional RTM

While RTM solves some of the limitations present in other migration methods, it still makes several simplifying assumptions. Two of these are that the data do not contain multiples, either internal or free-surface, and that the model is smooth. Failure to satisfy either of these constraints can lead to artifacts in the resulting image. To avoid this multiples should be attenuated prior to migration by the use of techniques such as SRME (see Verschuur (2006)). Not only is this process computationally expensive and imperfect, but it also causes the information about the subsurface that is contained in the multiples to be lost. The necessity of using a smooth model also causes available information which could be used to improve the results to be discarded. Reflectors with known locations, either from well logs, velocity analysis, or other means, provide information about the subsurface which could be used during migration to produce a more accurate image. Conventional RTM does not provide a means of using this information, however. Indeed, even if the exact velocity model were known, RTM would still not produce a perfect image. This is due to back propagated waves being partially transmitted through interfaces they should have been entirely reflected from, and being partially reflected from interfaces they should have been entirely transmitted through. Such back propagation along incorrect paths causes artifacts and makes true amplitude imaging challenging.

NEW METHOD

We propose a modification of RTM to improve the backpropagation by using available information about sharp interfaces. The key modification is that the boundaries of the data wavefield where recorded data is not available (typically the sides, bottom, and the cells at the top of the domain where no real receiver is present) are approximated with the numerically propagated source wavefield, as shown in Fig. 1. These approximated boundaries must be sufficiently thick so that spatial derivatives can be calculated. By Green's theorem (see Stolt and Weglein (2012) for a discussion), sufficient data is now available to reconstruct the forward modeled wavefield at any point inside the domain. Arrivals in the recorded data that match the source wave at the surface, will then also be back propagated correctly with this approach. This can allow internal and free-surface multiples to be used for imaging without producing the artifacts generally associated with these arrivals, and produces transmitted waves of the correct amplitude. As the information from the forward propagated source wavefield is now present in the data wavefield, the source wavefield is no longer required and only the data wavefield needs to be back-propagated. This approach therefore requires fewer computational resources than conventional RTM (although this advantage may be erased by a more expensive imaging condition). Other methods for dealing with the lack of receiver data on all

domain boundaries, and imaging with multiples, are described in Weglein et al. (2011), Farmer et al. (2006), Guitton (2002), and references therein.
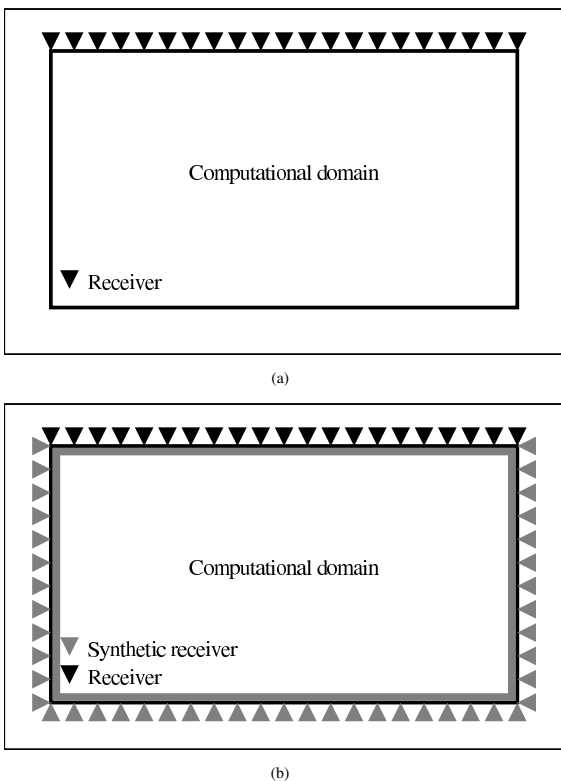

(a)

(b)

Figure 1: (a): Receivers are only located at the surface in regular RTM. (b): The forward propagated source wave is used to create synthetic receivers at the boundaries where real receivers are not present.

A demonstration of how, at interfaces that are known and included in the model, the new method correctly images with multiples is shown in Fig. 2. At the interfaces, the downward propagating wavefield from the surface data is met by waves propagating upwards from the bottom boundary (energy that was transmitted through the interfaces during forward modeling). This creates an appropriate interference so that the downgoing wave is entirely reflected at the boundary, rather than partially transmitted and partially reflected.

SYNTHETIC EXAMPLES

The first model tested was created to examine the ability of the new method to migrate internal multiples correctly. The model is relatively simple, with flat reflectors, and no lateral velocity heterogeneity. This is not a requirement of the method, but is rather used so that the artifacts from the internal multiples, if present, would stack coherently and so be clearly visible. We use an absorbing free-surface in the modeled data, to prevent the creation of free-surface multiples. The exact velocity model is used for both regular RTM and the new modified approach in the images shown in Fig. 3(a) and 3(b), respectively.
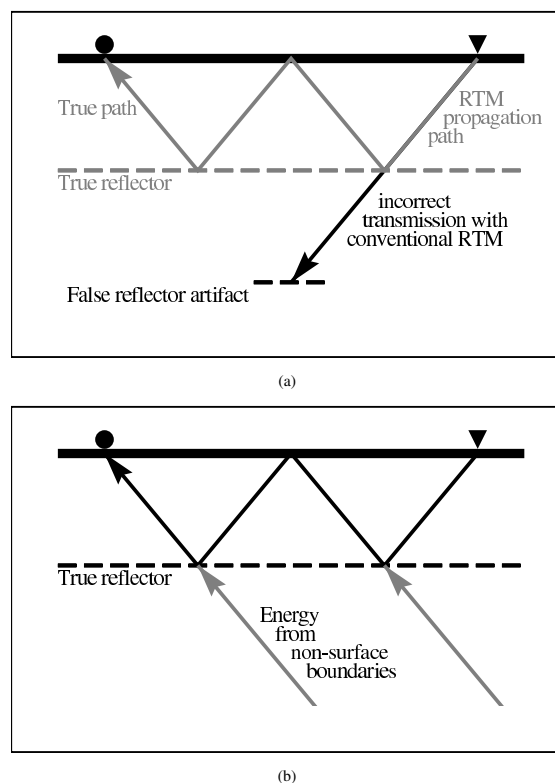

(a)

(b)

Figure 2: (a): Backward propagation of a multiple in the data along an incorrect path, leading to a 'phantom reflector' artifact. (b): With the multiple generating interface included in the velocity model, the new method back propagates the multiple along the correct path.

It is clear that the artifact from the internal multiple in the regular RTM image, indicated with an arrow, is absent from the image produced with the new method.

We use a second model to demonstrate the effect on free-surface multiples. The model, shown in Fig. 4(b), is designed to be representative of a marine survey, with small salt bodies below the sea floor. For this example a second velocity model is used during migration of the data, which is correct except for the lack of the salt bodies. This is done to demonstrate that the method correctly handles free-surface multiples that reflect off the sea floor even when the model below the sea floor is incorrect. The resulting image from regular RTM is shown in Fig. 4(c), with an artifact from the free-surface multiple indicated by arrows. Note that the multiple artifact has interfered with the image of one of the salt bodies (indicated with a circle). The image from the new method, in which the artifact is not present, is shown in Fig. 4(d). In Fig. 4(a) we show, for comparison, an image from data with an absorbing surface boundary to demonstrate the image that could be obtained with regular RTM if free-surface multiples were removed from the data.

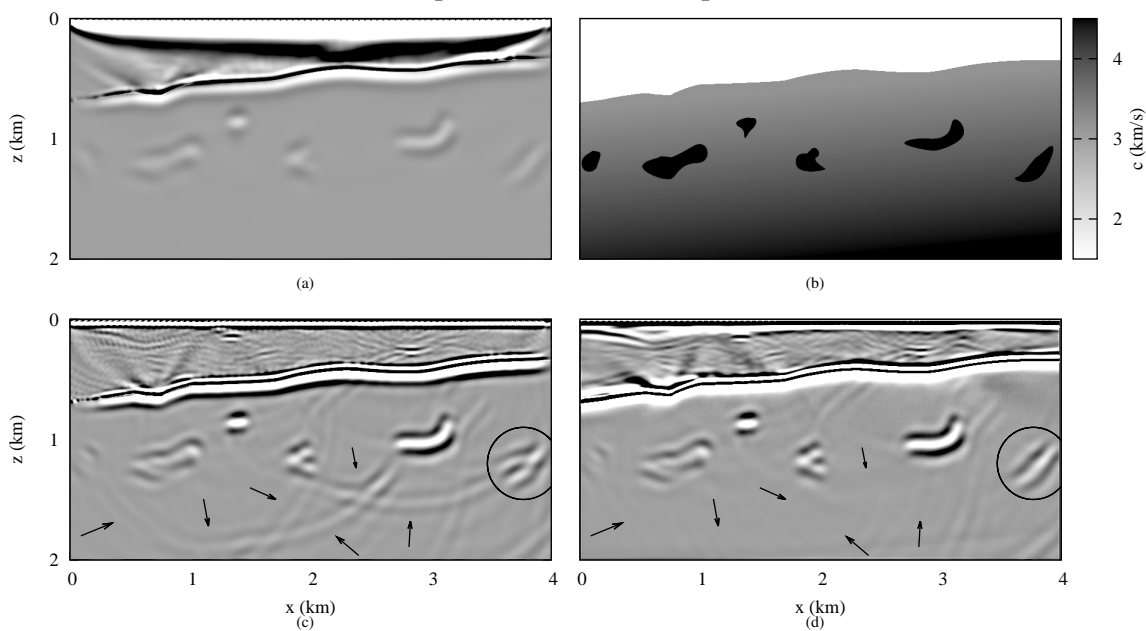**RTM in the presence of known sharp interfaces**

Figure 4: (a): A regular RTM image of the data when the free-surface is absorbing (representative of the image when free-surface multiple elimination has been performed on the data). (b): The exact model. (c): The regular RTM image when free-surface multiples are included. Arrows indicate artifacts caused by these multiples being incorrectly migrated. A salt body that is distorted because of these artifacts is circled. (d): The image produced by the new method when free-surface multiples are included.

IMAGING CONDITION

The images shown above all use the conventional zero lag cross-correlation imaging condition, with the single backpropagated wavefield used as both the source and data wavefields, followed by post-processing with a Laplacian filter. Further image improvements could be achieved with a modified imaging condition. The inclusion of multiples increases the need for an angle-dependent imaging condition. Primaries and multiples may image the same interface from above (with reflection coefficient R) and below (with $-R$), respectively, resulting in destructive rather than constructive interference of contributions to the image. This problem is not new, however, as the same situation can occur with primaries and turning waves.

We separate the wavefield into components traveling in the positive and negative directions in each spatial dimension (x, y, z). Following this, we determine wave propagation directions through the use of Poynting vectors, similar to approach 3 described in Vyas et al. (2011). This enables the separation of paths imaging the interface from below (multiples and over turned waves) from those imaging from above. The waves propagating toward the interface (when time is reversed) correspond to reflected and transmitted waves, while the largest wave propagating away from the interface is assumed to be the incident wave. Examining the propagation directions of these waves enables the reflector dip angle, and angle of the incident wave relative to this dip angle to be determined. The reflector image as a function of incident wave angle relative to reflector dip allows waves incident from below the reflector to be isolated. An example of this for the flat reflector model imaged in Fig. 3 is shown in Fig. 5. The sign of the amplitude

at these angles can be changed before collapsing the gather so that such waves add constructively, rather than destructively, to the image.

DISCUSSION

The method proposed has the potential to improve migrated images by exploiting known locations of sharp interfaces during backward propagation. One advantage of this is correctly propagating internal and free-surface multiples when the structures the waves reflect from are present in the model. This can use the information contained in these arrivals while simultaneously avoiding the artifacts created when they are incorrectly migrated by regular RTM. This is all achieved with a simple modification to existing RTM implementations and with reduced computational cost (excluding the imaging step). In addition, the method will only differ from regular RTM in the presence of sharp interfaces in the model. This implies that discontinuities can be placed in the model at the location of reflectors that are known with certainty, such as the sea floor, while regions of the model known with less certainty can be represented by smooth velocities, causing the method to behave similarly to regular RTM in those areas.

As with other migration algorithms, the effectiveness of the proposed method is dependent on the quality of the input data. Departures from reality in the source signature will result in imperfect cancellation of reflected waves at interfaces, potentially resulting in the presence of 'phantom reflector' artifacts, although these may have lower amplitude than with regular RTM. Inaccuracies in the propagation, for example failure to

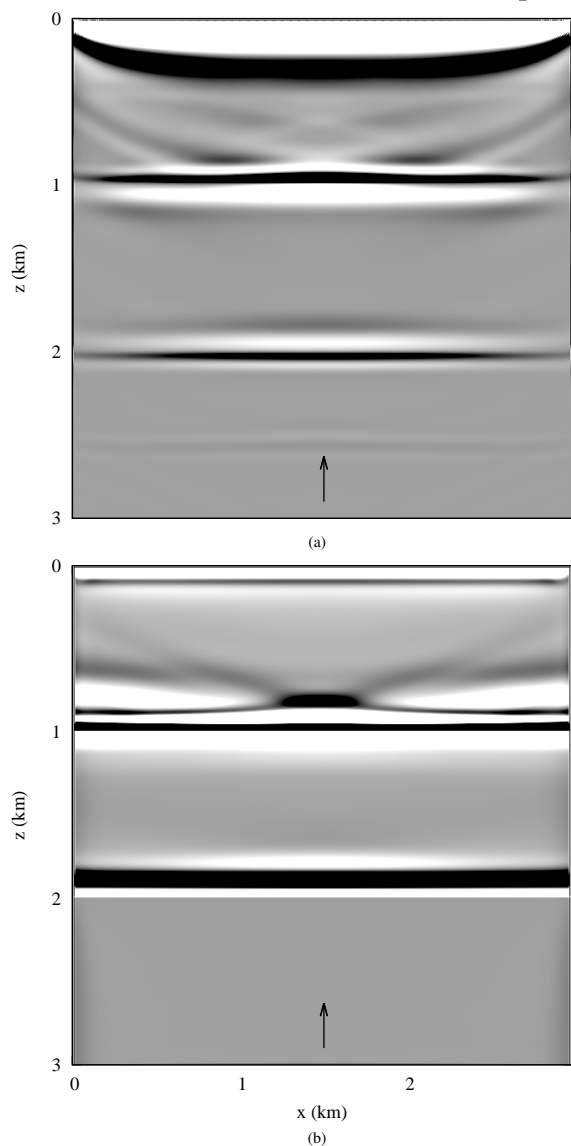**RTM in the presence of known sharp interfaces**

(a)

(b)

Figure 3: (a): The image produced by regular RTM, with an arrow indicating an artifact from the internal multiple. (b): The result of the new method.
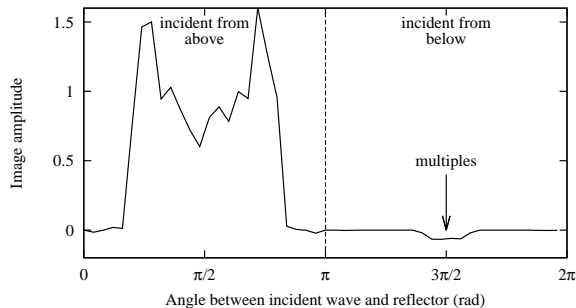

Figure 5: A stack over 31 shots of the imaged amplitude as a function of the angle between the incident wave and the reflector, for a single point on the upper reflector of the model imaged in Fig. 3. The waves incident from below the reflector (multiples and over turned waves) experience a reflection coefficient with opposite sign to those incident from above, as shown by the negative amplitude around $3\pi/2$. By reversing the sign of contributions incident from below the reflector before stacking over angle, such waves will add constructively to the image. In this example the shot spacing is such that the amplitude increases away from $\pi/2$ as, at greater angles from normal incidence, more shots stack into each angle, which is sufficient to overcome the decrease in amplitude from spherical spreading. The incident angle for multiples decays toward a constant angle more slowly, causing this effect to be less prominent.

CONCLUSIONS

We propose a modification to RTM to improve imaging by exploiting information available about the location of reflectors, such as the sea floor, to approximate the receiver data on the surfaces where real receiver data is not available. We show that the new method can not only avoid the artifacts caused by multiples in regular RTM images, but also enables useful contributions to the image by the multiples.

ACKNOWLEDGMENTS

correctly simulate attenuation, will also reduce effectiveness. While it is not necessary to use the exact velocity model in order for the method to improve the image, omitted reflectors can cause transmission losses to be underestimated in the source wave, resulting in the approximated boundaries of the data wavefield having incorrect amplitudes. Noise in the data, and incomplete receiver coverage, may also be sources of error.

The method relies on the velocity model being reasonably accurate. Correct cancellation at interfaces may not occur if errors are present in the velocity model. This suggests that the method may have applications in velocity analysis, as it could be used as an alternative means of identifying model errors.

REFERENCES

Baysal, E., D. Kosloff, and J. Sherwood, 1983, Reverse time migration: Geophysics, **48**, 1514–1524.

Dussaud, E., W. W. Symes, P. Williamson, L. Lemaistre, P. Singer, B. Denel, and A. Cherrett, 2008, Computational strategies for reverse-time migration: SEG Technical Program Expanded Abstracts 2008, Society of Exploration Geophysicists, 2267–2271.

Farmer, P., I. Jones, H. Zhou, R. Bloor, and M. Goodwin, 2006, Application of reverse time migration to complex imaging problems: First Break, 65.

Guitton, A., 2002, Shotprofile migration of multiple reflections: SEG Technical Program Expanded Abstracts 2002, Society of Exploration Geophysicists, 1296–1299.

Stolt, R., and A. Weglein, 2012, Seismic imaging and inversion: Volume 1: Application of linear inverse theory: Cambridge University Press.

Verschuur, D., 2006, Seismic multiple removal techniques: past, present and future: EAGE publications.

Vyas, M., X. Du, E. Mobley, and R. Fletcher, 2011, Methods for computing angle gathers using RTM: Presented at the 73rd Conference & Exhibition, EAGE, Extended Abstracts, European Association of Geoscientists and Engineers.

Weglein, A., R. Stolt, and J. Mayhan, 2011, Reverse-time migration and Green's theorem: Part I - The evolution of concepts, and setting the stage for the new RTM method: Journal of Seismic Exploration, **20**, 73.