FAST THREE-DIMENSIONAL TARGET-ORIENTED REVERSE TIME DATUMING

by

Shuqian Dong

A thesis submitted to the faculty of The University of Utah in partial fulfillment of the requirements for the degree of

Master of Science in Geophysics

Department of Geology and Geophysics

The University of Utah

October 2008
This thesis has been read by each member of the following supervisory committee and by majority vote has been found to be satisfactory.

Chair: Gerard T. Schuster

Michael Zhdanov

Richard D. Jarrard
To the Graduate Council of the University of Utah:

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Date

__________________________
Gerard T. Schuster
Chair, Supervisory Committee

Approved for the Major Department

__________________________
Marjorie A. Chan
Chair/Dean

Approved for the Graduate Council

__________________________
David S. Chapman
Dean of The Graduate School
ABSTRACT

Reverse time migration (RTM) is more accurate than traditional migration methods such as Kirchhoff and one-way wave equation methods because it computes numerical solutions to the complete wave equation. However, three-dimensional (3-D) RTM is limited in practice because of its high computational costs. I present a 3-D target-oriented reverse time datuming (RTD) method which can economically generate redatumed data in user-selected areas, such as beneath salt domes. Redatuming bypasses the complex velocity areas by solving the two-way wave equation using an accurate finite-difference strategy. The novel approach is a bottom-up strategy for calculating the Green’s functions, which can significantly reduce the computational time compared to conventional datuming. After redatuming, less computationally intensive migration methods such as the Kirchhoff method can be used to image the local target zone that typically contains less complex structures. The chief merit of RTD is that it can provide targeted subsurface images with full wave imaging technology at affordable computational costs.

The target-oriented RTD is tested on both 2-D and 3-D SEG/EAGE synthetic data sets and a 3-D field data set from the Gulf of Mexico. The results show that target-oriented RTD can reveal deep structures below complex structures with much less calculation effort than full volume RTM. The only requirement is that the area over the target zone is smaller than that of the acquisition survey.
To my family
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ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Gerard T. Schuster, for his guidance and support throughout my study at the University of Utah. I would like to thank my committee members Dr. Michael Zhdanov, Dr. Richard D. Jarrard for their advice and constructive criticism. I also thank Dr. Yi Luo and Dr. Min Zhou for their help on my thesis research work. I thank Dr. Sergio Chavez-Perez for his help on the field data processing. I thank Dr. Jianming Sheng, Dr. Zhiyong Jiang and Dr. Ruiqing He for their help on programming. I thank Dr. Xiang Xiao, Mr. Weiping Cao and Mr. Chaiwoot Boonyasiriwat for their help on my study and research work. I thank Mr. Ge Zhang for his help and suggestions on data processing. I thank Sherif Hanafy for his help on my study and research. I thank all UTAM students/sponsors for their support.

I am grateful to my parents and my wife for their support. They have created an enjoyable and pleasant atmosphere in my life.
CHAPTER 1

INTRODUCTION

Kirchhoff migration is usually considered as the most commonly used 3-D prestack migration algorithm because of its speed and stability advantages, but it has difficulties in imaging complex structures. This is because standard Kirchhoff migration is based on a high-frequency ray approximation which typically accounts for single-arrivals but ignores multi-pathing effects. One-way wave-equation-based depth migration can be used to handle multi-pathing events (Claerbout, 1971, 1985), but this method has a dip limitation and has problems in handling multiples and turning waves. Accounting for the defocusing effects, multi-arrivals, and turning waves caused by complex velocity distributions is one of the biggest challenges in exploration seismology (Gray et al., 2001).

It is generally agreed that full-wave (two-way wave) equation migration is more accurate for imaging reflections that propagate through structures in highly complex media (Biondi et al., 2002), if an accurate migration velocity is used. One example is reverse time migration (RTM). Based on the full solution of the two-way wave equation, RTM is not dip limited compared to one-way imaging methods and accounts for wave propagation in any direction (Baysal et al., 1983; McMechan, 1983; Whitmore, 1983). Moreover, RTM accounts for multiples and turning waves and therefore computes more accurate seismic images than Kirchhoff migration in highly complex media. However, RTM is not often used in industry because it is computationally expensive for 3-D prestack migration. The high computational cost arises from solving the two-way wave equation and the high storage cost for a 3-D implementation. Symes (2007) introduced an optimal checkpointing technique to avoid significant storage requirement for 3-D RTM, but the tradeoff is extra computation time.

In recent years, several methods have been proposed to overcome the high compu-
tation and memory storage requirements of RTM. Schuster (2002) shows that RTM is equivalent to a generalized diffraction stack migration, which inspired the development of a wavefront RTM technique (Zhou and Schuster, 2002) where the wave propagation equation is solved only in the wave front zone to reduce the computational costs. Later, Cao (2007) implemented the 3-D application of this method. Based on the idea of generalized diffraction stack migration, Luo (2002) and Luo and Schuster (2004) proposed a target-oriented reverse-time datuming (RTD) method, where the computation costs can be significantly reduced for target-oriented imaging. As a validation, Zhou and Luo (2002) presented some 2-D examples followed by Dong et al. (2007) who presented some 3-D examples of target-oriented RTD. Based on the target-oriented RTD method, Liu and Wang (2008) omitted the redatuming step and applied the imaging condition directly to the target areas. A related effort is by Wang et al. (2006) who combined the one-way wave equation based redatuming and Kirchhoff based migration to improve the speed and quality of subsalt velocity analysis.

In this work, I present the theory and application of the 3-D target-oriented RTD method. As a computationally inexpensive alternative to RTM, RTD extrapolates the wavefield to a subsalt artificial datum using the expensive but accurate finite-difference solutions to the full wave equation. In the redatuming step, only the velocity model above the datum is needed for the finite-difference (FD) solutions. Furthermore, a bottom-up strategy can reduce the FD computation by more than an order of magnitude for typical target-oriented applications. After redatuming, a less expensive method such as phase shift or Kirchhoff migration can be used because the sediments below the datum usually have less complex structures.

In the first part of this paper I present the theory of target-oriented RTD, and in the second part several numerical results are shown. I test the target-oriented RTD method on 2-D and 3-D SEG/EAGE synthetic data and then demonstrate an application of this method on a 3-D field data set from the Gulf of Mexico. For all these tests, Kirchhoff migration is applied to the original and redatumed data.
CHAPTER 2

THEORY

2.1 Target-oriented RTD

The target-oriented RTD was proposed by Luo (2002) and Luo and Schuster (2004) as a cheap and efficient alternative to full-volume RTM. The RTD method can be understood as backpropagating wavefields from both the source and receiver sides (Berryhill, 1979, 1984, 1986; Yilmaz and Lucas, 1986; Bevc, 1995) or as a correlation transform from surface seismic profile (SSP) data to single well profile (SWP) data (Schuster, 2009), which is demonstrated in Figure 2.1. The transform is mathematically described by the acoustic reciprocity equation of correlation type (Wapenaar, 2004; Schuster, 2009) given as:

\[
\mathbf{A}, \mathbf{B} \in S_{\text{datum}}: \quad \Im \left\{ \int_{S_0} \int_{S_0'} V_{\text{SWP}} G(\mathbf{A}|\mathbf{y})^* G(\mathbf{y}|\mathbf{x}) G(\mathbf{B}|\mathbf{x})^* d^2y d^2x \right\} \approx 2ik^2 \int_{S_0} \int_{S_0'} V_{\text{VSP}} G(\mathbf{A}|\mathbf{y})^* G(\mathbf{y}|\mathbf{x}) G(\mathbf{B}|\mathbf{x})^* d^2y d^2x, \tag{2.1}
\]

where \( \mathbf{x} \) and \( \mathbf{y} \) are the locations of source and receivers near the surface, and \( \mathbf{A} \) and \( \mathbf{B} \) are along the datum line. Here, \( G(\mathbf{A}|\mathbf{y}) \) and \( G(\mathbf{B}|\mathbf{x}) \) are the VSP Green’s functions for harmonic point sources in an acoustic medium with variable velocity and constant density, and \( G(\mathbf{y}|\mathbf{x}) \) is the SSP Green’s function where both the source and receiver are near the surface. The deviation of this equation is given in Appendix A.

Luo and Schuster (2004) suggested that, in a target-oriented mode, an efficient way to calculate the VSP Green’s functions is to place sources at the datum and receivers at the near surface. As an example, Figure 2.2a shows that, e.g., 13 finite-difference (FD) solutions (for the 13 sources along \( S_0 \)) are needed to compute the extrapolator kernel \( G(\mathbf{A}|\mathbf{y}) \) while Figure 2.2b suggests that only 5 FD solutions (for the 5 sources along \( S_0'' \)) are needed to find \( G(\mathbf{y}|\mathbf{A}) \). In this example, the area \( S_0'' \) in the subsurface
is assumed to be smaller than the area covered by the sources along $S_0$. Thus, it is computationally cheaper to first use a FD solver to compute $G(y|A)$ (for sources along the small horizontal buried plane $S_0''$) and then use reciprocity to find the Green’s functions for sources along the surface, i.e., $G(A|y) = G(y|A)$.

Table 2.1 shows examples of the CPU costs of standard datuming and the target-oriented approach. As can be seen, the bottomup method does not save computational time if the area of the target subsurface is same as that of the top surface in the 2-D SEG/EAGE salt example. While, the bottomup approach can save up to 90% of the computational costs, if the target subsurface is smaller than the top surface (3-D examples). This saving rate can be even higher if the target subsurface is less than several times smaller than the acquisition area on the surface.
Table 2.1. The computational cost comparisons between standard and target-oriented RTD where \( N_{src}^x \) and \( N_{src}^y \) are the numbers of sources in \( x \) and \( y \) directions respectively and 195 FD denotes the fact that 195 shot gathers need to be calculated by a FD method. In the 2-D SEG/EAGE salt example, the length of the target subsurface is the same as the top surface. So that, in this case, the standard and target-oriented RTD have the same computational costs. In the 3-D examples, the target subsurface is smaller than the top surface, and the target-oriented RTD save up to 90% of the computational costs.

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Figure 2.2. The computationally a) expensive (with 13 FD solutions) and b) inexpensive (with only 5 FD solutions) procedures for computing the extrapolation Green’s function $G(A|y)$ in equation 2.1.
2.2 RTD Algorithm

Figure 2.3 shows the five-step workflow of the target-oriented RTD method:

1. Calculate the VSP Green’s functions $G(x|A)$ by finite-difference methods, where $x$ is at the near surface and $A$ is at the new datum. In this case, the FD solutions are a set of band-limited Green’s functions with the same bandwidth as the data.

2. Use reciprocity to get the Green’s functions $G(A|x)$.

3. Transform the SSP seismic data $G(y|x)$ and the VSP Green’s functions $G(A|x)$ into the frequency domain.

4. Redatum the SSP data to the new datum by using Equation 2.1

5. Transform the redatumed data into the time domain.

In the frequency domain, the algorithm can be implemented in parallel on a distributed cluster. The gain in computational efficiency with the target-oriented approach is because the number of band-limited Green’s functions computed for sources on the new datum is significantly fewer than that on the original datum at the surface.

Since a two-way wave equation is solved by the FD method, artificial reflections from velocity contrasts within the model are a significant source of noise. Two strategies are used to suppress the undesired reflections: First, a properly smoothed model is used for calculating the Green’s functions, which can attenuate the backscattered waves without noticeably altering the wave propagation kinematics (Versteeg, 1993; Gray, 2000). Second, the density is properly adjusted to force acoustic impedance to be constant, which can avoid normal-incidence reflections from a velocity interface (Baysal et al., 1983; McMechan, 1983; Whitmore, 1983).

Adjustments along the data edges and model boundaries play another significant role in reducing artificial reflections from the edges. To reduce these artifacts, a cosine taper is applied over one wavelength along the edges of the original SSP survey. During the finite-difference computations, absorbing boundary conditions (Clayton and Engquist, 1977, 1980; Cerjan et al., 1985) are applied at the side and bottom boundaries. These steps attenuate most of the artificial reflections from model boundaries.
Workflow of target-oriented reverse-time datuming

Figure 2.3. The workflow of target-oriented reverse-time datuming, which, in frequency domain, can be implemented in parallel on a cluster.
CHAPTER 3
NUMERICAL RESULTS

To demonstrate the effectiveness of the target-oriented RTD method, I implement this algorithm on 2-D and 3-D SEG/EAGE synthetic data and a 3-D field data set from the Gulf of Mexico. For comparison, I then migrate the redatumed data as well as the original seismic data recorded at the top surface by using a Kirchhoff migration method.

3.1 2-D Synthetic Data Test

Synthetic examples associated with the 2-D SEG/EAGE salt model in Figure 3.1 are used to test the target-oriented RTD method. A finite-difference solution to the 2-D acoustic wave equation is used to compute the seismograms with a 15-Hz peak frequency Ricker wavelet as the source wavelet. For the SSP geometry in the salt model, there are 195 shots and 195 receivers at 40 m intervals on the model’s surface. A typical common shot gather (CSG) is shown in Figure 3.2a. To calculate the VSP Green’s functions, 195 shots at 40 m intervals are placed along the horizontal datum line which is 0.5 km beneath the surface, and 195 receivers at 40 m intervals are located along the same surface. These traces will be referred to as band-limited Green’s functions because the source is not impulsive in time. Figure 3.2b shows a typical VSP band-limited Green’s function.

Equation 2.1 is used to redatum the SSP data so that the redatumed sources and receivers are virtually distributed along the new horizontal datum at the depth of 0.5 km. To check the accuracy of the redatumed data, I also computed a finite-difference solution to the 2-D wave equation for a shot at the datum. The comparison between this redatumed virtual CSG with the true CSG, which is depicted in Figure 3.3, shows that the major events are correctly accounted for, but there are some artifacts in the
redatumed traces. These blemishes are mostly due to the far-field approximation and the finite aperture of the sources and receivers on the surface.

To test the effectiveness of the target-oriented RTD method for a subsalt target, I also redatumed the SSP data to a depth of 1.2 km, which is just below the salt dome in the model. Kirchhoff migration (KM) images are computed using the surface data and the redatumed data. The entire velocity model is used for Kirchhoff migration of SSP traces while only the subsalt velocity model is needed to migrate the redatumed data. Figure 3.4 shows the zero-offset data of the original SSP and the redatumed gathers. The comparison shows that the redatumed traces have less complexity than those along the top surface and are less contaminated by diffraction energy associated with the salt bottom. That is, the defocusing effects of the salt are avoided by redatuming below the salt.

The reflector images from Kirchhoff migrations of the SSP data before and after datuming are shown in Figures 3.5b and 3.5c respectively. For comparison, the RTM image of the original SSP data is shown in Figure 3.5d. The subsalt portion of the images computed from the redatumed data is of higher quality than the KM image obtained from the original surface data, and is comparable to the RTM image. This is because the standard Kirchhoff migration of SSP data is single-arrival based, where the first arrivals below the salt are typically weak due to defocusing from the salt. In contrast, the redatumed data below the salt are obtained by transforming many of these defocused early arrivals to strongly focused arrivals. The computational time for this redatumed approach is less than 1/3 that of standard RTM.
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3.2 3-D Synthetic Data Test

The 3-D target-oriented RTD algorithm is tested on the synthetic data associated with the 3-D SEG/EAGE salt model. This model has a complicated structural nature, which is representative of salt intrusions in the Gulf of Mexico. Because of computer limitations, only a part of the model is used to generate the synthetic data and test the target-oriented RTD algorithm. Figure 3.6 illustrates the velocity model with the size of 4.0 km along the x direction and 2.0 km along the y direction. A finite-difference solution to the 3-D acoustic wave equation is used to compute the seismograms with a 15-Hz peak frequency Ricker wavelet as the source wavelet. For the SSP geometry in the salt model, there are 1,700 shots and receivers evenly distributed in 20 inlines and 85 crosslines. The source and receiver intervals are 40 meters in the inline direction and 100 meters in the crossline direction. Figure 3.7a shows a typical common shot gather of the synthetic SSP seismograms. To reveal the structures below the salt dome, I redatum the SSP data to a datum at a depth of 1.2 km. Therefore, 800 VSP Green’s functions are calculated by placing sources at the new datum and 1,700 receivers at the near surface.

Equation 2.1 and a finite-difference method are used to redatum the SSP data to the new datum. A typical redatumed common shot gather is shown in Figure 3.7b. Kirchhoff migration is applied to these redatumed data. For comparison, Kirchhoff migration is applied to the SSP data using the entire velocity model. Figures 3.8 and 3.9 are the corresponding 3-D image cubes obtained by, respectively, migrating the original data and redatumed data. The subsalt portion of image in Figure 3.9 shows higher quality than the corresponding KM image obtained from the surface data (Figure 3.8). To compare the image quality in detail, different 2-D slices of the image cubes are shown. Figures 3.10a and 3.10b show the 3-D Kirchhoff migration images of the SSP data before and after redatuming respectively at inline 41. The reflector model of this inline is depicted in Figure 3.10c. Another inline example is shown in Figure 3.11, and Figures 3.12 and 3.13 depict the 3-D Kirchhoff migration images of the SSP data before and after redatuming at crosslines 161 and 201 respectively. Figures 3.14 and 3.15 show the 3-D Kirchhoff migration images of the SSP data before and after redatuming at the depths of 1.4 km and 1.5 km respectively. The comparisons at different inlines,
crosslines, and depth slices show that the subsalt migration images from the original SSP data are contaminated with noise and artifacts. In the migration images from the redatumed data, we can identify reflectors at their correct locations. These comparisons indicate that target-oriented RTD can significantly alleviate some of the defocusing effects of the salt. On the other hand, this method is estimated to be about 10 times faster than a standard RTM method for this example (see Table 4.1).
Figure 3.6. The 3-D SEG/EAGE synthetic salt model used for a 3-D test. The SSP experiment is synthesized with $85 \times 22$ shots and receivers evenly deployed on the surface with a 40-m interval.
Figure 3.7. Comparison of the original SSP data and the redatumed data. a) A common shot gather of the SSP synthetic seismograms generated from model depicted in Figure 3.6. b) Redatumed common shot gather with the source and receivers at the depth of 1.5 km below surface.
Figure 3.8. The stacked image after 3-D Kirchhoff migration of SSP data.

Figure 3.9. The stacked image after 3-D Kirchhoff migration of the redatumed data.
Figure 3.10. 2-D slices of the 3-D migration image cubes at inline 41: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data. c) The true reflector model. The horizontal dash line indicates the position of the new datum. Comparison between the reflector images in the boxed areas shows a noticeable improvement of the image quality for the redatumed data.
Figure 3.11. 2-D slices of the 3-D migration image cubes at inline 101: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data. c) The true reflector model. The horizontal dash line indicates the position of the new datum.
Figure 3.12. 2-D slices of the 3-D migration image cubes at crossline 161: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data. c) The true reflector model
Figure 3.13. 2-D slices of the 3-D migration image cubes at crossline 201: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data. c) The true reflector model
Figure 3.14. 2-D slices of the 3-D migration image cubes at depth of 1.4 km: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data. c) The true reflector model
Figure 3.15. 2-D slices of the 3-D migration image cubes at depth of 1.5 km: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data. c) The true reflector model.
3.3 3-D Field Data Test

I implement the target-oriented RTD method on a marine field data set recorded in the Gulf of Mexico. The seismic survey covers a rectangular area of 25 km by 20 km. In this area, the geological structures consist of an arcuate series of fold-thrust structures, which change orientation from approximately east-west to north-northwest-south-southeast (Mitra et al., 2006). The interval velocity model (Figure 3.16) shows large velocity gradients and high velocity variations in this area, which may cause serious defocusing effects in a seismic survey. Due to the complex wavefield, it is a challenge to reveal the structures in the deep area. Our goal is to redatum the surface seismic data to a deep datum close to the target zone and improve the image quality in this deep area.

The original seismic data were recorded by an ocean bottom cable (OBC) system. The pressure seismograms are recorded by hydrophones on the sea floor (about 150 meters below the sea level). More than 50,000 shots are distributed in 500 inlines and 100 crosslines. The shot intervals are 50 m in the inline direction and 200 m in the crossline direction, and the recorded time sampling interval is 4 ms. Figure 3.17a depicts a typical shot gather of the data. I redatumed the OBC data to a target area which is 1.5 km below the sea level. A finite-difference solution to the 3-D acoustic wave equation is used to compute the band limited VSP Green’s function in Equation 2.1 with a 25-Hz peak frequency Ricker wavelet as the source wavelet. More than 5,000 shots are located along the new datum to calculate the band limited VSP Green’s functions compared to 50,000 shots in the original survey.

Equation 2.1 is used to redatum these OBC data to the new datum, and a redatumed virtual shot gather is shown in Figure 3.17b. A Kirchhoff migration method is applied to the original OBC data and the redatumed data, where the entire velocity model is used for Kirchhoff migration of SSP traces while only the velocity below the datum is needed to migrate the redatumed data. Figures 3.18 and 3.19 are the corresponding 3-D image cubes obtained by, respectively, migrating the original data and redatumed data. The deep portion of Figure 3.19 image is of higher quality than the KM image obtained from the surface data in Figure 3.18.

To compare the image quality in detail, different slices of the image cubes are shown.
Figure 3.20 shows the 3-D Kirchhoff migration images of the SSP data before and after redatuming respectively at inline 21. Another inline example is shown in Figure 3.21. Figures 3.22 and 3.23 show the migration images at crosslines 61 and 101 respectively, while Figures 3.24 and 3.25 show the migration images at the depths of 2.0 km and 2.5 km, respectively. From these images, we can see more details of the deep reflectors, and it is easier to identify faults and continuous reflectors from the images of redatumed data than from the images of original data. The comparisons indicate that defocusing effects, multiples, and turning waves caused by the complex structures are relieved by the target-oriented RTD algorithm. On the other hand, this method is estimated to be about 100 times faster than a standard RTM method for this example.
Figure 3.16. The 3-D interval velocity model for the field data from the Gulf of Mexico. The original OBC data are redatumed to a new datum along the depth of 1.5 km below the surface. The VSP Green’s functions are calculated by using the upper part of this model above the new datum.
Figure 3.17. The original and redatumed data: a) A typical common shot gather of the original OBC data, where the source is at near sea surface and receivers are about 150 meters below the sea surface. b) A redatumed common shot gather, where source and receivers are redatumed to the plane 1.5 km below the sea surface.

Figure 3.18. The stacked image after 3-D Kirchhoff migration of SSP data.
Figure 3.19. The stacked image after 3-D Kirchhoff migration of the redatumed data.

Figure 3.20. 2-D slices of the 3-D migration image cubes at inline 21: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatnumed data.
Figure 3.21. 2-D slices of the 3-D migration image cubes at inline 121: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumsed data.

Figure 3.22. 2-D slices of the 3-D migration image cubes at crossline 61: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data.
Figure 3.23. 2-D slices of the 3-D migration image cubes at crossline 101: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data.

Figure 3.24. 2-D slices of the 3-D migration image cubes at depth of 2.0 km: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data.
Figure 3.25. 2-D slices of the 3-D migration image cubes at depth of 2.5 km: a) Kirchhoff migration image of the original surface seismic gathers. b) Kirchhoff migration image of the redatumed data.
CHAPTER 4

CONCLUSIONS

This work formulated the target-oriented RTD and validated it with synthetic and field data. I applied the RTD equations to the SSP traces associated with the 2-D and 3-D SEG/EAGE salt models. The resulting redatumed data compared well with the actual shot gathers with sources and receivers located at the new datum, and the migrated redatumed data more clearly revealed the deep structures beneath the salt. This is because the redatumed data have been mostly corrected of the defocusing effects of the salt. I also implemented the target-oriented RTD on a field data set from the Gulf of Mexico. The migration images from the redatumed data reveal the deep reflectors and faults in the target areas better than the migration images from the Kirchhoff original seismic data.

The benefits of the target-oriented RTD are the following:

1). The distorting effects of the overburden are avoided because the surface sources and receivers are redatumed to be below the overburden. This can be important for subsalt imaging.

2). Better resolution of the target can be achieved because the redatumed sources and receivers are closer to the target, and multi-arrivals that propagate from the surface to the datum are used for imaging below the overburden.

3). Using the bottom-up approach and target-oriented strategy, we can achieve much greater computational efficiency compared to standard RTD by wave extrapolation. This is because when we calculate the VSP Green’s functions, the sources are placed at the new datum which typically has a smaller area than that covered by the sources along the top surface. The computational costs for all numerical tests are summarized in Table 4.1, where the calculations are based on a Linux cluster consisting of 64 2.0 GHz dual-core processor nodes.
4). The redatumed data can be used for velocity model building for the target area below the overburden. The redatumed data have a shorter recording time and a narrower offset range compared to the original SSP data. Most importantly, the redatumed data generally have simpler seismic events because the distorting effects and the refraction waves caused by the overburden are avoided by the redatuming process. Thus, the speed and the quality of the velocity model building can be improved by using redatumed data.

In addition, a challenge of this method is the storage requirements of the band limited Green’s functions. This storage requirements is proportionally related to the area of the target zone. Thus, the target oriented RTD method works well mainly in the case where the target zone is much smaller than the seismic survey area.
<table>
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<th>RTM (CPU-hours)</th>
<th>RTD (CPU-hours)</th>
<th>Saving rate</th>
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<td>6.5</td>
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<tr>
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<tr>
<td>3-D GOM</td>
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<td>99%</td>
</tr>
<tr>
<td>example</td>
<td>(estimated)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1. The computational cpu costs for different numerical tests, where the calculations are based on a Linux cluster consisting of Sixty-four 2.0 GHz dual-core processor nodes.
APPENDIX

SSP→SWP TRANSFORM

Redatuming of surface seismic data to a deeper horizontal datum is equivalent to the SSP→SWP correlation transform obtained by a concatenation of the SSP→VSP and VSP→SWP transforms. These operations are described by the acoustic reciprocity equation of correlation type (Wapenaar, 2004; Schuster, 2009) and presented in the next sections.

A.1 SSP→VSP Transform

The starting point for the derivation of the SSP→VSP transform is the model depicted in Figure A.1 where \( x \) and \( y \) are the locations of source and receivers near the surface, and \( A \) and \( B \) are along the datum line. This configuration of sources and receivers is employed for a simultaneous VSP and SSP experiment. Using the dashed contour (and its infinite extension out of the page) defines the surface of 2-D integration to give the SSP→VSP correlation transform:

\[
\mathbf{B} \epsilon S_{\text{datum}}, y \epsilon S_0; \quad \text{VSP} \\{G(A|y)\} = \int_{S_0+S_\infty} \left[ G(B|x)^* \frac{\partial G(y|x)}{\partial n_x} - G(y|x) \frac{\partial G(B|x)^*}{\partial n_x} \right] d^2x,
\]

\[
\approx \int_{S_0} \left[ G(B|x)^* \frac{\partial G(y|x)}{\partial n_x} - G(y|x) \frac{\partial G(B|x)^*}{\partial n_x} \right] d^2x,
\]

\[
(A.1)
\]

where \( G(B|x) \) is the Green’s function for a harmonic point source in an acoustic medium with variably velocity and constant density. The integration over the half circle at infinity can be neglected by the Wapenaar anti-radiation condition (Wapenaar and Fokkema, 2006). Here, \( S_0 \) is the surface along which the airgun sources are excited; and \( G(B|x) \) for the integration along \( x \epsilon S_0 \) denotes the VSP Green’s function where the receiver at \( B \) is along the datum line which can be considered as a buried well. In
contrast, \( G(y|x) \) is the SSP Green’s function where both the source and receiver are near the surface.

The far-field approximation to the above equation yields (Wapenaar, 2004; Schuster, 2009)

\[
\begin{align*}
B \in S_{\text{datum}}, & \quad y \in S'_0; \quad VSP \quad \frac{VSP}{SSP} \frac{G(y|B) - G(y|B)^*}{G(B|x)^* G(y|x)} d^2x = 2ik \int_{S_o} VSP \quad \frac{VSP}{SSP} \frac{VSP}{SSP} G(B|x)^* \quad d^2x,
\end{align*}
\]

which is the SSP→VSP correlation transform which redatums the SSP shots near the sea surface to the new datum.

### A.2 VSP→SWP Correlation Transform

Similar to the previous transform, the receivers near the sea surface can be redatumed to the new datum line. Figure A.2 demonstrates the model used for this transform, where \( y \) are the locations of the VSP receivers which are near the surface and \( B \) is the VSP source located at the datum line. The dashed contour defines the surface of 2-D integration to give the VSP→SWP correlation transform. Based on the Wapenaar anti-radiation condition and far-field approximation the VSP→SWP transform can be described by the following equation:

\[
\begin{align*}
A, B \in S_{\text{datum}}; \quad \text{SWP} \quad \frac{SWP}{VSP} \frac{VSP}{SSP} \quad Im\left[ G(A|B) \right] = 2ik \int_{S'_0} VSP \quad \frac{VSP}{SSP} \frac{VSP}{SSP} G(A|y)^* G(B|y) d^2y. \tag{A.3}
\end{align*}
\]

Using the reciprocity principle in equation A.2 we get an expression for \( G(B|y) \),

\[
\begin{align*}
B \in S_{\text{datum}}, & \quad y \in S'_0; \quad VSP \quad \frac{VSP}{SSP} \quad \frac{VSP}{SSP} \quad G(B|y) = 2ik \int_{S_o} VSP \quad \frac{VSP}{SSP} \quad G(B|x)^* G(y|x) d^2x + G(B|y)^* \tag{A.4}
\end{align*}
\]

Inserting \( G(B|y) \) from the above equation into equation A.3 yields the SSP→SWP transform:

\[
\begin{align*}
A, B \in S_{\text{datum}}; \quad \text{SWP} \quad \frac{SWP}{VSP} \frac{VSP}{SSP} \frac{VSP}{SSP} \quad Im\left[ G(A|B) \right] = 2ik^2 \int_{S'_0} VSP \quad \frac{VSP}{SSP} \quad VSP \quad G(A|y)^* G(B|y)^* d^2y \quad d^2x
\end{align*}
\]

\[
\begin{align*}
+ \int_{S'_0} G(A|y)^* G(B|y)^* d^2y, \tag{A.5}
\end{align*}
\]

where reciprocity is invoked to interchange source and receiver locations in the SSP data \( G(x|y) \). The last integral on the right-hand side has a kernel that is a product
of acausal Green’s functions, which will not contribute to the redatumed traces after \( t \geq 0 \). Therefore, this last integral is ignored if the redatumed data are migrated to deeper depths so that we have

\[
\mathbf{A}, \mathbf{B} \epsilon_{\text{datum}}; \quad \text{Im}[G(\mathbf{A}|\mathbf{B})] \approx 2ik^2 \int_{S_0}^{S_0} \int_{S_0}^{S_0} G(\mathbf{A}|\mathbf{y})^* G(\mathbf{y}|\mathbf{x}) G(\mathbf{B}|\mathbf{x})^* d^2y \ d^2x.
\]

(A.6)

Above is the equation for RTD. It is similar to the classical redatuming equation used in seismic exploration (Berryhill, 1979, 1984, 1986; Yilmaz and Lucas, 1986; Bevc, 1995) Equation 2.1 says that the RTD data can be obtained by two back-projections of the SSP data, one for the receiver positions and one for the source locations of \( G(\mathbf{y}|\mathbf{x}) \). The VSP Green’s functions \( G(\mathbf{A}|\mathbf{y}) \) and \( G(\mathbf{B}|\mathbf{x}) \) can be computed using an assumed velocity model that is accurate.
Figure A.1. Diagram demonstration for SSP→VSP correlation transform. Integration surface denoted by dashed line. The SSP receivers are along $S_0'$ and the sources are distributed along the line $S_0$. The open geophones indicate the locations of virtual geophones at the datum. (Schuster, 2009)
Figure A.2. Diagram demonstration for VSP→SWP correlation transform. Integration surface denoted by dashed line. The VSP receivers are along $S_0$ and the sources are distributed along the datum line $S_{\text{datum}}$. The open geophones indicate the locations of virtual geophones at the datum. (Schuster, 2009)
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