Adapting An Accurate Reverse-Time Migration Method To Medical Ultrasound Imaging

Brayden K. Mi

***Abstract*—**Reverse time migration (RTM) has been widely used in the Petroleum exploration industry to image the subsurface and its properties since the early 1980s. It has advanced significantly in recent years and it can compute a subsurface image in very complicated geological settings. Seismic imaging and ultra-sound imaging share similar theoretical foundations and practical challenges. With modifications, the advanced seismic RTM method can be adopted for ultra-sound imaging applications to produce clear internal images of human organs, thus anomalous objects (tumors) may be identified. Such adoption can be directly used in ultra-sound data acquired with USCT equipment.

***Keywords*—**Depth imaging, Phase Shift Plus Interpolation (PSPI), Reverse time migration (RTM), Ultrasound computed tomography (USCT).

I. Introduction

REVERSE-time migration (RTM) has long been used in the petroleum industry and is one of the most important technological advancements in the past 20 years. The technology requires reverse-time propagation of recorded seismic wavefields and forward-time propagation of the signal wavelet used in the data acquisition. Imaging conditions are applied at each reverse propagation step to recover the true subsurface image. The technology normally requires an accurate construction of a velocity model, which is typically achieved by travel time tomography or full-waveform inversion. Human assistance and other a-priori information are normally required.

Ultrasound Computer Tomography (USCT) is mostly aimed at breast cancer imaging by utilizing the velocity and density contrast between healthy and cancerous tissues. USCT utilizes travel-time tomography to construct the velocity structure of an organ, which can be used for medical diagnostic purposes. Such a velocity model can subsequently be used in a migration process that is very similar to seismic pre-stack migration, to produce a high-resolution image.

RTM fully accounts for two-way wave propagation, including multiple arrivals and turning rays in the imaging process. It normally can produce images of higher quality and resolution. It has a significant advantage over raytracing-based methods in complicated velocity structures.

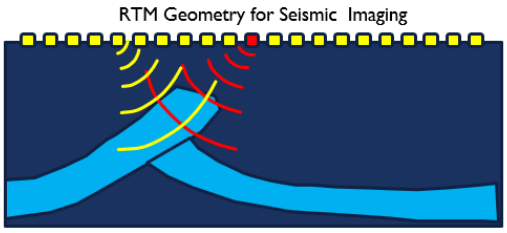
Raytracing-based algorithms have long been used in ultrasound medical imaging due to their simplicity and speed for real-time applications. However, the image quality may be sacrificed due to the poor imaging algorithms and hence the reliability of medical diagnostics.

With a synthetic and realistic cancerous breast velocity model, we demonstrated that RTM can be adapted to USCT acquisition geometry. In addition, the implementation of a high-accuracy wave field propagator is capable of producing high-fidelity images.

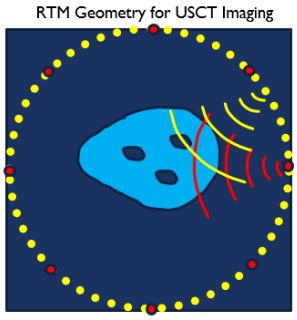
II. Adapting Reverse Time Migration to Ultrasound Imaging

Seismic data is typically acquired from the Earth's surface and processed from a flat datum, as shown in Fig. 1 (a). Shots are fired at surface locations and the returning wavefield is recorded by the receivers also located on the Earth's surface. The recorded wavefield is normally corrected to a flat datum before any further processing.

Fig. 1 (b) shows a 2D acquisition geometry of a USCT system, with receivers distributed on a circle, and with an ultrasound source located on the same circle. To apply RTM algorithms, the forward and backward wave propagators need to be modified to accommodate the circular geometry.



(a)



(b)

Fig. 1 Seismic RTM can be adapted to USCT by changing from flat acquisition geometry (a) to circular geometry (b).

III. PSPI Wavefield Extrapolator and Adapting to Circular Geometry

The wavefield at depth z can be obtained by extrapolation the wavefield at depth 0, given knowledge of the velocity field between 0 and z. Consider a mono-frequency wavefield at depth 0, $\varphi(k_x, z=0, \omega)$, which has been 2D forward Fourier transformed to frequency-wavenumber (ω,kx) domain, the wavefield at depth z can be written as (Gazdag, 1978),

$$\varphi(k_x, z, \omega) = \varphi(k_x, 0, \omega)\alpha(k_x, z, \omega)$$

where $\alpha(k_x, z, \omega)$ is the (ω,kx) domain wavefield extrapolator operating from 0 to z.

For homogeneous and isotropic media, the wavefield extrapolator is known analytically and the extrapolation step size is unlimited. For velocity v, α can be written as

$$\alpha(k_x, z, \omega) = e^{\pm iz\sqrt{\frac{\omega^2}{v^2} - k_x^2}}$$

where the plus and minus signs denote upward and downward extrapolation when the z-axis points downward.

For heterogeneous media, the extrapolation is done recursively with small steps so that local wave propagation can be approximated by homogeneous propagation theory.

Phase-shift-plus-interpolation (PSPI) wavefield propagator, originally developed by Gazdag and Sguazzero (1984), uses several constant velocities to produce reference extrapolated wavefields. The wavefield at any spatial location is computed by linear frequency-space (ω,x) domain interpolation between the reference wavefields according to the velocity function v(x). More reference velocities result in more accurate wavefield propagation.

The algorithm can be modified to fit USCT acquisition geometry by starting the wavefield extrapolation from the circular datum.

IV. Forward Modeling and RTM From a Flat Datum

Fig. 2 shows a notional cancerous breast velocity model, submerged in a fluid of Vp=1500 m/s. The velocities of the normal and cancerous tissues are assumed to be 1600 m/s and 1700 m/s, respectively. A zero-phase wavelet with a dominant frequency of 500KHz is used in this modeling exercise.

A 9-point approximation of the Laplacian operator is used in the finite-difference modeling when generating the synthetic shot gathers. The dimension of the model is 0.25m by 0.25 m with a spatial sampling rate of 0.5 mm in both X and Z directions. The modeling results show such a sample rate is sufficient to accommodate the wavelet dominant frequency without causing significant spatial aliasing within the acquisition aperture.

Four shots gathers are computed from the top, right, bottom, and left of the model to provide illumination. 2D Shot gather RTM with PSPI extrapolator, from a Z=0 datum is performed on the gathers and Fig. 3 shows the results.

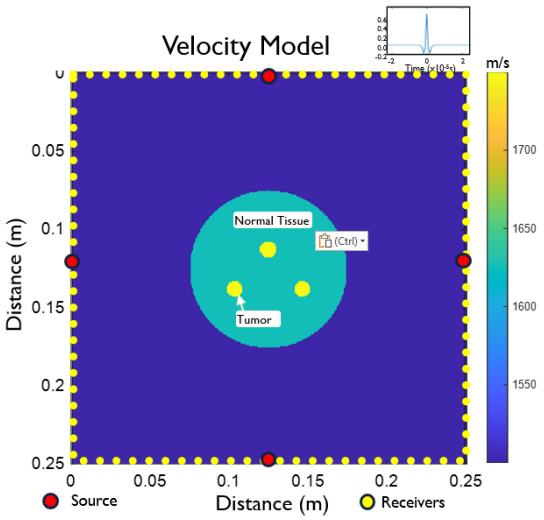
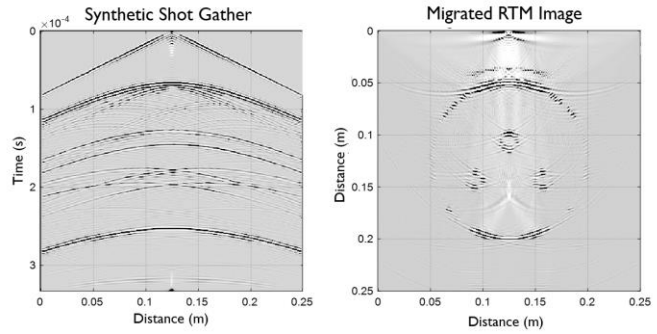
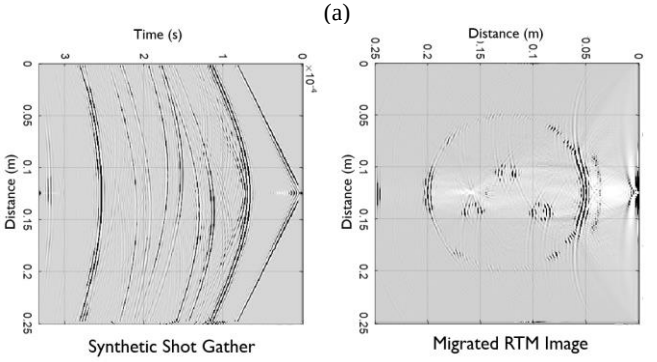


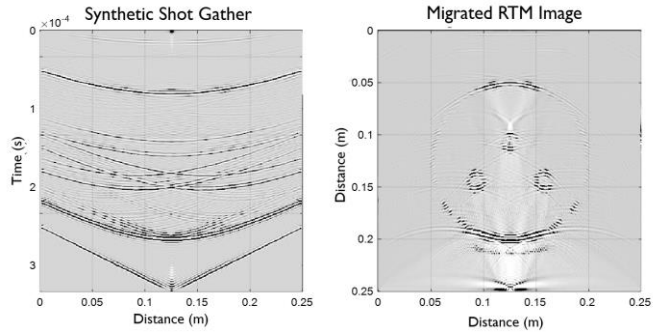
Fig. 2 A cancerous breast velocity model and flat acquisition geometry, showing both source and receivers are located on a flat datum.



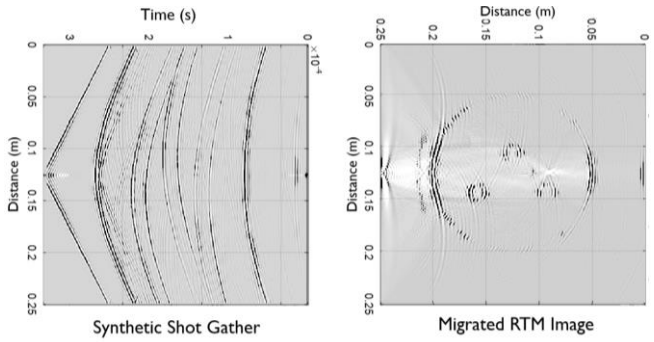
(a)



(b)



(c)



(d)

Fig. 3 Synthetic shot gathers and RTM migrated partial images of the cancerous breast model with flat geometry from directions (a) top (b)right (c)bottom (d) left of the model.

The four partial images are stacked to produce the final synthetic aperture image Fig 4. Note the lack of image at 45º,135 º, 225 º, and 315 º directions. This is mainly due to the insufficient illumination provided by only four shots from a flat datum. Adding additional shots at different locations will improve the illumination, hence a more complete image.

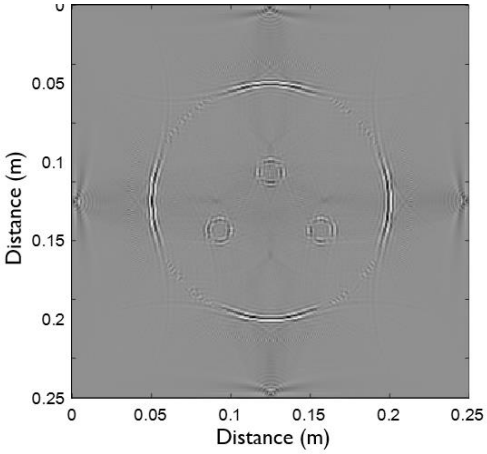


Fig. 4 Final synthetic aperture image from a flat-datum acquisition.

V. Forward Modeling and RTM From a Circular Datum

A similar experiment is carried out with circular acquisition geometry. The same modeling parameters are used, except that the shots and receivers are now placed on a circle (Fig. 5).

Four shots gathers are computed from the top, right, bottom, and left of the model to provide illumination. 2D Shot gather RTM with PSPI extrapolator, from the circular datum is performed on the gathers. and Fig. 6 shows the synthetic shot gathers and the RTM partial images.

The four partial images are stacked to produce the final synthetic aperture image (Fig 7). Note the general improvement of the final image, especially the portion in 45º,135º,225º, and 315º directions. This demonstrates that circular-datum acquisition has superior illumination capacities, compared with flat-datum geometry.

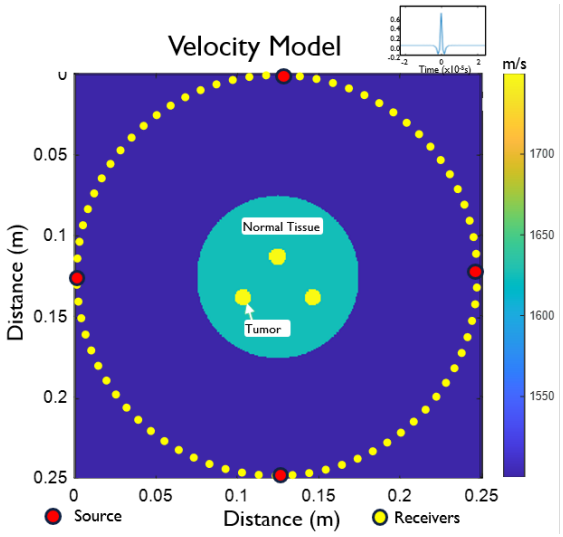
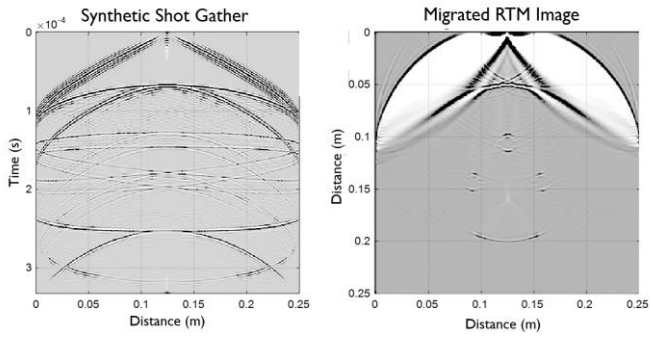
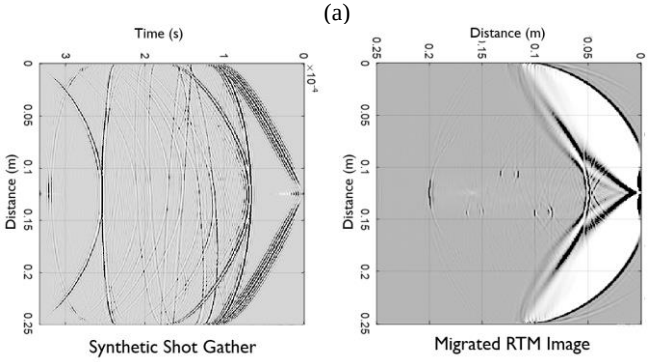


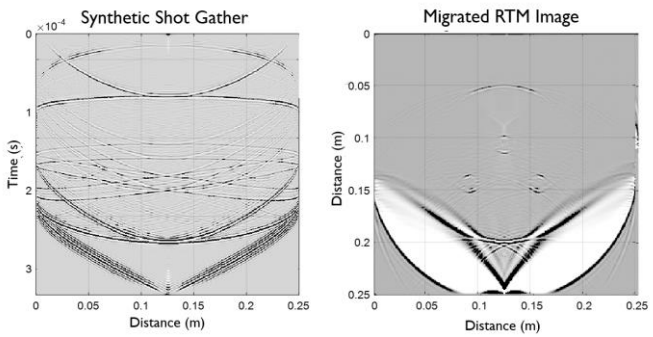
Fig. 5 A cancerous breast velocity model and USCT acquisition geometry, showing circular source and receiver positions.



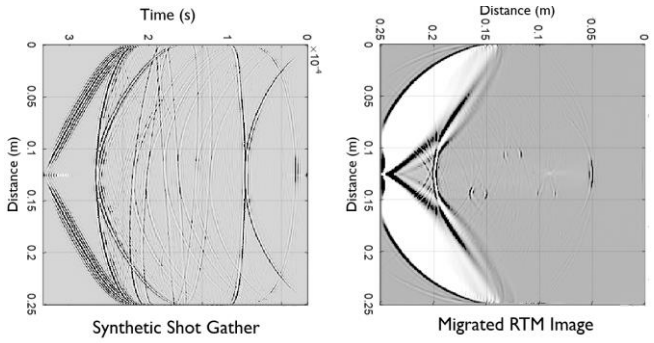
(a)



(b)



(c)



(d)

Fig. 6 Synthetic shot gathers and migrated partial images of the cancerous breast model with circular geometry from (a) top (b)right (c)bottom (d) left of the model.

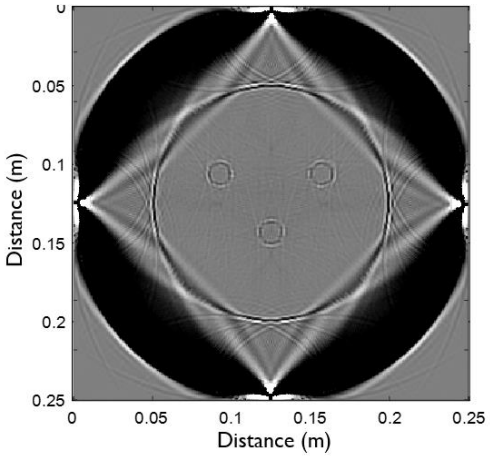


Fig. 7 Final synthetic aperture image from the circular-datum acquisition.

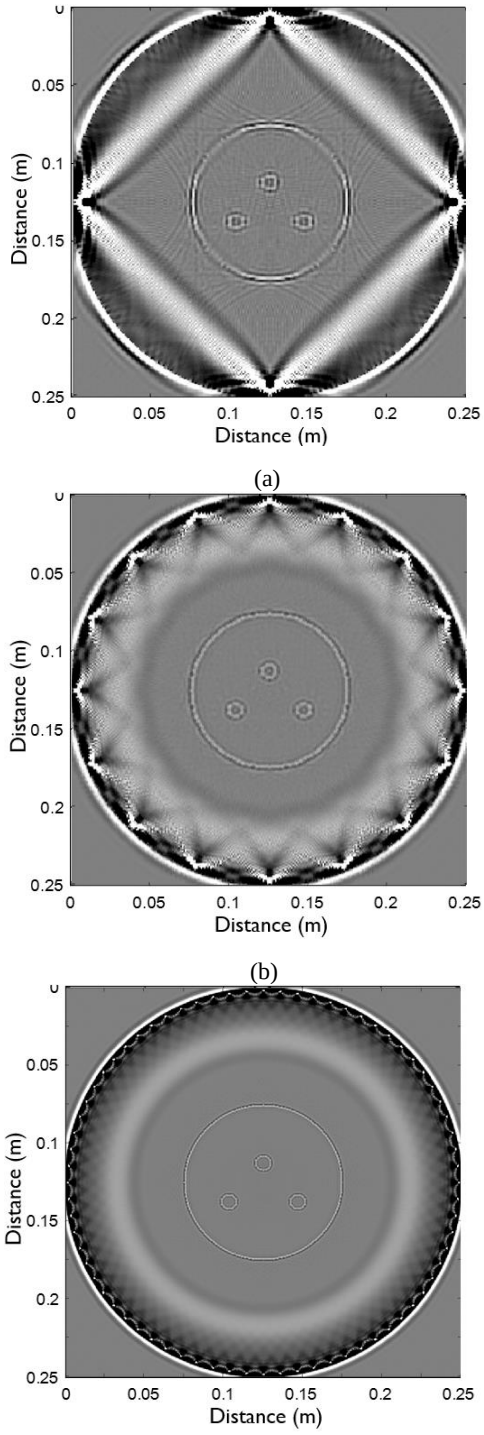
VI. Improving Quality and Resolution by Increasing Acquisition Density

Seismic data acquisition is typically highly redundant for seismic travel time tomography and imaging. The purpose of such redundancy is to utilize the power of stacking to suppress un-focused energy or random noises. Similar methods apply to ultrasound imaging. Increment in the spatial density of the shot points and receiver points can not only provide better illumination but also provide redundancy when it comes to noise reduction.

Fig. 8 shows the final images produced from the shot gathers acquired at every 90º, 22.5º, and 5º shot intervals. The corresponding numbers of shots are 4, 16, and 72, respectively. Significant migration noise can be seen in the 4-shot image, while the 72-shot image is far superior.

VII. Modeling and RTM of a Real Cancerous Breast

Unlike travel time tomography, which produces a velocity image, depth imaging produces an image of acoustic impedance boundaries. It is well recognized that, in ultrasound imaging, sharp acoustic impedance boundaries will be imaged better than those transitional boundaries.



(a)

(b)

(c)

Fig. 8 Increasing the acquisition shot density significantly improves the image quality and resolution. (a) 4 shots at 90º interval (b) 16 shots at 22.5º interval (c) 72 shots at 5º interval

Fig. 9 shows a velocity model of a real cancerous breast. The tumor is identified as the highest velocity body with strong velocity contrast with the normal breast tissue. Most other normal tissues display transitional velocity contrast.

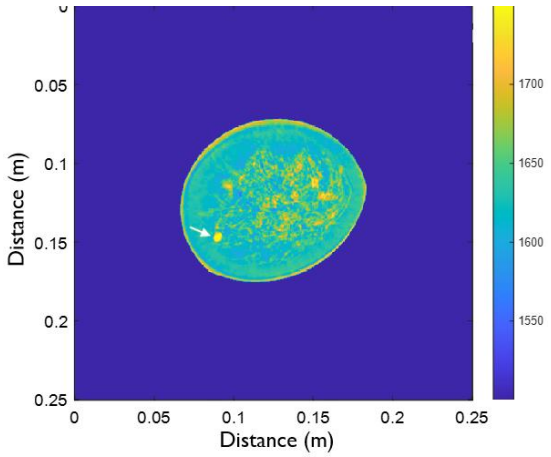


Fig. 9 Velocity model of a breast with the anomalous high-velocity area.

Fig. 10 shows a synthetic shot gather with the shot point at the center top of the model, and its corresponding RTM result.

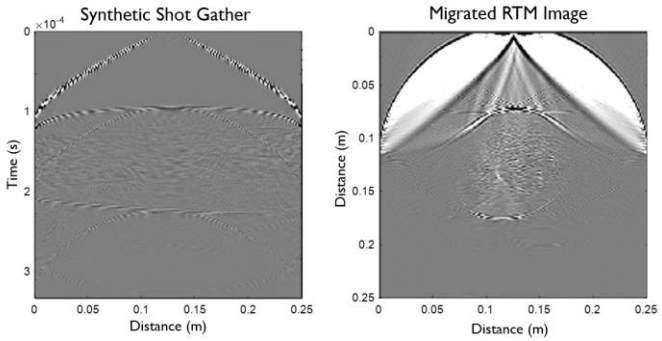


Fig. 10 A sample synthetic shot acquired from the top center of the model, and its RTM partial image.

The 4-shot synthetic experiment is shown in Fig. 11 (a). Despite the significant migration noise in the background, has successfully imaged the tumor. The 72-shot case, produced a much higher quality and resolution image, as expected.

VIII. Conclusions and Discussions

Seismic reverse-time migration can be adapted to ultra-sound data acquired in circular acquisition geometry in a typical USCT setting. The circular acquisition appears to have superior illumination capacity compared with the flat-datum acquisition. A refined PSPI wavefield propagator was used to accurately extrapolate the wavefield in heterogeneous media, which further enhanced the image quality and resolution.

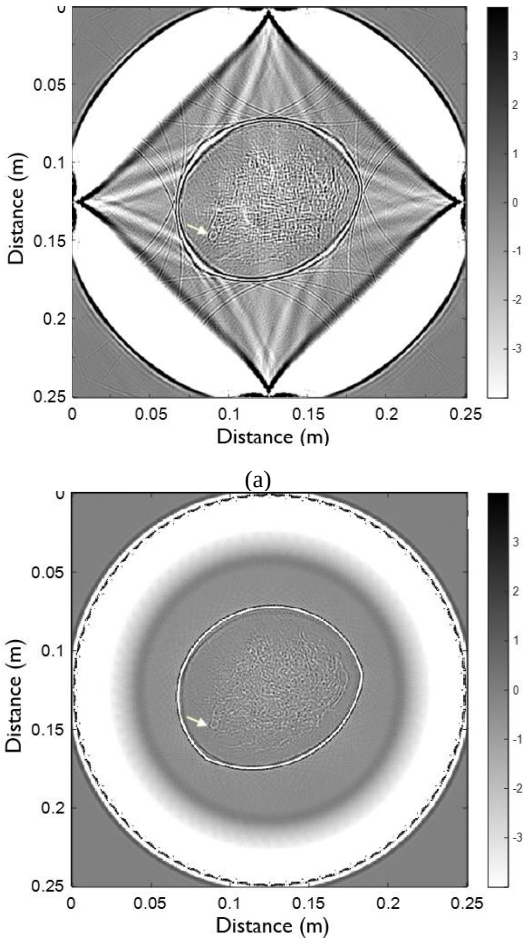


Fig. 11 Final synthetic aperture image from (a) 4-shot acquisition and (b) 72-shot acquisition.

Acknowledgment

The authors would like to acknowledge Dr. G. Margrave and the CREWES project, University of Calgary, for utilizing their freely available MATLAB Seismic Toolbox.

References

[1] J. Gazdag, "Wave equation migration with the phase-shift method," Geophysics, vol.43, pp. 1342-1351, Dec. 1978

[2] J. Gazdag, P. Sguazzero, "Migration of seismic data by phase shift plus interpolation", Geophysics, 49, 124-131, June 1984