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Reducing data storage in reverse time migration

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SUMMARY

Prestack reverse time migration (RTM) requires extensive data storage since it computes wavefields in forward time and accesses wavefields in reverse order. We first review several successful schemes that have been proposed to reduce data storage, but require more computational redundancies. We propose two effective strategies to reduce data storage during RTM. The first strategy is based on the Nyquist sampling theorem, which involves no extra computational cost. The fact is that the time sampling intervals required by numerical algorithms or given by field records is generally several times smaller than that satisfied by the Nyquist sampling theorem. Therefore, we can correlate the source wavefields with the receiver wavefields at the Nyquist time step, which helps decrease storage of time history. The second strategy is based on a lossless compression algorithm, which is widely used in computer science and information theory. The compression approach reduces storage significantly at a little computational cost. Numerical examples show that the two proposed strategies are effective and efficient.

Key words: reverse time migration; data storage; Nyquist theorem; compression algorithm; finite-difference

INTRODUCTION

Reverse time migration (RTM) was first introduced by Baysal et al. (1983) and Whitmore (1983). Recently, RTM has regained attention due to its ability to deal with complex geological structures, for example subsalt imaging in the Gulf of Mexico.

Although RTM algorithms can help improve accuracy of imaging complex structures, they involve extensive data storage, which is challenging and compromises the imaging quality. Several strategies have been successfully applied to reduce the wavefields storage of time history. A number of commercial RTM implementations store the snapshots at every sth step (s>1), and interpolate the wavefields. The industrial schemes are confined to a relatively small time step to avoid migration artifacts. Symes (2007) proposed a strategy called optimal checkpointing, which dramatically reduces memory complexity. The optimal checkpointing approach, however, involves moderate computational redundancies, which is dependent on the number of checkpoints. A pseudo-random-boundary method (Clapp, 2009; Fletcher and Robertsson, 2011) was presented, which significantly reduced memory and input/output (I/O) requirements. A boundary-saving approach only store wavefields in boundary grids and uses them to reconstruct wavefields in all grids at every time step. However, these strategies need to recalculate the whole time history of source wavefields, which means extensive computational redundancies.

An ideal strategy should balance the memory requirements and computational cost. Neither the full-storage approach nor the full-computation approach is preferred. According to the Nyquist sampling theorem, a bandlimited signal can be perfectly reconstructed if the time sampling interval is no more than 1/(2B), where B is the bandwidth of the original signal. However, the time step required by a numerical algorithm is generally much smaller than the Nyquist time step. Thus, the Nyquist time step can be considered as a good choice for balancing the storage and computation. In this paper, we propose two strategies to reduce storage required by RTM. The first one, Nyquist approach, is based on Nyquist sampling theorem, where the second one, the compression approach, is based on a lossless compression algorithm. The two approaches are quite easy to implement and do not change the original structure of RTM code. The two strategies can achieve the trade-off between storage and computational burden. Numerical results show the presented schemes are stable and effective.

METHODS

The cross-correlation imaging condition for prestack depth migration is given by

$$I(\mathbf{x}) = \int_0^T S(\mathbf{x},t)R(\mathbf{x},t)dt \ , \qquad (1)$$

where $I(\mathbf{x})$ is the migrated image, T is the maximum record time, and $S(\mathbf{x},t)$ and $R(\mathbf{x},t)$ denote the source wavefields and the receiver wavefields at time t and space location $\mathbf{x}$, respectively. Equation 1 means the migrated image is obtained by cross-correlating the source wavefields with the receiver wavefields, which determines the structure of RTM algorithms. The structure involves computations of source wavefields in the positive time direction and extrapolations of receiver wavefields in the negative time direction. This causes extensive memory storage requirements in RTM implementations.

The numerical algorithm can be implemented using various methods. In this paper, we employ the conventional finite-difference (FD) method to implement the RTM.

The Nyquist approach

According to the Nyquist sampling theorem, the time sampling rate, allowing to reconstruct signal without aliasing, is larger than twice the highest frequency of original shot records (assuming the minimum frequency to be 0 Hz). This means it is economic to store source wavefields with the Nyquist time step.

The first step is a temporal interpolation with anti-aliasing filter. The second step is storing forward wavefields at every Nyquist time step. The third step is to cross-correlate the source wavefields and the receiver wavefields at every Nyquist time step. The Nyquist time step Δt_{Nyq} is defined as

$$\Delta t_{Nyq} = \frac{1}{2\left(f_{\max} - f_{\min}\right)}, \tag{2}$$

where $f_{\max}$ and $f_{\min}$ are the highest and lowest frequency of seismic records.

Generally, the conventional RTM implementation updates the backward wavefields at the time step of Δt_{rec} given in seismic records, rather than at every Δt_{num} required by the stability of the numerical algorithm. This implementation will result in high-frequency aliasing, which can be eliminated by the temporal interpolation.

For simplicity, we take a two-layered model as an example to show the phenomenon. Figure. 1 shows the synthetic shot records and the amplitude spectrum of the trace at the distance x=3000 m. The source function is a Ricker wavelet with a dominant frequency of 20 Hz and a highest frequency of 60 Hz. Thus, the Nyquist time step is Δt_{Nyq}=8.33 ms. In Figure. 1a and 1d, the time sampling interval is 1 ms, which satisfies the stablity condition of the finite-difference method. Figure. 1b shows the shot record by updating the wavefields at every Δt_{rec} =8 ms, similar to the implementation of the conventional RTM algorithm. The amplitude spectrum of the trace at x=3000 m is shown in Figure. 1d. The shot record shown in Figure. 1c is calculated using the Nyquist approach, which first interpolates the source function from Δt_{rec} =8 ms to Δt_{num} =1 ms, and then updates and propagates the wavefields at the time step of 1ms. The shot record from the conventional RTM implementation in Figure. 1b is seriously contaminated by high-frequency noise. Furthermore, the high-frequency (at frequencies higher than 60 Hz) aliasing is also observed in the frequency spectrum (Figure. 1d). The results of the Nyquist approach match perfectly with the numerical results shown in Figure. 1a and 1d.

The compression approach

Compression techniques have been extensively applied in computer sciences and information theory (Salomon and Motta, 2010). Data compression is defined as the process of converting an input data stream into another data stream that has a smaller size. A stream can be a file on disk, a buffer in memory, or individual bits sent on a communication channel. All methods of data compression are based on the same principle, which is reducing or removing redundancies from the original data. Any nonrandom data has some structure, and this structure can be exploited to achieve a smaller representation of the data, where no structure is discernible. Thus, redundancy is a key concept in any discussion of data compression.

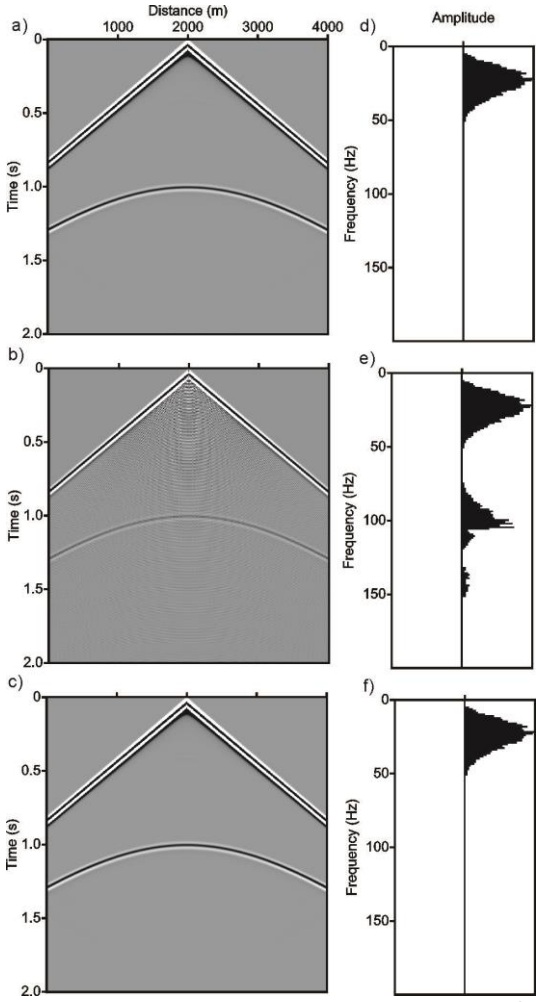

Figure 1. Synthetic shot records calculated by the finite-difference method (a), the conventional RTM implementation (b), and the Nyquist strategy (c) for a two-layered model. The amplitude spectra of a trace at x=3000 m in Figure 1a, 1b and 1c are shown in Figure 1d, 1e and 1f, respectively.

There are two classes of methods for data compression: lossy algorithms and lossless algorithms. If the result is not identical to the original data stream after it has been decompressed, the compression is called lossy, otherwise it is called lossless. In this paper, we employ a popular lossless compression algorithm called DEFLATE (Feldspar, 1997). The DEFLATE algorithm combines static Huffman coding (Huffman, 1952), a statistical method, with a variant of the LZ77 algorithm (Ziv and Lempel, 1977), a dictionary method. The implementation of the compression algorithm is complicated. Fortunately, Gailly and Adler (1995) released an open-source package in C/C++, which is quite convenient to be called in the form of a static/dynamic link library. Since the compression algorithm is not the focus of the paper, we do not describe it in detail.

There are two differences of the proposed strategy from the conventional RTM method. The first difference is compressing and writing the source wavefield to disk. The second one is reading the compressed source wavefield from disk and decompressing them into memory.

NUMERICAL RESULTS

In this section, we use the Sigsbee2a synthetic data set distributed by SMAARTJV to examine the abilities of the two proposed schemes. The grid size of the Sigsbee2a migration velocity model, shown in Figure 2a, is 2133 by 1201 grid points in the horizontal and the depth direction, respectively. The grid intervals are 37.5 ft by 25 ft. The number of shots is 500. The shot interval is 150 ft, and the receiver interval is 75 ft. The record length is 12 s with the sampling interval of 8 ms. The dominant frequency is 20 Hz and the highest frequency is 40 Hz. The Nyquist time step is 12.5 ms. The time interval satisfying the numerical stablility condition is 1 ms. The migration is performed on a workstation with one CPU of dual core 2.66 GHz and 64 GB memory. Figure 2b shows the migration result obtained from the conventional RTM implementation. To avoid high-frequency aliasing, we performed the temporal interpolation before the backward wavefield extrapolation for all results.

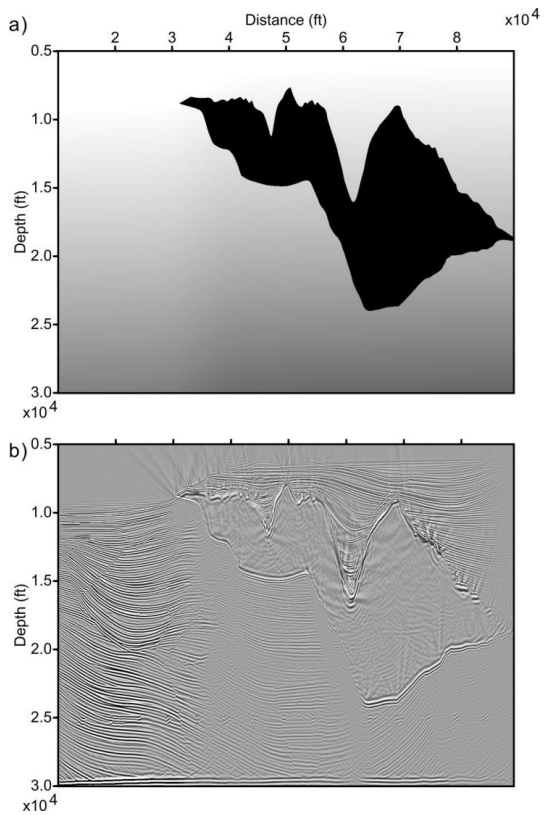

Figure 2. The Sigsbee2a migration velocity model (a) and the migration result obtained from RTM (b). The temporal interpolation is performed. The RTM result is obtained by cross-correlating the wavefields at every numerical time step.

The RTM result obtained from the Nyquist approach is shown in Figure 3. The cross-correlation in equation 1 is performed at every 12 ms rather than at every 8 ms or 1 ms. We compared the data storage and CPU time of the Nyquist approach with that of the conventional RTM implementation. The statistical data is summarized in Table 1.

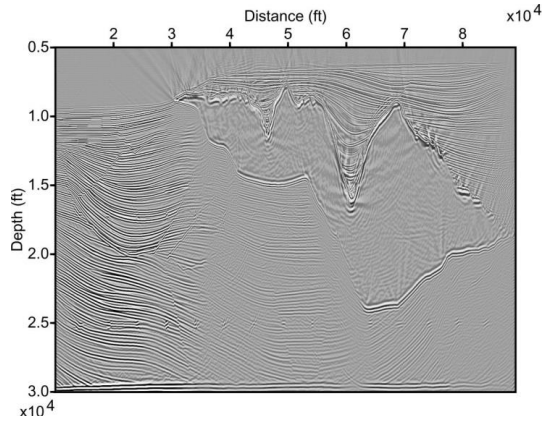

Figure 3. The RTM result obtained from the Nyquist approach. The temporal interpolation is performed. The RTM result is obtained by cross-correlating the wavefields at every Nyquist time step.

Table 1. Comparisons of storage and CPU time of the Nyquist strategy with those of the full-storage strategy. Each strategy is examined for cases of storing data in memory and on disk. The letters 'd' and 'm' mean that the source wavefield datum are saved on disk and in memory, respectively.

Strategy	Size (GB)	CPU time (s)
Full-storage (d)	41.48	2969
Full-storage (m)	41.48	1739
Nyquist (d)	4.148	1760
Nyquist (m)	4.148	1739

The Nyquist approach uses the Nyquist time step for imaging, which is different to the conventional RTM. Thus, it is necessary to investigate the influence of using the Nyquist time sampling on the final image. We applied the misfit method (Kristek et al., 2002) to quantitatively evaluate the accuracies of both the amplitude and the phase for images. We took the image of the conventional RTM as a reference image, and the image computed by the Nyquist approach as the examined one. The amplitude misfit and the phase misfit are shown in Figure 4a and Figure 4b, respectively. Figure 4 shows such small numerical errors of the amplitude and the phase that they can be neglected. Thus, we can conclude that the Nyquist approach is computationally accurate.

Figure 5 shows the RTM result by the compression scheme. Since we employ a lossless compression algorithm, there is no difference with the result shown in Figure 2b. Table 2 shows the comparisons of the storage and the computational efficiency of the compression approach with the full-storage strategy. Compared with the full-storage approach, the compression approach saves about 27% storage space, at the price of 40% more computational time. Although the process of compression/decompression is little more expensive, the compression approach may achieve a large speedup on a graphical processing unit (GPU) platform using CUDA technology. Nikitin et al. (2011) have already demonstrated the feasibility of data compression on GPUs.

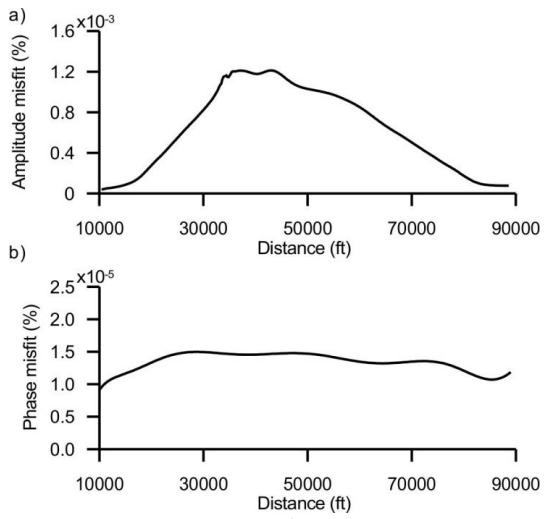

Figure 4. Accuracy analysis of the Nyquist approach: the amplitude misfit (a) and the phase misfit (b).

Table 2. Comparisons of storage and CPU time of the compression strategy with those of the full-storage strategy. Both strategies are examined for the case of storing data on disk.

Strategy	Size (GB)	CPU time (s)
Full-storage	41.48	2969
Compression	30.26	4153

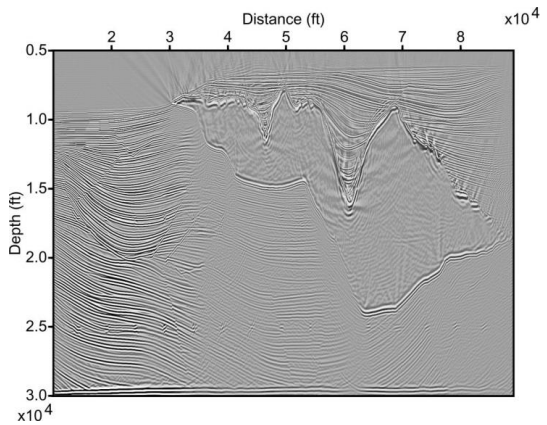

Figure 5. The RTM result obtained from the compression approach. The temporal interpolation is performed. The RTM result is obtained by cross-correlating the wavefields at every numerical time step.

CONCLUSIONS

Temporal interpolation of receiver wavefields extrapolation should be performed to avoid high-frequency aliasing. The two proposed strategies – the Nyquist and compression approach – can extensively reduce the data storage in RTM while the efficiency of the method is not compromised. The Nyquist approach, based on the Nyquist sampling theorem, does involve no extra computational effort. The compression approach, based on the DEFLATE lossless compression algorithm, does not lose any information, but involves moderate additional computational efforts to compress/decompress the forward wavefields. The numerical results from the synthetic Sigsbee2a dataset demonstrate that the strategies designed in this paper are effective and efficient.

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