Guided phase-shift de-ghosting

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SUMMARY

This paper presents a 3D receiver de-ghosting method for aliased data. First, anti-aliasing interpolation and Radon transform methods that are relevant to the proposed algorithm are reviewed and discussed. Next, the proposed method is formulated: the method ranks the wavenumber components in the input data based on their relative energy and iteratively de-ghosts individual wavenumber ranges. In other words, de-ghosting is gradual and guided by this ranking. This allows a reduction of the size of the de-ghosting problem at each iteration, and also the removal of aliasing effects. Application of the proposed de-ghosting algorithm to a real data example provides satisfactory results.

Introduction

Spatial aliasing has long been a prominent topic in seismic data processing research, with significant effort dedicated to interpolation, regularisation and sparse transforms over the last 20 years. A common theme in this body of work is the issue of how to determine a transformed domain representation of idealised regular, un-aliased data given real, irregularly sampled and aliased data. This is a highly under-determined problem, only partially ameliorated by the use of low frequency, un-aliased data as a constraint for de-aliasing higher frequencies. In the remainder of this introduction, I summarise past work on these topics that is relevant to the present paper.

Trad et al. (2003) discussed the sparse Radon transform as a means of dealing with aliasing and aperture effects. Several key points made by previous authors were underscored in this paper, and form the basis for the minimum weighted norm interpolation method (Liu and Sacchi 2004): model weights are iteratively incorporated in the transform operator, and these weights are carried out from lower to higher frequencies in order to reduce aliasing effects; the number of conjugate gradient iterations used to obtain the transformed domain is used as a way to reduce the number of significant singular values.

The anti-leakage interpolation method (Xu et al. 2005) reduces the wavenumber leakage induced by irregularly spaced trace locations using an iterative procedure: First, all Fourier components of the idealised data are initialised to zero. Then, in an iterative procedure, the real data Fourier coefficient with maximum energy is accumulated to the idealised, and the contribution of this coefficient is subtracted from the input data, determining a residual. This process is iterated until the residual reaches a pre-set minimum.

Schoneville et al. (2009) extended the anti-leakage method to deal with spatial aliasing: low, un-aliased frequencies are used to determine, by extrapolation, a wavenumber mask for higher frequencies. This mask is then used as a data weight in the anti-leakage iterations, so that maximum energy corresponds to actual signal and not its aliased replicas.

When single-component de-ghosting is formulated for the simple calm sea and constant cable depth case it can be applied as an inverse filter and the connection between de-ghosting and previous work on interpolation and sparse transforms may seem vague. However, in the case of a variable cable depth or rough sea surface, de-ghosting needs to be posed, similarly to sparse transform and interpolation, as an inversion problem, where the de-ghosted data is the solution to a linear system of equations. For example, the phase-shift de-ghosting algorithms of Grion et al. (2016a), (2016b) is formulated using phase-shift wavefield extrapolators between non-planar interfaces and is formulated as

$$\mathbf{p}_c(\mathbf{x}) = \mathbf{G}\mathbf{u}_0(\mathbf{k}), \qquad (1)$$

where, at a given temporal frequency, $\mathbf{p}_c(\mathbf{x})$ is pressure recorded along the streamer cable c and spatial location $\mathbf{x}$, and $\mathbf{u}_0(\mathbf{k})$ represents the wavenumber components of the up-going wavefield on a convenient horizontal datum, usually taken to be at mean sea level. $\mathbf{G}$ is the ghosting operator, defined by wavefield extrapolators and therefore a function of water velocity as well as of streamer depth and sea surface. In the case of N_x traces and N_k wavenumbers, $\mathbf{G}$ is a matrix of size (N_x X N_k). A 3D formulation of $\mathbf{G}$ is straightforward, but in the presence of aliasing this relies on data interpolation as a pre-processing step. A solution to (1) that can handle spatial aliasing is discussed in the next section.

Method

Özbek et al. (2010) introduced a 3D joint interpolation and de-ghosting method for multi-component streamer data. Wang et al. (2014) proposed a 3D τ-p joint de-ghosting and cross-line interpolation method for single component data that resembles in structure the anti-leakage interpolation algorithm: a low-frequency driven rank optimisation step is used to reduce the size of the problem, and the obtained result is accumulated in the estimated up-going wavefield. Ghosting of this partial wavefield provides an estimate of pressure, which when subtracted from the input data provides a residual. The process is iterated until the residual is minimised. Berkhout and Blacquiere (2016) discuss de-ghosting as a special case of de-blending. They do not discuss aliasing, but similarly to Wang et al. (2014) they also propose an iterative de-ghosting process. Differently from Wang et al. (2014), thresholding is used in the *x-t* domain during iterations as a way to reduce de-ghosting artefacts induced by poor SNR or imperfect knowledge of the ghost model parameters. The method discussed here combines the iterative process of the anti-leakage transform with the thresholding used by Berkhout and Blacquiere (2016).

In the proposed algorithm, $\mathbf{u_0}(\mathbf{k})$is defined to cover the wavenumber range of desired un-aliased data, and initialised to zero. At the same time, the residual $\mathbf{r_c}(\mathbf{x})$ is initialised to the recorded pressure data. The core of the algorithm works on sliding space-time windows extracted form 3D data. Within each window, equation (1) is solved up to the maximum un-aliased frequency. This resulting $\mathbf{u_0}(\mathbf{k})$ is used to estimate the *n* most prominent events in the residual, and for higher frequencies only these *n* events are de-ghosted by solving:

$$\mathbf{r}_c(\mathbf{x}) = \mathbf{G}^n \mathbf{u}_0^n(\mathbf{k}) \qquad (2)$$

In (2), $\mathbf{G}^n$refers to a partial ghosting operator constructed using only the wavenumber ranges of the *n* selected events. In other words, the de-ghosting process is guided by the most prominent events in the residual. The partial $\mathbf{u_0^n}$ wavefield is then thresholded, accumulated in $\mathbf{u_0}(\mathbf{k})$ and used to calculate a new residual:

$$\mathbf{r_c}(\mathbf{x}) = \mathbf{p}_c(\mathbf{x}) - \mathbf{G}\mathbf{u}_0(\mathbf{k}) \qquad (3)$$

The core of the algorithm is iteratively repeated until the residual has reached a desired value. In the solution of (2), the number of solver iterations used is initially kept low in order to extract the main components of the data, and later relaxed in subsequent iterations. Similarly, *n* is initially low and later increased.

Example

To test the algorithm, a shot gather with minimal pre-processing applied was decimated from a nominal group spacing of 12.5m to 100m (Figure 1, left). With this nominal trace spacing, aliasing for events propagating at the water velocity occurs at 7.5Hz. The time sampling interval is 4msec. The data was acquired in rough sea conditions, and a sea surface profile was estimated from the original, un-decimated data using the method described in Grion et al. (2016b) and used in formulating the **G** operator for both standard and guided phase shift de-ghosting. The streamer profile during acquisition was slanted, with a 2m/km slope. The standard phase-shift de-ghosting (Grion et al. 2016a) result is shown in Figure 1 next to the decimated data, and suffers from visible aliasing artefact. These are overwhelming at the far offsets but they are also visible at the near offsets.

For the guided de-ghosting test, 15 iterations were used, associated with continuous increases in the solver iterations, threshold and value of the *n* parameter. At each iteration, the *n* most prominent events were estimated using frequencies up to 7.5Hz. The final result is shown at the fight hand side of Figure 1, and no aliasing artefacts are visible. Figure 2 shows the estimated up-going wavefield $\mathbf{u_0}$ at the end of iteration 1, 3 5 and 7. De-ghosting is guided by the most energetic events in the data, and the first iteration focused mainly on far-offset aliased events travelling at the water velocity. Figure 3 shows the residuals $\mathbf{r_c}(\mathbf{x})$ for the same iterations. The final residual after 15 iterations is at -30dB with respect to the input pressure data.

Conclusions

Aliasing is the main obstacle to overcome for 3D de-ghosting. When the dimensionality of the problem is reduced by data selection this problem can be overcome: guided phase-shift de-ghosting

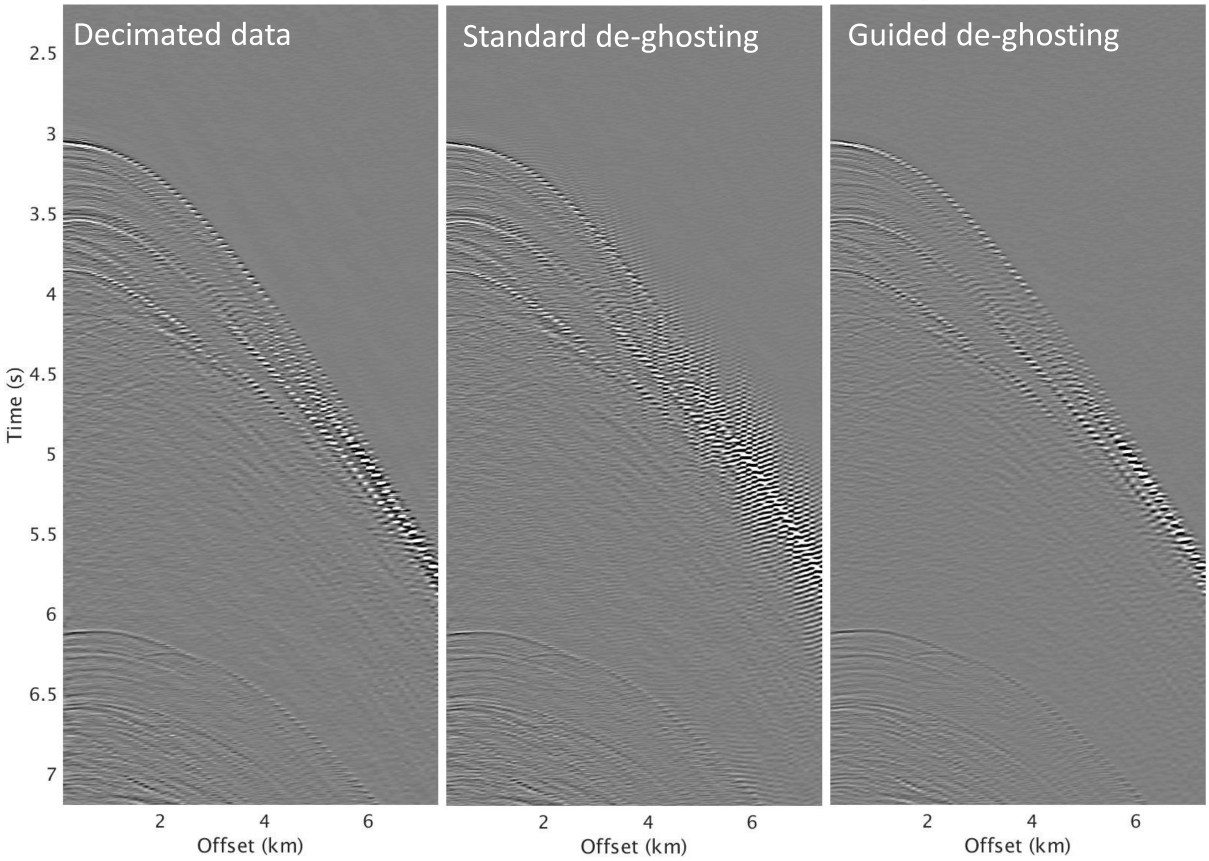

Figure 1 *Left: decimated real data with 100m nominal trace spacing. Middle: standard phase-shift de-ghosting. The far offsets are heavily affected by aliasing artefacts. Right: guided phase-shift de-ghosting.*

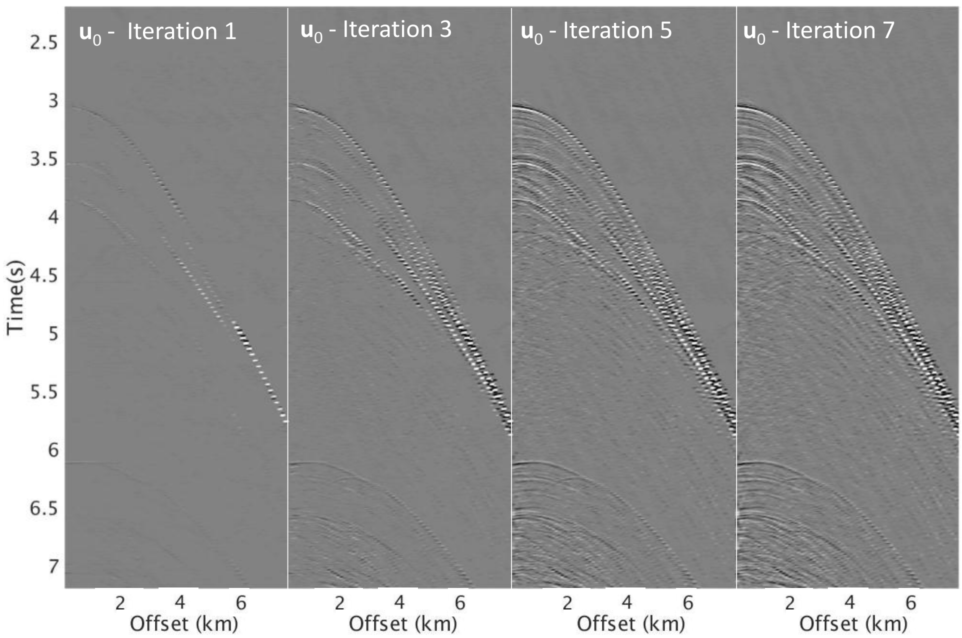

Figure 2 *De-ghosting results for iteration 1 to 7.*

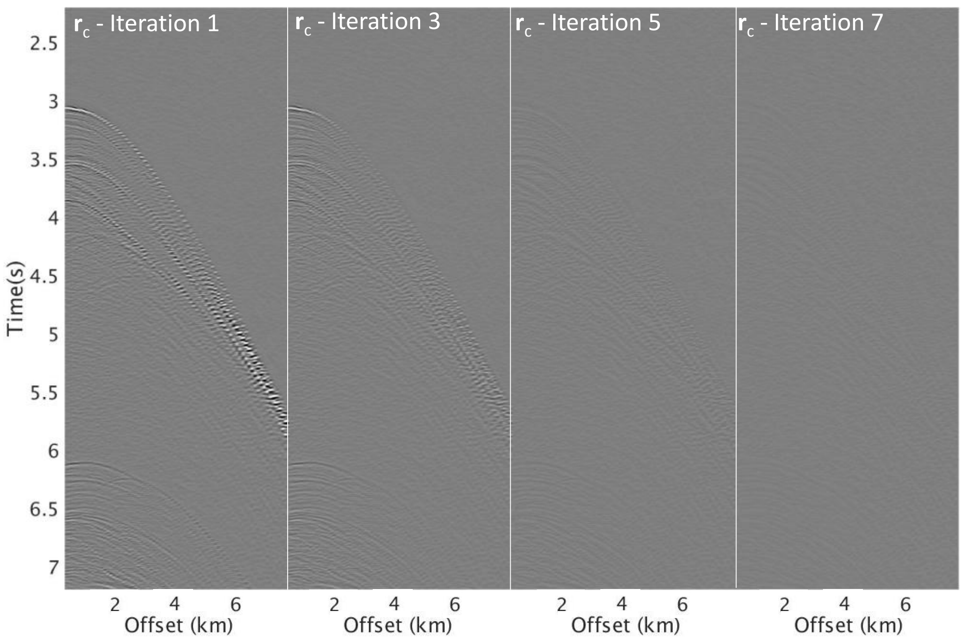

Figure 3 *Pressure residuals for iterations 1 to 7.*

builds up the up-going wavefield iteratively, giving precedence to the most prominent events in the data. The identification of these events is performed using low-frequency, un-aliased data. Application of the proposed method to a decimated shot gather shows that aliasing effects are successfully removed by the proposed method.

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References

Berkhout, G., Blacquiere, G., [2016]. Deghosting by echo-deblending. *Geophysical Prospecting*, **64**, 2, 406-420.

Grion, S., Telling, R., Holland, S. [2016a]. Phase-shift de-ghosting. *78th EAGE Conference & Exhibition,* Extended Abstracts, We SRS3 09.

Grion, S., Telling, R., Holland, S. [2016b]. Rough sea estimation for phase-shift de-ghosting. *86th Annual International Meeting, SEG,* Expanded Abstracts, 5129-5133.

Liu, B., Sacchi, D. [2004]. Minimum weighted norm interpolation of seismic records. *Geophysics*, **69**, 6, 1560-1568.

Özbek, A., Vassallo, M., Özdemir, K., van Manen2 D., Eggenberger, K. [2010]. Crossline wavefield reconstruction from multicomponent streamer data: Part 2 — Joint interpolation and 3D up/down separation by generalized matching pursuit. *Geophysics*, **75**, 6, WB69-WB85.

Schonewille, M., Klaedtke, A., Vigner, A. [2009].Anti-alias anti-leakage Fourier transform. *79th Annual International Meeting, SEG,* Expanded Abstracts, 3249-3253..

Trad, D., Ulrych, T., Sacchi, M. [2003]. Latest views of the sparse Radon transform. *Geophysics* **68**, 1, 386-399.

Wang, P., Ray, S., Nimsaila, K [2014]. 3D joint deghosting and crossline interpolation for marine single-component streamer data. *84th Annual International Meeting, SEG,* Expanded Abstracts, 3594-3598..

Xu, S., Y. Zhang, D. L. Pham, and G. Lambaré, [2005]. Antileakage Fourier transform for seismic data regularization. *Geophysics*, 70, 4, V87–V95.