**Adaptive de-ghosting by kurtosis maximisation**

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**Summary**

We discuss the reasons for adaptive de-ghosting and its advantages. The success of broadband processing relies on de-ghosting accuracy, and because the parameters of the physical process determining the ghost reflection are not precisely known, de-ghosting cannot be purely deterministic. The physical entities determining the receiver ghost are the sea surface, the receiver depth and the water velocity and for de-ghosting purposes they can be represented by an effective ghost delay-time and sea surface reflection coefficient. The de-ghosting optimisation metric we employ is based on the kurtosis of the data-autocorrelation. The kurtosis is a statistical measure often used to associate a measure of "peakedness" to a random variable. A synthetic example characterizes the main features of the adaptive procedure proposed, which can be sequenced in two steps. The optimisation of the ghost delay-time is robust to errors in the reflection coefficient and to noise, Therefore, it should be performed first. The reflection coefficient estimate is more sensitive to noise and requires the delay-time to be optimized in advance, and can therefore be carried out as a second step. A real data example demonstrates the applicabilityof the proposed method.

## Introduction

The sea surface is in general not calm and an exact effective reflection coefficient from its surface is not a-priori known and it can be frequency-dependent (see for example Orji et al., 2013). Also, the receiver depth is subject to positioning inaccuracies. The shallow water column between the receiver and the sea surface is where the water velocity is most subject to variability, being closest to the surface and its associated temperature and salinity changes due to weather and tides. Sea surface reflectivity, water velocity and receiver depth are known with a good degree of approximation that is sufficient for a variety of processing steps, like multiple attenuation and migration, but de-ghosting is highly sensitive to these parameters. This is due to the combination of two factors: the strong amplitude and phase changes that ghost interference imposes on seismic data, and the fact that in the frequency domain these changes are at their strongest in correspondence with the ghost notches, where the signal to noise ratio of the recorded data is at its minimum. There is therefore a general need to estimate a physical model for the ghost reflection as part of a de-ghosting process.

## Adaptive de-ghosting by kurtosis maximisation

Wang et al. (2013) discuss a bootstrap de-ghosting approach that requires the joint use of pre-migration data and its mirror, and optimizes the time-delay between primary and ghost. The authors do not attempt the estimation of the reflection coefficient. Masoomzadeh et al. (2013) point out that de-ghosting errors can be reduced by using a stochastic search for the optimum set of de-ghosting parameters that includes both delay-times and reflection coefficients that can vary with frequency. However, the search criteria or, in other words the objective function for the parameters optimisation, is not mentioned. Grion et al. (2013) compare de-ghosting results in the presence of calm and rough seas, and note that an adaptive de-ghosting that includes a statistical element is able to compensate rough sea effects for structural imaging purposes.

In adaptive de-ghosting, it is important to stress we are estimating "effective" parameters that best fulfil the objective of removing ghost reflections. These effective parameters are certainly linked to the physical properties of the water column above the streamer array, but they are also a function of ghost modelling assumptions:

- Constant water velocity.
- Specular reflection at the sea surface (scattering is ignored).
- 2D wave-field propagation.
- Known receiver locations.

The de-ghosting optimisation metric we employ is based on the kurtosis of the data-autocorrelation. The kurtosis is a statistical measure often used to associate a measure of "peakedness" to a random variable $x$ with mean $\eta$, expected to be non-Gaussian, and it is defined as:

$$k = \frac{\mu_4}{\sigma^4}, \qquad (1)$$

where $\mu_4 = E\left[(x - \eta)^4\right]$ is the 4$^{th}$ order central moment of $x$, and $\sigma$ its standard deviation. Various authors have considered the kurtosis for wavelet estimation purposes (e.g. Cambois and Hargreaves, 1994; Van der Baan, 2008).

The ghost model is

$$G = 1 - r(f)e^{-j\omega g_t},$$

where $r(f)$ is the frequency-dependent reflection coefficient, $\omega$ is the angular frequency and $g_t$ is the delay time between primary and ghost. This model is defined in the $\tau$-$p$ domain to accommodate 2D wavefield propagation, and $g_t$ is therefore a function of the cable depth profile, water velocity and of the propagation angle.
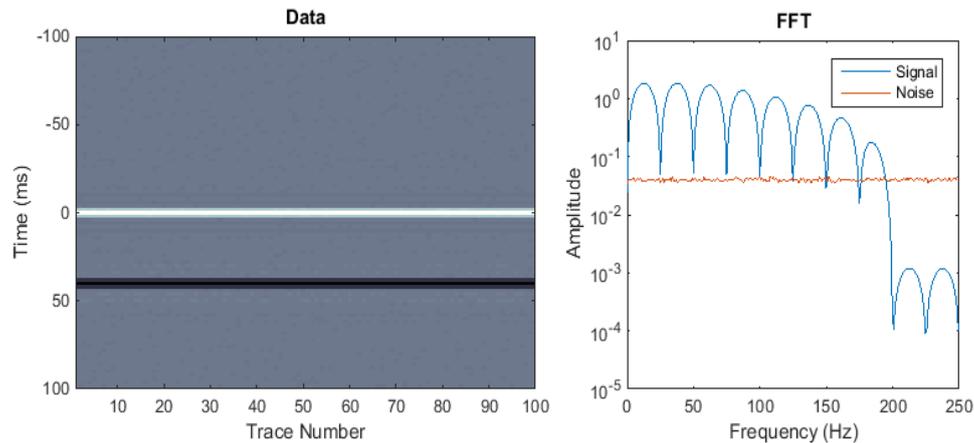
***Figure 1*** *Synthetic data (left) and its amplitude spectra (right).*

To illustrate the use of the proposed kurtosis-based metric to assess de-ghosting quality, we consider the following example. Figure 1 shows a synthetic dataset consisting of one primary and its ghost. The delay of the ghost with respect to the primary is 40ms, as expected from a 30m cable depth, and the reflection coefficient is -0.95. The data is contaminated by Gaussian white noise, and the amplitude spectra of signal and noise are also shown in Figure 1. The signal to noise ratio is variable with frequency, and has maximum values in the range 10-30dB in correspondence to the constructive interference between primary and ghost, and minimum values in the range 2dB to -7dB in correspondence with the ghost notches. The presence of noise has a negative effect on the estimation of de-ghosting parameters, but by working in sliding windows with a spatial size of about one hundred traces, and time length of the order of several hundreds of milliseconds, the effect of noise can be reduced. The data in Figure 1 represents one such window, and in a real data scenario would be part of a common-*p* section. The window size is a compromise between resolution – accounting for rapid changes in the ghost – and obtaining a robust estimate of parameters.

Figure 2 (left) shows the kurtosis values obtained when de-ghosting the synthetic data using the correct value for the reflection coefficient, and a range of delay-times between primary and ghost with respect to the correct value of 40ms. The correct value of 0ms is detected with high resolution. Figure 2 (middle) shows the values obtained when de-ghosting the data using the correct delay-time and a variety of reflection coefficient absolute values in the range 0.7 to 1. The correct value of 0.95 is detected, although resolution is lower than for the time delay optimisation case. This is a general conclusion; the reflection coefficient is more difficult to estimate than the delay-time between primary and ghost. To conclude this synthetic data example, Figure 2 (right) shows the kurtosis values for the case of joint optimisation of reflection coefficient and delay-time. It can be noted that the delay-time optimisation result is broadly independent from the knowledge of the exact reflection coefficient value, while the opposite does not hold. Therefore, this optimisation problem can be solved sequentially, with the kinematic aspect of the problem (the delay-time) solved
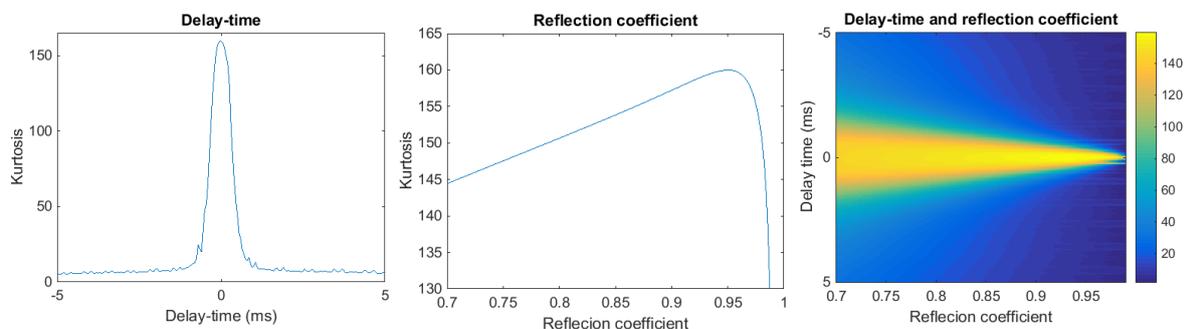


***Figure 2*** *Objective function for ghost delay-time (left), reflection coefficient (middle) and joint optimisation (right).*

first, followed by the amplitude aspect (the reflection coefficient).

**Examples**

As an application example, Figure 4 shows a real data common-$p$ section before and after de-ghosting using the discussed procedure. This 2D data was acquired in the presence of a rough sea with an observed significant wave height of 3m. The ray-parameter $p$ of the data in Figure 4 is 0.11ms/m, corresponding to about $9.5^o$ of propagation angle with respect to the vertical direction. After testing, it was decided to use a window size of 500ms and 81 shots. Figure 5 shows the estimated delay-times and reflection coefficient. The delay times are variations with respect to the delay-time expected for this $p$ value and cable depth (30m), and show values of the order of +/- 0.5ms. For the selected $p$-value, this delay corresponds to a cable depth positioning error of the order of +/- 0.4m. Within the data bandwidth, the estimated reflection coefficient varies between -1 and -0.7. Autocorrelations of this common $p$ section before and after de-ghosting are shown in Figure 6 and show a progressive removal of reverberating energy when adaptive de-ghosting is introduced.
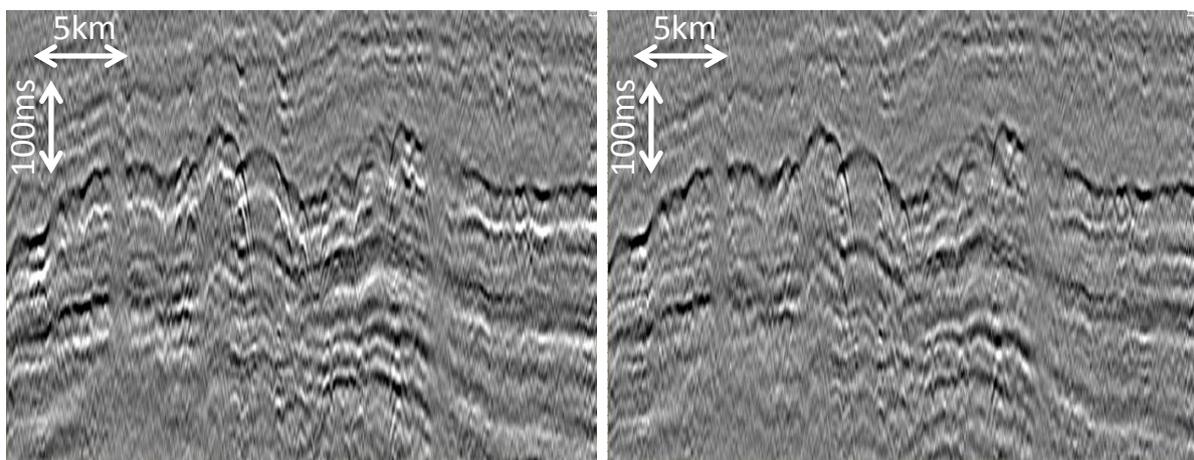


*Figure 4 A common-p section before (left) and after (right) adaptive de-ghosting with optimized time delays and frequency-dependent reflection coefficient.*
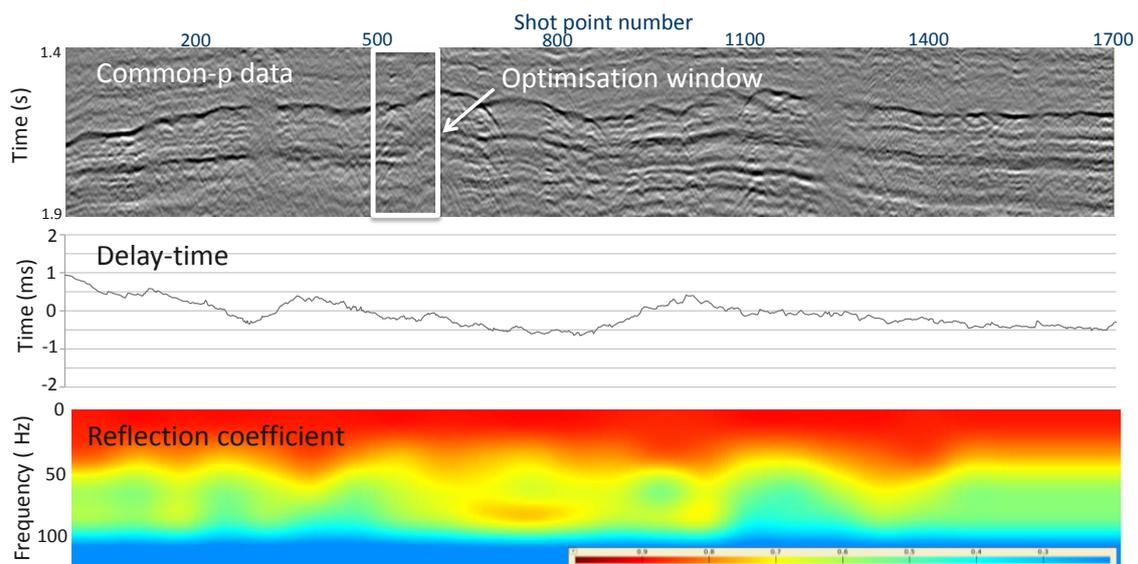


*Figure 5 De-ghosted common-p section (top), estimated delay-time between primary and ghost (middle) and estimated reflection coefficient (bottom).*

## Autocorrelations
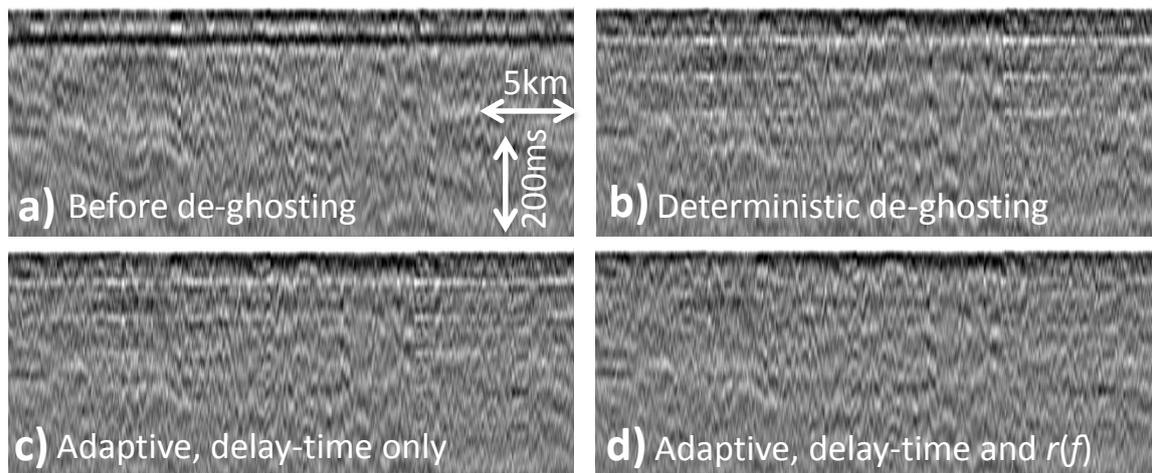


**Figure 6** *Autocorrelations of the common-p section in Figure 4. a) before de-ghosting, b) after deghosting with fixed parameters, c) after de-ghosting with optimized delay times and fixed reflection coefficient, d) after de-ghosting with optimized delay times and frequency-dependent reflection coefficient.*

**Conclusions**

The parameters of the physical process determining the ghost reflection are not precisely a-priori known, and de-ghosting is highly sensitive to these parameters. In the context of parametric adaptive de-ghosting, tests on synthetic and real data suggest that the kurtosis is a useful metric in assessing de-ghosting quality and can form the basis of an objective function for an optimisation algorithm.

**Acknowledgements**

**References**

Cambois, G. and Hargreaves, N.D. [1994] Zero-phase conversion of marine seismic data using one-parameter phase filters and kurtosis maximization. 64th Annual SEG Meeting Expanded Abstracts, 1591-1594.

Grion, S., Azmi, A., Pollatos, J., Riddalls, N. and Williams, R. G. [2013] Broadband processing with calm and rough seas: observations from a North Sea survey. 83rd Annual SEG Meeting Expanded Abstracts, 226-230.

Masoomzadeh H., Woodburn N. and Hardwick, A. [2013] Broadband processing of linear streamer data. 83rd Annual SEG Meeting Expanded Abstracts, 4635-4639.

Orji, O., Sollner, W. and Gelius, L., J. [2013] Sea surface reflection coefficient estimation. 83rd Annual SEG Meeting Expanded Abstracts, 51-55.

Van der Baan, M. [2008] Time-varying wavelet estimation and deconvolution by kurtosis maximization, Geophysics, **73** (2), V11-V18.

Wang, P., Ray, S., Peng, C., Li, Y., Poole, G. [2013] Premigration deghosting for marine streamer data using a bootstrap approach in Tau-P domain. 83rd Annual SEG Meeting Expanded Abstracts, 4221-4225.