# Deterministic marine deghosting: tutorial and recent advances

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## Summary (Arial 12pt bold or Calibri 12pt bold)

Marine streamer data are typically contaminated by the interference from ghosts on both source and receiver sides. Modern marine processing flows attempt to supress this interference via deterministic algorithms, rather than via statistical deconvolution as is typically employed in land processing. In the first part of this paper, we provide a tutorial-style description of the ghost phenomenon and its adverse effect on resolution. Next we describe a novel deghosting strategy which contains both deterministic and stochastic aspects, and which operates in the tau-p domain in order to overcome the problem of temporal non-stationarity of the ghost at high propagation angles. Finally, we examine our deghosting process on several data examples from diverse regions, including East Coast Canada.

## Introduction

It is well-known that marine seismic data resolution is degraded by the presence of sea-surface reflections on both source and receiver sides. The slightly delayed reflections trailing the original source pulse are called “ghosts”, and the resulting interference can be either constructive or destructive for different wavelengths. This interference is manifest as a series of notches in the amplitude spectrum of the ghosting operator, with rapid variation in the phase spectrum occurring in the vicinity of these notches. Figure 1 illustrates this notching phenomenon for a synthetic source-side ghost, and the green curve in Figure 2 shows notches on a real data example, where the presence of both source and receiver ghosts conspire with anelastic attenuation to drastically reduce the effective frequency content of the embedded wavelet. Because of the natural diversity provided by variation in propagation directions and shot/receiver depths, as well as by imperfections in the sea-surface reflections, the notches on this poststack display are not as deep as those shown in the prestack synthetic example in Figure 1, Still, the notching effect is very significant, and requires compensation.

There are several acquisition-based schemes aimed at suppressing this ghost effect, including variable-depth streamers or slanted cables (Soubaras and Dowle, 2010) and dual-sensor streamers combined with random-depth sources (Tenghamn et al.,2007; Carlson et al., 2007). The present paper deals with processing-based, rather than acquisition-based, solutions. A processing solution is desirable for two reasons: first it does not require added acquisition effort, and second it is applicable to existing legacy data which have not been acquired using any of the above specialized acquisition schemes.

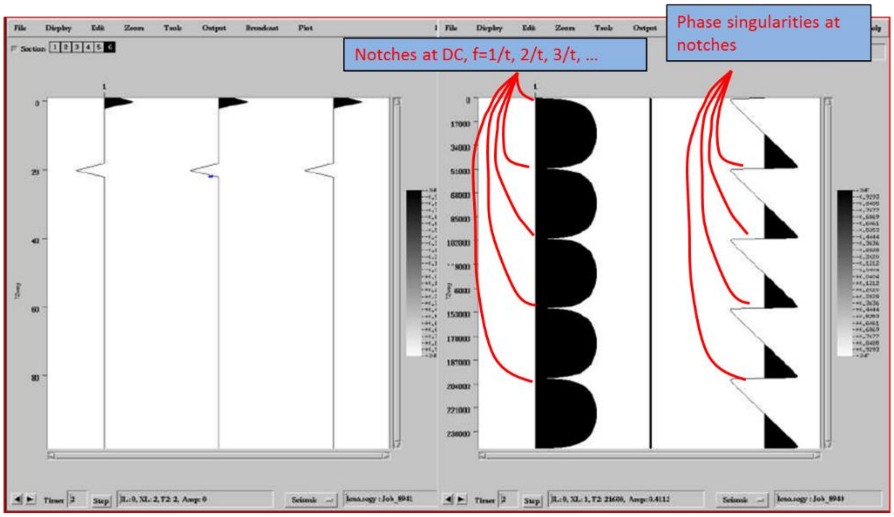


Figure 1: Synthetic source side ghost at normal incidence. Time domain, amplitude spectrum and phase spectrum displays shown in left, middle and right panes, respectively. Notches occur at regular frequency intervals, starting at DC, and the phase spectrum fluctuates wildly in the vicinity of the notches.


Figure 2: Average amplitude spectrum of a stacked data volume from West of Shetlands, UK. Green and red curves show the spectrum with and without application of the deghosting strategy discussed in this paper, respectively.

There are two possible approaches to deghosting in processing. The first of these is a statistical approach based on the classical minimum phase deconvolution algorithm of Robinson (1957), and the second of these is a deterministic approach which entails computation of the analytic inverse of the ghost operator. While statistical deconvolution has remained the workhorse in wavelet processing of land data, it has been eschewed in modern marine processing flows in favour of deterministic techniques. The present paper discusses a new deterministic method for deghosting.

## Theory and/or Method

#### Deghosting basics

We begin by revisiting the canonical model for the normal incidence ghost. The ghost effect may be described by the convolution of the uncontaminated trace with a ghosting operator. A one-sided ghost operator may be written in the time domain as

$$g_t = (1,0,0,\ldots 0,-r), \qquad (1)$$

where the number of zeros represents the two-way vertical propagation time from source (or receiver) at-depth to water surface (such time is denoted $t_d$ in the analysis below) and $r$ is the magnitude of the water surface reflection coefficient. Note that 0.0 < $r$ < 1.0, and consequently this ghosting operator is minimum phase. We can easily express this operator in the frequency domain as

$$G(w) = 1 - re^{\,iwt_d}, \qquad (2)$$

and its minimum phase inverse as:

$$G^{-1}(w) = \frac{1}{1 - re^{iwt_d}}\,. \qquad (3)$$

Note that the functional form of equation (2) gives rise to the notches and phase pathologies shown in Figure 1; in particular, notch depth increases as $r$ approaches unity.

Because the ghost operator and its inverse are minimum phase, it is possible to deghost using standard minimum phase deconvolution as noted earlier. In fact, such a scheme might seem compelling since it carries the practical advantage of not needing to know $r$ nor $t_d$. However, it also imposes a well-known assumption on the distribution of the reflectivity (e.g., white reflectivity), and such an assumption is viewed as being unnecessarily restrictive in marine processing where the wavelet distortion mechanisms, being somewhat simpler than in the land case, admit deterministic compensation. The assumption imposed on the reflectivity (i.e., in statistical deconvolution) runs an especially large risk of violation in the case of estimating the deghosting operator, whose long time domain length (and associated rapid variation across frequencies in its amplitude spectrum) makes it particularly hard to unravel from the underlying geology. Consequently, the marine processing community has shifted away from statistical deconvolution and deterministic approaches are now favoured for deghosting.

**Description of our new approach**

Masoomzadeh et al. (2013) provide details of our novel processing-based deghosting technique. The approach contains deterministic and stochastic aspects, both of which address various complexities of wave propagation.

***Deterministic aspects***

Note that if $r$ and $t_d$ were known with certainty, equation (3) could be used trivially in a deterministic deghosting process for normal incidence data. In practice equation 3 indeed forms the theoretical basis for our approach, but with two important modifications.

The first of these addresses the fact that we are dealing with oblique, rather than normal, incidence data in typical marine surveys. Massomzadeh et al. (2013) show that the time-delay associated with a source (or receiver) ghost for a plane wave propagating at an angle $\theta$ from the vertical is given by

$$t_d = \frac{2d\cos\theta}{v},$$

where $d$ is water depth and $v$ is water velocity. Such angle-dependence results in non-stationarity of the ghost operator as it appears on a trace in the *x-t* domain, especially at larger offsets. This non-stationarity in turn violates the convolutional model that forms the cornerstone of the derivation of our deterministic deghosting operator, and would lead to unacceptable wavelet distortions in practice. Fortunately, we can overcome this non-stationarity issue by performing the deghosting in the slant-stack ($\tau$-$p$), rather than *(x,t)*, domain,  By applying a shot-domain $\tau$-$p$ transform, we focus all energy associated with a particular ray parameter $p$ (i.e., with a particular emergence angle) onto a single trace, thereby restoring stationarity of the ghost effect. Note that this stationarity is only approximate. Perfect stationarity is not guaranteed for several reasons, including the following: (i) differing source-side propagation angles (and therefore source ghosts) do not all map to the same *p* trace in the presence of complex structure; (ii) the $\tau$-*p* transform is unable to honour intra-cable receiver depth variations which might exist because of bad weather (yet such variations affect the local character of the receiver ghost); (iii) intrinsic receiver ghost non-stationarity may exist because of rapid sea-level undulations taking place over the listen length; (iv) significant crossline offset which may be present on the far cables in a wide-tow 3D survey and which is not perfectly honoured in the $\tau$-*p* transform. Despite these issues, we typically observe excellent results in practice, implying that the ghost effect tends to exhibit sufficient stationarity in $\tau$-*p* space to permit its adequate removal.

The second important modification is to impart frequency and ray-parameter dependence to the surface reflection coefficient *r*. Our justification for such dependence is based on the fact that the sea-surface is not a perfect mirror (Williams and Pollatos, 2012) and invokes the physically-rooted argument that higher frequency and larger ray-parameter components of the wavefield ought to experience a less perfect reflection at the sea surface than their lower frequency/ray-parameter counterparts After recasting equation 3 in terms of ray parameter *p*, we may thus write our modified deterministic one-sided deghosting operator as

$$D(w,p) = \frac{1}{1 - r(w,p)e^{\frac{iw2d}{v}\sqrt{1-p^2v^2}}}, \qquad (4)$$

where it is understood that both source and receiver sides are included in the actual implementation.

Although the preceding analysis assumes a flat streamer cable. Masoomzadeh et al. (2013) describe certain modifications (not discussed here) which allow the methodology to be extended to the case of a linearly slanted cable.

***Stochastic aspects***

Selecting optimal values of shot/receiver depths and frequency-dependent reflection coefficients for use in equation (4) may be difficult, especially in the presence of significant sea surface undulations brought on by bad weather. Therefore, we typically perform a stochastic search for the most appropriate set of deghosting parameters, wherein the quality of each trial parameter set is judged by the autocorrelations of the provisionally deghosted traces.

Further improvements may be achieved by sorting the stochastically-deghosted traces into common ray-parameter ensembles. For each ensemble a separate single “global” operator is computed using a statistical deconvolution approach in which operator design is accomplished by averaging across all traces within the common-p ensemble. For the reader who is well-versed in surface-consistent deconvolution of land data, these *p*-dependent global operators are somewhat reminiscent of the “line” component in that latter algorithm, This final deconvolution step can help address any remmant deghosting imperfections which are common to the entire common-p ensemble, while safeguarding against the unwitting removal of geology through the use of global, rather than trace-by-trace, operators.

## Examples

The following example is from the TGS Tail of the Bank 2D data set recently acquired off of the East Coast of Canada. The above deghosting process is the main element in a so-called “broadband” flow which also includes a post-migration spectral smoothing step. Figure 3 shows a migrated stack after all final processing except that broadband processing was not performed. Figure 4 shows the same stack after inclusion of broadband processing. Note that independent zero-phasing operations were applied to both sections. Amplitude spectra corresponding to the images in Figures 3 and 4 are displayed in Figure 5. The resolution improvement after broadband processing is obvious and dramatic and the amplitude spectrum of the non-broadband image (green curve, Fig. 5) clearly shows strong imprinting by the ghosts. Additonal data examples will be shown in the oral presentation.

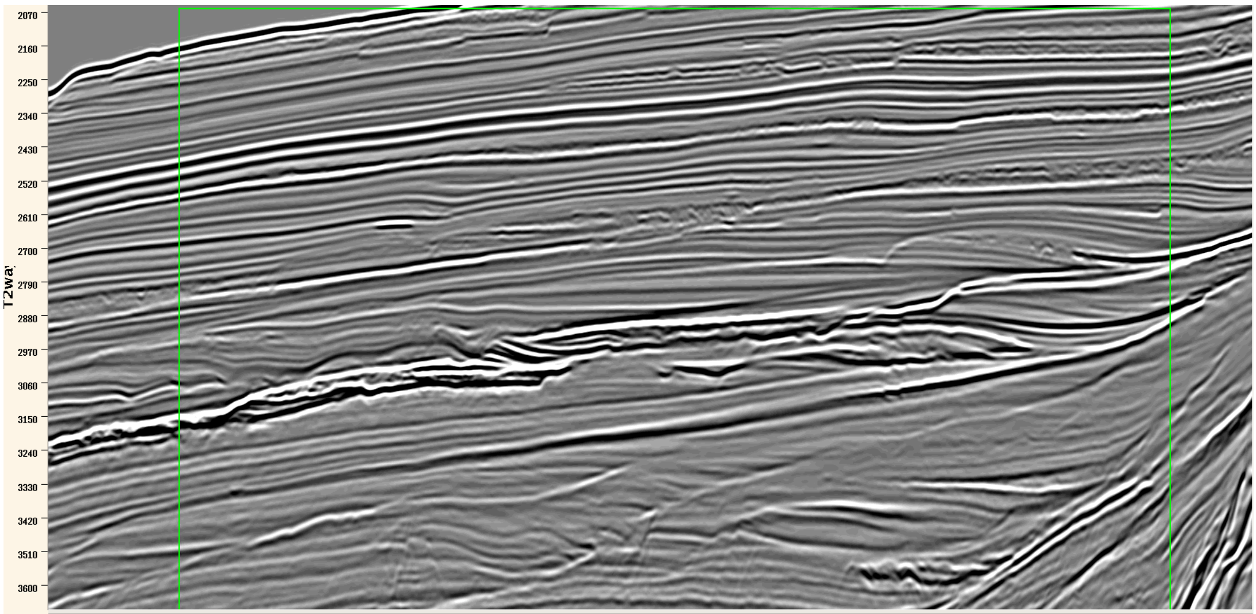


Figure 3:Tail of the Bank migrated inline without broadband processing.

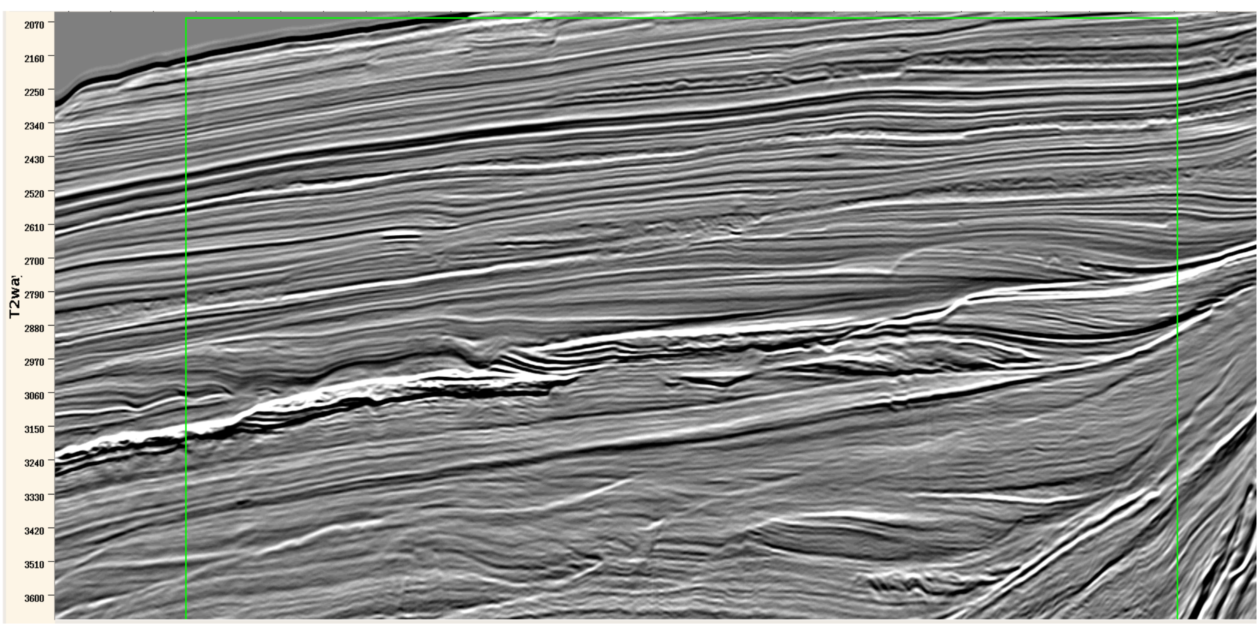


Figure 4:Tail of the Bank migrated inline with broadband processing.

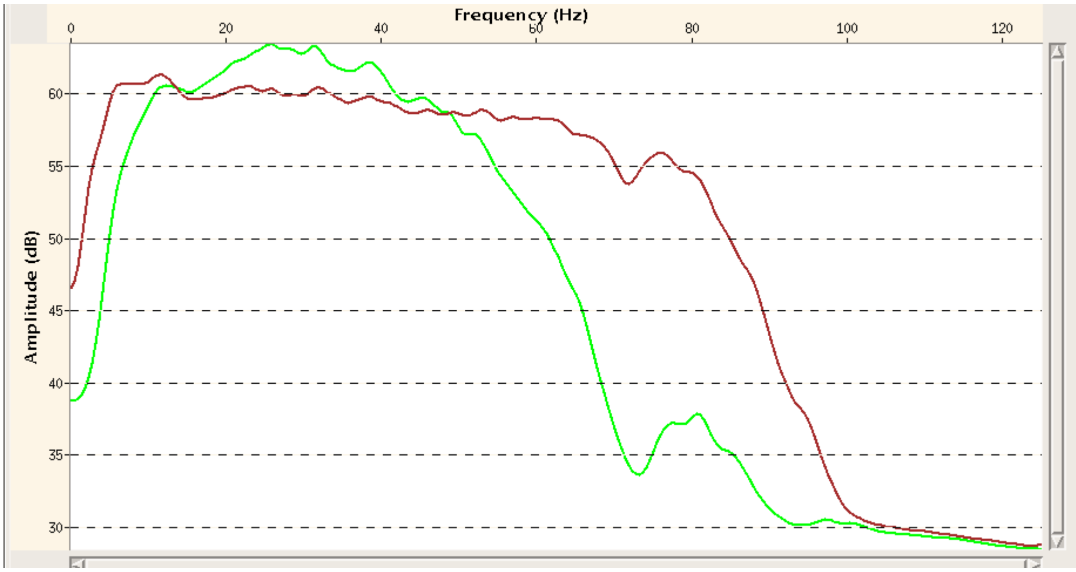

Figure5: Amplitude spectra associated with Figures 3 (green) and 4 (red).

## Conclusions

Resolution of marine seismic data may be significantly degraded by the presence of source and receiver side ghosts. We have presented a technique for deghosting in the $\tau$-*p* domain which is based on a deterministic framework, but which contains stochastic elements for parameter optimization. The method, which can be adapted to handle linearly slanted cables under certain modifications, has been applied successfully on numerous data sets and is considered an integral part of our marine wavelet processing toolkit.

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