Using a seismic reflector for resolving streamer depth and sea surface profiles

Ed Kragh[1] & Leendert Combee[2]

Introduction

In this short paper we show how the depth profile of a towed streamer and the shape of the sea surface above the towed streamer, at a particular instant, can be obtained from travel time and ghost notch frequency analysis on an isolated seismic reflector. The resulting streamer profiles indicate smooth long wavelength variations that do not follow the sea surface profiles. The sea surface profiles exhibit a dominant wavelength and amplitude that is consistent with an ocean wave spectrum. Both streamer and sea surface results are consistent with observation logs.

A nonhorizontal streamer depth profile introduces static shifts into the data and, combined with the sea-surface shape, perturbs the data bandwidth through changes in the ghost notch frequency. If both streamer and sea-surface profile were known, it might be possible to correct the data for these perturbations. Furthermore, detailed information on the streamer depth profile can be used for streamer depth quality control.

Currently, depth sensors are used for monitoring the streamer profile. The depth sensors are widely spaced and filtered; the *highest* detected frequency of the hydrostatic depth sensors is about 0.05 Hz. The *lowest* frequency recorded from the seismic data is limited by low cut filters to about 3 Hz. This 'gap' in our data bandwidth (from about 0.05–3 Hz) is where the sea surface waves lie, ranging from about 0.05–0.5 Hz (Carter *et al*. 1986), i.e. there is no direct information on the sea surface waveband.

The data – Orca Basin

The Orca Basin in the NW Gulf of Mexico contains a saline brine interface with horizontal stratification giving a vertical density gradient (Trabant & Presley 1978). Its seismic response is of a perfectly flat reflector with a high signal-to-noise ratio, which, in some places, is isolated about 200 ms above the water-bottom reflection. This reflection event is ideal for studying perturbations in the seismic data. First because of its isolated nature, which avoids confusion from interfering reflections, second, because it is flat and homogeneous, so changes to the wavelet can be assumed to be nongeological, and third, because of the broad-band, high signal-to-noise ratio of the reflection wavelet.

The data presented in this paper form a small part of an acquisition experiment designed to test the performance of the source array in marginal weather (Pieprzak *et al*. 1998). During the acquisition, the sea state was 4–5 (marginal weather), with a Significant Wave Height (SWH) of 3–4 m. Three 8 km streamers recorded the data. Figure 1 shows an example shot record recorded by streamer 1. The salinity interface reflection is the isolated event at 3.0 s two-way time (TWT). Residual bubble energy from the airgun array is evident at about 3.15 s TWT. The water bottom reflection is the event at about 3.25 s TWT ($\approx$2.4 km water depths).

Method

Spectra derived from short windows around an *isolated* reflection event allow the trace-to-trace variation in the ghost notches to be observed. If the receiver ghost notch can be distinguished from the source ghost notch, then the receiver ghost notch frequencies can be directly inverted to give the

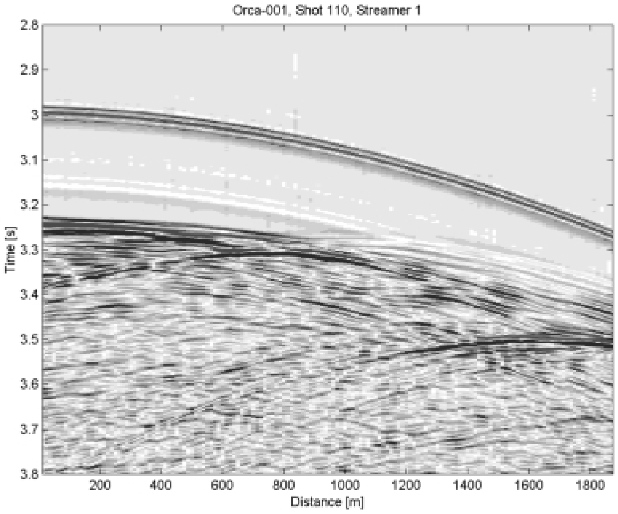

Figure 1 Example shot record from streamer 1. The salinity interface reflection is the isolated event at 3.0 s TWT. Residual bubble energy from the airgun array is event at about 3.15 s TWT. The water bottom reflection is the event at about 3.25 s TWT.

Correspondence: [1]Schlumberger Cambridge Research. High Cross, Madingley Road Cambridge, CB3 OEL, England, UK.
[2]Schlumberger Reservoir Evaluation—Seismic, Solbraaveien 23, N-1370 Asker, Norway.

local wave elevations above each receiver. To get the true wave elevation, the streamer profile needs to be known. This can be obtained from the moveout-corrected arrival time of the reflection event in question (Kragh & Combee 1999). The following steps are carried out for each streamer from a single shot record:

1 Isolate the salinity interface reflection. This is trivial for the data presented here, as the event is naturally isolated.

2 Pick the first arrival time and correct for offset – this gives the perturbations in streamer shape. The data were interpolated and picked to a positional accuracy of a few cm. The high signal-to-noise ratio on the salinity interface reflection was a prerequisite to achieve this. Correction for offset, is simply, the moveout of the reflected event. The horizontal nature of the reflecting horizon in an (approximately) homogeneous medium simplifies this step.

3 Compute spectra of each windowed trace around the salinity interface reflection. The spectral resolution was ≈ 0.5 Hz.

4 Pick the receiver notches, correct for offset and arrival angle. The apparent ghost notch period decreases with the offset by the cosine of the angle from the vertical; the notch frequency increases accordingly. For a shot record the shot depth is constant and the source ghost period should decrease exactly with the cosine of the angle from the vertical. (In this trial, the source depth was shallower than the streamers so the source ghost notch was easily distinguishable from the receiver ghost notch.)

5 Compute the local sea elevation from the ghost period and streamer elevation. The offset also affects the position of the inverted local wave elevations, since these are no longer vertically above the receivers. This is a simple geometric correction factor equal to the sine of the angle from the vertical. The correction is a small lateral shift.

Figure 2 shows example spectra computed from the isolated salinity reflection in Fig. 1. Each panels plots approximately 25 overlying spectra from increasing offsets. Top left: 0–300 m range, top right: 300–600 m range, bottom left 600–900 m range, bottom right: 900–1200 m range. The source ghost notch at around 125 Hz (6 m depth) is heavily filled in this example and is easily distinguishable from the receiver ghost notches (nominal depth 9 m), which show a spread of positions.

The ghost notches were picked and Fig. 3 shows plotted picks (black) with the expected moveout with offset plotted in red. The source ghost notch closely follows the expected moveout; a shot record contains only a single source notch. The scatter of the source ghost notch picks gives a feel for the errors involved in the spectral accuracy and the notch picking; the errors are very small. The receiver ghost notches show considerable scatter due to a combination of the wave elevation above each receiver and the receiver elevations.

The receiver notch picks were inverted for wave elevation above the streamer. Assuming a zero-mean sea, the reflection wavelet onset picks are then used to compute the absolute streamer elevations and sea-surface shape. This was possible for offsets up to 2 km. After that, it was difficult to pick the notches because of moveout distortion and interference of reflectors.

Results

Figure 4 (top panel) shows three wave elevation profiles, one from each streamer. They are vertically separated for visual clarity, and the vertical exaggeration is about 50 : 1. The following observations are noted, which indicate that the results indeed represent realistic and true sea-surface profiles

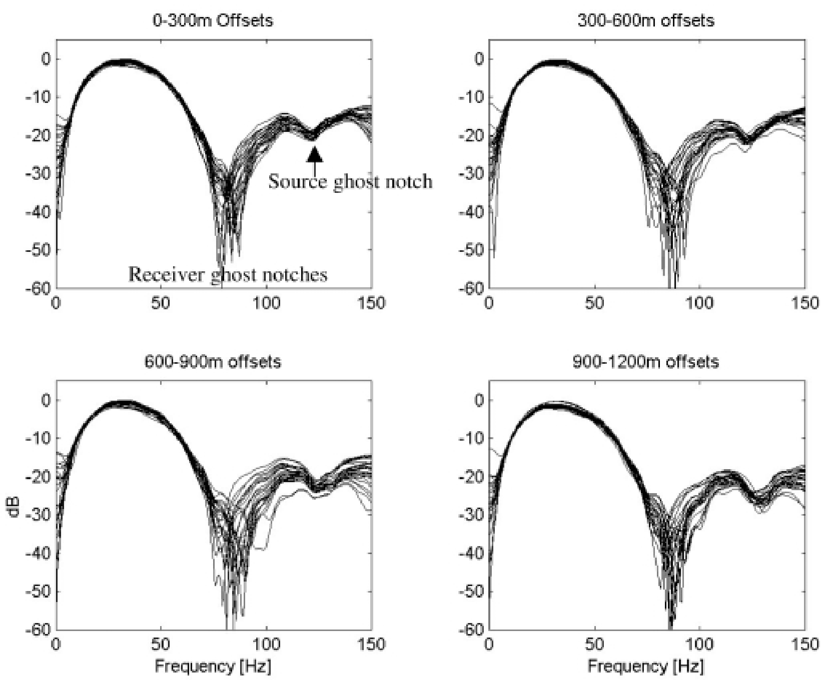

Figure 2 Amplitude spectra of the isolated salinity reflection in Fig. 1. Each panels plots approximately 25 overlying spectra from increasing offsets. Top left: 0–300 m range, top right: 300–600 m range, bottom left 600–900 m range, bottom right: 900–1200 m range. The source ghost notch at around 125 Hz (6 m depth, and in this example heavily filled) is easily distinguishable from the receiver ghost notches (nominal depth 9 m), which show a spread of positions.

and are not simply due to random perturbations in the data or errors in the method.

- The profiles are *not* random. They vary smoothly from one receiver to the next along the streamers. This is not a function of the method or the group length which is only slightly longer than the group spacing (12.5 m).
- The peak-to-trough wave elevations (SWH), are 2.7 m, 2.5 m and 2.4m for each streamer, respectively. The SWH was

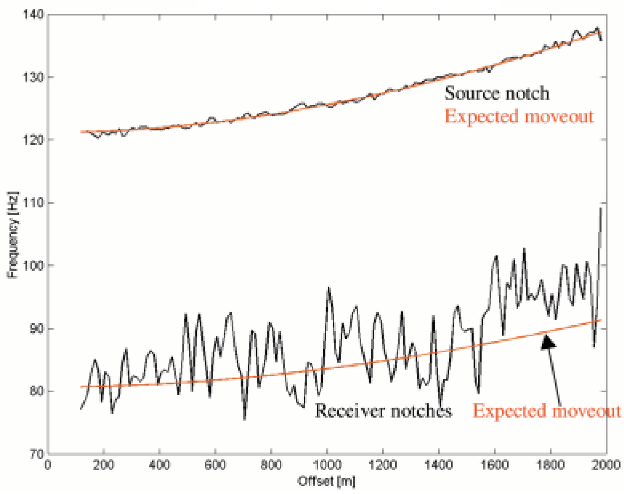

Figure 3 Source and Receiver ghost notch frequencies (black) for the spectra shown in Fig. 2, with the expected moveout with offset plotted in red. The source ghost notch closely follows the expected moveout – the raw data are a shot record containing only a single source notch. The scatter of the source notch picks gives a feel for the errors involved in the spectral accuracy and notch picking; they are very small. The receiver ghost notches show considerable scatter due to a combination of the wave elevation above each receiver and the receiver elevations.

estimated as 3–4 m on the observers' logs. This is not inconsistent. Because we are using group formed data for the inversion, the results will be slightly smoothed. However this effect is only small (Kragh & Combee 1999) because the dominant sea surface wavelengths are of the order of 100–200 m (Carter *et al*. 1986), which is long compared to the group length.

- There is no correlation of the profiles from streamer to streamer. This will obviously depend upon the sea state and swell conditions, but it is typically what we would expect with a cross-line streamer separation of 150 m.
- The bottom panel in Fig. 4 shows the average wave number spectrum of the sea surface profiles. The smooth blue line represents an isotropic ocean spectrum as described by Pierson & Moskowitz 1964) for a 4 m sea. It describes fully developed open fetch sea states. There is reasonable agreement, and the dominant wave energy occurs around the same wavelength (150–200 m).

Figure 5 shows the inverted streamer elevation profiles for the three streamers. The sea surface profiles (as shown in Fig. 4) are shown above each streamer on the same scale. The streamer profiles are smoothly varying compared to the sea surface profiles, and do not correlate with the sea surface shape. This is interesting in itself, and fits with what we might expect for a streamer under tension. Note that there is no constraint in the inversion that forces this result.

The nominal depth of streamer 1 was set to 9 m and the nominal depth of streamer 3 was set to 13 m. The results show a good match with these preset values, although it would appear that streamer 3 is slightly shallower than specified. The special profile of the second streamer, with the front end at a nominal depth of 20 m and the tail end at a

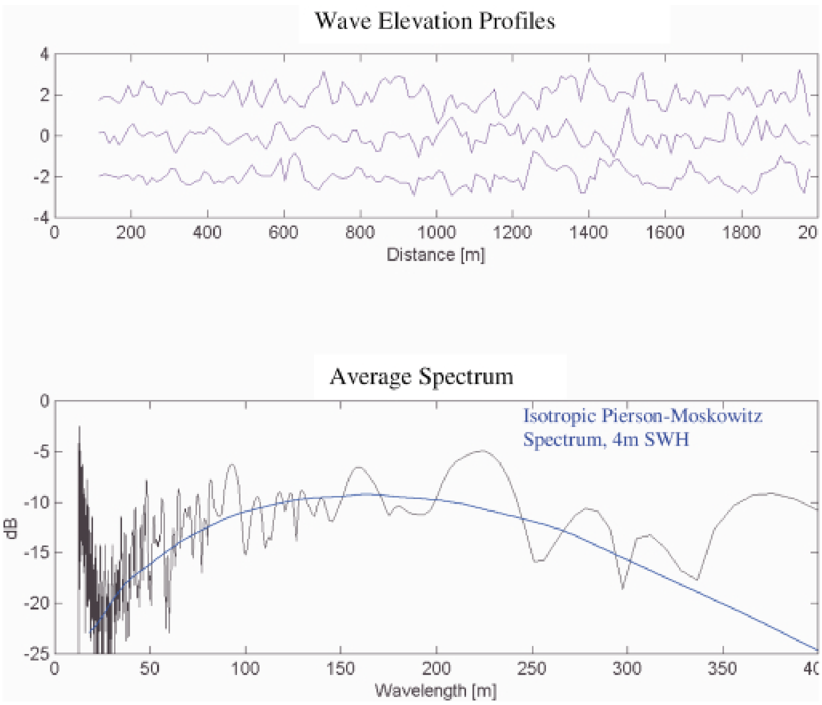

Figure 4 Top: Wave elevation profiles from each streamer. They are vertically separated for visual clarity, and the vertical exaggeration is about 50 : 1. Bottom: Average wave number spectrum of the inverted sea surface profiles. The smooth blue line represents the isotropic Pierson–Moskowitz spectrum for a 4 m sea. There is reasonable agreement, and the dominant wave energy occurs around the same wavelength.

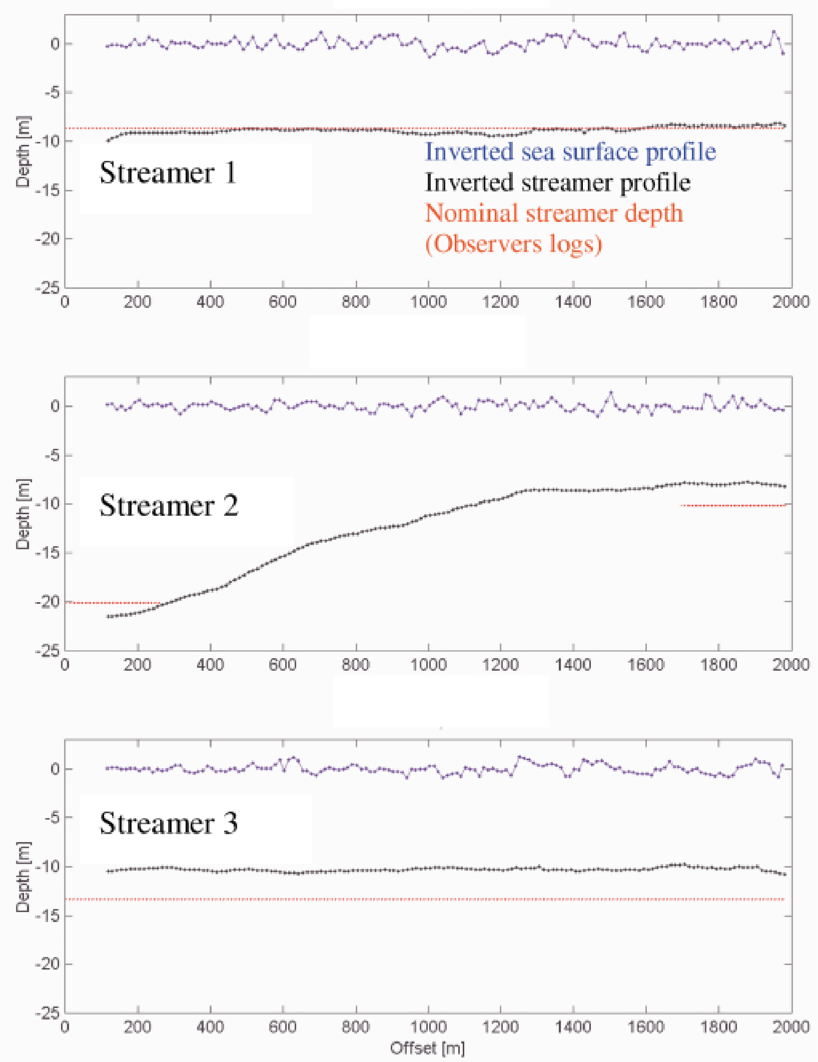

Figure 5 Inverted streamer elevation profiles for the three streamers. The sea surface profiles (as shown in Fig. 4) are shown above each streamer on the same scale. The streamer profiles are smoothly varying compared to the sea surface profiles, and do not correlate with the sea surface shape. Note that there is no constraint in the inversion that forces this result. The nominal streamer depths as recorded on the observers' logs are shown in red.

nominal depth at 10 m, was used for an experiment which required data with zero offset directly below the airguns. Again the results obtained from inversion show a good match between the preset depth values at the front and tail of the streamer and present a clear picture of the streamer profile in between. Unfortunately, no depth sensor data were available to verify the streamer profile.

Conclusions

The Orca Basin salinity interface reflection was inverted for the instantaneous elevation profile of both the streamer and sea surface. This has not been done before. The inverted sea surface profiles show wave elevations and wavelengths which agree with field observations and predictions from theory. The results are direct evidence of rough sea perturbations on real data.

The inverted streamer profiles show smoothly varying elevations in agreement with acquisition specifications. The streamer profiles do not correlate with the sea surface elevations – the streamer does not follow the sea surface profile.

While the saline brine interface of the Orca Basin serves as a near perfect reflector for the purpose of combined travel time and ghost notch inversion, the same approach can in be applied with some success to other isolated seismic events such as the reflection of the direct wave from the seafloor (Kragh & Combee 1999).

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