Signal to noise – the key to increased marine seismic bandwidth

R. Gareth Williams[1*] and Jon Pollatos[1] question the conventional wisdom on seismic acquisition suggesting that wider bandwidth can be achieved by revisiting signal to noise issues with deeper towing of streamers.

Increased seismic bandwidth is a desirable feature for many reasons in the search for hydrocarbon reserves and later in the development and production of those reserves. A broader bandwidth in seismic images provides higher resolution that enables thinner beds to be interpreted in greater detail. In this context, it is important to recall that increased frequency bandwidth directly implies increased temporal resolution even if the increase in bandwidth is derived from additional low frequencies. This may seem counter intuitive but recall that a spike has a completely flat amplitude spectrum and removing low frequencies from that spectrum will spread the spike into a broader wavelet.

This improved resolution may also reduce thin bed conflicts when analyzing AVO effects. It is therefore important that we are able to preserve the full bandwidth on pre-stack data in a way that does not complicate AVO. A wider low frequency response provides better penetration into deeper sections and below difficult overburdens such as salt and basalt. However, we want to achieve this without compromising the higher frequency portion of the full bandwidth above these problematic layers.

The low frequencies can also play a valuable role in improving inversion results – the so called frequency gap between seismic image and velocity models can be significantly reduced, thus allowing better well ties and more reliable extrapolation of inversion results away from well locations. Indeed, in many cases, an improved low frequency response is likely to be the biggest benefit of broadband seismic for reducing drilling risk.

Finally, a more subtle point is that increased bandwidth also means greater total signal strength and hence improved signal to noise which reinforces all of the other advantages above.

Noise limitations on the bandwidth

The usable bandwidth of seismic data is determined not by just the signal but rather by the signal to noise ratio. If the signal to noise is high enough, then we should be able to interpret the signal. In terms of the bandwidth, this means that a good signal to noise is needed at all the frequencies that are going to be included in the final results for interpretation. This is true for both stacked data and pre-stack data so we cannot rely wholly on the signal to noise benefits of stacking the data.

There are two main sources of noise when we record marine seismic data – the recording equipment itself and the environment. Noise can derive from energy propagating within the seismic streamers themselves and equipment manufacturers have gone to great lengths over decades to reduce the contaminating noise from these effects. Figure 1 shows data recorded in an ultra-deep water environment with a 'conventional' streamer depth of 8 m. The raw data is dominated by ultra-low frequency energy but a simple low-cut frequency filter can remove this successfully. It is clear that the low frequency limit of the seismic data is caused by this equipment noise.

After removal of the ultra-low frequency noise, the shot record in Figure 1b exhibits several other types of noise. First we see some linear noise propagating from the head of the cable which is associated with 'cable jerk' caused by the cable not being towed smoothly through the water. Second, we see noisy traces with bursts of 'swell noise' and thirdly there is an overall background noise. This background noise can be caused by a variety of near surface effects including wave and ship wash turbulence, ship noise, and remnant energy from previous shots. Conventional processing techniques have been developed to remove or at least reduce these noise types but these can also damage the signal and ultimately it is desirable to lower the noise floor by reducing these types of noise when recording the data.

Reducing the noise: quiet recording

Figure 2 shows data recorded with the same equipment as in Figure 1 and, as close as possible, the same location. The source array was identical but the streamer was towed at a depth of 32 m. The raw data is again dominated by the ultra-low frequency energy and in Figure 2b has been removed with the same low-cut filter as in Figure 1. In this instance the cable jerk, linear noise has increased and is propagating from both the head and tail of the cable. This increase in noise was caused by limitations of the towing equipment for this particular trial. The limited lead-ins and ropes to the

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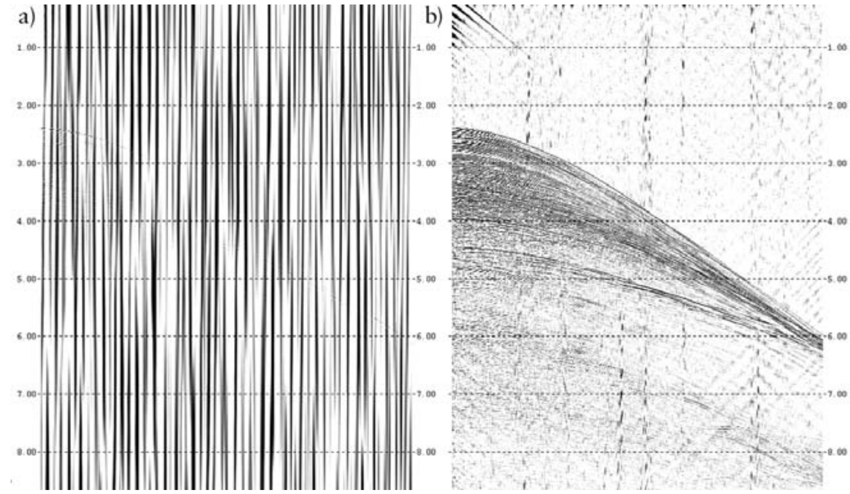

Figure 1 *Shot record recorded with an ION gel-filled DigiStreamer at 8 m depth – a) raw data dominated by ultra-low frequency cable noise and b) after applying a 2 Hz low cut filter. On the filtered data, note the linear cable jerk from the head of the cable, the bursts of swell noise, and the background 'random' noise.*

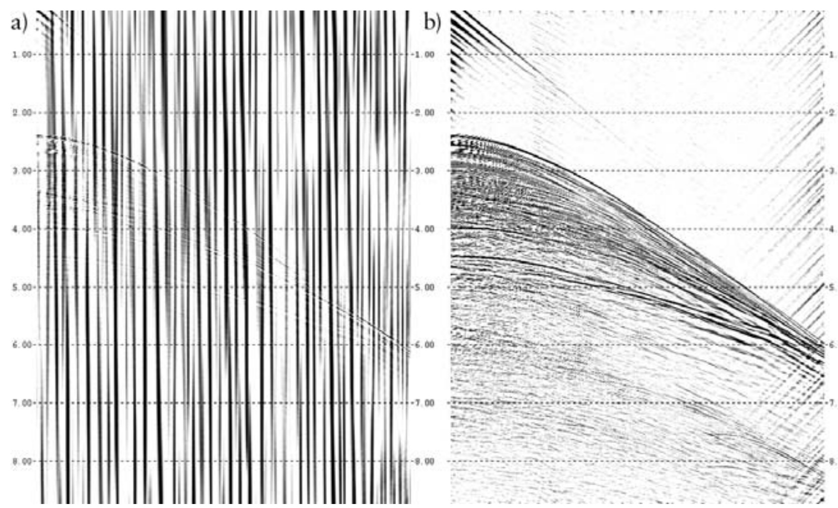

Figure 2 *Shot record recorded with the same cable and source array but with a cable depth of 32 m a) raw and b) after applying a 2 Hz low cut filter. On the raw data, note the increased amount of signal visible through the noise. On the filtered data, note the stronger cable jerk noise from head and tail of the cable but also the absence of swell noise and apparently a reduced background 'random' noise floor. The increased cable jerk noise is caused by limitations on the towing equipment used in this particular experiment.*

tail buoy meant that, for example, the tail buoy was biting into the waves and jerking the cable more than at 8 m tow depth. On the other hand, there is no apparent swell noise and the background noise also appears to have been substantially reduced. Moreover, the raw data in Figure 2a exhibits more signal appearing through the sub-2Hz noise than that in Figure 1a; it seems that the total signal to noise has been improved by simply towing at 32 m instead of 8 m.

Signal strength and ghost notches

The data in Figures 1 and 2 are from an experiment where a 2D line was recorded three times with identical recording equipment and source array but with a streamer depth of 8 m on the first pass, 16 m on the second pass, and 32 m on the third pass. No attempt was made to tow deeper than 32 m in order to avoid any possibility of either reduced hydrophone sensitivity or triggering the streamer recovery devices. The 16 m pass was shot in the reverse direction in order to avoid time circling back to the start of the line. Figure 3 shows a shot at the same location from each of the three passes – note the difference in signal in the 16 m shot: although the shot point is the same, the vessel is sailing in the opposite direction. Since it is normal practice to attenuate swell noise as well as the other types of noise described above, these techniques have been applied in order to optimise the S/N on the three shot records shown.

It is well understood that both source and receiver ghosts affect the signal strength of seismic data and that this effect is frequency dependent. At some frequencies, the ghost reflections cause constructive interference that reinforces the signal while at others they cause destructive interference that reduces the signal strength. This results in 'notches' in the amplitude spectrum of the recorded signal. If the ghost reflections have equal strength to the upcoming primaries, the destructive interference will completely cancel the signal at the notch frequencies whilst doubling it at intermediate frequencies. However, if the sea surface is not a perfect mirror, the ghost strength is less than that of the upcoming primary and both constructive and destructive interference are reduced in magnitude.

Figure 4 shows amplitude spectra estimated within each of the boxes marked on Figure 3. For each shot record we have an estimate of the amplitude spectra for both the signal below the water bottom reflector and the residual noise above that event. It is immediately apparent that except at very low frequencies, the signal and noise have good separation.

The 16 m signal spectrum shows a broad, receiver ghost notch centred on 45 Hz. Although it is approximately 20 dB down from the peak signal strength, it is still well above the noise floor. The ghost spectrum does provide some boost to the amplitude of the 16 m cable over the 8 m at low frequencies but there is little to separate them at higher frequencies.

The 32 m signal spectrum provides a boost of signal strength at low frequencies as expected – it is over 12 dB higher at 5 Hz – and the constructive interference also provides a similar gain at around 84 Hz. Also as expected, the 32 m signal spectrum exhibits notches at approximately 24 Hz, 48 Hz and 72 Hz but surprisingly they are not very deep – only approximately 12 dB down. The 92 Hz receiver notch is further weakened by the roll off of the 6 m source ghost. This result suggests the down-going ghosts are weaker than the upcoming primaries. When recording this data, the sea state was reported as 1 m to 2 m. The interaction between seismic waves and a 'rough' sea surface is likely to be complex and will at least depend on the spatial wavelength of the sea surface waves relative to seismic wavelengths. Nevertheless, it is reasonable to expect the sea surface reflection coefficient to be less than -1 unless we record in a flat calm.

The combined source and receiver signature can be modelled with varying ghost strengths to estimate what sea surface reflection coefficient is needed for the ghost notches to be 12 dB down. Figure 5 shows the result of modelling the signature of the airgun array used in this trial with a 32 m cable for a sea surface reflection coefficient of -0.85. The receiver ghost notches are approximately 12 dB down.

When the cable is at 32m, the vertical receiver ghost arrives approximately 40 ms after the upcoming primary and is therefore well separated in time from the primary and from the source ghost of the primary. Therefore, on a near offset

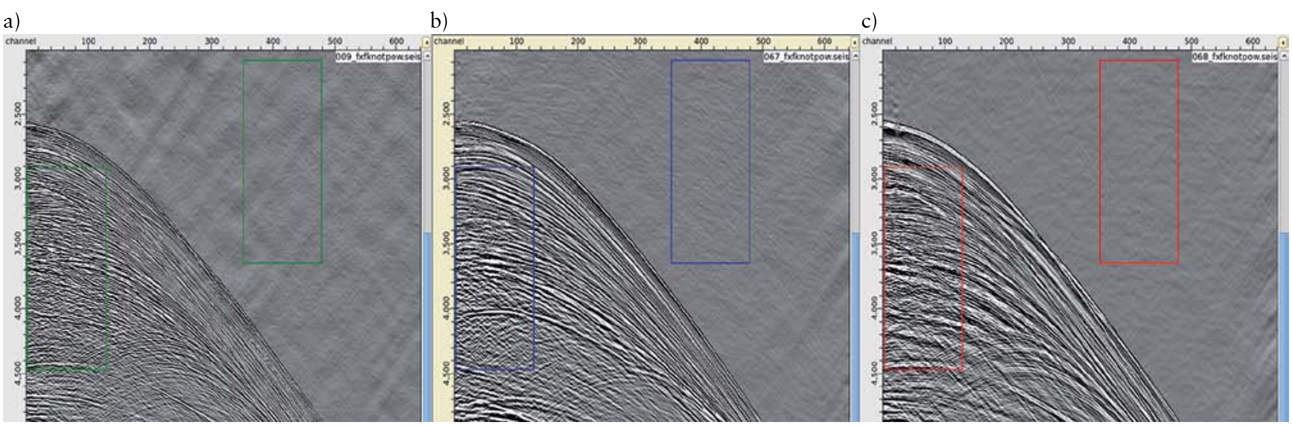

Figure 3 *Shot records recorded at the same shot point on three separate passes of the boat a) recorded at 8 m, b) recorded at 16 m, and c) recorded at 32 m. For all three shots, the only change in recording parameters is the cable depth but for the 16 m pass, the line was shot in the reverse direction so the data shown in b) differs from a) and c). Standard noise suppression techniques such as swell noise attenuation and linear noise filtering have been applied to optimize the S/N of each dataset. The boxes indicate the design windows used to estimate the signal and noise spectra shown in Figure 4.*

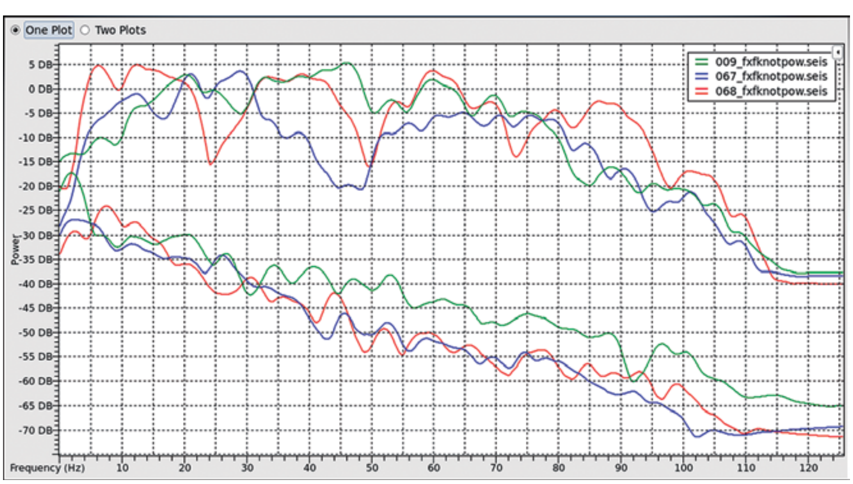

Figure 4 *Signal and noise amplitude spectra for each of the shot records in Figure 3. The signal is above the noise except at very low frequencies. The 32 m signal shows a 12 dB uplift over the 8 m signal at 5 Hz and at 90 Hz while the 32 m receiver ghost notches at 24 Hz, 48 Hz, and 72 Hz are approximately 12 dB down from the peak. The 96 Hz receiver ghost notch is further weakened by the edge of the 6 m source ghost notch at 120 Hz.*

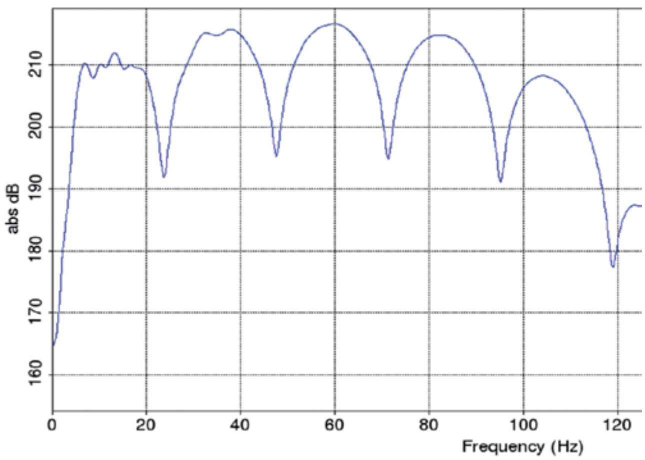

***Figure 5** Modelled signature with a sea surface reflection coefficient of -0.85 and a cable depth of 32 m. The receiver ghost notches are 12 dB down from the peak amplitude.*

seismic trace from the 32 m data, it is possible to measure the peak amplitude of the water bottom reflection and immediately beneath it measure the peak amplitude of the source ghost. It is then possible to also measure the peak amplitude of the receiver ghost and even the receiver ghost of the source ghost. If the sea surface reflection coefficient is constant, both the source and receiver ghost should have the same amplitude and the 'coefficient' of the ghost of the ghost should equal the square of the individual ghost coefficients. In practice, the source ghost occurs once per shot but the receiver ghost varies over time down the trace and from trace to trace as the sea surface waves move past the cable. Nevertheless, estimating the sea surface reflection coefficient in this way and averaging over a number of traces provides an estimated reflection coefficient of -0.87 +/-0.07 and the ghost of the ghost has an estimated coefficient of -0.71 +/- 0.13. These measurements are thus consistent with the modelled spectrum in Figure 5 and the observed signal spectra in Figure 4.

An alternative way of examining the signal to noise of the data recorded in the ghost notches is to apply band pass filters. Figure 6 shows the results of a very tight, 2-4 Hz band pass filter applied to both the 8 m and 32 m shot records shown in Figures 1 and 2 after noise suppression. Although there is inevitably some leakage from the edge of this pass band, the same filter has been applied to both datasets. It is apparent that the 32 m data contains much higher signal levels.

Figure 7 shows the 32 m data filtered to pass only the energy in each of the receiver ghost notches. The 96 Hz result has been enlarged to allow clearer visual display of the signal. Each of the results shows clear signal and although again there will be some leakage from the edges of the filters, it is noticeable that there is no sign of a background noise floor – for example, the filter edge effects are visible above the water bottom reflection but the background noise is not. Moreover, it is clear that the signal in the frequency bands is propagating into the earth well below the sea floor.

Conclusions and discussion

The results of this field trial have shown that the recording equipment provides a lower limit to the usable seismic bandwidth and that this lower limit is currently around 2 Hz. Furthermore, the signal to noise ratio close to this lower limit can be significantly boosted solely by recording with a flat, deep cable. At higher frequencies, modern recording equipment is very quiet and at the same time, towing the cable deep, lowers the noise floor associated with near sea surface effects. As expected theoretically, a deep cable leads to a weakening of the signal strength in the receiver ghost notches but in a fairly typical sea state of approximately 1 m, the sea surface reflection coefficient is sufficiently reduced that the ghost notches are not prohibitively deep. As a result, it is possible to record broadband seismic data with a flat, deep, hydrophone only cable – provided the sea is not completely flat and calm. This raises the possibility that we should revise our recording specifications to include monitoring the depth of ghost notches and to avoid recording when they become too deep, i.e., when the sea is calm.

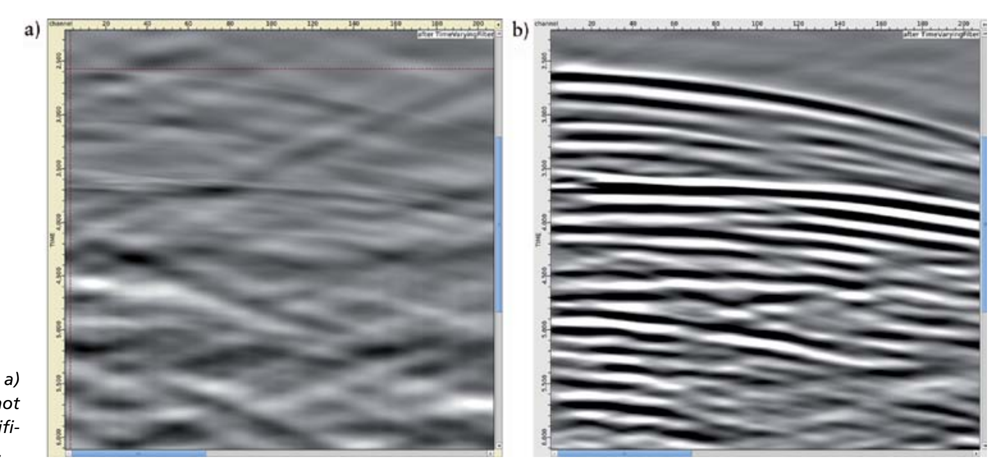

***Figure 6** 2–4Hz bandpass filter of a) 8 m shot record and b) 32 m shot record. The 32 m record has significantly stronger low frequency signal.*

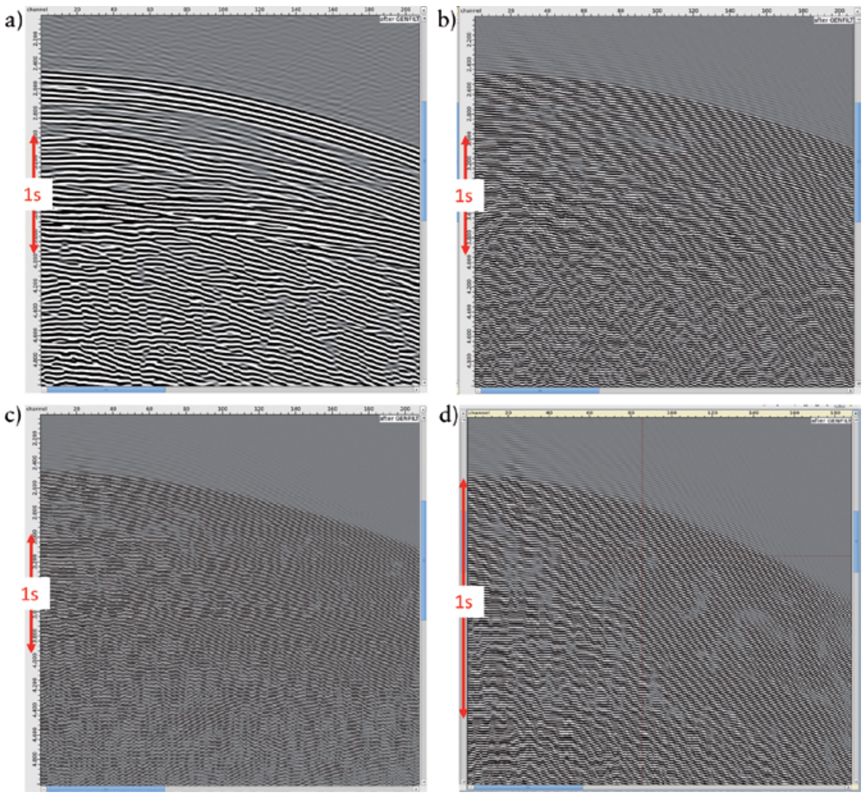

Figure 7 *Bandpass filtered results from the 32 m shot record passing a tight frequency notch around a) 24 Hz, b) 48 Hz, c) 72 Hz, and d) 96 Hz. These frequencies are centred on the ghost frequency notches where the signal strength is weakened but good S/N is observed well below the seabed in all the results. The 96 Hz result has been 'zoomed' to allow visual inspection of the high frequency signal content; its signal strength is weakened by the broad 6 m source ghost notch at approximately 125–130Hz.*

Conventional industry wisdom would have expected the ghost notches to be deeper and to therefore have an unusable signal to noise; an extension to the low frequency bandwidth would have been achieved but only at the expense of limiting the higher frequencies. In this trial, the low frequency bandwidth was extended but the higher frequency limit was maintained or even increased by the constructive interference at around 85-90 Hz. Moreover, the use of a flat cable means AVO can be interpreted in a conventional manner.

An obvious question is 'why has this not been noticed before'? A probable answer is that as seismic recording equipment has become quieter over the last 25 years or so, observations made with older equipment have not been re-tested and have become assumptions rather than observations. For example, attempts at using a slant cable to increase bandwidth in the 1980s foundered on the earth absorbing higher frequencies and the recording equipment applying 8 Hz low cut filters to remove energy such as bulge waves in fluid streamers.

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