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Broadband Data from Flat Streamers: Considerations for Acquisition and Processing

Phil Fontana
Polarcus
Dubai
phil.fontana@polarcus.com

Edward Hager
Polarcus
Singapore
ed.hager@polarcus.com

SUMMARY

Broadband acquisition aims to improve the bandwidth of seismic data, which in practice means extending the low-frequency end of the spectrum without limiting the high-frequencies beyond the natural earth response (Q-factor). These "unconventional" techniques focus on the receiver-side ghost, and commonly used are co-located velocity and pressure sensors and dual-depth hydrophone or variable depth hydrophones, which either capture phase or timing differences respectively of the receiver ghost. All these methods rely on processing to achieve the final receiver side de-ghosted data as the "dumb sum" of the measurements will lead to poor results, or post-stack broadband data in the case of slant streamer.

With sufficient signal-to-noise in the data it is possible to de-ghost the receivers towed at a moderate single depth by tuning the acquisition design, with consideration of the source *emission* response in combination with the streamer *reception* response.

A test line was acquired that shows the equivalency of slant streamer and flat depth streamers in terms of post-stack amplitude spectra, showing that the acquisition design and pre-stack deghosting processing methodology is effective in providing broadband data.

Key words: broadband, de-ghost, slant

INTRODUCTION

There is currently a large degree of attention in the marine seismic industry focused on the acquisition and processing of "broadband" towed streamer data. The term "broadband" has been adopted to refer to the ability of extending the frequency band of recorded marine streamer seismic data by attenuating, or completely removing, the effects of source and receiver ghosts.

Several techniques have been implemented by various seismic contractors that leverage some aspect of the seismic acquisition configuration to allow attenuation of the source and receiver ghosts. These techniques rely on either varying the arrival times of ghost pulses relative to their primaries by varying the tow depth of components in the source and receiver systems, or by leveraging phase differences between primary and ghosts acquired by co-located sets of pressure and motion sensors. One aspect of relying on these "unconventional" acquisition techniques is that the source and receiver ghosts have to be addressed separately. In other words, the source has to be de-ghosted using techniques that are independent of those used to de-ghost the received signals. In all cases involving "special" acquisition techniques, a considerable processing effort is required to produce a final de-ghosted dataset. This processing can involve a variety of techniques including synthesising the low-frequency velocity measurements, alignment of over-under streamers and estimations of the ghost filter. If the raw measurements are summed using a "dumb" approach (amplitude domain) the results are usually poor, and in the case of slant streamer only provides a post-stack broadband dataset.

However, recently, there have been a number of processing techniques introduced that claim to be able to de-ghost data acquired with "conventional" hydrophone only streamers towed at a single depth. The basic premise of these techniques relies on there being sufficient signal-to-noise at the frequencies attenuated by the ghost responses to allow specially designed de-ghosting operators to correct both the amplitude and phase of the received signals for the effects of both the source and receiver ghost responses.

The parameters for declaring the success of these de-ghosting processes are the resulting "compaction" of the seismic wavelets in the imaged sections, before and after amplitude spectra showing recovery of low frequencies, filling in of ghost frequency notches, and extension of the high frequency content of the processed signals to the extent allowed by the earth's attenuation characteristics. Additionally, in several instances, test data have been acquired through well locations and subsequent inversions of the broadband processed data are shown to tie very accurately to the acoustic impedances logged in the wells.

The experience gained through these broadband projects have led to the formulation of several propositions on how to optimize the signal-to-noise in the flat streamer data in order to take full advantage of available de-ghosting processing techniques. Amongst these propositions are proposals concerning optimum tow depth for sources and streamers and whether or not it is advantageous to attempt to de-ghost the source during acquisition.

SOURCE AND STREAMER DEPTH CONSIDERATIONS

As one of the major objectives of broadband acquisition and processing is to enhance the low frequency content of the recorded seismic data, it should be a primary objective in acquisition to ensure that the lowest frequencies possible are generated by the air gun source array.

The lowest frequencies in the source output spectrum are derived from the residual bubble pulses in the time domain pressure signature. The longest bubble periods produce the lowest frequencies.

The expression for computing the bubble period for an air gun is:

$$\mathbf{T_b = cp_w^{1/2} * (P^{1/3}\, V^{1/3} / P_s^{5/6})}$$

Where **c** is a constant, $\mathbf{p_w}$ is sea-water density, **P** is the air gun firing pressure, **V** is the air gun volume, and $\mathbf{P_s}$ is the hydrostatic pressure at the depth of the air gun. Notice that the bubble period is almost inversely proportional to the depth of the air gun. This means that longer bubble periods are generated at shallower tow depths. In other words, shallower air guns produce more low frequency energy than deeper air guns.

An example of this relationship is displayed in Figure 1

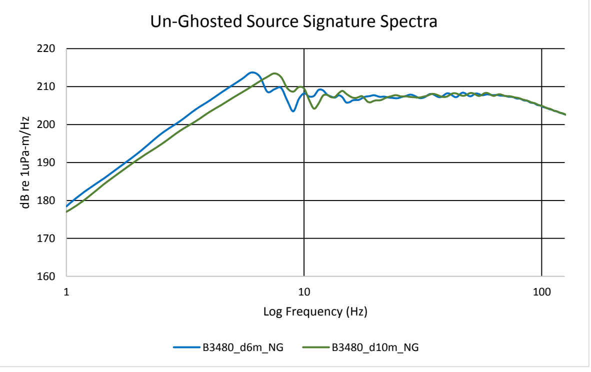

Figure 1. Un-ghosted spectra from air gun arrays at 6m (blue) and 10m (green) depths

As can be clearly observed, there is significantly more low frequency energy potential in the array towed at 6m compared to 10m.

Also note, these spectra are un-ghosted and represent the inherent low frequencies generated from the source. In the real world, the far-field source signature contains the effects of the source ghost which acts to attenuate these low frequencies. However, the ghost effect does not move the position of the low frequency spectral peak, only its amplitude. If it is accepted that the current de-ghosting processing techniques can effectively mitigate the source ghost then there is the potential to fully recover the inherent low frequencies generated by the air gun array. As there are more potential low frequencies with shallow source tow depths, we propose that source tow depths for broadband processing should be in the range between 5m and 8m, there is no compelling reason to tow the air guns deeper.

This leads to a discussion about the efficacy of attempting to de-ghost the source as part of the acquisition effort. These techniques usually feature 3 sub-arrays with 2 shallow and one deep towed, in a "V" formation. By design then the source ghost will be only partially attenuated due to the asymmetry, with spectra showing reduced mid and high frequencies; and in addition the signature varies more with the emission angle than an equivalent single depth source. However the low-frequency response is improved over using all 3 sub-arrays at the shallow depth.

As mentioned above, broadband techniques that rely heavily on de-ghosting the receivers through "non-conventional" acquisition techniques have to look to separate techniques to deal with the source ghost. However, if the plan is to employ a de-ghosting processing scheme on "conventional" streamer data then there are advantages to allowing the source ghost to develop.

The de-ghosting processing routines we are familiar with rely on there being adequate signal-to-noise at the ghost notch frequencies to allow the generation of stable and effective de-ghosting operators. Figure 2 shows an example of measured signal and noise spectra for two different receiver depths and demonstrates that this condition can be met with modern low noise and wide dynamic range hydrophone-only streamer technology.

A proposition for optimizing the signal-to-noise at the receiver ghost notch frequencies is to tow the streamers at a multiple of the source depth. The reasoning is that at ½ the source ghost notch frequency the primary and ghost signals are coherent. Typically, this can add about 6 dB to the source output at those specific frequencies.

By towing a streamer at twice the source depth we essentially use the positive effect of the source ghost to compensate for the negative effect of the receiver ghost. This is demonstrated in Figure 3 which shows an overlay of the ghost response for a 12m receiver depth on top of the ghosted spectrum from an air gun array towed at 6m. In this example the peak of the ghosted source spectrum coincides with the notch from a 12m deep receiver thus optimizing the potential signal-to-noise at that notch frequency.

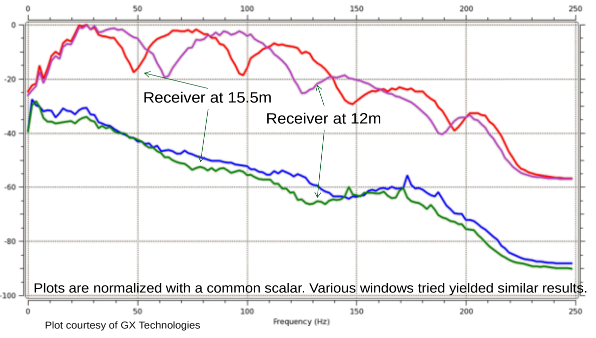

Figure 2. Signal and noise spectra from two towed streamer depths

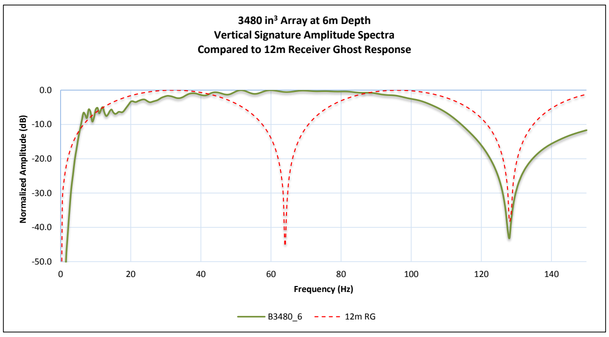

Figure 3. Spectrum from 6m deep air gun array and the ghost response from a 12m deep receiver

There may be a concern that the second ghost notch from a streamer at twice the source depth will reinforce the primary source notch thus greatly reducing the signal-to-noise at the first source ghost notch frequency and thus inhibiting a de-ghosting processing routine from filling that notch. However, that argument assumes normal incidence propagation on both the source and receiver side, that is, it should be remembered that the formula for the ghost notch frequency ($\mathbf{F_{notch}}$) includes a cosine term:

$$\mathbf{F_{notch}} = \text{water velocity} / 2 * \text{Depth} * \cos(\Theta)$$

Where **Depth** is either the source or receiver depth, and **Θ** can be either the emission or incidence angle of the raypath.

Figure 4 shows spectra for an air gun array at 6m depth for 0, 10, 20, 30, and 40 degree emission angles from the vertical. In this display, the source ghost notch frequency moves out to higher values as the incident angle moves away from the vertical. This phenomena is inherent in the geometry of shallow reflection data, where the emission angle of the source output has an effect and where there actually may be some received frequencies near the high frequency source notches. Therefore, in the shallow data there can be source notch diversity due to the range of source emission angles. Deeper data generally does not return frequencies as high as the source notch, so notch re-enforcement shouldn't be an issue. So, it seems that in any gather domain that incorporates a range of offsets there will be little effect from potential source and receiver notch reinforcement if the receivers are at depth multiples of the source.

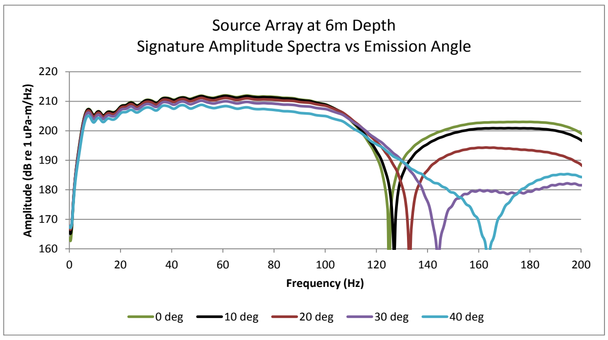

Figure 4. Air gun array amplitude spectra as a function of source emission angle

If this is indeed the case then the uplift of leveraging the positive aspects of the source ghost at the mid-band receiver notch frequencies for broadband processing should outweigh any downside concern about coincident source and receiver notches at the higher frequency source notch frequencies.

FIELD TRIALS

A test line was shot with different broadband tow geometries to test the differences in the resultant data. The vessel configuration was 6 streamers of 8100 m length with 648 channels:

Streamer-1:	Slanted from 8 m to 30 m at 8 km
Streamer-2:	Flat at 24 m
Streamer-3:	Flat at 12 m (only 636 channels recorded)
Streamer-4:	Flat at 6 m (only 636 channels recorded)
Streamer-5:	Flat at 18 m
Streamer-6:	Slanted from 8 m to 30 m at 6 km and then back to 8 m.

Streamer 2 and 3 were towed under/over as were streamers 4 and 5.

Data as processed via a standard processing flow with the addition of DownUnder GeoSolutions' DUG Broad™ prior to 2D Kirchhoff PSTM. DUG Broad™ uses receiver depth, source depth, obliquity (incidence angle), sea-state (reflection coefficient) and SNR estimate to generate de-ghosted broadband data.
Figures 5 and 6 show summary amplitude spectra of the results before and after both source and receiver side deghosting. We can see that the shallow 6m tow (purple) has relatively poor low frequency content but with the best highs, conversely the 24m deep-tow (red) has the best low-frequency response but not that much different for the mid and high frequencies. The flat tow depths in between these extremes and the slant configurations are similar in their response.
This shows that with high SNR data from modern solid streamers it is possible to achieve broadband data from flat streamers. The advantages of this data is that there is greater pre-stack consistency for processes such as SRME (in some formulations) and deterministic seabed demultiple; AVO analysis with a consistent low-frequency content across the offset range. Also there are the operational considerations where the entire streamer is deep and therefore less prone to weather effects; the ability to acquire the data in shallower water than slant; and the streamer is safely within its operating depth range.

CONCLUSIONS

In the last few years there have been several processing techniques developed for producing broadband data from conventional single depth hydrophone-only streamer surveys. These techniques rely on there being sufficient signal-to-noise at ghost notch frequencies to allow for the derivation and application of stable and effective de-ghosting operators.

Based upon some simple fundamentals of air gun physics and source and receiver side ghosting, we are proposing guidelines concerning source and streamer depth relationships to optimize the signal-to-noise at ghost notch frequencies to take full advantage of the new processing techniques.

These guidelines have been tested in the field and empirical results show that the results are comparable between slant and flat streamer validating the design and processing methods.

ACKNOWLEDGMENTS

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We also acknowledge Ophir Energy, Apache, and Polarcus Muli-Client for permission to show data examples

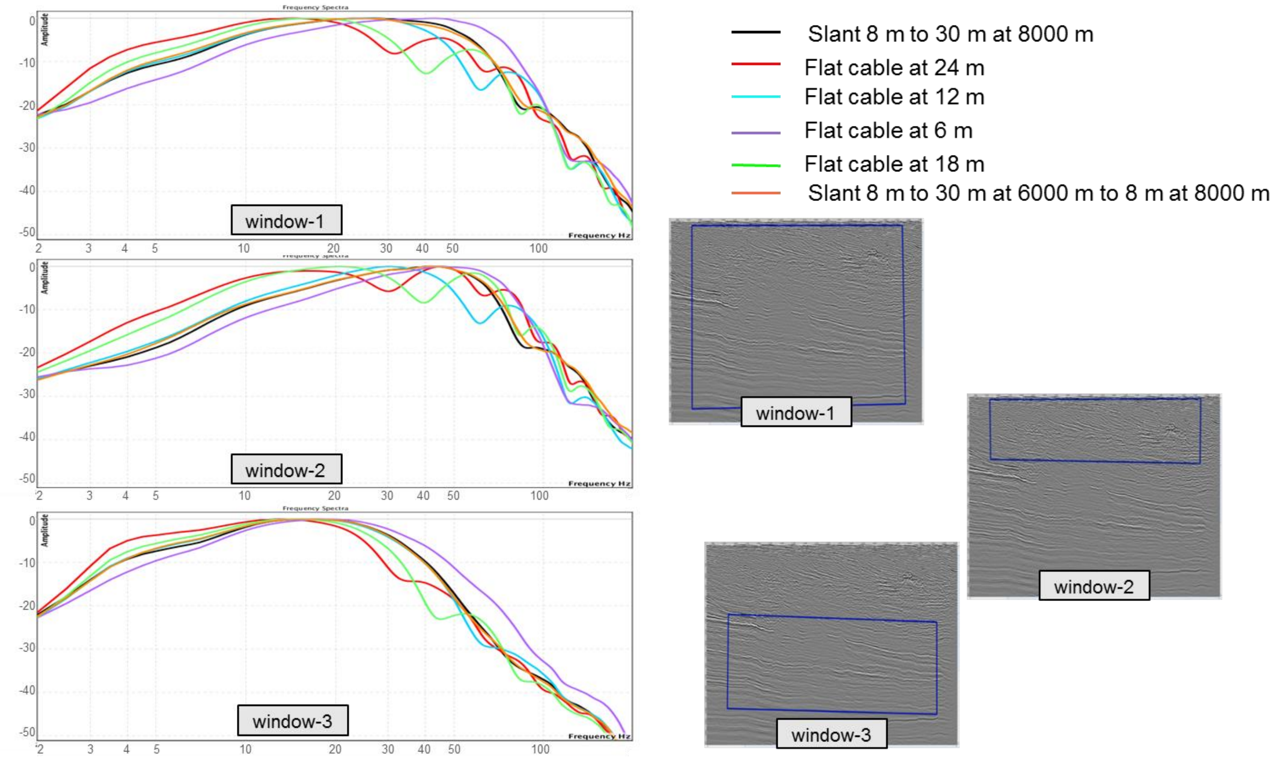

Figure 5. Amplitude spectra without broadband processing (Log frequency scale)

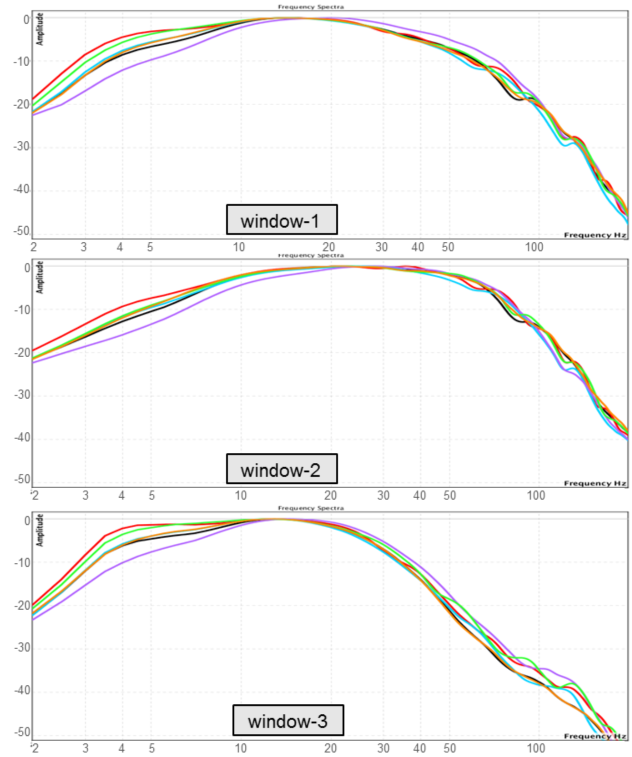

Figure 6. Amplitude spectra with pre-stack broadband processing using DUG broad. Comparing the spectra with Figure 5 we can see that the variability due to the towing depths has been greatly reduced with the application of pre-stack deghosting