Acquisition of marine point receiver seismic data with a towed streamer.

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Summary

A new concept for the acquisition of point receiver towed streamer data is introduced. Recording of point receiver data, rather than the analogue outputs of hardwired arrays, enables both dynamic group forming and enhanced attenuation of noise. Dynamic group forming allows better signal preservation and enhanced frequency recovery, particularly at far offsets. Data adaptive noise attenuation methods allows improved attenuation of the low frequency noise induced by water flow around the streamer, enabling the enhancement of the low frequency signal-to-noise ratio through avoidance of low cut filters. Point receiver marine seismic data will improve the dynamic range of the seismic signal and enhance the viability of time-lapse monitoring of reservoirs with towed streamer data.

Introduction

The current method of acquiring towed streamer marine seismic data involves the deployment of 2D arrays of hydrophones, which are distributed along the length of each streamer. The individual outputs of each hydrophone within an array are hardwired together to give an analogue array response. The analogue array response is then digitised and transmitted along the streamer to the recording instrument on the vessel. The individual hydrophones forming the 2D arrays are often distributed with non-equidistant spacing, and these analogue arrays may overlap with one another to enhance their frequency-independent, wavenumber filter response. The 2D arrays are designed to provide spatial anti-alias filtering of the seismic data and attenuate both in-line, water-borne noise and water cross-flow induced noise. The 2D hydrophone array forms an analogue wavenumber filter that is frequency invariant. Figure 1 (top) provides a schematic illustration of hard-wired, group-formed data recording.

A novel towed streamer seismic data acquisition system utilising point receiver recording has been developed. The system exploits recent advances in both electronics and data communication networks to allow the recording of more than 4,000 individual hydrophones on each of up to 20 streamers; giving a total of up to 80,000 channels. The system incorporates sophisticated signal processing software for real-time digital group forming of the point receiver data. The signal processing software allows for the correction of perturbations in the seismic data and completes real-time, intelligent, dynamic group forming, which incorporates high-fidelity, data-adaptive noise attenuation. Figure 1 (bottom) describes the system for recording point receiver marine seismic data.

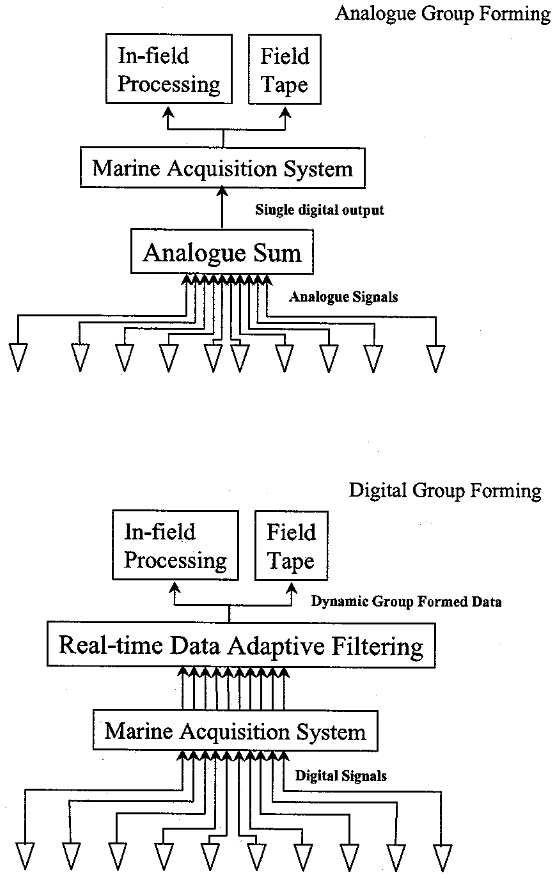

Figure 1. A comparison of the systems used to acquire conventional hard-wired, group formed data (top) and point receiver digital data with real-time, data adaptive noise attenuation.

Signal and Noise

One of the key sources of marine seismic data quality degradation is the reliance on hardwired group forming in conventional systems. Newman and Mahoney (1973) described how the performance of hardwired analogue arrays would be compromised by errors in the positioning and sensitivity of the individual sensor elements. Ongkiehong and Huizer (1987) showed that uncorrected perturbations at the individual sensors would introduce pseudo-random 'noise-beneath-the-signal' into the seismic data upon array forming. The noise-beneath-the-signal often defines the random noise level measured in seismic data and limits the effective dynamic range of the seismic signal.

Figure 2 (top) shows a synthetic marine seismogram after group forming of individual sensor elements that had a typical 10% sensitivity standard deviation. The FK spectrum shows defocusing of the seismic energy as it is smeared across all wavenumbers. The pseudo-random noise that is the smeared signal often defines the noise floor, limiting the dynamic range of our desired seismic signal.

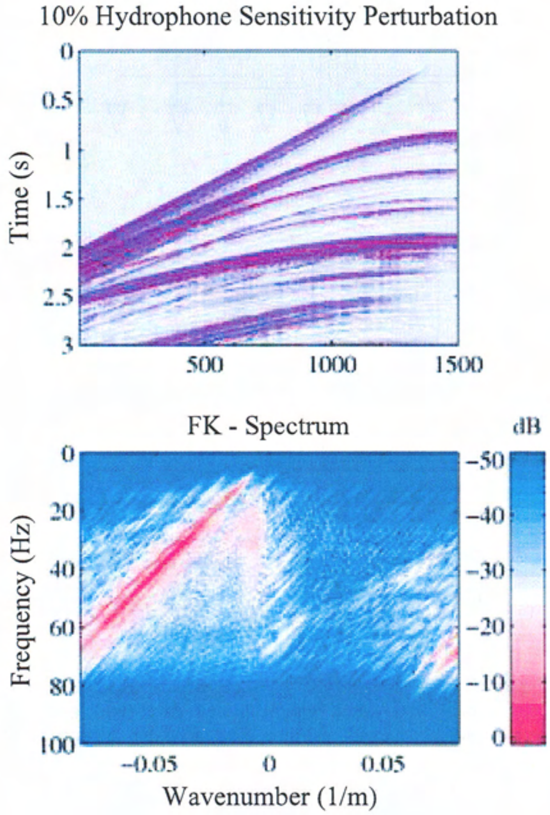

Figure 2. Synthetic marine seismic record (top), which was group formed from hydrophone elements having a 10% standard deviation in sensitivity. The FK spectrum of the seismogram (bottom) shows the smearing of signal across all wavenumbers, generating pseudo-random noise behind the signal.

Another undesirable property of hardwired analogue arrays is the attenuation of the desired signal because of non-vertical incidence at the streamer. Figure 3 shows the wavenumber response of a typical marine hardwired array. The signal pass region lies between $0m^{-1}$ and $0.07m^{-1}$ wavenumbers, with the noise attenuation region for wavenumbers greater than $0.07m^{-1}$. The gain of the filter in the signal pass region is only equal to 1 for the $0m^{-1}$ wavenumber, which corresponds to vertical incidence at the array. The gain of the wavenumber filter drops off with increasing wavenumber, which means that the higher frequencies of signals arriving at the receiver array will be attenuated by hardwired array forming.

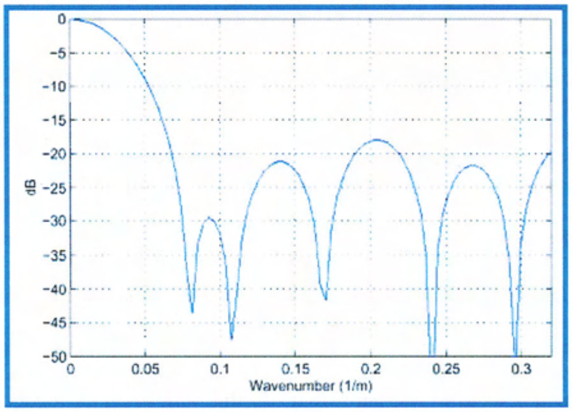

Figure 3. Typical wavenumber response of a hardwired marine receiver array.

Deviation from vertical incidence at the receiver array becomes more pronounced as the distance from the source to the receiver array increases. Non-vertical incidence also dominates the recording of diffractions, and reflections from complex sub-surface structures. The frequency independent nature of hardwired analogue arrays attenuates the higher frequencies from events arriving at the receiver array at non-vertical angles of incidence.

The length of the receiver array is a key parameter determining the amount of high frequency signal attenuation suffered by events that arrive at the streamer at non-vertical angles of incidence. Figure 4 shows the impact of array length on the pre-stack signal bandwidth of a typical target reflector from a depth of 3km recorded at an offset of 2,000m from the seismic source. An 80Hz signal is attenuated by about 6dB by a 12m linear array. A 60Hz signal suffers 3dB attenuation. 6m linear arrays attenuate 80Hz signal by only about 1dB.

Hardwired arrays, therefore, compromise the bandwidth and vertical resolution of complex and dipping structures during imaging. Hardwired arrays also impose an offset-dependent high-cut filter on pre-stack data, compromising the inversion of amplitude versus offset (AVO) responses.

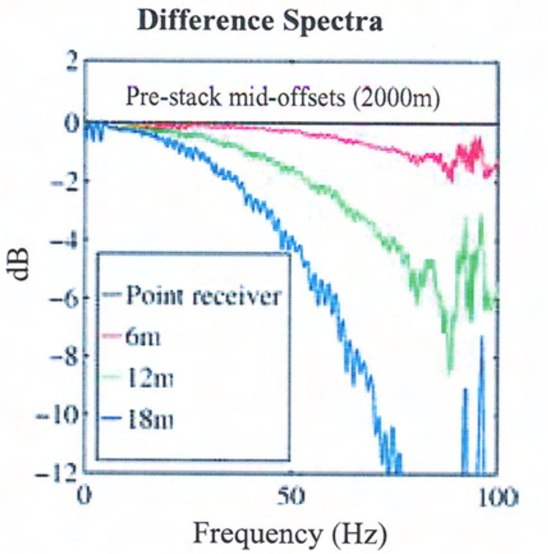

Figure 4. The impact of receiver array length on the attenuation of high frequency signal for a typical target reflector recorded at an offset of 2000m from the seismic source.

Point receiver recording leaves all frequencies intact, irrespective of the seismic event's angle of incidence at the receiver array.

The principal noise source affecting marine towed streamer data is induced by flow of water across the streamer. Vertical cross-flow can be induced by wave action and is often termed swell noise. Horizontal cross-flow is induced by local sea water currents and as the vessel turns during line changes. All sources of cross-flow generate vibrations that propagate down the seismic streamer in a number of characteristic modes, amplitudes, apparent velocities and frequencies, which are partly determined by the construction of the seismic streamer and how the hydrophones are de-coupled from the various streamer vibrations.

Figure 5 Shows a typical towed streamer shot record recorded with 6.25m hardwired receiver arrays. The shot record is contaminated with bursts of swell noise induced by the sea-state, which propagate down the streamer at an apparent velocity of $30ms^{-1}$. The apparent velocity of the swell noise is dependent in part on the relative velocity of the vessel and the shallow sea currents. Cross-flow induced noise is always 2D in nature as it propagates down the length of the streamer.

One of the key requirements of noise attenuation filtering is prior adequate sampling of both the noise modes and the desired signal. The swell noise waveforms in figure 5 are clearly aliased, even at 6.25m receiver array sampling. The 6.25m hardwired group has not been particularly effective in attenuating swell noise in this example. Resorting to longer array lengths would attenuate a little more swell noise, but would also degrade the quality and bandwidth of the signal as discussed earlier, through the introduction of more noise-behind-the-signal and attenuation of high frequencies. Swell noise contamination can be reduced in the field by towing the streamers deeper in the water and applying a higher frequency, low cut filter. The higher frequency, low cut filter obviously removes important low frequency signal. Towing the streamer at deeper water depths lowers the frequency of the receiver ghost notch, attenuating important high frequency signal, while enhancing the amplitude of low frequency signal – using a range of different water depths in the same 3D survey leads to inconsistency in signal bandwidth, compromising the final 3D images and interpretations.

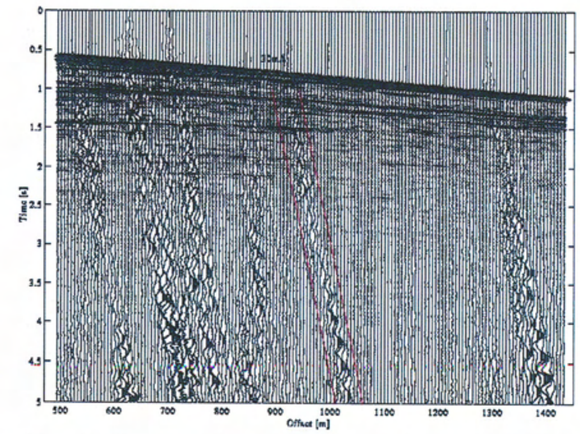

Figure 5. Shows a typical towed streamer shot record recorded with 6.25m hardwired receiver arrays. The shot record is contaminated with bursts of swell noise induced by the sea-state, which propagate down the streamer at an apparent velocity of $30ms^{-1}$.

Any residual swell noise left after data recording can only be attenuated further using techniques reserved for random noise suppression, because the swell noise has not been recorded with sufficient spatial fidelity to enable the application of filtering techniques that exploit spatio-temporal coherency. Random, or incoherent noise suppression techniques, such as stack, band-pass filters, random noise suppression using FX deconvolution or muting of swell noise contaminated traces followed by interpolation, all have a significant detrimental effect on signal bandwidth and fidelity.

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Too much contamination of the seismic shot records by cross-flow induced noise leads to the temporary abandonment of data acquisition until data quality improves, increasing the cost of marine seismic surveying to both client and service provider, and delaying the delivery of the final processed data volume for interpretation.

Point Receiver Concept

Sampling and the use of anti-alias filtering are standard techniques in time domain digital recording. In contrast to temporal sampling, however, the initial sampling interval in space along a marine seismic streamer is limited by cost considerations and operational efficiency. These criteria have always influenced and limited the design of analogue hydrophone arrays in marine seismic streamers.

Point receiver recording allows the extension of basic sampling rules to the spatial domain. Pre-processing of point receiver data facilitates the computation of group formed data, which is essentially free of aliased noise. The spatial separation of point receivers distributed along the seismic streamer must be chosen to facilitate the attenuation of noise.

Once the signal and noise wavefields are sampled by the point receivers, residual sensor calibration corrections are applied to the data before transmission to the marine acquisition system on the vessel to enhance signal fidelity. The calibration corrected point receiver data are then filtered using real-time, powerful, data-adaptive beamformers to attenuate both cross-flow induced noise and other vibration noise that may be introduced by the vessel's towing configuration. The data-adaptive beamformer is designed to protect the desired seismic signal for all of the frequencies and wavenumbers corresponding to the complete range of dips that could be expected at the seismic streamer (Özbek 1998 and 2000). The noise attenuation afforded by the data-adaptive beamformer is applied over only that spatial and temporal aperture where the noise is stationary and can be attenuated. The data-adaptive beamformer and its signal protection component can be designed to cope with other contingencies, such as loss of a point receiver within the streamer, without significantly affecting signal fidelity.

Marine point receiver recording in a towed streamer will lead to a revolutionary improvement in the quality and flexibility of seismic data. A number of benefits will be afforded by point receiver recording:

- Full signal bandwidth protection, irrespective of offset or angle of incidence at the streamer. Improving the resolution of structural images and the inversion of AVO anomalies.
- Offset- and/or time-dependent dynamic group forming to improve the efficiency of sub-surface image determination.
- Improved survey turn around time through attenuation of swell- and weather-related noise while maintaining high signal fidelity.
- Retention of low frequency signal through the use of data-adaptive beamforming instead of low cut filtering, improving the accuracy of acoustic impedance inversion and matching of seismic data to well logs.
- Time-lapse ready towed streamer seismic data. High fidelity data delivered after data-adaptive beamforming and point receiver calibration will extend the dynamic range of the seismic signal and enable the monitoring of weaker time-lapse responses than can be detected though the use of systems employing hardwired group forming.
- Improvement of signal bandwidth at both low and high frequencies during marginal weather through data-adaptive noise attenuation.
- Acquisition of seismic data during line change through the attenuation of cross-flow induced noise.
- Acquisition of genuine 3D towed streamer data using novel pseudo-random acquisition geometries, enabled through the attenuation of cross-flow induced noise.

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Acknowledgments

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