The recent demand for high-resolution broadband seismic data has created a growth in so-called broadband solutions. However, there has been no definition of what actually qualifies as “broadband”. This means that a variety of different techniques ranging from full equipment, acquisition and processing solutions to simple data whitening in processing have been bracketed together as “broadband”. We describe a truly broadband, integrated solution, involving equipment, acquisition and processing which enables the effects of both the source and receiver ghosts to be removed to deliver ghost-free data with the broadest bandwidth (in excess of six octaves) and the best signal-to-noise ratio at low frequencies, down to 2.5Hz.

ATTENUATION OF THE RECIPIER GHOST

In conventional acquisition the bandwidth is limited by the source and receiver ghost notches in the amplitude spectrum, caused by interference between the upgoing and downgoing waves, at frequencies which depend on the source and streamer depths and emergent angles. In this solution, the receiver ghost is tackled by using a variable-depth solid streamer, towed in a proprietary curved configuration, to create ghost notch diversity. This is exploited by advanced deghosting algorithms to produce high-resolution data with bandwidth from about 2.5Hz to the source ghost notch.

A toolbox of different deghosting algorithms, including fully 3D solutions, has been developed for performing Ghost Wavefield Elimination (GWE) that is applied to the data either pre-imaging (Wang 2012, Poole 2013, Wang 2018) or post-imaging using the joint-decon solution (Soubaras 2010). This will help towards creating an ideal broadband wavelet — i.e. one with a sharp central peak and minimal sidelobes.

Exceptional low frequencies are recorded using a deep-towed hydrophone; this solution capitalize on the exceptional low-noise characteristics of truly-solid foam-filled streamers (Dowle 2006), which can be towed deeper than some other streamers, to acquire high-quality signal down to 2.5Hz. Towing at an average depth of 40m provides an 11dB increase in response at 5Hz over towing at 10m, due to the shape of the zero-Hz ghost notch (see figure 1). This increase is in addition to the improvement in signal-to-noise ratio achieved by towing at depth and avoiding the sea-state noise, and the fact that solid streamers are proven to be 10-15dB quieter than gel streamers below 10Hz in vibration tank tests.

ATTENUATION OF THE SOURCE GHOST

To attenuate the source ghost notch, a similar ghost diversity technique is employed. A synchronized multi-level source is used to defocus the source ghost and generate wavefronts with reduced, unfocused notches in the amplitude spectrum, enabling source designature for the full bandwidth (Siliqi 2013). The combination of variable-depth receivers and synchronized multi-level sources delivers truly broadband data, limited only by the acquisition sample interval. The different source depths are synchronized so that the deeper array fires at the exact delay of the travel time between the two levels, so the down-going wavefields are synchronized and produce a focussed primary reflection, while their respective ghosts (upgoing wavefields) are unsynchronized and produce unfocussed ghost reflections (see figure 2). The optimum depths for the airguns are achieved when the notch caused by one gun level corresponds to the maximum energy of the other. Figure 3 shows the spectral output of a source array with airguns deployed at 6m and 9m depths with a 2ms time delay between them. The ghost notch of a one-layer source array (6m) is filled and the extra low frequencies generated by 9m airguns are visible.

A synchronized multi-level source is a compact solution for acquiring broadband data with variable depth steamers. It can be deployed in the flip-flop mode necessary for 3D broadband surveys and has all the benefits of a standard marine source in terms of robustness, directivity and repeatability. In order to maintain the same directivity created by conventional source arrays, a 3D spatial distribution...
of airguns across the layer-depths is used and the resulting directivity pattern remains at the same quality range as that for a conventional source, even for frequencies corresponding to the one-layer source notch (see figure 4).

The multi-level source allows defocusing of the ghosts, but does not entirely eliminate them. Nevertheless, the absence of deep notches in the spectra allows perfect designature of the seismic across the full bandwidth. While the accuracy of pressure field modelling is sufficient for source array design it is not precise enough for building source designature operators. These can be more accurately designed using recorded near-field hydrophone measurements (Ziolkowski 1982, Poole 2013). This direct measurement approach delivers a more accurate estimation of the bubble effect and low frequencies in general, which are fundamental for broadband acquisition. Figure 5 illustrates the effect of accurate designature on the residual bubble, which generally causes low-frequency artefacts. The technique allows an accurate designature process through the entire bandwidth which encompasses residual deghosting, de-bubbling and zero-phasing in the same step. Several acquisitions worldwide (including North West Australia) have demonstrated the benefits of this technique in delivering ghost-free images with a full bandwidth from 2.5Hz up to 200Hz, see figure 6.

Improved imaging at depth and facies variation identification are provided by the lower frequencies whilst the high frequencies clarify the interpretation of thin beds, stratigraphic traps and lateral resolution of channels. For the deeper parts of the section, the highest frequencies will vanish due to the anelastic attenuation of the earth and will not contribute to the image, but the lack of a source ghost still increases clarity as shown in figure 7. The full bandwidth present in the shallow section enables precise imaging for shallow-hazard mapping and accurate velocity picking.

**BENEFITS OF TRULY BROADBAND DATA FOR EXPLORATION**

As broadband data provide both low and high frequencies, it is ideal for exploration as potential targets at all scales can be identified.
levels can be imaged. Truly broadband wavelets are characterized by a sharp central peak and minimal side lobes. The individual peaks or troughs of these seismic wavelets correspond to true stratigraphic horizons, and therefore enable more accurate seismic interpretation, providing clear distinction between stratigraphic packages and high resolution of fine details without the tuning interference experienced with conventional band-limited seismic data. The low frequencies give an envelope to the seismic signal that shapes the larger-scale impedance variations, or in geological terms the major lithology variations. This increases confidence in correlating seismic interpretation across faults and other major structural features, see figure III.

Three octaves of signal are generally considered necessary for adequate seismic resolution; therefore, in order to achieve sufficient bandwidth in areas where high frequencies are limited, e.g. below salt or basalt where frequencies above 20Hz tend not to penetrate, it is necessary to extend the low frequencies. Lower frequencies are affected less by attenuation and are affected less by attenuation and low frequencies. Lower frequencies penetrate, it is necessary to extend the frequencies above 20Hz tend not to achieve sufficient bandwidth in seismic resolution; therefore, in order to consider necessary for adequate low-frequency bandwidth. The lack of low frequencies in conventional seismic data means that a low-frequency model must be included in the inversion process in order to recover absolute impedance values. Usually, the low-frequency information is obtained from MMD-derived seismic velocities, which provide frequencies up to about 4Hz, and by interpolating low-passed filtered-impedance logs between well locations, using interpreted horizons as a guide, for the 4-10Hz frequencies. If the wells are sparse and the geology complex, the low-frequency model derived from the wells may be inaccurate and tend to yield results that are biased towards the initial model.

The ultra-low frequencies provided by variable-depth streamer broadband data fill in the frequency gap, enabling inversion to be performed using only the seismic velocities without the need for a log-derived low-frequency model, to yield accurate impedance and Vp/Vs estimates, even where there is little or no available well data (figure 10). In the 3D example from North West Australia shown in figure 11, the inversion was performed using the same 0-5Hz initial model derived from seismic velocities (Michel 2012). The broadband inversion delivered improved inversion results and well-ties, with a better delineation of the thickness of the gas-bearing zone to reduce uncertainty in lithology prediction. In areas all over the world, from offshore Brazil (Kneller 2013) to the North Sea (Heikell 2013) and Australia, the extended bandwidth has provided significantly improved and more geologically realistic inversion results, with greater dynamic range and more reliable lithology estimates.

Ultra-low frequencies also provide discrimination of different sedimentary facies. Figure 12 shows an example of 3D frequency decomposition and colour blend from a broadband multi-client dataset in Angola Block 22, where a turbidite channel complex with various phases of sediment fill, meander growth and incisions can be identified clearly. Without the ultra-low frequencies this picture would be incomplete as the red channel would not fill in the frequency gap, enabling inversion to be performed using only the seismic velocities without the need for a log-derived low-frequency model.
not be visible. This kind of information is key to tracking reservoir sands around potential traps.

BROADBAND SEISMIC THROUGHOUT THE E&P CYCLE
Broadband seismic is increasingly proving its value at all stages of the exploration and production cycle. Sharp wavelets without sidelobes enable accurate interpretation and easier identification of stratigraphic packages to reduce exploration risk. Ultra-low frequencies deliver more detailed facies discrimination, more quantitative seismic inversion results and therefore more reliable lithology predictions away from existing wells. This leads to more accurate reservoir models and better development plans. Once production is underway the benefits of broadband for 3D surveys are extended into 4D monitoring to provide better dynamic reservoir models to maximise hydrocarbon recovery.

Over the last three years variable-depth streamer acquisition has established a strong position in the marine broadband market with over 40,000 km of 2D and 200,000 km² of 3D, wide- and full-azimuth data including 25,000 km² of BroadSource data. With the commercialization of the multi-level broadband source extending the frequency range to the recording interval Nyquist, it continues to set the benchmark in terms of bandwidth, with the optimum signal-to-noise ratio at low frequencies, thanks to the uniquely deep tow, delivering over six octaves of data. This frequency range of physically recorded signal cannot even be approached by solutions which do not record the full bandwidth but rely on processing to extend the frequency range.

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