BRINGING BROADBAND TO THE SUBSEA

SIMON BALDOCK AND NICK MYZIUK, TGS, USA, HASSAN MASOOMZADEH, ANTHONY HARDWICK, TOM TRAVIS, AND NICK WOODBURN, TGS, UK, EXAMINE A NEW PROCESS DESIGNED TO DELIVER BROADBAND DATA FROM CONVENTIONAL STREAMER SEISMIC.

Seismic data acquired with an airgun source and recorded on pressure sensors has been the standard for offshore oil and gas exploration for many years. One problem with this type of data is that, for various reasons, its useable bandwidth is limited to approximately 70 Hz (bandwidth is defined as the difference between the upper and lower frequencies in a continuous set of frequencies). There are many reasons why it is desirable to utilise data with an increased bandwidth (e.g. upward of 150 Hz) for E&P purposes. Such 'broadband' seismic data has many advantages over conventional marine streamer data. However, numerous obstacles must be overcome before broadband data can be utilised for E&P objectives. In this article, the principal mechanisms for the limitation of bandwidth in marine seismic data are reviewed, before moving on to look at the ways in which the industry has responded to the challenge of providing broadband data. Finally, the article will focus on a process that delivers broadband data from conventional streamer seismic.

The convolutional model of the Earth

Seismic acquisition and processing are often described by means of the convolutional model: $g(t) = w(t) * r(t)$.

Here, the recorded data, $g(t)$, is thought of as the result of the convolution of a source wavelet, $w(t)$, with the Earth's reflectivity series, $r(t)$. The goal of seismic data processing is to recover the reflectivity series from the recorded data. The ideal source wavelet has the maximum amount of energy concentrated into the shortest possible time. This kind of pulse will be broadband – rich in both low and high frequencies. The low frequencies help to reduce the 'sidelobes' of the wavelet, while the high and low frequencies together create a wavelet that is short in duration. Such a source wavelet will allow the top and base of reflecting packages to be identified with the highest resolution. Unfortunately, a number of processes operate to reduce the bandwidth of the source wavelet. These include near surface effects (such as sea state) and acquisition artifacts such as the source 'bubble' effect. There are also processes, such as spherical spreading, that operate on the source pulse as it travels through the Earth. However, two factors serve to significantly reduce the bandwidth of the source wavelet. The first is the interference between the source pulse and reflections from the water surface ('ghosts') and the second is the fact that the earth acts as a filter, which attenuates high frequencies in the source wavefield as it travels through the Earth.

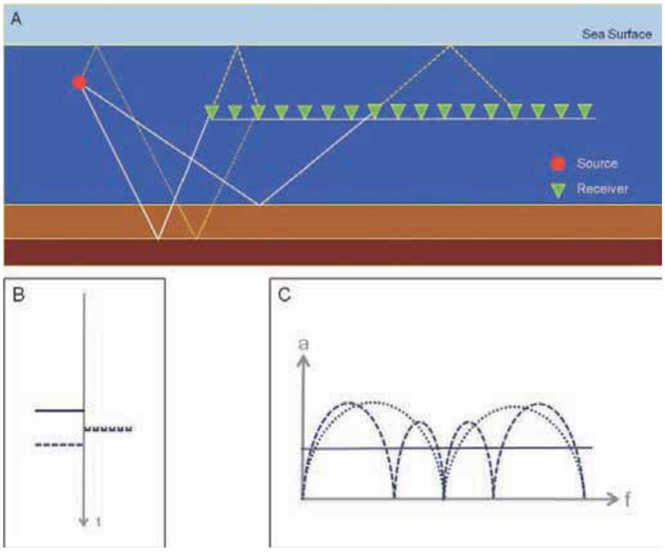

Figure 1. *A) diagram illustrating the angle dependency of source and receiver ghosts. The solid white lines illustrate travel paths without receiver ghosts; the dotted yellow line indicates the travel path of the source ghost and the dashed yellow lines the receiver ghost. B) & C) Time and frequency domain of source and receiver ghosts. Solid line, no ghosts; dotted line, source ghost, dashed line source and receiver ghosts.*

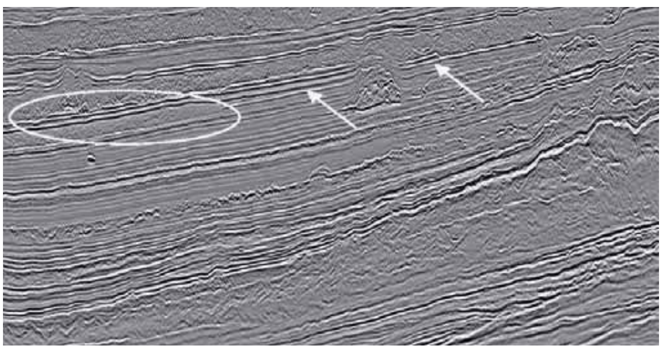

Figure 2. *Kirchhoff pre-stack time migration of data before Clari-Fi.*

Figure 3. *Kirchhoff pre-stack time migration of data after Clari-Fi.*

The ghost effect

The air-water interface acts like an acoustic mirror with a reflection coefficient of -1. When the marine source fires, some energy travels upwards toward the surface. This energy will be almost perfectly reflected at the sea surface where it will undergo a polarity reversal. The result is that when the source pulse is emitted a 'ghost' wavefield (time delayed and polarity-reversed) is created alongside it. In the case of vertical (1D) travel paths, the energy from these two wavefields will sum destructively (sum to zero) at harmonics of the frequency $f = V_w/2_z$ where V_w is the water velocity and z is the source depth. Furthermore, there will be maximum constructive summation at harmonics of the frequency $f = V_w/4z$. This process of constructive and destructive summation creates notches and peaks in the amplitude spectra of the seismic data. For non-vertical travel paths, the delay between the original and ghost wavefields is angle-dependent, causing the frequencies at which destructive or constructive summation occurs to change with the take off angle of energy from the source.

A ghost effect also occurs on the receiver side. When the upgoing wavefield containing the original source wavefield and its ghost arrives at the receivers, it continues to travel upward before being reflected at the sea surface where it undergoes a polarity reversal. The reflected downgoing wavefield, delayed by its additional journey to the sea surface, is simultaneously recorded by the receivers with the upgoing wavefield. The summation of these two wavefields (the upgoing and the downgoing) creates a second set of notches in the amplitude spectrum of the data, boosting some frequencies and reducing others. Like the source ghost, the receiver ghost is angle-dependent. In this case, the delay between upgoing and downgoing wavefields is a function of the emergence angle of the upgoing wavefield. The ghost effect for sources and receivers is illustrated in Figure 1.

The result of all these interactions is to lengthen the source pulse, causing a loss of resolution at reflecting interfaces. In addition, the loss of low frequencies due to the combined effects of the source and receiver ghosts creates a problem for the imaging of deep reflectors, such as subsalt and sub-basalt structures, as well as being problematic for processes such as pre-stack inversion, where low frequencies are critical to achieving a stable inversion result.

A number of solutions to the problem of the ghost effect have been proposed, which can be conveniently (though not precisely) divided into acquisition solutions and processing solutions. Acquisition solutions typically exploit one or more features of the acquisition process. For example, by recording both the pressure and velocity components of the wavefield it is possible to combine them in such a way as to eliminate the receiver ghost. By recording with receivers placed at different depths, it is again possible to combine the separate recordings so as to suppress the receiver ghost. The same technique may be applied to sources located at different depths allowing the source ghost to be removed. By combining processes it is possible to suppress both the source and receiver ghost.

Processing solutions usually treat the ghost effect as an inverse problem that can be solved by computing an inverse operator to remove (deconvolve) the ghosts from the data. If the deconvolution is performed pre-migration, then it is necessary to take into account the 3D nature of the ghost wavefields. If a 1D operator is used then the process should be applied to zero-offset migrated sections or stacks.

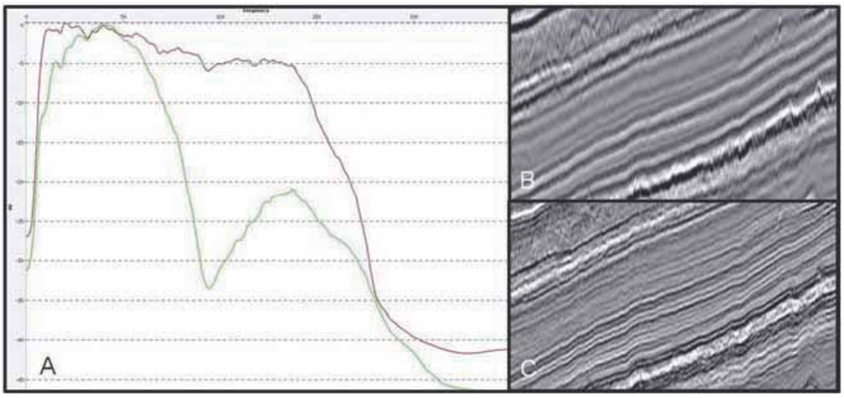

Figure 4. *Results of applying Clari-Fi to a 2D line from West Africa. A) Amplitude spectra shown before Clari-Fi (green) and after (brown). B) Zoom of the PSTM data shown in Figure 2 (before Clari-Fi). C) Zoom of the PSTM data shown in Figure 3 (after Clari-Fi) the increase in resolution can be clearly seen.*

Attenuation

As energy travels through the Earth, it is diminished through a set of processes that may be collected together under the heading of attenuation. Attenuation is measured by the geophysical parameter Q, also known as the quality factor. For processing purposes, Q is normally given as an effective parameter that incorporates two different attenuation effects: intrinsic attenuation and extrinsic attenuation.

$Q_{eff} = Q_{int} + Q_{ext}$.

In intrinsic attenuation, also referred to as absorption, the seismic wavefield loses energy in the form of heat as it travels through the Earth. The degree of absorption is a property of the material through which the energy is travelling. Absorption is frequency dependent, with higher frequencies being more attenuated than low frequencies. For deeper targets, this will lengthen the wavelet still further, causing loss of resolution as well as amplitude. The frequency-dependent nature of the energy loss also causes a distortion in phase. Extrinsic attenuation includes a number of factors such as mode conversion and scattering, which also contribute to energy loss. Since far offsets travel longer in the Earth than near offsets, attenuation is offset dependent; because it is determined largely by lithology it will vary spatially.

As the degree of attenuation depends on the travel path the optimum place for the Q correction to be applied is during pre-stack time or pre-stack depth migration. In these cases it is necessary to derive a spatially varying Q model as well as a velocity model. An alternative approach is to apply pre-stack correction using a single effective Q value to correct for phase and amplitude and then apply a post-migration residual correction.

A new process

The Clari-Fi process developed by TGS is a broadband solution that corrects for both the ghost effect and attenuation. It consists of two main steps. In the first, the effects of the source and receiver ghosts are suppressed, while in the second, effective attenuation is compensated for by means of a phase and amplitude Q correction. In the example shown here, a deterministic deconvolution is used to address the ghost effect (Figures 2 - 4). As has been shown, the ghost effect is not a 1D problem. To address this, a multi-dimensional deconvolution is applied in the tau-p domain. In this domain each p-trace represents a common emergence angle, making it the preferred domain for de-ghosting. Once the ghost effect has been solved and in order to achieve broadband data in the shallow and deep parts of the section, compensation for attenuation must be applied. A single-value Q correction, applied either before or after migration represents a reasonable balance between the recovery of high frequencies and the minimisation of noise. An important aspect of the process is careful denoising of the data. Any process that seeks to broaden the spectrum must take care to broaden the signal spectrum and not the noise. In order to maximise the whitening of the signal spectrum, a multi-dimensional noise attenuation approach is used. Throughout the processing, noise is removed by means of targeted noise attenuation in the domain most appropriate for that step; typically the shot, receiver, CMP and offset domains are used.

By means of a systematic approach that deals first with the ghost effect and then with attenuation, this system represents a robust methodology for achieving broadband data that is applicable to any conventional horizontal streamer data set. Furthermore, since it is a prestack process, CMP gathers are automatically created as part of the process.

Figures 2 and 3 show the results of performing the new process on 2D data from offshore West Africa. A Kirchhoff pre-stack time migration (PSTM) stack after preliminary denoise is shown in Figure 2. The PSTM after Clari-Fi is shown in Figure 3. The increased resolution can be clearly seen in several places (highlighted by white arrows). In addition, the increase in low frequency has helped to reduce the 'sidelobes' of events so that top and base of geological packages can be more clearly identified; these are identified with white circles. Figure 4A shows amplitude spectra before and after the new process was used, where the removal of the source and receiver notches at low and high frequencies is clearly evident. Figure 4C shows a zoom of Figure 3 showing the resulting increased bandwidth.

Summary

Broadband data represent a step-change in marine seismic data acquisition and processing. Structures that were hitherto too small to be resolved by conventional data can now be identified and mapped in detail. By dealing with the ghost effect and the results of effective Q, the Clari-Fi technique provides a way to recover a broadband signal in both the shallow and deep sections. OT