Interferometric imaging of ocean bottom noise

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Summary

A study is presented which describes the origin of very low frequency noise observed in ocean bottom recordings.
A strong correlation between the noise amplitude and the observed surface sea state is observed. Surface swell generates pressure waves which propagate downwards to the sea floor. At the sea floor interface secondary, predominantly shear, Scholte waves emanate as trapped wave guides.
Interferometric imaging of this low frequency wave guided energy can yield transmission characteristics of the near surface. From this, inferences can be made as to shear velocity, mud thickness and sensor coupling quality.
A prerequisite for this technique is a multi-directional particle sensor which is able to record undistorted temporal frequencies to below 0.1Hz.

Introduction

During the Fall of 2005, Exxon-Mobil together with RXT and GX Technology conducted a series of seismic source tests in the Gulf of Mexico with the primary goal of boosting the returned low frequency reflectors. The recording device was an Input-Output VectorSeis Ocean OBC system which utilizes a pressure detector and three fully digital accelerometers which measure vertical, horizontal radial and horizontal transverse particle motion. These detectors have completely flat amplitude & phase responses (Ridyard, Behn and Rouquette, 2004). When combined with an "open" low end instrument filter, the total system is capable of recording undistorted frequencies to almost DC i.e. 0Hz.
Three individual 240 channel cables were laid end-on to create an effective 18km cable. Water depth varied from 30 to 50m over the 18km length. Sensor groups were spaced 25m apart and listening times were 18secs per record.
Early observations, made on the returned seismic records, were the high levels of low frequency background noise. Under normal recording circumstances instrument responses or low-cut filters would have attenuated this noise.
Throughout the experiment, which lasted twelve days, a considerable number of "noise only" records were made, including some continuous listening periods of several hours. These records were analyzed and form the basis of this presentation.

Noise recordings

Figures 1A, 1B and 1C are examples of noise records as observed on the pressure, vertical and radial horizontal sensors. The horizontal axis is 6km and the vertical 18secs. All displays are true relative amplitude. Figures 2A and 2B are FK transform plots of the pressure and vertical component, respectively.
The pressure component is dominated by very low frequency, low velocity (10m/sec) noise whose peak frequency is about 0.15Hz.
Both vertical and horizontal sensors are dominated with semi-coherent noise in the 0.3-2.0Hz range with velocities of 100-300m/sec. The amplitude of the vertical component is about twice that of the horizontal.

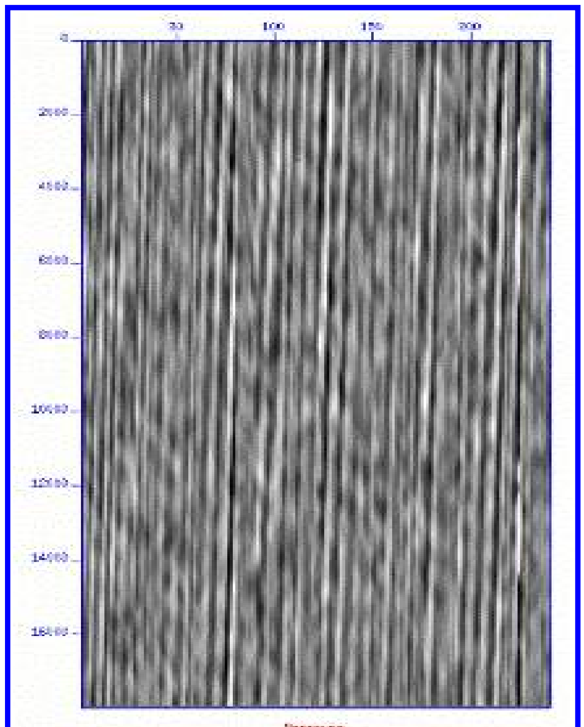

Fig 1A Typical Noise record: Pressure phone

Sea state & recorded noise levels

The origin of the very low frequency (0.15Hz) noise observed on the hydrophone has been well documented in

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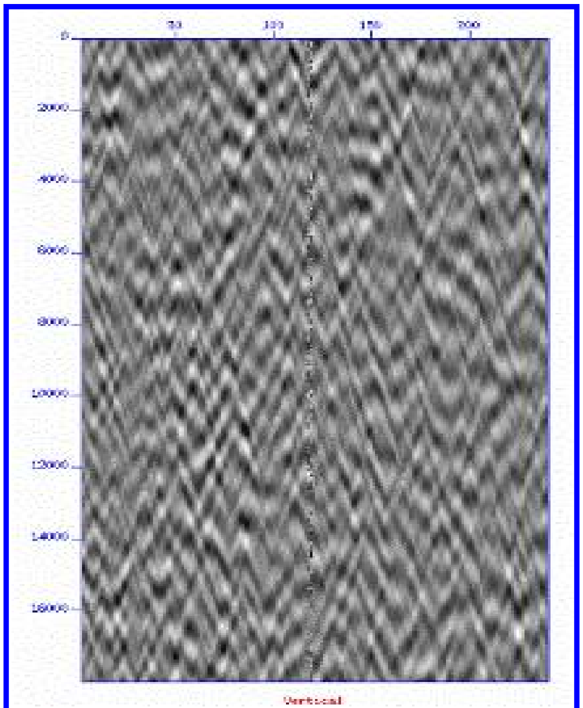

Fig. 1B Typical noise record: Vertical accelerometer

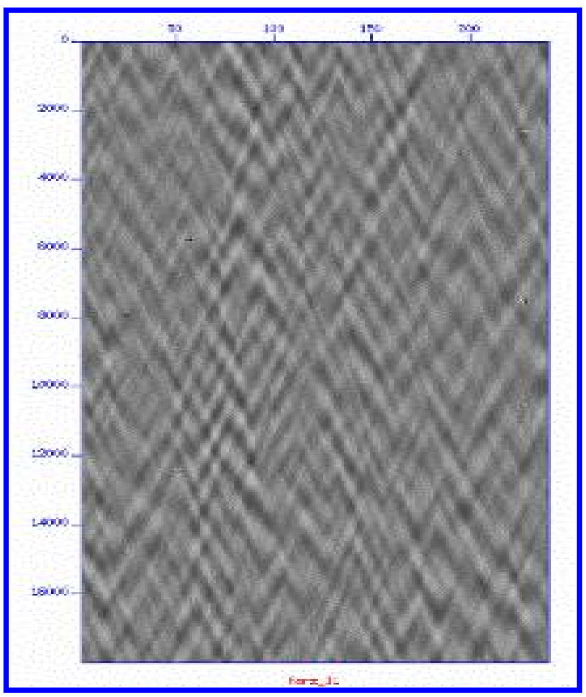

Fig. 1C Typical noise record: Radial horizontal accelerometer

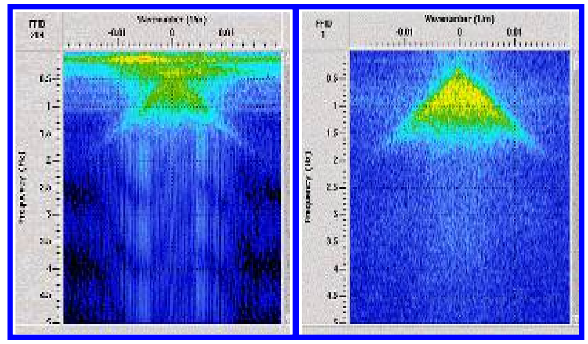

Fig 2A Pressure (FK) ***Fig 2B Vertical (FK)***

the world of Oceanography (Crawford, Webb and Hildebrand 1993). Weather and gravity at the sea surface result in swells. These swells propagate slowly along the sea surface (an apparent velocity of 10m/sec on our data). The different water height results in pressure changes detected only on the hydrophones. The amplitude of this noise was measured periodically over twelve days. At the same time, the "sea state" as observed on the sea surface was recorded. As expected, there was a strong correlation.

The particle motion sensors do not display any swell induced pressure noise but are instead dominated by a higher frequency noise of approximately 0.3-2.0Hz.

At first it was speculated that the noise was a strum like noise propagating up and down the cable. However, this was later ruled out after a clear continuity of the coherent noise trains was observed between physically unconnected cables. This suggested that this noise may be propagating in the upper layer of the sea floor.

Interestingly, the noise on these sensors also showed a strong amplitude correlation with sea state. This suggested that this noise may still be somehow related to surface swells.

During normal marine seismic exploration activity airgun sources generate acoustic pressure energy in the water layer. When the source is close to the sea floor (30m or less), as is often case in ocean bottom acquisition, the pressure wave can excite the mud layer to form a secondary wave-guided and trapped Scholte wave (also referred to as "Stonley" or "Interface" waves). Scholte waves appear on the seismic records as coherent, often dispersive, low frequency, low velocity events with similar visible characteristics to ground roll on land seismic records. They require that the shear velocity of the mud be less than the pressure wave velocity in the overlying water column.

Although the frequencies are lower, the linear events observed on our accelerometer noise data appear to have similar velocities to the Scholte waves observed on the seismic data recorded at the same location. Could the noise

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observed on the accelerometers be Scholte waves causally related to surface swells?

Several studies in the field of Oceanography confirm that this is indeed a common and widespread phenomenon.
The sea surface swells additionally generate acoustic pressure waves which propagate downwards towards the sea floor. On interaction with sea floor, minor perturbations scatter the pressure waves in the form of Scholte waves. Moreover, it is very efficiently generated (Tuthill & Lewis 1981, Schreiner & Dorman 1990).
During field tests over sediment and basalt sea floors Lewis and Dorman (1998) also confirmed the presence of secondary Scholte waves. They observed that the wave primarily affected only the particle sensors and not the pressure sensor.
They also suggest that minor irregularities on the sea floor interface are the catalysts which give rise to the secondary Scholte waves. These could be reefs, any solid objects, animals or even the seismic sensor itself.

Interferometric imaging

The overwhelming evidence suggests that the noise on the particle motion sensors are indeed secondary Scholte waves propagating in the near surface mud layer.
Interferometric imaging of the noise records was then tested to confirm this hypothesis. If any energy was being transmitted in the mud layer, it should, given enough statistics, be detected with this method.

Clearbout (1968) demonstrated that for the 1D case a reflection response can be synthesized from the auto-correlation of the transmission response. The implication of this was that any natural source in the subsurface could generate the transmission.
Later, Rickett and Claerbout (1999) conjectured that cross-correlating noise traces recorded at two locations on the surface would produce a wavefield that would be recorded at one of the locations if there was a source at the other.
The term Interferometric imaging was given by Schuster (2001) and was simply stated as "any algorithm which inverted cross-correlated data".
Most of the documented passive seismic studies have relied on random micro-seismic and earthquake activity as the source. Several studies have proposed drilling noise as the source. In our case, the source is the secondary sea floor noise.
For our experiment, approximately 400 consecutive noise records made over a total time period of 4 hours were used. Each record consisted of 720 channels (3x240 channels from 3 independent cables). For each channel, the records were concatenated into a super record of several hours duration. Each trace in the super record was then cross-correlated with every other trace in super record generating N^2 data records.

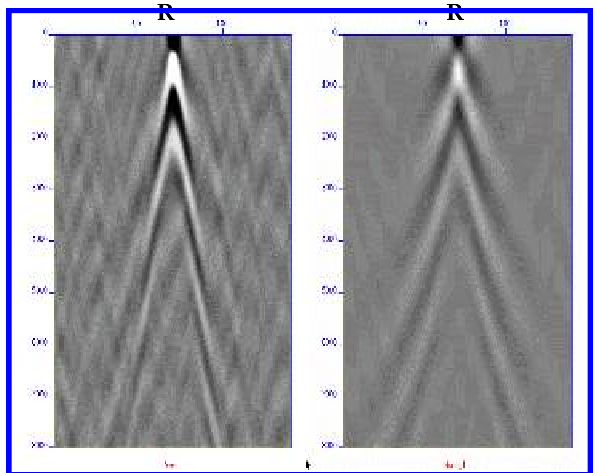

Fig. 3A Vertical *Fig. 3B Radial Horizontal*

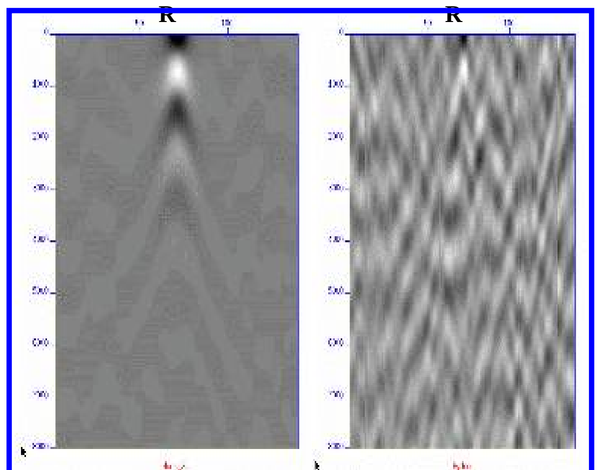

Fig. 3C Transverse Horizontal *Fig. 3D Pressure*

Figures 3A-D show the results of the interferometric imaging for the 4 components at a single receiver location (R). These displays are analogous to a common receiver gather with the receiver at location R and sources at all other locations.

Clearly, coherent energy is being transmitted between the receivers. Observations made on interferometric images are as follows:-
• The vertical particle motion has the strongest events, followed by the radial horizontal.
• Velocities of the first arrival ranged from about 100m/sec at nearest offsets increasing to over 300m/sec at distances of 2-3km.

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• A 90 degree phase shift was observed between vertical and radial horizontal (suggesting retrograde elliptical motion).
• The transverse horizontal had less coherent energy and was usually lower frequency.
• Along the 18km line length the amplitude ratio between the vertical and radial horizontal varied. The dominant frequency also varied.
• Virtually no coherent energy is observed on the pressure inversion. An observation also made by Lewis and Dorman (1998).

All of these characteristics are consistent with Scholte wave observation and theory.

Further experiments using as few as 20 noise records were still able to isolate the transmission energy.

Sea floor properties and coupling

Interferometric images were made at every location along the 18km line length. This potentially holds a lot of information pertaining to the sea floor properties. It is beyond the scope of this paper to describe all in great detail. However, some include inversion for shear velocity and mud layer thickness.

Because we have a mechanism to describe the noise on the accelerometers, the amplitude of auto-correlations taken from the "Super-shot" noise records (where the noise traces are cross-correlated with themselves) it can yield a quality factor which is a combination of sea floor transmission below the receiver and embedded coupling quality. This amplitude could subsequently be used for surface consistent corrections.

Conclusions

Sea Surface swells generate low frequency pressure waves which propagate downwards to the sea floor.

When these waves encounter local perturbations on the sea floor a secondary wave is generated. Interferometric imaging clarifies the transmission response of the secondary noise and confirms it is trapped Stoneley/Scholte wave. Analysis of the wave properties can potentially yield additional information relating to coupling quality, sea floor properties and sea surface conditions at the time of recording.

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