Attenuating the ice flexural wave on arctic seismic data

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Summary

Satisfactorily attenuating source-generated coherent noise on seismic data can be a challenging exercise for the processor, especially when the noise is as strong as the notorious ice flexural wave often observed in the arctic. One of the strongest known coherent noises, the flexural wave originates in uniform plates of ice floating on liquid water, commonly associated with both river channels and offshore sea ice. The flexural wave is distinguished not only by its strength, but by the large dispersion often observed. High frequencies often travel at speeds approaching that of the compressional wave in ice, while low frequencies are sometimes slower than the air wave. These properties make the ice flexural wave difficult to attenuate with most conventional coherent noise techniques. We demonstrate here that the Fourier-transformed radial trace (R-T) domain provides a natural framework for the separation of highly dispersed source-generated source noise from reflections. Using a set of experimental multi-component seismic data from Hansen Harbour in the MacKenzie Delta, we demonstrate significant attenuation of the ice flexural wave in spite of the substantial spatial aliasing of the noise.

Introduction

Seismic exploration in arctic regions is always a difficult task; the arctic is notorious for the difficulty of its near-surface conditions, which lead to both source-generated noise and difficult statics problems. In order to minimize the problem with geophone coupling and statics caused by summer ground conditions, much seismic activity has been relegated to winter, when the surface is uniformly frozen. For survey lines which cross river channels or extend out onto the floating sea ice, however, a new problem arises, particularly for seismic crews using surface sources. This problem, the ice flexural wave, arises when seismic energy is trapped within the water- and air-bounded ice layer and insufficiently radiated through the water and into the firmer sediments beneath. The flexural wave, similar to the vibration of a drum membrane, can be described as coupled P-SV modes internally reflected within the ice layer waveguide (Ewing et al, 1957). Because the ice wave modes are confined to the ice layer, they attenuate only as the reciprocal of the distance from the source, thus often overwhelming reflection energy attenuating as the reciprocal of source distance squared. Furthermore, for homogeneous ice of uniform thickness, the ice modes can exhibit such wide dispersion that the noise is distributed over most of a source gather.

Source deployment greatly influences the generation of ice wave modes. A source placed on the ice surface or buried within it radiates most of its energy as coherent noise, while a source placed in the water beneath the ice, or even better, implanted in the sediments beneath, is much more efficient at radiating useful elastic energy downward into the earth layers to be imaged. Nevertheless, logistics and other practical considerations sometimes dictate the use of a surface source, usually a vertical vibrator, since only vertical particle motion can be transmitted through the ice layer and water into the earth beneath.

The ice flexural wave is among the most difficult to adequately attenuate because: (1) The large amplitude of the noise relative to weak reflections often overwhelms the dynamic range of the recording system. When this occurs, no amount of processing can restore reflection signal. (2) Acquisition parameters like station spacing are usually optimized to sample vertically traveling reflection; so coherent noise is often badly sampled spatially. (3) The large dispersion often displayed by ice modes means that any f-k filter designed to attenuate all noise velocities will inevitably cut reflections as well.

Solutions

In recognition of the fact that the best way to deal with the ice wave is not to generate it in the first place, various acquisition measures have been tried over the years. Among the more bizarre (but successful) of these was the very labour-intensive technique of sawing large slots in the ice perpendicular to the seismic line to interrupt the wave guide (Proubasta, 1985). This works if you have the time and the equipment, and the ice isn't too thick.

If generating ice wave modes is inevitable, then acquisition parameters should be chosen which allow the modes to be recorded with good spatial fidelity, so that they can be accurately modeled and subtracted from the data, or transformed into a domain where it separates more readily from the underlying reflection signal (if any). We demonstrate the transform separation technique here.

We have already remarked on the failure of the f-k domain to adequately separate signal and ice wave noise, due to the large dispersion often present in the ice wave. The radial trace (R-T) domain, however, because of the geometry of its mapping trajectories, provides exactly the kind of separation required (Henley, 2003). If the R-T origin is placed at the apparent source position, each constant velocity R-T sampling trajectory aligns with a single frequency component of the dispersed noise. This means that the Fourier transform of each radial trace will consist of the broad spectrum due to reflection energy and a few very narrow, large-amplitude peaks at the fundamental and harmonic frequencies of the particular ice mode sampled by that R-T trajectory. A simple editing technique can remove the ice wave peaks, leaving the reflection spectrum intact.

An example

In 2001, CREWES acquired an experimental set of seismic data in the Hansen Harbour area of the MacKenzie Delta. The survey consists of a set of 201 shots recorded by a single 50 station spread of 3-C geophones spaced 15 metres apart. The receiver spread straddled the shoreline of the Beaufort Sea, with roughly half the phones planted on floating sea ice, the other half on land. The much longer source line, with the same station spacing, was centred on the receiver spread, extending 75 stations beyond the ends of the receiver spread. Thus, roughly half the shots were on floating ice, and half on land, as with the receivers. As an experiment, the line was recorded using both buried dynamite and vertical vibrator. We show here only the vibrator data, since they are most affected by the ice wave noise.

As expected, source gathers recorded for source positions on the floating ice show the copious generation of the ice wave modes, as shown in Figure 1.

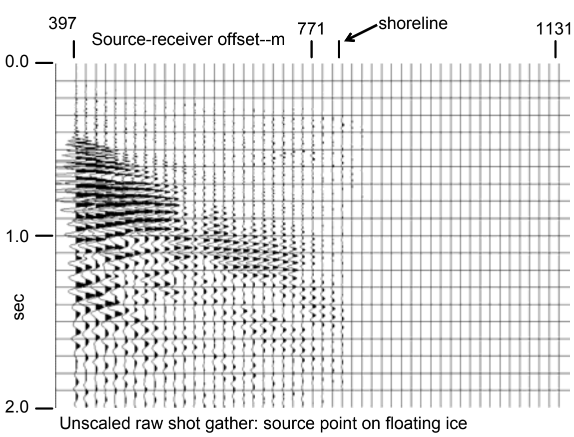


Fig. 1: Raw source gather from Hansen Harbour; source on floating ice

The traces are displayed in true relative trace amplitude to illustrate the strength of the noise, while Figure 2 shows the same source gather after relative trace scaling. This figure shows that the ice wave propagation stops abruptly at the shoreline, and that the land-based geophones record at least some energy that resembles reflections.

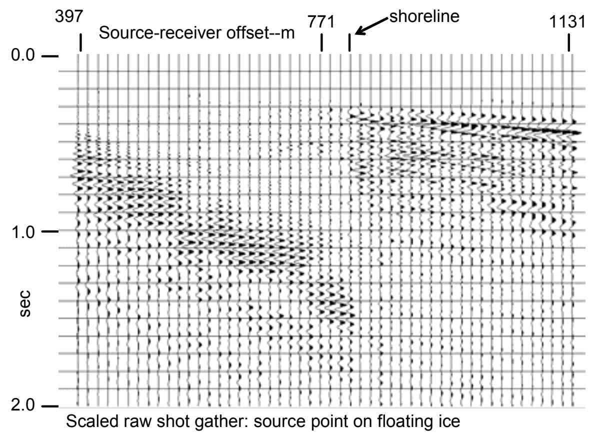


Fig. 2: Raw source gather from Hansen Harbour; source on floating ice, traces normalized

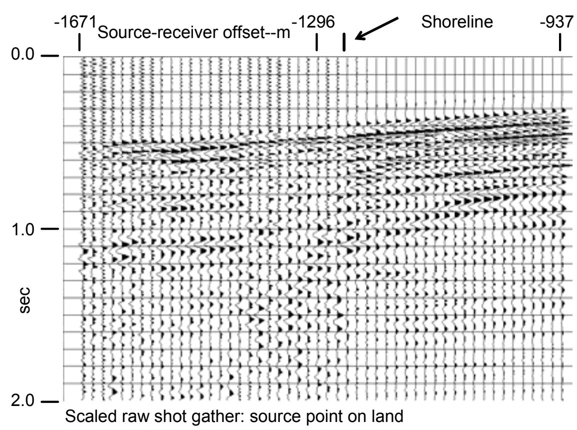


Fig. 3: Raw source gather from Hansen Harbour; source on land, traces normalized

A source gather for which the source was positioned on land is shown in Figure 3 for contrast. No ice wave is generated, and reflection energy can be seen even on those phones positioned on the floating ice.

To illustrate how the R-T transform captures the ice wave modes, Figure 4 shows the same source gather as Figure 1 with three R-T trajectories overlaid. Note that each trajectory aligns with only a single frequency component of the dispersed ice wave.

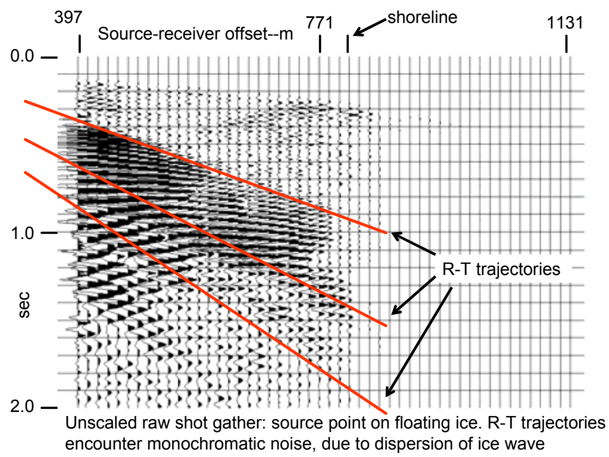


Fig. 4: Raw source gather from Figure 1 with R-T trajectories showing how each R-T trajectory samples the ice wave at a single frequency.

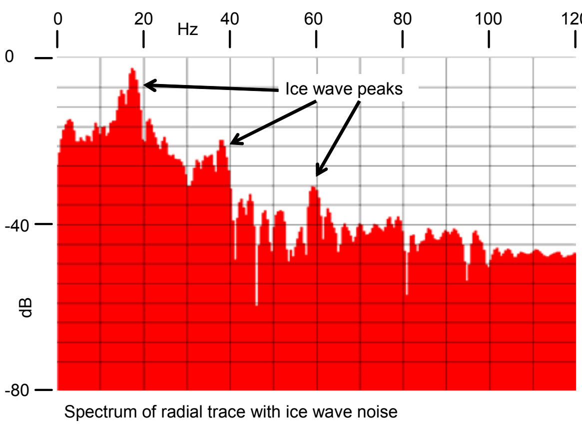


Fig. 5: Radial trace from source gather in Figure 1 shows prominent narrow spectral peaks corresponding to dispersive ice flexural wave.

We show in Figure 5 the spectrum of a typical radial trace extracted from the source gather in Figure 1.The monochromatic nature of the ice wave when sampled along such a trajectory is evident from the three narrow spectral peaks at harmonic frequencies just below 20, 40, and 60 Hz. The peaks are relatively narrow and extend significantly above the background spectrum, making them easy targets for a non-linear automatic spectral editing technique termed 'spectral clipping'. In this method, raw spectral amplitude values which deviate from a broad running median spectrum by more than a 'threshold' amount are replaced with the median values at the same frequency, as seen in Figure 6.

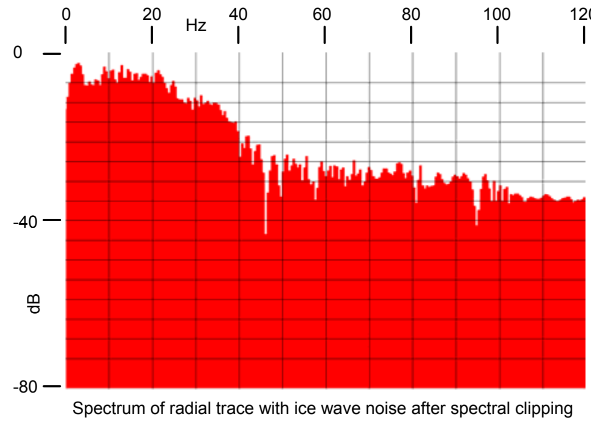


Fig. 6: Spectral clipping has eliminated monochromatic spectral peaks, leaving background signal spectrum relatively unaffected.

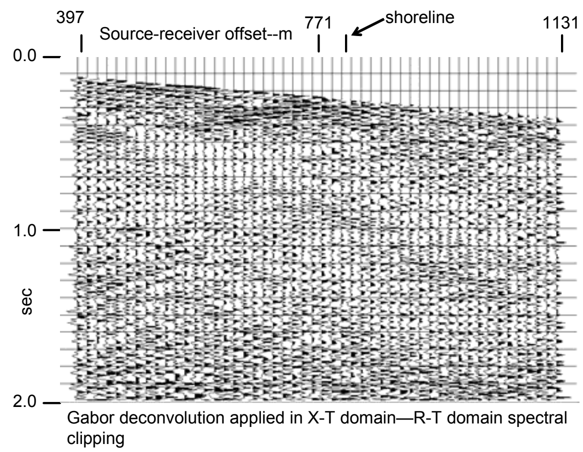


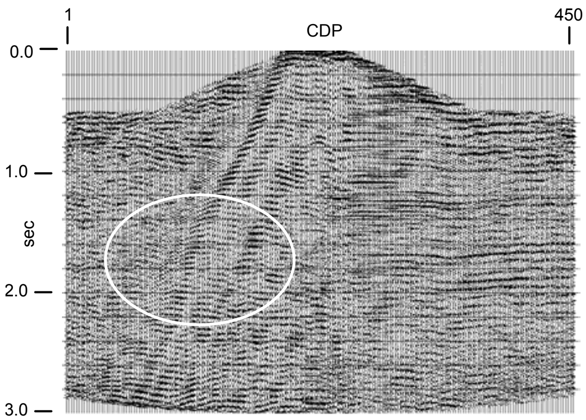
Fig. 7: Source gather of Figure 1 after spectral clipping in the R-T domain, followed by Gabor deconvolution whitening in X-T. Compare with Figure 4.

After the spectrum of each radial trace is edited, it is inverse Fourier transformed and the R-T gather inverse transformed back to the X-T domain. In the X-T domain, non-stationary Gabor deconvolution is applied to further whiten the spectrum and emphasize any reflections (Margrave et al, 2003).

Figure 7 shows the original shot gather from Figure 1 after R-T domain spectral clipping and X-T domain Gabor deconvolution. While remnants of the ice wave are still visible, legitimate reflection fragments can also be seen. The strong direct arrival through the floating ice, and its shoreline reflection can also be seen at the top of the gather.

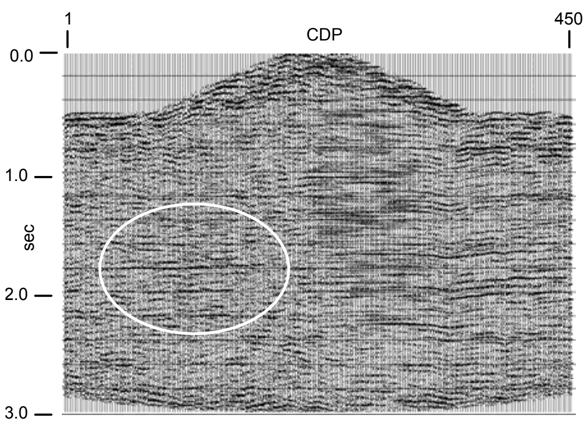
In order to show the imaging benefits of removing the ice wave, we show in Figure 8 the brute stack of the Hansen Harbour line, with no coherent noise attenuation applied, but

Gabor deconvolution applied to the source gathers in the X-T domain. In comparison, Figure 9 shows the same data, stacked after applying spectral clipping in the R-T domain and Gabor deconvolution in the X-T domain to all the source gathers. The improvement is significant, especially in the zone outlined in white.



Brute stack of Hansen Harbour line with no ice wave filtering

Fig. 8: Brute stack of vertical component of Hansen Harbour 3-C experimental line—no coherent noise attenuation.



Brute stack of Hansen Harbour line after ice wave filtering

Fig. 9: Hansen Harbour line after R-T domain ice wave attenuation.

Discussion

While not shown, an attempt was made to model the ice wave and remove it by subtraction. This effort used both the vertical and inline horizontal components of the data and their known phase relation to form a common-mode estimate of the ice wave modes. While the modeled ice wave was quite good, subtracting it proved not to be as effective as applying the non-linear spectral clipping technique reported here. We conjecture that the amplitudes of the reflections are so small that the accuracy with which the ice wave must be modeled for efficient cancellation by subtraction exceeds the accuracy of our common-mode modeling technique.

Conclusions

It is always best not to generate a coherent noise in the first place, if there are any options not to do so. If the noise is unavoidable, however, it should at least be properly spatially sampled in the field. For the notorious ice flexural wave, however, because of its characteristics, which include large dispersion, a non-linear procedure called spectral clipping, applied in the radial trace domain, can attenuate the noise sufficiently to enable imaging of underlying reflections.

References

Ewing, W.M., Jardetzky, W.W., and Press, F., 1957, Elastic waves in layered media, McGraw-Hill, pp281-327.

Henley, D.C., 2003, Coherent noise attenuation in the radial trace domain, Geophysics **68**, No. 4 (July-August 2003); pp1408-1416.

Margrave, G.F., Lamoureux, M.P., Grossman, J.P., and Iliescu, V., 2002, Gabor deconvolution of seismic data for source waveform and Q correction, 72nd Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 2210.

Proubasta, D., 1985, Ice-Saw—an incisive solution to seismic noise, The Leading Edge, **4**, No. 10 (Oct 1985), pp18-82.

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