# Attenuating the ice flexural wave on arctic seismic data

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2005 CSEG National Convention

## Abstract

Among the challenges facing seismic explorationists in the arctic environment is a type of source-generated noise practically unique to this setting, the ice flexural wave. One of the strongest known coherent noises, the flexural wave originates in uniform plates of ice floating on liquid water, a situation commonly associated with both river channels and offshore sea ice. In addition to its strength, one of its distinguishing characteristics is the large dispersion often observed, with high frequencies often traveling at speeds approaching that of the compressional wave in ice and low frequencies moving at speeds as low as that of the air wave. These properties make the flexural wave difficult to attenuate with most standard coherent noise techniques. We demonstrate here that the radial trace (R-T) domain provides a natural framework for the separation of highly dispersed source-generated noise from reflections. Using a set of field seismic data from Hansen Harbour in the MacKenzie Delta, we show significant attenuation of the ice flexural wave, in spite of the fact that the noise is substantially spatially aliased.

## Introduction: the problem

Difficult near surface conditions, which vary dramatically with the seasons, make the arctic one of the more challenging environments in which to conduct seismic exploration. Much exploration activity occurs in the winter, when the surface is frozen and provides more consistent coupling conditions for sources and receivers. One consequence of winter, however, is the formation of ice sheets of relatively uniform thickness over river channels, ponds, and sheltered near-shore areas of the sea. Because these ice sheets are supported by a layer of liquid water, seismic energy injected into the ice is not efficiently radiated from the ice through the water and into the firmer sediments beneath. Instead, much of the energy is trapped within the ice as flexural waves (similar to those excited in a drum membrane). These waves can be described as coupled P-SV modes internally reflected within the ice layer waveguide (Ewing et al, 1957). Because they're confined to the ice layer, the ice wave modes attenuate only as the reciprocal of the distance from the source, thus often overwhelming reflection energy attenuating with the reciprocal square of source distance. Furthermore, depending upon the ice thickness and uniformity, the flexural modes can be very highly dispersed, high frequencies at high velocities and low frequencies at low velocities.

The location of the source greatly affects the generation of ice flexural waves. A source placed on the surface or inside the ice layer itself radiates most of its energy as coherent noise, while a source within the water layer, or better yet, buried in the sediments, 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.

Of all the coherent noise modes encountered in seismic data acquisition, the ice flexural modes are among the most difficult to attenuate adequately for several reasons: (1) The large velocity contrast between the ice and both the air above and water beneath favours the excitation of the ice wave at such large amplitudes that the dynamic range of the recording system is insufficient to record simultaneously the ice wave and the much weaker reflection signal. (2) Seismic acquisition parameters such as station spacing are usually optimised to properly record only vertically travelling reflections; so coherent noises are often badly spatially aliased. (3) The large dispersion often displayed by ice modes means that it is difficult or impossible to construct an f-k filter that will attenuate noise over a very wide range of velocities while leaving the reflections unaffected.

## A solution

In order to avoid generating ice waves in the first place, if the source positions cannot be moved off the ice, one drastic solution used with some success twenty years ago was to saw slots in the ice perpendicular to the seismic line (Proubasta, 1985) to physically interrupt the wave path. Since this method requires special equipment and lots of time, it is not considered practical for a lot of acquisition.

Attenuation of the ice wave, once generated, can be considerably assisted by choosing field acquisition parameters, especially station spacing, that favour the recording of the ice wave with no spatial aliasing. When the coherent ice wave is recorded with full fidelity, it can then be accurately modelled and removed from the data, or transformed into a domain where it separates more readily from the underlying reflection signal. It is the latter approach that we demonstrate here.

We have already suggested that the f-k domain does not separate signal and the ice wave noise, because of the large dispersion often displayed by the noise. The radial trace (R-T) domain, however, because of its geometry, 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 spectrum of each radial trace will contain a narrow peak at the frequency of its captured noise component. The peaks of the R-T spectra can then be edited to remove the ice wave noise before transforming back to the original X-T domain.

## An example

In 2001 an experimental set of seismic data was acquired by CREWES in the Hansen Harbour area of the MacKenzie Delta. The data set consists of a set of 201 shots recorded by a single 50 station spread of single 3-C geophones spaced at 15 metres. The receiver spread straddled the shoreline of the Beaufort Sea, with roughly half the phones planted on floating ice, the other half on land. The source stations were also spaced 15 metres apart, with the first station at a large positive source-receiver offset out on the floating ice and the last station at a large negative offset on land. The source line was centred on the fixed receiver spread, but was four times as long, extending 1½ spread lengths on either end of the receiver spread. While the line was recorded with both buried dynamite and a vertical vibrator source, we show only the vibrator data, since those are most affected by the ice wave. 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. This display is shown in true relative trace amplitude to illustrate the strength of the ice wave modes. Figure 2 shows the same source gather after relative trace scaling. In this figure it can be seen that the ice wave propagation stops abruptly at the shoreline, and that the land-based phones record at least some energy that looks like reflections. Figure 3 is a source gather for a source position on land; and it can be seen that no ice wave is generated, and reflection energy can be seen even on those phones placed on the floating ice.

Figure 4 shows The same source gather as Figure 1 with three R-T sample trajectories overlaid, to illustrate how the trajectories each sample only a single frequency of the ice wave.

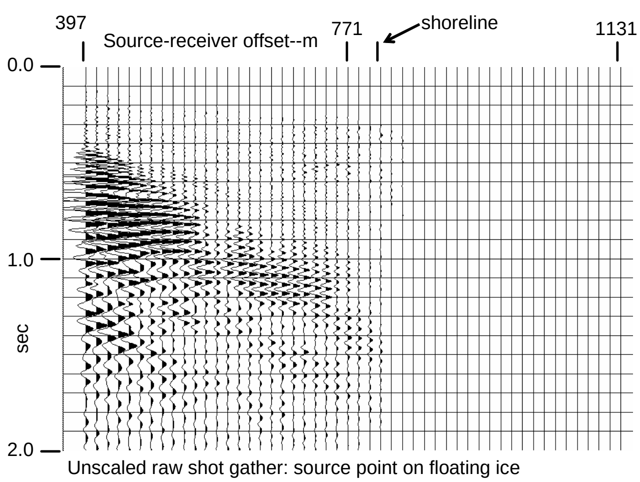



*Fig. 1. Raw source gather from Hansen Harbour, source on floating ice. Relative trace amplitudes preserved.*

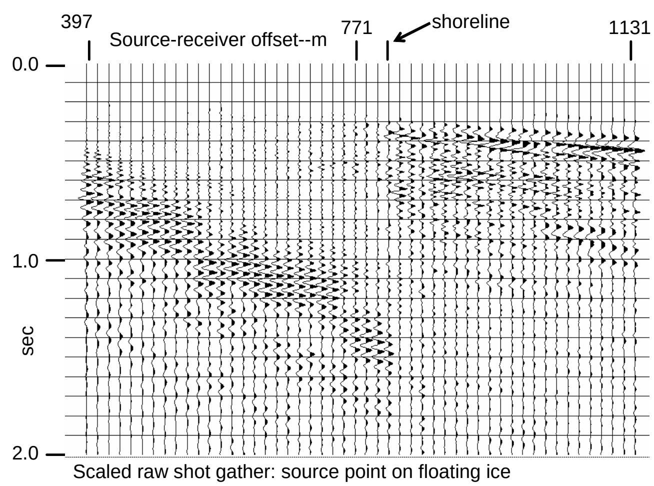



*Fig. 2. Raw source gather from Hansen Harbour, source on floating Ice. Trace amplitudes normalized.*

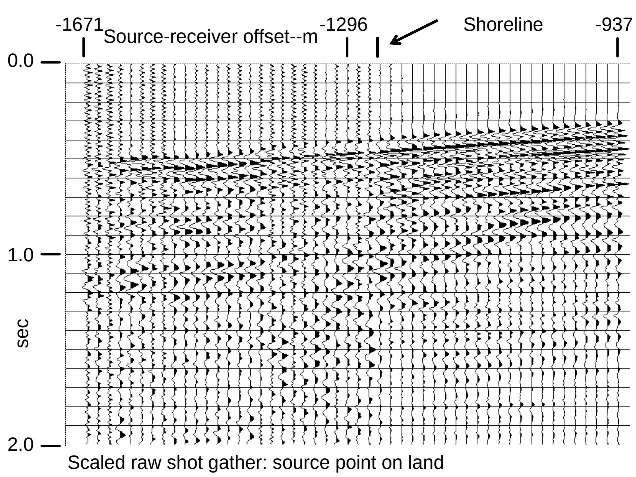



*Fig. 3. Raw source gather from Hansen Harbour, source on land. Trace amplitudes normalized. Reflections seen even on geophones planted on floating ice.*

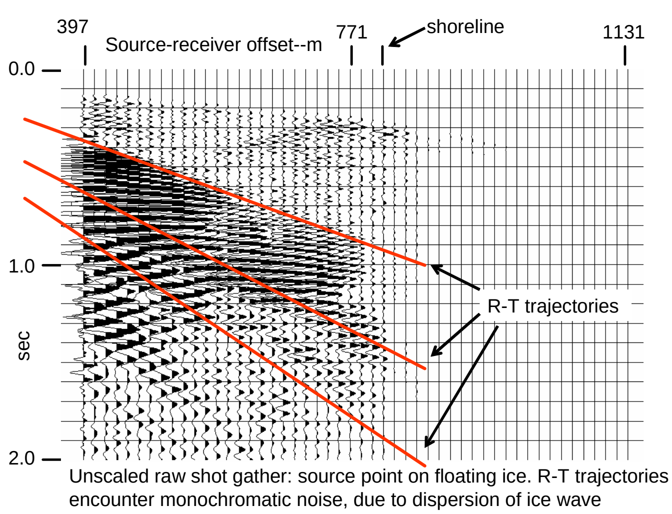



*Fig. 4. Raw source gather from Figure 1 with R-T trajectories showing how each R-T trajectory samples the ice wave at a single frequency.*

Figure 5 shows 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 an R-T trajectory is evident from the three narrow peaks at harmonic frequencies just below 20, 40, and 60 Hz. Because the peaks are relatively narrow and extend significantly above the background spectrum, they can be eliminated by a non-linear procedure termed 'spectral clipping'. In this technique, a running median is used to compute a smooth background spectrum without peaks or notches. The raw spectral amplitude at each frequency is then compared to the median background, and any amplitude that deviates from the median by more than a specified threshold is set to the corresponding median value, with its phase unchanged. Figure 6 shows the spectrum of Figure 5 after spectral clipping has been performed. To attenuate the dispersed ice wave, therefore, we simply transform a source gather to the R-T domain, take the Fourier transform of each radial trace, perform spectral clipping, inverse Fourier transform each radial trace, and invert the R-T transform.

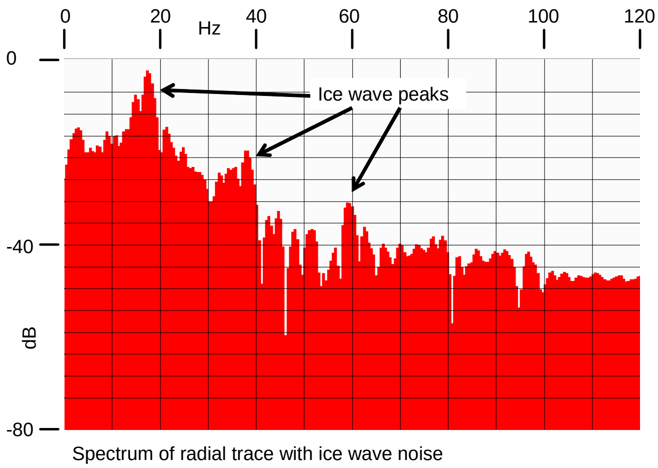



*Fig. 5. Radial trace from source gather in Figure 1 shows prominent narrow spectral peaks corresponding to dispersive ice flexural wave.*

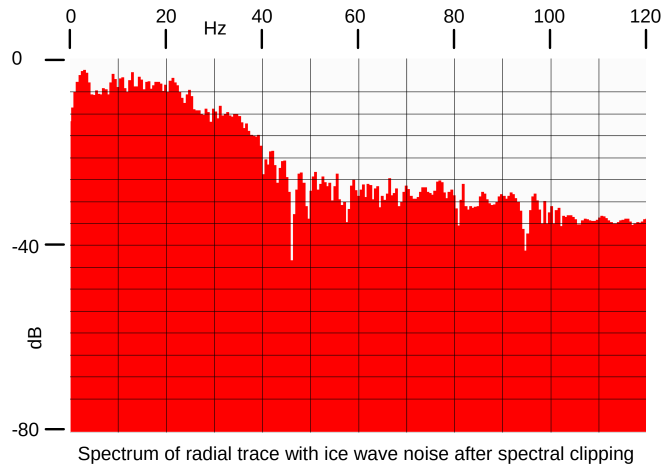



*Fig. 6. Spectral clipping eliminates monochromatic spectral peaks, leaving background signal spectrum relatively unaffected.*

Figure 7 shows the source gather from Figure 1 after the application of R-T domain spectral clipping. While there is some residual of the ice wave present on this gather, its amplitude is great;ly diminished, and some hints of underlying reflection signal may be seen. Figure 8 shows the same gather after the additional step of Gabor deconvolution. The time-varying spectral whitening incorporated in this procedure has attenuated the ice wave residual even further, and hints of reflection signal can now be seen even more prominently, particularly at about 0.6-0.8 sec in the near offsets and about 1.3-1.5 sec in the far offsets.

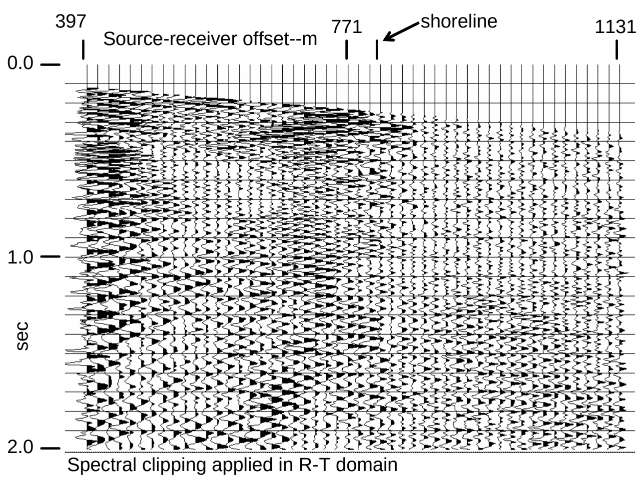



*Fig. 7. Source gather from Figure 1 after spectral clipping in the R-T domain. Ice wave residual still visible, but much diminished.*

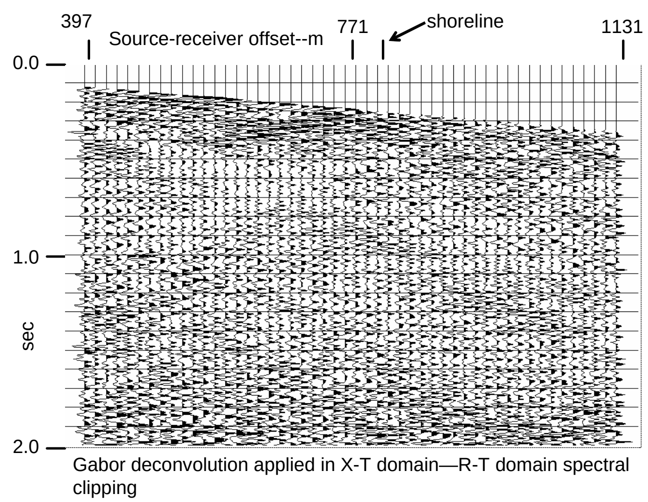



*Fig. 8. Source gather from Figure 7 after the additional step of Gabor deconvolution whitening. Underlying reflections much more visible.*

To demonstrate the significant improvement in imaging due to ice wave attenuation, we show the brute stack of the Hansen Harbour line in Figure 9. No noise attenuation has been applied to these data, and the image degradation due to the ice wave is quite apparent. Even prestack Gabor deconvolution has been unable to reduce the noise level enough to properly image the underlying reflections. After R-T domain ice wave attenuation, however, the stack is as shown in Figure 10. All other processing is identical for the two sections.

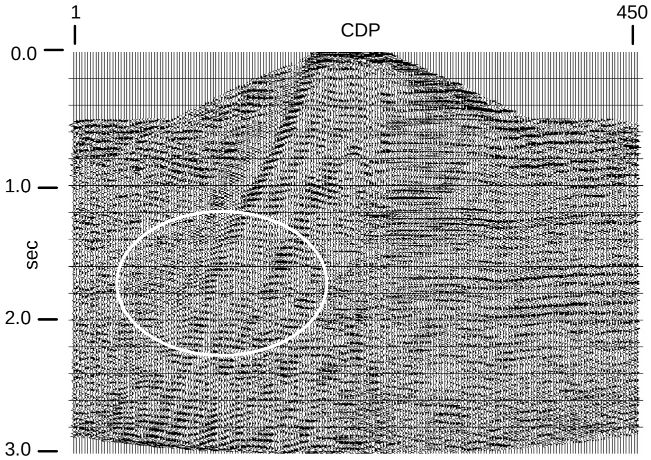
Although we can only speculate, we feel that the ice wave could be even more effectively attenuated if it were recorded without spatial aliasing. The ice wave on the Hansen Harbour data is aliased at almost all frequencies, due to the 15 metre spacing of the receivers. Reducing the spacing to 3-5 metres would enable the wave to be recorded with much greater fidelity and hence attenuated more effectively.

## Conclusions

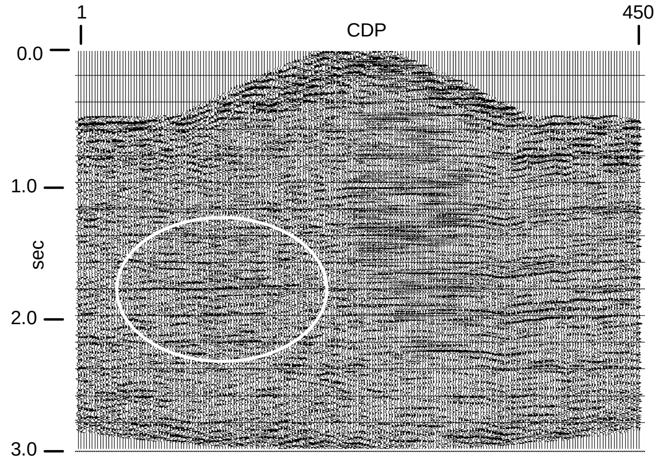
The ice flexural wave often observed on seismic data from the arctic is so strong that acquisition options that avoid exciting its modes are to be preferred whenever possible. If a survey must cross floating ice with a surface source, and generating the ice wave is unavoidable, then at least the wave should be properly sampled. Even when it is aliased, however, a non-linear procedure called spectral clipping, applied in the radial trace domain, can attenuate the noise sufficiently to enable imaging of underlying reflections.

## Acknowledgements

The author thanks the CREWES consortium and its sponsors for support and advice.




Brute stack of Hansen Harbour line with no ice wave filtering




Brute stack of Hansen Harbour line after ice wave filtering

*Fig. 9. Brute stack of the vertical component of the Hansen Harbour 3-C experimental line—no coherent noise attenuation.*

*Fig. 10. Hansen Harbour line after R-T domain ice wave attenuation. Reflection continuity improved at all levels.*

## References

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Proubasta, D., 1985, Ice-Saw—an incisive solution to seismic noise, The Leading Edge, **4**, No.10 (oct 1985), pp 18-82.