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Advances in Seismic Interference Noise Attenuation

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Summary

This paper presents recent advances in the area of seismic interference (SI) attenuation for towed streamer data. We show how high amplitude and broadside SI noise can be nearly perfectly attenuated as long as the interfering noise is incoherent from shot-to-shot. Furthermore, we present a new algorithm that also allows us to attenuate nearly all forms of shot-to-shot coherent noise. These algorithms have effectively eliminated the need for reshooting/timesharing due to SI noise in the North Sea, and have therefore contributed to a significant improvement in acquisition efficiency.

Introduction

For towed streamer marine acquisition seismic interference (SI) occurs when two or more seismic vessels operate in close proximity and the acoustic energy from the source(s) on one vessel is recorded by the receivers on the other vessel(s). The main component of SI in a shallow water environment is normally acoustic energy reflecting up and down in the water-layer. As such it has little value with regards to seismic imaging, and only represents noise that needs to be attenuated in processing.

To avoid too much SI noise in surveys conducted in areas where multiple seismic parties operate, contractors have traditionally chosen to commence timesharing. This means that, only one vessel shoots, while the other vessel(s) in the area circle on standby. This ensures that everyone acquires high quality data. However, it is also a costly and inefficient approach, often resulting in significant delays and cost overruns. The alternative to timesharing is to continue to acquire data and then remove, or at least attenuate, the SI in processing. Compared to timesharing, this is a much cheaper option. Recent advances in processing, combined with the ever increasing drive to reduce costs have recently made this a preferred approach (Elboth and Laurain, 2017).

Background

Historically, a number of methods for SI attenuation have been proposed, - we refer to Janssen et al. (2013) for an overview. In Sept 2012 a seminar was organized by the Norwegian oil and gas industry and authorities in Stavanger on the topic of "how to reduce time sharing from SI noise", where all the major contractors presented their acquisition and processing solutions. At that time everyone seemed to favor an SI attenuation workflow where the source-cable data was 2D transformed into Tau-P domain, and sorted according to p-values. A random noise attenuation tool was applied, before the identified noise was sorted back to Tau-P, reverse transformed and finally (adaptively) subtracted from the original data. This approach, illustrated in Figure 1, is appealing, since it takes advantage of the relative linearity of seismic interference compared to the reflection seismic data, which normally is more curved. Implicitly, the algorithm relies on some shot-to-shot randomness in the arrival time of the SI.

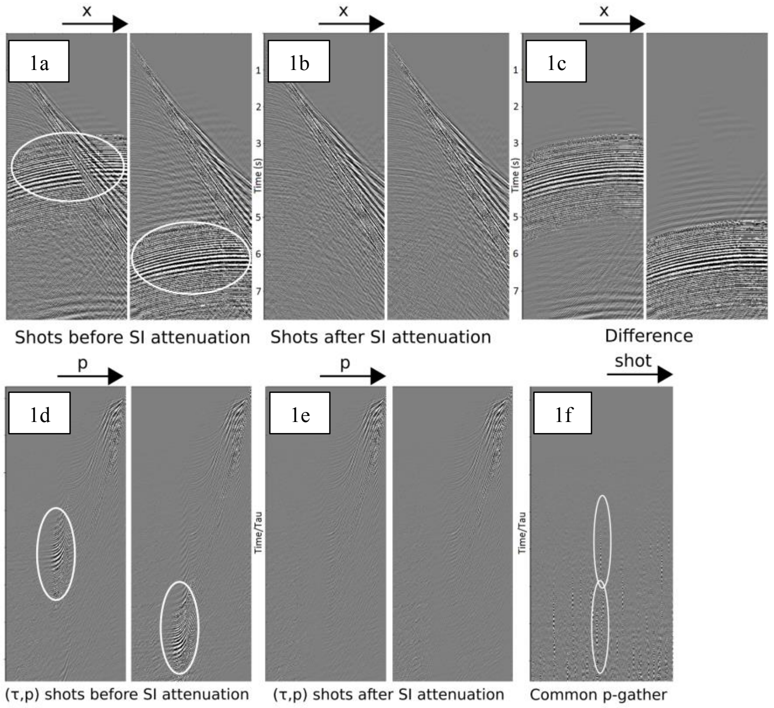

Figure 1. *A commonly used algorithm for SI attenuation: Top: Two consecutive shot gathers before (1a), after (1b) and difference (1c) from SI attenuation. Bottom: The before (1d) and after (1e) data transformed to the Tau-P space. The near linear SI maps into a relative small area in Tau-P space, and the shot-to-shot randomness of the SI arrival time relates to the 'random noise' that appears in the common-p sorted gather (1f). In this case the vessel (source) that generated the SI was around 10km away and broadside.*

In two accompanying papers focusing on acquisition (Elboth and Laurain 2017) and 4D (Laurain and Elboth 2017) we'll show how insight into SI attenuation has allowed us to tailor the seismic acquisition in order to avoid shot-to-shot coherent SI. The main point being that we actively coordinate the speed of the involved seismic vessels to avoid SI that is shot-to-shot coherent (comes in at the same time in consecutive shots).

In this paper we will describe how modifications to the Tau-P SI attenuation approach have enabled us to deal with a much larger variety of SI and coherent noises. The new algorithm(s) has recently been used to denoise a large number of problematic lines from a 35000 km^2 North Sea survey that contained SI noise from up to five different sources simultaneously, and has been used successfully on three 4D projects from the same area (Laurain and Elboth 2017).

Method/Algorithm

Wang and Nimsaila (2014) described a sparse Tau-P approach applied in local spatial windows, and illustrated how it may produce fewer artefacts, and offer better signal protection in the presence of SI noise, compared to the more conventional least-squares Tau-P transform. The basic 2D algorithm attempts to fit a sparse $f - p_x$ model, M, to the input data, D, when inverse Tau-P transformed:

$$D(f; x^i) = \sum_j e^{-i2\pi f x^i p_x^j} M\big(f;\, p_x^j\big). \qquad (1)$$

Here f is frequency, x^i is the receiver location and p_x^j is the slowness pair (i: trace index; j: slowness index). Tau-P coefficients (P-values) relating to SI noise are isolated based on the median value from a number of neighboring source-cable shots. The resulting noise is transformed back to the offset-time domain and subtracted from the input. In this way, the SI noise is attenuated while the signal is preserved as described by Zhang and Wang (2015). One problem with this approach is that it assumes that the SI noise is shot-to shot incoherent. In most cases, variations in vessel speeds and shot-point intervals create sufficient shot-to-shot randomization of the SI and the algorithm gives excellent results. However, experience has shown that we occasionally record shot-to-shot coherent SI, which may cause trouble for the above mentioned algorithm.

We have developed two solutions to this problem. Firstly, we have initiated cross-party coordination during acquisition to coordinate and adjust vessel speeds to reduce the shot-to-shot coherent SI as explained in Elboth and Laurain, (2017). Secondly, we have developed a new algorithm that is able to effectively attenuate shot-to-shot coherent noise. This algorithm is surprisingly straight forward to implement: In a "standard" SI attenuation flow, 20 to 50 consecutive source-cable consecutive shot gathers in a sliding window go into the SI attenuation processing algorithm. With a dual source SPI of 18.75 m the inline (2D) data aperture is between 750 m and 1875 m. This can be compared to the cross-line distance between neighbouring lines which for 12 streamers at 75 m separation is 450 m. (Individual source-cable combinations from neighbouring lines can be as close as 75 m away.) The point is that without extending the absolute data aperture, we can "borrow" shots from a neighbouring line (source-cable), and mix these in to break up any shot-to-shot coherent SI along neighbouring inline shots. In this way we implicitly go from 2D to 3D denoising, even though we only need to perform 2D Tau-P transforms. We refer to this approach as "line mixing", and it is based on two underlying assumptions:

1. We have a neighbouring line, shot in the same direction.
2. The SI acquired on this neighbouring line is significantly different from the SI on the line we want to denoise.

Assuming a traditional race-track acquisition pattern (1) is nearly always fulfilled, at least on one of the sides. Item (2) has also been fulfilled on all datasets tested to date. After the algorithm, we remove every other shot (the ones that were mixed in from the neighbouring line), to respect the original source-cable line.

Examples

We present three examples of SI attenuation from data that was acquired during the 2015 and 2016 season in the Tampen area of the North Sea. Figure 1 shows the results of applying our proposed algorithm to gathers with broadside SI from a source that was around 10 km away. In this case the SI noise train is only visible for about 1s, but compared to the reflection data the SI has very high amplitude. This is not a problem for the denoising algorithm. In fact, high amplitude noise (compared to the reflection data) is easier to statistically identify and then attenuate compared to low amplitude noise. We can also notice that the SI comes in at significantly different time in the consecutive shots. This is because the SI vessel and seismic vessel had shot-point intervals of 25 and 18.75 m respectively. For this reason, no "line mixing" or vessel speed coordination was needed. We note that excellent denoising results were obtained, and that no seismic reflection data is visible in the difference plot.

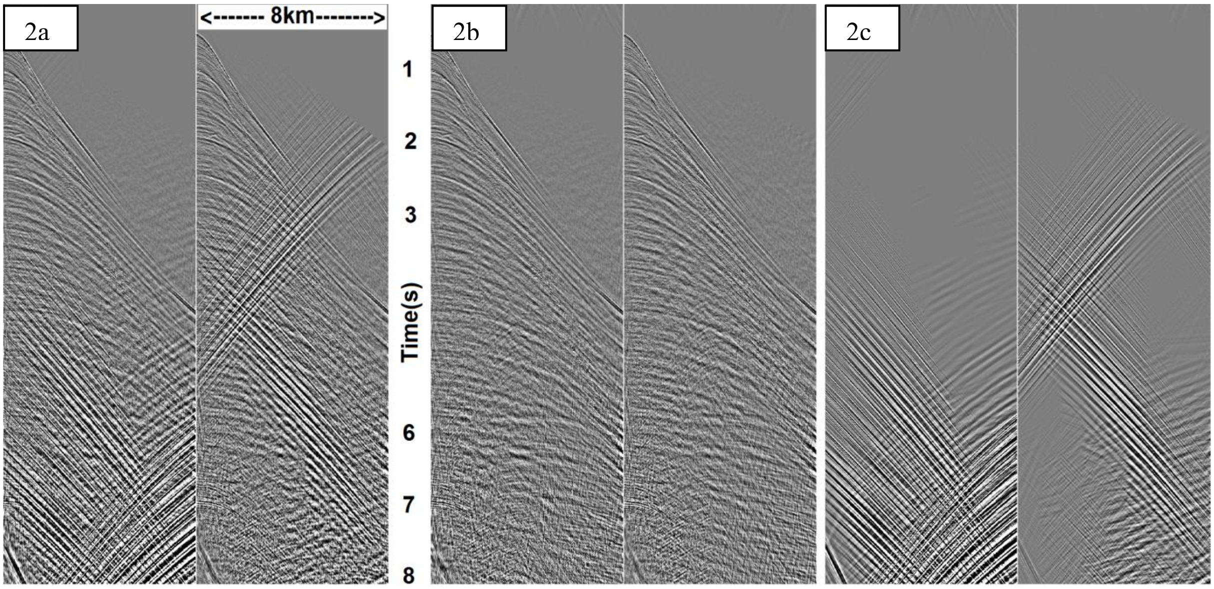

Figure 2. *Before (2a), after (2b) and difference (2c) plot of two consecutive seismic shot gathers with SI noise from to different sources. Here, the nearly perfect SI attenuation was achieved because the vessel speeds were actively adjusted during the acquisition to break up any shot-to-shot coherent SI.*

Figure 2 shows two shot gathers with both head and tail noise from around 25 km away, originating from two 4D surveys acquired at the nearby Gullfaks and Snorre oilfields. In this case the shot-to-shot randomness of the SI was achieved by actively adjusting the speed of the three involved vessels which all had a SPI of 18.75 m. By slowing down or speeding up the individual vessels by typically 0.2 to 0.4 kn, any shot-to-shot coherent SI was avoided. To our knowledge, this is the first time this kind of cross-party coordination has been used during acquisition. We refer to Elboth and Laurain (2017) for more details. Again an excellent denoising result is achieved, and no reflection data is visible in the difference plot. No "line mixing" was needed in this case either.

Figure 3 shows shot gathers with near continuous SI noise. In this case, most of the SI came from a vessel that was operating 80 km to 100 km to the side. Experience has taught us that with this vessel separation we often do not observe any SI at all. However, on some occasions, we may observe reasonably strong and nearly continuous SI. The apparent intermittency may be explained by variations in the local geology and topography (hardness and shape of the water bottom). Another influencing factor is the sea state (the weather conditions). A flat sea-surface acts as a nearly perfect reflector of acoustic energy, and can help SI noise travel longer.

With a typical water depth of 200 m, SI in the North Sea will bounce up and down in the water column many times. Each of these bounces is manifested as an event in the SI train. With distance, these SI trains can grow very long, and at 80-100 km we sometimes observe SI-trains that reach the same length as the shot-point interval (SPI) of the survey. In case like this it becomes difficult to break the shot-to-shot SI coherence, and our ability to attenuate the SI in processing is reduced. In order to attenuate this SI, we used the “line mixing” approach described in the method section. The result is a nearly perfect denoising, without any apparent seismic reflection data in the difference plot.

Conclusions

The seismic interference (SI) noise examples shown in this article are well beyond what should have been accepted according to “normal” acquisition contracts. A few years ago, this kind of noise would most likely have resulted in reshooting/standby, which comes at a significant cost. We have shown that through advances in acquisition and processing we can successfully attenuate very strong SI noise from as close as ~7 km away. We have demonstrated the effectiveness of our approach even in the case the data is almost fully contaminated by SI noise. During the last two years these algorithms have been successfully applied to more than 35000 km^2 of newly acquired North Sea data, and on at least three different 4D surveys acquired in the same area. These advances have also virtually eliminated the need for timesharing and reshooting during the last two acquisition seasons in the North Sea, and thus enabled a significant improvement in efficiency / reduction in cost.

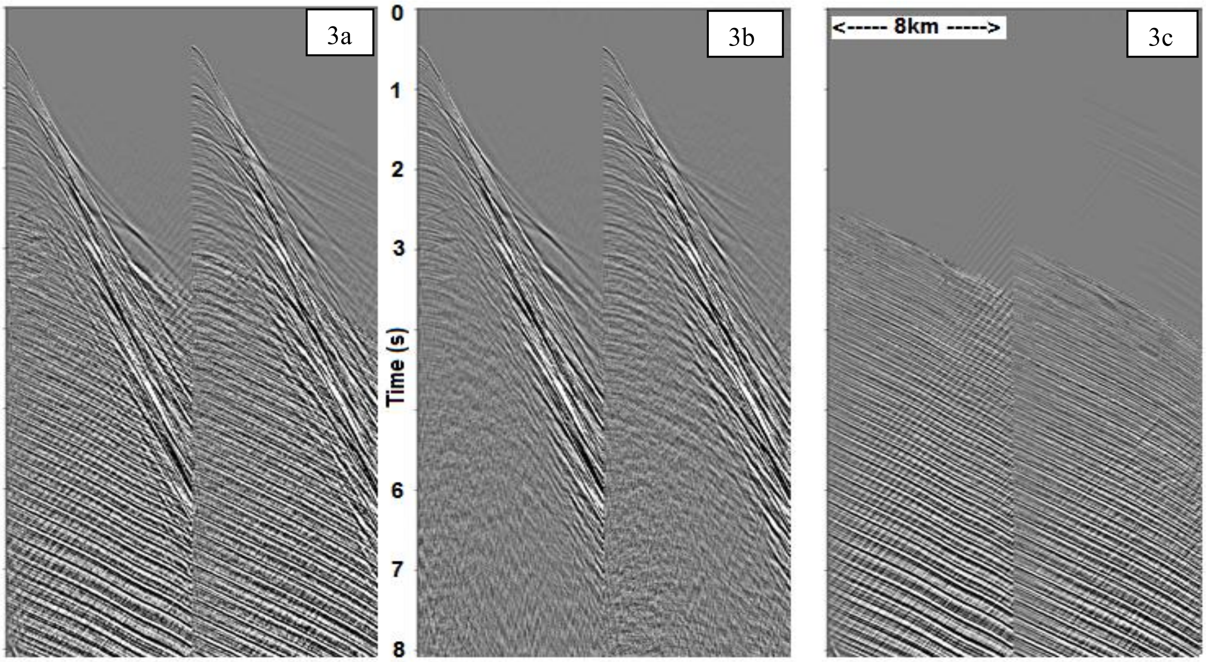

Figure 3. *Before (3a), after (3b) and difference (3c) plot of two consecutive seismic shot gathers with nearly continuous SI noise.*

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