Image courtesy of CGG.

THE MAGIC OF MITIGATION

JO FIRTH AND THOMAS ELBOTH, CGG, SHOW HOW NEW SEISMIC INTERFERENCE MITIGATION TECHNIQUES CAN ELIMINATE TIME-SHARING AND MAKE SEISMIC ACQUISITION SIGNIFICANTLY MORE EFFICIENT.

Seismic interference (SI) has long been a problem for seismic data acquisition in congested offshore areas, such as the North Sea, as it both reduces data quality and causes costly vessel downtime. However, following recent advances in processing algorithms and new cooperative management techniques developed by CGG in conjunction with Statoil and Reservoir Imaging Ltd (RIL), downtime or time-sharing due to SI has been effectively eliminated.

SI occurs when two or more seismic vessels are shooting simultaneously in close proximity to each other and recording noise from each other's sources. It is a common problem in congested areas, especially in relatively shallow areas such as the North Sea, where SI noise can often be observed at distances of over 100 km.

The main component of SI noise is usually acoustic energy reflecting up and down in the water layer. This energy does not contain much useful seismic information and needs to be attenuated during seismic imaging. On the Norwegian Continental Shelf, where the seismic acquisition window is limited due to fisheries and poor winter weather, SI can have a significant impact on the success of an acquisition season.

The traditional mitigation measure is time-sharing, where the different parties agree to distribute the time slots to acquire the survey. This method is costly and inefficient as one vessel is on standby as the other is acquiring data, therefore increasing the total acquisition time. In the North Sea, historical data from Statoil show that vessels have spent an average of 12% of their time on standby due to time-sharing.[1] It is reasonable to assume that historical maximum accepted noise levels and minimum separations have resulted in a similar reduction in productivity in other areas of the world.

CGG has been working with Statoil and RIL to develop a series of tools and procedures to reduce the impact of SI and minimise time-sharing. Over the last three North Sea acquisition seasons (2014 - 2016) significant advances in seismic interference management have been achieved, alongside improvements in SI noise attenuation algorithms, to effectively eliminate the need for time-sharing. During the 2016 North Sea acquisition season, up to five vessels operated simultaneously within a radius of 60 km, and individual vessels were acquiring data as close as 8 km apart, allowing considerable increases in efficiency (Table 1). This was achieved through an improved understanding of SI noise, which enabled careful planning and cooperation between contractors.

Several authors[2,3,4] have shown that controlling the moveout of SI and the randomness of the arrival time on consecutive seismic records is of major importance for SI attenuation, and is significantly more important than the amplitude of the SI noise. Most contractors use a tau-p approach to remove SI in processing, and in general, this is very successful, with the exception of broadside, shot-to-shot coherent SI noise. By analysis of SI-contaminated data, based on the apparent slowness (p, or dip in terms of time/distance) of the interference and its amplitude for each shot of the sequence, combined with testing of SI removal algorithms, Laurain et al. (2014)[5] established a series of noise thresholds in the p-domain for zones of acceptable SI and zones where SI attenuation methods need to be tested.

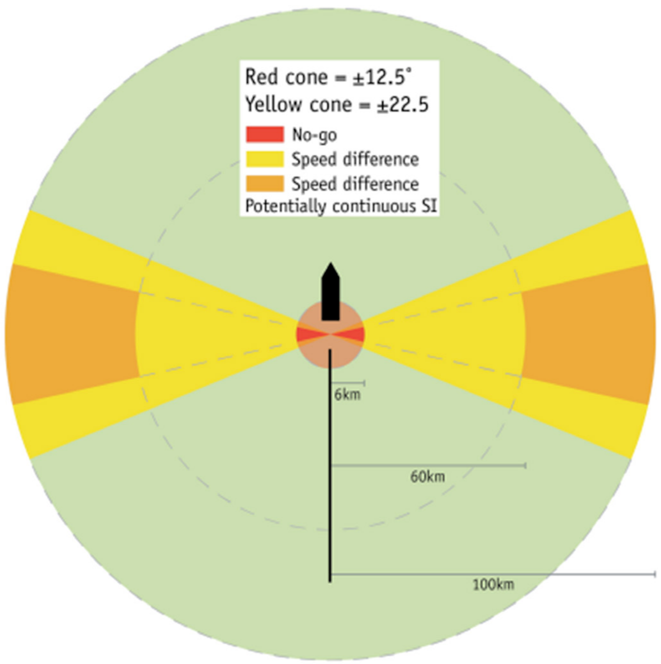

Figure 1. *Cones around an acquiring vessel where SI might be problematic in the Tampen area.*

These criteria were further developed into a planning tool by mapping the threshold values in p to angles from the sailing direction in the space domain.[6] These describe a cone around the acquiring vessel, perpendicular to the sail line direction, where SI might be problematic (Figure 1). The lateral extension is based on the assumption that SI ceases to be a problem at distances greater than ~100 km, although this assumption can be updated depending on water depths and sea bottom characteristics. In general, only the interference from the direct arrival propagating through the water is used for the purpose of planning acquisition cooperation schedules, as this is easy and quick to compute.

Cross-party coordination

In the Horda-Tampen area of the North Sea, three proprietary and two multi-client surveys were acquired in the 2015 season. Due to the acquisition time constraints, all had to occur at the same time. It was agreed that all the acquisition contractors should provide acquisition plans and the range of speeds the different vessels could achieve to an independent third party in advance of the acquisition on a daily basis. The aim was to either avoid seismic interference completely or to accept only a level of SI that could easily be attenuated in processing.[7] Interference cones were simulated based on positioning of the seismic vessels in accordance with the supplied acquisition plans and vessel speeds. Where there were conflicts, the vessel speeds were adjusted and the simulation was rerun until a good compromise was reached. The third party distributed the updated plans, which had been optimised to minimise time-sharing and ensure good data quality, to the acquisition contractors and coordinated all the acquisition in the area. Prior to this, vessel-to-vessel coordination between different contractors had been found to be challenging, but using an independent third party to take care of all the coordination made cooperation easier.

Not only did this procedure deliver a considerable reduction

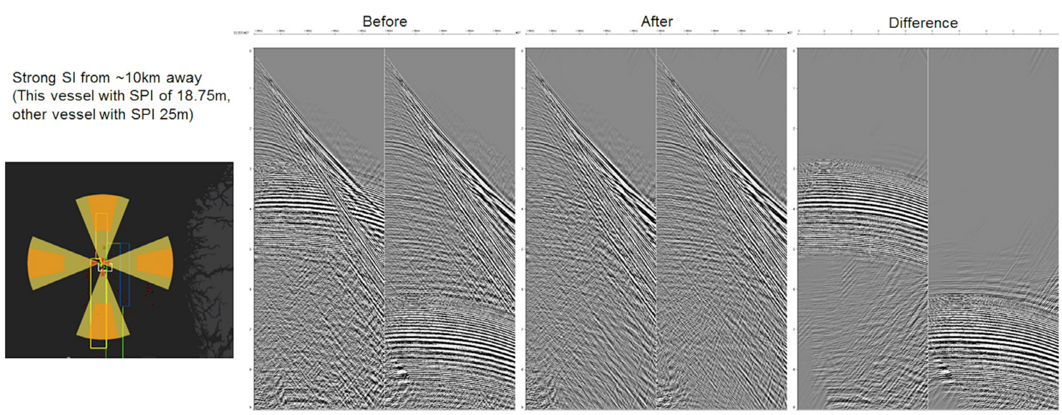

Figure 2. *Even strong SI can be attenuated effectively if the noise is shot-to-shot incoherent, as in this case with different shotpoint intervals for the two vessels.*

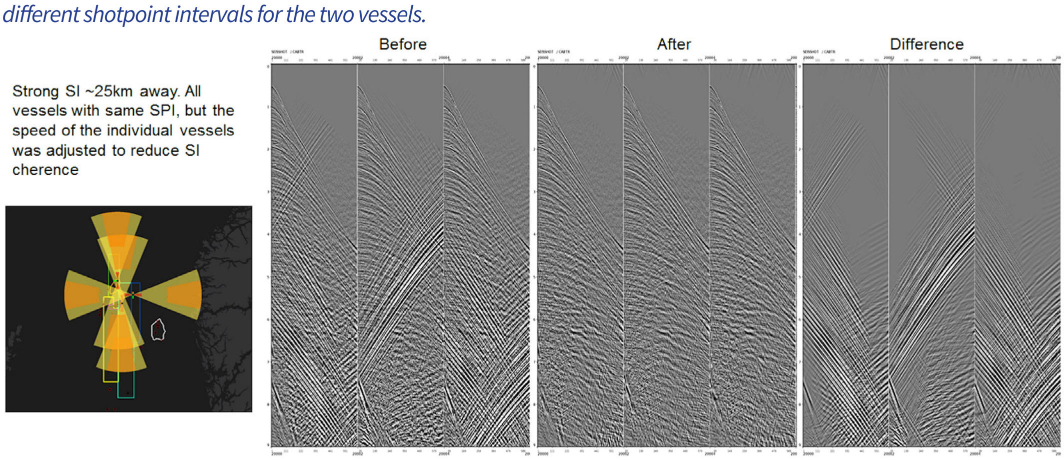

Figure 3. *Shots with strong SI from two sources. By adjusting the vessel speeds it was possible to reduce SI coherence so that it could be attenuated.*

in downtime due to SI in 2015, with lost time reduced to an average of 3%, it also provided many valuable lessons for ongoing improvement. These were put into place in the 2016 season where several different parties participated in this cooperative planning in the North Sea. In 2015 some line-turns were extended to try and avoid broadside SI, but in 2016 greater emphasis was placed on adjusting vessel speeds.

Vessel speeds were not only actively adjusted to prevent the vessels from entering any noise cone; they were also adjusted to ensure sufficient time differences in the arrival of SI on the shot gathers. The idea was to avoid time-sharing and to continue acquisition, with thorough QC and testing of any noisy data to ensure the SI noise could be attenuated. Where this was not possible the line would have to have been reacquired. Figure 2 shows that where the shotpoint intervals are different, so that the SI noise is incoherent from shot-to-shot, even strong SI noise can be attenuated. Where vessels had the same shotpoint interval, adjusting the vessel speeds to reduce SI coherence also enabled attenuation of the noise, as shown in Figure 3. All of the participants in the coordination in 2016 had zero-percent standby or reshooting due to SI, except for one (who was unfortunate in encountering a significant amount of continuous SI noise from a source around 70 km away). It should also be noted that no reshooting was needed in any of the cases where vessels operated as close as 8 km apart.

Processing advances

CGG has also recently developed a new noise attenuation algorithm,[8] which enables nearly all forms of shot-to-shot coherent noise to be attenuated. When combined with vessel coordination, this method effectively eliminated the need for reshooting or time-sharing in the North Sea due to SI noise, significantly improving acquisition efficiency.

In the most commonly used approach to SI attenuation, the data are transformed into the tau-p domain, where, being approximately linear, the SI noise tends to map to a relatively small area. Consecutive shots are then sorted into common p gathers and the noise is identified using a random noise attenuation tool, then sorted back to tau-p shots and reverse-transformed, as shown in Figure 4. Finally, this noise is adaptively subtracted from the input data, so as to preserve the signal whilst attenuating the SI noise.[9] Wang and Nimsaila (2014)[10] showed that a sparse tau-p approach applied in local spatial windows offered even better signal protection in the presence of SI noise and produced fewer artefacts compared with the more conventional least-squares tau-p transform. This is the technique now used as standard by CGG.

The method takes advantage of the relative linearity of the SI noise compared with the more curved seismic reflection data, but also relies on incoherence of the noise from shot-to-shot. In most cases, variations in vessel speeds and shotpoint intervals provide sufficient randomisation of the noise and excellent results are achieved, even for strong SI, as seen earlier. However, occasionally, even with cross-party coordination in place, shot-to-shot coherent SI noise is recorded, which remains challenging for this approach.

The company's solution to this is to apply 'line-mixing' to break up any shot-to-shot coherent SI along neighbouring inline shots. In the standard attenuation algorithm, consecutive source-cable shot gathers are used in a sliding inline window, with an inline aperture of 750 - 1875 m (20 - 50 shots), compared with a crossline neighbouring sail line distance of 450 m (for a typical North Sea sail line of 12 streamers at 75 m separation). Mixing in 'borrowed' shots from a neighbouring source-cable line breaks up coherent shot-to-shot SI and implicitly moves from 2D to 3D denoising, although CGG only uses 2D tau-p transforms.

In order for this approach to work, it is necessary to have a neighbouring line, shot in the same direction, with any SI acquired on this neighbouring line being significantly different from the SI on the

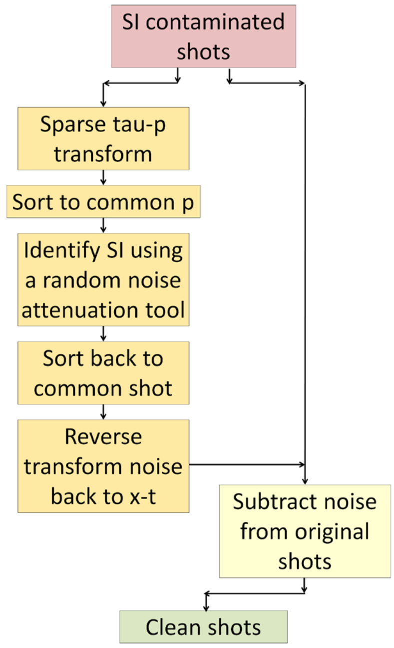

Figure 4. *Standard tau-p SI noise attenuation workflow.*

Table 1. SI downtime statistics 2014 - 2016 (data courtesy of Statoil).					
Year	**Min vessel separation**	**Max SI noise level**	**Lost time due to SI**	**Cross-party coordination**	**Number of participants**
< 2014	~40 km	20 µBar	12%	No	-
2014	~40 km	40 µBar	10%	No	-
2015	~25 km	No limit	3%	Yes	7
2016	~8 km	No limit	1%	Yes	6

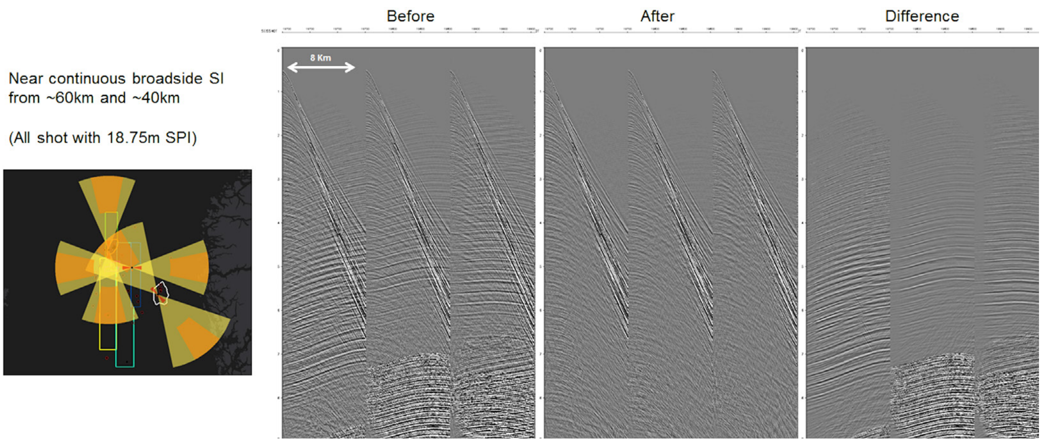

Figure 5. *Using the sail-line mixing approach CGG is also able to attenuate even near-continuous broadside SI.*

line being denoised. With traditional race-track acquisition the first condition is almost always met, and the second has also been fulfilled on all data sets tested so far. The algorithm is applied to the mixed data then the mixed-in shots are dropped, to leave only the original data. This technique has been shown to be successful, as seen in Figure 5, where there was near-continuous broadside interference.

The improvement in SI attenuation achieved using the 'line-mixing' approach over the conventional single-line method is shown in Figure 6. Here, there was near-continuous SI noise coming from a vessel that was operating 80 - 100 km to the side. At such distances SI is not often observed, but occasionally reasonably strong and near-continuous SI may occur, depending on the sea state and the seafloor geology and bathymetry. A calm, flat sea surface acts as a nearly perfect reflector of acoustic energy and can help SI travel further.

In the North Sea, water depths are typically around 200 m and SI bounces up and down many times in the water column. Each bounce shows as an event in the SI noise train, and these can grow very long, so that at a distance of 80 - 100 km they can reach the same length as the shotpoint interval. In such cases, it is not possible to break the shot-to-shot SI coherence by altering speed, reducing the ability to attenuate the SI in processing. By using the 'line-mixing' approach, nearly perfect denoising was achieved without any apparent seismic reflection data appearing in the difference plot.

4D implications

In the North Sea a fairly high proportion of the acquisition is for 4D monitoring, which causes additional concerns as to whether accepting data with increased SI content might affect the 4D signal. As an example, Statoil acquired three monitor surveys in the North Sea in 2016: towed-streamer surveys over Gullfaks and Troll, and an OBC survey over Gullfaks. QCs show that the noise level on these 4D surveys is significantly higher than on the previous vintages. However, initial processing results are promising, and the data quality does not seem to be negatively affected by the SI noise.[11] This means that SI coordination combined with a suitable QC workflow should be considered for all acquisitions, including 4D.

By using an independent third party to coordinate all the acquisition in the Norwegian Sea to avoid shot-to-shot coherent (and, where possible, broadside) SI, significant improvements in acquisition efficiency were achieved during the 2015 and 2016 acquisition seasons. The cost of the coordination is that some vessels have to slow down during acquisition of some lines. However, the cost of these speed adjustments is typically less than 2%, compared with an average 12% loss for standby when time-sharing. Combining this with the flexibility of being able to operate as close as 8 km apart enables overall operational efficiency to be considerably increased. The amplitude of the noise is no longer a limiting factor; it is the direction and coherency that are important in assessing the ease of its removal. Modern processing algorithms can attenuate virtually any SI. Even the most challenging shot-to-shot coherent broadside noise has been shown to be successfully attenuated by using sail line mixing. With these advances in knowledge and acquisition methods, time-sharing to avoid SI noise should become a thing of the past.

Acknowledgements

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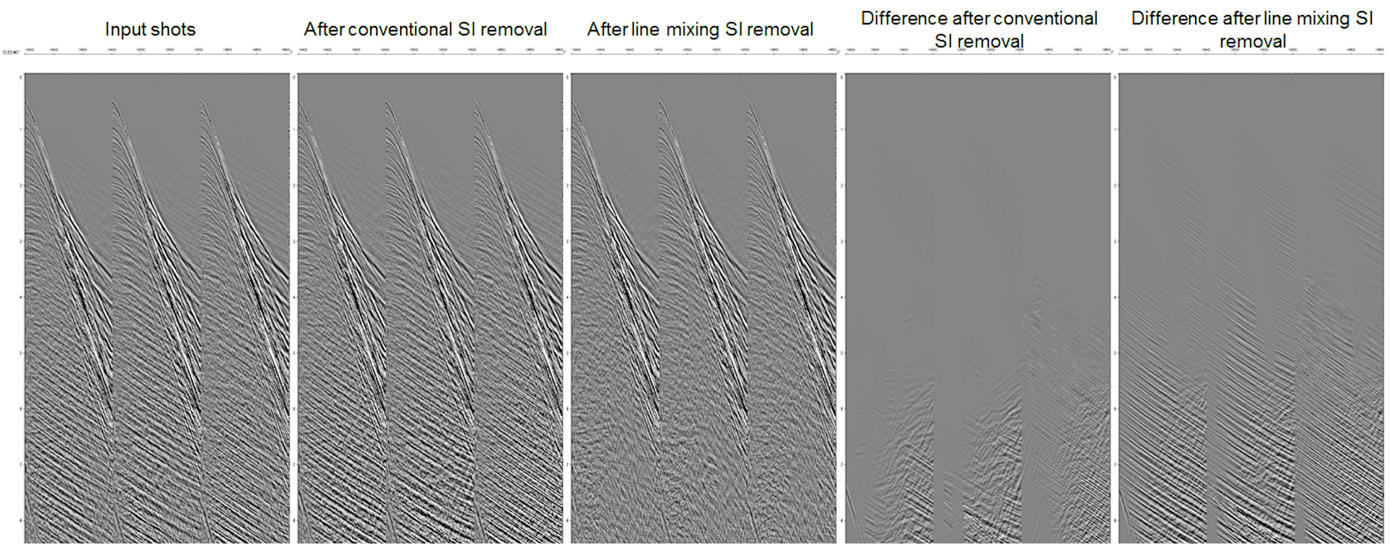

Figure 6. *For shot records with near-continuous SI, the line-mixing SI attenuation workflow gives excellent results, without attenuation of the underlying signal.*