Research Programme
- Short Calls, Final Report -

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Host Organisation name	University College Dublin
Project Title	Surface wave removal from Seismic reflection data using seismic interferometry
Contract Number	2017-sc-034

Date: 14/11/2018

This report covers the period November 1st 2017 to October 31st 2018

2. (a) Project information:

Final project report (*max **2500**words, excluding figures and headings*):

(i) *Progress* of objectives and scientific/engineering targets beyond the state of the art & *methods* used

The main objective of the project was to find the best practices for the surface wave ("ground roll") removal from the seismic reflection records. Since traditional f-k (velocity) filtering may fail in the presence of shallow structural complexities usually found in onshore seismic surveys, we examined the suitability of seismic interferometry to achieve this task.

Seismic interferometry (SI) (initial conjecture by Claerbout (1968)) is a data driven method aimed to obtained virtual records, i.e. the inter-receiver Green's function by the correlation of the traces recorded at two receivers, given that the receivers are completely surrounded by either impulsive or white noise sources (e.g. Wapenaar, 2004; van Manen et al., 2005, 2006; Wapenaar and Fokkema, 2006; Slob and Wapenaar, 2007). In such a (theoretical) case, the recovered Green's functions contain the complete wavefield, including body waves, surfaces waves and the complex seismogram tail (coda) comprising multiply scattered waves. However, in exploration seismology, the sources are commonly placed at the surface and, as a consequence, the ambient noise field (generated by the field operations) and active shot gathers are dominated by surface waves. Thus, surface waves are more readily reproduced by SI (Nakata et al., 2015).

Thus, in surface-wave interferometry, surface waves propagating between two receiver locations are estimated as if one receiver had recorded the response due to a source of surface-wave energy at the other receiver. It is shown in the next section that if multiple active sources are available, the recovered surface wavefield can be efficiently separated from the reflection events; these new surface-wave responses can then be removed from the recorded reflection seismic data.

SI was first proposed for the surface wave removal in seismic reflection surveys by Dong et al. (2006) and Halliday et al. (2007). Although the theory can be considered to be well understood, the application of this method can be challenging. In addition, since the application of this methodology is generally done with confidential data, the limitations of the method are not well addressed in the literature and hence are poorly understood. This study served as a pilot project towards finding best practices, defining future directions and understanding the limitations in the implementation of this fully data-driven methodology.

The workflow for generating the surface wavefield by the seismic interferometry and removing it from the recorded data is show in Fig. 1.

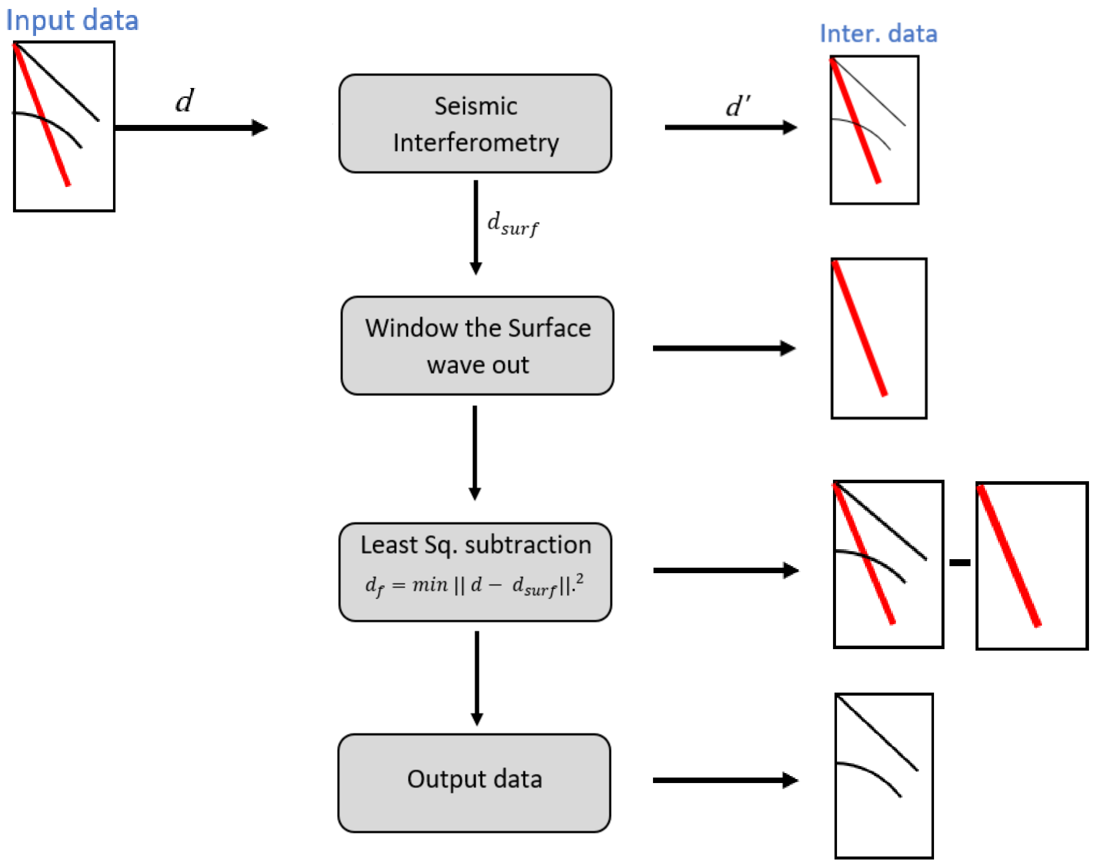


Figure 1. *Workflow for the surface wave removal. d denotes the input data; d' is the interferometric data; dsurf is predicted surface wave gather and df is the the output data (having only body waves).*

The success of the procedure depends on our ability to (a) recover the surface wavefield, and (b) being able to separate it from the reflection events. Hence we addressed the following questions:

- How efficiently can we recover surface waves by seismic interferometry?
- Can we separate surface waves from reflections in places where they overlap (have similar arrival times)?

We addressed these questions using synthetic data: we started with a simple 2-layered model, and then proceeded with a much more complex heterogeneous model to mimic a more realistic scenario. The datasets were calculated by numerically solving wave equation by finite difference approach. The model properties are shown in Table 1, while a synthetic shot gather is shown in Fig. 2. The blue circle in Fig. 2 denotes the critical portion of the shot gather, where the reflection event is hidden below the large-amplitude surface waves.

Table 1: Velocities and layer thicknesses of a simple 2-layered model (Model 1)

Layer's No.	P velocity (m/s)	S velocity (m/s)	Density (g/cc)	Thickness (m)
1	2000	1100	1.8	500
2	3000	1600	2	Infinite

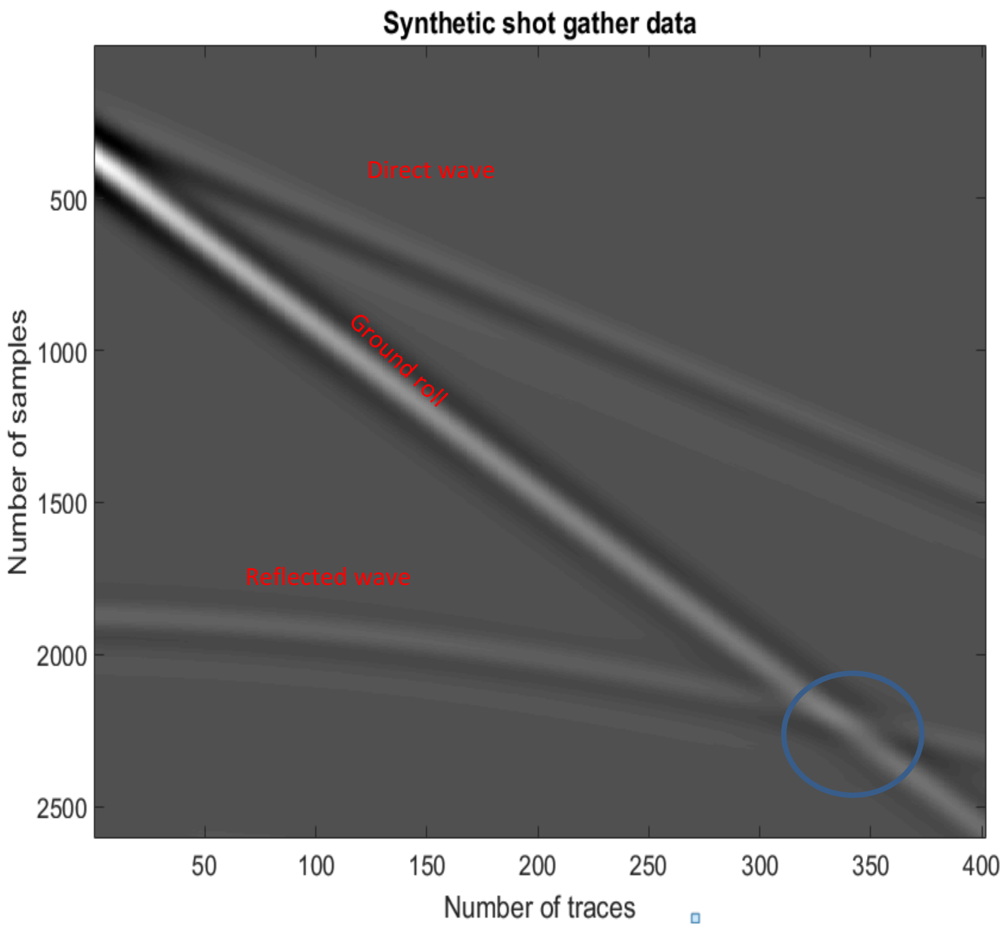


Figure 2: *Synthetic shot gather for 2-layered model. 3 branches (from top to bottom) represent the direct waves, surface waves and reflected waves, respectively. The numbers on the x-axis denote the trace numbers, while the numbers on y-axis denote samples (milliseconds). Note the large amplitudes of the surface waves. The blue circle around the trace 340 denotes a critical portion of the shot gather where the reflection event is overprinted by the surface waves.*

Separation of reflection and surface waves with equal arrival times

In order to successfully remove surface waves from the reflection records, it is crucial to be able to separate the reflections from the surface waves which have similar travel times (marked by the blue circle in Fig. 2). Our results, shown in Fig. 3b, demonstrate that the seismic interferometry of the active data can achieve this task, given that the number of active sources is large.

The black traces in Fig. 3b are interferometric traces, obtained by cross-correlating active data recorded at locations A and B (Fig. 3a), respectively, for different positions of active sources. While the surface wave recorded at positions A and B will have exactly the same time-delay for any position of the source, this is not the case for the reflected waves. As a result, the surface waves always have the same position on the all interferometric traces (regardless of the source position), which corresponds to the actual travel time between the receivers A and B. In contrast, the reflected waves exhibit something like a NMO effect, and have the correct travel times only for so-called "stationary source locations" (Forghani and Snieder, 2010). Consequently, when summed over all the sources (red trace in Fig. 3b), surfaces waves will interfere constructively, while the reflections will partially cancel out. The efficiency of this process will depend on the number of sources. For comparison, the actual (calculated) trace between locations A and B is shown as a purple trace in Fig 3b.

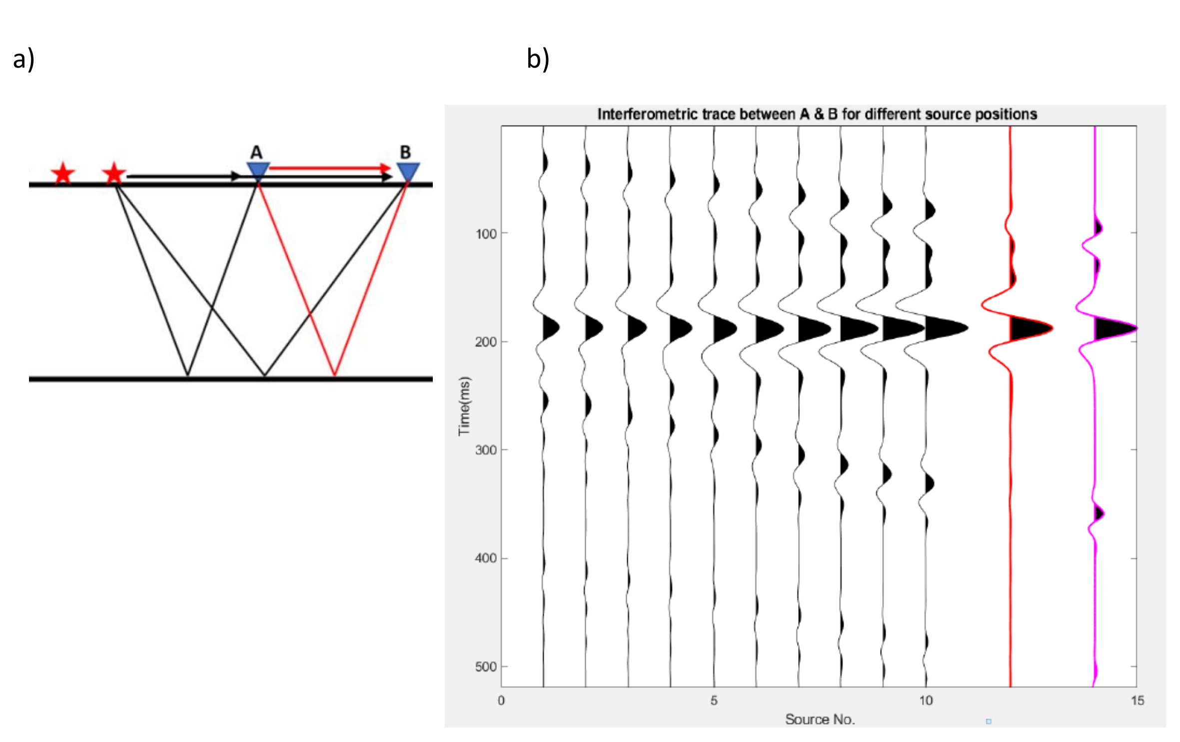


Figure 3. *a) Schematic of the surface and reflected waves propagation, b) Cross-correlation gather. The black traces are interferometric traces (cross-correlation functions) of the data recorded at positions A and B plotted against the distance between the source and the midpoint between the locations A and B. Red trace is the sum of all the black traces. The purple trace is the actual Green's function recorded between A and B.*

Surface wave removal by the least square adaptive subtraction

After the prediction of ground roll using cross correlation of recordings, a least-squares filtering approach is used to optimize the subtraction of the estimated ground roll from the common-source gather. We do not additionally phase- or amplitude-correct the recovered surface wave, although this may become a requirement in a general case where the source wavelet is not a symmetrical Ricker wavelet like used here. The ground roll has been suppressed effectively, while the body waves crossing the ground roll have mostly been preserved during the filtering process, as desired. It can be clearly seen in Fig. 4 that the reflection is preserved which was mixed with surface waves.

Fig. 5 shows the shot gather after the removal of surface waves. The reflection events are partially preserved, where their complete removal is prevented by the side lobes of the interferometric surface waves, which is a consequence of the cross-correlation. Yet, the reflection events can be seen more distinct and continuous after ground roll attenuation using Interferometry (Fig. 5).

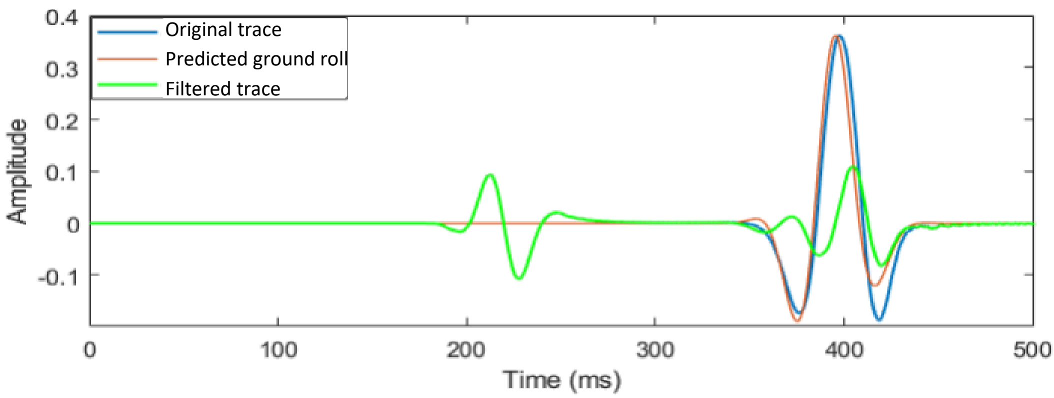


Figure 4. *The blue trace is the original shot gather data, red trace is the predicted ground roll and green trace is the filtered data (output data).*

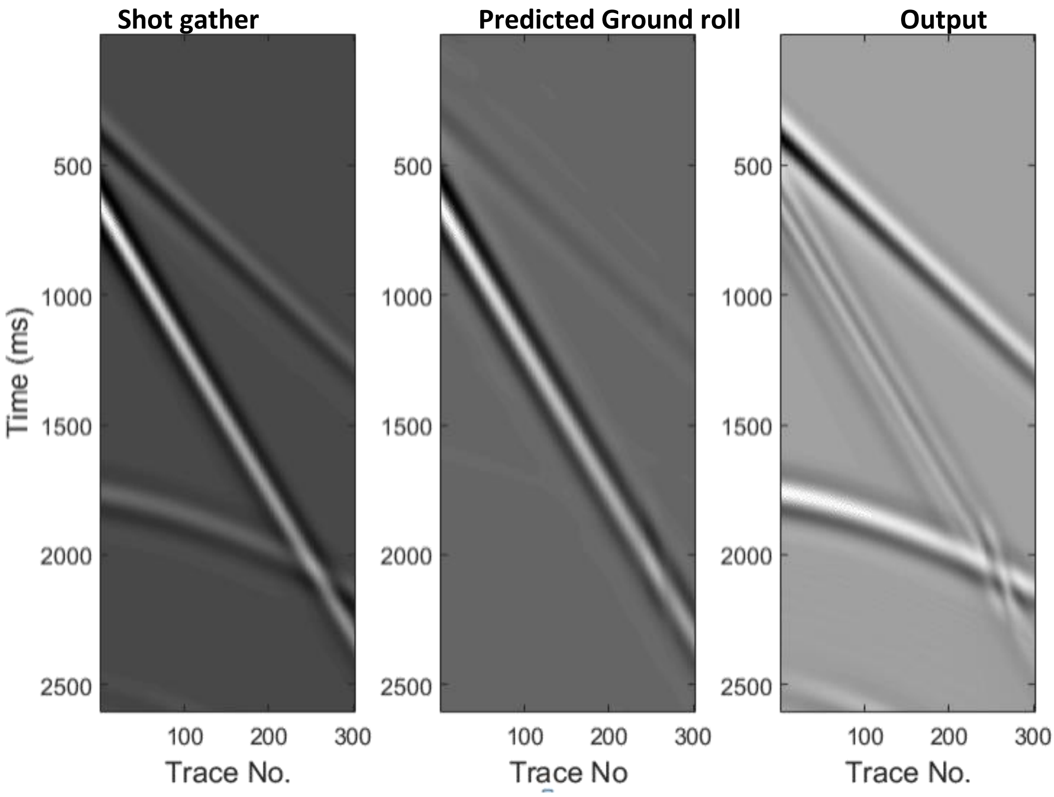
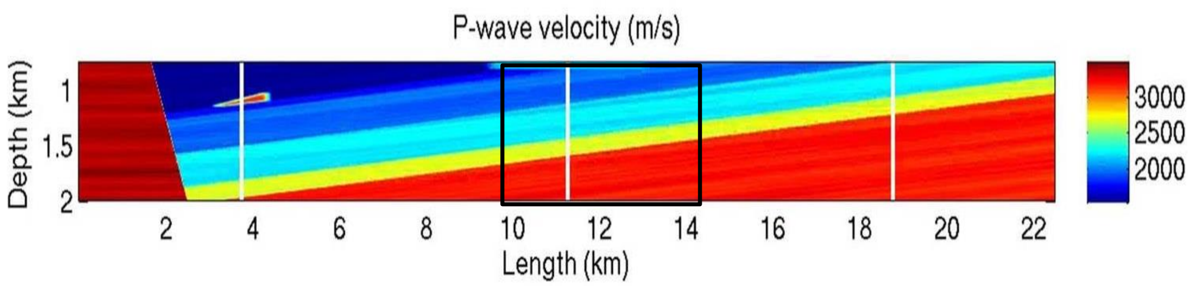


Figure 5 Left: *Recorded shot gather; Middle: estimated ground roll using cross correlation; Right: Filtered data using least square subtraction method* (output data).

A realistic scenario – synthetic model 2

We introduced a more realistic 2D layered model (Fig. 6a) with near surface complexity, including the vertical and horizontal velocity gradient. This allowed us to test the interferometry theory in an Earth-like setting. Receivers were located on the free surface at horizontal locations from 25 m to 22000 m with a separation of 12.5 m, and shot gathers were generated by implementing a source at every 25 m interval. The number of shot points for the entire 2D line were 800. The traces recorded from these sources were used to estimate the ground roll, between all receiver pairs. The shot gather data and the estimated ground roll are shown in figure 6b.

a)



b)

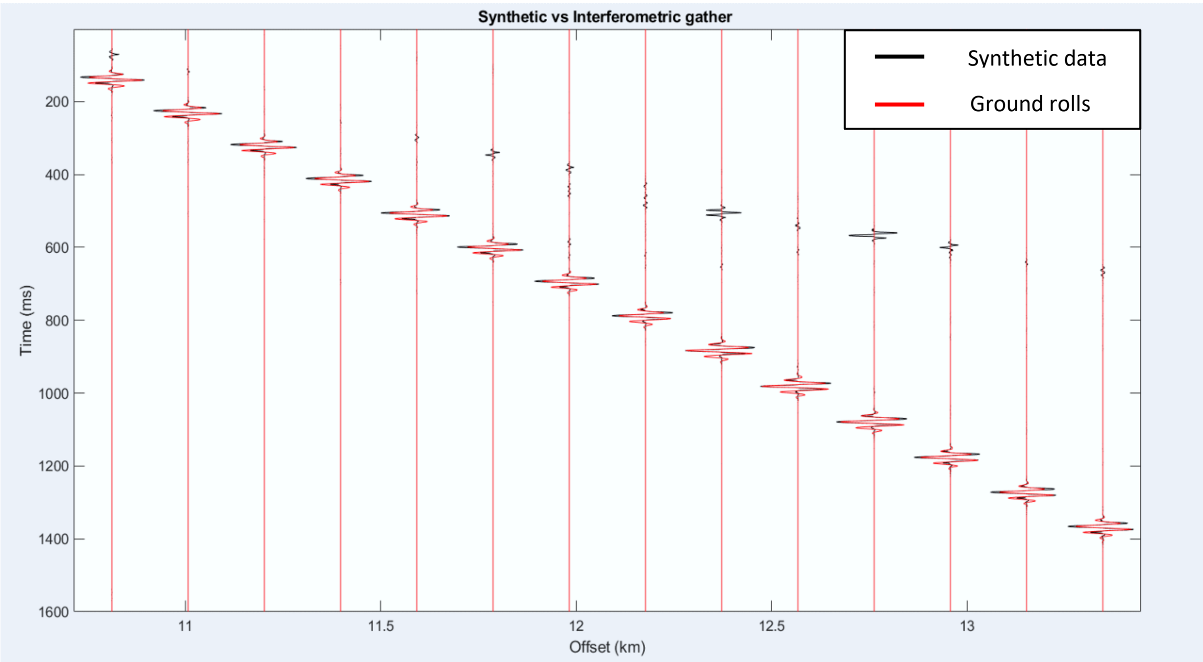


Figure 6 *(a) 2D complex velocity model (b) Comparison of synthetic data and estimated ground rolls. The shot gather is calculated for the area encompassed by the black rectangle in a). Note that due to the very large amplitudes of ground roll, the other wave types are barely visible in the above diagram.*

The synthetic shot gather for the model in Fig. 6a, corrected for the estimated ground roll, is shown in Fig. 7. The ground roll has been suppressed effectively, while the reflection events crossing the ground roll have mostly been preserved during the filtering process, as desired. However, it can be clearly observed that a further processing is required to achieve a better match between the observed and interferometric surface wavefield.

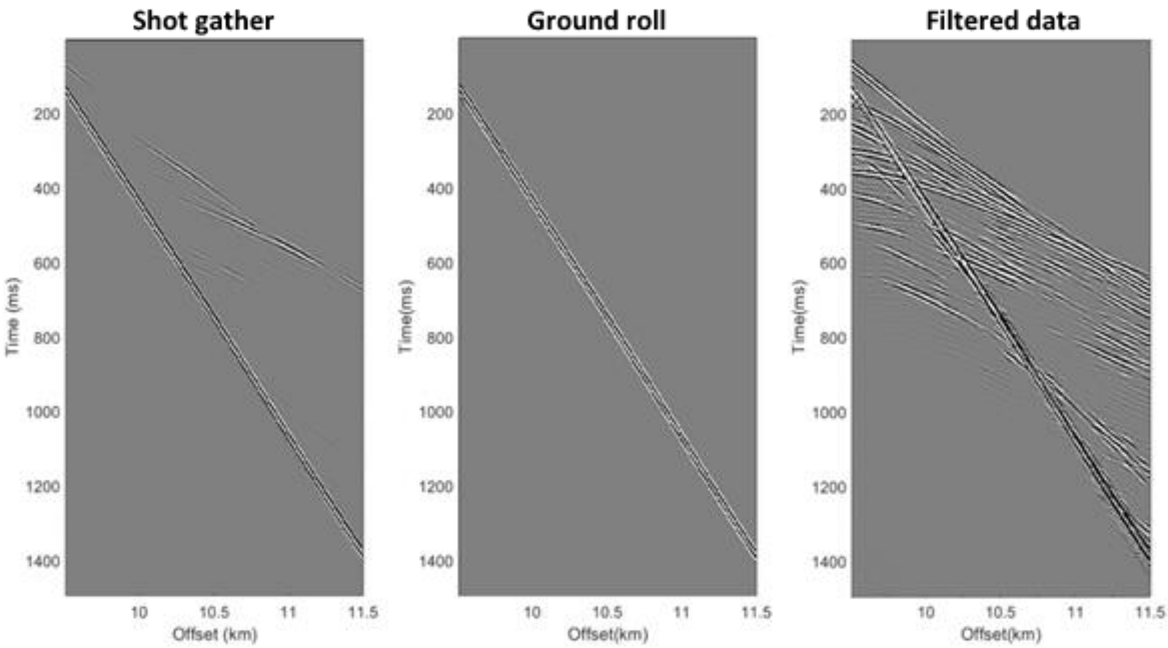


Figure 7. *(a) Shot gather data (b) estimated ground roll using interferometry (c) filtered data using least square subtraction method.*

Interim conclusions

We have shown synthetically that surface waves propagating between two surface locations can be predicted and removed from the active data using seismic interferometry. The accuracy of the surface wave prediction and their separation from the reflection events depends on the number of sources used for the cross-correlation. The reason is that with the increasing number of sources, the cancellation of the reflection events with various travel times (physical and non-physical) becomes more efficient, while the surface wavefield stacks constructively for any source position. This was illustrated by using a simple 2-layered model.

A complex model which includes horizontal and vertical velocity gradients was used to illustrate the suitability of the method for the real-Earth scenario. Despite the strong complexity of the model, the reflected and surface waves were separated to a large extent. This owes to a data-driven concept on which the interferometry lies.

This part of work, however, highlighted the requirement of additional shaping of the interferometric surface wavefield in order to match the recorded data.

Matching the interferometric and recorded surface waves

A further improvement is required in the shaping of the interferometry-synthesised surface waves in order to efficiently remove them from the reflection data.

The cross-correlation is a process in which the amplitude spectra of the two input signals are multiplied, while their phase spectra are subtracted. Consequently, apart from the fact that the amplitude spectrum of the resultant signal is changed, its phase spectrum contains only the information of the phase difference between the two input records, while the information about the initial phase of the actual recorded surface wave is lost. In a case of two closely spaced station with almost identical surface waves records, their cross-correlation will be a nearly zero-phase signal with the amplitude spectrum which is the square of the input amplitude spectra. In layman terms, the consequences can be described as follows:

a) In the case of the identical input zero-phase signals (e.g. Ricker wavelet), the resultant wavelet will comprise side lobes, which will make the direct subtraction of the observed and interferometric data less efficient (Fig. 8)
b) In the case of the identical non-zero-phase signals, the resultant wavelet will be zero-phase due to the loss of the phase information during the cross-correlation (Fig. 9)

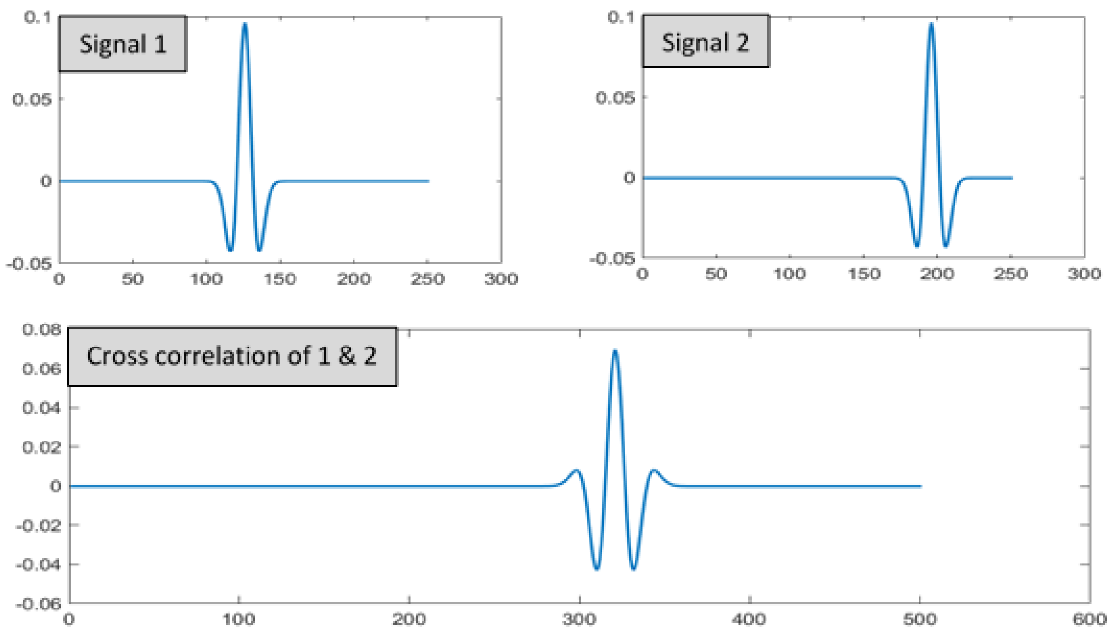


***Figure 8**. (top) Input zero-phase signals 1 and 2 (bottom) Cross correlation of signals 1 & 2. Note the side lobes of the cross-correlated signals which prevent the exact matching between the signal 1 (or 2) and the cross-correlated signal.*

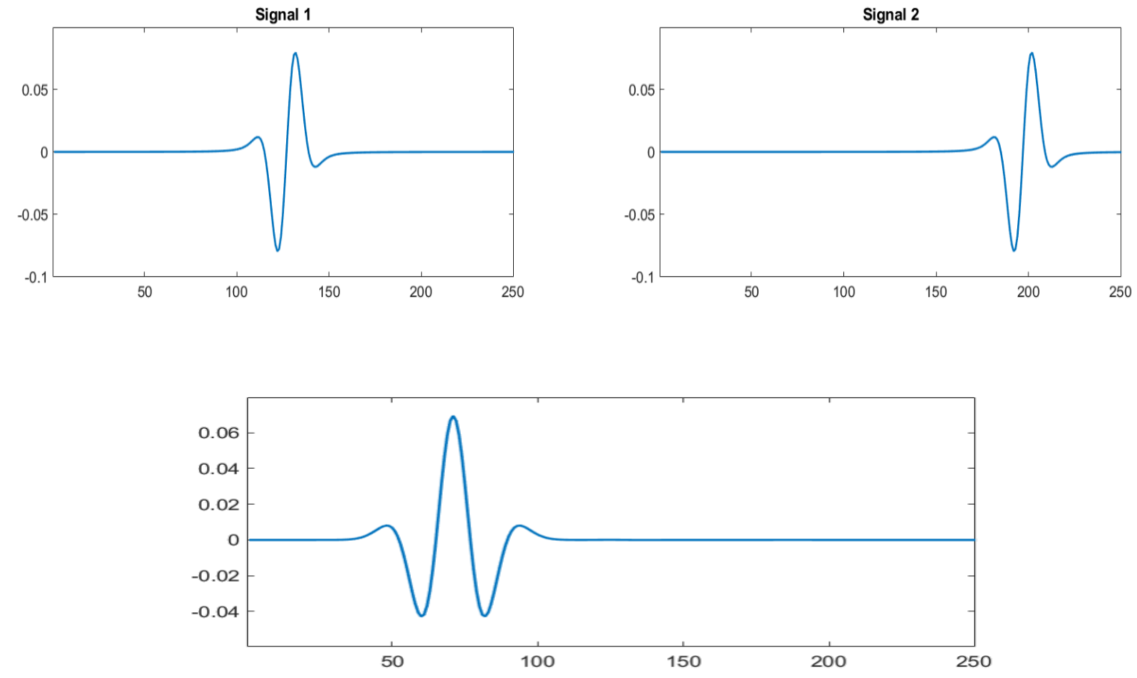


Figure 9*. (top) Input non zero-phase signals 1 and 2 (bottom) Cross correlation of signals 1 & 2. Note that the output signal lost the information about the absolute phase of the input signals, which prevents the match between the cross-correlated and input data.*

Thus, the interferometric signal contains the information about the phase difference between the two receivers (virtual source-receiver pair), while the absolute phase of the observed surface wavelet is lost. In order to match the two, the direct interferometric result should be combined with the amplitude and phase information of the one of the observed wavelets. This can be achieved through the process of deconvolution (alternatively, the convolution could be used for convenience to recover the phase, but additional manipulation is needed in that case to correct the side lobes of the output wavelet).

The procedure was tested on the simple 2-layered model shown in Fig. 2 and the results are shown below in Figs. 10-13. Note the diminishing of the side lobes on the interferometric data after deconvolution in the right panel of Fig. 10. The nature of the improvement is clearly visible in Fig. 11, where the trace 120 is shown. The difference in the efficiency of the ground roll removal from an observed shot gather by the pure cross-correlation interferometry and deconvolution interferometry is shown in Fig. 12. A large improvement can be noted in the case of deconvolution. This can be furtherly illustrated by examining the single-trace residuals in Fig 13.

A small implementation problem stems from the fact that the deconvolution time-shifts the cross-correlation gather, so the search over different time-shifts needs to be combined with the adaptive subtraction in order to find the minimum residual of surface wave. Such a procedure is time consuming and needs to be optimised. This is the subject of immediate further study.

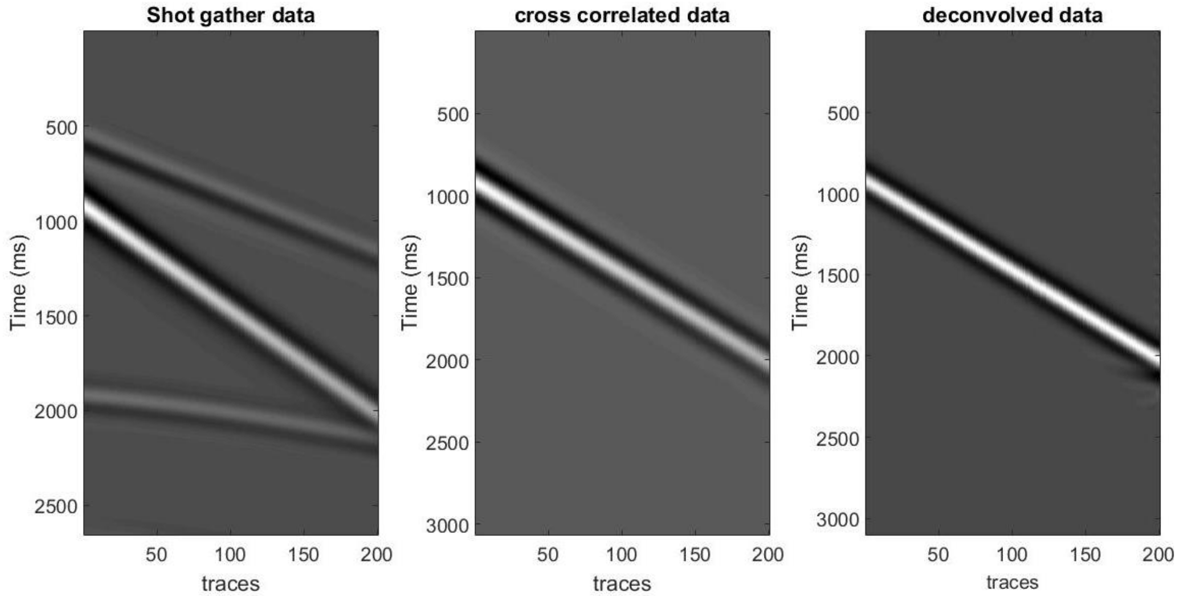


Figure 10. *(left) A shot gather for the simple model in Fig. 2a; (middle) Cross-correlated (interferometric) surface wavefield; (right) the interferometric surface waves after deconvolution. Note the diminishing of side lobes.*

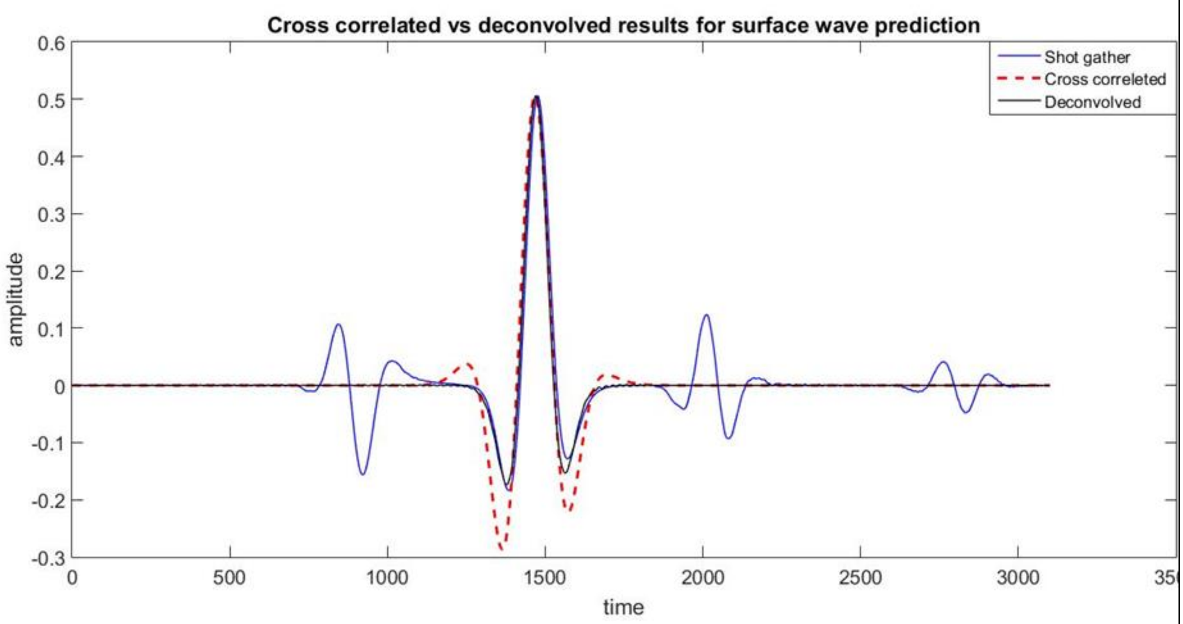


Figure 11. *Observed data (blue), cross-corelated surface waves data (dashed red), and cross-correlated and deconvolved data (black), for trace 110 in Fig. 10. Note the cancellation of the side lobes and excellent match between the observed and deconvolved interferometric data.*

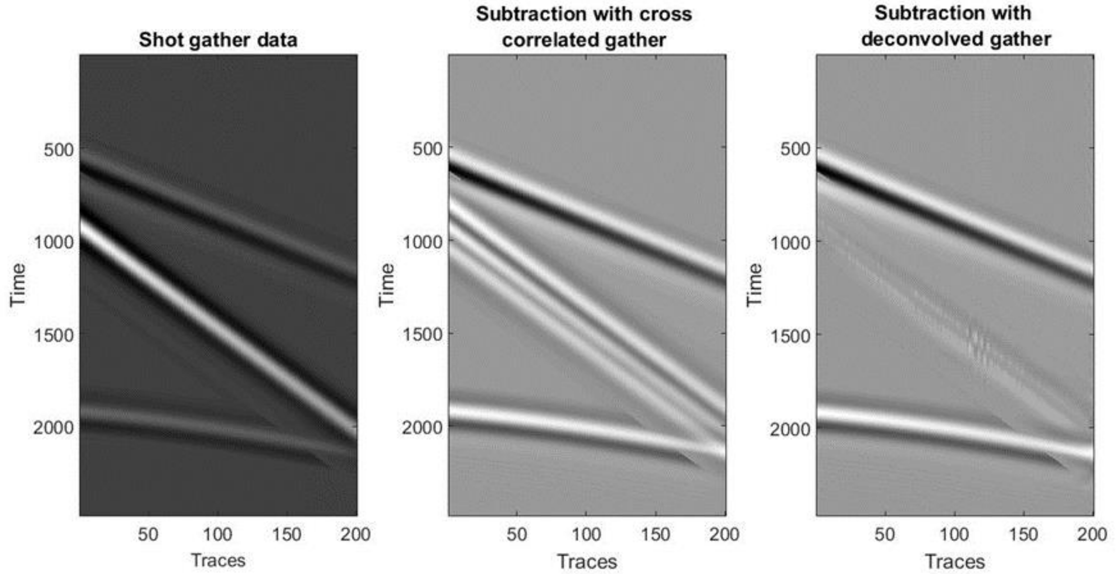


Figure 12*. Surface wave removal from shot gather. (left) the observed shot gather; (middle) remaining strong side lobes after the interferometric surface-wave removal using cross-correlation only; (right) minimal surface wave residual after correcting the input data with the deconvolved interferometric gather.*

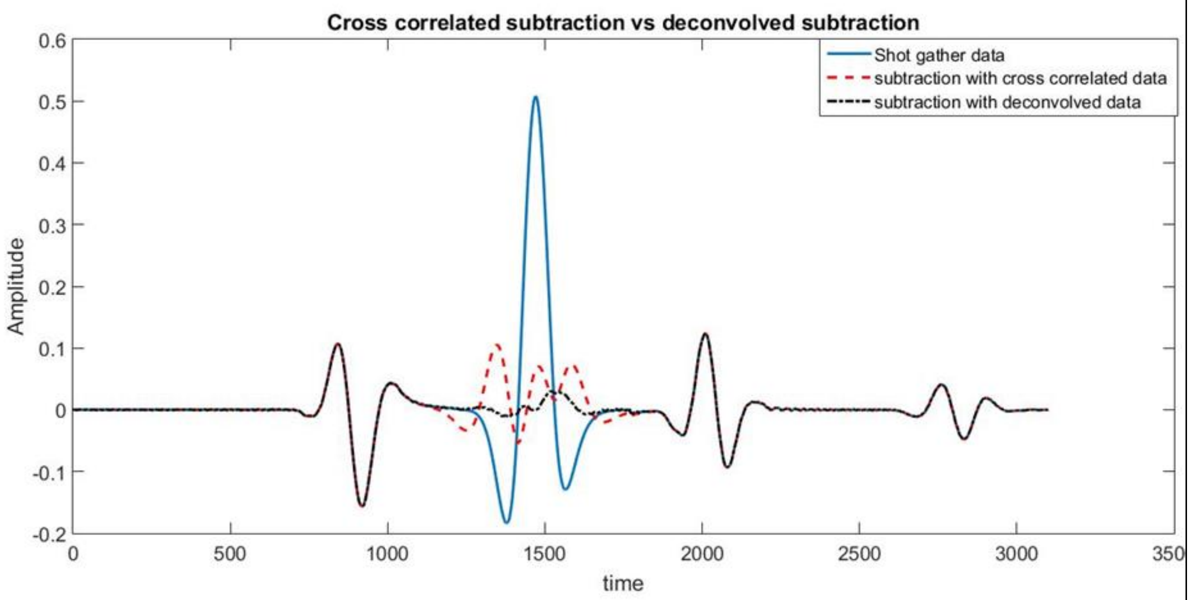


Figure 13*. The residual of the surface wave wiggle after correcting it with the cross-correlation interferometric data (dashed red line) and deconvolved interferometric data (dotted black line). Note the large improvement by using the deconvolution.*

The results presented in this report suggest that the interferometric data combined with the spectral information of the observed surface wavelets is a promising data-driven approach to remove surface waves from seismic reflection data. It can be particularly advantageous in the complex onshore settings where the geophone arrays and f-k filtering are usually not efficient enough. After fully implemented, the method will be tested on a demanding real dataset from the highly scattering medium.

References:

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Wapenaar, K. and Fokkema, J. (2006) 'Green's function representations for seismic interferometry', GEOPHYSICS, 71(4), p. SI33-SI46. doi: 10.1190/1.2213955.

(ii) Implementation (please include any issues with timelines, milestones, management etc. or deviations from the original implementation plan)

Both reviewers suggested that the proposed timelines are too short for such a project. Accordingly, the project was extended from the originally proposed 6 to 8 months. Although such a project requires at least a year of the active research, the maximum available funds – if spread over a year – would not be sufficient to attract a skilled Research Assistant. The 8 months compromise were long enough to develop a concept for the proposed work, but it was not sufficient to fully implement and publish the findings. However, the candidate expressed his interest in conducting further research and publishing the paper, beyond the timelines of the project. The main risk involves his employment in an Oil and Gas company outside Ireland immediately upon the project end.

(iii) Outputs (please provide a short description *and* complete the table below)

Output 1: Development of the concept for the exact surface wave matching by interferometric output in a complex medium. It involves the cross-correlation of the signals generated by multiple active sources followed by (de)convolution, in order to reconstruct the surface wavefield separated from reflection events. Due to the short project time, the best practices and full implementation of the methodology are still under investigation.

Output 2: Matlab codes for (i) generation of the cross-correlation gathers from recorded data, and (ii) adaptive subtraction of the interferometric from the real/synthetic data. The codes assume sorting the data by some auxiliary dedicated software prior to applying the cross-correlation. The current approach in adaptive subtraction assumes the adaptation of the amplitudes of the interferometric shot gather in order to minimise the residual energy when subtracted from real/synthetic data.

Task No.	Deliverable description	Planned delivery (as per proposal)	Date of delivery
1	Matlab code for generating cross-correlation gathers from recorded data	Month 3 (according to the reviewers' recommendations, available time and funds, the duration of the project was extended from the proposed 6 months to 8 months → the deliverable times were shifted accordingly)	17/08/2018
2	Matlab code for adaptive subtraction (least squares) of surface wave recorded by SI from the recorded shot gathers	Month 4.5	1/9/2018
3	Final report	Month 6 (proposed end of the project)	15/11/2018

Publications to date:

Lokmer, I.; Barala, S.; O'Brien, G. (2018): Surface wave interferometry: an application to seismic reflection data, Geoscience 2018 (Geological Survey Ireland), Dublin Castle, Dublin, Ireland, 6-NOV-18.

4. Data/outputs submitted with final report *(please list the documents, presentations, datasets etc. submitted with this report)*

a. Matlab codes for calculating cross-correlation gather from the recorded/synthetic data and subtraction between the real/synthetic and interferometric data: ***SI_Codes.zip***

b. Poster presented at *Geoscience 2018* conference: ***GSI_SurfWaveInterferometry_Nov2018.pdf***

c. Final invoice for the outstanding amount of the budget.

SUPPLEMENTARY MATERIAL

Impact/value of the project

Theoretical advances in geophysics have significantly impacted our understanding of the Earth and have allowed us to produce the images of the subsurface at unprecedented levels of detail. It is now common to image paleo-river systems at the metre scale under 3 km of rock and 2 km of ocean let alone the feat of imaging the Earths deep interior. However, these theoretical advances on their own are not sufficient to answer scientific questions or routinely image the subsurface. Data quality and advanced computational techniques are necessary to extract any benefit from theory. The practical implementation of any method, in this case seismic interferometry, is crucial to its success and adoption in academic studies and industrial applications. By undertaking this pilot study into the practical aspects of SI for surface wave removal, not discussed extensively in the literature, the value of this theoretical method can be quantified. When accomplished and tested on real data, this will impact academic studies where this method is being employed but often without thorough assessment of the data quality and hence resultant outputs. From an industry perspective, investment in methods which may not offer any potential uplift on cheaper techniques is inefficient. The ability to screen and selectively pick the appropriate methods has a significant impact on workflows and costs. Hence we are thankful to the Geological Survey Ireland who made it possible to carry out this pilot study and strengthen the ties between the academia and industry in a sensible and mutually beneficial manner. To our knowledge, this type of study was not carried out in Ireland before, on an academic or industrial level. Finally, other areas requiring images of the shallow subsurface, e.g. hydrology and wastage and contamination studies, can benefit from a practical guide to advanced theoretical seismic methods where the expertise or knowledge to fully exploit detailed seismic theory may not exist within these fields.