PACIFIC

Passive seismic techniques for environmentally friendly and cost efficient mineral exploration

D3.2 – Successful extraction of body-wave data

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<tr>
<th>Grant agreement number</th>
<th>Due date of Deliverable</th>
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<td>776622</td>
<td>30/04/2019</td>
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<td>01/06/2018</td>
<td>10/05/2019</td>
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**Description**

Report on the completion of the retrieval of nodes at the Marathon pilot site.

**Dissemination Level**

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Executive Summary

A key goal of the PACIFIC project is to develop methodologies for the extraction of body waves from passive seismic data, for use in the environmentally sustainable environments. Recovering body waves from ambient noise data has proved to be challenging as they are usually weak and ambient noise fields are rich in surface waves. Here we propose and test a method, based on the Radon Transformation, that helps suppress surface waves and enhance reflected body waves. The method exploits the ‘moveout’ differences between reflected body (hyperbolic) and surface waves (linear) and is tested on synthetic 2D & 3D model data prior to its application to ambient noise field data. We refer to it as Radon Correlation. Synthetic tests are very encouraging, showing clear body wave recovery that cannot be seen in raw cross-correlated data. Using these synthetics to have a choice of parameters, we then move to field passive data from the Marathon site within PACIFIC. We generate virtual shot gathers by applying Radon Correlation to single virtual sources into a linear array of receivers. Again, results are very encouraging with clear reflected body wave recovery from the ambient noise data and determined by clear hyperbolic arrivals on the virtual shot gathers. There is a hint that using time windows that contain active blast seismic coda possibly further enhances body wave recovery. Finally, velocity analysis on these virtual shot gathers leads to a P-wave velocity model that compares well with models derived from surface wave dispersion analysis of the same ambient noise data. However, these models are not currently publicly available and hence are not shown here, in this report.
1 Introduction

Cross-correlation has been used to correlate recorded passive seismic signals at spatially distributed receivers in order to recover coherent seismic waves. These recovered seismic wavefields mainly comprise surface waves (Bakulin and Clearbout, 1968; Wapenaar, 2003) that mask weak body waves, making them difficult to detect. These recovered seismic waves can be used to characterize the subsurface (Weaver and Lobkis, 2001; van Tiggelen, 2003; Snieder, 2004; Scherbaum, 1978; Boulenger, 2015). The effect of source distribution, source strength, number of sources, the length of recorded signals and the topography of receivers have been discussed in the context of coherent arrival recovery (Thorbecke and Draganov, 2011; Shapiro and Campillo, 2004, Draganov et al., 2007, 2009). As mentioned, body waves are often absent or masked by strong surface waves following noise cross correlation. Noise sources themselves are often close to the Earth’s surface and rich in surface waves, mitigating against relatively strong body waves in the correlated wave field.

The aim of this report is to outline a pathway to body wave extraction, so that these body waves can be used to image the subsurface. Here we focus on an approach which we call Radon Correlation.

One of the key distinguishing features between surface waves (“ground roll”) and reflected body waves crossing a linear seismic array is the ‘moveout’. Surface waves with in-line sources show a linear moveout of the true velocity of propagation. In contrast, body waves with an in-line source exhibit hyperbolic moveout across the array. This difference can be exploited to suppress surface waves and enhance body waves. Specifically, we use the Radon-correlation to correlate the signals using a hyperbolic geometry in an effort to extract body waves. Radon-correlation is not a simple correlation method. It is an inversion-based correlation that looks for reflection hyperbolic events as model-space properties. Each hyperbola is defined by time-velocity-offset inputs. During correlation, surface waves are eliminated from the section by employing a low velocity elimination procedure. By cross correlating a given receiver with all other receivers (in a profile, for example), virtual shot gathers can be created. Using Radon-correlation permits the extraction of hyperbolic (reflected) events from these virtual shot gathers. These events can then be used to image the subsurface using standard reflection seismic methodologies.

Since the main objective is to extract body waves from ambient noise data and to evaluate our extraction scheme, it is important to first apply the Radon Correlation method on synthetic simulated signals from a known model. To do so, synthetic passive signals have been simulated using a full wavefield elastic wave propagator, through 2D and 3D models. In this report we only include one simple 2D case to demonstrate the principle and basic performance, prior to an initial test application on real data from the Marathon site.
2 Seismic Modelling

2.1 2D Elastic Seismic Modelling

Wave simulation snapshots from a single homogenous layer model (1000m x 400m) with Vp = 1600 m/s is shown in Fig 1, to demonstrate elastic wave propagation through a model. The full wavefield forward modelling scheme is based on a standard finite difference staggered grid (Virieux, 1986). The source is a vertical force mono-pole Ricker wavelet with a dominate frequency of 15 Hz.

![Wave simulation snapshots](image)

**Fig 1 Snapshots of recorded elastic wavefield in Vertical (left panel) and Horizontal (right panel) components at 0.075, 0.125 and 0.175 (s) from top to bottom.**

This scheme captures the full elastic wavefield and can be used for arbitrarily heterogeneous velocity structures. It is implemented in both 2D and 3D.

2.2 Simulating Passive signal

In the physical world, noise is continuous and varies in ‘quality’ in space and time, hence stacking correlation functions is an important part of the processing procedure. Here we simulate passive seismic signals by using many shots (~ 500) that are shifted in phase and space within a given simulation (Fig 2), generating a random wavefield. Each trace is recorded for 0.6 sec on synthetic receivers 5 m apart. For stacking purposes, we run this scenario 10 times, each time with a different random set of shot locations and timings. We apply this procedure to a simple two-layer model, demonstrated in Fig 2.
**Fig 2** A simple two-layer model with P-waves velocities broadly appropriate for the Marathon site (Vp1=4000m/s; Vp2=5000m/s). Randomly located and timed shots near the surface of the model (light blue stars) are used to generate a noise field.

**Fig 3** Wavefield generated by the shot distribution in Fig 2.

Fig 3 shows the recorded passive signals for this synthetic simulation (generated by a multitude of randomly distributed phase-incoherent shots). As the sources are close to the surface, they generate a substantial amount of surface waves. Fig 4 shows the cross correlation of the first trace with all other traces along the profile. This can be considered as a virtual shot gather. This figure is dominated by coherent ground roll (surface waves) and there is no evidence of a reflected P-wave from the interface at 800m depth, on this virtual shot gather (see Fig 5 for comparison).
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D3.2_SUCCESSFUL EXTRACTION OF BODY-WAVE DATA

The Normalized cross-correlation of the first trace with all other traces

Fig 4 Virtual shot gather – the cross correlation of the first trace with all other traces along the profile (for the data in Figure 3).

Fig 5 Active source shot gather for the model in Fig 2– the shot is located at the second receiver and recorded at all other receivers across the profile. Several arrivals can be seen (i) direct P-arrival (ii) ground roll (iii) reflected P from interface at 800m depth (at 0.4s at zero-offset) (iv) P-to-S conversion from the interface at 800m depth.

Fig 5 shows the results of a synthetic active shot in the velocity model in Fig 2. As expected, a clear reflected branch can be seen from the interface at 800m depth indicated by (iii) in the figure.

We have also tested a second model with thinner, lower velocity layer at the surface (Fig 6). In this case we generate noise by distributing sources throughout the model. The rationale for this is to see the effect of having our noise field already rich in body waves. We follow the same procedures as outlined above (see Fig 7 and Fig 8). As expected, the noise field is less 'structured' than in Fig 3. Nonetheless the cross correlation of the first trace in this noise field with all other traces in the profile (a virtual shot gather, Fig 8), does not show a body wave reflection associated with the reflector at
110m depth. The autocorrelation of the noise traces is shown in Fig 9, there may be a hint of the reflector at the Two-Way Time (TWT) equivalent to 110m depth, but it is very weak (if present).

![Fig 6](image1.png)

*Fig 6* The light blue stars show the locations of the arbitrary sources throughout the model.

![Fig 7](image2.png)

*Fig 7* Recorded passive signals due to activation of 501 sources distributed arbitrarily throughout the model in *Fig 6*.

We hypothesise that the reason for poor reflection recovery is that the data are dominated by coherent linear arrivals that could mask hyperbolic events associated with reflected branches.
In the next section we introduce a processing method in order to enhance hyperbolic arrivals and suppress linear arrivals, to extract reflected body waves from passive data. We start by using synthetic data from Fig 2-Fig 4 inclusive.

### 2.3 Correlation in Radon domain

The Radon transform is defined by Johan Radon (1917) as an integral of some physical property of a medium along a particular path, which is given by

\[
u(\tau, p) = \int d(x,t = \sqrt{\tau^2 + p^2 x^2})dx\]

Fig 8 Virtual shot gather. The cross-correlation of the first trace with all other traces in the profile.

Fig 9 The auto-correlation section for data in Fig 7.
In exploration geophysics, if \( d(x, t) \) is the original seismogram, \( u(\tau, p) \) is the data in the Radon transform domain. \( t \) is the two-way time, \( x \) is a spatial variable such as offset, \( \tau \) is the intercept two-way time and \( p \) is the slope of the curvature on which the transform trajectory is defined.

The conventional inverse Radon transform is given by

\[
d(t, x) = \int d(p, \tau = \sqrt{\tau^2 - p^2 x^2}) dp
\]

The procedure can be undertaken in both the time and frequency domain. In this report we applied damped least square method to move from data-space to model-space. The advantage of employing the Radon transform is its ability to find seismic arrivals with a hyperbolic shape, in the passive seismic section, as we expect these shapes from reflected body waves. A search can be made for these curves based on a velocity sweep between a chosen range (the bottom of the range should be larger than the ground roll velocity, if not it will get smeared-in and short offset range and may appear as a shallow reflection). Another advantage of applying Radon is its ability to eliminating the linear events that dominate the recorded signals.

### 2.4 Extracting body wave from passive signals using Radon Correlation

The results of correlations demonstrated that we were unable to see hyperbolic events related to body waves especially in the short time window available for stacking (Fig 4). In order to extract body waves from recorded passive signals, a processing module called Radon-correlation is designed to remove unwanted linear events during correlation. We test the Radon-correlation method on the simple 2D velocity model shown in Fig 2 and the synthetic passive data from Fig 3. Here, for each virtual source-receiver pair, we calculate the Radon Transform for 10 different realisations of the passive noise field, and stack the 10 results for that pair. The method gives some very promising results. A clear reflected branch associated with the reflector at 800m depth can now be seen in the virtual shot gather in Fig 10. This event is clear enough to allow excellent recovery of the velocity and structure of the underlying medium, from passive reflection data.

![Fig 10 Virtual shot gather following Radon Correlation (RC) processing of synthetic ambient noise. The original data area from Fig 3. Compared with Fig 4 (which contains the same data, prior to RC processing). Compared also to Fig 5, which is the equivalent active shot gather. Here ground roll has been removed by the RC processing. The apparent arrival at 0.08 sec (at zero offset) is likely smearing of unwanted ground roll. The arrival at 0.4 sec (at zero offset) is a recovered reflection from the interface at 800m depth in Fig 2.](image)
2.5 Extracting body waves from real recorded passive signals

2.5.1 Extracting body waves using Radon-Correlation

Since the Radon-correlation shows the ability to detect body waves from synthetic signals, here we apply the method to real recorded passive signals. As we have a lot more data available in comparison to the synthetic case, for the real data case we stack the correlations first and then carry out the Radon Transform on the stacked data. Stacking is undertaken over 100,000s of 2 sec windows. We used the recorded signals to generate virtual shot gathers on 01 Oct and 09 Oct, as examples. We chose the 09 Oct window as it also has an active off-line blast which generates substantial coda.

Fig 11 shows recorded ambient noise signals along line 1004 (Fig 12), the result of stacked cross-correlation for an hour recording (01/Oct), the result of stacked auto-correlation for an hour recording (01/Oct) and the result of applying Radon Correlation on stacked cross-correlated data. It is clear from the hyperbolic arrivals that the application of Radon Correlation has succeeded in extracting reflected body waves from the real ambient noise data. There was no active blast in this time window.
Fig 11 (a) The recorded passive signal at line-1004; (b) Normalized cross-correlation result; (c) Normalized auto-correlation result; (d) Extracted body waves using RC.
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Fig 12 The location of laid out sensors (blue circle colour) and the boreholes (Orange circle colour).

Fig 13 Extract body waves on 09 Oct using Radon Correlation on a virtual shot gather. An active blast is present in this window and its coda waves form part of the ambient noise field at the time used in this figure.

Fig 13 shows body waves extracted from the field data using Radon Correlation, in a time window that included an active blast rich in coda waves. It can be seen that clear body waves have been recovered in the virtual shot gather and that the blast may have enhanced body wave recovery (compared with Fig 11).

Finally, we have used a suite of virtual shot gathers from the real data to undertake body wave velocity analysis along the profile, allowing us to derive a body wave velocity structure (in addition to a preliminary identification of some reflectors). Although these models are not shown in this report,
initial comparisons between this body wave model and models derived from surface wave dispersion analysis of the same ambient noise data, are very encouraging.
3 Conclusion

In the report we highlight progress made in the recovery of reflected body waves from ambient noise data in a mining environment. Specifically, we have used Radon Correlation (RC) to highlight hyperbolic events that are related to propagating body waves in the subsurface. The result of RC on synthetic data shows that extracted body waves from passive synthetic data show a good matching with events from synthetic active shot records created from the same models. This method has been applied to recorded signals by sensors located on line 1004 in the Marathon dataset, showing clear reflected body wave recovery. A total of 122 virtual shot records were created that can be used, through employing standard reflection methodology, to image the sub-surface.
4 Bibliography


