Receiver Function Analysis of Time-Lapse 3-C/3-D Seismic Reflection Data

Le Gao and Igor Morozov
University of Saskatchewan, Saskatchewan, Canada. Email: le.gao@usask.ca

Abstract
The receiver-function (RF) technique is a useful approach for constraining the S-wave velocity and travel times of the near surface. RFs are time series representing the time delays and relative amplitude variations between the direct P- and S waves converted in the near surface. Although being one of the primary tools of earthquake seismology, the RF method is still poorly studied for exploration seismic datasets. Nevertheless, RF images should be useful for determining the S-wave statics and mapping the variations of the shallow subsurface in various exploration applications. We apply the RF method to three vintages of time-lapse, 3C/3D reflection data collected at the Weyburn oil field in southern Saskatchewan, Canada. Travel-time lags of converted (P/S) waves within the shallow subsurface are mapped for each acquisition year as well as their time-lapse variations. The results reveal a general variation in the P/S lags across the study area and also shallow ‘channel’-like structures in the time-lapse RF images. By combining the RF results with the P-wave refraction model, S-wave statics are also calculated for the dataset. The mapped statics also indicate similar spatial variations within the study area.

Introduction
The shallow subsurface contains strong variations of low seismic velocities that often lead to significant and highly spatially variable travel-time perturbations (statics) affecting the deeper reflections. Knowledge of the shallow subsurface is critical for surface reflection imaging on land, and especially for evaluating the statics. Shear- (S-) wave statics represent the greatest challenge, because compared to the compressional (P-) wave velocity, the S-wave velocity is much lower and the values of S-wave static shifts can be 2-10 times larger than P-wave statics (Li et al., 2012).

Receiver functions (RF) are among the most reliable and high-resolution approach for constraining the S-wave velocity structure of the near subsurface, particularly in combination with surface-wave inversion (Moreira et al., 2013, Lawrence and Wiens, 2004). The RF approach relies on dense receiver coverage, three-component (3-C) recording, and multiple shots conducted from different azimuths. The principle of RF imaging of the shallow S-wave structure consists in identifying the P- to S-wave (P/S) mode conversions trailing the direct and/or reflected P waves. This method originated in earthquake seismology, where it currently represents the standard tool for mapping the S-wave velocity structure and layer thickness within the crust and upper mantle of the Earth (Langston, 1979; Ammon, 1991). The first application of the RF method was given by Vinnik (1977), who identified the P/S waves converted on the 410 km and 660 km discontinuities within the mantle. This method has also been applied in much shallower, wide-angle, controlled-source studies, in which it allowed mapping of 200 m to 15 km thick sedimentary covers (Morozov et al., 1998; Morozov and Din, 2008). In reflection seismic exploration, the first applications of the RF method were given by Li (2002) and van Manen et al. (2003), who used the RFs to constrain the S-wave statics.

The procedure for computing the RFs (summarized below) uses deconvolution of the source signature, which reveals detailed information about the relatively shallow layers beneath the receiver. By means of RF deconvolution, the converted S-wave energy can also be removed from the vertical component of reflectivity, which could improve the fidelity of reflection P-wave imaging. However, RF analysis is still not commonly performed on 3-D reflection seismic data on land, and there exist very few tools suitable for it in the conventional reflection processing software.

In this paper, we illustrate the RF analysis in 3C/3D seismic data by using a time-lapse dataset acquired as part of the International Energy Agency Greenhouse Gas R&D Programme CO2 Capture and Storage Project in southern Saskatchewan, Canada (White, 2009). We show how the receiver functions can be extracted from exploration records and used for mapping shear-wave velocity variations to the depths of about 10-100 m. With detailed receiver sampling and comparatively high frequencies of a reflection dataset, detailed 2-D maps of the near-surface S-wave velocity and statics are obtained.

Method
In the convolutional earth model, the seismic record is a convolution of the source wavelet, the reflected and/or converted P- and S-wave signals, and receiver response. For a 3-C signal, the corresponding receiver functions can therefore be obtained by applying a common inverse filter, $W^{-1}$, to each component of the records (Morozov and Gao, 2014):

$$
\begin{pmatrix}
R_Z \\
R_R \\
R_T
\end{pmatrix} =
\begin{pmatrix}
W^{-1}u_Z \\
W^{-1}u_R \\
W^{-1}u_T
\end{pmatrix},
$$

where $R_Z$, $R_R$, $R_T$ are the vertical, radial and transverse receiver function respectively, and $u_Z$, $u_R$, $u_T$ are the components of the seismic record at the receiver. Generally, the inverse filter...
$W^{-1}$ is constructed by spiking the direct P-wave arrival in the vertical component. The inverse filter in equation (1) removes the waveform signature and isolates the converted-wave responses in horizontal components. This procedure represents deconvolution aiming to highlight the difference between the primary P- and secondary P/S-wave travel times above the converting boundary.

In contrast to the typical case in earthquake seismology, the primary P-wave in exploration cases represent refractions travelling subhorizontally and approaching the receivers at oblique angles. Figure 1a shows the receiver end of a refracted P-wave ray in a layered model with two possible secondary rays corresponding to a P/S mode conversion and a P-wave multiple reflection from the free surface. The principle of RF imaging consists in picking the time lag between the primary P wave and the following peak in the deconvolved horizontal components (Figure 1b).

For a consistent secondary arrival identified in the RF, we should verify the certainty of the converted P/S conversion or P-wave multiple interpretation (Figure 1a). First, the RF peak can be due to the time lag $\delta t_{ps}$ between the primary P-wave and converted S-wave arrivals (dashed line in Figure 1a). By approximating the converted S wave as traveling near vertically, its time lag relative to the refracted P wave can be estimated by using as (Morozov and Din, 2008):

$$\delta t_{ps} = h \left( \frac{1}{V_s} - \frac{\cos \theta_p}{V_p} \right), \quad (2)$$

where $V_p$ and $V_s$ are the P- and S-wave velocities, respectively, $h$ is the thickness of the low-velocity overburden, and $\theta_p$ is the critical angle for P waves.

Another possible interpretation of the RF arrival is the P-wave multiple between the free surface and the refracting boundary (grey lines in Figure 1a). Theoretically, at near-vertical incidence, such a multiple is cancelled by RF deconvolution (Ammon 1991). However, in controlled-source RF recordings, and particularly at large incidence angles, this cancellation may be incomplete and complicated by the local structure (Morozov and Gao, 2014), and therefore, we need to consider the Ppp interpretation. The time lag $\delta t_{pp}$ between the primary P and Ppp waves can be expressed as:

$$\delta t_{pp} = \frac{2h \cos \theta_p}{V_p}. \quad (3)$$

As illustrated in the next section and also in Morozov and Gao (2014), these two interpretations can be distinguished based on the travel-time moveouts with variable ray parameter, and also on the amplitudes.

Finally, if the observed RF lags correspond to P/S conversions (as in the next section), the S-wave statics ($t_s$) relative to the refracting interface can be derived based on the P- and S-wave velocities, P-wave static ($t_P$) and the measured RF lag:

$$t_s = t_P + \delta t_{PS} - h \left( \frac{\cos \theta_s}{V_s} - \frac{\cos \theta_P}{V_p} \right). \quad (4)$$

**Application to Weyburn 3-D/3-C Dataset**

The study area is located near Weyburn in south-eastern Saskatchewan (Figure 2). The survey included 630 shots and 986 receiver stations in 19 lines with nominal source and receiver intervals of 160 m. The general goal of the project was to monitor the propagation and possible leakage of CO$_2$ during its geological storage and enhanced oil recovery (White et al., 2004). In the present study, three time-lapse vintages of the seismic data are
used, which were acquired with nearly identical geometries of shot and receiver spreads in 1999 (baseline survey prior to CO₂ injection), 2001, and 2002 (monitor surveys).

Prior to the RF analysis, routine data reduction and processing was applied to the seismic data by using ProMAX and in-house software (Morozov, 2008). This processing started with trace editing and picking the first arrivals. The subsequent steps related to post-stack CMP imaging (modeling and correction for surface-consistent statics, amplitude equalization, and velocity analysis) were only conducted for the baseline dataset. Further processing aimed at accurate pre-stack calibration of the time-lapse seismic datasets. Time, amplitude, and phase corrections were applied to each monitor dataset on a trace-by-trace basis in order to match them with the baseline dataset (Morozov and Gao, 2009). This resulted with all three dataset vintages having a common (P-wave) refraction and stacking velocity models. In addition to these models, information about the time and amplitude calibration was retained as time-lapse information. After the pre-stack calibration of the amplitudes, the horizontal-component data were rotated into the radial and transverse directions relative to the source-receiver offsets. Finally, by using the common refraction and velocity models, filtering and stacking was performed for each of the three time-lapse datasets independently.

According to the refraction model derived during the reflection seismic processing above, the average depth of the shallow subsurface was near 26 m, and the average P-wave velocity below this boundary was estimated to be 2300 m/s. Above the refractor, the measured velocity was 1966 m/s. This boundary therefore represents an about 18% impedance contrast, on which significant P/S mode conversions as well as PpP multiples can be expected.

Figure 3. Application of RF to common-receiver gather from receiver #181: (a) Vertical RF and interpreted P-wave arrival times (red); (b) Radial RF and interpreted S-wave arrive times (blue)

Figure 4. The time differences between P- and S-wave arrivals calculated by RF method in each year. The black dots are the actual picks on common receiver gathers.
Receiver function deconvolution

To derive the RFs, we sorted the data into common-receiver gathers and aligned all records on the times of the first arrivals picked in the vertical component. After this, we constructed the minimum-phase spiking filters ($W^{-1}$ in equation (1)) for each trace in the vertical-component receiver gathers. These filters were then used to deconvolve the vertical, radial, and transverse common-receiver gathers from the corresponding vintages of the dataset. To reduce the high-frequency noise boosted by deconvolution, band-pass filters were applied to the resulting RFs. Finally, after visually inspecting the common-receiver RF sections and determining the ranges of records containing the optimal RF data quality, these ranges were stacked producing a single RF for each receiver.

A sample RF gather from one receiver is shown in Figure 3. As an input to the minimum-phase spiking deconvolution, the first arrivals in these records were aligned at 50 ms. The deconvolved vertical-component records should generally contain a single pulse within the deconvolution operator length, which can be used for quality control (Figure 3a). In the deconvolved radial RFs, the primary P-wave pulse is also the largest peak, followed by a peak caused by the interpreted P- to S-wave conversion. The records show a consistent, 30 ms lag between the S- and P-wave arrivals (blue and red lines in Figure 3). Due to the effects of noise and likely near-surface heterogeneity, there is a scatter in the values of times for different shots of about ±5 ms.

The observed travel-time RF lags correlate with the interpretation of P/S conversions in the near surface. To investigate the alternate interpretation of RF lags (Figure 3) being caused by a P-wave multiple, we use the predictions for the time lags in equations 2 and 3. Based on the refraction model parameters above and the S-wave velocity of 600 m/s, the time lag for the converted P/S mode should be $\delta t_{ps} \approx 35$ ms, and for a P-wave multiple, are and $\delta t_{pp} \approx 12.7$ ms in the forward modeling. The first of these values is close to the time lags observed in the data (Figure 3), and we can therefore associate these arrivals with P/S mode conversion. In addition, this interpretation is consistent with observing this arrival in the radial-component records.

After stacking the RFs for each receiver, the time lags were picked and spatially interpolated to obtain P/S lag-time maps (Figure 4). The P/S time lags range from 25 ms to 60 ms and show a general decrease from the northeast to southwest of the study area during each of the acquisition years, and especially in 2002. In 2002, the variation of the P/S lags are substantially larger than in the preceding surveys. From the histogram of the time difference picks (Figure 5), we can see that compared with 1999, larger time lags were present in 2002, which were also mostly distributed within the eastern part of the survey area (Figure 4).

Time-lapse results

The P/S lag-time maps from the monitor datasets were further compared with the baseline survey (Figure 6). The total variations of the time lags between the surveys range from about 8 ms to 8 ms. The time lags of the monitor datasets in most of the survey area are slightly reduced (by around 2 ms) relative to the baseline survey. These two maps also suggest several channel-like structures (green dashed lines in Figure 6) with P/S lag times decreasing from the northwest to southwest. These structures appear especially prominent in the comparison of year 2002 to the baseline (Figure 6b).

Based on the time differences between the P- and S-wave arrivals and the known P-wave velocity in the refraction model, we can estimate the S-wave velocity variations above the refractor. By inverting equation 2 for $V_s$, the estimated average S-wave velocity in the near surface is about 550 m/s. Because

![Figure 5. Histograms of time difference for the three years of data.](image-url)
Figure 6. RF time-lag differences between monitor and baseline surveys (labelled). The green dashed lines indicate the interpreted channel-like shallow structures. The black dots are the actual picks on common receiver gathers.

Figure 7. Relative $V_s/V_p$ ratio variations between the baseline and monitor surveys (labelled). The black dots are the actual picks on common receiver gathers.
the temporal variations of $V_P$ between the baseline and monitor datasets are corrected in our pre-stack calibration procedure, we only present the variations of the $V_S/V_P$ ratio between the baseline and monitors (Figure 7). From these maps, the $V_S/V_P$ ratio varies by about $\pm 15\%$ between the different years of acquisition, with relatively increased ratios within the channels interpreted in Figure 6. This variation can likely be explained by variations of water content and the depth of the water table in the different years of acquisition.

The relation of $V_S/V_P$ to the depth of the water table and generally water content within the subsurface is difficult to ascertain. On one hand, the shear-wave velocity is generally insensitive to water saturation, and therefore the observed variation of $V_S/V_P$ could be caused by the variations of $V_P$. On the other hand, pore- and wave-induced fluid flows affect the attenuation of $S$ waves. This attenuation should be strong in the near surface, and consequently it can cause wave dispersion and variations of $S$-wave velocities (De Meersman, 2013). Thus, a certain amount of shallow $V_S$ variation could be attributed to changing water saturation during the different years of data acquisition.

**S-wave statics**

An important application of the RF analysis to reflection seismic datasets is in inferring the S-wave statics, which could help improving the converted-wave reflection imaging (van Manen et al., 2003). Figure 8 shows the S-wave statics derived by using equation 4 for each acquisition year of the Weyburn dataset. From these maps, the S-wave statics vary from 20 ms to 40 ms and show a decreasing trend from the northeast to southwest. In 2002, some larger statics are also seen in the southeast corner, which are suggested by the larger P/S time lags in Figure 4. Unfortunately, converted-wave reflection imaging has not been performed for this dataset, and therefore these statics cannot be illustrated by a stacked image.

**Conclusions**

The receiver-function (RF) method is feasible and useful in land 3C/3D reflection seismic imaging as well as in time-lapse studies. Identification of converted-wave arrivals in the RFs leads to the measurements of the relative time lags between the $P$- and $S$-waves propagating within the near subsurface. Shallow $S$-wave velocities can be obtained by combining these time lags with $P$-wave velocities derived from refraction measurements. The resulting constraints on the near-surface $S$-wave structure allows improving the $S$-wave static corrections. By using independent RF measurements, the deviations of these statics from the conventional scaled $P$-wave statics can be detected.

In application to the Weyburn time-lapse reflection dataset, the time lags between the primary $P$ and converted $P/S$ waves are close to about 35 ms, which corresponds to the $S$-wave velocities of 550 m/s within the near surface. Spatial variations of the $P/S$ time lags and $V_S/V_P$ velocity ratios as well as their variations with time were mapped within the study area. The temporal variations are interpreted as related to changes in water content within the near surface affecting the $P$-wave velocities, and potentially to some degree $S$-wave velocities as well.

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