## Title:
## A Time-Frequency Approach to the Analysis of Time-Lapse VSP

Anna Droujinina[†,‡], Colin MacBeth[‡] and Patrick Corbett[‡]
[†]British Geological Survey, West Mains Road, Edinburgh, UK
[‡]Department of Petroleum Engineering, Heriot-Watt University, UK

## SUMMARY

An equalization tool based on the time-frequency representation of a signal (Cohen,1995) is applied to repeat VSP data. It is shown that this processing distinguishes between the footprint of the acquisition components and subsurface changes. The advantages of the method are compounded by the use of the Wigner-Ville transform, which has a higher resolution than the Short-Time Fourier transform or the Wavelet transform (Tobback et al.,1996). This makes it possible to monitor small changes in seismic attributes more effectively and examine the repeatability of seismic sources. Time-frequency filtering is a particularly effective technique for removing the random components of seismic signals, and also has the potential to eliminate the footprint in 4-D seismic data and, hence, to extract information about changes in reservoir properties present in seismic data.


## INTRODUCTION

In reservoir monitoring, changes in seismic attributes are normally associated with rock properties. However, seismic data are also very sensitive to acquisition parameters, recording system characteristics and near-surface conditions, which also change with time. It is thus extremely important to eliminate these as they cause differences in seismic attributes from one survey to another that do not directly correspond to subsurface changes, and complicate interpretation of the time-lapse data. Here, we avoid the commonly used data "matching" techniques for tackling the repeatability problems of time-lapse data. This is because of the difficulties in finding a satisfactory calibration event, as all parts of the subsurface could change during stress re-distribution. Instead, we propose transforming seismic signals into the time-frequency domain.

Time-frequency representations for a wide variety of purposes are well developed within sonar and speech analysis, and also music decomposition (timbre morphing). In fact, linear time-frequency representations of seismic signals via the Short Time Fourier transform have been actively used in seismology and seismic processing since the 1960's. Unfortunately, the linear representations have a limited resolution when discriminating weak reflection patterns in seismic data with a high noise content. In seismic literature, non-linear methods based upon the bilinear representations have been published only in recent years (Tobback et al.,1996). In particular, the Wigner distribution function (WDF) has been shown to be far more effective, due to its better localization properties. Here, it is shown that the WDF can be applied to problems that arise in the field of time-lapse VSP.

## TIME-FREQUENCY ANALYSIS

The time-frequency distribution is a transform that maps a 1-D signal into a 2-D time-frequency map, which describes how the spectral content of the data evolves with time. The WDF $W(t,\omega)$ of the signal $x(t)$ described in a time domain is given by the Fourier transform of a local autocorrelation function $R_{xx}(t,\tau) = x(t+\frac{\tau}{2})x^{\star}(t-\frac{\tau}{2})$ over the time shift $\tau$ as (Cohen,1995)

$$W_x(t,\omega) = \int R_{xx}(t,\tau)exp(-i\omega\tau)d\tau.$$

The frequency-domain WDF is defined by (Cohen,1995)

$$W_x(t,\omega) = \frac{1}{2\pi}\int X(\omega+\frac{\xi}{2})X^{\star}(\omega-\frac{\xi}{2})exp(i\xi t)d\xi$$

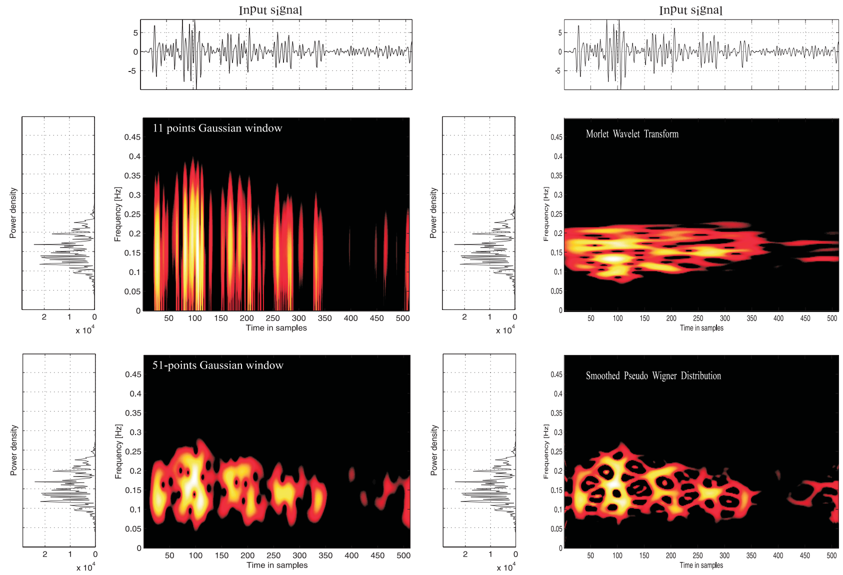



Figure 1: To check the performance of various methods, four types of signal distribution in the time-frequency domain have been considered: the short-time Fourier transform (a-b), the discrete Wavelet transform (c), and the Pseudo Wigner-Ville distribution function (d).

with $X(\omega)$ being the direct Fourier transform of the signal $x(t)$. Since the WDF gives the decay envelope over time for each frequency component, it is possible to reconstruct the time-sampled signal from its time-frequency decomposition up to a constant phase factor (Boudreaux-Bartels et al.,1986):

$$x(t_1)x^\star(t_2) = \int W_x[\frac{1}{2}(t_1+t_2),\omega]exp[i\omega(t_1-t_2)]d\omega$$

and

$$X(\omega_1)X^\star(\omega_2) = \frac{1}{2\pi}\int W_x[t,\frac{1}{2}(\omega_1+\omega_2)]exp[-i(\omega_1-\omega_2)t]dt.$$

The principle above allows a straightforward extension of the WDF to remove the noise energy from seismic sections in the $t-f$ domain. In our work, the integration of the WDF with respect to $t$ and $\omega$ is also used to give the instantaneous time delay and instantaneous frequency, respectively (Cohen,1995):

$$\Omega(t) = \int \xi W_x(t,\xi)d\xi, \;\; T(\omega) = \int \tau W_x(\tau,\omega)d\tau.$$

This is used for highlight differences in the surveys. An additional measure is expressed in terms of time and frequency dependent correlation coefficients via the time-frequency coherency function which is defined as (White and Boashash,1990)

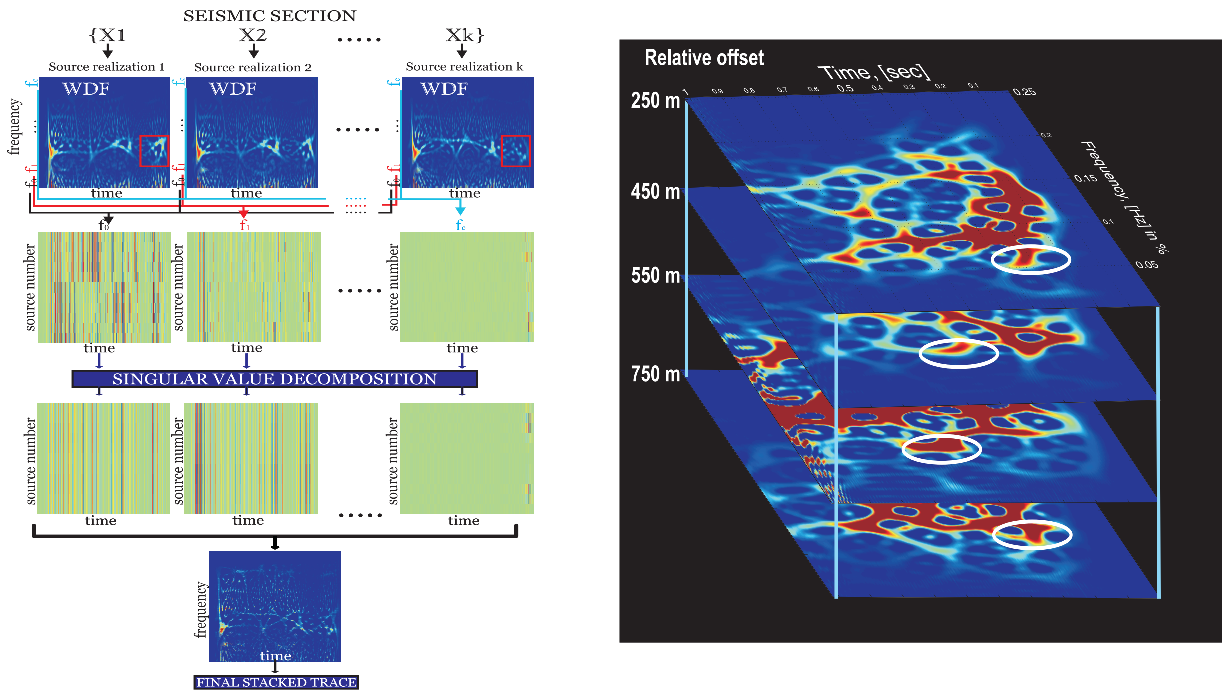
$$C_{xy}(t,\omega) = \frac{W_{xy}(t,\omega)}{\sqrt{W_x(t,\omega)W_y(t,\omega)}}$$

with $W_{xy}$ being the cross-WDF of two signals $x(t)$ and $y(t)$.

## METHOD

The novel aspect of the method presented here is the combination of the time-frequency analysis methods and eigenanalysis techniques, to the application of time-lapse VSP data. In VSP acquisition, seismic sources are activated many times while remaining at a fixed surface location, and the source signature can change significantly time after time. Hence, the usual averaging over the common shot-receiver gather may result in a highly unconsistent source wavelet. In order to reduce an influence of incoherent/random components in the stacking procedure, an equalization processing tool has been assembled using the above theory. The algorithm presented in Fig.2a is based on the singular value decomposition technique (SVD) of the $t-f$ representations. The cut-off SVD (Freire and Ulrych,1988) is calculated over a common shot-receiver gather for each sampling frequency $f_k$. This causes a strong spatial filtering and, consequently, rejects incoherent events. Finally, the resulting modified distribution is deconvolved into the 1-D time-domain signal. Filtering

Figure 2: (a) Source signature correlation algorithm. (b) Filtering in $t - f$ domain. The circle indicates the selected wave mode to be suppressed.




(a) (b)

in $t - f$ domain was also found to be well suited to multiple suppression and the separation of up- and downgoing events for VSP data processing (Fig.2b). The offset VSP traces deconvolved with the WDF can be used for wave mode identification and suppression. The circles indicate the downgoing shear waves. This study concludes that useful reflection energy, or uncorrelated noise energy can easily be identified occure within the specific time and frequency intervals in $t - f$ plane.

## APPLICATION TO MULTI-COMPONENT VSP DATA

Time-lapse VSP data were acquired over the gas-oil storage reservoir during the first year of the steam-injection pilot project to monitor the expansion of the steam zone. It is characterized by densely spaced high-permeability fractures running through a low-permeability matrix. Here, an application of standard VSP processing procedures for wavefield separation is complicated by source signature changes with depth and high-energy downgoing shear wavefield (Hartemink et al.,1997). As a result, the relatively weak reflection patterns to be analyzed for possible time-lapse changes are not revealed. The method described above (see Fig.2a) has been applied to the data to estimate the average stacking trace. A set of displays in Fig.3 illustrates the result of the filtering in $t - f$ domain for the separation of up- and downgoing wavefield energy. The principle presented in Fig.2b has been implemented on the base and repeat surveys in order to estimate the downgoing shear waves.

## CONCLUSIONS

We show that time-frequency transforms can be used to account for the acquisition foot-print, and in particular the lack of source repeatability. The technique is also well suited to the rejection of multiples, and separates up- and downgoing wavefields. It has been shown that the time-frequency coherency function based on the cross-WDF is a powerful tool for the examination of the similarity/differences between base and monitor surveys. This is an important step towards improving repeatability of time-lapse VSP data. It has the potential to be used on larger 4D datasets.

## ACKNOWLEDGMENTS

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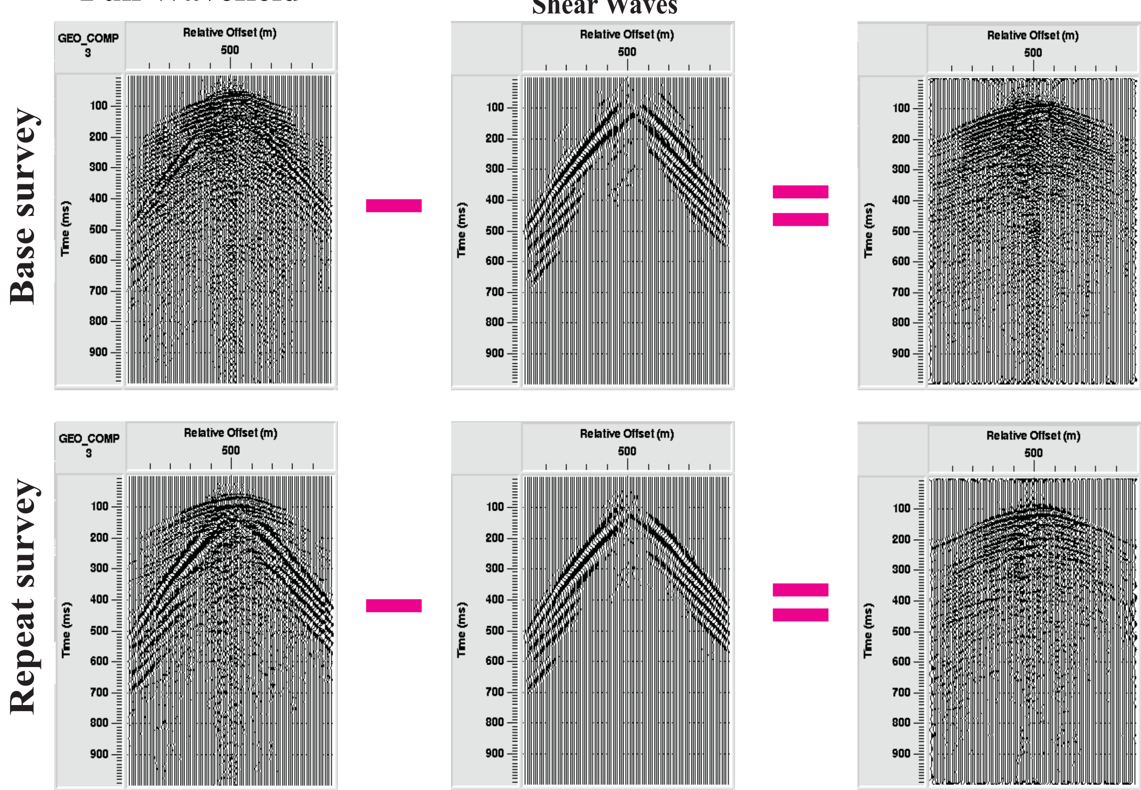


Figure 3: An example of up- and downgoing wavefield separation using the filtering in $t-f$ domain.

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