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Time-frequency analysis of seismic data by time-reassigned multi-synchrosqueezing transform to detect low frequency shadows

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Extended Abstract

Summary
Identification of low-frequency shadows is very important in the sense that they are related to gas reservoirs. These low-frequency shadows, produced by gas attenuation on seismic waves, cause the low frequencies under the gas reservoirs to have stronger amplitudes compared to the amplitudes of the high frequencies. Therefore, if proper time accuracy is considered in the identification of this indicator, the gas reservoir, and consequently, its position will be identified with considerable accuracy. One of the methods of identifying low-frequency shadows is time-frequency transforms. Therefore, those time-frequency transforms that have good time and frequency resolution, can be of great help in identifying low-frequency shadows. In this research, a method called time-reassigned multi-synchrosqueezing transform (TMSST) is used that acts better than common time-frequency transforms such as short-time Fourier transform (STFT), reassignment method (RM), synchrosqueezing transform (SST) and multi-synchrosqueezing transform (MSST) in terms of time and frequency resolution. Therefore, by applying this transform on a synthetic dataset and a real dataset, its performance has been demonstrated. As a seismic application, single-frequency sections obtained from a hydrocarbon field were prepared in MATLAB environment and low-frequency shadow anomalies were detected using this time-frequency method with high resolution. In addition, in this study, the Rennie parameter, which is directly related to the sparsity, has been used to evaluate the energy concentration. The number obtained for the Rennie parameter using the method proposed in this paper is another reason for proving the remarkable performance of this method in obtaining time-frequency representation with high time and high frequency resolution at the same time.

Introduction
Different processes generate low-frequency seismic anomalies beneath gas reservoirs. In some instances, hydrocarbon-rich zones of such reservoirs might be considered as low-frequency domain anomalies that display no discernible time delay relative to reservoir reflections.

Seismic imaging is the last step in the processing chain of seismic data analysis and is typically the result of the two phases of processing and interpretation. Both processing and interpretation can benefit from the use of seismic traces. Therefore, it is crucial and necessary to be able to view signals and extract signal-related data. Time and frequency domains are two typical techniques of displaying a seismic trace. Actually, it is impossible to enjoy all these benefits simultaneously. As a result, it seems critical to create a tool that can show these two components of the signal at the same time. The analysis of a non-stationary signal, whose frequency content varies over time, benefits greatly from this representation that is referred to time-frequency representation (TFR).

Methodology and Approaches
The STFT of the signal x(t) which is derived from the Fourier transform of the windowed signal $g(\tau - t)x(\tau)$ should be localized in $\tau \in [t - \Delta_t, t + \Delta_t]$. Therefore, we have:

$$STFT_x^g(t,\omega) = \int_{-\infty}^{+\infty} g(\tau - t)x(\tau)e^{-i\omega(\tau-t)}d\tau$$

where g(t) is a real value window with supp{g}$\in [-\Delta_t, \Delta_t]$.

The RM technique that reassigns the coefficients both in time and frequency is obtained by moving data of the term $|STFT_x^g(t,\omega)|$ from the current coordinate (t,ω) to a new coordinate $(\hat{t}(t,\omega), \widehat{\omega}(t,\omega))$ as (Chabyshova and Goloshubin, 2014):

$$RM(t,\omega) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} |STFT_x^g(\eta,\nu)|\delta(t-\hat{t}(\eta,\nu))\delta(\omega-\widehat{\omega}(\eta,\nu))d\eta d\nu$$

$$\widehat{\omega}(t,\omega) = \omega - \Im\left\{\frac{STFT_x^{dg}(t,\omega)}{STFT_x^g(t,\omega)}\right\}$$

$$\hat{t}(t,\omega) = t + \Re\left\{\frac{STFT_x^{tg}(t,\omega)}{STFT_x^g(t,\omega)}\right\}$$

where, $\widehat{\omega}(t,\omega)$ and $\hat{t}(t,\omega)$ are the estimated IF and GD.

To address the inadequacy in the RM technique for signal recovery, the SST method also uses the phase information of the signal in addition to amplitude information. Squeezing the blurry energies into the related true IF trajectory across the frequency direction done by the SST method can be expressed as (Yu et al, 2018):

$$SST(t,\omega) = \int_{-\infty}^{+\infty} STFT_x^g(t,\nu)\delta(\omega-\omega_0(t,\nu))d\nu$$

$$\omega_0(t,\omega) = \omega - \Im\left\{\frac{STFT_x^{dg}(t,\omega)}{STFT_x^g(t,\omega)}\right\}$$

where, $\omega_0(t,\omega)$ is the estimated IF.

A more accurate estimation of IF using the MSST method to lead to a more concentrated TFR can be expressed by:

$$SST^{[N]}(t,\omega) = \int_{-\infty}^{+\infty} STFT_x^g(t,\nu)\delta\left(\omega-\widehat{\omega}_k^N(t,\omega)\right)d\nu = \int_{-\infty}^{+\infty} SST^{[N-1]}(t,\nu)\delta\left(\omega-\widehat{\omega}_k(t,\nu)\right)d\nu$$

$$\widehat{\omega}_k^N(t,\omega) = \varphi_k'(t) + \left(\frac{\varphi_k''(t)^2}{1+\varphi_k''(t)^2}\right)^N(\omega - \varphi_k'(t))$$

Finally, for a strong frequency varying signal, the two-dimensional group delay estimate and the final expression of the TMSST, which is based on the multiple fixed-point iterations, can be written as (Yu et al, 2020):

$$\hat{t}(t,\omega) = -\acute{\varphi}(\omega) + \frac{\varphi''(\omega)^2}{\sigma^2 + \varphi''(\omega)^2}\left(t + \acute{\varphi}(\omega)\right)$$

$$Ts^{[N]}(u,\omega) = \int_{-\infty}^{+\infty} G(t,\omega)\delta\left(u - \hat{t}^{[N]}(t,\omega)\right)dt$$

Results and Conclusions

In this paper, we have introduced a novel seismic time-frequency approach using time-reassigned multi-synchrosqueezing transform (TMSST). The TMSST method is a fixed-point iterative technique that can be used on signals with large frequency variations. It can also address the limitation of the MSST method to produce blurry time-frequency representation and reassign the TF coefficients across time direction. The TMSST method can be adaptive in analyzing seismic data. The TMSST method has a substantially higher time-frequency resolution than other current

time-frequency analysis (TFA) methods and can thus be considered as a robust and promising tool for seismic data interpretation. We have also illustrated the strength of the TMSST method over traditional TFA methods by applying these methods on both synthetic and real seismic data.