WAVELET EXTRACTION AND LOCAL SEISMIC PHASE CORRECTION USING NORMALIZED FIRST-ORDER STATISTICS

DIAKO HARIRI NAGHADEH and CHRISTOPHER KEITH MORLEY

Petroleum Geophysics, Department of Geological sciences, Chiang Mai University, Chiang Mai, Thailand. diako.h@cmu.ac.th

(Received February 16, 2015; revised version accepted January 9, 2016)

ABSTRACT

Hariri Naghadeh, D. and Morley, C.K., 2016. Wavelet extraction and local seismic phase correction using normalized first-order statistics. *Journal of Seismic Exploration*, 25: 163-176.

In this paper wavelet phase is extracted using normalized first-order statistics, which are introduced as an indicator of localized seismic signal phase. The analysis demonstrates sharpness of the probability distribution of a discrete time series, which is more robust than that obtained by applying higher-order statistics. The normalized first-order statistical value of the zero phase signal is higher than that of the non-zero phase signal, hence it is used as a signal phase correction controller to produce zero-phase signals. The most important parameter for correctly estimating the phase pertains to the best length of time window used for local phase correction. Incorrect window length creates non-zero phase wavelets. To choose the correct time window length, a continuous wavelet transform is applied, using a Morlet wavelet to decompose signals to wavelets. Based on the time-distance between maximum energy of wavelet coefficients normalized by the scale, it is possible to choose the best window length for local phase correction. Synthetic and real data examples are used to demonstrate the effectiveness of this method in both wavelet extraction and for local correction of signal phase. Results of the seismic phase correction using this method demonstrate superiority over the local Kurtosis and local skewness methods, because of high stability and dynamical range. Normalized first-order statistics permit a short window length not only as a phase correction controller but also as a thin layer detector.

KEY WORDS: normalized first-order statistics, Kurtosis, Morlet wavelet, wavelet phase, skewness.

INTRODUCTION

Seismic data are one of the main sources information for estimating reservoir properties. Since information obtained from well logs is limited to a narrow zone around the well path, a seismic data is used to project properties between wells. While well log data alone can be used to predict rock properties

0963-0651/16/$5.00

between wells using geo-statistical methods, the resulting estimates can have a high degree of uncertainty depending upon geological conditions and data quality. In seismic sections amplitude variation occurs due to impedance contrasts at layer boundaries. Acoustic impedance (AI), which is related to subsurface rock properties, is obtained by seismic inversion. Since AI is the product of density and velocity, wells with logs of these properties can be used to generate impedance logs. To obtain an AI section from a seismic cube requires a wavelet estimated from well data or from seismic data and filter coefficients from the estimated wavelet. Inaccurate estimation of the wavelet can cause inaccurate reflection coefficients (RC) and AI estimations. It is possible to extract the amplitude spectrum (AS) of the wavelet from the seismic data but estimation of the best phase property is not easy. Any mistake in phase estimation can cause a major error in RC and AI estimations. Different techniques in estimating the wavelet phase from seismic data have been proposed. These include:

a. Automatic phase correction of common-midpoint stacked data (Levy and Oldenburg, 1987)

b. Maximum Kurtosis phase correction (White, 1988)

c. Time-varying wavelet estimation and deconvolution by Kurtosis maximization (van der Baan, 2008)

d. Nonstationary phase estimation using regularized local Kurtosis maximization (van der Baan and Fomel, 2009)

e. Short-time wavelet estimation in the homomorphic domain (Herrera and van der Baan, 2012)

f. Local skewness attribute as a seismic phase detector (Fomel and van der Baan, 2014)

Real seismic signals are not zero phase and they have to be rendered zero-phase to be suitable for interpretation and automatic tracking on workstations (Mansar and Rodriguez, 1996). Perturbation of wavelet phase can be caused by acquisition and processing, consequently it is necessary to process the data for zero phasing and to correct residual phase distortions.

In this paper, normalized first-order statistics (NFOS) are introduced as an approach for statistical estimation of wavelet phase, to indicate local seismic phase, and for phase correction. The high stability of NFOS even using short time windows with a few samples creates an ability to correct residual phase distortions based on the maximum NFOS (M-NFOS) criteria.

NFOS

NFOS measure the sharpness of the probability distribution of a discrete time series. The NFOS of a sequence x_t is defined as

$$\mathrm{NFOS}(x) = \mathrm{Mod}(x_t)/\mathrm{STD}(x_t) \quad , \tag{1}$$

where, Mod and STD are mode and standard deviation of a time series, respectively. The mode is the number that occurs most often within a set of numbers. Mode is chosen as a first-order statistic (FOS) because it is insensitive to outliers even in small samples and it has high stability. In statistics, FOS refers to a function which uses a linear term or first power of a sample, as opposed to skewness and Kurtosis, which use the third and fourth power of a sample. Skewness and Kurtosis due to the higher powers are significantly less robust than FOS. Also, they are more sensitive to outliers than FOS.

In Fig. 1a the input synthetic trace contains a set of Ricker wavelets with a gradually variable phase from -90 to $+90$ degrees. In Fig. 1b NFOS value for trace (1a) is calculated. It is clear that zero-phase signal has M-NFOS value. This provides to find desired phase estimation based on M-NFOS criteria. In Fig. 1c phase shifted synthetic trace to obtain zero phased trace based on M-NFOS criteria is shown.

Wavelet properties estimation

A seismogram is modeled by convolution of the source wavelet with the reflection series plus noise. To obtain a reflection series, it is necessary to know the source wavelet amplitude and the phase spectrum. The AS of seismic data is similar to the AS of a wavelet. The AS averages the amplitude spectra of all traces in each time window. We found that zero phase signals exhibit M-NFOS, so the correct estimated RC can have high NFOS values and it is possible to choose the best phase of wavelet based on M-NFOS criteria.

Since seismic data is highly variable it is necessary to divide the seismic data into many windows in order to choose the best wavelet in each window. The procedure is to first choose the zero-phase wavelet with AS that is calculated from all traces in the window. Secondly a series of constant phase rotations are applied to the seismic data using eq. (2). The angle corresponding to the M-NFOS value of the phase changed data determines the most likely wavelet phase.

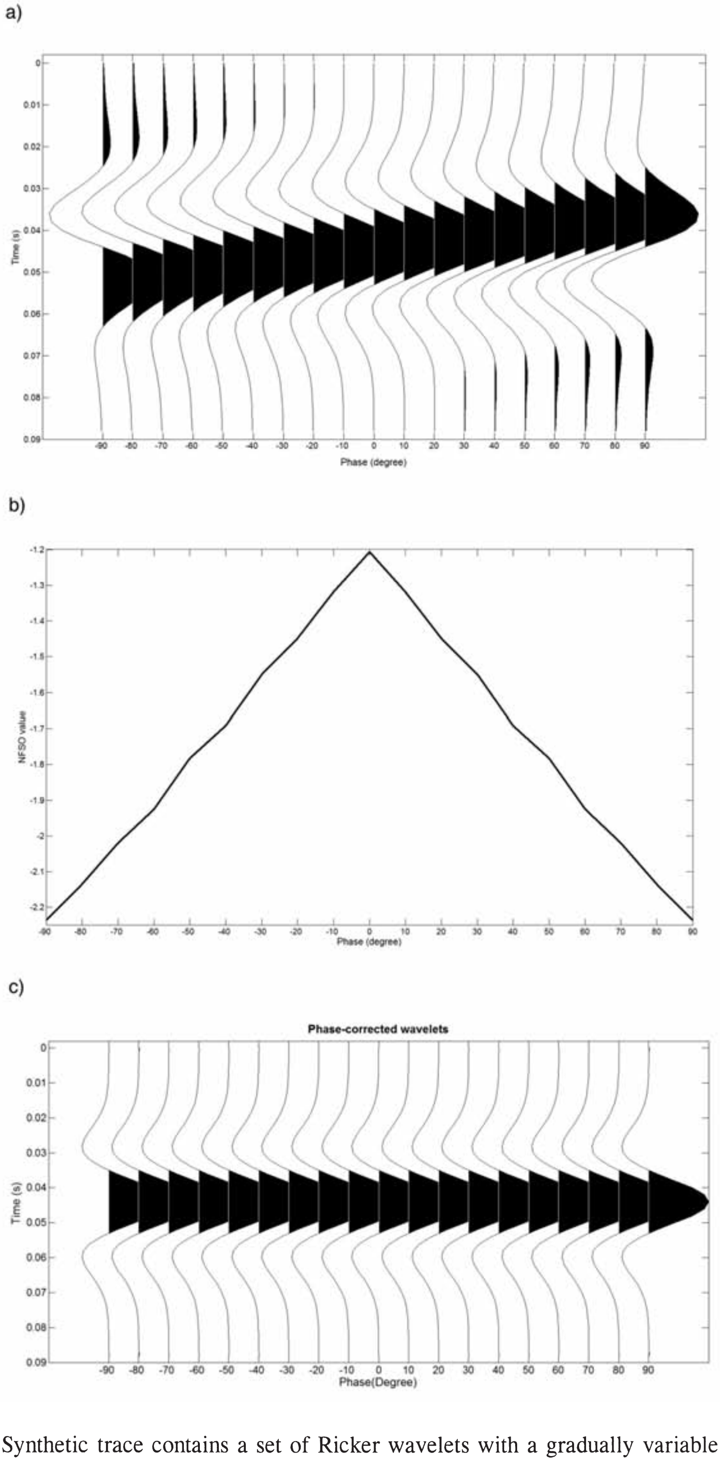


Fig. 1. (a) Synthetic trace contains a set of Ricker wavelets with a gradually variable phase from −90 to +90 degrees; (b) Calculated NFOS value for trace (a); (c) Zero phased trace (a).

$$x_{rot}(t) = \cos(\theta)\cdot x(t) + \sin(\theta)\cdot H[x(t)] \quad , \tag{2}$$

where x_{rot} is the rotated data with the phase rotation angle θ and H is the Hilbert transform. Once the AS and phase information is obtained, it is possible to construct a wavelet for conducting seismic inversion and determining the correct RC.

To show the ability of the NFOS method, we compared the results of wavelet extraction using NFOS and Kurtosis. Synthetic seismic data created by convolution of the reflection series with the zero phase wavelet was used (Fig.2). It is concluded that the length of the time window plays a much more important role in wavelet and RC estimation using Kurtosis than NFOS. A short time window results in incorrect wavelet phase estimation using Kurtosis. By choosing different lengths of window, the results show that estimated RC using extracted wavelets by NFOS are better than those by Kurtosis (Fig. 3). To obtain RC, a sparse deconvolution method (Robinson and Treitel, 1980) based on NFOS criteria was used.

Seismic local phase correction using NFOS

In this section the use of NFOS for seismic signal local phase correction is discussed. The procedure involves dividing each trace into many windows. The data in each window is then phase rotated by a constant phase angle and the NFOS value is calculated for each rotation angle. The results showed that the M-NFOS value determines the best phase rotation in order to make zero-phase wavelets. The most important parameter for phase correction is choosing the best window length. Poor choice of window length can create new wavelets with non-zero phase and resolution of data will be decreased. To choose the best time window length the continuous wavelet transform (CWT) method was applied, using a Morlet wavelet as the mother wavelet. Using equation 3 the data can be decomposed signals to wavelets.

$$X_w(s,T) = \langle x(t),\psi_{s,T}(t) \rangle = \int_{-\infty}^{+\infty} x(t)\cdot(1/\sqrt{s})\bar{\psi}[(t-T)/s]dt \quad , \tag{3}$$

where s is the scale value, T is the translation value, $\bar{\psi}$ is the complex conjugate of ψ and $X_w(s,T)$ is the time scale map (Sinha et al., 2005).

The CWT provides a different approach to time-frequency analysis. Instead of producing a time-frequency spectrum, it produces a time-scale map called a scalogram (Rioul and Vetterli, 1991). So based on the time distance between maximum energy of each wavelet coefficient, it is possible to choose the best window length to do phase correction (Fig 4).

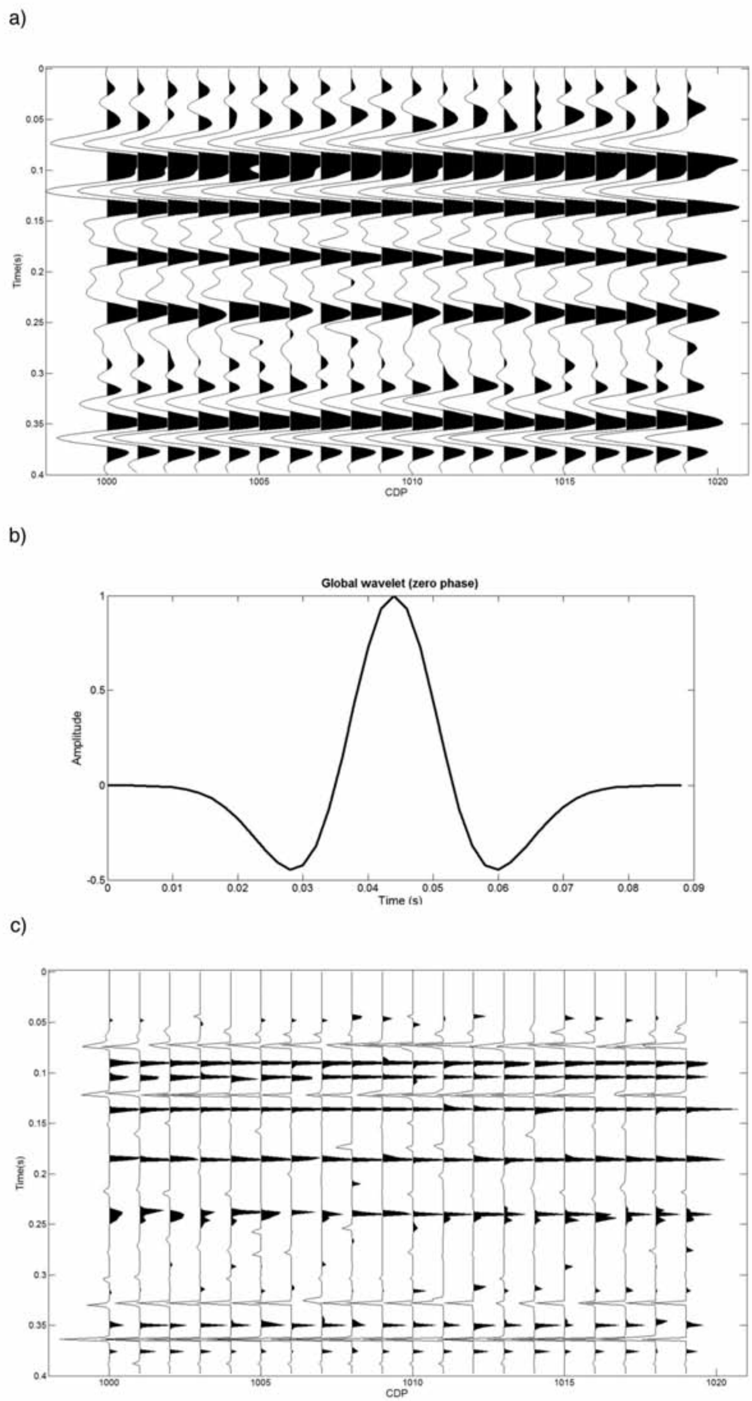


Fig. 2. (a) Synthetic seismic section. (b) Global zero phase wavelet. (c) Reflection series that obtained by deconvolution of (a) with (b).

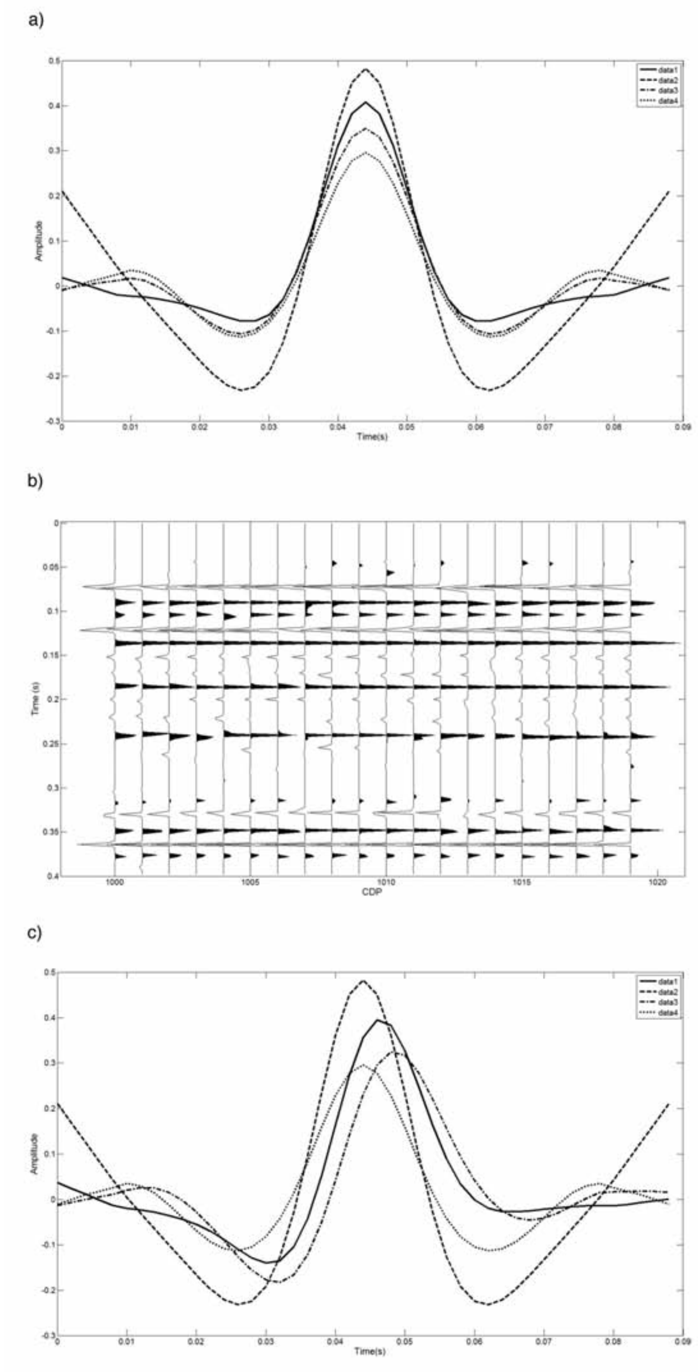
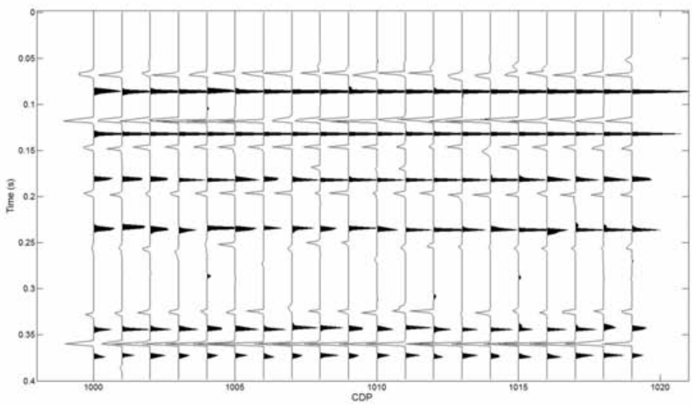
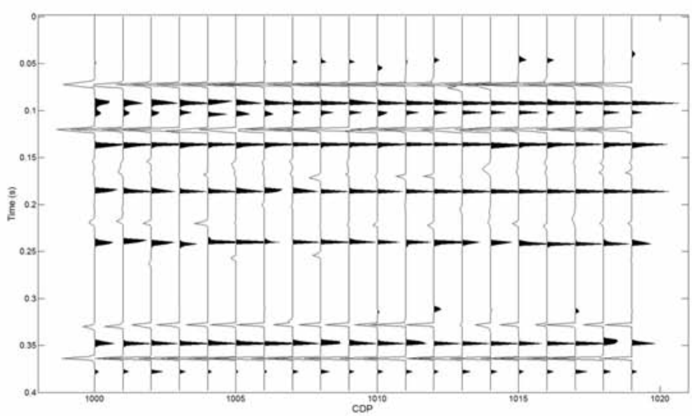


Fig. 3. (a) Time-varying wavelets that extracted using NFOS with 45 samples time window. (b) Estimated RC using deconvolution of 2a with (a). (c) Time-varying wavelets extracted using Kurtosis with 45 sample time window.

d)



e)



f)

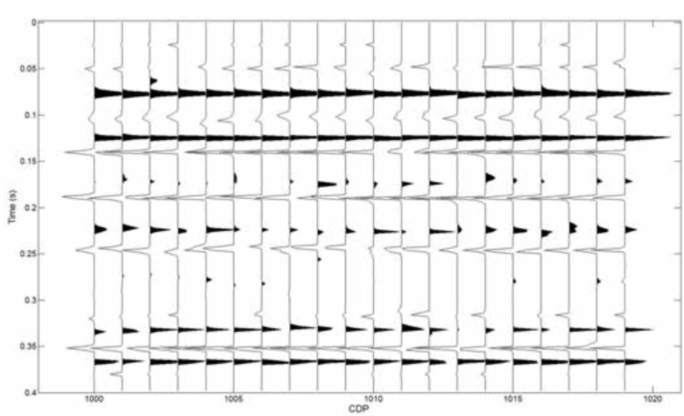


Fig. 3. (d) Estimated RC using deconvolution of 2a with (c). (e) Estimated RC using NFOS with 20 sample time window. (f) Estimated RC using Kurtosis with 20 sample time window.

To show NFOS ability in signal phase correction, synthetic and real seismic data were tested and the results compared with local Kurtosis and local skewness. To estimate the propagation wavelet a long window needs to be applied, and to estimate a local one short analysis windows are used. Estimation variance increases with the order of a moment (Mendel, 1991). In other words, less samples are needed to estimate NFOS with the same accuracy as skewness and Kurtosis because of the low-order statistic (LOS) property. Due to the third and fourth power terms in skewness and Kurtosis, the values of these measures can be arbitrarily large, especially when there are one or more large outliers in the data. Since, we need to use short analysis windows to estimate phase locally then NFOS is the best technique for local signal phase correction based on FOS. This allows use of smaller analysis windows so that the resulting technique can not only to do zero-phasing of the seismic data, but it also acts as an analysis tool to detect subtle stratigraphic features in the local geology or to detect temporal and/or spatial variations in the propagating wavelet.

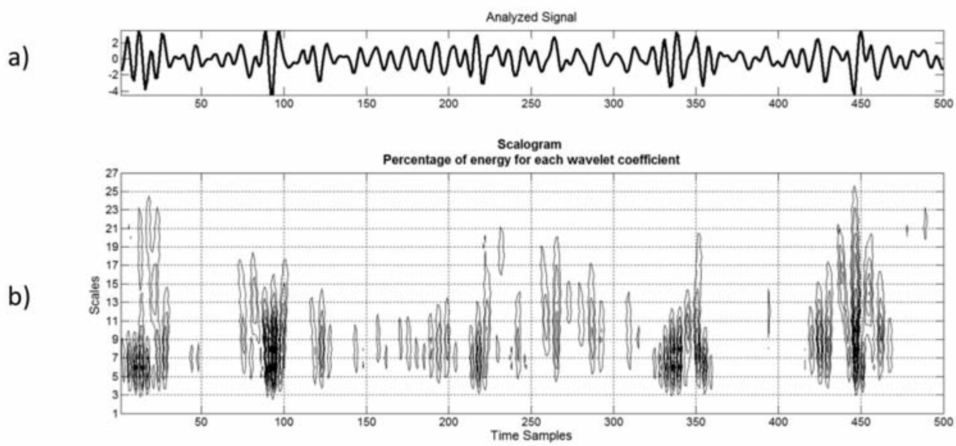


Fig. 4. (a) Analyzed signal; (b) Scalogram obtained by CWT using Morlet wavelet. Based on the time distance between maximum energy of wavelet coefficients normalized by the scale, it is possible to choose the best window length to do phase correction.

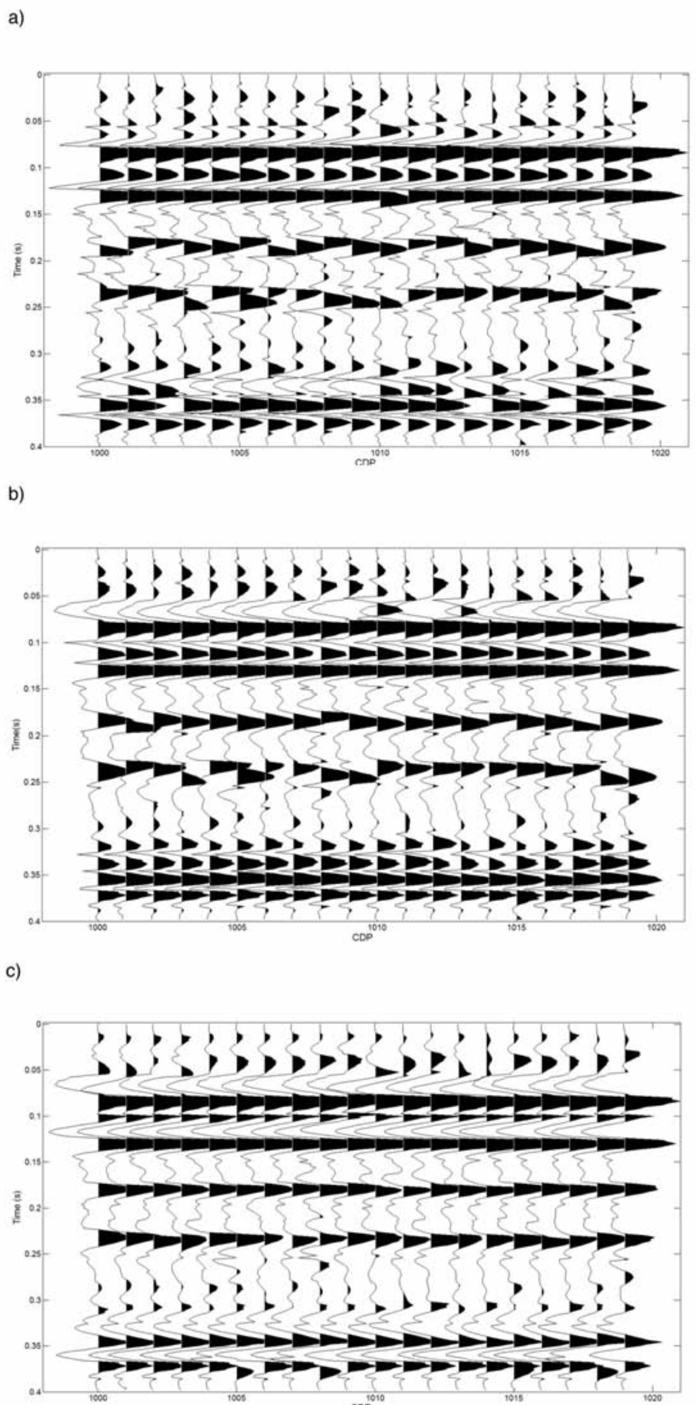


Fig. 5. (a) Phase corrected synthetic data (Fig 2a) using Kurtosis; (b) Phase corrected synthetic data (Fig. 2a) using skewness; (c) Phase corrected synthetic data (Fig 2a) using NFOS.

In Figs. 5a, 5b and 5c the results of phase corrected synthetic seismic data (Fig. 2a) using Kurtosis, skewness and NFOS are shown, respectively. Comparison of the results show that high-order statistics (HOS) create artificially high amplitude reflectors especially when short time window lengths are used for signal phase correction and they are not able to correctly detect thin layers. Conversely using NFOS both separates thin layers and does phase correction well, even where short time window lengths are used.

In Figs. 6a, 6b and 6c the estimated reflection series from phase corrected synthetic data sets (Figs. 5a, 5b and 5c) using Kurtosis, skewness and NFOS are shown. Comparing them with the estimated reflection series obtained from synthetic data (Fig. 2c) emphasis that HOS especially Kurtosis can create wavelets with inverse polarity.

A part of real seismic data from New Zealand entitled "Bo_Parihaka, inline 3793" is used to compare result of phase correction. In Figs. 7a, 7b, 7c and 7d real data, phase corrected data after applying NFOS, Kurtosis and skewness are shown, respectively. Results demonstrate that using Kurtosis can create reflectors with inverse polarity and it is not able to detect thin layers because it needs a large number of samples and large time windows to correct the phase of signals correctly. A phase corrected section that was created using skewness shows an improvement compared with Kurtosis, but it also has problem with thin layer detection too. In some regions, phase distortions especially at closely spaced reflectors are obvious. It shows that skewness as a third-order statistic has problem with short time window lengths too. The phase corrected section that was obtained by NFOS, shows that not only it can modify phase correctly but also it can detect thin layers and it does not have any problem with short time windows at all. Arrows in phase corrected real sections highlight the positive aspects of NFOS and problems when applying other methods.

CONCLUSION

We have presented an approach to non-stationary phase identification, which is based on NFOS. Since, skewness and Kurtosis are HOS they need large samples for wavelet phase extraction and they have problems with small samples. To indicate local seismic phase and to conduct phase correction, NFOS was chosen because it is based on LOS criteria, and consequently does not have any problem with short time windows and it has high stability to phase correction. Not only does using NFOS avoid creating phase distortions in closely spaced reflections but also it results in the detection of thin layers and increases reflector continuity. Comparing the results of synthetic and real seismic data phase detection using skewness, Kurtosis and NFOS show that Kurtosis picks mostly signals with inversed polarity, while skewness is not able

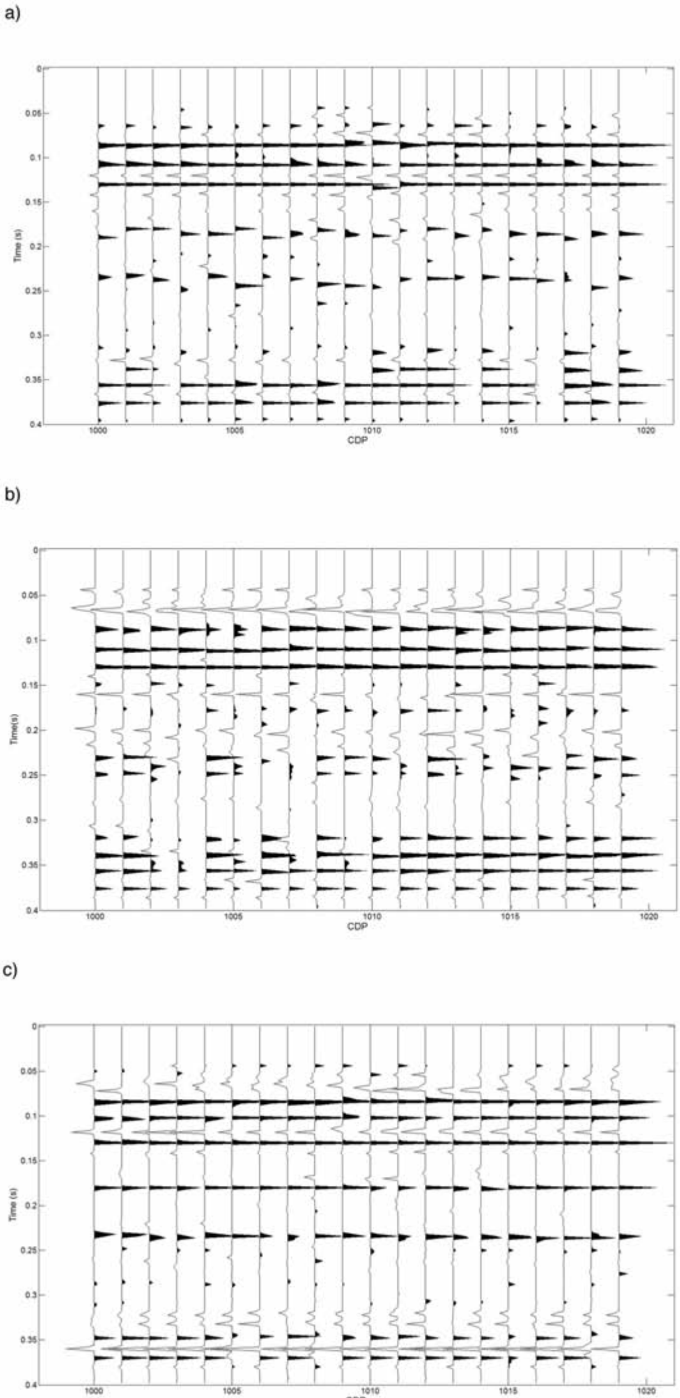


Fig. 6. (a) Estimated reflection series from 5a; (b) Estimated reflection series from 5b; (c) Estimated reflection series from 5c.

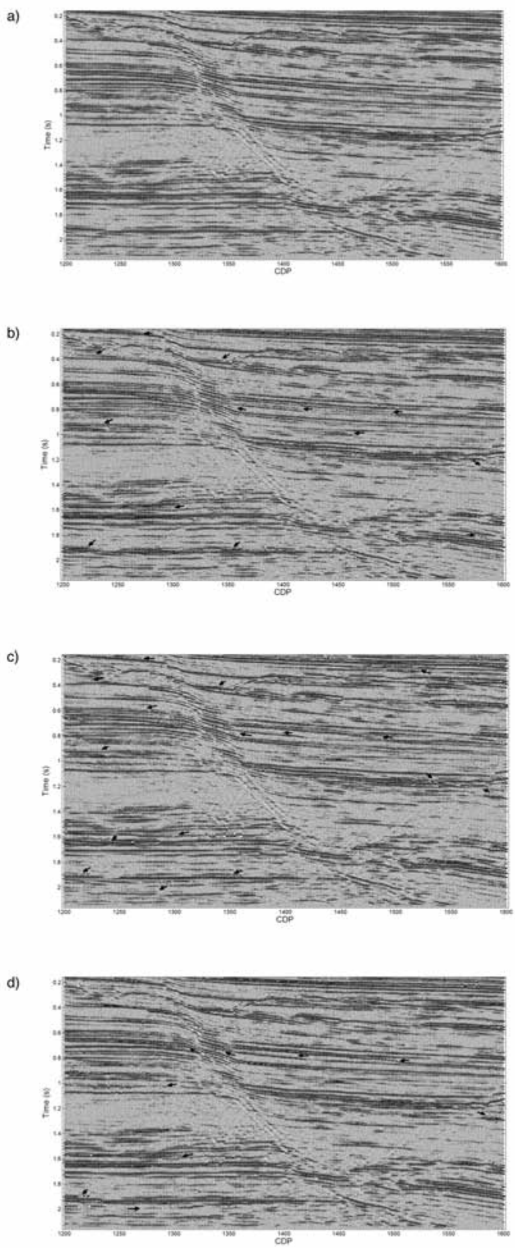


Fig. 7. (a) Real seismic data; (b) Phase corrected data (a) using NFOS; (c) Phase corrected data (a) using Kurtosis; (b) Phase corrected data (a) using skewness.

to detect thin layers, and also creates phase distortion in closed reflections. NFOS pick the original signals so it is more suitable for picking optimal phase rotations.

ACKNOWLEDGMENTS

The authors thank GNS science (Institute of Geological and Nuclear Sciences of New Zealand, www.gns.cri.nz) for permission to use and show the real data examples.

REFERENCES

Fomel, S. and van der Baan, M., 2014. Local skewness attribute as a seismic phase detector. Interpretat., 2: SA49-SA56.

Herrera, H.R. and Mirkov, V.D.B., 2011. Revisiting homomorphic wavelet estimation and phase unwrapping. CSPG CSEG CWLS Conv., Calgary.

Mansar, S. and Rodriguez, J.M., 1996. Analyzing and zero phasing seismic data using wavelet transform. Extended Abstr., 58th EAEG Conf., Amsterdam.

Mendel, J.M., 1991. Tutorial on higher-order statistics (spectra) in signal processing and system theory. Proc. IEEE, 79: 278-305.

Levy, S., Oldenburg, D.W., 1987. Automatic phase correction of common-midpoint stacked data. Geophysics, 52: 51-59.

Rioul, O. and Vetterli, M., 1991. Wavelets and signal processing. IEEE Signal Proc., 8(4): 14-38.

Robinson, E.A. and Treitel, S., 1980. Geophysical Signal Analysis. Prentice-Hall, Englewood Cliffs, NJ.

Sinha, S., Partha, S.R., Phil, A.D. and Castagna, J.P., 2005. Spectral decomposition of seismic data with continuous-wavelet transform. Geophysics, 70(6): V11-V18.

van der Baan, M., 2008. Time-varying wavelet estimation and deconvolution by Kurtosis maximization. Geophysics, 73(2): V11-V18. doi: 10.1190/1.2831936.

van der Baan, M. and Fomel, S., 2009. Non-stationary phase estimation using regularized local Kurtosis maximization. Geophysics, 74(6): A75-A80. doi: 10.1190/1.3213533.

White, R.E., 1988. Maximum Kurtosis phase correction. Geophys. J. Internat., 95: 371-389.