Repeatability Measure for Broadband 4D seismic

J. Burren (Petroleum geo-services) & D. Lecerf* (Petroleum Geo-Services)

SUMMARY

Future time-lapse broadband surveys should provide better reservoir monitoring resolution by extending the 4D signal bandwidth. In this paper, we will review the consequence of extending the signal bandwidth for the computation of 4D attributes, such as the repeatability measurement NRMS. The re-formulation of NRMS shows the sensitivity of the repeatability metric with regards to signal time-shift and signal bandwidth. Broadening the 4D signal bandwidth will result in an increase of the overall NRMS value for an equivalent seismic data with the same level on non-repeatable noise. To compare the quality of 4D seismic, regardless of bandwidth, we propose a new repeatability measure called CNRMS. The bandwidth Calibrated NRMS provides repeatability metric for any 4D seismic as it would be calculated with a reference signal bandwidth.

Introduction

Today the seismic industry is proposing new resolution standards for 3D imaging using seismic data with an extended bandwidth. Such new broadband acquisition and processing technologies have not yet been validated for 4D surveys; to be certified as a broadband solution, they must provide excellent wavefield repeatability for all frequencies.

Day et al. (2010) have shown how broadband data acquired using a dual-sensor towed-streamer can be successfully integrated with conventional streamer data for a band-limited 4D study. Extrapolating the up-going and down-going pressure fields allows a new total-pressure wavefield to be created, equivalent to a conventional hydrophone-only dataset. The cable re-datuming ability not only ensures backward compatibility for continuing the 4D reservoir monitoring cycle, but also provides opportunity for future broadband time-lapse surveys. Subsequently, it is important to understand the implication of the extended signal bandwidth on 4D repeatability measurements such as NRMS.

NRMS for 4D signal with extended bandwidth

The NRMS attribute, defined as normalized RMS of the difference between two datasets, is used routinely as a quality control measurement for time-lapse data. Several investigations have been published describing the sensitivity of the NRMS value to the acquisition geometry repeatability, for example Landro (1999), Kragh and Christie (2002) and Eiken *et al*. (2003). The final NRMS value is often used to quantify the quality of the 4D signal. In most cases, the NRMS values are used without considering the signal bandwidth of the data despite publications indicating a dependency of the NRMS value to the data dominant frequency, Calvert (2005). With the advent of 4D broadband technology, it is important to understand the performance of this repeatability metric.

Figure 1 illustrates the NRMS frequency dependency using a real broadband dataset acquired in the same area (with different azimuth). The band limited datasets (b) present lower NRMS than the broadband datasets (a).

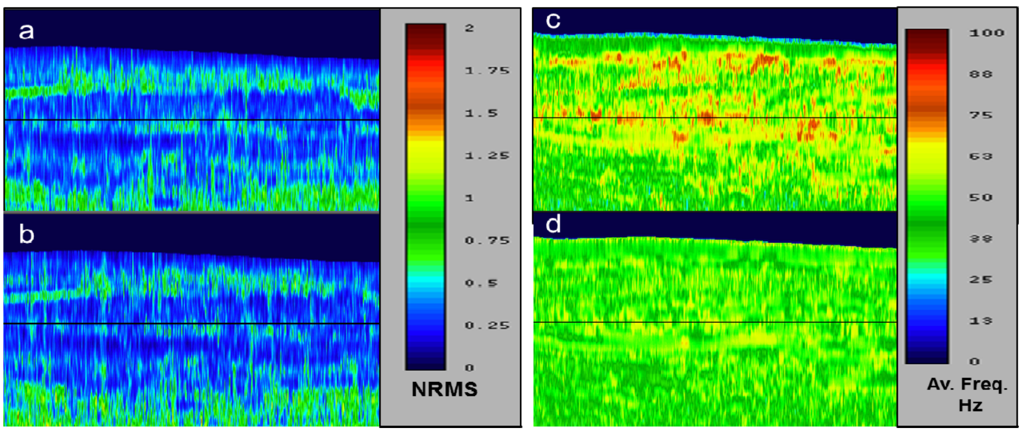

Figure 1 *Repeatability metric comparison between broadband and band limited datasets: (a) NRMS for two broadband datasets; (b) NRMS for same datasets with a bandpass filter applied; (c) the average frequency for the data shown in (a), ≈70 Hz; and (d) the data average frequency for the data shown in (b), ≈50 Hz. Using same data, the band limited signal present lower NRMS than the broadband signal.*

Equation (1) defines the NRMS metric as the normalized energy of the difference between two seismic traces (base, *b* and monitor, *m*):

$$NRMS = 2\frac{RMS\,(b-m)}{RMS\,(b)+RMS\,(m)} \tag{1}$$

We can rewrite the expression by introducing new variables:

$$NRMS^{2} \approx 4\frac{(1-S)^{2}\,SN + 1 + S^{2} + S\left(2\pi\tau f_{d}\right)^{2}\,SN}{\left(1+S\right)^{2}\left(1+SN\right)} \tag{2}$$

Where: S = Energy Ratio, RMS (m) / RMS (b) ; SN = Signal to Noise Ratio; τ = Time-shift, f_d *= RMS frequency (dominant frequency)*

The NRMS expression (2) is a generalization of different simplifications proposed in the literature (noted here with consistent formulation).

$$NRMS^{2} \approx SDR^{-1} + \left(2\pi\,\tau\,f_{d}\right)^{2} \qquad (3)\ \ \text{(Cantillo, 2012)}$$

$$NRMS^{2} \approx 4\frac{(1-S)^{2}\,SN + 1 + S^{2}}{\left(1+S\right)^{2}\left(1+SN\right)} \qquad (4)\ \ \text{(Harris, 2005)}$$

Expression (3) assumes noise free data with a RMS ratio S close to 1; SDR is defined as the trace similarity, Cantillo (2012). Note that formulation (4) does not include any time-shift considerations, Harris (2005).

In expressions (2), only the first term of a Taylor series has been retained, including the time-shift (τ) and the dominant frequency (f_d) implying these expressions are valid for small time-shifts. Higher order terms of the Taylor expansion would be needed to account for larger time-shifts. It should also be noted that any phase rotation and amplitude spectrum variations between base and monitor have been ignored; a matching filter should correct for such global discrepancies between the two signals. In addition, the signal to noise ratio is assumed to be similar between the base and the monitor.

The proposed formulation (2) describes the NRMS function of the Energy Ratio (S), Signal to Noise Ratio (SN), Time-shift (τ) and RMS frequency or dominant frequency (f_d). Clearly, both a variation in the time-shift and a change in the signal bandwidth significantly influence the overall NRMS value even if the differences between the two traces are very small.
Figure 2 illustrates the dependency of the NRMS with regards to the time-shift τ and the dominant frequency f_d (directly related to the signal bandwidth). The NRMS is computed for different time-shift between pairs of synthetic seismic traces having different signal bandwidth. The example assumes no phase rotation and no amplitude spectrum variation between the two traces and that both datasets have similar signal to noise.

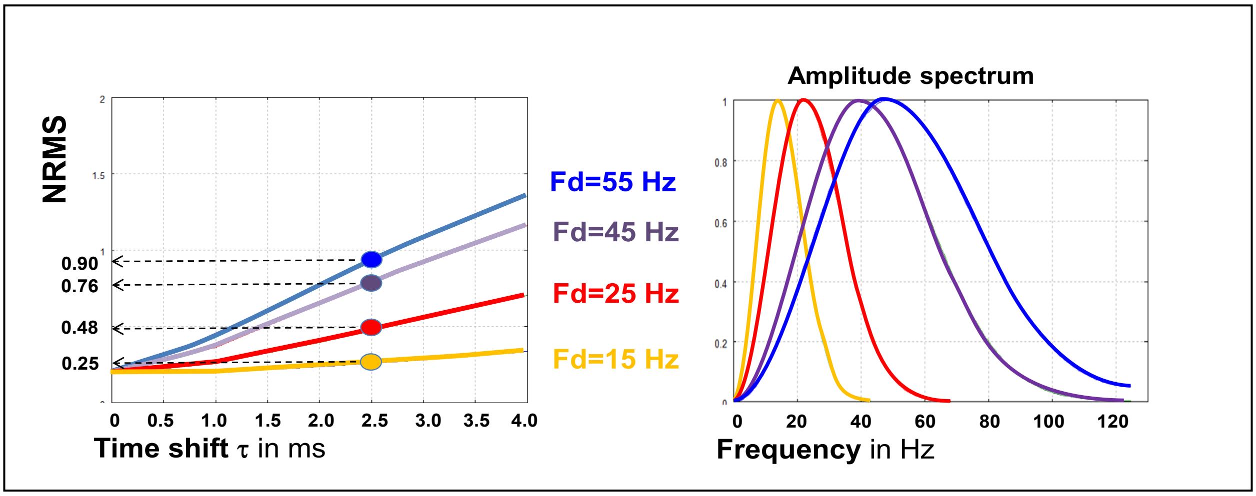

Figure 2 *Graph (left) showing the change in NRMS with time-shift, τ, and dominant frequency, f_d. Each curve represents a different signal bandwidth for the pairs of traces. For a given time-shift (circles 2.5ms) the NRMS increases with the increasing signal bandwidth. Amplitude spectra (right) for the different signals. It can be noted that the dominant frequency contains the bandwidth information and may be different to the peak frequency.*

For a given time-shift the NRMS value will increase significantly with a change in the signal bandwidth. In other words, low frequency datasets will have lower NRMS while the presence of high frequency content will automatically lead to an increase in NRMS. Consequently, the NRMS between two sets of 4D data with different bandwidth cannot be compared directly. For the same quality of seismic, the datasets with larger bandwidth will always have a higher NRMS and appearing less repeatable.

Bandwidth Calibrated NRMS:

In order to define a repeatability metric that can be applied to data with different bandwidth, we introduce a new repeatability measure called bandwidth calibrated NRMS or ***CNRMS***:

$$CNRMS^2 = 4\frac{(1-S)^2 + 2S(1-\rho_{bm})\left(f_{dref}/f_d\right)^2}{\left(1+S\right)^2} \qquad (5)$$

Where: S = Energy ratio, RMS (m) / RMS (b); ρ_{bm} = Correlation coefficient between base and monitor; f_d = RMS frequency (dominant frequency); f_{dref}: reference RMS frequency (reference frequency)

In the proposed form, this measurement is valid for small timing variations between base and monitor.

Figure 3 describes the same situation as in figure 2; using the new CNRMS measurement the curves are very similar for the different bandwidth examples. In this example, the NRMS has been calibrated using a reference dominant frequency of 40 Hz.

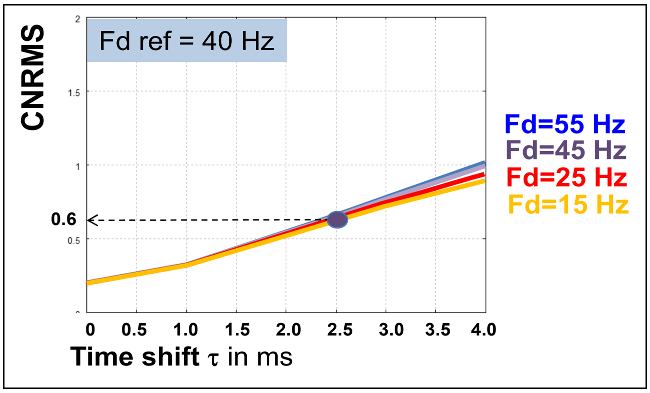

Figure 3 *Graph showing the change in CNRMS with time-shift, τ, and dominant frequency, f_d. A reference frequency of 40 Hz was used to compute the CNRMS values. For a given time-shift (circles for 2.5 ms), all data now give similar and comparable CNRMS value regardless of the bandwidth.*

Conclusion

The formulation of the NRMS equation explains mathematically why, for constant time shift values, the NRMS computation will lead to larger values if the data bandwidth is increased. A new repeatability measure, called CNRMS, introduces a normalization process with regards to a reference dominant frequency. It provides almost identical repeatability values for a given time-shift regardless of the effective data bandwidth.

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