Repeatability measure for broadband 4D seismic

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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, primarily the widely used 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.
In order to extend the 4D signal bandwidth without compromising the repeatability, we propose that up-going pressure wavefields extracted from dual-sensor streamer are used for base and monitor surveys. It ensures the HF repeatability and highest 4D resolution.

Introduction

Today the seismic industry is proposing new resolution standards for 3D imaging using seismic data with an extended bandwidth. These 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.

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 dominant frequency of the data (Calvert, 2005). Therefore, 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 two 4D synthetic data example; the narrowband data provides a considerably lower NRMS than the broadband data despite the underlying differences between base and monitor being identical for both models.

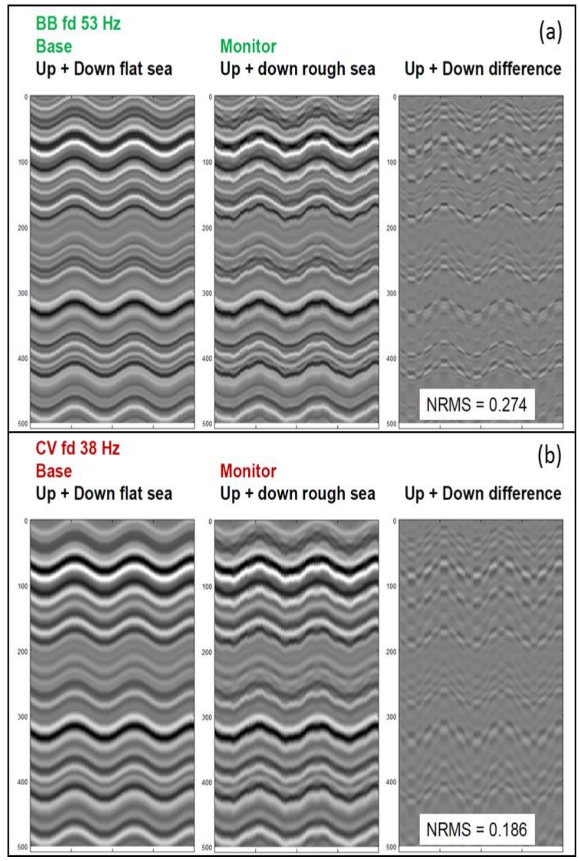

Figure 1: Repeatability metric comparisons for two 4D synthetic data examples created using different dominant frequencies: (a) base, monitor, difference and NRMS for a broadband dataset with a dominant frequency of 53Hz; (b) base, monitor, difference and NRMS for a narrowband dataset with a dominant frequency of 38Hz.

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

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

We can rewrite the expression by introducing new variables:

$$NRMS^2 \approx 4\frac{(1-S)^2 SN + 1 + S^2 + S(2\pi\tau f_d)^2 SN}{(1+S)^2(1+SN)} \quad (2)$$

Where:
S = Energy Ratio, RMS (m) / RMS (b);
SN = Signal to Noise Ratio;
τ = Time-shif;
fd = RMS freq. (dominant freq.)

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

$$NRMS^2 \approx SDR^{-1} + (2\pi\,\tau\, f_d)^2 \text{ (Cantillo, 2012)} \quad (3)$$

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

(Note that expression (3) assumes noise free data with a RMS ratio S close to 1, SDR is defined as the trace similarity (Cantillo, 2012) and formulation (4) does not specifically include any time-shift considerations.
The proposed formulation (2) describes NRMS as a function of the Energy Ratio (S), Signal to Noise Ratio (SN), Time-shift (τ) and RMS frequency or dominant frequency (fd). 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. Only the first term of a Taylor series has been retained implying this expression is valid for small time-shifts; higher-order terms of the Taylor expansion would be needed to account for larger time-shifts.

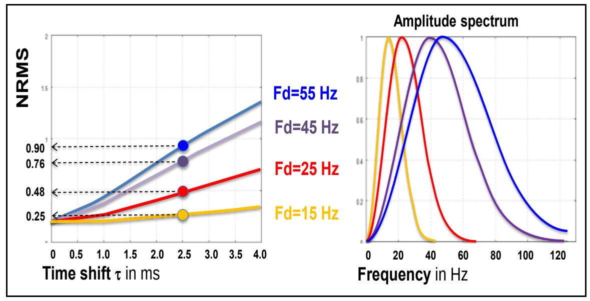

Figure 2: Graph (left) showing the change in NRMS with time-shift, τ and dominant frequency, fd. For a given time-shift (2.5ms) the NRMS increases with the increasing signal bandwidth. Amplitude spectra (right) for the different signals.

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 NRMS on these properties. The NRMS is computed for different time-shifts between pairs of synthetic seismic traces; the experiment is repeated for traces with 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.)

As observed previously in figure 1, the graphical representation of expression (2) shown in figure 2 illustrates that a lower frequency dataset will have a smaller NRMS than one with higher frequencies when in presence of the same time shift between base and monitor. Consequently, the NRMS between two sets of 4D data with different bandwidths cannot be compared directly. For the same quality of seismic, the datasets with larger bandwidth will always have a higher NRMS, 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:

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

Where S = Energy ratio, RMS (m) / RMS (b);
ρ bm = Correlation coefficient between base and monitor;
fd = RMS freq. (dominant freq.); fdref: reference RMS freq. (reference freq.)

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

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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.

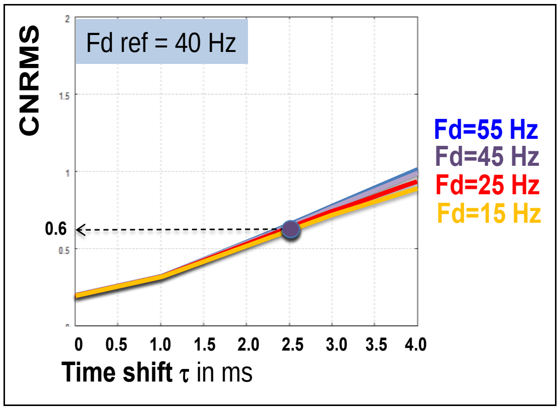

Figure 3: Graph showing the change in CNRMS with time-shift (τ) and dominant frequency (fd). A reference frequency of 40 Hz was used to compute the CNRMS values. For a given time-shift (circles for 2.5 ms), all data now give similar and comparable CNRMS value regardless of the bandwidth.

How to increase repeatability for 4D broadband dataset?

Extending the frequency bandwidth for 4D datasets using de-ghosting processing techniques will increase the sensitivity of the seismic response to reservoir changes and make the repeatability even more challenging. But can we increase the 4D signal bandwidth without increasing the NRMS (and improve the CNRMS)? Positive steps may be made to towards this objective if the non-repeatable part of the signal can be removed, especially for the high frequencies. A significant aspect of this relates to the sea-state and its interaction with the recorded signal.

Figure 4 illustrates the ability of a dual-sensor recording system to perform accurate wavefield separation providing an opportunity to extend the signal bandwidth by selecting the consistent up-going wavefield (P-UP) and discarding the down-going wavefields (ghost) affected by the sea-state variation.

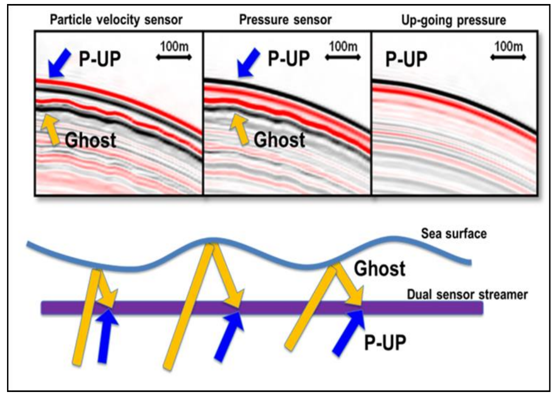

Figure 4: Zoom on a common shot gather (left) showing the recording of the vertical particle-velocity sensor, pressure sensor and the reconstructed up-going pressure wavefield. The receiver ghost undulation (yellow arrow) is due to the sea surface reflection while the up-going pressure wavefield (blue arrow) stays continuous.

The benefits of using only the up-going pressure field for broadband 4D is demonstrated using repeated sail-lines recorded with a dual-sensor towed streamer (figure 5).

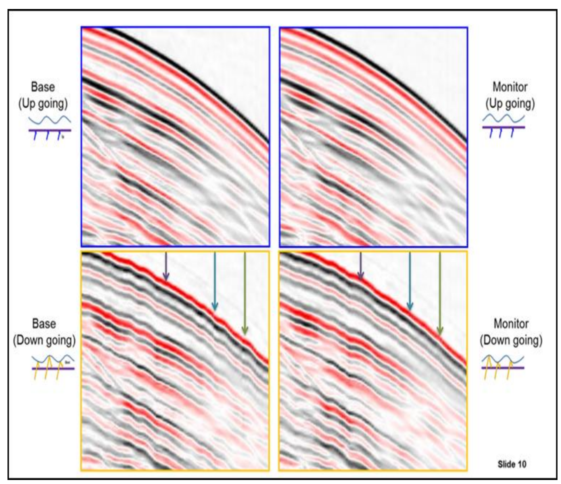

Figure 5: Repeated shot gathers for the up-going wavefield (top) and for the down-going (bottom) wavefields. While the up-going is consistent between base and monitor, the down-going (ghost) clearly shows disparate undulation related to the swell effect. The "base" and "monitor" were acquired a few months apart, using the same seismic vessel, to evaluate acquisition repeatability issues

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The use of the up-going wavefield for 4D not only recovers the frequencies in the receiver ghost notches but also preserves the most repeatable part of the seismic signal, and as noted by previous authors (e.g. Laws and Kragh, 2002), it also clearly illustrates that the down-going field (receiver ghost) is modified by the sea-state variations and consequently is ill-suited for 4D broadband.

Conclusions

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

In order to extend the 4D signal bandwidth without compromising the repeatability, we propose that up-going pressure wavefields extracted from dual-sensor streamer are used for base and monitor surveys. It ensures the best possible broadband repeatability and highest 4D resolution.

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EDITED REFERENCES

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