Innovative QCs for more effective 4D processing

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Summary

Time-lapse seismic data have long proved to be valuable datasets for monitoring production and fluid injection in reservoirs. Quality and timing of 4D data deliverables must be in line with challenging production and development deadlines. Reducing the processing turnaround time of monitor surveys is therefore a prime value task.

Quality controls (QCs) produced along 4D seismic processing give assurance over the time-lapse data quality improvement. They highlight the non-repeatability resulting from acquisition or processing and guide though the required 4D processing steps.

Efficient innovative QCs that allow faster and more straightforward assessment of the 4D signal quality after each processing steps will help with the reduction of processing turnaround.

Classical 4D QCs are mostly based on Kragh and Christie's [1] NRMS and predictability (PRED) concepts. They have been the most widely used tools for analyzing 4D repeatability noise.

Although routinely used, their output is sometimes not intuitive, they often lack for sensitivity regarding the variations one is willing to observe as detailed by Cantillo (2011) [2]. They offer a large range of possible ambiguous interpretations.
We propose novel attributes and innovative QCs to assess 4D data quality.
These new attributes and QCs are described as:

- SDR: Signal to Distortion Ratio,
- SDR vs. NRMS cross plot
- NRMS BandPass
- NCCP: Noise Characterization Cross Plot,
- RPTSC: Relative Phase Difference Time Shift Cube,

The use of these QC attributes improves the guidance along the processing steps as well as a better evaluation of the confidence one can have in the data after each step during 4D processing.

Thanks to their unambiguous interpretation, these innovative QCs methods have allowed to significantly reduce the processing turnaround of full integrity 4D monitor datasets.

Introduction

4D QCs aim to quantify the non-repeatability of seismic measurements between Base (b) and Monitor (m) datasets.
4D Seismic processing aims to reduce the non-repeatability according to the information drawn from the QCs. We need to know which phenomenon causes this non-repeatability and which process needs to be applied, followed by whether its application has been efficient.
Innovative QCs must lay the focus on only one non-repeatability or 4D difference parameter (i.e.time shift or amplitude distortion) and lead to non ambiguous understanding. QCs should also strongly react to the variation range that is expected. The computation time is also of utmost importance since it must be calculated at every step of the 4D processing.

Signal to Distortion Ratio (SDR)

The SDR (Signal to Distortion Ratio) introduced by [2], enables the observation of the distortion between traces regardless of other parameters.
The SDR attribute flows from the analysis of the 4D problem in the framework of the 1D convolutional model.

This attribute and the following developments were initially detailed by Cantillo (2012) [3].

The 4D signal is the difference of two similar seismic measurements b and m .The SDR estimates the energy which remains in the 4D difference data after any possible time shift between b and m has been removed.
It can be expressed in the following manner:

The maximum (ρ_{max}) of the normalized cross correlation function ($\Phi_{bm}(\tau)$) between Base (b) and Monitor (m) for each pair of traces and in a given QC window is calculated as follows:

$$\rho_{max} = \frac{max_{\tau}(\Phi_{bm}(\tau))}{\sqrt{\phi_{bb}(0)\phi_{mm}(0)}}$$

Thereby, a SDR value for each pair of traces is obtained:

$$SDR = \frac{\rho_{max}^2}{1-\rho_{max}^2}$$

The SDR value ranges from 0 to ∞. Practically a value of 1 means that there is absolutely no similarity between the base and monitor traces as the distortion amplitude bears the same magnitude as the base amplitude. On the other

end of the range, even if by construction SDR is theoretically unbounded, a value around SDR≃312.2 (25 dB), means an almost perfect fit in shape of the monitor trace to the base trace.
The scale offered by the SDR is more sensitive to detect non repeatability effects in the overburden as detailed in [3].
The SDR is normally computed between base and monitor traces in areas and time window where no production occured. Should it be computed in places where production had occured, the SDR looses its nature and is strongly perturbated by the genuine time-lapse signal.

SDR base maps

SDR is thus a very efficient attribute to generate base map QCs. As shown on Figure 1, insensitivity to time shift is sometimes crucial to clearly determine the origin of signal non-repeatability.

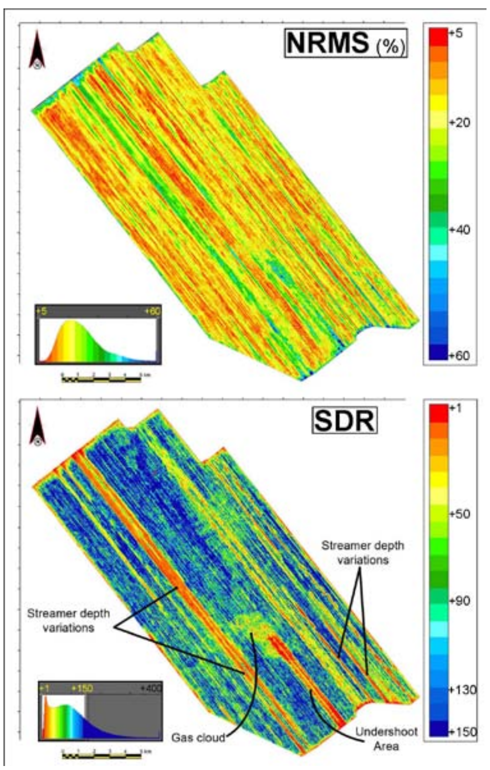

Figure 1: NRMS and SDR base maps close to the water bottom of a West Africa 4D survey.

Figure 1 shows that SDR highlights acquisition related problems that lead to signal distortion in a much clearer way compared to NRMS which confuses distortion with time shifting.

In the example shown there is a partially documented streamer depth problem on the base volume. The nominal 6 meter streamer depth had not always been respected. Streamers dived down to 9 meter on some lines.
The streamer depth, which impacts the signal notch frequency in the spectrum of the base survey, led to clear signal distortion highlighted by red stripes on the SDR map.

The monitor survey undershoot is a place where significant signal distortion is expected due the non-repeatability of the source and receiver positions. This area is also clearly highlighted on the SDR base map. Thus this zone can be easily identified and the magnitude of the associated signal distortion be precisely measured.

On the NRMS map, the undershoot area and the streamer depth variations are obscured by their own time shifts. The SDR base map is very efficient to guide the different 4D processing steps aimed to compensate for non repeatability effects. It gives clear indications on the quality of uplift brought by the successive processing steps. On Figure 2, we observe the geographical distribution of distortion improvements during major processing steps.

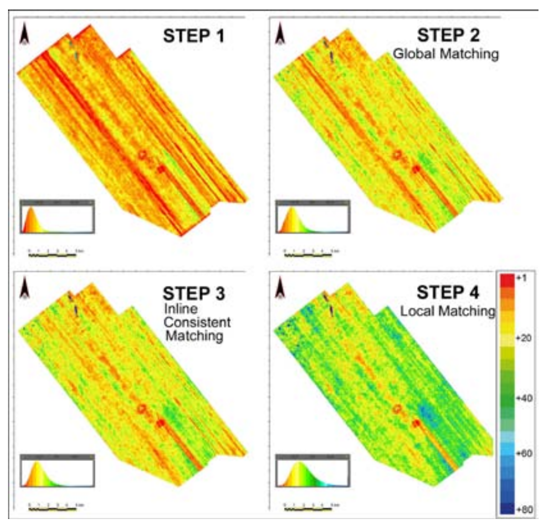

Figure 2: SDR base maps in the overburden, using a deeper window than on Figure 1, at successive processing steps.

SDR vs. NRMS cross plots

During processing, the PRED vs. NRMS cross plot is commonly used as a quality assessment tool. This highlights the progress achieved in the amplitude difference reduction in the overburden. This is a primary QC for 4D processing studies.
PRED, NRMS and SDR are computed across the whole 3D volumes in a given time interval and after each major

processing step. This allows evaluating the influence of each processing step on repeatability. Commonly used PRED vs. NRMS cross plots are a poorly discriminatory QC.
Cross plots of SDR vs. NRMS allows observing repeatability differences better than the PRED vs. NRMS. On Figure 3 displays, the density of data points in the cross-plot have been colour coded to enhance QC readings.

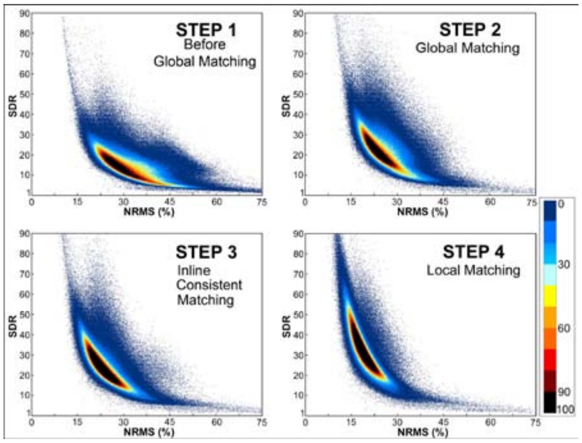

Figure 3: SDR vs. NRMS cross-plots at four important processing steps of a 4D Processing sequence. Colour represents the density of data points.

On Figure 3, one can immediately identify which are the processing steps leading to less distortion between surveys (the SDR increases) and the lowest NRMS.
The distortion variation in the overburden is an important QC target to assess 4D processing quality. The SDR vs. NRMS cross-plot has shown its ability to compare the different processing steps quality of several 4D datasets, allowing to quantify the repeatability improvement between successive processing stages.

NRMS Band Pass

The decay of the base–monitor difference energy in the overburden is a meaningful indicator of the repeatability improvement. The layers above reservoirs act as high cut filters on the propagating wavelet.
Therefore it is useless to correct for repeatability inaccuracies supported by the higher end of the frequency spectrum measured in the overburden. These discrepancies will have no impact on the 4D signal in the reservoir which is supported by lower frequencies.

NRMS BandPass was introduced for the specific problems observed on a West Africa 4D survey where a 30Hz difference was observed in maximum frequency between the overburden (across which QCs are computed) and the reservoir. Anomalies appearing in the higher frequencies, did not have any influence on the 4D signal detectability and quality. It was therefore unnecessary to compensate for these high frequency anomalies.

The NRMS Band Pass process calculates the frequency spectrum in the reservoir interval to automatically correct the NRMS computation performed on a shallower window, according to the effective spectrum in the reservoir area. A NRMS Band Pass map is then obtained; showing only the non-repetability effects that will impact the production related time-lapse signal.

Noise Characterization Cross Plot (NCCP)

In order to better understand the non-repeatability of a 4D seismic survey, we propose a statistical method to distinguish ambient noise and repeatability noise in 4D data with the Noise Characterization Cross Plot (NCCP).

Ambient noise is mostly random - it is independent from the measurement and could be considered as constant in amplitude. It corresponds to noise mostly linked to the environment and human related activities: swell, drag turbulences on streamers and interferences from production installations among other sources. This noise is hence independent from seismic amplitude and is represented as a horizontal iso value line on our cross plot.
However, repeatability noise corresponds to the base and monitor dataset discrepancies related to seismic acquisition. These differences are due to the acquisition parameters that cannot be perfectly repeated like source position and power as well as streamers depth and position. The iso repeatability lines will appear as white slanted lines on Figure 5
One can see on Figure 4, that ambient and repeatability noise levels are represented only in the area of interest of the NCCP cross plot. This area represents where the amount of data is sufficient to be statistically significant.

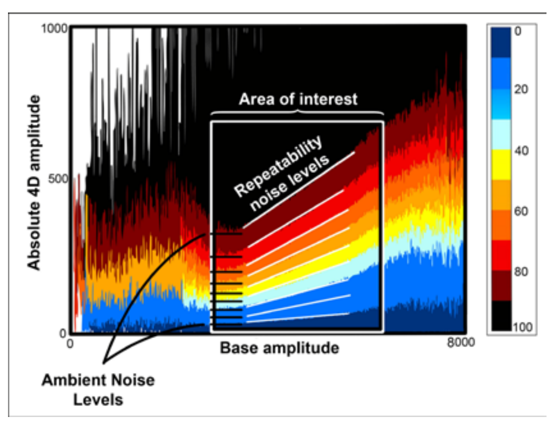

Figure 4: Area of interest of the NCCP cross plot.

To build the NCCP cross plot, 4D absolute amplitude (absolute value of the difference between monitor amplitude and base amplitude) is plotted as a function of base amplitude. Cumulative distribution functions along the 4D absolute amplitude axis are computed for any base amplitude value and then displayed on the graph. Each colour coded iso-value of probability separates areas with different probability value.

Ambient noise levels are the lowest levels of each iso-value of probability that can be picked on the NCCP. Figure 6 is a simplified sketch of Figure 5 - the line located between the red and orange areas of Figure 5 represents the separation between 70 % probability that the 4D anomalies have an amplitude greater than the ambient noise amplitude. The line between red and beige areas on Figure 6, corresponds to a repeatability noise level leading to a probability of 30% that 4D anomalies can not be detected. Thus, there is a probability area; the beige area corresponds to the probability that 4D anomalies have an amplitude level intermediate between repeatability noise and ambient noise. In this area, 4D anomalies shall be considered as qualitative only.

The NCCP quantifies the probability to detect 4D signal. The primary purpose is that NCCP enables comparison of the slopes of repeatability noise and the level of ambient noise between processing steps and also between different 4D projects. It is a very efficient QC to quantify the efficiency of the processing steps applied to the base and monitor datasets. Ultimately it will quantify whether the 4D signal is detectable.

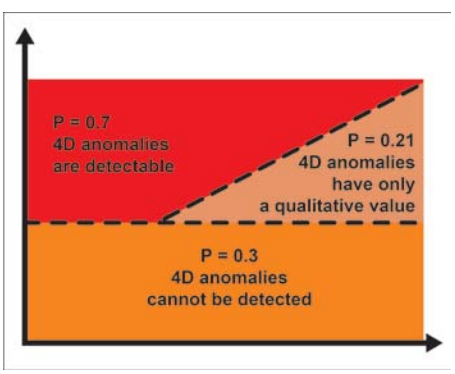

Figure 5: Iso-value of probability (dotted line) that separates red and orange areas of Figure 5 and defines the detectability zones of the 4D anomalies.

Relative Phase Difference Time Shift Cube (RPTSC)

The difference between the instantaneous phases measured on the base and on the monitor surveys can be easily converted into a time difference using instantaneous frequencies after Taner et al. [4]. RPTSC algorithm is sensitive to very small variations between base and monitor (about 10 µs). This computation is fast and leads to a 3D volume where residual time shifts, often time variant, can be observed as in Figure 6.
These observations are done independently from the large time shift variations due to the 4D signal in the reservoir.

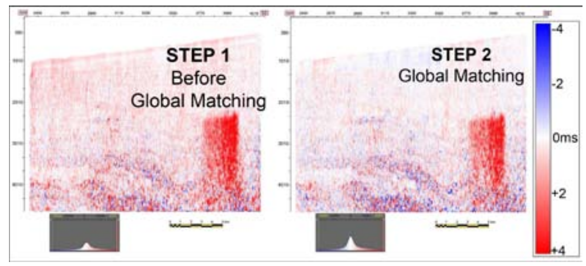

Figure 6: RPTSC of a producing field. The global matching between step 1 and step 2 has corrected the +200 µs time shift constant outlined by the QC completed after processing step 1.

Conclusions

The confidence given to 4D data during interpretation depends on the seismic repeatability in production-spared zones. NRMS and PRED are the most commonly used attributes when analyzing 4D noise and non-repeatability in time-lapse studies.

Innovative QC attributes, as well as the better practices for determining 4D seismic data quality have been proposed. These attributes allow for a better guidance along the processing steps as well as an improved evaluation of the confidence gained in the data, step after step during the 4D dedicated processing.

This paper introduces new attributes and QCs, such as Signal to Distortion Ratio (SDR), Noise Characterization Cross Plot (NCCP), Relative Phase Difference Time Shift Cube (RPTSC), NRMS BandPass and SDR vs. NRMS cross plots. These innovative QC methods reduce the processing turnaround of full integrity 4D monitor datasets by approximately 30%, enabling a quicker delivery of high confidence 4D seismic signal and making possible an increased impact on the field monitoring through more frequent reservoir model updates.

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