Simultaneous time-lapse processing for improved repeatability

Xinxiang Li,[1] **Rodney Couzens,**[2] **Jeff P. Grossman**[2*] **and Ken Lazorko**[2] present with a supporting case study a QC procedure for the simultaneous processing of multi-vintage time-lapse datasets which can improve the repeatability of the time-lapse data.

In conjunction with amplitude-friendly simultaneous processing of time-lapse seismic data, we introduce a QC scheme that steers the processing towards optimal time-lapse repeatability. We compute NRMS errors between stacked traces for different vintages of a survey after each main step of simultaneous processing. A processing step (which may include intermediate steps) is considered acceptable only when its overall NRMS (normalized root-mean-squared) error value is at most equal to its value from the previous processing step. We demonstrate this QC scheme with a well-designed time-lapse dataset.

The concept of simultaneous processing of multi-vintage time-lapse datasets is described in Lumley, et al. (2003). The premise is to process multi-vintage datasets as one dataset, especially when they are acquired for time-lapse analysis purposes. We believe simultaneous processing provides an opportunity to improve time-lapse repeatability, and should be considered even when two different vintages of data are not acquired specifically with time-lapse analysis in mind. There are some processes in simultaneous processing that work differently from those in 'parallel processing' (Lumley et al., 2003), where different vintages of a time-lapse survey are processed as separate surveys but using the same or similar flow. Before such processes can be discussed, we need to reconsider the meaning of surface consistency within the context of simultaneous processing. Although normally, we think of surface consistency as a constraint requiring a common operator (such as a static time shift, an amplitude scalar, or an earth wavelet response) at each surface location, it is more realistic to compute different operators for different sources and receivers even if they are located at the same surface location. 'Surface consistency' therefore is better thought of as 'source and receiver consistency', especially in the context of the simultaneous processing of multi-vintage datasets.

One of the most significant advantages of simultaneous processing is derived from the common refraction statics computation, which allows source and receiver consistent statics to be obtained from a common near surface model. To actually realize this advantage, however, any bandwidth, phase, and time differences between vintages must be reconciled prior to first break picking. Other source and receiver consistent operators, such as deconvolution operators and amplitude scalars, may also be computed by treating different vintages as one dataset. Source and receiver consistent residual statics are determined with the objective of producing the best common CDP stacks, particularly within the no-change zones which are expected to be time-lapse invariant (Lumley et al., 2003). Stacking and migration velocities are determined with the same objective.

Simultaneous processing enables repeatability monitoring throughout the flow rather than at the end of the processing sequence after a single reconciliation effort, thus providing the opportunity to optimize the flow as processing proceeds. A standard repeatability metric to use in this monitoring process is the NRMS error between two traces (Calvert, 2005, Pevzner, et al., 2010, Atkinson, 2011). It is defined as the RMS value of the difference between two input traces, normalized by the average of the RMS values of the two input traces. The RMS values are computed in a common time window within the interpreted no-change zone and a common frequency band. By definition, NRMS values are always between 0 and 2. For two very similar traces which are aligned in time this value is close to zero, while for two identical traces with opposite polarity the NRMS value is 2. NRMS error values increase substantially for identical traces which are not well aligned in time.

This last property has been viewed as a potential weakness by some. Cantillo (2012) points out in recent work that the concept of repeatability is largely a matter of intrinsic shape, and perhaps it should have a lesser emphasis on small time shifts than NRMS does. Motivated by this sensitivity, Cantillo (2012) defined a new repeatability measure called signal-to-distortion ratio (SDR) to better characterize shape similarity in the presence of time-shifts. Cantillo also developed an asymptotic expression relating NRMS and SDR for the case of small time-shifts (on the order of 5 ms), and showed that in this case the two measures are effectively equivalent.

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Thus, early in the processing where there can be large time-shifts across vintages, such as for multi-vintage cases that were not suitably designed as time-lapse surveys, SDR could turn out to be more beneficial than NRMS in guiding the processing until time differences are sufficiently reduced. Generally, however when different vintages of data are acquired with repeatability in mind, meaningful NRMS values can be obtained throughout the processing sequence and provide useful feedback on how well the processing strategies employed are coping with receiver tilt, varying shot-hole depths, different geometries, different source and receiver types/signatures, and changing surface conditions (freeze/thaw, water table height). This of course assumes that no-change zones contain sufficient coherent energy for analysis.

Simultaneous processing with NRMS QC

An essential part of our simultaneous amplitude-friendly time-lapse processing is the addition of an extra QC component to the conventional amplitude-friendly processing flow. The QC component includes the computation of NRMS errors from stacks of different vintage data, after each key processing step. A processing step is accepted only if it increases the repeatability from the previous step. Strictly speaking, a step may include a few intermediate steps – the only requirement is that there be a sequence of steps that leads to improved repeatability. A case in point is deconvolution and the non-repeatable high frequency noise it tends to boost – post-deconvolution noise attenuation may be required to improve repeatability, particularly in low-fold regions.

The computation of the NRMS error is straightforward. However, we should carefully choose the time window and frequency band for NRMS computation. The time window must be restricted to times shallower than the target zones where any real changes of interest need to be preserved. A reasonable length of good-quality data must be included. The frequency band for NRMS computation must be wide enough to capture a large majority of the reflection signal, yet exclude frequencies with poor signal-to-noise ratio. The bandwidth can also be expanded in step with any signal-to-noise improvements as the processing flow progresses.

NRMS error evaluation should be considered at each of the following steps in the processing flow:

- Starting point: data with geometrical spreading correction and refraction statics application
- Source and receiver consistent amplitude-correction
- Groundroll removal and other pre-decon noise attenuation
- Source and receiver consistent deconvolution
- Source and receiver consistent amplitude-correction
- Velocity and residual statics update
- Post-decon noise attenuation

- CDP trim statics
- Post-stack noise attenuation
- Post-stack migration
- PSTM stack

NRMS repeatability measurements can change significantly at any one of these steps. There could be other processing steps specific to individual time-lapse surveys that should be in the list. For example, a phase matching between different source types can make significant differences in repeatability.

Data examples

We have processed the Pouce Coupe 4D/3C survey using our simultaneous amplitude-friendly time-lapse processing methodology. The seismic data was acquired specifically for the purpose of time-lapse analysis. The geophones were buried for all phases. The dynamite sources were located at the same surface locations with the same charge depth and size across the different phases of the time-lapse survey. The only exceptions were the occasional location where the hole integrity had been compromised; in those cases shallower holes were re-drilled very nearby with smaller charge sizes.

There are three vintages in this survey. Figure 1 shows a number of trace triplets extracted from a relatively clean part of the datasets. Each triplet contains one trace from each of the three vintages, with the sources at a fixed surface location and recorded from the same receiver. The traces displayed in Figure 1(a) are raw data with geometrical spreading correction applied. The repeatability and the lack of it are quite easy to identify by inspection. Although the repeatability is evident in terms of wavelet shape similarity, the amplitude levels of the traces quite often are different. Different triplets also seem to have different amplitude levels. These amplitude differences can be corrected, at least partially, by source and receiver consistent scaling as shown in Figure 1(b). From the changes shown in Figure 1(b), it is expected that the repeatability will be improved on the stacks after source and receiver consistent amplitude-correction. In fact, as shown in Figure 3 below, source and receiver consistent amplitude correction is the step that reduces NRMS error the most for this particular dataset.

Deconvolution is a process that changes amplitude and phase variations of traces considerably. However, we found that the overall NRMS error did not change much after deconvolution (see Figure 3). At high-fold CDP locations, deconvolution either maintained or improved the repeatability. It significantly reduced the repeatability at low-fold locations, due to the non-repeatable noise in broader bandwidth. As expected, the application of residual statics and trim statics, as well as post-stack denoising processing, and poststack 3D f-xy prediction filtering (also called f-xy decon) all progressively improved the repeatability. Interpolation was also applied to re-create traces at low-
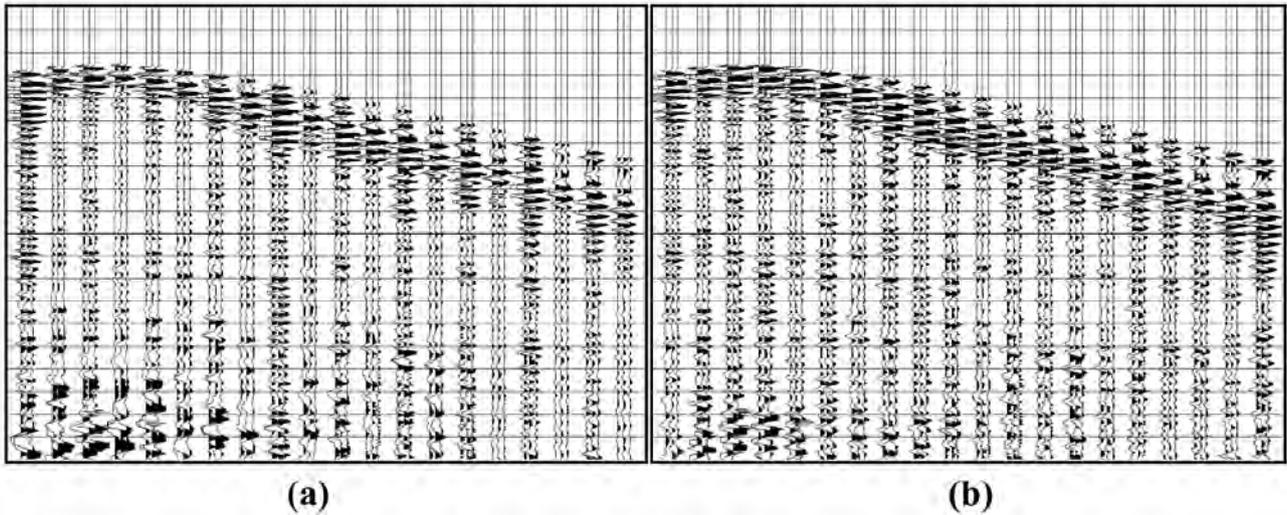
Figure 1 *Trace triplets from raw data with geometrical spreading correction, before (a) and after (b) source and receiver consistent amplitude-correction. The resulting repeatability improvement is evident.*
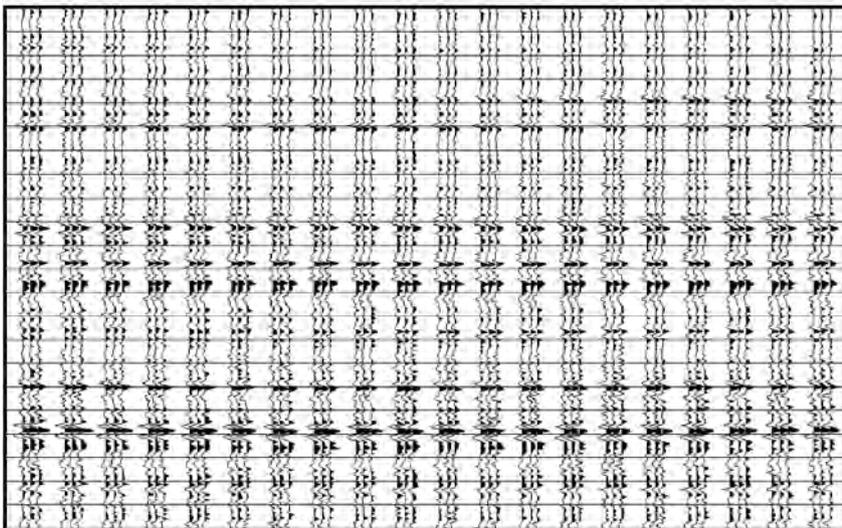

Figure 2 *Trace triplets from final migration stacks within the no-change zone. Traces from the same CDP locations are displayed in groups of three. Strong repeatability is evident in terms of shape similarity, temporal alignment, and amplitude variation.*

fold locations from neighbouring higher-fold traces, and this improved the repeatability at those locations while preserving it elsewhere. The interpolation process was in the original plan when the data was acquired, and is not a standard process for the sake of repeatability improvement. Figure 2 shows some trace triplets from final migrated stacks. Although we found for this dataset that migration did not reduce the NRMS error, the strong repeatability of the three phases is quite evident.

In summary, Figure 3 displays the NRMS error measurements at all major processing steps. The NRMS error between two stack volumes is estimated as the average of the NRMS errors of the individual stack traces over a range of high-fold CDP locations. Figure 3 clearly shows the gradual improvement of the time-lapse repeatability. The symbols used for each of the steps in the plot are defined in Table 1.

Symbol	Process
OAC	offset dependent geometrical spreading correction
SC1	source and receiver consistent amplitude correction
REF	refraction statics correction
SCD	source and receiver consistent deconvolution
RS2	two iterations of residual statics correction
TST	CDP trim statics correction
FXY	f-xy decon on stacks
TVSWFXY	spectral whitening and f-xy decon

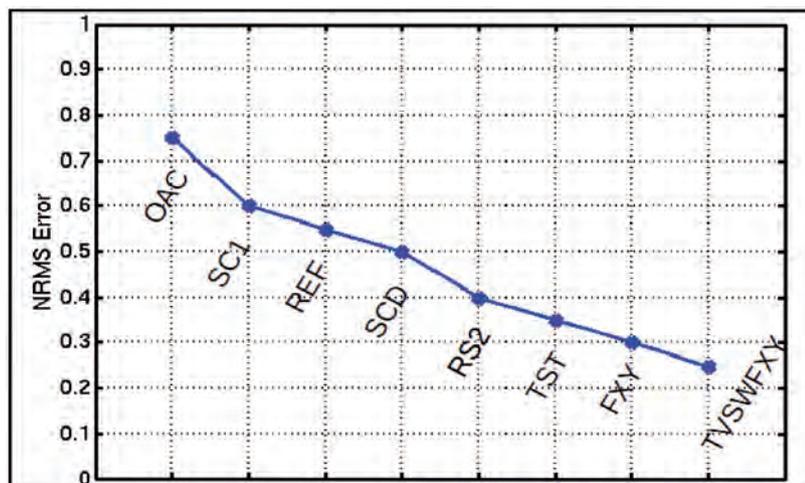**Table 1** *Symbols used to represent main processes in Figure 3.*

Figure 3 Estimates of the average NRMS errors for entire stack volumes between phase 1 and 2 are displayed against a number of processing steps. Progressive repeatability improvement is clearly seen. The symbols for each step are defined in Table 1.

Conclusions

Single-vintage data processing aims at producing the best quality stacked volume or pre-stack gathers, with little regard for the non-repeatable aspects of different vintages. However, a time-lapse survey aims at obtaining meaningful differences between different vintages in the survey at the reservoir level. Reflection signal from no-change zones – where time-lapse effects are not expected – should be made as repeatable as possible, meaning differences between vintages at these zones must be minimized. Such differences can and do arise from variable acquisition conditions (geometrical, seasonal, or otherwise). We propose a time-lapse processing flow that employs not only the amplitude-preserving simultaneous processing of all vintages as one dataset; we also employ a QC procedure to help guide the processing sequence toward progressive improvement of repeatability. This involves computing NRMS errors in the no-change zones between stacked traces for different vintages of a survey after each main step of simultaneous processing. We also replace the notion of surface consistency with that of source and receiver consistency as a more appropriate constraint for simultaneous processing across vintages. We show how this approach works for a real data example.

Early in the processing, where there can be large time-shifts across vintages, such as for multi-vintage cases that were not suitably designed as time-lapse surveys, SDR rather than NRMS may provide a more useful repeatability metric for guiding the processing until such time differences are sufficiently resolved. It is very possible that some standard processing steps have to be modified to fit properly into the processing stream.

Generally speaking, source and receiver matching, amplitude balancing, statics, and noise attenuation are the main steps where significant repeatability improvements are expected.

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