Multi-Vintage, Pre-Stack Calibration of 3-C 3-D Time-Lapse Seismic Data

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Summary

A new processing model for calibration of time-lapse 3-D, including 3-C, datasets is proposed. Pre-stack data from all vintages are sorted in a single multi-component dataset, which is concurrently carried through the same processing sequence. All data are calibrated on the trace-by-trace basis, which also allows extraction of additional information about the differential statics, amplitudes, spectra, and detailed velocity variations between the time-lapse datasets. This scheme allows controlling processing consistency at all stages of analysis and achieves accurate and model-independent calibration. The resulting calibrated pre-stack datasets are suitable for all types of analysis, from production of stacked or migrated images to three-component AVO measurements and time-lapse comparisons.

Introduction

Calibration of different seismic datasets is the most critical part of time-lapse seismic monitoring. Such calibration involves maintaining constant positions of the source and receivers, consistent charge types and sizes, and similar recording conditions. In seismic processing, proper calibration also requires common binning, identical processing steps, equalization of the wavelet, and statics and velocity models that can be correlated between the different vintages of the dataset.

Even with highly repeatable recording, the last two of the above items (consistent velocity and statics models) are particularly difficult to achieve in conventional time-lapse processing (e.g., Sensor Geophysical, 2005). Typically, different vintages of the dataset are first processed independently by using common processing flows, velocity, and refraction models. Surface-consistent and CMP trim statics are used to adjust the differences of the monitor datasets. The data are further stacked, coherency-filtered, and migrated, after which time stretching and wavelet calibration is performed with the migrated datasets. As one can see, most of these procedures are performed either independently on the different vintages or by using stacked or spatially-filtered data, which is insufficient for accurate calibration. Furthermore, such procedure is particularly inadequate if preservation and calibration of amplitude variations with offset (AVO) is essential, as in the 3-D 3-C survey of this study.

Here, we propose a fully pre-stack process of multi-component time-lapse 3-D calibration that is free from the above inaccuracies and limitations. For any number of vintages, the approach allows performing the imaging operations only once (e.g., for the baseline dataset) while keeping track of all pre-stack differences between them at all stages. The approach is illustrated on the baseline (1999) and two monitor surveys

(2001 and 2002) of the 3-C 3-D dataset from Encana. The datasets became available to us through our participation in Phase II of the IEA Weyburn CO_2 Sequestration and Monitoring project.

Method and Application

The key idea of pre-stack calibration simply consists in treating the various vintages of the dataset as components of a single multi-component seismic dataset. For example, the three 3-C datasets of this study form a nine-component 3-D dataset. At the various stages of imaging, additional "components" may be added, such as velocity profiles, well-log records, or depth-to-time mapping functions. In seismic processing software, these components are grouped into "trace ensembles" associated with particular source-receiver pairs. If certain component or vintage is absent, the corresponding ensemble still remains valid and is processed based on its actual content.

Calibrated processing occurs in two stages. First one of the datasets (e.g., the vertical-component baseline) is processed to the best possible final image by utilizing the procedures outlined in the *Introduction*. This may involve modifications of the wavelet and amplitudes, for example by using the surface-consistent deconvolution or spectral whitening. At the second stage, pre-stack records can be calibrated within each of the multi-component, multi-vintage ensembles, ensuring their matching the baseline dataset kinematically. Such kinematic matching involves:

1) Static shifts to match the first-arrival times.
2) Time shifts to match the reference reflections. This can also be used to tie all datasets to the wells or to the geological model.
3) Amplitude scaling and wavelet phase rotations.
4) Spectral balancing.
5) Measurement and compensation of the normal moveout (NMO) differences between the different vintages.

All of the corrections above can be evaluated by maximizing cross-correlations of the coresponding waveforms. Corrections 2)-5) can be time-variant in order, for example, to eliminate the differences in background velocities, attenuation, and geometrical spreading. As a result of this procedure, various differential properties are extracted directly from the pre-stack data, such as the differences in statics, Δt, in logarithms of amplitudes, $\Delta \log A$, or relative spectral slopes, $\Delta(d\log A/df)$. To the first-order approximation, any of such parameters (denoted p below) can be decomposed into the corresponding sources and receiver contributions:

$$\Delta p \approx \Delta p_S + \Delta p_R + p'(d)\Delta d\ , \qquad (1)$$

where d is the source-receiver offset, and $p'(d)$ is the estimated slope of the offset dependence of p (for example, the first-break moveout). These deviations can also be approximated in a surface-consistent manner:

$$\Delta p \approx \Delta p(\mathbf{r}_S) + \Delta p(\mathbf{r}_R) + p'(d)\Delta d\ , \qquad (2)$$

where $\mathbf{r}_S$ and $\mathbf{r}_R$ are the vectors of source and receiver surface coordinates, respectively. Note that expressions (1) and (2) are exactly the same as used in the statics inversion problem, and therefore the same approaches and software can be used for deriving them (Morozov and Jhajhria, this Convention). Such approximations can be particularly useful for identifying the main contributions to the differences between dataset vintages (Figure 1). By using these approximated solutions as a starting model, detailed "residual" variations Δp can be picked by using waveform cross-correlations.

After applying corrections 1)-5), all dataset vintages become kinematically equivalent, i.e., they should stack giving all comparable reflections at the same times. For example, note that in Weyburn vertical-component dataset, alignment of the first-arrival travel times alone results in all reflections being also aligned within 2-4 ms ranges (Figure 2). This small residual difference can be easily corrected by time-variant operations 2)-5) above. Following this calibration, detailed post-stack and pre-stack analysis (such as AVO) can be carried out by the usual techniques. For this purpose, the calibrated multi-component, multi-vintage dataset can be sorted into the CMP ensemble order.

In addition to multi-vintage record calibration, pre-stack processing allows natural and accurate treatment of multi-component data. Thus, the horizontal-component data are routinely rotated into radial and transverse records, and the vertical and radial responses are transformed into the P- and SV-wave amplitudes.

Clearly, the above full pre-stack processing and calibration procedure is facilitated by the use of flexible multi-component ensembles. This may be difficult to achieve in the traditional CMP processing systems designed for single-component data, such as ProMAX, Disco/Focus, Omega, or Seismic UNIX. However, we have developed an extensive processing package (http://seisweb.usask.ca/igeos) with native multi-component capabilities (Morozov and Smithson, 1997). Several other unique features of the package (Chubak and Morozov, 2006) allowed easy implementation of this calibration model.

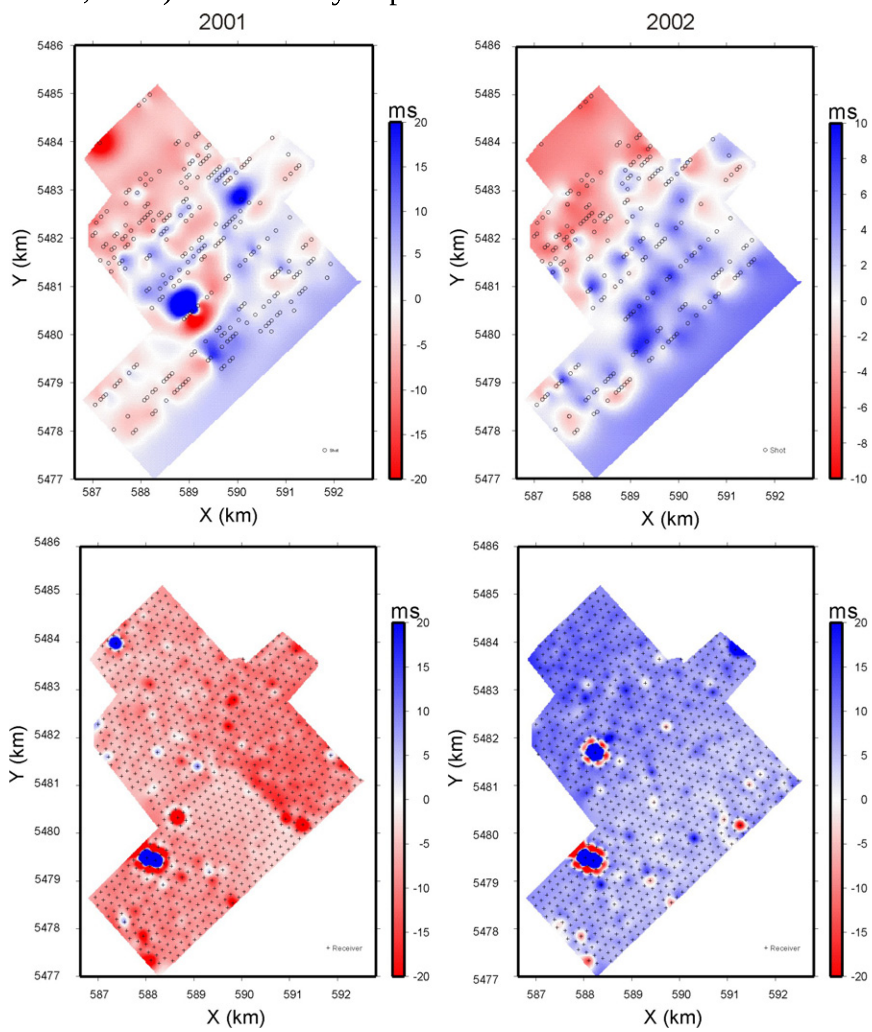

Figure 1: Differential statics measured between the 2001 and 2002 monitor datasets and the baseline. Upper row: source static terms Δt_S in eq. (1); bottom row: receiver terms Δt_R. Note the apparent effects of the subsurface structure in the source terms and of the acquisition patterns in receiver terms.

Conclusions

Synchronous, fully pre-stack processing allows achieving accurate and model-independent calibration of time-lapse 3-D datasets. The resulting calibrated pre-stack datasets are suitable for all types of analysis, from production of calibrated stacked or migrated images to three-component AVO measurements and comparisons. The approach is particularly advantageous for 3-C datasets requiring consistent multi-component data analysis.

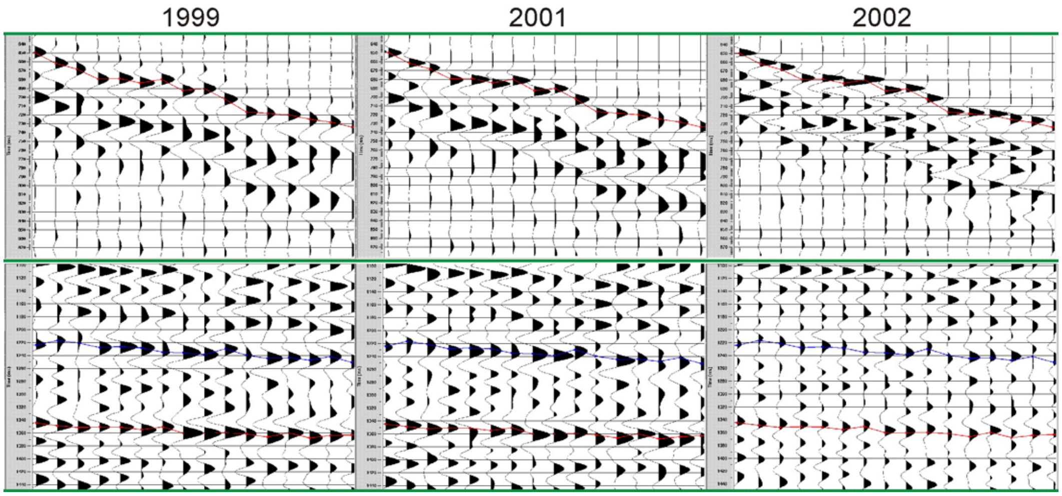

Figure 2: A fragment of a shot record from the time-lapse vertical-component Weyburn 3-D 3-C dataset (vintages labelled). Upper row: first-arrival time window; bottom row: reflections from the target area in the same traces. Red and blue lines indicate the first arrivals and selected reflections picked from the baseline (1999) data. Note that after the first arrivals are aligned, the reflections in 2001 and 2002 datasets also move to within 2 - 4 ms of those in the baseline dataset.

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References

Chubak, G., and I. B. Morozov, 2006. Integrated software framework for processing of geophysical data, *Computers & Geosciences*, 32, 767-775, 2006.

Morozov, I. B., and A. Jhajhria, 2009. Integrated Analysis and Inversion of 3D Refraction Travel Times, 2009 CSPG/CSEG/CWLS Convention

Morozov, I. B., and S. B. Smithson, 1997. A new system for multicomponent seismic processing, *Computers & Geosciences*, 23, 689-696.

Sensor Geophysical Ltd., 2005. Re-processing sequence of Weyburn Phase I seismic data, Internal project report.