Impact of Sonic Calibration in the Predictability between a Seismic Trace and its corresponding Reflectivity

Edson Silva (Infotec), Carlos Seabra (Halliburton), Ricardo de Campos (Petrobras), and Fabricio Augusto (Halliburton).

This paper was prepared for presentation during the 14th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 3-6, 2015.

Abstract

The calibrated sonic log (CSL) is commonly used as input to generate synthetic seismograms, instead the original sonic log (OSL), since the sonic and the surface seismic are measured at different frequencies, due to the dispersion effect.

In this paper, however, quantitative results show that, sometimes, the OSL can be the best option. Actually, this model proposes a comparison between them, in order to decide which is most suitable. In other words, it is intended to purpose adding a few steps, which appear in 'orange' in the Figure 1, to the usual approach (in 'white') when building synthetics.

A total of 16 wells were used. For each well, a reflectivity was computed for the CSL and another for the OSL. These two reflectivity series were then compared with the seismic data. To do so, a 'Predictability' (a measure of similarity defined later) between the reflectivity and the respective seismic trace was calculated. From all those wells, a chart was built, comparing the CSL with the OSL. As the result, in 65% of the samples, the OSL yielded higher Predictability.

Introduction

Consistent with Box and Lowrey (2003), seismic interpretation projects have to initiate with the challenge to tie seismic reflectors to geologic elements via synthetic seismograms. Conversely, synthetics usually do not tie to the seismic, and involve stretching (occasionally squeezing). Check-shot surveys, in turn, are often used in an effort to define the amount of stretching required. Nevertheless, the time-depth relationship (TDR) from sonic typically varies by disturbing quantities from the TDR from check-shot. There is frequently no apparent pattern to the incongruities.

There are several reasons why the check-shot does not tie the sonic. One of them, according to Halliburton (2008), is the dispersion effect.

This paper deals specifically with the estimation of the Goodness-of-fit of the synthetic seismogram to seismic. This quantitative measure, also entitled 'Predictability', was used to compare the synthetic calculated from the sonic calibrated through check-shot surveys with the synthetic from the OSL. The objective of this analysis is inform, as this approach, which of them has higher similarity in relation to the seismic data.

The Figure 1 shows the complete purpose when generating synthetic seismograms.

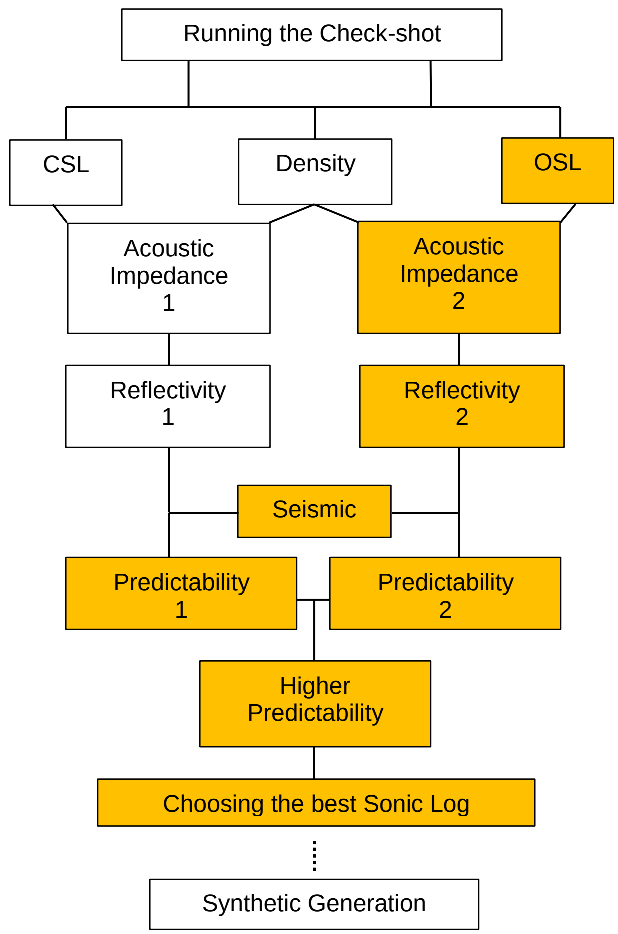


Figure 1 – The whole scheme ('orange' + 'white') of the approach recommended by this paper. The usual method appears only in 'white'.

As this approach, firstly, it is essential to run the respective check-shot, in order to take the timing of the sonic log into agreement with seismic times from a check-shot survey. Secondly, it is important to use both CSL and OSL to compute de reflectivity. Finally, both reflectivity series will be compared to decide regarding which of them will be indeed used to create the seismogram.

In order to present those results, several seismograms, coming from both the CSL and OSL, were built. To do so, 16 wells were used:

- 3 in Gulf of Mexico;
- 4 in Santos basin;
- 9 in Campos/Espírito Santo basin.

From all those wells, 200 predictability samples were calculated in relation to the seismic. “Ceteris paribus”, the original and the calibrated sonic logs were used as input to each well. As a result, a table was built, comparing the synthetics with the respective seismic data, that is, informing which of them has the best Goodness-of-fit.

Theory

When generating synthetic seismograms, a reflectivity is convolved with a wavelet. The reflectivity is calculated as the impedance contrast between the geological layers. In turn, the acoustic impedance is calculated as the product between the density and the sonic velocity. Accordingly, as Kearey, Brooks & Hill (2002), the reflection coefficient may be written as

$$\mathrm{RC} = \frac{\rho_2 v_1 - \rho_2 v_1}{\rho_2 v_1 + \rho_2 v_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \qquad (1)$$

where ρ_1, v_1, Z_1, ρ_2, v_2, and Z_2 are the density, P-wave velocity, and acoustic impedance values in the first and second layers, respectively.

Nonetheless, in accordance with Box and Lowrey (2003), synthetics normally do not tie to the seismic, and require the usage of check-shot surveys, for instance. In turn, the time-depth relationships from check-shots usually differ from sonic logs. There are many causes why the check-shot does not tie sonic and they may be grouped into three categories:

- The sonic is contaminated;
- The check-shots are contaminated;
- Both measure different aspects, in function of the dispersion effects. The corrections necessary to convert sonic measurements to check-shot measurements are called SLED (sonic log environmental and dispersion) corrections herein.

Hence, following Box and Lowrey (2003), a three stage correction process is required to remedy this three stage problem: (1) purifying the logs; (2) rejecting check-shots that are inaccurate or unrepresentative; and (3) applying the appropriate SLED correction. To sum up, interpreters faced with making synthetic seismograms in wells without check-shots, as a result, could rely on the following method:

- Purify the logs;
- Apply the SLED (8% shallow, 0% deep);
- Build the synthetic seismogram;
- Bulk shift to account for any section missing (above the top of the log);
- Make adjustments (stretch or squeeze) of no more than ±1% to account for remaining imperfections.

If interpreters have developed comfort with this method, as Box and Lowrey (2003), they may decide not to record check-shot surveys, saving substantial rig time and money.

As stated by Halliburton (2008), an accurate synthetic depends on sonic log calibration using data from a VSP or check-shot survey. This calibration is necessary because a few reasons, such as:

- Sonic log and surface seismic are measured at different frequencies (dispersion effect);
- Sonic log and surface seismic can measure different rock and fluid volumes (fluid differences, invaded zones, damaged borehole, non-vertical ray paths, etc.).

In this way, as this author, calibration of the sonic log includes an analysis of the data to determine the cause of the differences (drift) between the sonic and the check-shots. Depending on the cause of the drift, different methods of correction are used. The corrected sonic log is converted to interval velocity. Acoustic impedance is calculated using the corrected velocity log and the bulk density. Changes in acoustic impedance are used to create a reflection coefficient log, which is subsequently convolved with a desired wavelet to create a synthetic seismic trace.

As White & Simm (2003), there is a good practice in well ties, which constitutes important measures in quality controlling them. It is a quantitative method, called ‘Goodness-of-fit’, which is measured by a single scalar, named ‘Predictability’, and relies on measurements from the data, without preconceptions, of which seismic wavelets should look like.

This method is capable to assessing the reliability of the tie (Ma, White and Hu, 2010), using parameters such as cross-correlation coefficient.

A coherency matching technique, defined in White 1980, Walden and White 1998, gives a number of outputs that effectively define whether the tie is good or not (White and Simm, 2003):

1) shape of the wavelet;

2) phase characteristics of the wavelet;

3) quantitative measures related to the tie;

a) estimation of the goodness-of-fit of the synthetic to seismic;

b) estimate of the likely phase error (or accuracy) of the wavelet.

By way of DUARTE (2007), Goodness-of-fit is the degree of adherence, that is to say, measure of agreement between the observed data and the theoretical data from a given distribution. One of the mathematical expressions used is as follows:

$$g = \sum |x_i - d_i|^p, \quad (2)$$

where,

x_i is the observed data;

d_i is the theoretical data; and

p is a integer number.

Alternatively, consistent with White & Simm (2003), in order to define goodness-of-fit, two terms are introduced:

1. the energy of a trace is the sum of squares of a segment of a time series;

2. the residuals are the difference between a seismic trace (recorded surface-seismic data) and its matched or filtered reflectivity (predicted surface-seismic data), that is, matched or filtered synthetic seismogram.

A simple measure of goodness-of-fit is the proportion of total trace energy predicted (PEP) by the synthetic seismogram. PEP, which may also be called 'Predictability' (P) for simplicity, can be measured directly from the seismic trace and the optimally matched (filtered) well-log reflectivity:

$$P = 1 - (\text{energy in the residuals/trace energy}) \quad (3)$$

Or, as shown in Ma, White and Hu (2010):

$$PEP = 1 - \frac{\sum_t (y_t - \hat{s}_t)^2}{\sum_t {y_t}^2} \quad (4)$$

where $\hat{s}_t$ is the predicted surface-seismic data and y_t is the recorded surface-seismic data.

This can be written on a different way, in place of Hampson (2004), as exposed in the Equation (2), in which PEP measures the goodness of the match R vs S:

$$PEE = \frac{\text{Output Energy} - \text{Residual Energy}}{\text{Output Energy}} \quad (5)$$

$$= \frac{|S|^2 - |S - R * W|^2}{|S|^2} \quad (6)$$

Schlumberger (2014) presents another approach, which is effectively utilized in this paper. Firstly, the autocorrelations Acor1(t) and Acor2(t) are computed from the well and the seismic data. Secondly, the cross-correlation between them is calculated. The autocorrelations and the cross-correlation are then tapered from time zero with a cosine taper up to max-lag samples, using:

$$\text{Max}_{\text{lag}} = \left(\frac{4n}{3k} - 1\right) * 0.5\,, \quad (7)$$

where

n is the number of input samples in the window; and

k has been set from experience to be

$$k = \frac{n * SR}{100}\,, \quad (8)$$

where, in turn,

SR represents the sample rate of the data (in miliseconds).

Consequently, the Predictability is computed with the Equation 9 based on the tapered autocorrelations and cross-correlations:

$$\text{Predictability} = \frac{\sum \text{Xcor}(t)^2 * 100}{\sum(\text{Acor1}(t) * \text{ACOR2}(t))}\,, \quad (9)$$

The results range from 0 to 100, where the number 100 means perfectly matching data.

Predictability is a measure of the similarity of the underlying reflectivity and, as such, has some advantages in relation to the simple correlation:

- It is independent of the wavelet on the seismic; and
- It is fairly insensitive to amplitude scaling differences and wavelet phase uncertainty between the two time series.

Method

The following resources were used:

- 16 wells;
- Sonic and density logs for each well;
- Check-shot for each well;
- Seismic data.

For each well, the respective check-shot was run, in order to bring the timing of the sonic log into agreement with seismic times from a check-shot survey. This resulted in the Figure 2.

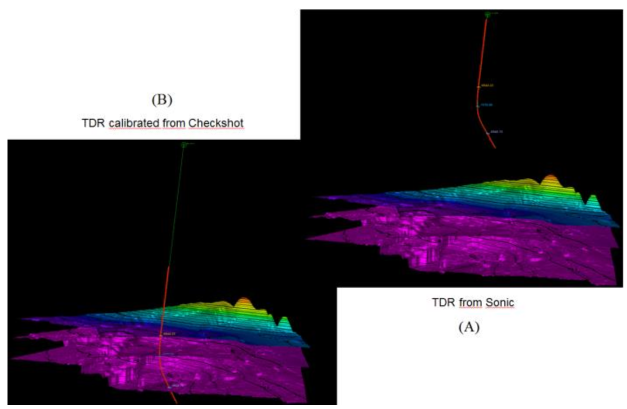


Figure 2 – (A) Well positioned using a TDR from the original sonic; (B) Well positioned using a TDR from the calibrated sonic.

A total of 100 comparisons were made between the reflectivity and the seismic trace. To do so, 200 Predictability results were calculated. Firstly, the whole reflectivity window was used. Secondly, it was divided into windows of 500, 200, and 100ms, respectively. The quantity of results for each window was the following:

- 32 for the total window;
- 30 for 500ms;
- 90 for 200ms;

- 48 for 100ms.

From this, a chart was built, stablishing a comparison between the Predictability coming from the calibrated sonic and the Predictability from the original sonic.

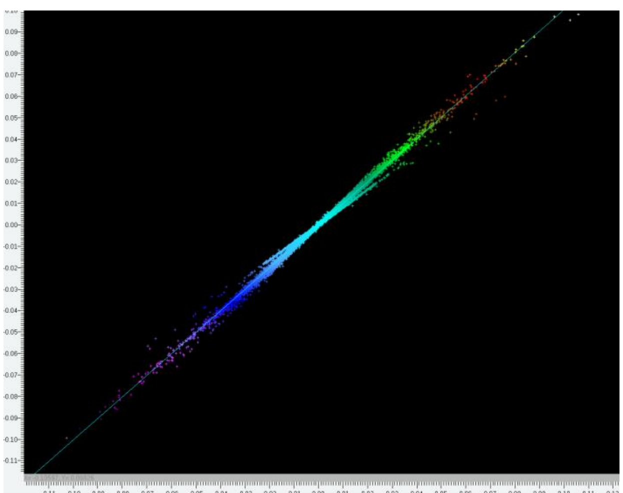
The chart has 11 columns, with the following information:

- General → Sonic log used (calibrated or original);
- Start Time → The beginning of the Reflectivity Window;
- Reflectivity Window → The length of the Reflectivity Window;
- End Time → The end of the Reflectivity Window;
- Predictability → The Predictability between the reflectivity and the seismic trace.

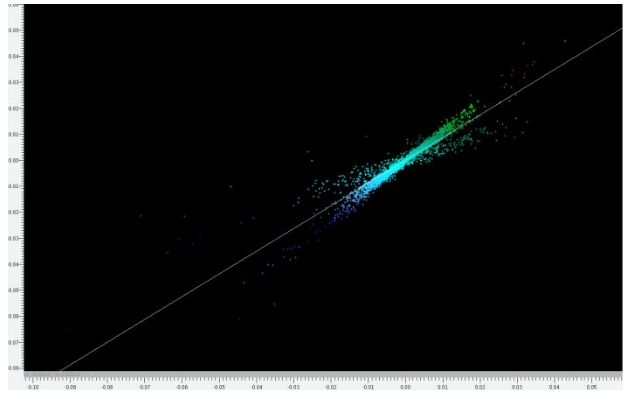
As the result, from the chart, a graphic was built, informing how much calibrated sonic logs have obtained higher Predictability and how much were favorable to the original log.

Results

In order to illustrate qualitatively the impact of the sonic calibration on the reflectivity, Figure 3 displays cross plots concerning to two arbitrary wells. For each of the two screen shots, the reflectivity coming from the calibrated and from the original sonic log were plotted against each other.



(A)



(B)

Figure 3 (A and B) – Cross plots between the reflectivity from the calibrated and the reflectivity from the original sonic log.

For one well used in this paper, two reflection coefficients, before and after sonic calibration, are illustrated in the Figure 4, in order to demonstrate the impact of that process in the reflectivity.

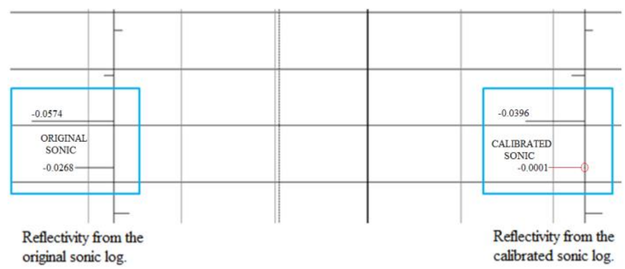


Figure 4 – Two reflection coefficients, before and after sonic calibration.

In order to carry out the numerical tests, for each the 16 wells, 4 time windows were created with the following time sizes: 100, 200, 500ms and the complete time window (reflectivity size). Then, the Predictability was calculated for each time window and released on a table, as exhibited in the Figure 5 (A, B, C, and D), respectively.

Type	Start Time (ms)	Reflectivity Window (ms)	End Time (ms)	Predictability (%)	
Original	1248	1820	3068	35,089	(A)
Calibrated	1248	1820	3068	32,538	
Original	1224	1256	2480	24,768	
Calibrated	1224	1256	2480	20,787	
Original	676	2152	2828	27,504	
Calibrated	676	2152	2828	25,725	
Original	1500	200	1700	77,600	(B)
Calibrated	1500	200	1700	76,727	
Original	1500	200	1700	82,119	
Calibrated	1500	200	1700	81,337	
Original	900	200	1100	93,100	
Calibrated	900	200	1100	91,851	

Type	Start Time (ms)	Reflectivity Window (ms)	End Time (ms)	Predictability (%)	
Original	1248	500	1748	35,408	
Calibrated	1248	500	1748	34,874	
Original	1224	500	1724	50,268	(C)
Calibrated	1224	500	1724	45,291	
Original	676	500	1176	77,756	
Calibrated	676	500	1176	70,948	
Original	3248	100	3348	84,863	
Calibrated	3248	100	3348	81,091	
Original	2876	100	2976	91,421	(D)
Calibrated	2876	100	2976	90,792	
Original	2824	100	2924	75,090	
Calibrated	2824	100	2924	73,394	

Figure 5 (A, B, C and D) – The four tables derived from each of the four time windows.

From the values available in the table, a chart was built, also for each time window, comparing the Predictability originating from the calibrated sonic to the Predictability from the sonic out of calibration.

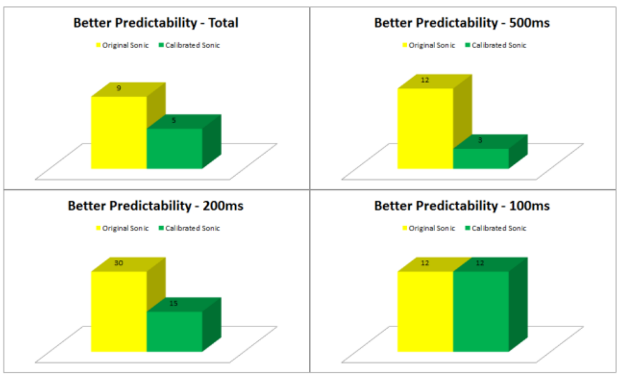


Figure 6 – The four column charts from the four respective time windows.

Finally, Predictability values of all time windows were put together. Again, these values from both calibrated and original sonic were plotted against each other, as can be seen in the Figure 7.

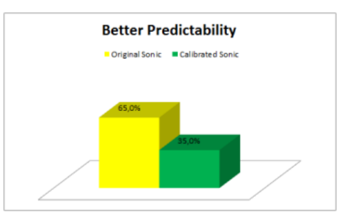


Figure 7 – The resulting Predictability of the four time windows together.

Conclusions

The Figure 3 shows that there is indeed difference between the reflectivity from the calibrated and from the original sonic log, which can impact consequently the resulting synthetic seismogram.

Although, consistent with Box and Lowrey (2003), check-shot surveys are frequently used in an effort to determine the amount of stretching necessary, the Figure 7 indicates that the reflectivity coming from the original sonic has higher Predictability in relation to the seismic than from the calibrated sonic.

Interpreters may be determined to use check-shot surveys or may have felt comfortable with the method presented by Box and Lowrey (2003), choosing not to use them. For both cases, in terms of what has been exposed so far, it is recommended to calculate the Predictability between the reflectivity and the seismic, comparing the values from the calibrated sonic to the values from the sonic with no calibration, before generating synthetic seismograms.

For that reason, it is suggested to compute the reflectivity for both calibrated and original sonic, in order to evaluate them.

In Schlumberger (2014), the Predictability expression displayed in Equation 9 is meant to purposes different of those presented here. It is used, for instance, to compare the Predictability for different well positions, with respect to the seismic data.

This paper proposes to utilize that approach to compare the input calibrated and original sonic logs. Other methodologies, as given in the Equation 6, take into account the wavelet, and not the underlying reflectivity, which do not result into those advantages shown in Schlumberger (2014) with regard to the simple correlation:

- The independence of the wavelet on the seismic;
- The reasonable insensitivity regarding the amplitude scaling differences and wavelet phase uncertainty between the two time series.

To the point, when generating synthetic seismograms, this work recommends three steps:

- The check-shots has to be run for the respective well (Figure 2);
- A reflectivity has to be computed for both calibrated and original sonic;
- For each reflectivity, Predictability is calculated. The higher Predictability will indicate what the sonic log must be used as input in synthetic generation.

Acknowledgments

The authors acknowledge Schlumberger and Halliburton, for providing the applications, and express special gratitude to Petrobras (CSA - Centro de Suporte à Aplicação /GDSI), which kindly supported this paper.

References

BOX, R.; LOWREY, P. Reconciling sonic logs with check-shot surveys: Stretching synthetic seismograms. The Leading Edge, v. 22, p. 510, 2003.doi: 10.1190/1.1587672.

DUARTE, O. O. Dicionário Enciclopédico Inglês-Português de Geofísica e Geologia. 3. ed. Rio de Janeiro: SBGf, 2007.

HALLIBURTON. Halliburton Wireline and Perforating Services. Houston, 2008. Available in: http://www.halliburton.com/public/lp/contents/Books_and_Catalogs/web/WPS_PS_Catalog/Web/WPS_PS_CAT.pdf . Access on: 5th March, 2015.

HAMPSON, D. (2004), Summary of the Roy White Wavelet Extraction and Well-Seismic Scanning techniques in Hampson-Russell software In the knowledge base of the Hampson-Russell software. Hampson-Russell Calgary Office, (November 2008).

KEAREY, P. BROOKS, M. HILL, I. An Introduction to Geophysical Exploration, 3. ed. Oxford: Blackwell Science, 2002.

MA, H.; WHITE, R.; HU, T. Wavelet estimation by matching well-log, VSP, and surface-seismic data. Applied Geophysics, v. 7, p. 384-391, 2010. doi:10.1007/s11770-010-0264-y

SCHLUMBERGER. Petrel Seismic Well Tie. Houston, 2012. (Manual about Petrel Seismic Well Tie course – Schlumberger).

WALDEN, A.T.; WHITE, R.E. Seismic wavelet estimation: a frequency domain solution to a geophysical noisy input-output problem, IEEE Transactions on Geoscience and Remote Sensing, v. 36, p. 287-297, 1998.

WHITE, R.E. Partial coherence matching of synthetic seismograms with seismic traces. Geophysical Prospecting, v. 28, p. 333-358, 1980.

WHITE, R.E. The accuracy of well ties: practical procedures and examples, Expanded Abstract RC1.5, 67th SEG Meeting, Dallas, 1997.

WHITE, R.; SIMM, R. Tutorial: Good practice in well ties In first break, European Association of Geoscientists and Engineers, v. 21, October. 2003.