Depth calibration of DAS VSP data at CaMI Field Research Station

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ABSTRACT

The correct localization of vertical seismic profile data in the surrounding geology is a very important step during processing and interpretation. Geophone data usually have very accurate positions along the well that help in this localization. In contrast, distributed acoustic sensing data positions are not as accurate because they do not have point locations like geophones and also because of the imperfect knowledge of the fibre location in the well and surface. We test two methods to calibrate the depths of distributed acoustic sensing vertical data from the Containment and Monitoring Institute Field Research Station. The first method uses the frequency spectra but requires the presence of patterns related to the well casing. The second method correlates consistent scalars from the seismic data with the sonic log to obtain a vertical shift. Only the second method gave us values to calibrate the data with the geology.

INTRODUCTION

The Containment and Monitoring Institute Field Research Station, CaMI-FRS, is a research facility where up to 400 tonnes of CO_2 are being injected annually with a plan to operate for 5 years (Macquet et al., 2019).The CO_2 injection requires constant monitoring and at CaMI-FRS a diverse set of technologies are present to do that Lawton et al. (2017).

One of these technologies is Distributed Acoustic Sensing or DAS that uses an optical fibre as a sensor instead of the most conventional geophones (Mateeva et al., 2013). A light pulse is sent through the fibre and due to the fibre impurities some of the light is backscattered. A seismic wave can cause strain in the fibre, perturbing this backscattered light and a device called interrogator, connected to the fibre, can calculate this strain by analyzing the backscattered light (Hartog, 2018).

At CaMI-FRS, a 5km loop of optical fibre is permanently installed to monitor the CO_2 injection. Part of this fibre is located inside two 300m depth observation wells where it records active and passive seismic data. One problem is that the location of the seismic traces produced by the fibre is not known exactly due to the distributed nature of the measurements and the uncertainty in the fibre depths.

We test two data driven methods to calibrate the depth of DAS VSP data from CaMI-FRS. The first is the method of Madsen et al. (2016) This method requires the correlation of some patterns in the spectra with the casing separations in the well. We were able to find this pattern only at shallow depths. The other method is the one in Mateeva and Zwartjes (2017), that correlates consistent scalars from the DAS data with well data. We obtained three possible answers with this method.

In the first section we show the spectral analysis method with CaMI-FRS data. In the

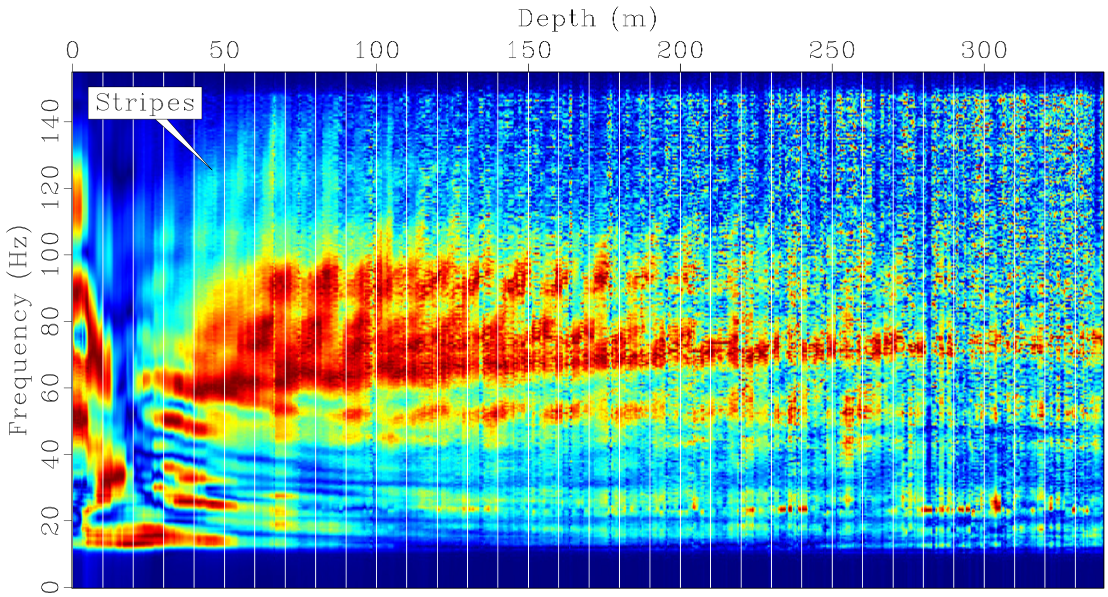

FIG. 1. Normalized frequency spectrum of the DAS VSP shot gather 21132, the closest, just $9m$, from the well. The depth axis is the original depth calibration. Some stripes can be seen in the top left part.

second section we describe and calculate DAS VSP consistent scalars, also with CaMI-FRS data to obtain new depth calibrations.

SPECTRAL ANALYSIS METHOD

The spectral analysis method of Madsen et al. (2016) calculates the normalized frequency spectrum of a DAS VSP shot gather. The Figure 1 shows this spectrum for the shot position 21132, the closest, only 9m, to the well at CaMI FRS. The depth calibration is the original.

This method requires the identification of patterns related with the tube casing where the fibre could resonate at high frequencies at points where the fibre is clamped to the well. Although Figure 1 shows patterns in the $60-100$Hz band, they do not appear to be periodic.

However, there are a few 10m periodic stripes in the $100-140$Hz band between 40m and 100m depth. Few other shot gathers close to the well also show this pattern. In contrast, at shot gathers far from the well ($>$ 80m) the pattern is absent. The completion schematic of this well reports that most of the well, 336.03m is formed by 37 tube sections, with an average length of 9.08m per section. This value is close to the width of the stripes.

CONSISTENT SCALARS METHOD

The method of Mateeva and Zwartjes (2017) looks for similarities between a sonic log and a set of consistent scalars calculated from the DAS data. It is important to correct for effects not related to surface locations before calculating this scalars. In our case, we corrected for spherical divergence by applying a squared power gain along the depth axis.

The consistent scalars are calculated as in Taner and Koehler (1981). The seismic trace recorded at source position i and receiver position j can be expressed as the product of four terms in the frequency domain (Taner and Koehler, 1981):

$$F_{ij}(\omega) \quad = \quad S_i(\omega)R_j(\omega)C_k(\omega)D_l(\omega), \tag{1}$$

where S_i is the source contribution at position i, R_j is the receiver contribution at position j, C_k is the subsurface contribution at midpoint $k = (i + j)/2$ and D_l is the contribution at offset $l = i - j$.

In the VSP case, the biggest contribution comes from the direct arrivals, so the terms for subsurface and offset are ignored. Although this is a nonlinear equation, it can be solved using linear methods by taking logarithms:

$$\ln F_{ij}(\omega) \quad = \quad \ln S_i(\omega) + \ln R_j(\omega) \tag{2}$$

This equation is then separated in amplitude and phase terms. We are interested in the amplitude scalars that we express using lowercase letters:

$$f_{ij} \quad = \quad s_i + r_j, \tag{3}$$

where f_{ij} is the logarithm of the RMS trace amplitude, s_i is the logarithm of the source consistent scalar and r_j is the logarithm of the receiver consistent scalars. By formulating this equation for every source and receiver pair, a linear system can be formed:

$$\begin{bmatrix} f_{11} \\ \vdots \\ f_{mn} \end{bmatrix} \quad = \quad \begin{bmatrix} 1 & \cdots & 0 & 1 & \cdots & 0 \\ & \ddots & & & \ddots & \\ 0 & \cdots & 1 & 0 & \cdots & 1 \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_m \\ r_1 \\ \vdots \\ r_n \end{bmatrix}, \tag{4}$$

and solved for the source and receiver consistent scalars using linear optimization. As we are interested in only the receiver scalars, the source ones are discarded. Figure 2 shows the DAS VSP shot gathers used to calculate the consistent scalars. As shown in the figure, we only use the first 0.36s of each shot.

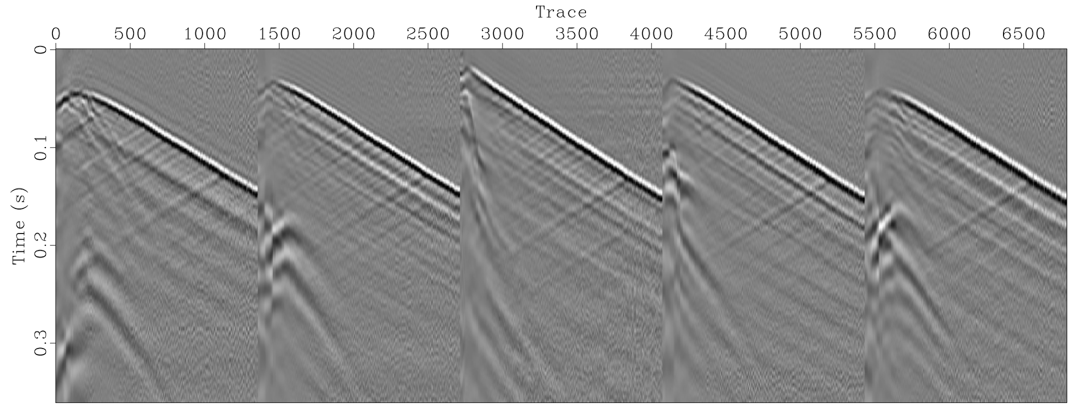

FIG. 2. DAS VSP shot gathers used for the consistent scalars calculation. Their shot numbers, from left to right are 21124, 21127, 21132, 21134 and 21136. Above, from left to right, their distances to the well are -72m, -42m, 9m, 28m and 48m. The negative offsets are located North of the well and the positive at the South.

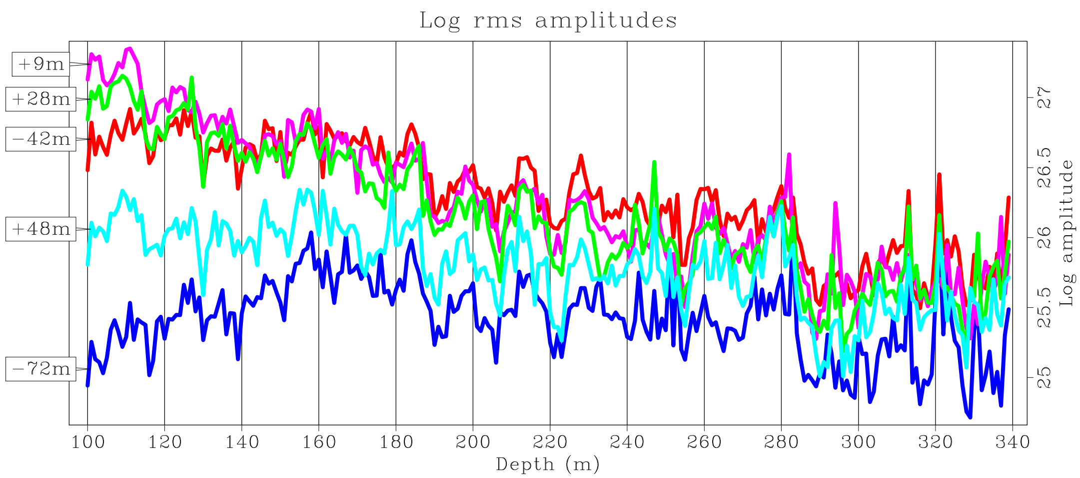

FIG. 3. Logarithms of the RMS amplitudes of the DAS VSP shot gathers in Figure 2.

Figure 3 shows the logarithms of the RMS amplitudes of the DAS VSP shot gathers in Figure 2. We used depths below $100m$ to avoid the S-wave events that appear above this depth. As mentioned before, we are interested in the consistent amplitudes related to the first arrivals, so muting everything else is an option. However, we did not find a noticeable difference without muting. In the same figure, despite the amplitude differences, it is possible to see patterns in different shot gathers at the same depth.

We use the linear system of Equation 4 to solve for the receiver consistent scalars using the logarithms of the RMS amplitudes shown in Figure 3. These scalars are multiplied by -1 and used as argument of the exponential function to remove the logarithm introduced in Equation 2. Figure 4 shows these inverted consistent scalars and the sonic log.

It is interesting to notice some similarities between the sonic log and the consistent scalars in Figure 4 that can be related to the same geology. For example, the three prominent peaks in the sonic log labelled "zone 1" resemble the three peaks in the consistent scalars plot with the same label. In the same way, the features labelled "zone 2" in both plots show

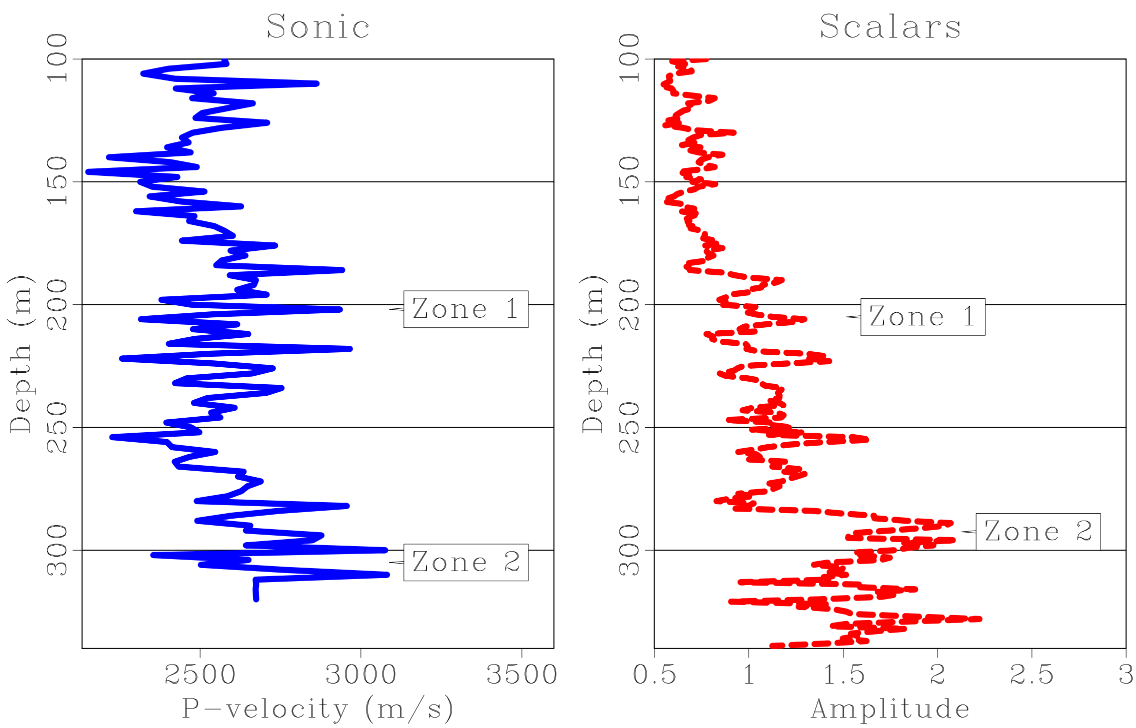

FIG. 4. The left part is the sonic log in the well containing the DAS. The right part are the consistent scalars obtained by inverting the system in Equation 4, multiplying by -1 and being used as argument of the exponential function.

some similarities.

Figure 5 shows the cross-correlation of the consistent scalars and the sonic log. In this calculation the sonic log is the signal that is moved. This means that the lag of the maximum correlation, at 19.5m, is because the sonic log is moved downwards or, equivalently, the consistent scalars are moved upwards.

We tested three possible vertical shifts of the consistent scalars with respect to the sonic log as Figure 6 shows. The first shift, on the left, is 4.5m upwards and lines up the three peaks shown in "zone 1" of Figure 4. The second shift, on the centre, is 12m downwards and lines up the two peaks in "zone 2" of Figure 4. Finally, the last shift, on the right, is 19.5m upwards and corresponds to the lag of the cross-correlation maximum between consistent scalars and sonic log.

Figure 7 shows the DAS VSP shot gather, the closest to the well, before and after the depth corrections obtained by the consistent scalars method. Top left is the original depth calibration while top right is after moving the shot upwards 4.5m. Bottom left is after moving it downwards $12m$ and bottom right after moving it upwards 19.5m.

DISCUSSION

The spectral method depended on the correlation of patterns in the frequency spectrum with the tube casing. In the original paper, (Madsen et al., 2016), these patterns existed

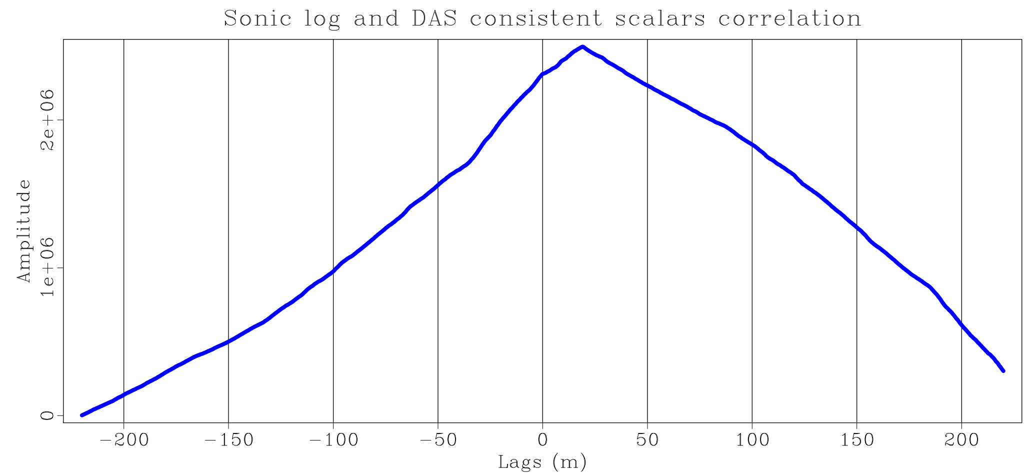

FIG. 5. Cross-correlation of the consistent scalars and the sonic log of Figure 4. The maximum value occurs at 19.5m.

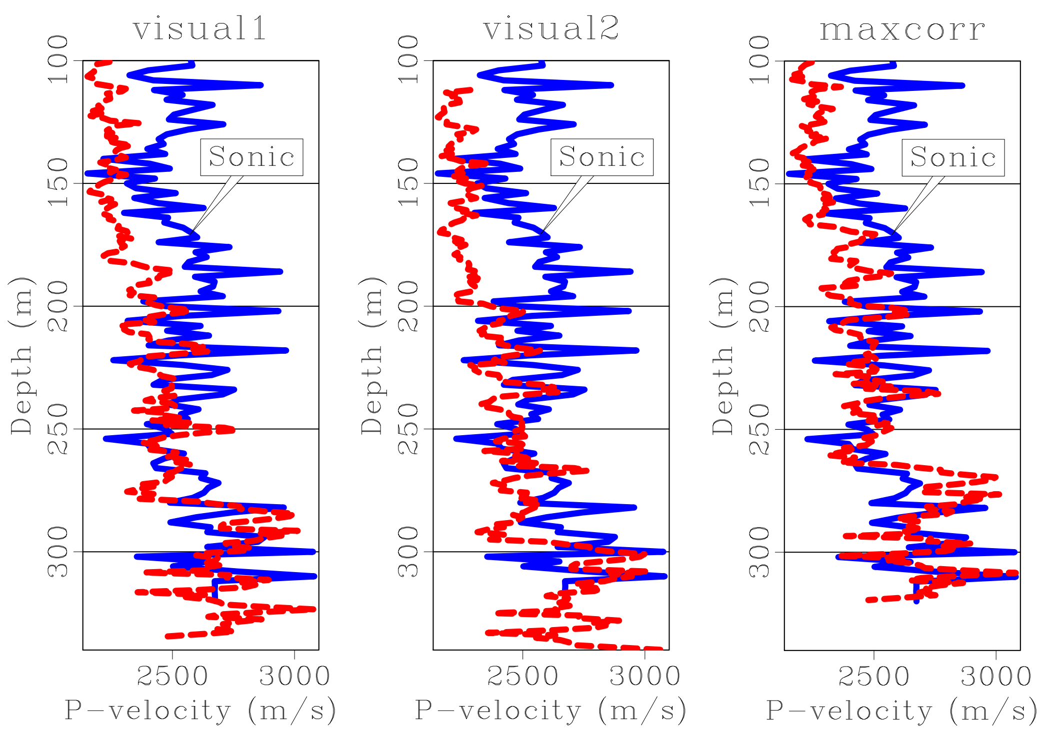

FIG. 6. Three different vertical shifts of the consistent scalars, in dashed lines, with respect to the sonic log. On the left, the vertical shift is 4.5m upward to line up the three peaks in "zone 1" of Figure 4. On the centre, the shift is 12m downward to align the two peaks in "zone 1" of Figure 4. On the right, the shift is 19.5m upward, obtained from the lag of the cross-correlation maximum between the consistent scalars and the sonic log.

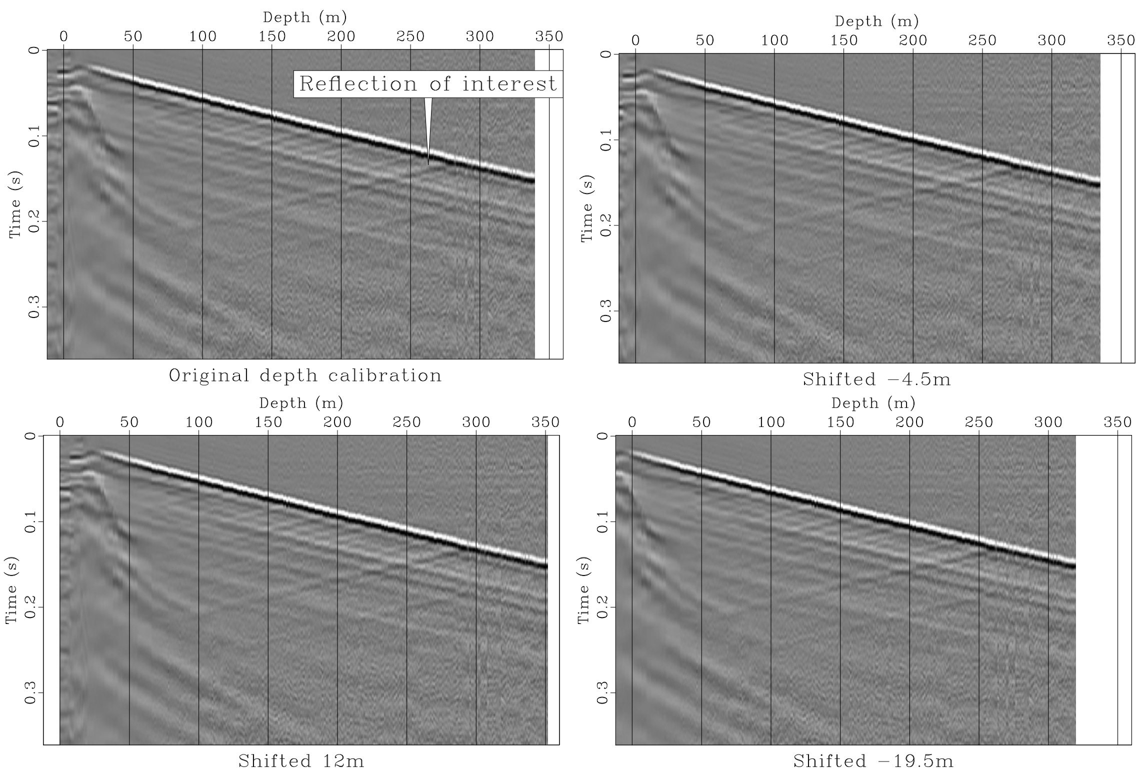

FIG. 7. DAS VSP shot gather 132 at 9m from the well. Top left is the original depth calibration. Top right is after moving the shot upwards 4.5m. Bottom left is after moving it downwards $12m$. Bottom right is after moving it upwards 19.5m. The reflector of interest is marked on the original gather. This reflector corresponds to the top of the CO_2 injection zone.

because the fibre was pressed against the casing separations and the tube vibrations leaked to the fibre at these points. At CaMI-FRS the fibre installation is different. However, some stripes that are almost the same length of the tubes can be seen at shallow depths.

We obtained three plausible answers by the consistent scalars method. Two of them try to line up prominent features in the sonic well log with the consistent scalars and the other measures the maximum correlation between them. The problem with lining up features is that other important but less prominent features do not line up well. For example, lining up the three main features between 180m and 220m in the sonic log, in Figure 4, aligns the important events at 300m, where the reservoir is located, with less prominent features. See the left part of Figure 6.

Although the maximum correlation seems to be the less biased of the three vertical shifts, its value occurs where the sonic log and the consistent scalars have their maximum overlap. This raises suspicion about the validity of this vertical shift.

The reflection event corresponding to the top of the CO_2 injection zone has been identified in Gordon (2019), and is marked in the Figure 7. One problem is that after performing the corridor stack, this reflector stacks 20ms above the corresponding event in the synthetic seismograms created from the sonic log (Gordon, 2019). By shifting the gather upwards, like the first and third corrections, we are increasing even more the mismatch between the corridor stack and the synthetic seismogram. On the other hand, the other correction is decreasing this mismatch.

CONCLUSIONS

By using the spectral analysis method we identified some stripes in the gather spectrum that can be related with the casing in the observation well at shallow depths. However, this was not enough to provide a vertical shift to calibrate the DAS gather due to the insufficient information to match the stripes to the actual tube depths.

The consistent scalars method provided us with three plausible vertical shifts to calibrate the DAS depth. Two of them are related to prominent features in the sonic log while the other is the result of the cross-correlation of the consistent scalars and the sonic log.

Each of the three shifts obtained by the consistent scalars method have pros and cons, but overall, the second shift, $12m$ in the downward direction seems to be the more promising because aligns the reflection of interest with a prominent sonic log feature and also decreases the mismatch between the corridor stack and the synthetic seismogram.

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