Fiber trace registration by cross-correlation - can we successfully predict helically wound fibre pitch angle from recorded data?

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ABSTRACT

The Containment and Monitoring Institutes (CaMI) Field Research Station (FRS) contains an approximately 5 km long optical fibre loop comprised of straight fibre cables and helically wound fibre cables that are spliced together end-to-end. The fibre loop traverses two wells, observation well 1 (OBS1) and observation well 2 (OBS2), and a 1 km horizontal trench along the surface with straight and helically wound fibre cables. We have interpolated fibre trace co-ordinates (*x,y,z*) in the past for a walk-away/walk-around VSP (Snowflake) using GPS and downhole gyroscope surveys, but it was never entirely clear if we were using the correct trace spacing for helical fibre data, or which coordinates should be assigned to what DAS trace. Quality-control checks performed by interleaving straight and helical fibre traces using interpolated coordinates plus arbitrary channel assignment shifts showed that the calculated helical fibre trace spacing was close, but not correct.

In this report, we use a cross-correlation and linear regression method on co-located seismic data to estimate a helical pseudo-pitch angle. The slope and intercept from the linear regression can be used to register datasets by fractional channel number. If one of the co-located datasets has a known trace spacing, we can also predict an unknown trace spacing for the other dataset, for example, helical fibre cable trace spacing from a known geophone, accelerometer, or straight fibre trace spacing. In future, we plan to 1) interpolate co-ordinates using trace spacings calculated from estimated pseudo-pitch angles, and 2) locate channels in one dataset that are functionally at the same location as channels in the other dataset based on the linear-regression results, and use those to better match interpolated co-ordinates to data traces without an interpretive step.

INTRODUCTION

The Containment and Monitoring Institutes Field Research Station (CaMI.FRS) contains an approximately 5 km long optical fibre loop comprised of straight fibre cables and helically wound fibre cables that are spliced together end-to-end. The fibre loop traverses two wells, observation well 1 (OBS1) and observation well 2 (OBS2), and a 1 km horizontal trench along the surface with straight and helically wound fibre cables. Hall and Lawton (2019) derived an equation to calculate helical fibre trace spacing in the loop given the trace spacing reported by a DAS interrogator, the nominal pitch angle of the helical fibre cable (nominally 30 degrees), the indices of refraction of the straight fibre (assumed to be 1.5), helical fibre (assumed to be 1.468), and interrogator software (1.5).

Co-ordinates (*x,y,z*) for a walk-away/walk-around VSP (Snowflake) were interpolated using the interrogator fibre trace spacing (0.6667 m) and calculated helical trace spacing (0.5899 m), as well as GPS coordinates for well surface locations and the position of electrodes in the horizontal trench, gyroscopic surveys in the wells, reported depth of fibre in the wells and the length of the trench. The results were encouraging, but it was never entirely clear which coordinates should be assigned to which DAS trace, and interleaving traces using calculated coordinates plus arbitrary channel shifts showed that the calculated helical fibre trace spacing was close, but not correct (cf. Figures 16 and 17, Hall et al., 2019a). Reasons for this may include, 1) incorrect indices of refraction for the straight and helical fibres, or 2) the actual helical pitch angle varies enough from the nominal pitch angle to affect our results.

In this report, we use a cross-correlation and linear regression method on our seismic data to estimate a pseudo-pitch angle that can be used to better register two datasets with different trace-spacings. If we have no knowledge of indices of refraction or trace spacing, we can use this method to register two datasets purely by channel number. We may also approach the problem from the geometry side by using the pseudo-pitch angle instead of the nominal pitch angle to calculate the helical trace spacing.

THEORY

Hall et al. (2019a) derived the following equation relating distance along the axis of a fibre seem by DAS interrogator (*Dsoftware*) to distance along a fibre (*Dactual*) for helically wound fibre cables:

$$Dactual = Dsoftware \cdot \cos(\theta) \cdot \frac{IRsoftware}{IRactual}, \tag{1}$$

where θ is the pitch angle, *IRsoftware* is the index of refraction set in the DAS interrogator software and *IRactual* is the actual index of refraction of the fibre (Figure 1). For two co-located cables where cable 1 has pitch angle $\theta1$ and cable 2 has pitch angle $\theta2$

$$Dsoftware = \frac{Dactual1}{\cos(\theta1)} * \frac{IRactual1}{IRsoftware} = \frac{Dactual2}{\cos(\theta2)} * \frac{IRactual2}{IRsoftware} \tag{2}$$

and

$$Dactual2 = \frac{Dactual1}{\cos(\theta1)} * \frac{IRactual1}{IRactual2} * \cos(\theta2). \tag{3}$$

For the case where cable 1 is not helically wound (straight fibre cable), $\theta1 = 0$ and $\cos(\theta1)$ = 1. If *Dactual1* is the trace spacing reported by the interrogator, we are now able to calculate helical fibre trace spacing (*Dactual2).*

Solving for pitch angle gives

$$\theta = \theta2 = cos^{-1}\left(\frac{Dactual2*IRactual2}{Dactual11*IRactual1}\right). \tag{4}$$

If we disregard the indices of refraction and generalize the equation, we obtain a pseudo-pitch angle

$$\varphi = cos^{-1}\left(\frac{Dactual2}{Dactual1}\right), \tag{5}$$

which gives us a reasonable answer if $Dactual2 \leq Dactual1$. If $\frac{Dactual2}{Dactual1} > 1$, φ becomes an imaginary number.

If we don't know the trace spacings for datasets 1 and 2, we can still use Equation 5 to calculate a pseudo-pitch angle for two co-located datasets which can be used to register those datasets if we are able to estimate the ratio *Dactual2/Dactual1.* We propose to do this by cross-correlating each channel from dataset1 with all the channels in dataset2 and using the cross-correlation maximum amplitude at zero lag to find which channel numbers in dataset 2 best match channel numbers in dataset1. This should be a linear relationship. We may now use cross-plot those results and use linear regression to obtain the slope (m) and intercept (b) of the best-fit line to those channel numbers (Figure 2). We expect that the linear regression step will provide some robustness in the case of noisy input data. For this example,

$$m = \frac{\Delta chan2}{\Delta chan1}. \tag{6}$$

We may relate dataset1 and dataset2 channels to a common distance by

$$Dactual = \Delta chan1 * \mathrm{Dactual1} = \Delta chan2 * \mathrm{Dactual2} \tag{7}$$

$$Dactual2 = \frac{\Delta chan1}{\Delta chan2} Dactual1 = \frac{1}{\mathrm{m}} Dactual1 \tag{8}$$

Note that if we were to cross-correlate single traces from dataset2 with all traces in dataset1 Equation 6 becomes

$$Dactual2 = \frac{\Delta chan2}{\Delta chan1} Dactual1 = \mathrm{m} * Dactual1, \tag{9}$$

and

$$m = \frac{Dactual2}{Dactual1}. \tag{10}$$

Substituting Equation 10 into Equation 5 gives us,

$$\varphi = cos^{-1}(m), \tag{11}$$

which is an estimate of the pitch angle and is the primary goal of this report.

Now that we have estimated a slope and intercept relating channel numbers between the two datasets, we may use the equation of a line to calculate fractional channel numbers (*chan2*) for dataset2, given integer channel numbers (*chan1*) from dataset1. We should also be able to determine which *chan2* is located at the boundary between dataset1 and dataset2 by assuming the boundary is located at *chan1 = chan2*:

$$chan2 = m * chan2 + b \tag{12}$$

$$chan2 = \frac{b}{(1-m)}. \tag{13}$$

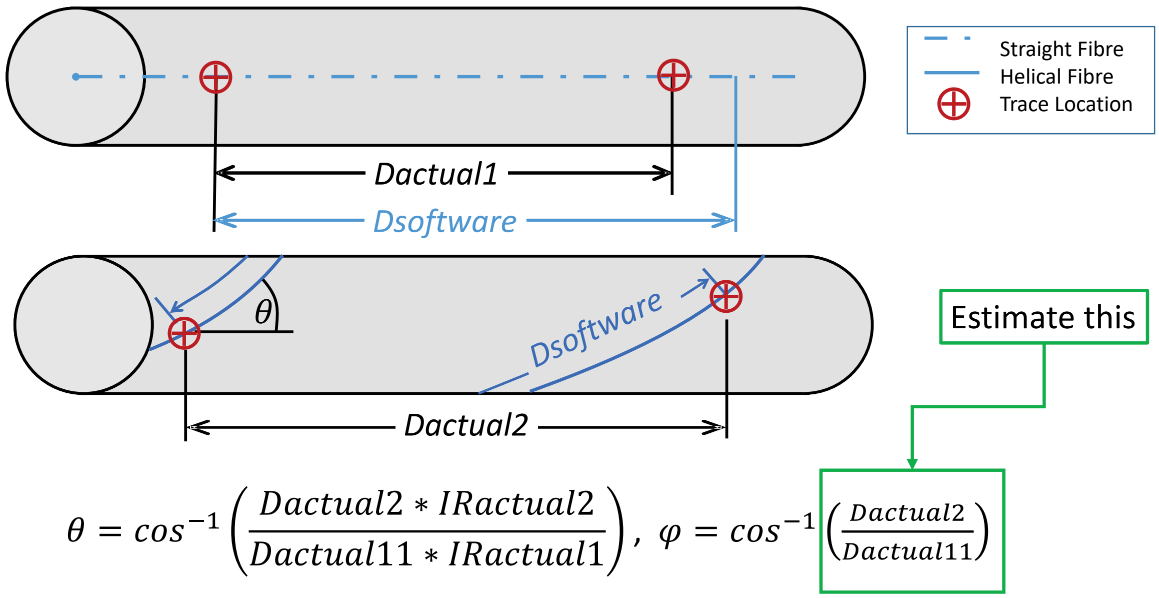

Figure 1. Relationship between distance along helical fibre (dx1) and distance along the cable, where *dx1* = distance along fibre, *dx2* = distance along cable, *ir1* = index of refraction of fibre in helical cable, *ir2* = index of refraction in interrogator software, and θ = pitch angle, and φ = pseudo-pitch angle.

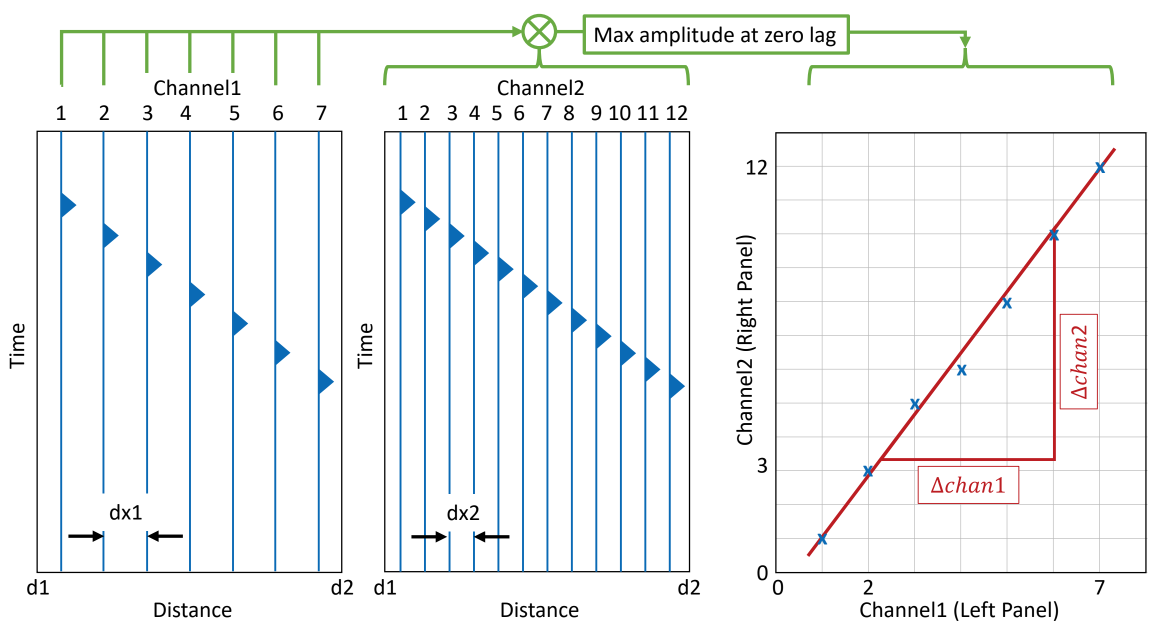

Figure 2. Proposed method to estimate *Dactual2/Dactual1* = *Δchan1/Δchan2* = *1/slope* by cross-correlations followed by linear regression.

METHOD

We gathered accelerometer (Scorpion recorder), geophone (Geode and Aries recorders), and DAS data (Fotech interrogator) for common source points from the 2018 (Snowflake) VSP conducted at the CaMI.FRS, using source points arbitrarily restricted to being within

65 m of observation well 2 (OBS2), and more than 20 m away from above ground junction boxes with fibre splices, and 20 m away from the corners of the classroom trailer that contained the DAS interrogator (Figure 3). This was to exclude source gathers with high-amplitude horizontal noise due to source noise in the DAS data due to either internal coupling in the DAS interrogator, or source shaking of wooden posts holding fibre junction boxes above ground level.

We used the Matlab® functions *xcorr2*() and *fitlm*() to determine a robust least-squares linear fit to cross-correlation channel number results for each dataset comparison at each source location after normalizing all input trace amplitudes. As the linear regression is sensitive to input trace window selections and noise, we arbitrarily discarded any slope estimates that were more than +/- one standard deviation from the median.

Some questions about the input data that we need to consider are: 1) Can we resolve time-zero mismatches between datasets? We don't believe that we can, but this should be tested. 2) Should we convert accelerometer data to velocity before cross-correlating with geophone data? 3) Should we convert accelerometer and geophone data to strain-rate before cross-correlating with DAS data? 4) Should we bandpass input data to try to match frequency content before cross-correlating?

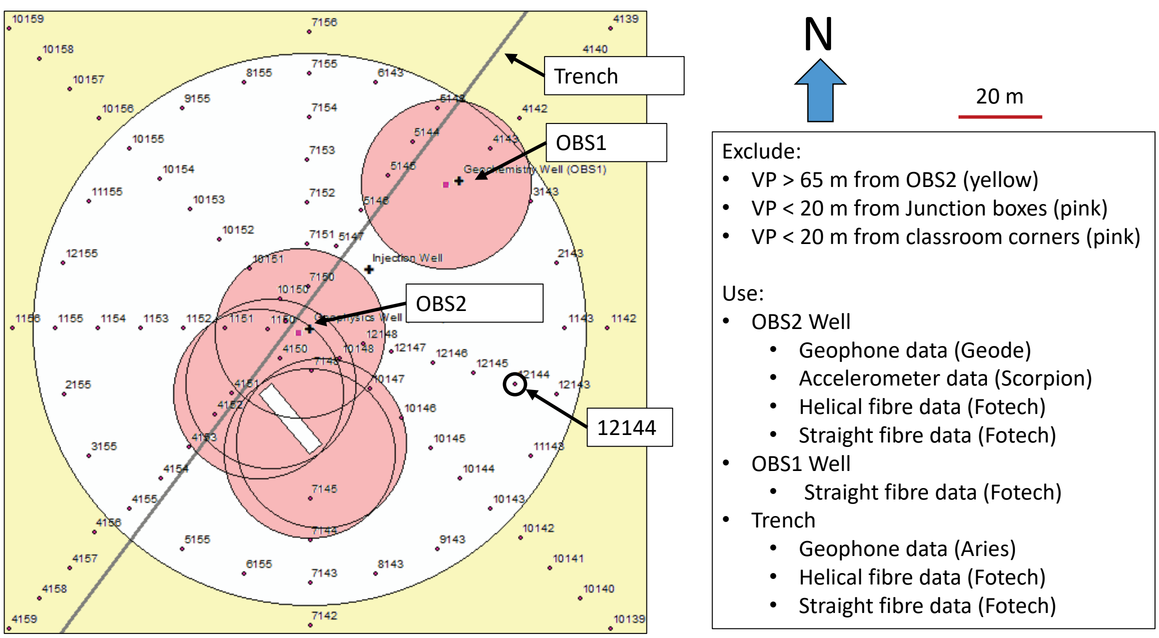

Figure 3. Vibe Points within 65 m of OBS 2 used for this report. White circle=65 m radius from OBS2. White rectangle = classroom ATCO trailer. Pink circles = 20 m radius centered on the four corners of the classroom trailer and on the two fibre junction box posts near OBS1 and OBS2 (pink squares). Most of the following figures show data examples from VP 12144.

RESULTS

A summary of all results can be found in Appendix A. For the remainder of this section, references to "up-going" fibre in a well mean that channel depth decreases with increasing channel number (higher channel numbers are assumed to be further from the interrogator), and “down-going” fibre means that channel depth increases with increasing channel number.

OBS2: Testing

Prior knowledge about accelerometer and geophone data

Accelerometer and geophone data in OBS2 have a large advantage over DAS data, in that we have measured depth information below ground level for each receiver in the well from the field. If we apply the depth information to geophone (nominal 5 m trace spacing) and integrated accelerometer (nominal 1 m trace spacing) data, merge the datasets, and sort by receiver depth, we get the results shown in Figure 4a, where the geophone traces have first breaks that are visibly earlier than the accelerometer first-breaks. Either time-zero is inconsistent between the two datasets or reported receiver depths are incorrect. Unfortunately, we regularly see time-zero differences between different recorders. For example, Gordon (2019) reported a 7 sample shift between a Silixa interrogator and the Geode recorder on an earlier VSP acquired at the same field site.

Based on first break picks for 28 VP, the geophone first break picks are 1.4 ms earlier than accelerometer first-break-picks on average. Integrating the accelerometer data widens this gap to 3.6 ms. Using an average velocity of 2691.8 m/s (calculated from first break picks), we can determine that 3.6 ms in time is equivalent to 9.7 m in depth. Figure 4b shows the effect of altering reported geophone depths by 9.7 m, and Figure 4c shows the effect of bulk shifting geophone times by 3.6 ms. Both cases line up the first breaks nicely, however, examination of the character of data at later times (red ellipses, Figure 4) shows that the most likely explanation is that the reported receiver depths are correct, but time-zero is not. Since the Scorpion (accelerometer) recorder was the primary, and the Geode (geophone) recorder was triggered over a radio link, we choose to believe that accelerometer time-zero is correct and the radio link for Geode triggers was not calibrated properly.

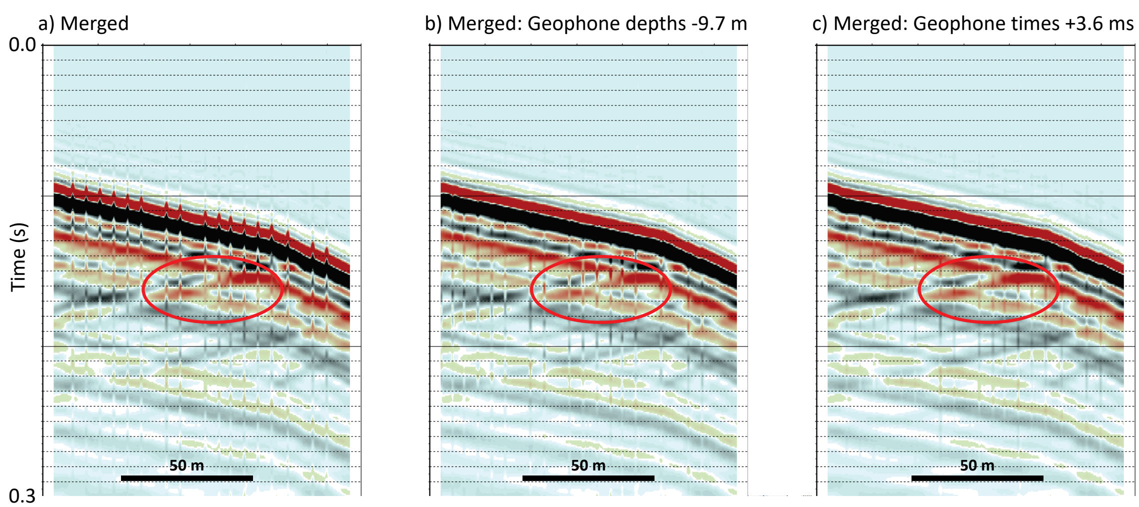

Figure 4. Time-zero issues between geophone and integrated accelerometer datasets. Dead traces are not displayed. The break in slope on the right-hand-side of the figures is not due to a change

in velocity, it is because the accelerometer trace-spacing switches from ~1 m to ~2 m at the bottom of the well.

Effects of time-zero and integration on accelerometer and geophone data

Nominal accelerometer and geophone trace-spacings are 1 m and 5m respectively, so we predict that $m = 1/5 = 0.2$ and $\varphi = 78.46$. Figure 5 shows our results for geophone data with a 3.6 ms bulk time shift cross-correlated with integrated accelerometer data and the maximum cross-correlation amplitude search restricted to zero lag. Figure 6 shows results with no time shift applied to the input geophone data, but the maximum cross-correlation maximum amplitude search restricted to +/- six lags. The estimated pseudo-pitch angle is similar in both cases.

However, if we use our estimated slope and intercept to calculate a fractional accelerometer channel number for each geophone channel, we find we get different answer for different input data. Figure 7a shows zero-lag results for input geophone (velocity) and accelerometer (acceleration) data with no time-shifts before and after bandpass filtering to attempt to better match frequency content of the input datasets. The optimal result for this comparison would be a horizontal line at accelerometer channel 0. Figure 7b shows +/- 6 lag results for the same data, but with the accelerometer data converted to velocity by integration. Finally, Figure 7c shows zero-lag results for geophone and integrated accelerometer data with and without a bandpass filter, for geophone data with and without a +3.6 ms bulk time shift. The difference in accelerometer channel number when the time-shift is applied to the geophone data before cross-correlation is about ten channels, or 10 m at the nominal accelerometer trace spacing. This number is a close match to the 9.7 m difference found using first-break information in the previous section. The best results are from the zero-lag cross-correlation of geophone and integrated accelerometer data after correcting time-zero.

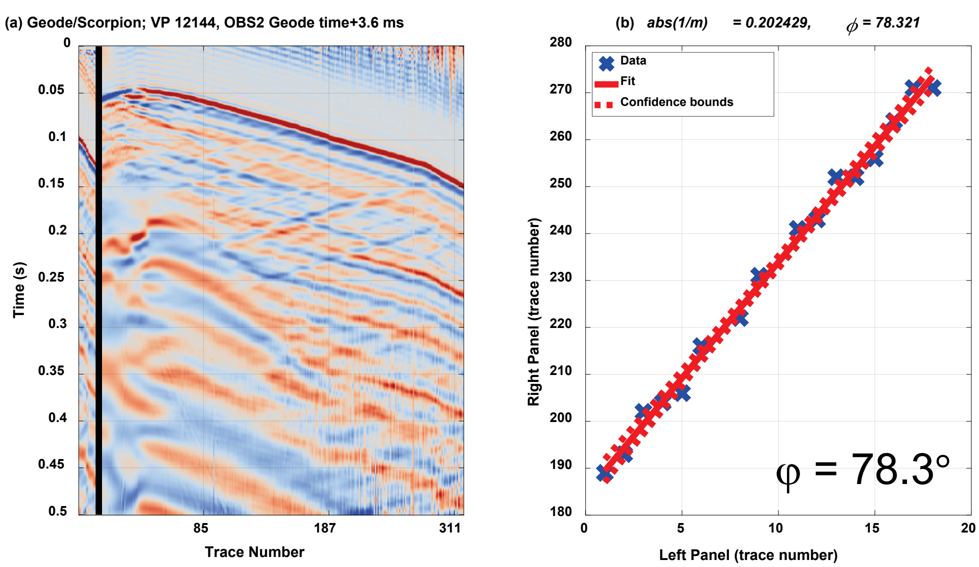

Figure 5. Geophone (3.6 ms bulk-shift) and integrated accelerometer data. Cross-correlation maximum amplitude search restricted to zero lag.

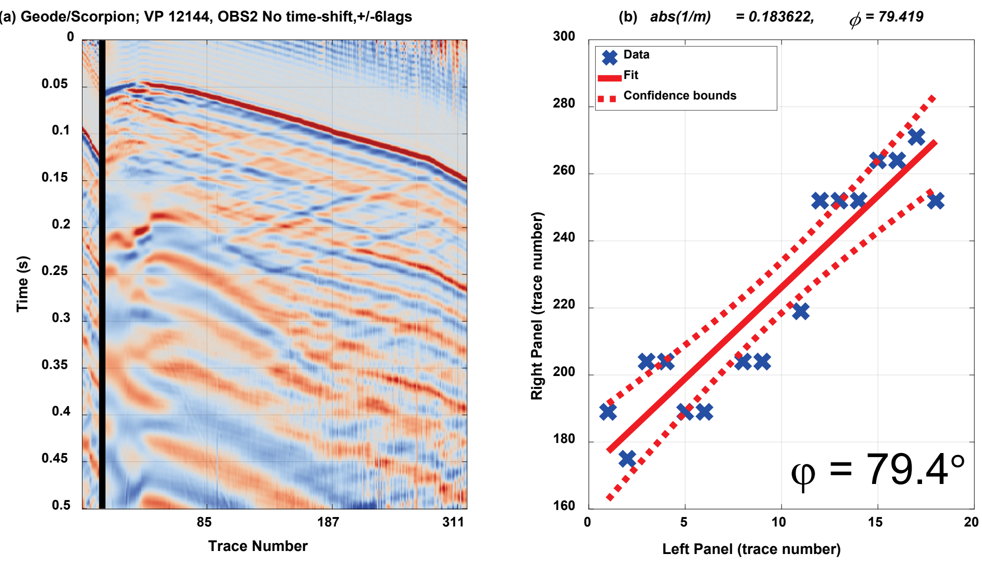

Figure 6. Geophone (No time-shift) and integrated accelerometer data. Cross-correlation maximum amplitude search restricted to +/- 6 lags.

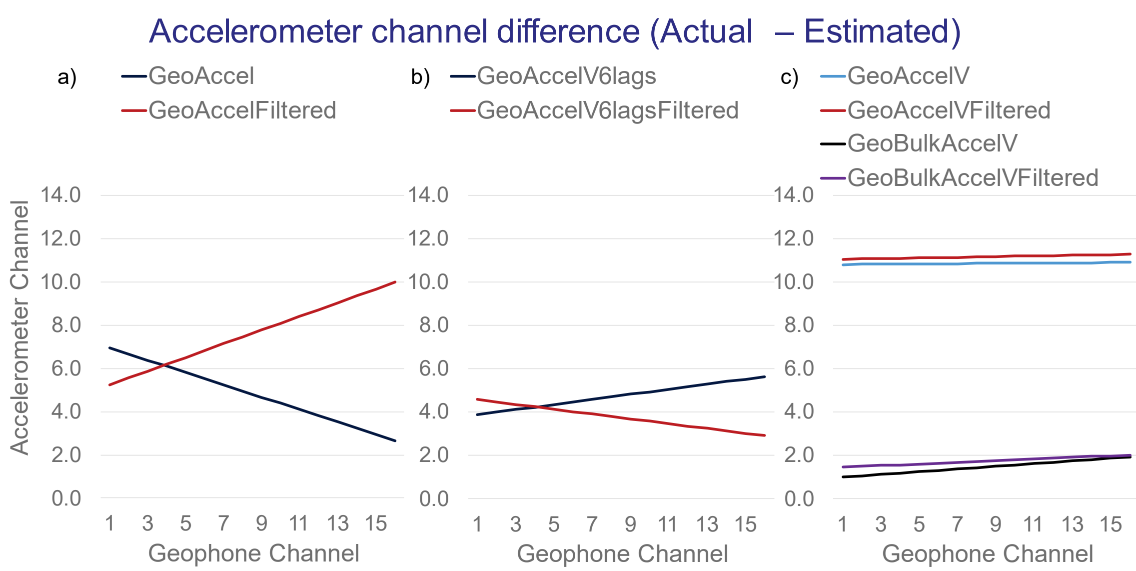

Figure 7. Difference between actual and estimated accelerometer channel numbers for a variety of input data types.

Same receiver types

For testing, we can cross-correlate up-going and down-going fibre to estimate φ (Figure 8). We can also simulate down-going and up-going fibre in a well by doubling our accelerometer and geophone data (Figure 9). In all cases, *Dactual1* = *Dactual2* and we predict the slope will be exactly 1 and φ will be 0. The estimate is exactly equal to the prediction accelerometer and geophone data (eg. Figure 9)., but we obtain a pseudo-pitch angle of up to a maximum of 4 degrees for straight fibre data (Figure 9) and 7 degrees for helical fibre data (not shown). Note that a small change in slope where the slope is close to

1.0 results in a large change in pitch angle. How bad is it in this case? A pseudo-pitch angle of 4 degrees and a software trace spacing of 0.667 m gives an estimated trace spacing of 0.665 m, a difference of 2 mm. A 7-degree pseudo-pitch angle results in a 5 mm error giving us a trace spacing equal to 0.662 m.

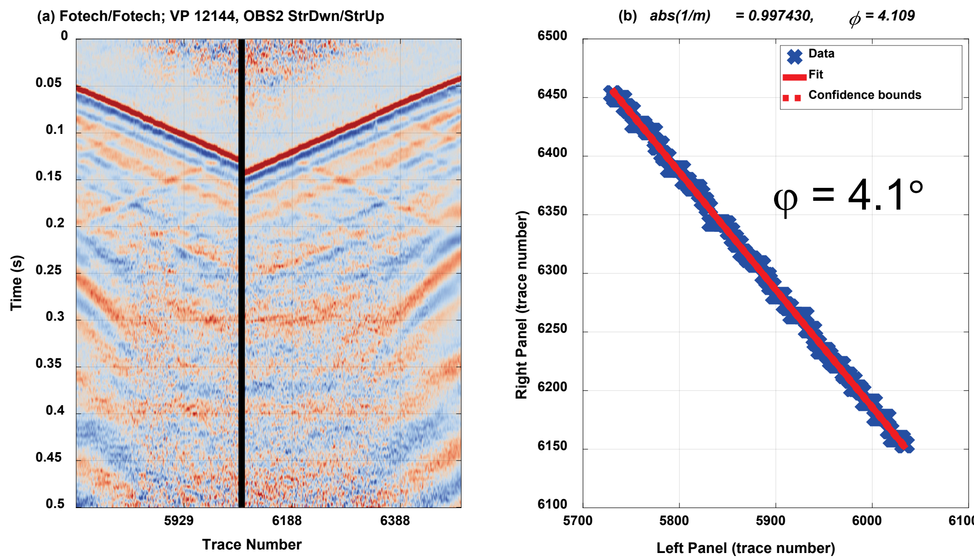

Figure 8. Up-going and Down-going straight fibre in OBS2.

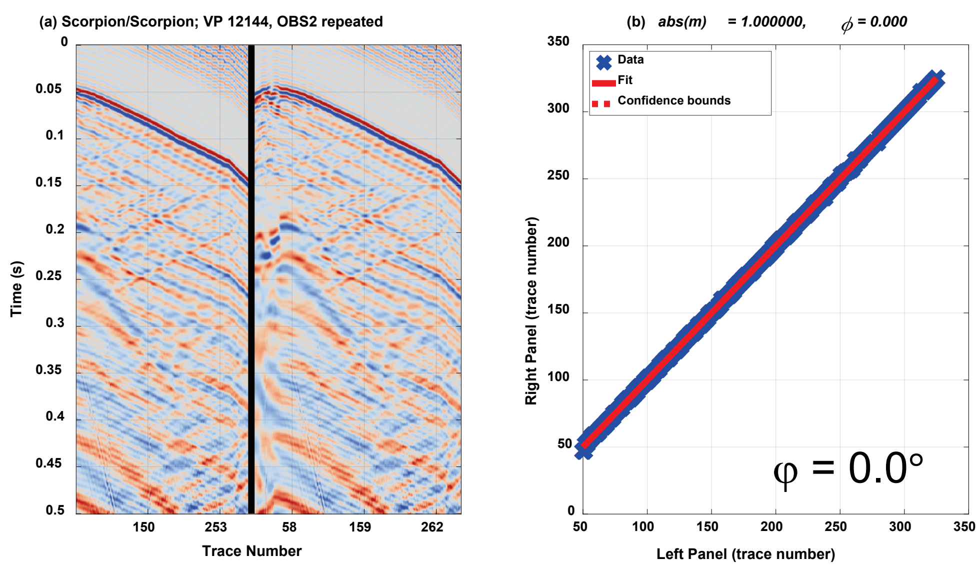

Figure 9. Doubled accelerometer data in OBS2.

OBS2 and Trench: Helical pitch estimate

Figure 10 shows an example of pseudo-pitch angle estimation in the OBS2 well, and Figure 11 show the same for the trench. Table 1 is a summary of pseudo-pitch angle (φ) and pitch angle (θ) estimates for the helically wound fibre cable at the CaMI.FRS. This is a subset of Table A1. The average estimated trace spacings are different enough for the trench and well data (Table 1) that we speculate the helical cable has stretched vertically in the well.

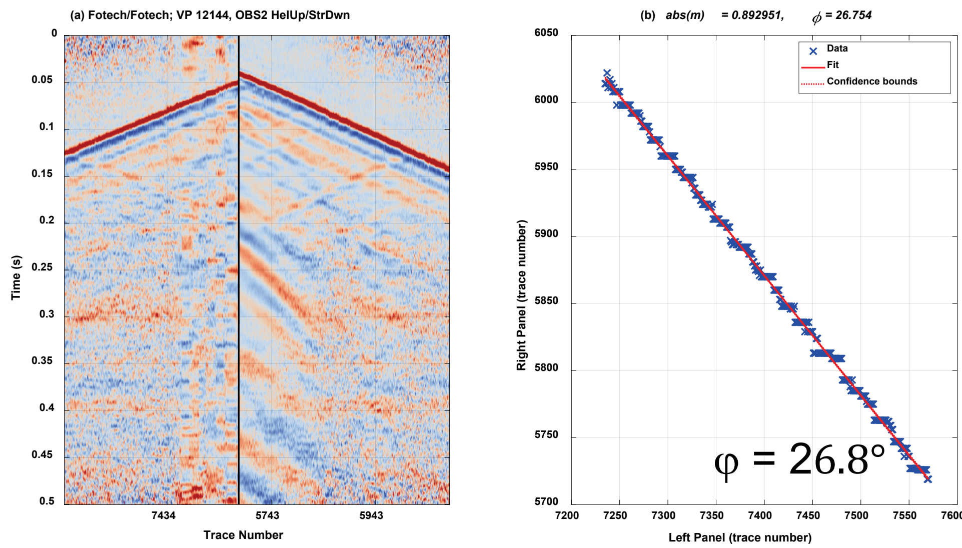

Figure 10. Helical and straight fibre in OBS2.

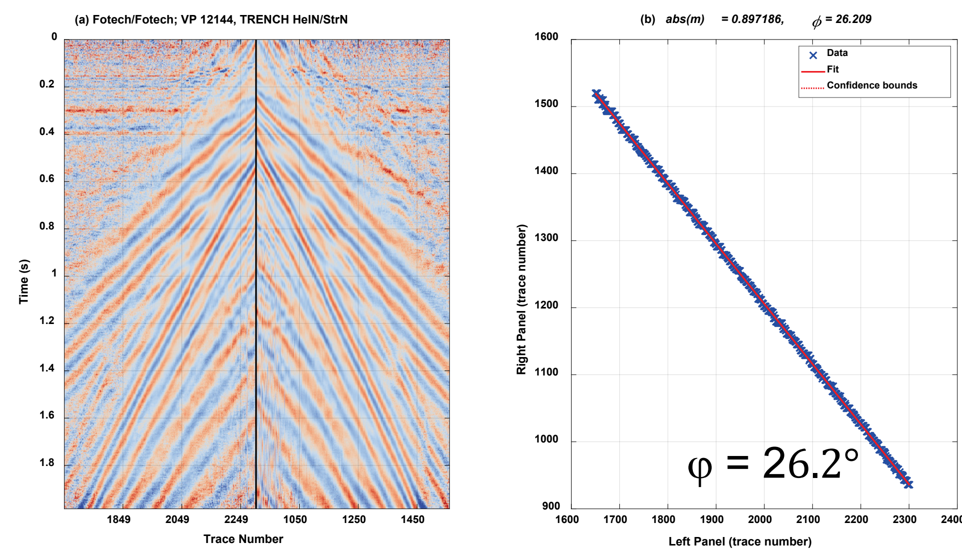

Figure 11. Helical and straight fibre in northern trench.

Table 1. Summary of pitch angle estimates. Note that this is a subset of Table A1.

Run Name	nVP	*m*	*φ (deg)*	*θ (deg)*
HelDwnStrDwnObs2.xlsx	22	0.888	27.4	29.6
HelDwnStrUpObs2.xlsx	21	0.889	27.3	29.5
HelUpStrDwnObs2.xlsx	18	0.891	27.0	29.3
HelUpStrUpObs2.xlsx	21	0.891	27.0	29.3
StrDwnHelDwnObs2.xlsx	18	0.886	27.6	29.9

StrDwnHelUpObs2.xlsx	20	0.889	27.3	29.6
StrUpHelDwnObs2.xlsx	18	0.884	27.8	30.1
StrUpHelUpObs2.xlsx	23	0.889	27.3	29.6
	Average	**0.888**	**27.3**	**29.6**
HelNorthStrNorthTrench.xlsx	20	0.897	26.2	28.6
HelSouthStrSouthTrench.xlsx	20	0.896	26.3	28.7
StrNorthHelNorthTrench.xlsx	18	0.898	26.1	28.5
StrSouthHelSouthTrench.xlsx	26	0.898	26.1	28.5
	Average	**0.897**	**26.2**	**28.5**

Table 2 summarizes helical trace spacing predictions for nominal 30 degree pitch angles with and without index of refraction corrections, and for pseudo-pitch angle estimates for helically wound fiber in OBS and in the trench. It also shows the predicted number of traces that will result for each of these trace spacings for an arbitrary fixed distance of 300 m. The 9 trace difference between the trench estimate from the data and calculated from the nominal pitch angle may well explain earlier difficulties interleaving helical and straight fibre data by co-ordinates (Hall et. al, 2019a). This means that, in this example, we could have used the pseudo-pitch angle results from Table 2 instead of running more cross-correlations and linear regressions.

Table 2. Predicted and calculated helical trace spacing.

	θ (deg)	*φ (deg)*	*m*	*Dactual (m)*	*deltaD (m)*	*TD (m)*	*Ntraces*
Nominal θ	30.0	30.0	0.866	0.577	0.089	300	520
Nominal θ *with IR*	30.0	27.8	0.885	0.590	0.077	300	509
OBS2 *m* estimate	29.6	27.3	0.888	0.592	0.075	300	507
Trench *m* estimate	28.5	26.2	0.897	0.598	0.069	300	502

DATA REGISTRATION

Moving beyond matching channel numbers to better assigning x, y, and z coordinates to DAS traces depends on the availability of co-located dataset with a known geometry. For the dataset used in these examples, we have multi-component geophones and straight and helical fibre cables cemented in on the outside of the OBS2 will casing, and a string of temporary multicomponent accelerometers inside the casing. In addition, geophones were planted along the trench on the surface. Table 3 shows the results of cross-correlating geophone and accelerometer data converted to strain-rate (Hall et al., 2019b, Monsegney et al, 2020) with straight and helical fibre data and compares the results to OBS2 and trench *Dactual* estimates from Table 2.

We only had 8 geophones south of OBS 2 along the trench, which turns out to not be enough data to estimate a good helical trace spacing. For the other geophone and accelerometer data cross-correlated with straight and helical fibre data, the maximum difference between fibre trace spacing calculated from pseudo-pitch angles estimated solely from fibre data is on the order of 3 cm.

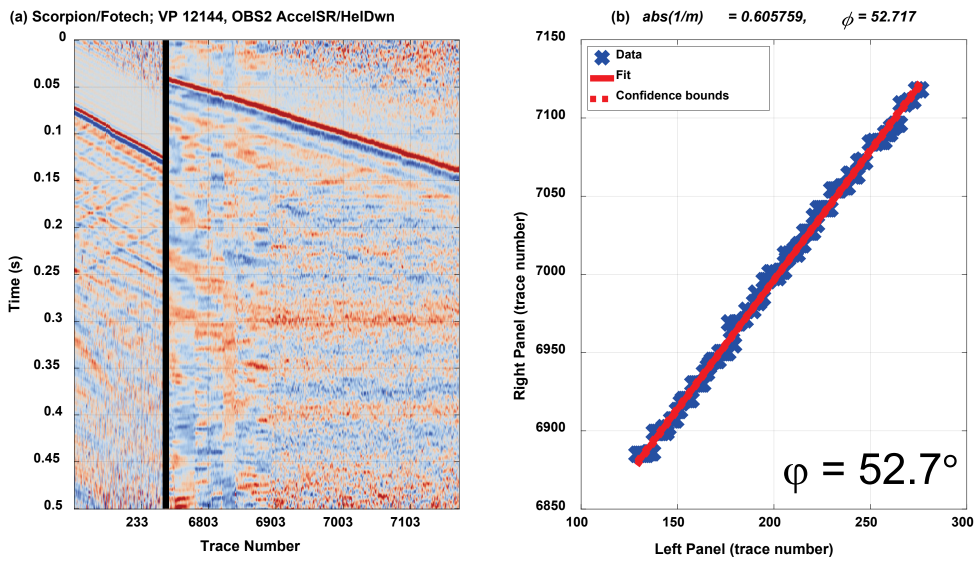

Figure 12. OBS2 Accelerometer/Helical Down.

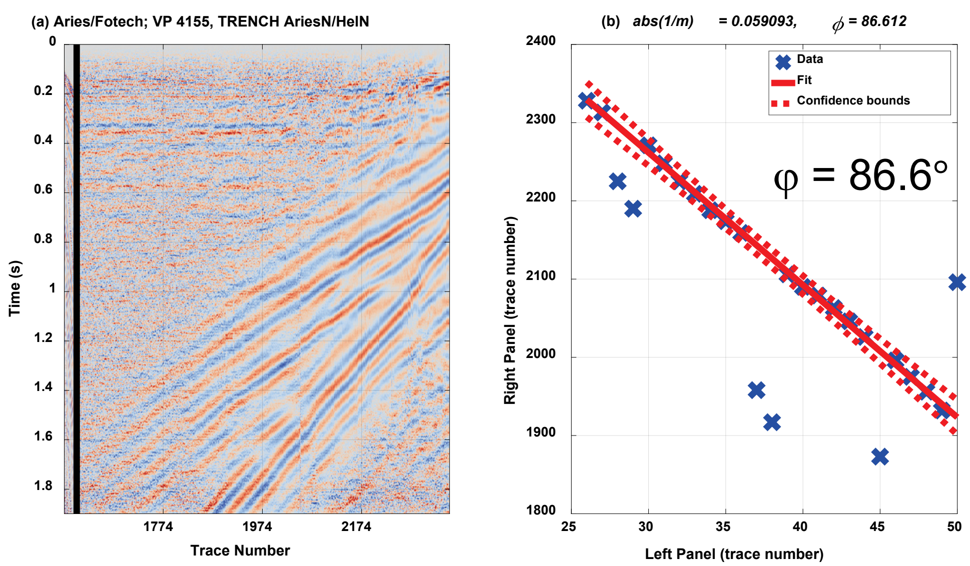

Figure 13. Trench N Geophone/Helical.

Table 3. Summary of results for geophone and accelerometer strain-rate data cross-correlated with helical and straight fibre data shown in Figures 10 and 11. Predicted helical trace spacing (dx2) was calculated using Equation1 and the average pitch angles (bold) from Table 1. A 5-10-100-110 Ormsby bandpass filter was applied before cross-correlation in all cases.

Run Name	nVP	*Nom. D1 (m)*	Nom. *m*	Est. *m*	Nom. *φ (deg)*	Est. ϕ (deg)	*Dactual (m)*	Est. *D2 (m)*	*ΔD2 (m)*
GeoSR HelDwn	26	5	0.118	0.122	83.2	83.0	0.592	0.610	0.018

OBS2									
GeoSR StrDwn OBS2	22	5	0.133	0.137	82.3	82.1	0.667	0.685	0.018
AccelSR HelDwn OBS2	25	1	0.592	0.596	53.7	53.4	0.592	0.596	0.003
AccelSR StrDwn OBS2	24	1	0.667	0.671	48.2	47.9	0.667	0.671	0.004
GeoSR Hel NorthTrench	19	10	0.060	0.060	86.6	86.6	0.598	0.599	0.000
GeoSR Str NorthTrench	21	10	0.067	0.063	86.2	86.4	0.667	0.634	0.032

DISCUSSION

We can estimate a pseudo-pitch angle for helically wound fibre cables solely from the recorded data if there is a co-located dataset, using cross-correlations and linear regression. This process requires no prior knowledge of trace spacings for the two datasets, or, in the DAS case, knowledge of the indices of refraction of the fibre or the index of refraction used in the DAS interrogator software. The pseudo-pitch angle is robust in the sense that we obtain similar answers for unfiltered and bandpass filtered input data and matching the domains of the input data (acceleration, velocity, strain-rate) does not seem to change the pseudo-pitch angle estimate significantly.

If the co-located dataset has a known trace spacing, we can also predict an unknown trace spacing, for example, the helical fibre cable trace spacing from a known geophone, accelerometer, or straight fibre trace spacing. We may also use the slope and intercept from the linear regression step to register datasets by dataset channel number. (eg. Figure 14 and Figure 15) Here, we find that a domain mismatch for the input datasets gives us a bad estimate of the intercept, as will a time-zero mismatch between the two datasets. Bandpass filtering the datasets does not significantly affect result if there are no time-zero problems, or time-zero problems have been fixed before cross-correlation, and both input datasets are in the same domain.

It is necessary to estimate pseudo-pitch angles for multiple source gathers and combine the results statistically. All tables in this report have a column labelled ‘nVP,’ whose values are always less, sometime significantly less that the total number of input gathers. We arbitrarily removed any slopes that were not in the range (median(slope-stdev <= slope <= median slope+stdev). This is because the cross-correlation results, and hence the linear regression slope and intercept results are sensitive to the trace range chosen for the input data. The distance range for one dataset must be entirely contained within the distance range for the second dataset, or the slope will be changed by large numbers of non-unique matches at the ends of the trace range. Large numbers of noisy traces also affect the quality of the results.

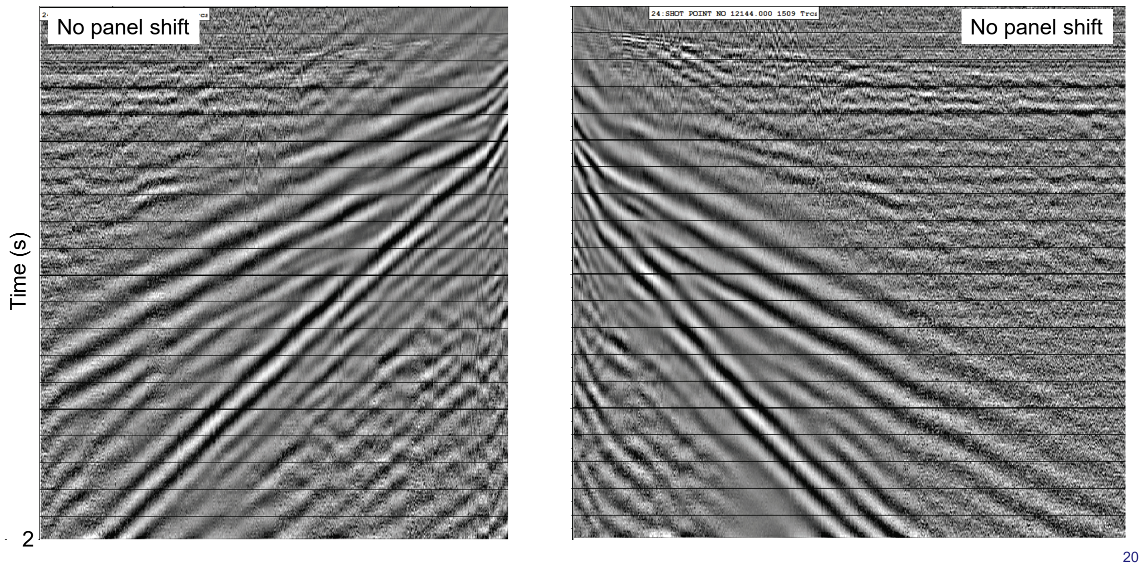

Figure 14. Trench helical and straight fibre data interleaved using the linear relationship between straight and helical channel numbers.

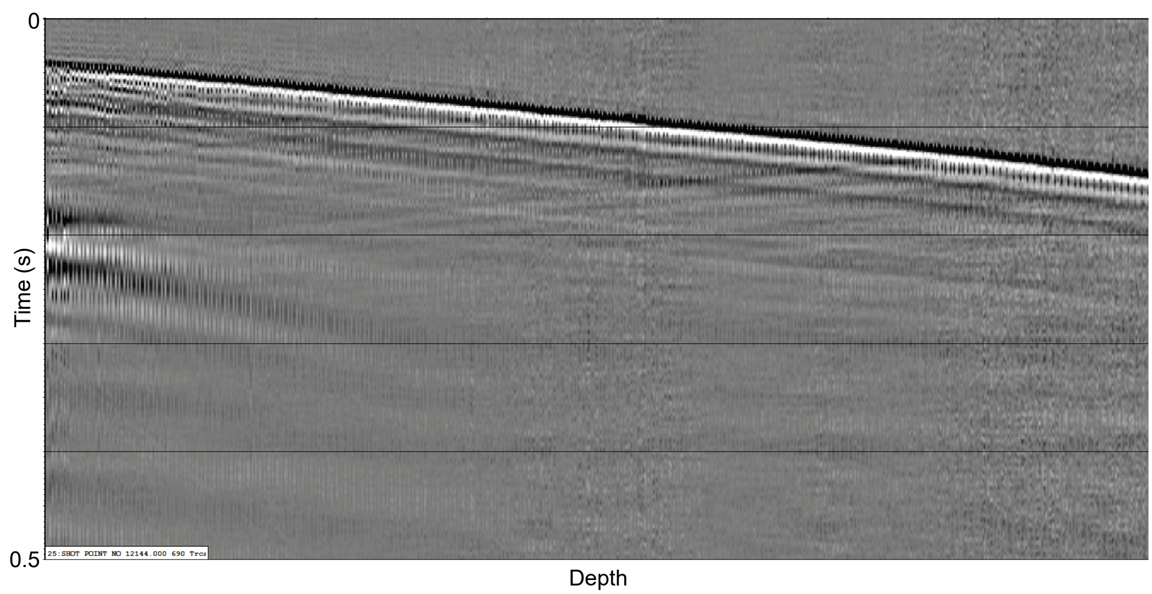

Figure 15. OBS 2 accelerometer data converted to strain rate and interleaved with helical fibre data using the linear relationship between accelerometer and helical channel numbers.

FUTURE WORK

We know that there is a time-zero problem between the downhole geophone and accelerometer data, but we have thus far assumed that there are no time-zero mismatches between all the other recording systems, which is unlikely. This needs more attention before we continue to final dataset registrations and geometry assignments.

We propose to complete dataset registration by finding integer or near-integer predicted channel numbers where we can say that this trace in this dataset is at the same location as that trace in that dataset. We should then be able to use these traces as indices to better match interpolated co-ordinates (Hall et al., 2019a) to channel numbers.

ACKNOWLEDGEMENTS

The sponsors of CREWES are gratefully thanked for continued support. This work was funded by CREWES industrial sponsors, NSERC (Natural Science and Engineering Research Council of Canada) through the grant CRDPJ 543578-19. We would also like to thank Fotech for field acquisition, Schlumberger for the use of donated Vista software, and all CREWES sponsors and CaMI.FRS JPI subscribers for their continued support.

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APPENDIX A

Table A1 summarizes the results of all linear-regressions of cross-correlation results that have been run to date. Cross-correlations were run on twenty-seven source gathers, but only slope results in the range of median slope +/- one standard deviation were retained for the pseudo-pitch angle estimation. Figure A1 displays run number from Table A1 plotted against the mean estimated slope for nVP source gathers, and Figure A2 displays run number plotted against the mean pitch (or pseudo-pitch) calculated from the estimated slope with no index of refraction corrections. Naming conventions are:

- Accel: accelerometer data
- AccelV: accelerometer data converted to velocity
- AccelSR: accelerometer data converted to strain rate
- Geo: geophone data
- GeoBulk: geophone data bulk-shifted 3.6 ms before cross-correlation
- GeoSR: geophone data converted to strain rate
- Up: fibre data where increasing channel number correspond to decreasing depth
- Dwn: fibre data where increasing channel number corresponds to increasing depth
- Filtered: datasets 1 and 2 have been band-pass filtered before cross-correlation
- OBS1, OBS2, Trench: data are from observation wells 1 or 2 or from the trench
- North: trench north of OBS2
- South: trench south of OBS2

Table A1. Summary of results.

Run Name	Run	nVP	MeanSlope	MeanIntercept	MeanPitch
AccelAccel	1	21	0.999979931	0.015189536	0.151536126
AccelAccelSR	2	24	1	-3.30656E-15	1.09131E-06
AccelHelDwn	3	21	1.66335151	6664.415329	53.04292335
AccelHelDwnFiltered	4	19	1.68388079	6642.040542	53.56689777
AccelHelUp	5	17	-1.653438099	7685.452241	52.78485659
AccelHelUpFiltered	6	20	-1.675384354	7708.022945	53.35149668
AccelSRHelDwn	7	22	1.646274688	6667.127774	52.59521121
AccelSRHelDwnFiltered	8	25	1.679058988	6641.233902	53.42871146
AccelSRHelUp	9	19	-1.644495629	7685.170218	52.54806775
AccelSRHelUpFiltered	10	24	-1.674556755	7710.057769	53.31390609
AccelSRStrDwn	11	18	1.465010271	5616.815732	46.95314849
AccelSRStrDwnFiltered	12	24	1.490701629	5595.809594	47.84623988
AccelSRStrUp	13	23	-1.468821182	6570.178438	47.09130123
AccelSRStrUpFiltered	14	25	-1.491271317	6589.933834	47.86812978
AccelStrDwn	15	20	1.474012483	5615.813616	47.27917144
AccelStrDwnFiltered	16	22	1.492770995	5596.119467	47.9396696
AccelStrUp	17	20	-1.475506362	6570.277256	47.33281299
AccelStrUpFiltered	18	24	-1.493704367	6589.935932	47.97210661
AriesSRHelNorthTrench	19	11	-16.70745128	2737.860037	86.56342982
AriesSRHelSouthTrench	20	10	-24.82123443	2911.122776	87.49381836
AriesSRStrNorthTrench	21	11	15.76750346	516.2790653	86.32878985
AriesSRStrSouthTrench	22	10	20.06229031	3941.819978	86.81585568
GeoAccel	23	22	5.276945798	178.3680169	78.78288633
GeoAccelFiltered	24	19	4.67542561	180.6749594	77.62009531
GeoAccelSR	25	22	-5.036119769	297.8314625	78.54626208
GeoAccelV	26	24	4.984185666	174.8166864	78.42422514
GeoAccelVFiltered	27	25	4.975903345	174.5796115	78.40446256
GeoBulkAccel	28	19	4.951711859	184.4852572	78.34839804
GeoBulkAccelSR	29	17	-4.963338588	307.0730719	78.37650289
GeoGeo	30	22	1	1.31426E-15	8.53774E-07
GeoGeoSR	31	27	1	2.80708E-15	0
GeoHelDwn	32	17	8.066749594	6972.786593	82.87788396
GeoHelDwnFiltered	33	26	8.237092595	6955.562315	83.02438236
GeoHelUp	34	18	-7.99534485	7379.207794	82.8136661
GeoHelUpFiltered	35	18	-8.202407348	7396.356677	82.9966383
GeoSRHelDwn	36	18	-8.086589708	7156.56626	82.89633824
GeoSRHelDwnFiltered	37	26	-8.1970813	7138.968544	82.99143494
GeoSRHelUp	38	21	8.011158752	7197.965867	82.82881781
GeoSRHelUpFiltered	39	25	8.181123796	7213.530007	82.97786995

GeoSRStrDwn	40	20	-7.229883866	6052.264618	82.04935446
GeoSRStrDwnFiltered	41	22	-7.300694705	6037.071897	82.12575983
GeoSRStrUp	42	26	7.194501589	6134.154896	82.0088864
GeoSRStrUpFiltered	43	22	7.32299485	6148.43925	82.15049437
GeoStrDwn	44	16	7.136597644	5889.023615	81.94446229
GeoStrDwnFiltered	45	20	7.320457471	5873.131844	82.14696562
GeoStrUp	46	21	-7.175939417	6297.021909	81.98786911
GeoStrUpFiltered	47	20	-7.425546321	6312.975636	82.25910683
HelDwnHelDwnObs2	48	25	1.000013671	-0.096275204	0.059912422
HelDwnHelUpObs2	49	20	-1.002378906	14368.8162	4.935620528
HelDwnStrDwnObs2	50	22	0.88800788	-302.6567749	27.37507575
HelDwnStrUpObs2	51	21	-0.888932524	12494.74972	27.25895076
HelNorthStrNorthTrench	52	20	-0.897458931	3000.552882	26.17390434
HelSouthStrSouthTrench	53	20	-0.896496048	6547.969331	26.29865335
HelUpHelDwnObs2	54	26	-1.008324178	14413.61676	7.666362043
HelUpHelUpObs2	55	20	0.999983608	0.119149727	0.166507956
HelUpStrDwnObs2	56	18	-0.891038251	12464.5154	26.99507948
HelUpStrUpObs2	57	21	0.890746981	-276.7440729	27.03224564
StrDwnHelDwnObs2	58	18	1.128374584	327.416163	27.59408468
StrDwnHelUpObs2	59	20	-1.125320728	14006.7185	27.29636551
StrDwnStrDwnObs1	60	20	1.00003697	-0.120852128	1.719115578
StrDwnStrDwnObs2	61	20	1.000580584	-3.418961129	2.487769253
StrDwnStrUpObs1	62	18	-1.000794297	9912.446977	3.03654807
StrDwnStrUpObs2	63	19	-1.001524035	12194.70387	3.099314866
StrNorthHelNorthTrench	64	18	-1.113152543	3341.901222	26.05799256
StrSouthHelSouthTrench	65	26	-1.113414027	7295.849263	26.08494265
StrUpHelDwnObs2	66	18	-1.130817115	14092.9691	27.83033881
StrUpHelUpObs2	67	23	1.125455788	292.9812537	27.30900118
StrUpStrDwnObs1	68	18	-1.000595953	9911.830333	3.022142898
StrUpStrDwnObs2	69	19	-1.001552528	12195.54694	3.504407487
StrUpStrUpObs1	70	21	0.999990776	0.006722716	1.826862063
StrUpStrUpObs2	71	22	1.000421433	-2.645343753	2.225126676

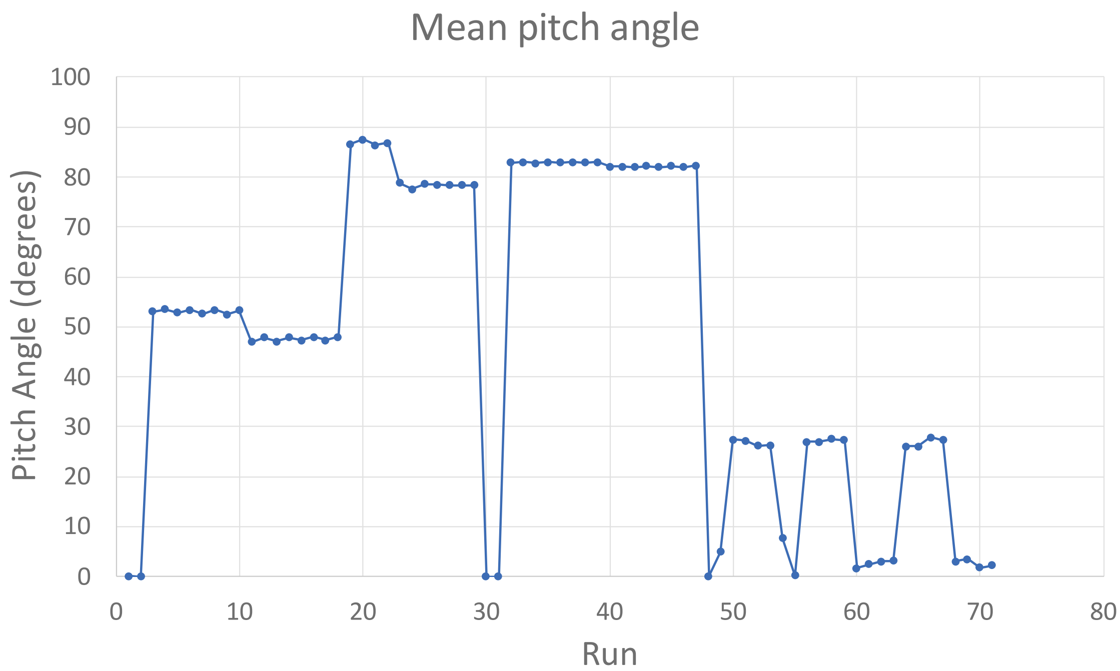

FIG. A1. Run number and average pitch angle.

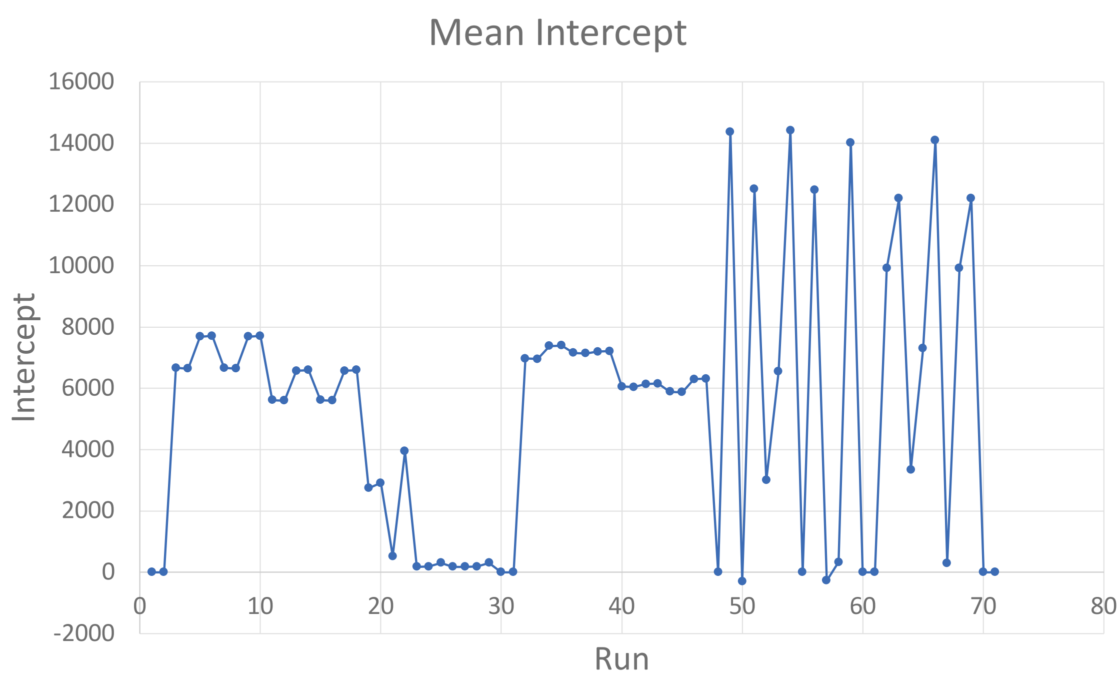

FIG. A2. Run number and average intercept.