A new system for efficiently acquiring vertical seismic profile surveys

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SUMMARY

A vertical seismic profile (VSP) survey involves placing sensors in a borehole to record the passage of energy transmitted using a source of seismic energy placed on the surface. The sensors are usually contained within sondes that are coupled to the borehole wall using mechanical clamps. Existing VSP acquisition systems are generally unsuitable for acquisition using the wireline units typically used for minerals logging. In this paper we describe a new multis-sonde VSP acquisition system specifically designed for acquiring high-resolution VSP surveys in hard-rock environments.

Key words: Vertical seismic profile.

INTRODUCTION

A vertical seismic profile (VSP) survey involves placing sensors in a borehole to record the passage of energy transmitted using a source of seismic energy placed on the surface. The sensors are usually contained within sondes that are coupled to the borehole wall using mechanical clamps. As the seismic energy passes through the sub-surface it arrives at the sensor positions at different times (Figure 1). The time taken to arrive at each sonde is referred to as the one-way travel-time and is a measurement of the bulk p-wave velocity. The term bulk is used here as the volume of rock being interrogated is much larger than that sampled by a sonic log, which is generally confined to the area close to the borehole wall (usually considerably less than 1 m). Although a variety of different VSP acquisition geometries exist the most commonly employed is the zero-offset VSP, where the source is placed adjacent to the borehole. In this configuration the difference in time taken to travel from the source to a pair of receiver positions is the interval velocity (the velocity of that layer encompassed by the two positions). As well as velocity information, VSP data can also be processed further to obtain other valuable products such as a corridor stack, a trace that shows the sub-surface reflections, and the seismic quality factor Q.

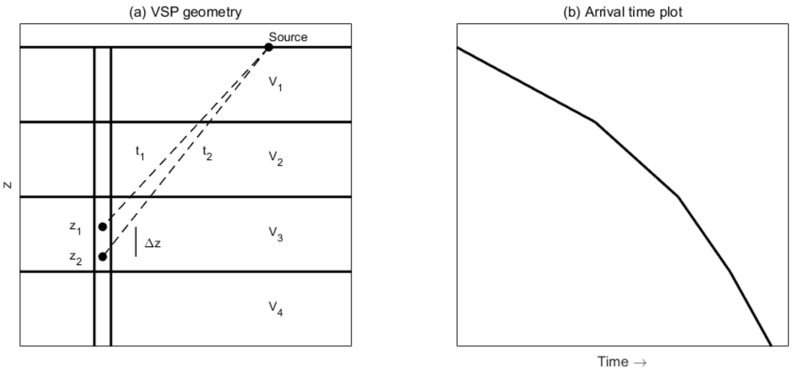

Figure 1. (a) Diagrammatic representation of a VSP survey and (b) resulting arrival time plot.

The number of sondes employed in a survey is typically much smaller than the number of depths at which we wish to record data. The tool(s) are therefore positioned at different depths and the energy source at the surface repeatedly fired until all depths have been acquired. The larger the number of sondes employed the faster the survey is to acquire. A limited number of sondes are typically employed, however, due to the cost of the equipment and the time required to rig-up (Dean et al. 2015). Although the use of VSPs is well established in the oil industry the use of VSP measurements is becoming increasingly attractive in the minerals industry as velocity measurements from core are often difficult to make and even obtaining the core itself is expensive (Grant et al. 2018). Unfortunately, the VSP data acquisition systems currently available tend to be unsuitable for this work.

Existing VSP acquisition systems fall into one of two categories:

- Expensive, high-performance, multi-level tools aimed at oilfield services.
- Simple, single-level tools for near-surface acquisition.

Oilfield service tools are often designed for use at temperatures and pressures (e.g. 195°C and 20,000 psi) not often encountered at typical mineral exploration drilling depths. They also employ expensive telemetry systems that limit the number of sondes that can be used, require an additional telemetry sonde at the top of the string, and often employ expensive heptacables with embedded fibre-optic cables. Near-surface tools have much lower pressure ratings (e.g. 300 m water depth) and are deployed as a single sonde. The cable typically require a pair of wires for each geophone, as well as caliper power (totalling at least seven), greater than that found in typical mineral wireline logging cable (limited to just four).

In this paper we describe the construction of a new, specially designed, VSP tool that overcomes many of the limitations of the existing instruments. We begin by looking at the impact of sonde spacing and source timing.

THE IMPACT OF SONDE SPACING AND SOURCE TIMING

Oilfield VSP surveys are often made with depth intervals of around 15-20 m. For mineral surveys in shallow (100-200 m) holes, however, the depth resolution required is much smaller, typically around 2 m. Although high depth resolution surveys can be acquired by interleaving the sondes the derived interval velocities, as shown in Figure 2, show unrealistically large variations and require smoothing, removing the high resolution gained from the small sampling intervals.

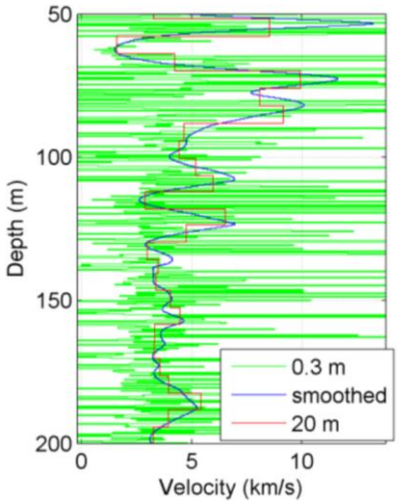

Figure 2. Raw interval velocities (shown in green) acquired at a depth interval of 0.3 m using a tool with a sonde spacing of 15 m (Adapted from Dean et al. (2016)).

To identify the source of these flucations we need to look at the errors associated with the calculation of interval velocity. The values V_{int} are calculated by dividing the trace depth Δz spacing by the travel time difference Δt between pairs of traces

$$V_{int} = \frac{\Delta z}{\Delta t} \tag{1}$$

The error in the value of the interval velocity is given by

$$\mathrm{E}(V_{int}) = V_{int}\sqrt{\left({}^{\mathrm{E}(\Delta z)}/_{\Delta z}\right)^2 + \left({}^{\mathrm{E}(\Delta t)}/_{\Delta t}\right)^2} \tag{2}$$

(from the standard error propagation equations). If we assume that there is no error in Δt then the percentage error in V_{int} will be equal to that in Δz. Figure 3a shows the maximum interval depth error allowed to achieve a velocity error of 1%, whilst Figure 3b shows the velocity error resulting from different depth interval errors assuming a nominal depth interval of 2 m. Thus to keep the error at a maximum of 1% we need to ensure that the spacing between the shuttles is known to within 0.02 m (note that accurate knowledge of the distance between shuttles is key, rather than the distance being a set value).

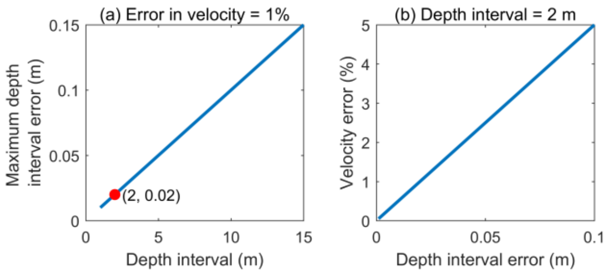

Figure 3. (a) The maximum error in the depth interval relative to the depth interval to achieve a velocity error of 1%. (b) The error in the velocity relative to the depth interval error given a nominal depth interval of 2 m.

The velocities themselves are derived from picking the time of the same event on traces from different depths. Assuming the errors in the velocity come only from the time-picking then equation 2 becomes

$$\mathrm{E}(V_{int}) = V_{int} \, {}^{\mathrm{E}(\Delta t)}/_{\Delta t} \tag{3}$$

As $\Delta t = \Delta s / V_{int}$ we can express $\mathrm{E}(V_{int})$ with respect to Δs

$$\mathrm{E}(V_{int}) = V_{int}^2 \mathrm{E}(\Delta t)/\Delta s \tag{4}$$

Figure 4a shows how the resulting velocity uncertainty varies with depth interval for a fixed velocity of 2,000 m/s and time uncertainty of 0.1 ms. As the spacing gets smaller the uncertainty increased dramatically. Figure 4b shows the uncertainty in velocity given a fixed depth interval and time uncertainty. Finally, Figure 4c is perhaps the most important, this shows the uncertainty in velocity for a fixed velocity and depth interval for different time uncertainty values. Even for small time uncertainty values the effect on velocity is quite dramatic, for example a value of ±0.2 ms gives a velocity uncertainty of 400 m/s.

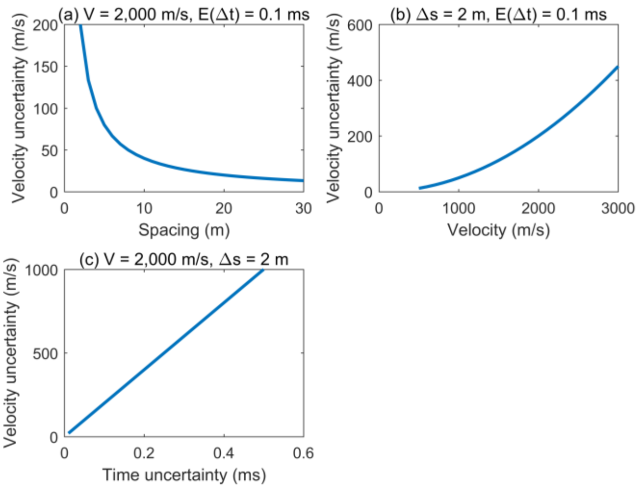

Figure 4. (a) The uncertainty in the velocity resulting from an error in the time-pick of 0.1 ms for different depth spacing. (b) The uncertainty in the velocity resulting from an error in the time-pick of 0.1 ms given a depth interval of 2 m for different velocities. (c) The uncertainty in the velocity for a velocity of 2,000 m/s and spacing of 2 m for different time-pick errors.

The trigger accuracy of commonly used acquisition systems is usually claimed to be highly accurate, for example the results shown here were obtained using a system with a claimed accuracy of 1/32 of a sample interval, which at a sample rate of 0.25 ms would be ~0.008 ms. The need to hold data in memory before recording begins (‘pre-trigger’), however, means that there is often significant jitter in the results. For example, Figure 5 shows surface data recorded using geophones placed beneath the hammer plate and at an offset of 15 m. The system was triggered using a standard piezoelectric trigger but despite this timing errors averaging more than 1 ms are clearly visible. If known, the sub-sample time shifts can be easily removed in the frequency domain (Figure 6a) prior to stacking, although this is not possible is the data is automatically stacked during acquisition. There is a noticeable difference between the stack of the raw and corrected traces (Figure 6b) and the latter have, as expected, a larger high-frequency content (Figure 6c).

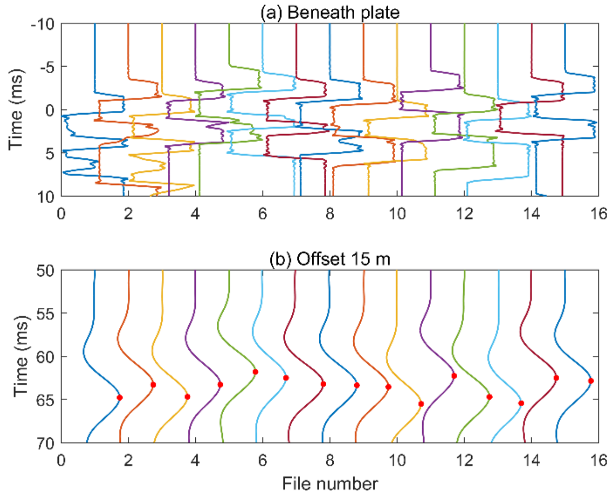

Figure 5. Traces recorded using geophones placed (a) beneath the baseplate and (b) at an offset of 15 m. Each colour indicates a different shot. The red dots on (b) are the first break picks. The data was recorded with a sample interval of 0.25 ms.

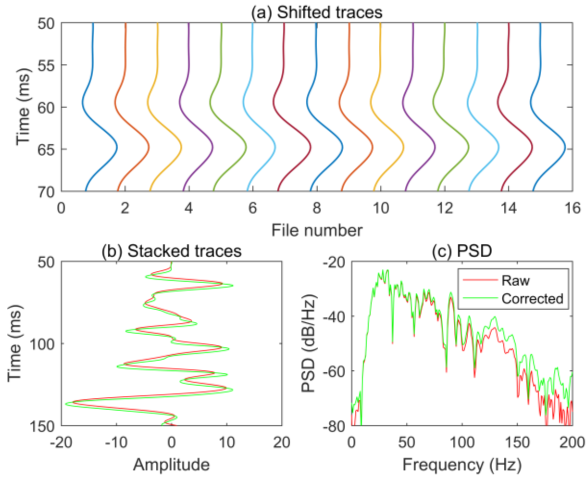

Figure 6. (a) Traces shown in Figure 5a after trigger time variation has been removed, (b) stacked traces for the raw and time-corrected data, (c) power spectral density plots for the traces shown in (b).

Perhaps more importantly, if source related triggering errors are not corrected, then the errors in the interval velocities will be significant. For example, using the time-picks shown in Figure 5b and assuming a measurement spacing of 2 m results in interval velocities of -1,400 to 14,000 m/s averaging ±3,400 m/s (the true value should be 0). Even if the source timing is known there might be small time difference introduced by variations in the near surface introduced by the source itself (e.g. ground compaction associated with multiple shots).

Our approach to obtaining more accurate interval velocity profiles is based on avoiding source related timing effects by removing the need to interleave the shuttles to get small depth intervals. We achieved this by making the shuttle spacing much smaller than commonly used (2 m), and using continuously recording sondes with the source trigger times recorded and the seismic traces separated and shifted in processing (combing). In the next section we will detail the system hardware.

SYSTEM HARDWARE

A photo of a string of four sondes is shown in Figure 7, note that the sonde length is short enough to enable 2 m sensor spacing. The tool diameter is 54 mm (small hole) and 64 mm (wide hole) enabling it to be used in holes as small as 76 mm and as large as 356 mm. Each tool contains three 14 Hz omnidirectional geophone allowing three-component recording.

Figure 7. String of four sondes (2 m sensor spacing), shown with the calipers fully open.

The surface system was designed to be as simple as possible and consists of the following components (Figure 8):

(a) Tool caliper control: this opens and closes the calipers on the tool.
(b) Power supply.
(c) Seismic interface box: this contains (from left to right on Figure 8c):
    i. Wireline cable connector.
    ii. Laptop computer connector.
    iii. Trigger inputs and outputs (rising edge, falling edge and contact-closure in and out are supported, enabling the use of a variety of sources including weight drops and Vibroseis).
    iv. Triggering test button and status lights.
    v. Tool depth display.
    vi. GPS antenna connector.

For source triggering the source can either be connected directly to the interface box (Figure 8c) or, if the source is far from the recording system, GPS timing can be employed with the source(s) acting autonomously. Similarly the sondes can be used in two-way communication mode, or as autonomous or 'blind' recorders.

Figure 8: VSP System components: (a) Tool caliper control, (b) power supply, (c) seismic interface box.

SYSTEM OPERATION

The description of the operation of the system will be done with reference to the software screenshot shown in Figure 9. The panel along the bottom shows the status of the system components: the sondes, the timing, depth controller and source interface. The panel on the left shows the current status of the sondes (in this case just two). The sondes are working correctly so are shown in green, the information to the right of the sondes shows their orientation and current temperature. The panel across the top shows the depth of the top (‘T’) and bottom (‘B’) of the string along with the rate of change (‘R’). The plot in the middle summarises the status of the survey, each point (most of which are currently red) indicates the depths at which data needs to be recorded. Once recording at that depth beings the point turns blue, once enough shots have been recorded the point turns green. The table in the top left shows the survey status as a table. The bottom right of the screen is the observers log showing a variety of automatically generated entries along with those manually entered by the user.

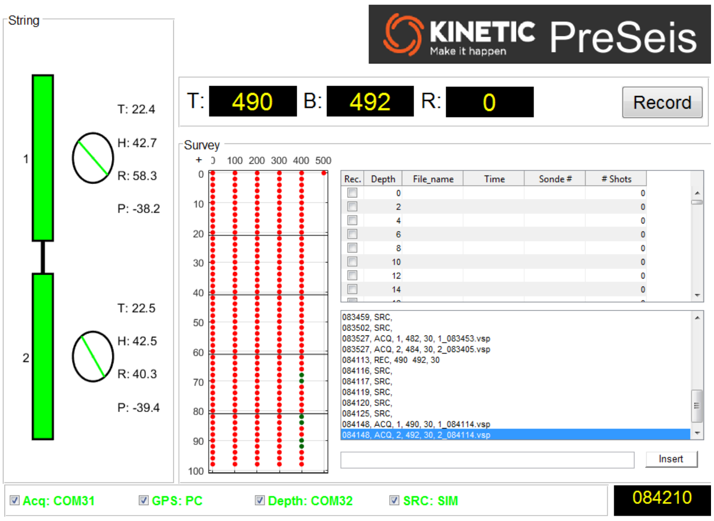

Figure 9: VSP software screendump.

Acquisition proceeds as follows:

i. Once the desired depth is reached and the tools are clamped the operator presses the *Record* button. The system checks that the current depth is included in the survey, if it is, then the sonde’s clocks are synchronised and recording (for a set period, typically 30 s) begins.

ii. While recording is in progress the source is either triggered or monitored (depending on the source mode being employed) and the number of valid shots recorded calculated once the recording is complete.

iii. After recording is complete the sondes each transmit a QC message and if the data is deemed to be acceptable then the survey progress is updated.

iv. If sufficient records have been acquired then the depth is complete and the tool is moved to a new depth.

v. Logging typically proceeds starting from the bottom of the hole, once acquisition is complete the sondes are removed from the hole and the data downloaded, using a Bluetooth, Zigbee or USB connection.

vi. Using the information contained in the observers log the data is then combed to separate out each individual record.

RESULTS

Figure 10a shows a raw 30 s record containing 6 shots, the time of the shots, as recorded by the surface acquisition module, is shown by the red vertical lines. Figure 10b shows the six records after they have been combed out of the raw trace, the red points in this case indicate the position of the maximum value of the first-break while Figure 10c shows the stack of the traces. The mean value of the picks was 24 ms with a standard deviation of less than 0.3 ms (in contrast the data in Figure 5 had a standard deviation in time picks of 1.2 ms). Close inspection of the picks shows that one trace (the one shown in purple) differed from the others and when this is excluded the variation drops to just 0.14 ms.

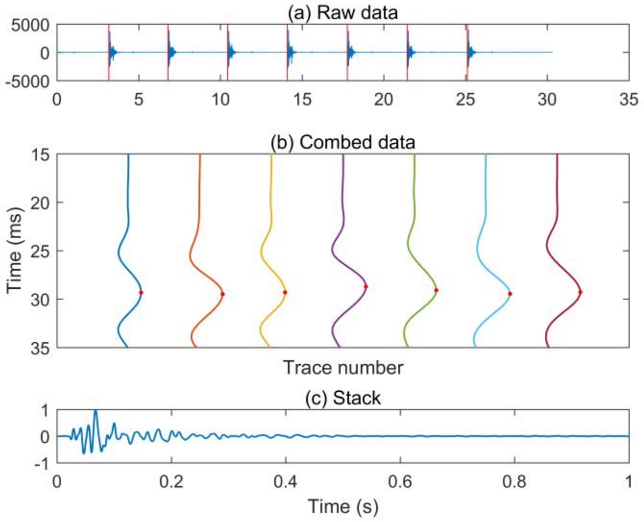

Figure 10: (a) raw data showing six shots recorded over a 30 s period. (b) the six records removed ('combed') from the data shown in (a). (c) Resulting stacked trace.

The effects of the errors in the travel-time picks are summarised in Table 1 which shows the error in the interval velocity for two different time-travel errors (1.2 ms and 0.14 ms) given a measurement spacing of 2 m. As the velocity increases the error resulting from the larger travel-time error (1.2 ms) becomes more significant increasing from 15% to 55%. The smaller travel-time error (0.14 ms), however, results in smaller velocity errors (2% to 12%).

Table 1. Errors in the calculated velocity resulting from errors in the time picks (E(t)) of 1.2 and 0.14 ms given a spacing of 2 m.

True velocity (m/s)	Travel time (ms)	Error in velocity (m/s) E(t) = 1.2	E(t) = 0.14
300	6.7	46	6
400	5	77	11
500	4	115	17
800	2.5	259	42
1000	2	375	65
1500	1.3	711	143
2000	1.0	1091	246

DISCUSSION AND CONCLUSIONS

The value of VSP data has long been acknowledged in the oil industry but acquisition is typically limited by the small number of wells, and offshore by the cost of rig-time. VSP acquisition in the mining industry, conversely, does not suffer from a lack of holes nor from the desire for VSP data but does suffer from a lack of suitable instrumentation. In this paper we have described a new, custom-built, VSP acquisition system that employs an approach (data being stored on the sonde) not previously employed. This approach overcomes many of the issues involved with using the use of conventional (either designed for the oil industry or near-surface) VSP tools. By acquiring longer files containing a number of shots and storing the data on the tool we avoid the lengthy cycle times associated with data buffering, transmission and recording encountered in some other acquisition systems. The need to acquire highly accurate velocity information is achieved by having small sonde spacing and accurate source trigger timing. This allows variations in travel-time due to the source to be avoided during acquisition and accurate data combing after acquisition.

The new system allows VSPs to be acquired rapidly by employing a robust acquisition system with limited bandwidth requirements that can be used on the standard 4-core cables commonly employed for mineral logging. The use of multiple sondes (the number if theoretically limitless) increases acquisition efficiency significantly over single-level tools without significantly increasing rig-up time (rigging up a string of four tools takes only 10 minutes). The use of simple QC metrics, rather than having the operator attempt to interpret the data in real-time, has enabled us to create a very simple operator interface.

We hope that the availability of this new system will help the value of VSP in the mineral industry to be realised.

ACKNOWLEDGMENTS

Thanks to those at Curtin University and the Kinetic Group who assisted with this project. This project was supported by the Australian Government Department of Industry Innovation and Science, via the Innovations Connection stream of the Entrepreneurs Program.

REFERENCES

Dean, T., M. Clark, T. Cuny, and J. Puech. 2016, Is there value in highly spatially sampled zero-offset vertical seismic profiles? In 78th EAGE Conference & Exhibition. Vienna, Austria.

Dean, T., A. Constantinou, T. Cuny, B. Frignet, A. Hartog, T. Kimura, R. Kolesar, D. Lane, and G. Lees. 2015, Vertical seismic profiles: Now just another log? Paper read at SEG Technical Program Expanded Abstracts.

Grant, A., T. Dean, H. Rossiter, and B. Armitage. 2018, The application of VSP in the Pilbara. In Proceedings of the Australasian Exploration Geoscience Conference. Sydney, Australia.