WASM: Minerals, Energy and Chemical Engineering

Improvement of Borehole Seismic Data Quality Control and Assessment by Statistical Approach

Sergei Tcherkashnev

This thesis is presented for the Degree of
Master of Philosophy (Geophysics)
of
Curtin University

October 2020

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature:

Date: 21 October 2020

Dedication

This thesis is dedicated to my parents; Alexei and Svetlana, and my family whose love and support inspires me to achieve my goals.

Abstract

Quality control and evaluation of borehole seismic data and logs is currently done by visual inspection of the data as it is collected, analysis of the computed quality control plots and relies to a great extent on the experience of the seismic acquisition specialists and a client witness. There are a limited number of borehole seismic quality control systems currently available. Current industry standards affect data quality; increase acquisition time and rig-time and ultimately lead to lost opportunities and revenue for the client. In 2010 approximately sixty offshore exploration wells had VSP surveys with the estimated rig time losses up to US$6.6M. Major contributions to those losses were due to longer acquisition time, delays caused by hardware malfunctions, slow survey level acquisition process and more time spent analysing data visually than expected.

Thus it is of a critical importance to evaluate, develop, optimise and implement quality control framework and methods to ensure an efficient and cost effective approach to borehole seismic surveys. A proposed Quality Control Assurance Technology (QCAT) approach is based on a deep understanding of borehole seismic acquisition, processing, interpretation and uses statistics for credibility and usefulness of analysed information. The solution provides cost effective, valuable and comprehensive quality control metrics for the clients and service companies to use in order to refine their acquisition methods. These quality control elements will also enable the client to manage risk and make sound decisions based on empirical evidence. The developed methodology uses signal processing algorithms, seismic attributes analysis and statistical evaluation of borehole seismic data. The developed concept and methodology need not be limited to quality control of borehole seismic data only. It is expected that the principles developed during this work will equally

apply to QC other wireline logs, logging while drilling datasets and fibre-optic distributed acoustic sensing (DAS) in real time.

The combination of QCAT approaches and quality control indicators are designed to be independent of personnel expertise and other externalities which currently affect the effectiveness of present quality control systems. The QCAT results also enable clients to make decisions based on empirical metrics in order to minimise the drilling rig time losses and potentially lost revenue and opportunity.

Acknowledgments

Firstly, I would like to thank my supervisors, Professor Milovan Urosevic and Dr. J. Christian Dupuis, who helped in refining my objectives, their encouragement and provided technical support.

Special thanks extend to Mary and Collin Humphries for the very kind provision VSProwess software (UK) for data processing, along with their rescue emails and remote technical support. Many thanks to I. Ambrosimov, S. Byriak from Deco Geophysical (Russia) for providing RadExPro software, I.V. Tishchenko from GSD Ltd. (Russia) for SeisWin-QC software, Schlumberger for VISTA software to QC and process borehole seismic data.

I would like to thank the sponsor of this project, ASTO Geophysical Consulting Pty. Ltd. (Perth, Australia) for research sponsorship, and use of company computational resources. Thanks to Dr. Alexei Shevchenko (PetroTrace Chief Scientist, Russia) who has helped with VSP QC software development, in various applications of geophysics and statistics. Thanks to Avalon (UK), JSC GITAS (Russia), PAO NPP VNIIGIS (Russia), Petrofiber (Russia), Sercel Borehole Seismic Division (France), and Schlumberger borehole seismic equipment manufacturer, the Department of Mines and Petroleum (Perth, Australia) and numerous Oil & Gas Mining companies for the provision of raw data.

Content

List of Figures

List of Tables

1 Introduction

A record of one or more physical measurements as a function of depth in a borehole is called a geophysical well log (Sheriff, 1990). Geophysical well logging is necessary because geological sampling (cuttings, cores) obtained during drilling leaves a very inaccurate description of the formation encountered. Geophysical logging technology has become a multi-billion dollars industry that employs many people in the energy sector and in scientific organisations. Geophysical measurements in boreholes are widely used in the petroleum industry for structural, stratigraphic characterisation and fluid monitoring and are also used in civil engineering and scientific geophysical research activities.

Wireline geophysical logs are recorded using downhole sensors deployed on a cable when the drilling tools are no longer in use. In well logging, there is one important geophysical method that measures velocity as a function of depth. It involves deploying a probe into a borehole and recording energy from a seismic source on the surface. This method is called vertical seismic profiling (VSP). VSP provides a time-to-depth link between surface seismic measurements recorded in time and the wireline logs (resistivity, pressure, saturation, nuclear, acoustic, density, ect.) recorded with respect to depth. VSP measurements include additional important information such as direct measurements of seismic fields and characterisation of elastic and anelastic rock properties and anisotropy parameters for the rock mass around the borehole. These measurements are used to validate and calibrate surface seismic processing and interpretation results. A schematic view of different VSP acquisition scenarios including a Zero Offset, Offset, Walkaway, Deviated-Well and 3D VSP is shown in Figure 1. It is worth mentioning other VSP acquisition scenarios including check-shot, Walkaround, AVO-Walkaway, reverse VSP, Drill Bit and Seismic While Drilling.

VSP and sonic measurements can provide velocity information in a borehole. In many cases VSP has the advantages over the sonic measurements due to missing near surface intervals in logging programs, poor quality of sonic data (bad cement bonding, washouts, tool noise and malfunctions), anisotropy effect in deviated wells and sonic / seismic frequency dispersion affecting accuracy of seismic well tie.

Quality Control or QC is a set of procedures that are intended to ensure that the provided product has the set of quality criteria and successfully meets the client's or customer's requirement. Today, quality control and evaluation of borehole seismic data and logs is done by seismic acquisition specialists, field engineers and a real time (RT) support person from the service company or a client witness. The assessment is done by visual inspection of the data as it is collected, analysis of the computed quality control plots, evaluation of seismic attributes and relies to a great extent on the experience of the observer. There are a limited number of automated quality control systems. The performance of the RT support personnel depends on externalities such as level of personnel expertise, internet connection speed and reliability of the software/hardware used. The current industry standard affects the data quality, increase acquisition time and rig-time and ultimately leads to lost opportunity and revenue for the client.

This was the motivation for my research that aims to evaluate, develop, optimise and implement Quality Control and Quality Assurance Technology (QCAT), frameworks and methods to assure an efficient and cost effective approach to borehole seismic surveys. The approaches I am proposing are based on a deep understanding of VSP acquisition, processing, interpretation and use statistics for credibility and usefulness of analysed information. A software solution can provide cost effective, valuable and comprehensive quality control metrics for the clients and service companies to use in order to refine their acquisition methods. These quality control elements will also enable the client to manage risk and make sound decisions based on empirical evidence.

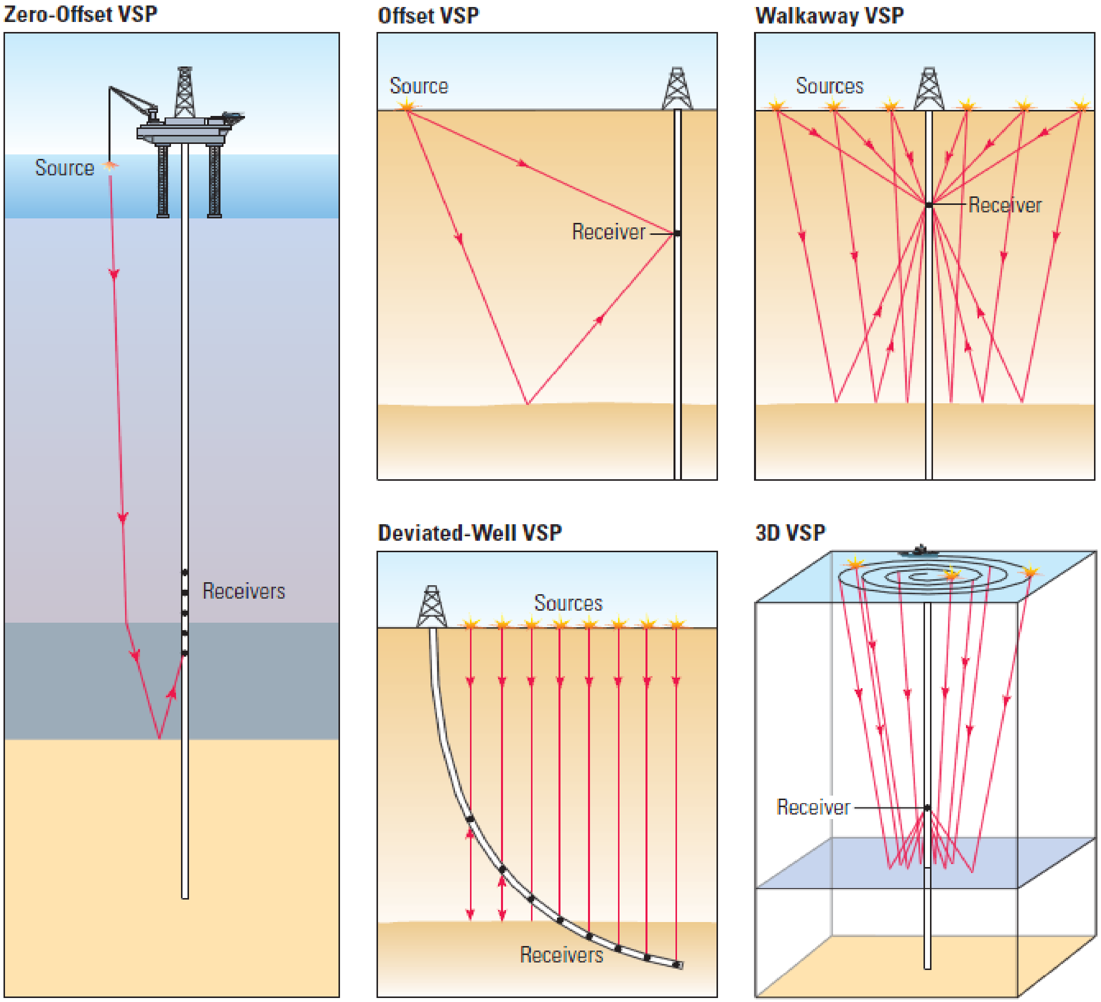


Figure 1. VSP acquisition scenarios (OFR 2003, Schlumberger).

1.1 Research Objectives

The main objective of this work is to develop methodologies, algorithms, workflows and an automated expert system for comprehensive and efficient QCAT evaluation of borehole seismic data. The proposed technology called, “Borehole Evaluation Seismic Tool for Quality Control” (BESTQC) uses signal processing algorithms, seismic attributes analysis and statistical evaluation of borehole seismic data.

The research objectives for improvement and enhancement of borehole seismic services are to

- Characterise the performance of existing acquisition systems
- Detect operational problems
- Assist field engineers to acquire superior data quality in real time
- Provide detailed data quality inputs for field reports
- Inform clients and service providers about any data quality issues
- Reduce acquisition time and rig time losses
- Improve VSP acquisition for better efficiency and higher quality assurance

The purpose of BESTQC technology is to give Oil & Gas & Mining operators or their delegates an indication of borehole seismic data quality. This allows fast and simple assessment of the survey progress and it will be used to:

- Learn about sources of seismic noise within a data set
- Evaluate VSP data quality using signal processing and seismic attributes analysis

- Compute comprehensive Quality Control indicators using statistical approaches
- Evaluate acquisition efficiency using Operation Timing Analysis

The developed concept and methodology need not be limited to quality control of borehole seismic data only. I expect that the principles developed during this work will equally apply to QC other wireline logs and logging while drilling datasets in real time.

1.2 Background

The first well logs that were recorded eighty years ago had no provision for data quality control (Theys, 1991). The development of increasingly sophisticated logging techniques has led to the introduction of a large number of tests to validate acquired data. A comprehensive introduction to borehole measurements quality control has been published by Theys in 1991.

These days borehole seismic data quality can be assured by stringent control of depth, calibrations, signal processing and operating procedures. Undoubtedly an understanding of borehole seismic acquisition, the performance of rigorous quality checks of acquisition systems, survey parameters and compliance with standard operation procedures are the prerequisites for an accurate evaluation of a geological formation and reservoir properties. However the correct and valid interpretation of the recorded borehole seismic information depends on accuracy, precision, limitation of errors of inputs, the uncertainty of the measurements and must be based on modern Quality Control and Quality Assurance Technology (QCAT) applied in real-time. Unfortunately the current QCAT procedures are outdated, limited and based on service provider in-house expertise, practices and do not satisfy the high quality control standards required by a client.

I have undertaken an extensive search to assess the current state of QCAT using publically available borehole seismic acquisition and processing reports from major VSP contractors (Schlumberger, Baker Hughes VSFusion, Halliburton and Weatherford). I have also discussed at length with VSP hardware manufactures (Avalon, GITAS, OYO, PetroGeoService, Sercel, and Schlumberger) and petroleum operators (Apache, BP, Chevron, Gazprom, ENI, LukOil, Rosneft, Santos, Shell, and Woodside). I have also read articles published in geophysical journals. The field acquisition reports used for the assessment of the technology can be found at Geoscience Australia (www.geoscience.gov.au) and the Department of Mines and Petroleum (www.dmp.wa.gov.au). Some information was published and presented at ASEG (www.publish.csiro.au/nid/224.htm), SEG (www.seg.org), EAGE (www.eage.org), Galperin's Reading (www.geovers.com), the geophysical conferences, Curtin University Exploration Geophysics publications, CREWES (www.crewes.org) and other research reports.

After numerous discussions at geophysical conferences (ASGE, EAGE, EAGO, SEG, SPE), workshops and through personal communications with seismic experts from major operators, servicing companies, consultants and research scientists, I have come to the conclusion that QCAT procedures are limited, basic and in some cases do not comply with the modern quality control requirements of most clients. This is generally because these issues are seen to have lower priorities and thus lack funding for development and engineering of comprehensive QCAT applications.

1.3 Why is quality control important?

Borehole seismic data is acquired by using the dedicated surface and downhole equipment as shown in Figure 2. The acquisition equipment must pass the internal and external quality control checks before and after a job to ensure that the high quality data is recorded. The proposed quality control approach is important for following reasons.

First, it will lead to an improvement in geophysical quality control methodology for assessing borehole seismic data quality. It will lead to a greater understanding of the factors that impact the service and data quality and hence contribute to more comprehensive and meaningful analysis during field acquisition and post-mortem analysis.

Second, it will have implications for improvement and development of best field acquisition recording practices by highlighting data quality issues that are related to hardware limitations and possibly to highlight some areas for development of the crews.

Third, it will contribute to the improvement of VSP acquisition efficiency and assure higher data quality.

The fourth area of significant contribution is the evaluation of acquisition efficiency using Operation Timing Analysis which could be benchmarked against the best practice results.

Fifth, the research activities used in the study are focused on gaining detailed qualitative and quantitative inputs for reporting and to inform a client and a service provider about any data quality issues during the acquisition phase such that the survey can be modified to ensure best data quality.

Finally, the combination of QCAT approaches and quality control indicators are designed to be independent of personnel expertise and other externalities which currently affect the effectiveness of present quality control systems. The QCAT results will enable clients to make decisions based on empirical metrics in order to minimise the drilling rig time losses and potentially lost revenue and opportunity.

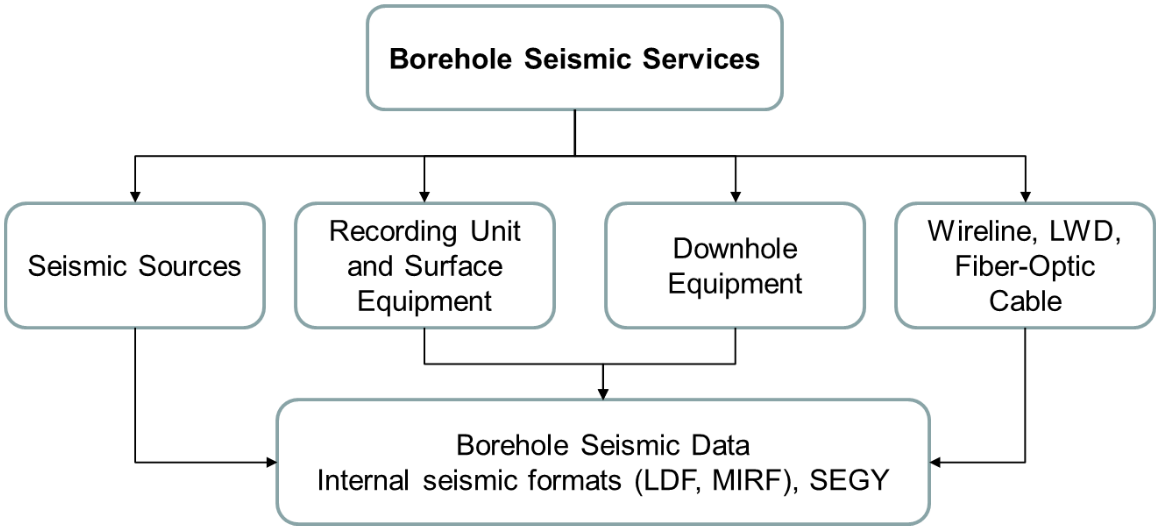


Figure 2. Borehole seismic acquisition components.

1.4 Borehole Seismic Field Procedures and Breakdown Time

Below is a real example of VSP operation procedures. The procedures are documented after every VSP project by a field specialist and provided to the client. Table 1 summarises the operation procedures usually conducted during VSP acquisition.

The VSP operation breakdown time is presented in Figure 3 for one Australian offshore VSP project in 2008. Based on the cumulative time curve, it is possible to evaluate the efficiency of VSP acquisition. Obviously any measurement must be benchmarked. Figure 4 shows a comparison of the acquisition time for two VSP contractors. The operation statistics derived from eight VSP acquisition projects completed for one operator by two VSP logging contractors over the depth interval 1600-3600 m. The information source is VSP acquisition reports available in the Department Mines and Petroleum – DWAMP (www.dmp.wa.gov.au). It is evident that the contractor B is more efficient than the contractor A. Each contractor has own winch, the different operation procedures, the experienced/unexperienced field engineers and it leads to the variation of acquisition time. The common parameters here are the same logging depth from 1600-3600m and 15m spacing between the sondes.

Operation Procedure	Procedure Description
Rig Up	Assemble VSP downhole hardware at Rig Floor
In situ tool check	Acquisition system check in a borehole
Run In Hole (RIH)	Deployment and descending at a bottom of well
Downgoing QC Shots	QC shooting to evaluate the performance
GR Correlation	Depth correlation using the Gamma Ray log
VSP Survey Levels	Recording VSP data (main process)
Checkshot QC levels	Recording Checkshot data (main process)
POOH	Pull Out Of Hole

Rig Down	Disassemble VSP equipment at Rig Floor

Table 1. VSP operation time mnemonics and procedure description.

The total VSP acquisition time is a sum of individual acquisition procedures. Lost time is a difference between total VSP time and planned time. The planned time is the median operation time value from eight wells. It becomes evident that the actual Survey Level operation time and Total Operating time are significantly longer than the planned ones. A median difference between the planned and the actual Survey Level Time is 1:15 hrs. per well (Figure 5).

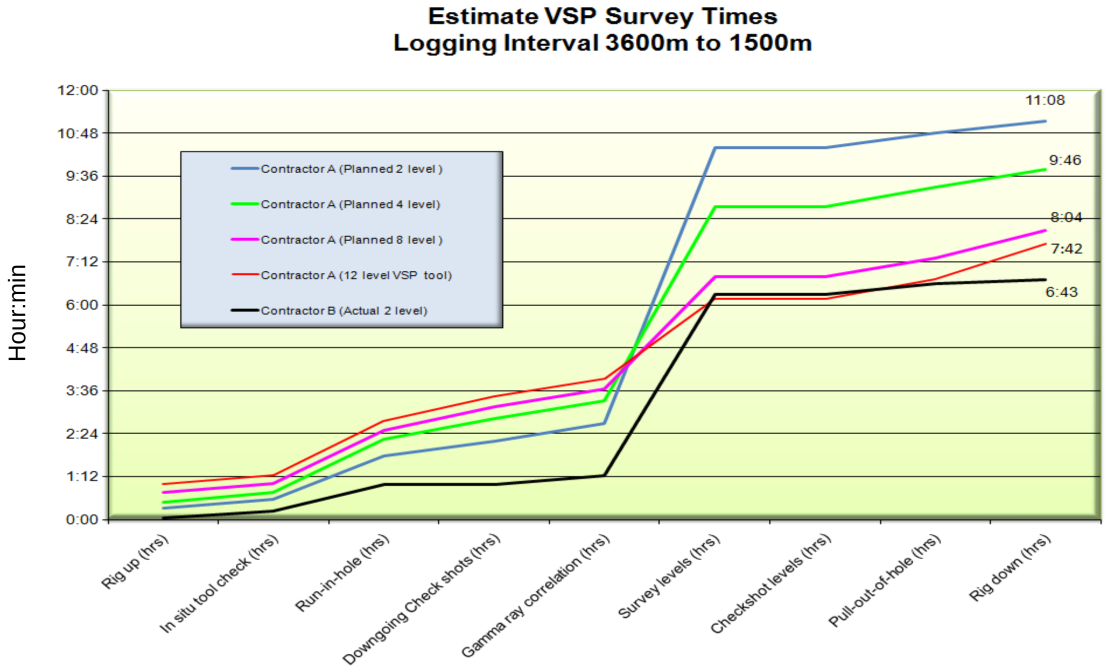


Figure 3. The VSP operation time statistics. Source DWAMP.

That translates to a significant loss in revenues. Operators pay a high daily rate for operations; a deep-water drilling rig is between $500,000 to $550,000 in 2011. According to ODS-Petrodata (www.ods-petrodata.com/odsp/day_rate_index.php) that is up from a day rate of $450,000 to $500,000 a year ago and more than double the price per day on the spot market just three years ago. Note that the standby cost for an offshore drilling rig in Australia including the daily rate is between

$30-40k per hour or $1M for 24 hours in average. The estimated median total lost time of 3:42 hrs. (Figure 6) is equivalent of US$110k per well. In total rig time losses, the cost for eight offshore exploration wells is estimated at US$880k. There were 31 exploration wells drilled in offshore Australia with every well having a VSP survey in 2008. The author estimates that the drilling rig time losses for all 31 offshore wells could potentially cost a $3.41M to Australian and International operators. In 2010 approximately sixty offshore exploration wells were drilled with the potential cost of up to US$6.6M. Major contributions to those losses were due to longer acquisition time, delays caused by hardware malfunctions, slow survey level acquisition process and more time spent analysing data than expected.

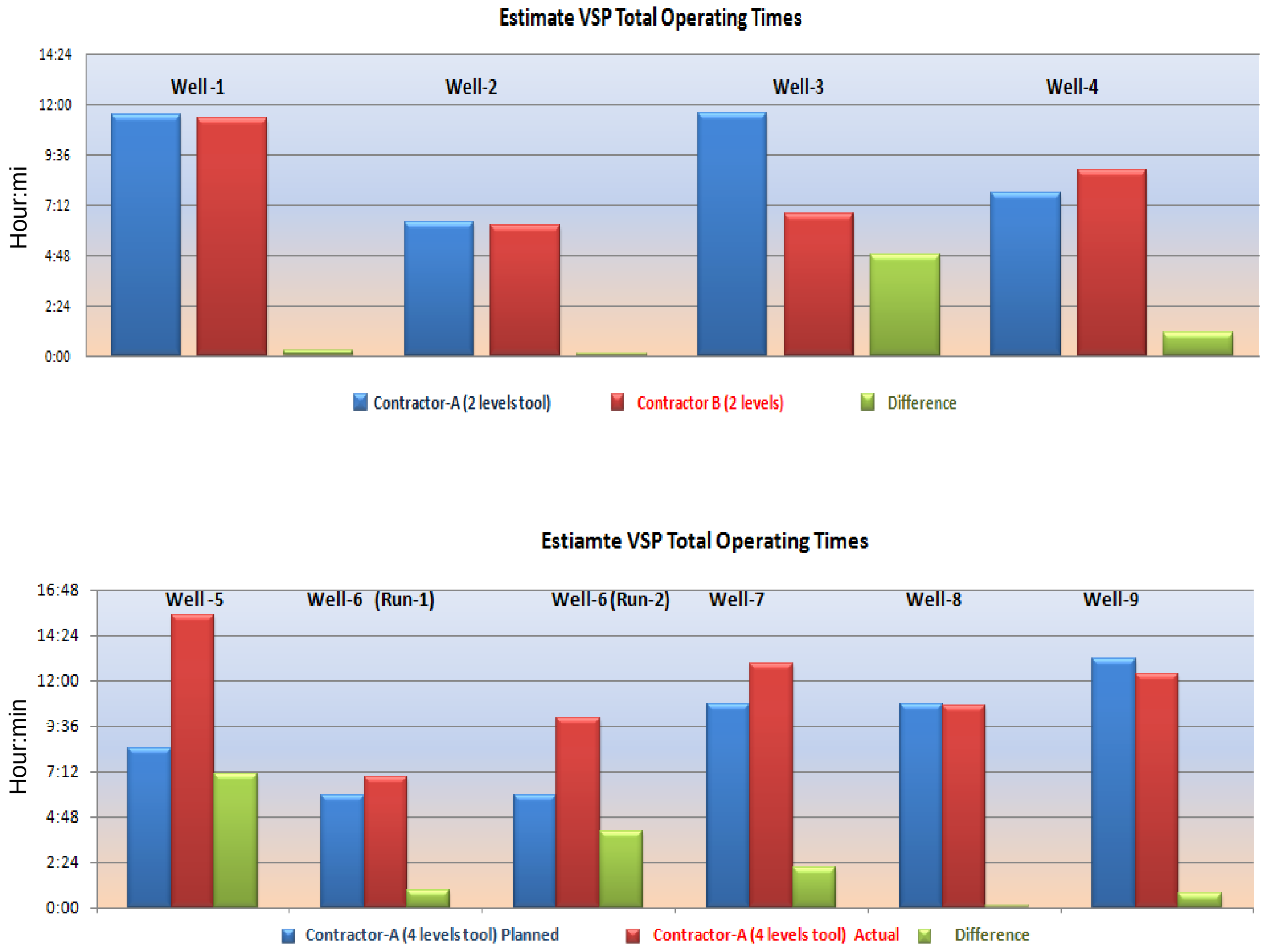


Figure 4. The VSP Operating Times. Source DWAMP.

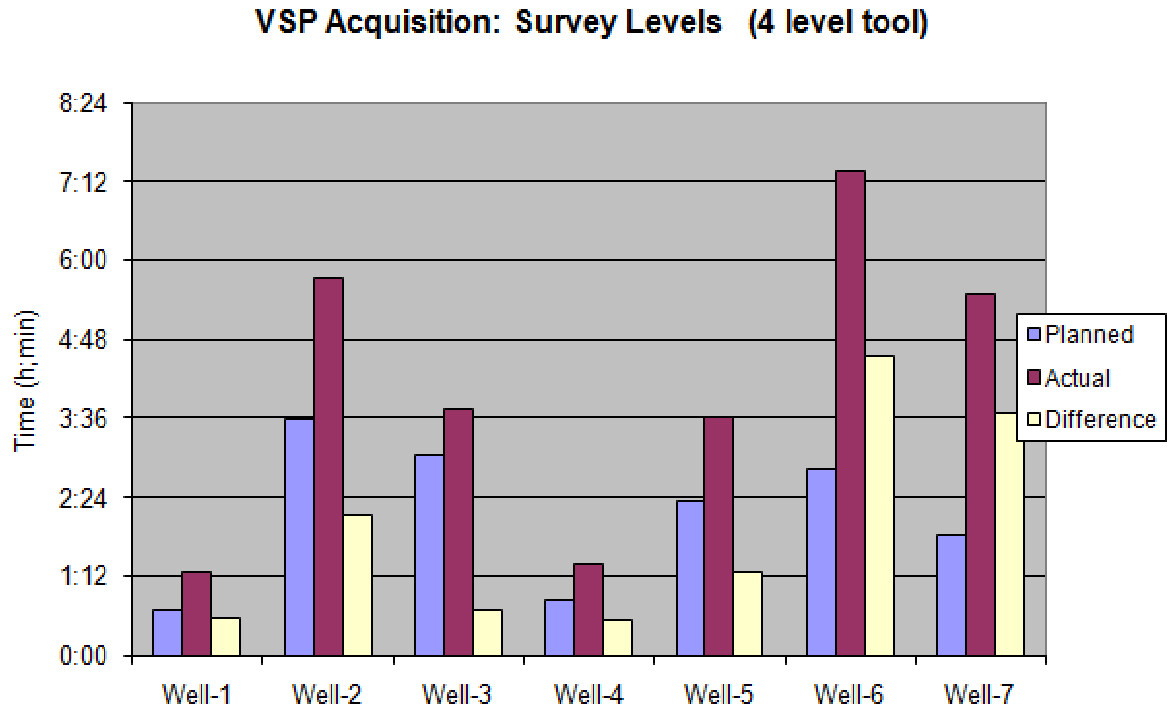


Figure 5. VSP Operation time related to Survey Level procedures only. Source DWAMP.

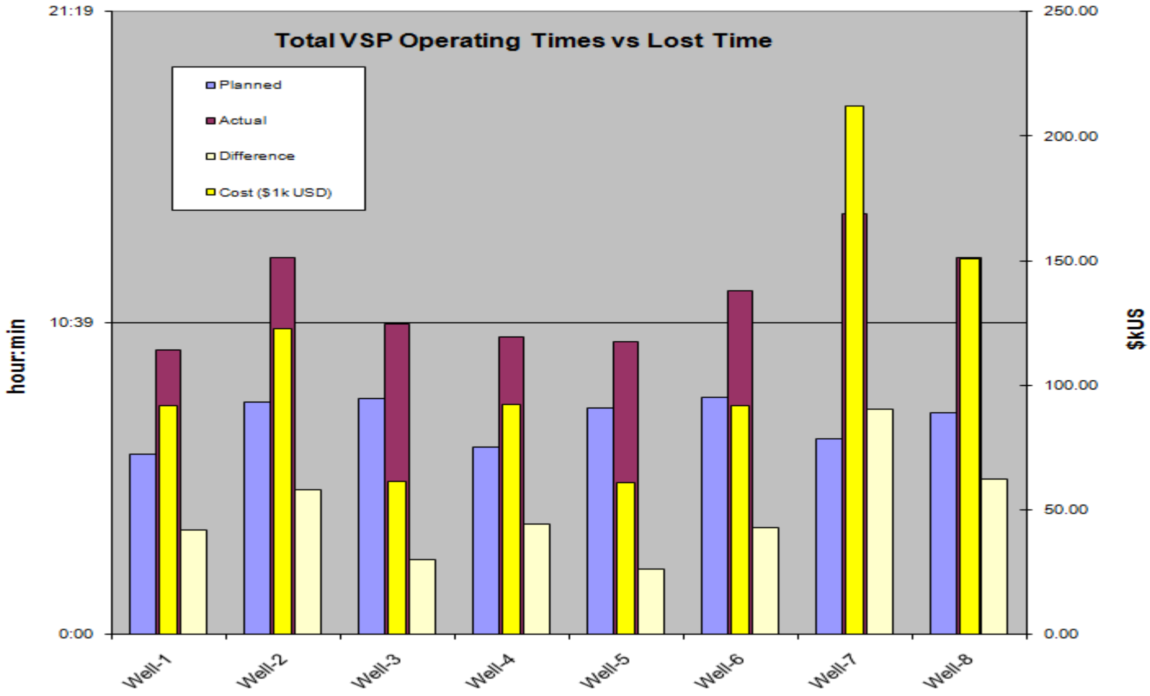


Figure 6. Total VSP Operating time versus Lost Time. Source DWAMP.

1.5 Data Quality Overview

Comprehensive research has been carried out into current quality control practices. A few publications related to surface seismic quality control were reviewed as well (Hoover 2006, Lansley 2006, Tishenko et al., 2010, Krylov 2016). This was followed by extensive discussions with industry experts from major servicing companies (Baker Hughes VSFusion, Halliburton, Schlumberger, Weatherford) and discussions with the VSP hardware manufactures (Avalon, GITAS, OYO, PetroGeoService, Sercel, Schlumberger) and the petroleum operators (Apache, BP, Chevron, Gazprom, ENI, Impex, Rosneft, Santos, Shell, Woodside). Based on the conducted evaluation the current VSP quality control practices are summarised and listed in Table 2.

Item	VSP Service Quality Procedures	Methods
1	Consistent and defined surface signal	Visual QC. QC plots
2	Clean 1st Break and consistent time break	Visual QC of X,Y,Z QC plots
3	Good body wave. No tube wave. No ringing	Visual QC of X,Y,Z QC plots
4	Signal Not saturated. Not Weak.	Visual QC of X,Y,Z QC plots
5	Good coupling, No Noise	Visual QC. Shaker QC plots
6	Signals agree with expected sensor response	Visual QC of X,Y,Z QC plots
7	Shots with good Signal/Noise ratio	Visual QC of X,Y,Z QC plots
8	Accurate Geometry of source and receiver	Visual QC geometry parameters
9	Low Noise Level	Visual QC using X,Y,Z QC plots
10	Signal Quality and Arrival Times	Amplitude and Times QC plots
11	P-wave upgoing waves	Visual QC using reflection waves
12	Signal Data Quality Evaluation	Visual QC using QC plots
13	Acquisition report	Acquisition report with QC plots

Table 2. The current quality control practices.

Based on the information shown in Table 2 and VSP operation time analysis (Figure 3 - Figure 6) the research results indicate about

- Significant difference in VSP acquisition time between various contractors
- Significant variations between planned and actual VSP acquisition time
- Often longer than necessary VSP acquisition time

- Only visual assessment and control of data quality
- Limited control procedures to evaluate the data quality in real time
- The majority of VSP acquisition vendors do not compute QC data from recording systems as it is done by surface seismic companies. For example, surface seismic QC data from recording systems are stored in two types of data files ADS-TA (Trace attributes) and ADS-TE (Trace edit). ADS-TA and ADS-TE files are intended as adjuncts to primary data storage files such as SEG-D, SEG-SPS, UKOOA P1/90, SEG-P1.
- ADS-TA (Trace attributes) contains: Source files with identifier info, date and time, good/bad flag, source info, ambient and coherent noise info. Receiver files with identifier, resistance, tilt, leakage, rms signal, rms ambient noise, first break pick time, first break amplitude, frequency info. Entity files with vibrator info, airgun info, streamer depth and heading sensors, tailbuoys, etc.
- ADS-TE (Trace edit) contains identification, traces excluded and included when and by whom, attribute(s) used

Proposed quality control approaches are based on the first arrivals and RMS amplitudes of raw repeat shots, signal-to-noise evaluation of stacked data, statistical data analysis and field operation timing analysis derived from the VSP data.

Note that signal processing, noise estimation and attributes analysis are widely used in the geophysical industry. They are used to some extent to evaluate the VSP data quality in real time and after the acquisition. The author proposes to use these results and analyse them using the statistical process control (SPC).

Statistical process control (SPC) is defined as “a method of quality control which employs statistical methods to monitor and control a process. This helps to ensure that the process operates efficiently, producing more specification-conforming products with less waste (rework or scrap). SPC can be applied to any process where the "conforming product" (product meeting specifications) output can be measured. Key tools used in SPC include run charts, control charts, a focus on continuous improvement, and the design of experiments” (Wikipedia).

1.6 Proposed Research Strategy

A proposed research strategy includes the following:

- Collect VSP acquisition system information (downhole tools, registration systems, seismic sources)
- Access to the released VSP data from the manufactures (Avalon, GITAS, PetroGeoService, Sercel, Schlumberger) and the service providers (Baker Hughes VSFusion, Halliburton, Schlumberger, Weatherford) and the operators (Apache, BP, Chevron, ConocoPhillips, ENI, Shell, etc.)
  - Offshore VSP with Airgun
  - Land VSP with Airgun, Dynamite, Vibroseis, Weight Drop
- Learn about sources of seismic noise within the provided data sets
- Perform signal, noise processing and statistical analysis using:
  - VSP processing packages (VSProwess, RadExProVSP, VISTA, ASTO)
  - Arrival Times, Amplitudes, Seismic attributes
  - Statistics in Excel, Matlab, etc.
- Define QC flag – Green (excellent data), Yellow (fair data), Red (bad data) using the computed SPC statistics
- Develop prototype VSP QC software

2. Borehole Seismic Acquisition Systems

All modern borehole seismic acquisition systems consist of the downhole and the surface equipment. The downhole equipment is made of multiple modules (tools or sondes) containing three component geophones/accelerometers, an analog-to-digital convertor (ADC) and a digital telemetry inside each of them. A downhole sonde with a 3C sensor package uses a clamping / anchoring arm for good coupling between the geophones and the borehole wall. The borehole seismic acquisition systems with hydrophones receivers are not considered for analysis in this thesis due to the limited applications and tube wave noise contamination (Greenwood et al. 2011, Van Zaanen et al. 2017). The surface equipment includes a recording unit, a digital telemetry interface box controlling of the tool operational modes as data transmitted uphole via a 1, 3, 4, 7 wire logging cable. Special channels are used for digital recording of surface reference signals. The acquisition software provides interaction with all system parts, testing functions and operation parameters of borehole modules, controlling all steps of data acquisition process, QC, data pre-processing and data reformatting from the internal formats into SEG-Y format. The parameters of the wireline borehole seismic acquisition system from various manufactures are listed in Table 3.

Unfortunately there are not many published references comparing borehole seismic acquisition systems made by different tool manufactures and service providers. A number of key wireline borehole seismic acquisition system findings to date are highlighted here:

<u>Similarity</u>

1. Omni-tilted 3 component (X, Y, Z) geophones
2. Sampling interval 0.25; 0.5; 1.0; 2.0; 4.0 msec and a recorded frequency band 2-500 Hz
3. Waveform digitisation at the sensor package with dynamic range up to 120 dB
4. High-temperature tools up to 150-175 degC
5. High pressure tool up to 25-30 kpsi

6. Conventional size tools (3-4”) and light, slim-hole tools (11 kg, 2 4”)
7. Anchoring force for high vector fidelity and low tube wave noise (a force ratio 10:1)
8. Min / Max borehole diameter 59 / 400 mm
9. Combinability with GR, tractor, pressure testing and other wireline tools
10. Wireline tractor, pipe and thru drill string conveyance in a highly deviated well
11. Downhole testability (X-talk, Noise, Gain, Etc.)
12. Real time QC plots for visualisation by a field specialist

<u>Difference</u>

1. A number of tools varies from 32, 40, 120 (GITAS, SLB, Sercel GeoWave-II) up to 1000 3C levels (Paulsson OpticSeis)
2. High-temperature tools from 175 degC (SLB VSI, GITAS AMC), 205 degC (Sercel GeoWave-II) up to 320 degC (Paulsson OpticSeis)
3. Downhole accelerometers from Schlumberger verses geophones from other vendors
4. Background noise level is 100 nV (Sercel SlimWave) and 30 nV (GITAS AMC)
5. An analog-digital convertor is 24 bit (in the most of tools) and 32 bit (GITAS AMC)
6. Mechanical (25-45 sec per 4 shuttles) and magnetic anchoring (0.3 sec in GITAS AMC)
7. An isolated sensor package (SLB VSI) versus monolith tools from other vendors
8. A shaker package for tool coupling evaluation (SLB VSI)
9. Oriented 3C accelerometers (SLB VSI), 3C geophones (Avalon Slimwave) versus non-oriented tools from other vendors
10. A single geophone per X, Y, Z component versus Dual, Quadro geophones (Avalon GeoChain, Sercel GeoWave)

Common Acquisition Hardware & Tool Problems

- Geophones/ accelerometers damage and failure
- Instrumental noise (cross-talk noise)
- 50, 60 Hz harmonic noise from a telemetry cartridge
- Amplifier gain problem
- Low (poor insulation) and high background noise (failure of an acquisition card)
- Cable head leakage, tangled interspace cables
- Anchoring mechanism failure

All borehole seismic acquisition systems include built-in quality control evaluation tests before and after the field work and summarised in a filed report. Those evaluation tests includes following

- Electrical noise low/ high
- Electrical distortion
- System dynamic range
- Amplifier gain
- Crosstalk X, Y, Z
- Impulse response

It is worth mentioning the success of deploying of fibre-optic distributed acoustic sensing (DAS) technology for standard VSP operations, hydraulic fracturing and reservoir monitoring as permanent and retrievable sensors.

Many servicing companies such as Baker Hughes (USA), Halliburton (USA), PetroFiber (Russia), OptaSense (UK), Schlumberger (USA), Silixa (UK) produce a wide range of DAS systems with the temperature 350°C and the pressure 30,000 psi, including one-component distributed acoustic sensors and uphole digitisation by an interrogator unit. Tubing conveyed DAS designed according to completion specifications, allow safe installation, namely in highly deviated production / injector wells. Therefore, it can be installed simultaneously on the treatment well completion representing only a marginal cost of the whole installation. An encased DAS inside of a wireline cable (Hardog A., 2014) allows the Zero Offset VSP data to be recorded in a 5 km borehole with 10m spacing during 6 minutes instead of 20 hours using the standard wireline 3C geophones.

Unfortunately a DAS cable is not installed in every borehole for a number of reasons:

- complexity with DAS deployment remains a challenge to operators
- novel technology which requires additional CAPEX
- a high level of investment in big data infrastructure with powerful PC, efficient processing software and storage capacity
- competition from the conventional 3C VSP technology
- low signal-to-noise ratio
- 1C measurements

Paramteres	READ	CGG	AVALON	OYO	SLB	GITAS
	Delta-8 Slim	SST-500	GeoChain 32	HDSeis / DS-325	VSI	AMC-VSP (MSAT)
	3.62(shuttle)	3.62 (shuttle)	3.3 w nodes, 3 w/o nodes	3-1/4	3"3/8(85.7mm), 2"1/2(63.5mm) slim	2" (48mm)
Diameter (inch)	1.2(shuttle)	0.81(shuttle)	0.884	1.11	2.9	1.23
Length (m)	180	150	180	150	150, 175	150, 175
Temp (degC)	17.0	20.0	20.0	15.0	20, 25	80, 100 (Mpa) or 14.5 (kpsi)
Pressure (kpsi)		4.00	3-1/2	4.50	3 1/2 (88.9mm)	2"1/4 (50mm)
min HD (inch)		16.1	13 (22 w large arm)	12 w extension arm	22 (558.8mm) extension arm	12 w extension arm
max HD (inch)	up to 8	up to 12	up to 32	up to 32	up to 40	up to 32 and more (memory storage)
Array	20.0	10 m standard	min 1 m , max 75 m	min 2 m max 15 m	min 2.5 m max 30 m	min 2 m max 30 m
Spacing (meter)	hepta	Hyd-Hepta	Hepta 7-H-422K	26c	Hepta 7	26c
Inter-connecting cable		less than 90 seconds 12 units at 7 inch hole	open 30 in 9 5/8 CSG simultaneously for all shuttles.	17 seconds open & anchor @ 5 inch	XX seconds open & anchor @ 5 inch	XX seconds open & anchor @ 5 inch
Full arm Open/Anchor time (second)	60kg including 20m cable	33 lbs	38 lbs	72 lbs	70 lbs (32 kg)	23 lbs (11kg)
Sensor ppackage weight	50 kg	330 lbs (hydraulic clamping mechanisms with single arms)	200 lbs max.(mechanical)		63.9 ± 11.0 lbf mechanical	63.9 ± 11.0 lbf mechanical
Clamping force	1.5?	10.0	5.0	10.0	10.0	11.0
Force to weight ratio		Good	Good	Good	Very good	Very Good
Horizontal coupling	SM4 10Hz 3C Gimbal	OYO SMC1850 10Hz Fixed or gimbal mounted orthogonal 3C	SM4HT 10Hz, 3 component gimballed package or fixed 3C	3-axis Orthogonal OYO-SMC-1850 15Hz omni-directional	3-axis Orthogonal OYO 20Hz omni-directional	3-axis Orthogonal OYO-SMC-1850 15Hz omni-directional
Geophone		Fitted as stnadrad in all HSU	No	Optional 4C	NO	TBC
Hydrophone		> 500Hz	10-290Hz SM4V w standard arm, 10-260Hz SM4H w. standard arm, 10-500Hz fixed SM4V w short arm	> 650 Hz	~380 Hz (1msec), 780Hz (0.5msec)	> 2000 Hz fpr 1/8 ms sampling
Bandwitdh		1/4. 1/2, 1, 2 ms	0.5 ms - 4 shuttles, 1.0 ms - 8 shuttles, 2.0 ms - 16 shuttles, 3.0 ms - 24 shuttles, 4.0 mse - 32 shuttles	1/8, 1/4, 1/2, 1, 2 ms	1/2, 1, 2, 4 ms	1/8, 1/4, 1/2, 1, 2, 4 ms
Sampling Rate		24 bit Delta Sigma	24bit Delta-Sigma	24 bit Sigma-Delta	24 bit	32 bit Sigma-Delta
Downhole ADC (# Bit)		> 110 dB		106 dB@ 1/4 ms, 24dB gain	105 dB@ 1 ms, 36dB gain	150 dB@ 1 ms, 24dB gain
Dynamic Range		TBC		TBC	TBC	0.06-0.1mkV
Background noise		Pulse test geophone pulse test amplifiers	Pulse testing of all elements	System Diagnostic including EIN, THD, Gain and Sensor Tests	System Diagnostic including EIN, THD, Gain and Sensor Tests	System Diagnostic including EIN, THD, Gain and Sensor Tests
Insitu Test (calibration)		Record length + 2 seconds	Recording length + 1 secpnd		10sec	10 sec
Interval between shot			32 sec (could be easily extended if required)		Yes	AMC-8 Record Time (1sec - 41%)
Continous Recording	GR	w GR ?	GR (GRT-1) or CCL	CCL	GR+CasingCollarLocation	GR+CasingCollarLocation
Combination	Hepta	Hepta	Hepta	Fibre Optic	Hepta	1C,3C,7C
Logging cable						

Table 3. The parameters of borehole seismic acquisition systems.

3. Borehole Seismic Sources

Borehole seismic checkshot, zero-offset, fixed-offset, vertical incidence, walkaway and 3D VSP surveys require a consistent, wide frequency and a strong seismic source. Predictable and efficient source performance improves data quality and speeds up project turnaround, as well as improving safety and minimising environmental impact. High pressure air guns, explosive shots, P, S vibroseis trucks and various weight drop sources have different power outputs, stability of the wavelet, frequency content and produce variable pattern of emitted wavefield, including coherent noises. A very important aspect of seismic sources is repeatability especially for 4D seismic and CO2 sequestration projects. There are published examples comparing various seismic sources (Meunier et al., 2008). A wide range of seismic source were used to acquire land 4D VSP data; it includes weight drop sources, MV vibroseis (6000 lbs), IVI Mini-Buggy vibroseis (16000lbs) and limited amount of explosive shots (Pevzner, et al., 2010).

Modern borehole seismic acquisition systems have the capability to interface with vibrator electronics, airgun, and explosives controllers and to record surface reference channels for quality control of seismic source performance. PC based airgun synchronisation controllers also record individual gun timing, sensor signals, near- and far-field hydrophones, gun pressure, and depth information. Land vibroseis P, S-wave source offers reliability and repeatability with increased signal-to-noise ratio due to a few vibrators working simultaneously and acquiring repeat shots as necessary. Explosive sources offer high-energy, broadband output. They are suitable for remote and land operations. Tuned airgun arrays are repeatable, reliable and widely used for a fixed offset land and marine VSP surveys. Airguns are the predominant source used in marine borehole seismic and a fixed offset VSP on land if vibroseis is not available.

There are a few examples highlighting importance of seismic source monitoring and compensation for source signature variations to improve data quality. The shown examples have been processed by the author.

Source changes could be due to numerous effects. Figure 7 shows the amplitude-frequency plots for ZVSP and Offset VSP recorded with a 5 level Avalon ASR tool with two vibrators during flip-flop operation (the tool was at the same depth) where poor performance one of source attributed to bad quality downhole data. Note significant variations of the amplitude spectrum during the OVSP survey at the depth 3126 m, 2006 m, 1516 m and 566 m. Unfortunately a reference geophone was not recorded during this survey despite the recommendations in a technical program. A reference geophone must be used for VSP with vibroseis. Examples provided show significant time /amplitude variations during vibroseis acquisition, hence requirement for a reference geophone.

Figure 8 shows an offshore ZVSP Z-axis wavefield recorded with a 4 level Schlumberger VSI tool with a 3x250 cu.inc airgun cluster and a Trisor-OFS in-sea gun controller. Note significant wavefield variations at the depth 1500-1400 m (Figure 8, left). The gun controller provides excellent reference signature which can be used to remove pressure variations in VSP processing. Source signature deconvolution using a reference geophone removed influence of the pressure drop and source signal shape changes (Figure 8, right).

Figure 9 shows a land ZVSP Z-axis wavefield recorded with a 4 level Schlumberger VSI tool with a 500 gram explosives and a SGD-SP controller. Note significant wavefield variations over the logging interval (Figure 9, left). The controller provides the reference signature which can be used to remove static and amplitude variations in VSP processing (Figure 9, right).

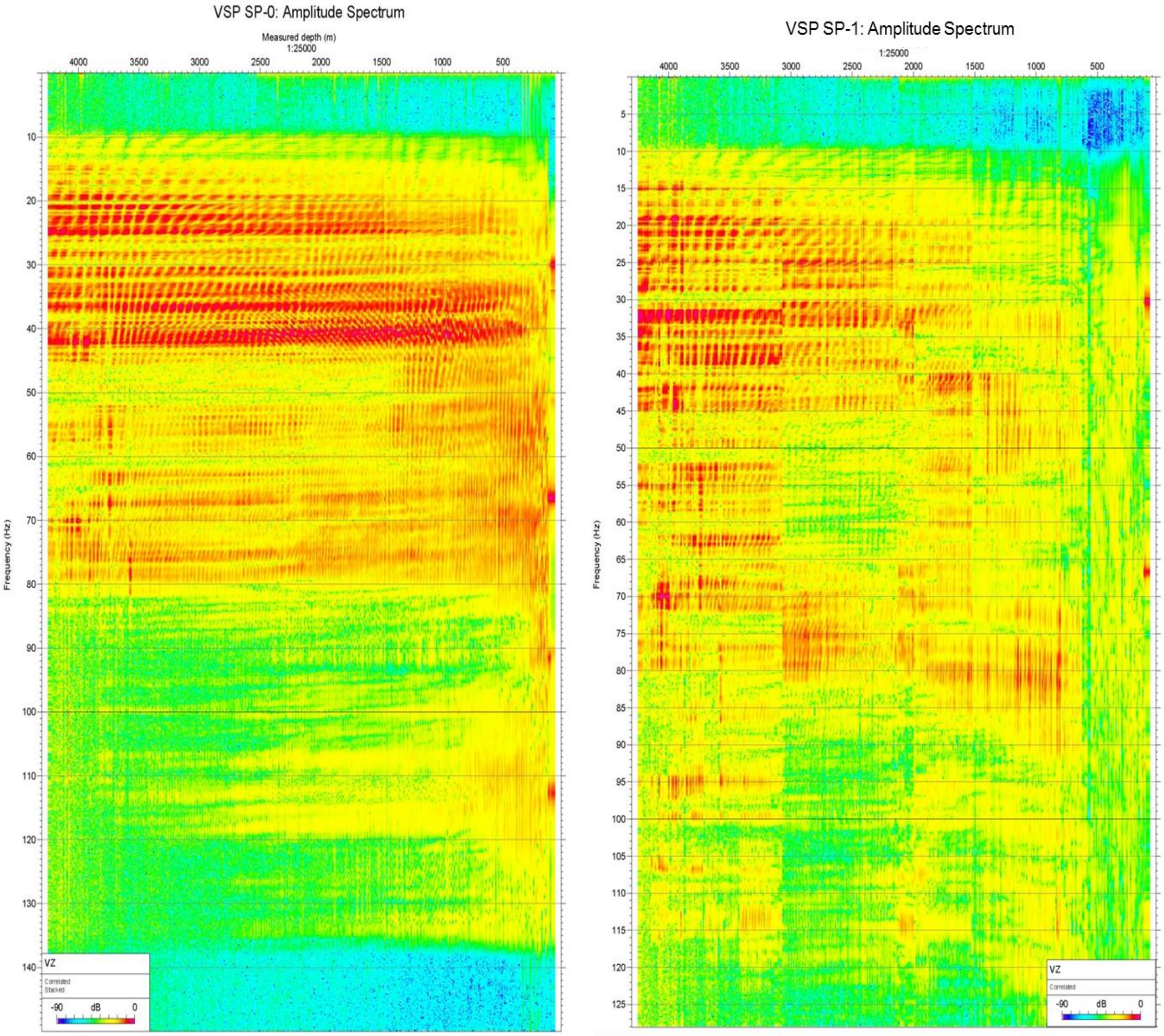


Figure 7. Amplitude Spectra for ZVSP SP-0 (left) and OVSP SP-1 (right) for flip-flop acquisition (Tcherkashnev S.).

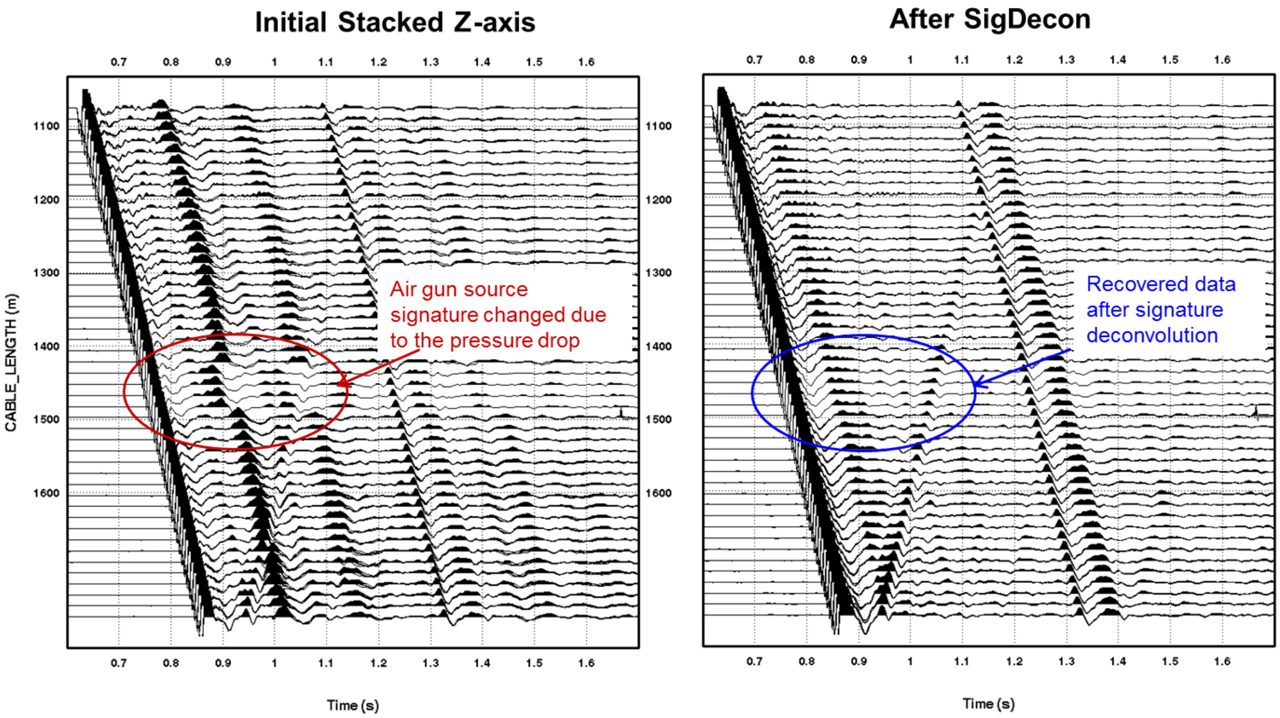


Figure 8. An offshore ZVSP Z-axis before (left) and after signature decon (right) using the reference hydrophone (Tcherkashnev S.).

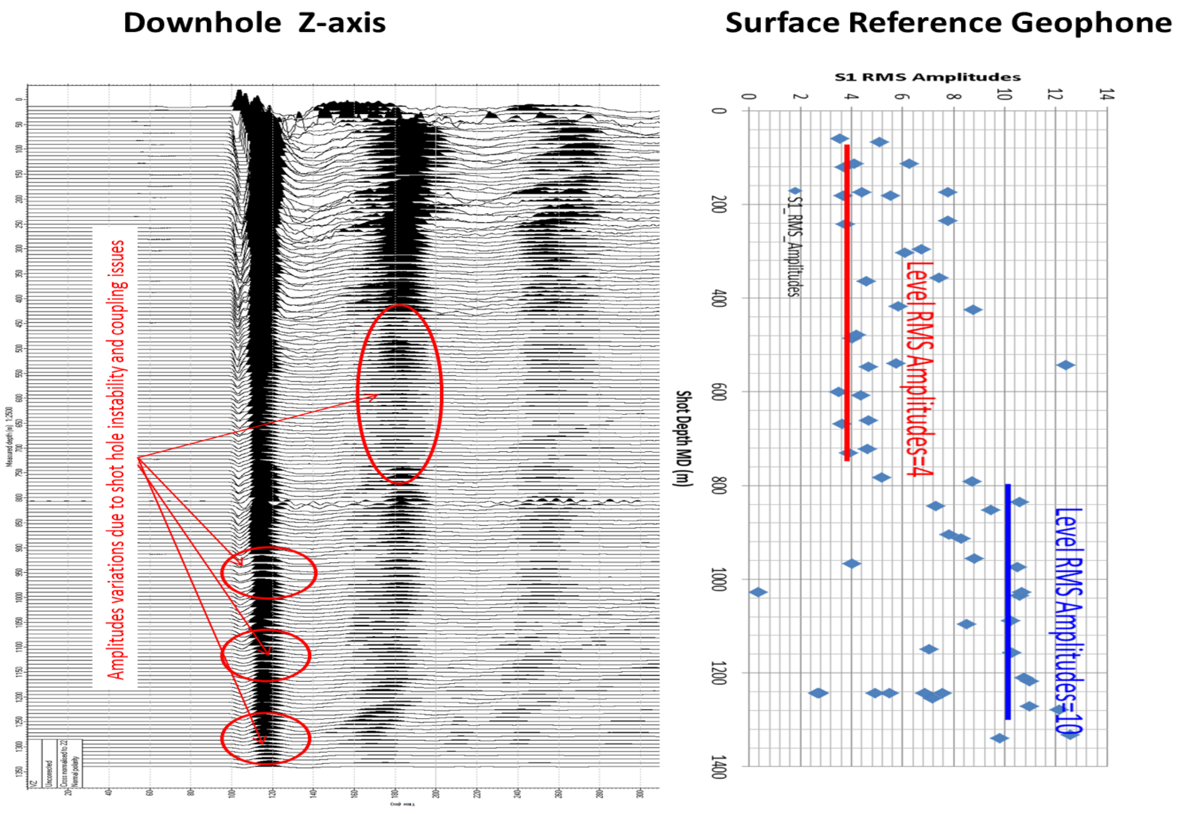


Figure 9. A land ZVSP Z-axis with dynamite (left) and the surface geophone RMS amplitudes (right) (Tcherkashnev S.).

4. Borehole Seismic Signal and Noise

A seismic signal is a combination of the direct, the reflected and diffracted P, S body waves. Seismic noise is usually the microseismic signals before the body wave arrivals. One of the main borehole data quality assessment objectives is to evaluate a level of signal, a level of noise and signal-to-noise ratio (SNR). There are a few approaches in estimating those attributes (Matlab signal processing library, Hatton et al., 1986, Beloysov 2012, Krylov 2016). The success of SNR improvement depends on understanding of the ways noise and seismic signals differ.

The noise can be classified as coherent and non-coherent. Repeatable noise is coherent noise. While ambient noise and instrumental self-noise noise could be non-coherent. Noise can be filtered out during processing with some success depending on a noise level and its nature. It is very important to know the characteristic of the noise before taking any actions.

Detected noises during borehole seismic survey are:

- Microseismic noise (natural seismicity)
- Casing ringing (poor cement, free casing)
- Tool ringing due to poor coupling (washouts, large hole, cable waves)
- Tube wave (hydro wave) due to close distance of a seismic source to a borehole
- Borehole noise caused by fluid movement, debris falling and logging cable movement
- Rig noise (mechanical, electrical), radio noise
- Seismic source generated
- A tool instrumental noise (mechanical, electrical)

5. Research Results

The borehole seismic results include the P and S-waves downgoing arrival times are used to compute accurate time-depth relation and velocities. It's important to evaluate the accuracy of time measurements and to quantify time variations.

The most common borehole seismic survey is a Zero Offset VSP survey. A ZVSP survey in a 3 km deep borehole includes downhole seismic recordings using a multilevel seismic tool fitted with three component geophones or accelerometers. Usually 3-5-7 repeat shots are taken at every tool position (10m - 15m depth interval) as per a VSP acquisition program provided by the client. It consists of 3000 downhole traces (3 axis * 5 repeat shots * 200 depth levels) with a 5 second record length and surface reference hydrophone/geophone traces for every shot. Figure 10 shows one set of the downhole repeat traces (X,Y,Z axis) before stacking and the vibroseis reference channels. Figure 11 shows Zero Offset VSP downhole traces (Z axis) after stacking five repeat shots and the amplitude spectrum. The repeat shots are recorded in order to improve the data quality during signal processing later on and for consistency representation of the recorded data. It is achieved by removing bad or noisy traces before stacking, increasing the signal to noise ratio during stacking. It makes enough data for statistical evaluation.

Kinematics Approach - Transit Time, Slowness

Figure 12 and Figure 13 show another example of seismic signals registered by a surface reference geophone and a 3 level downhole tool (Z-axis) during a land VSP acquisition with a single Sercel Mertz M22/601 P-wave vibrator. Figure 13 shows the deselected noisy and checkshot traces (grey) which were recorded on the way down without depth correlation. These traces are after cross correlation of vibrograms with a reference sweep and include 3 repeat traces. Note that signal variations are more evident on the downhole Z-axis traces than on the surface geophone ones

(Figure 14, Figure 15). The repeated shots were stacked using the median algorithm without time shifts from the reference geophone times. The author has acquired these data.

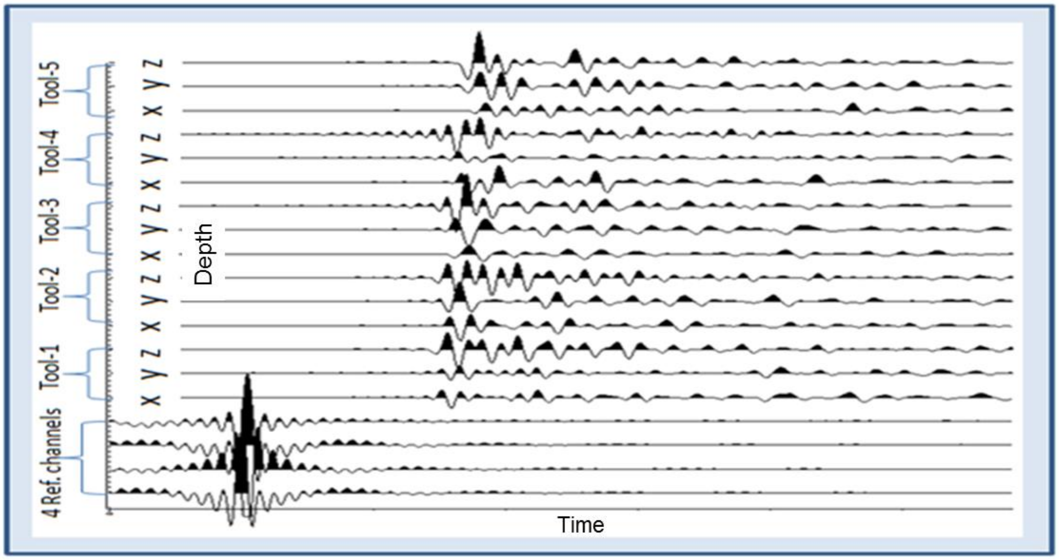


Figure 10. QC display showing reference channels and the raw 3C downhole waveforms (RadExPro).

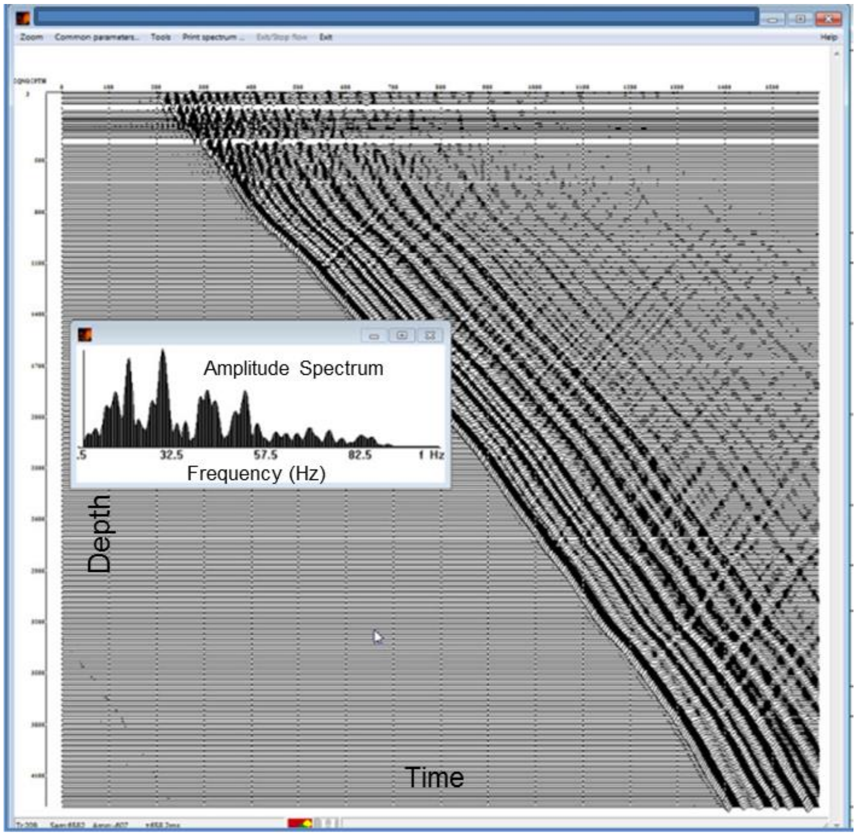


Figure 11. Zero Offset VSP Z-axis traces and the Amplitude Spectrum (RadExPro).

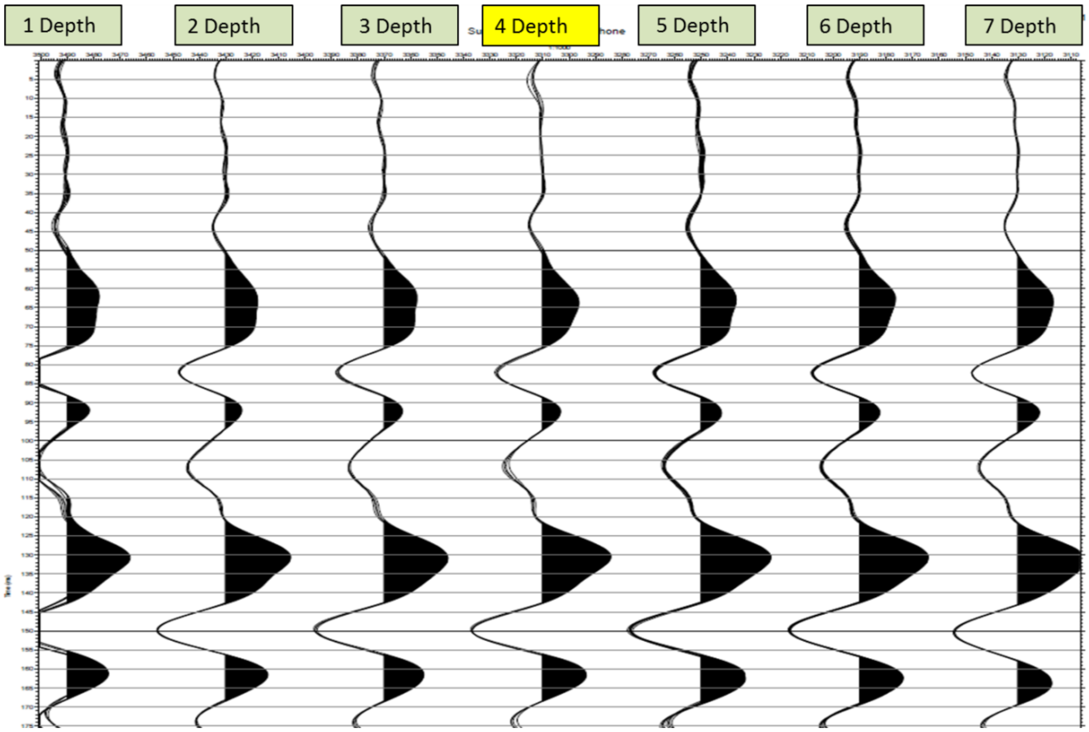


Figure 12. A surface reference geophone for a land VSP with a vibrator (Tcherkashnev S.)

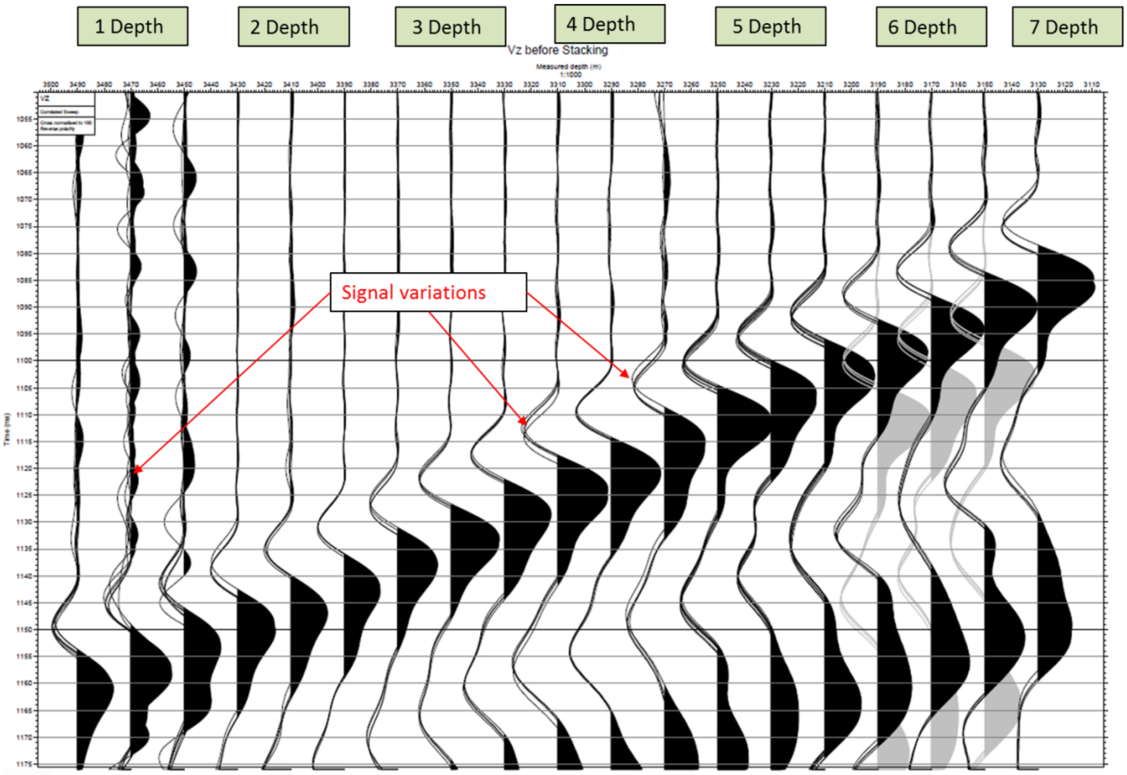


Figure 13. A land VSP with a vibrator. Downhole Z-axis (Tcherkashnev S.).

The primary quality control curve is the standard deviation of the time estimate for every trace. The standard deviation gives an assessment of the time accuracy (Figure 15).

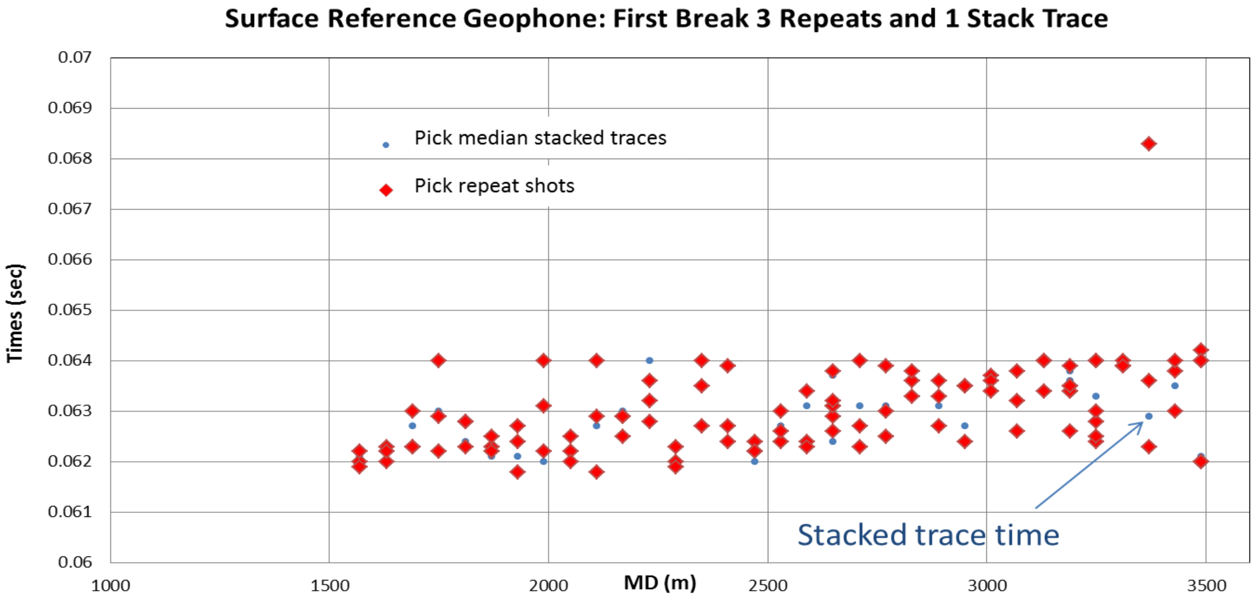


Figure 14. The first break time of the surface reference geophone for three repeat traces and one stacked trace. (Tcherkashnev S.).

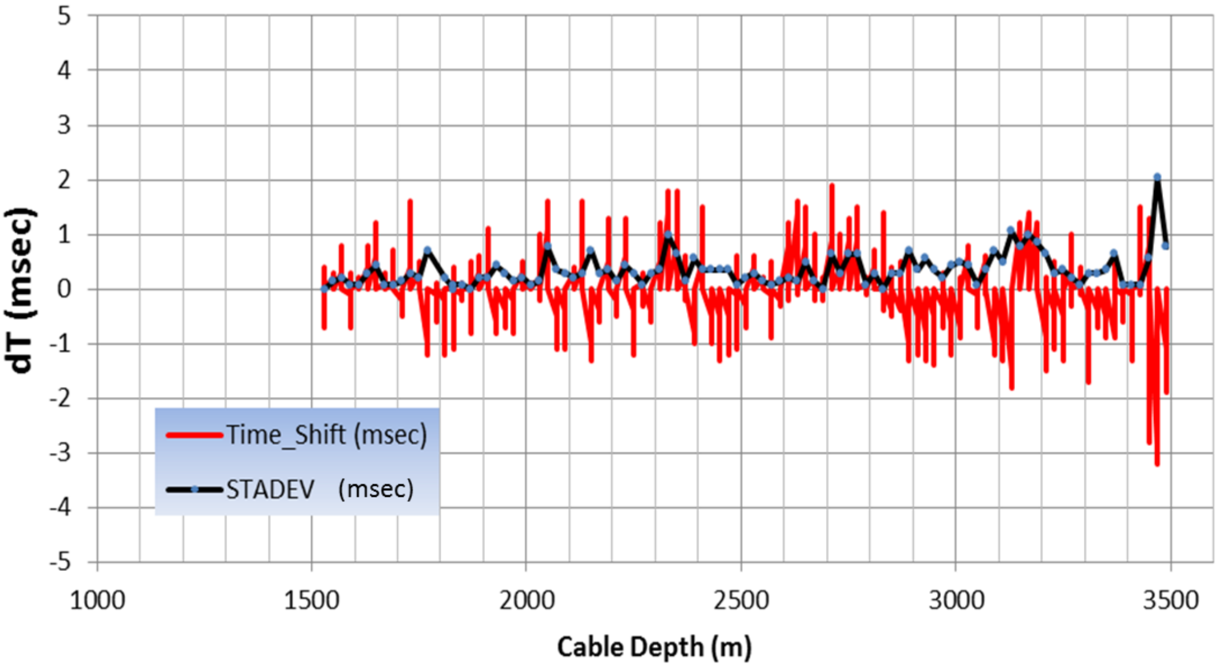


Figure 15. A land vibroseis ZVSP survey. The downhole Z-axis time difference (dT) of the repeat shots and Standard Deviation -STADEV (Tcherkashnev S.).

In addition to the standard deviation curves, a curve called Goodness is also computed (Figure 16). Goodness is calculated as follows:

Goodness = 1 – Standard deviation/slowness (1)

Thus, in the example of a standard deviation of 2 msec/m and a slowness of 200 msec/m, the Goodness would be 0.99. (Goodness = 1 – 2 (msec/m) /200 (msec/m)).

Time slowness estimates can be divided into 3 categories of Goodness

Good	Goodness > 0.98
Fair	0.98 < Goodness < 0.90
Bad	Goodness < 0.90

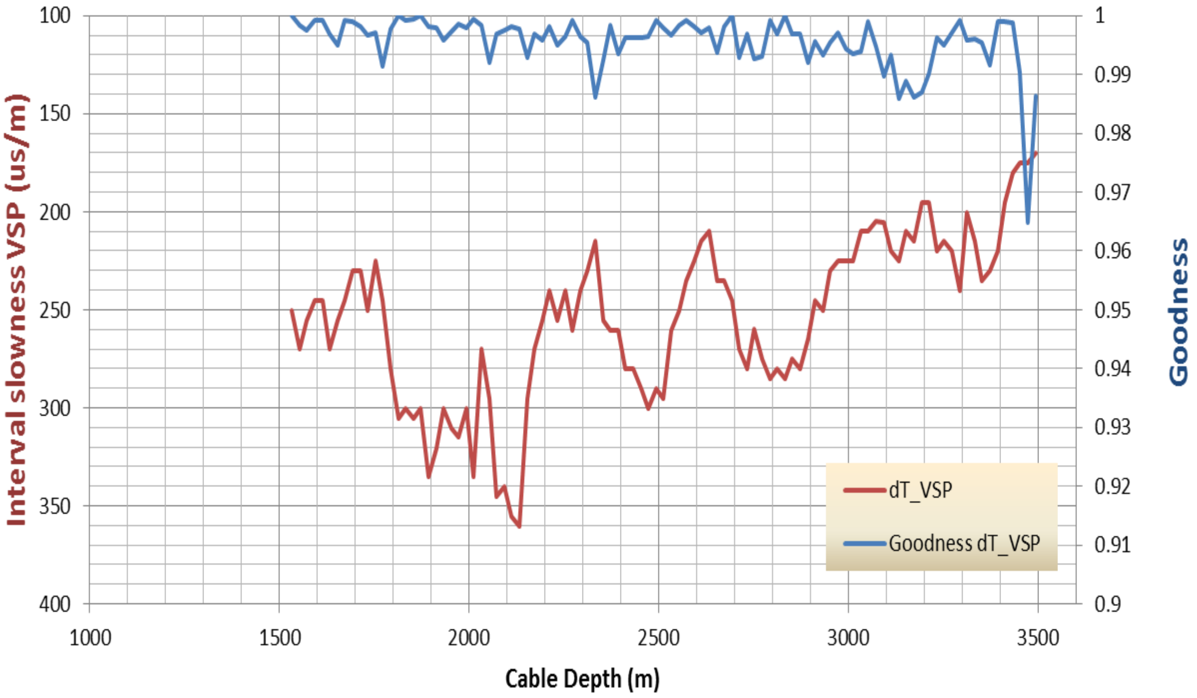


Figure 16. VSP Interval slowness and Goodness for a land VSP as in Figure 15 (Tcherkashnev S.).

To evaluate quality of the kinematic results, it makes sense plotting the VSP slowness curve, the Goodness curve, the standard deviation curve, together with the dynamic characteristics such as the signal, the noise amplitudes and SNR.

Dynamic Approach – Signal, Noise, SNR

Signal-to-noise ratio (SNR or S/N) is a measure that compares the level of a desired signal to the level of background noise. S/N ratio is defined either as the ratio of signal power to the noise power or the ratio of mean-square normalised amplitudes, or the signal peak to the noise mean-square normalised amplitudes or as the ratio of average amplitude before and after first break, often expressed in decibels. A ratio higher than 1:1 (greater than 0 dB) indicates more signal than noise. One of the most widespread methods in geophysics is measuring of mean-square normalised amplitudes in two or three windows and calculation of their ratios to each other (Figure 17). Figure 18 shows the signal and the noise RMS amplitudes computed in a 100 msec window. It is clear that noisy traces at the bottom on a borehole are above the signal level and can be omitted from data processing based on $S < N$. Another good QC check is a level of signal and noise on the horizontal components. Usually for a zero offset VSP survey in a vertical well in the horizontal geology, the amplitudes of the horizontal X, Y components are a few times smaller (Figure 19, Figure 20). A plot of the signal and the noise RMS amplitudes can be used to evaluate, 1) amplifier gain issues, 2) the noise levels and 3) a chance to process the horizontal components (Figure 21, Figure 22). Note the amplitude variations between the repeat shots for the same depth in those plots which can indicate either instability in source excitation or problems within downhole registration.

A land ZVSP survey acquired with the explosive charges of 0.5 kg at 5 m deep holes and a repeated ZVSP survey with 2x150 cu.inch air guns is shown in Figure 23. Note that the airgun source has a higher frequency content and more consistent Z-axis vertical wavefield. Data analysis revealed that signal-to-noise ratio is 5-6 times weaker from the explosive shots (Figure 24). Based on these results an airgun is a preferable seismic source for borehole seismic surveys onshore Papua New Guinea.

SNR helps to select optimum surface seismic and VSP acquisitions parameters. Figure 25 shows a vibrosource summary table before starting a simultaneous 3D Seismic and 3D VSP survey. After careful S/N evaluation analysis, the vibrator parameters were selected to provide a linear sweep with 0 degree and 270 degree phase for each vib fleet. Figure 26 displays a S/N attribute map as 3D VSP data was acquired. It helps to drive decision-making process of acquiring high quality data.

Another example shows S/N of the DAS data before and after noise attenuation quantifying an effective noise cancelation approach as shown in Figure 27 (S. Tcherkashnev et al., 2018). Figure 28 shows comparison of P-wave S/N ratio for wireline, clamped geophones and tubing-deployed DAS fibre-optic from separate VSP surveys in the same well (T. Daley et al., 2013). Filtered DAS data has a band-pass filter of 5–180 Hz applied to improve (S/N).

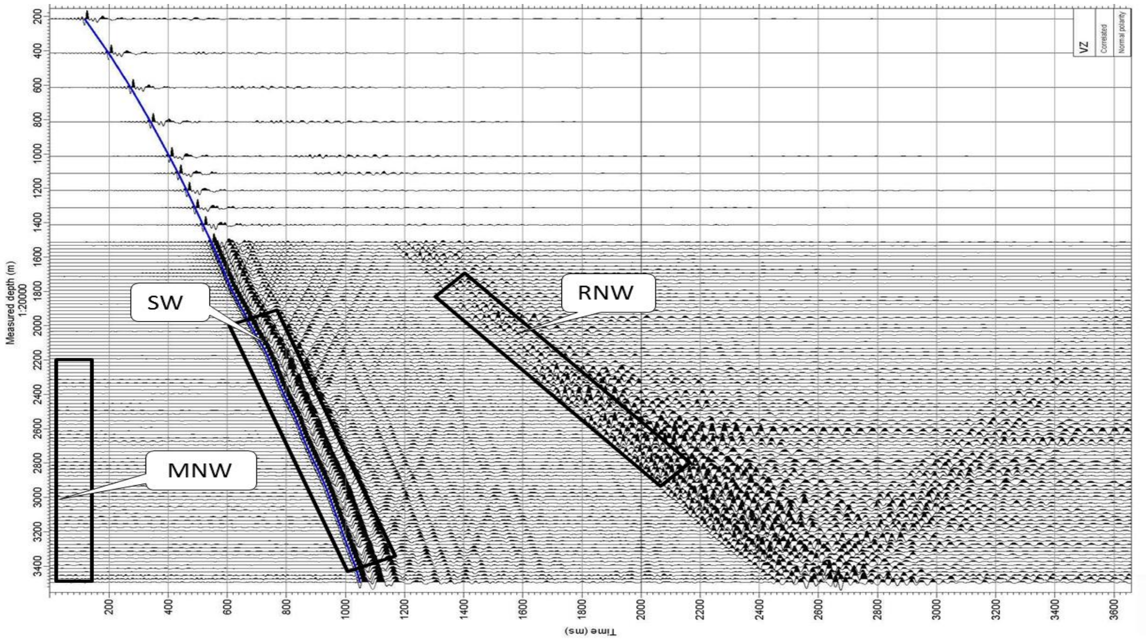


Figure 17. A land ZVSP with a vibroseis source. MNW - microseismic window; SW - signal window; RNW - regular noise window (Tcherkashnev S.)

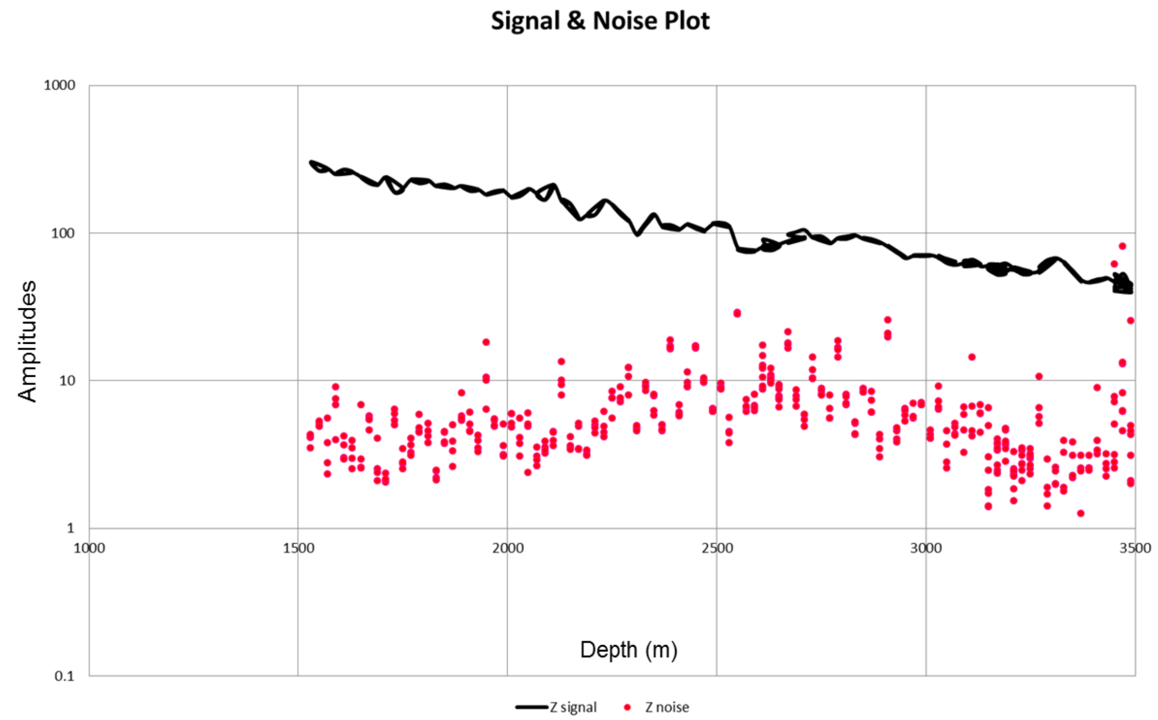


Figure 18. A land VSP with a vibroseis source. The signal and noise Z-axis RMS amplitudes in a 100msec window for all repeat shots before stacking (Tcherkashnev S.).

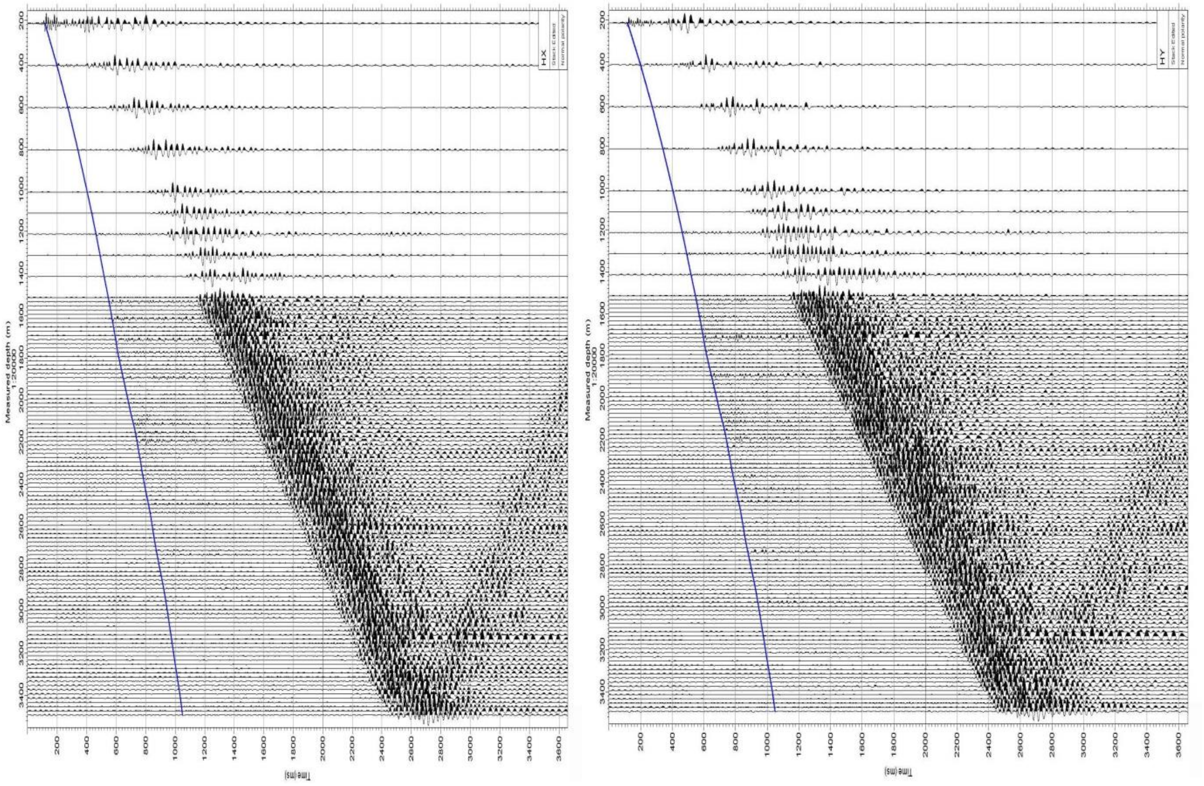


Figure 19. A land ZVSP with a vibroseis source. The X-axis (left) and Y-axis (right) (Tcherkashnev S.).

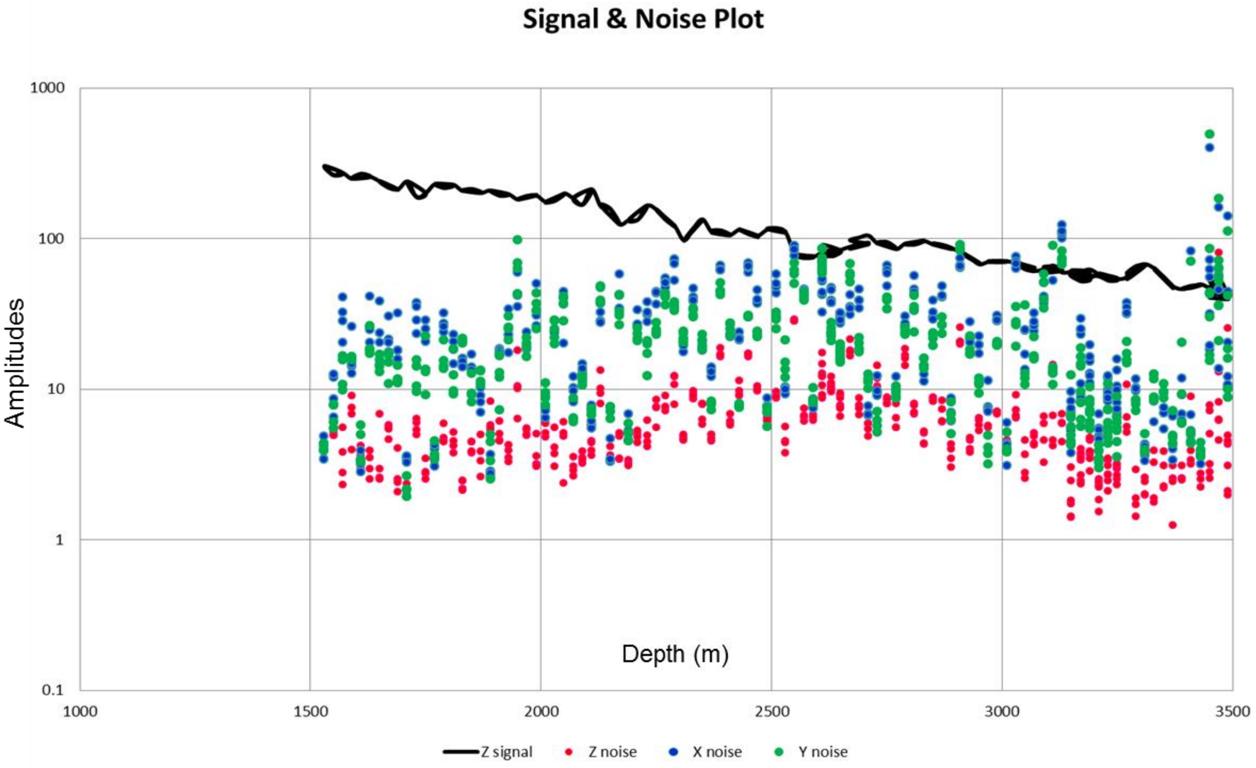


Figure 20. A land VSP with a vibroseis source. Signal Z-axis and noise Z-axis, X-axis and Y–axis for all repeat shots before stacking (Tcherkashnev S.).

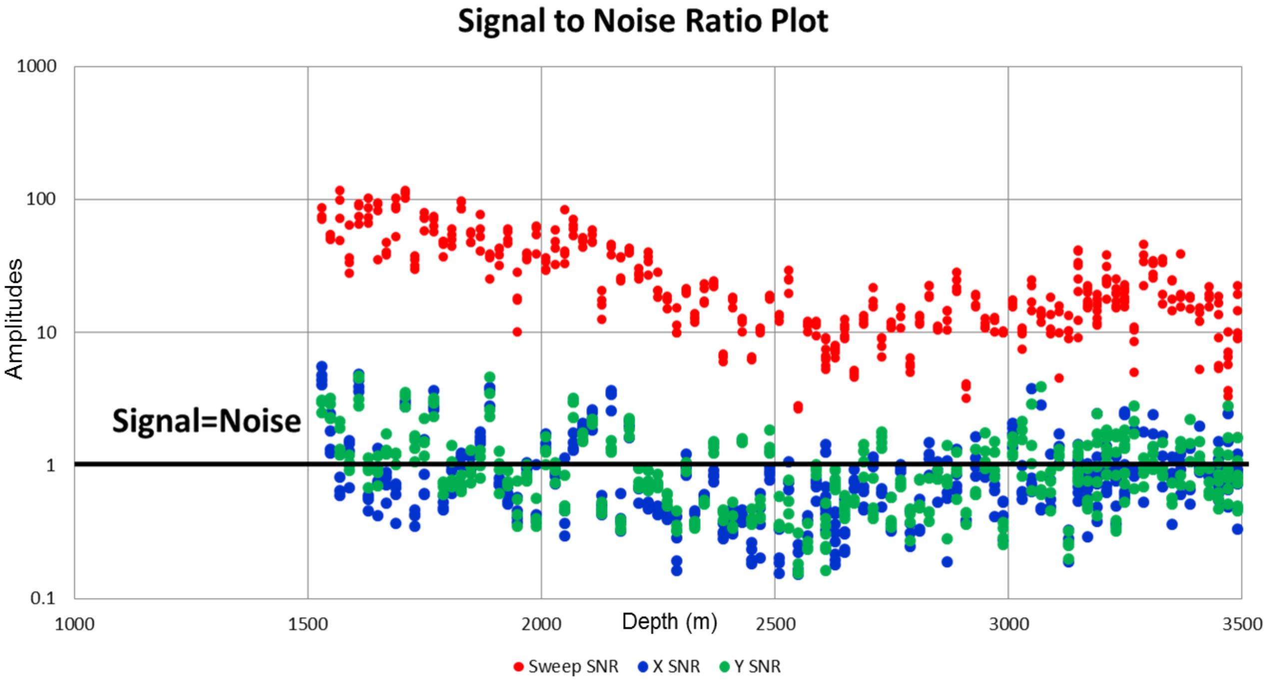


Figure 21. A land VSP with a vibroseis source. SNR Z-axis, X-axis and Y–axis for the repeat shots before stacking. Note the amplitude variations between the repeat shots for the same depth (Tcherkashnev S.).

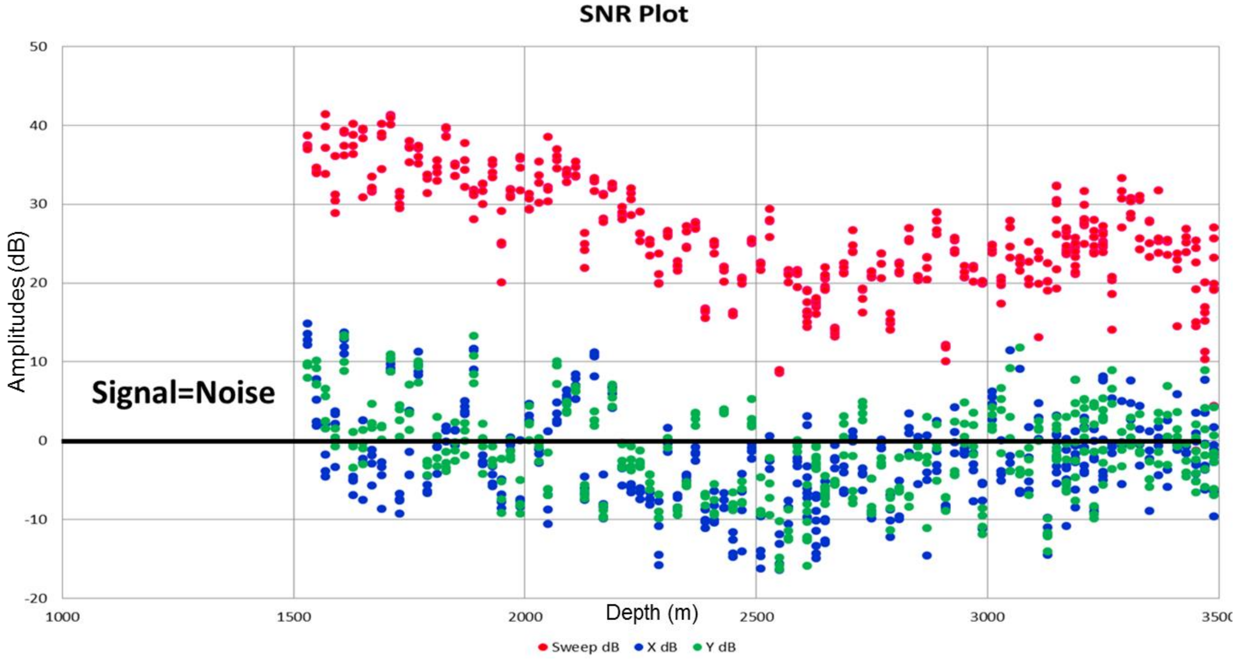


Figure 22. A land VSP with a vibroseis source. SNR Z-axis, X-axis and Y–axis in dB. for the repeat shots before stacking. Note the amplitude variations between the repeat shots for the same depth (Tcherkashnev S.).

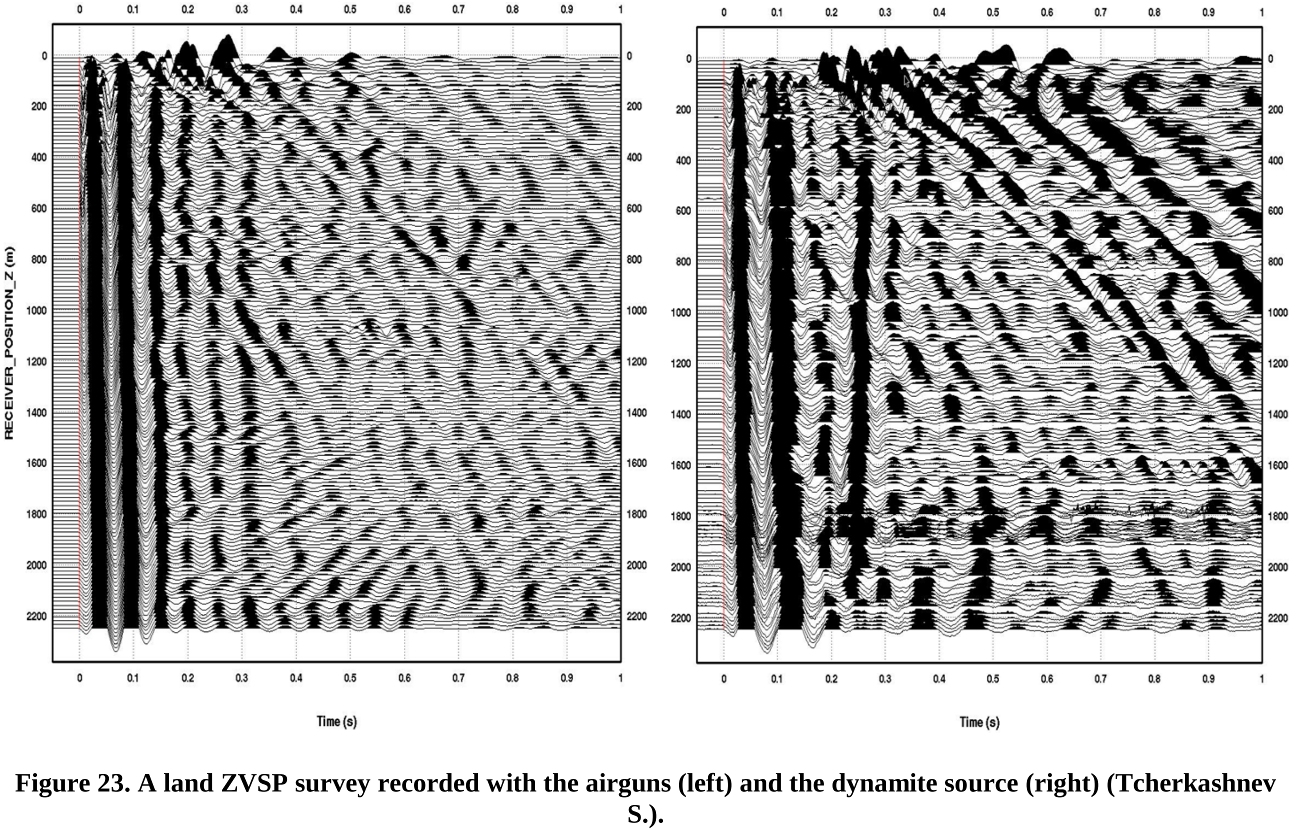


Figure 23. A land ZVSP survey recorded with the airguns (left) and the dynamite source (right) (Tcherkashnev S.).

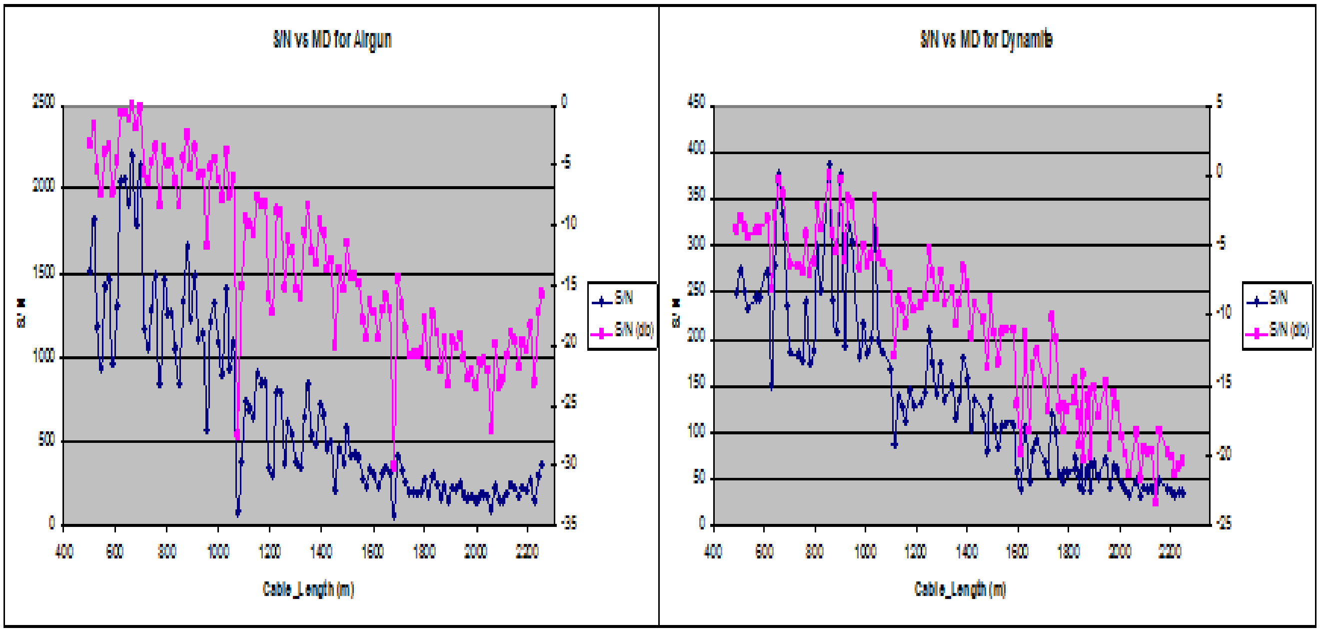
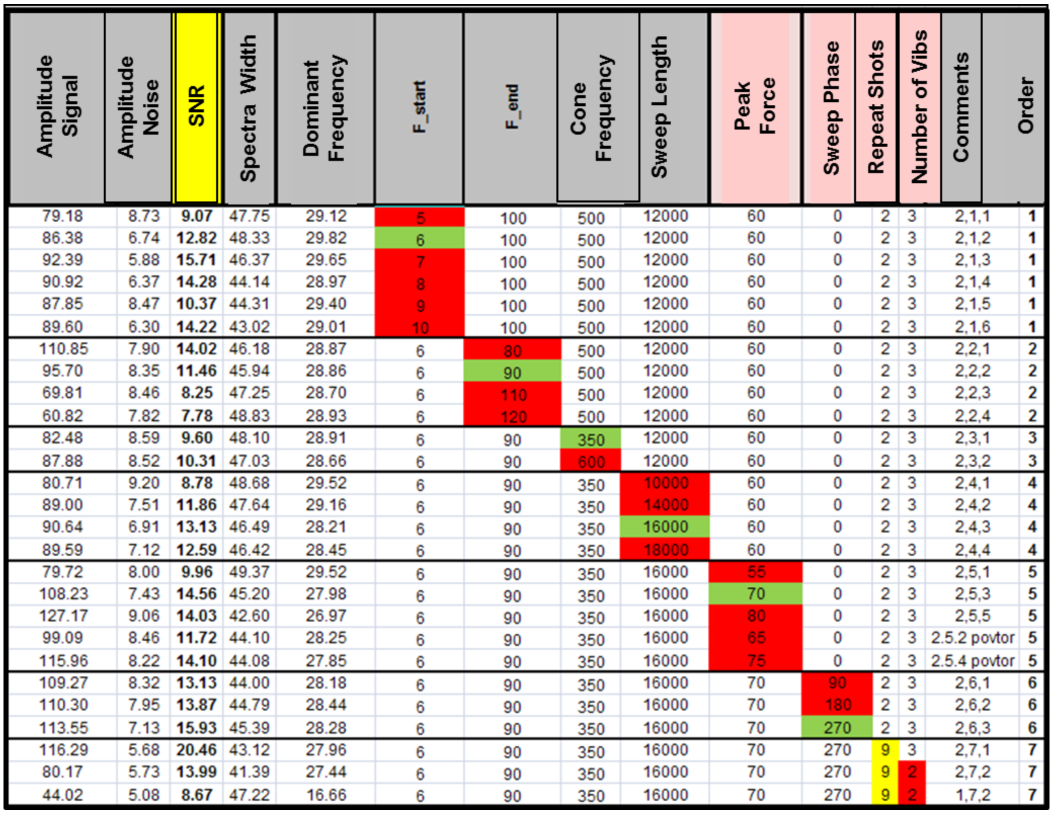


Figure 24. SNR ratio for an airgun source is 5 times higher than for a dynamite source. SNR can help to evaluate source efficiency (Tcherkashnev S.).



Amplitude Signal	Amplitude Noise	SNR	Spectra Width	Dominant Frequency	F_start	F_end	Cone Frequency	Sweep Length	Peak Force	Sweep Phase	Repeat Shots	Number of Vibs	Comments	Order
79.18	8.73	**9.07**	47.75	29.12	5	100	500	12000	60	0	2	3	2,1,1	**1**
86.38	6.74	**12.82**	48.33	29.82	6	100	500	12000	60	0	2	3	2,1,2	**1**
92.39	5.88	**15.71**	46.37	29.65	7	100	500	12000	60	0	2	3	2,1,3	**1**
90.92	6.37	**14.28**	44.14	28.97	8	100	500	12000	60	0	2	3	2,1,4	**1**
87.85	8.47	**10.37**	44.31	29.40	9	100	500	12000	60	0	2	3	2,1,5	**1**
89.60	6.30	**14.22**	43.02	29.01	10	100	500	12000	60	0	2	3	2,1,6	**1**
110.85	7.90	**14.02**	46.18	28.87	6	80	500	12000	60	0	2	3	2,2,1	**2**
95.70	8.35	**11.46**	45.94	28.86	6	90	500	12000	60	0	2	3	2,2,2	**2**
69.81	8.46	**8.25**	47.25	28.70	6	110	500	12000	60	0	2	3	2,2,3	**2**
60.82	7.82	**7.78**	48.83	28.93	6	120	500	12000	60	0	2	3	2,2,4	**2**
82.48	8.59	**9.60**	48.10	28.91	6	90	350	12000	60	0	2	3	2,3,1	**3**
87.88	8.52	**10.31**	47.03	28.66	6	90	600	12000	60	0	2	3	2,3,2	**3**
80.71	9.20	**8.78**	48.68	29.52	6	90	350	10000	60	0	2	3	2,4,1	**4**
89.00	7.51	**11.86**	47.64	29.16	6	90	350	14000	60	0	2	3	2,4,2	**4**
90.64	6.91	**13.13**	46.49	28.21	6	90	350	16000	60	0	2	3	2,4,3	**4**
89.59	7.12	**12.59**	46.42	28.45	6	90	350	18000	60	0	2	3	2,4,4	**4**
79.72	8.00	**9.96**	49.37	29.52	6	90	350	16000	55	0	2	3	2,5,1	**5**
108.23	7.43	**14.56**	45.20	27.98	6	90	350	16000	70	0	2	3	2,5,3	**5**
127.17	9.06	**14.03**	42.60	26.97	6	90	350	16000	80	0	2	3	2,5,5	**5**
99.09	8.46	**11.72**	44.10	28.25	6	90	350	16000	65	0	2	3	2.5.2 povtor	**5**
115.96	8.22	**14.10**	44.08	27.85	6	90	350	16000	75	0	2	3	2.5.4 povtor	**5**
109.27	8.32	**13.13**	44.00	28.18	6	90	350	16000	70	90	2	3	2,6,1	**6**
110.30	7.95	**13.87**	44.79	28.44	6	90	350	16000	70	180	2	3	2,6,2	**6**
113.55	7.13	**15.93**	45.39	28.28	6	90	350	16000	70	270	2	3	2,6,3	**6**
116.29	5.68	**20.46**	43.12	27.96	6	90	350	16000	70	270	9	3	2,7,1	**7**
80.17	5.73	**13.99**	41.39	27.44	6	90	350	16000	70	270	9	2	2,7,2	**7**
44.02	5.08	**8.67**	47.22	16.66	6	90	350	16000	70	270	9	2	1,7,2	**7**

Figure 25. SNR results help to choose the optimum VSP acquisition parameters with a vibroseis source. (Courtesy of GazpromNeft, Russia)

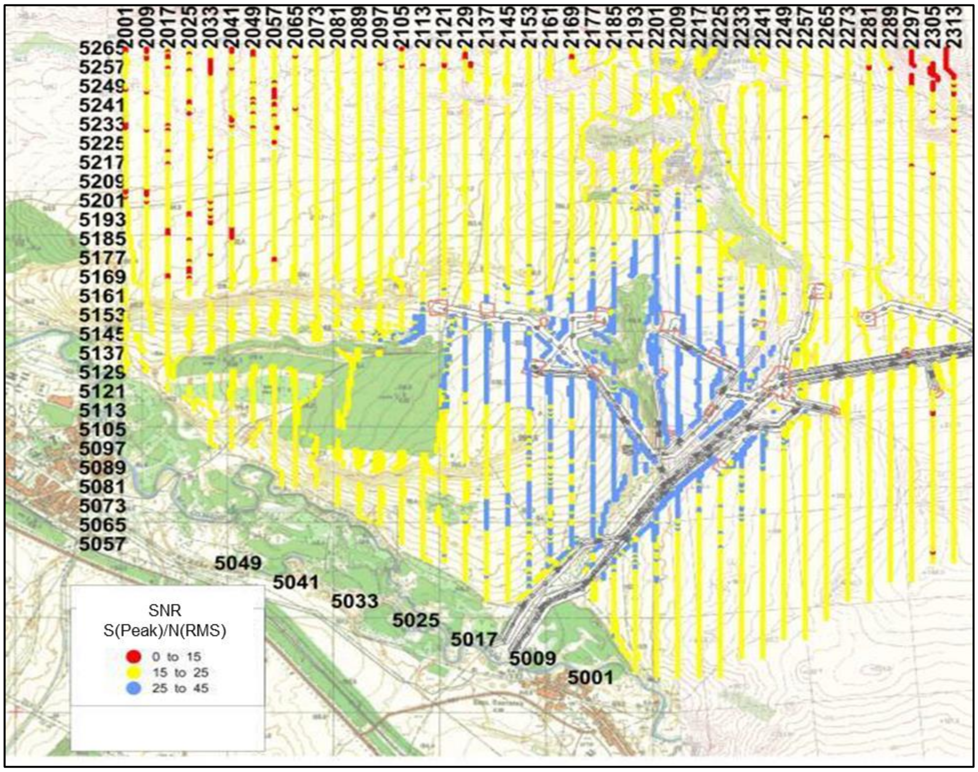


Figure 26. SNR from a land 3D VSP with a vibroseis source (Courtesy of GazpromNeft, Russia).

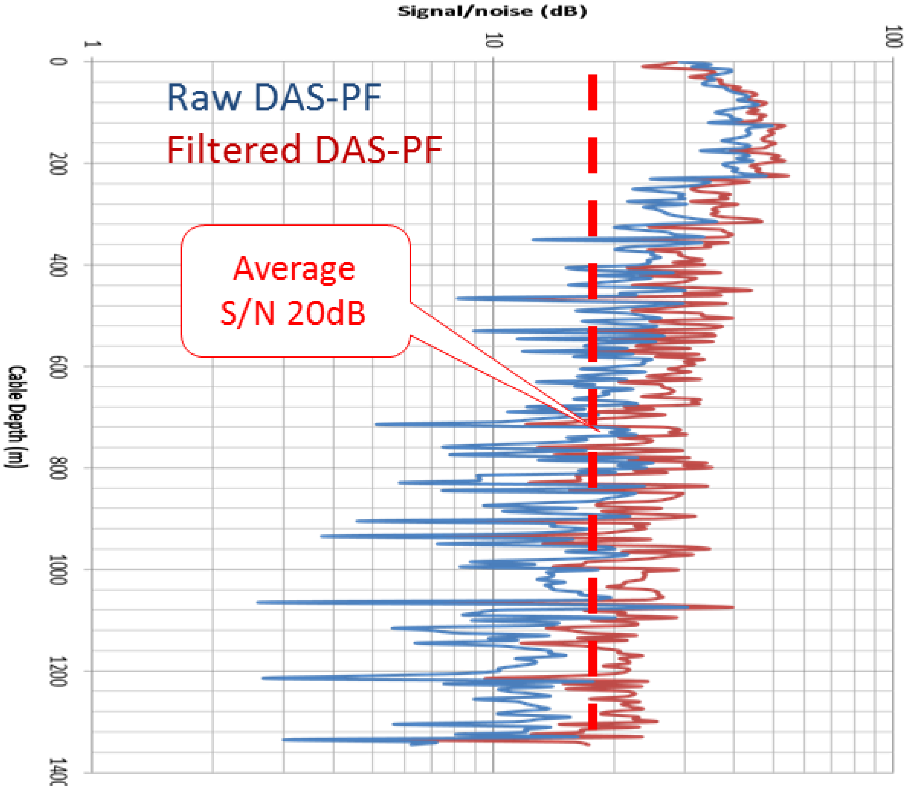


Figure 27. SNR from a land ZVSP DAS survey with 1.6 kg explosives. (PetroFiber & ASTO, Russia, 2015).

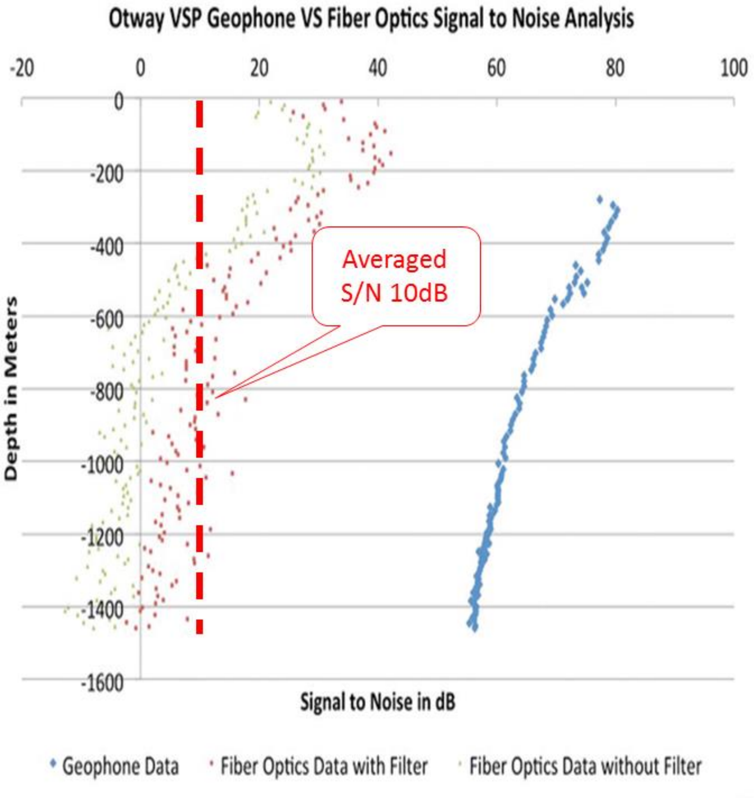


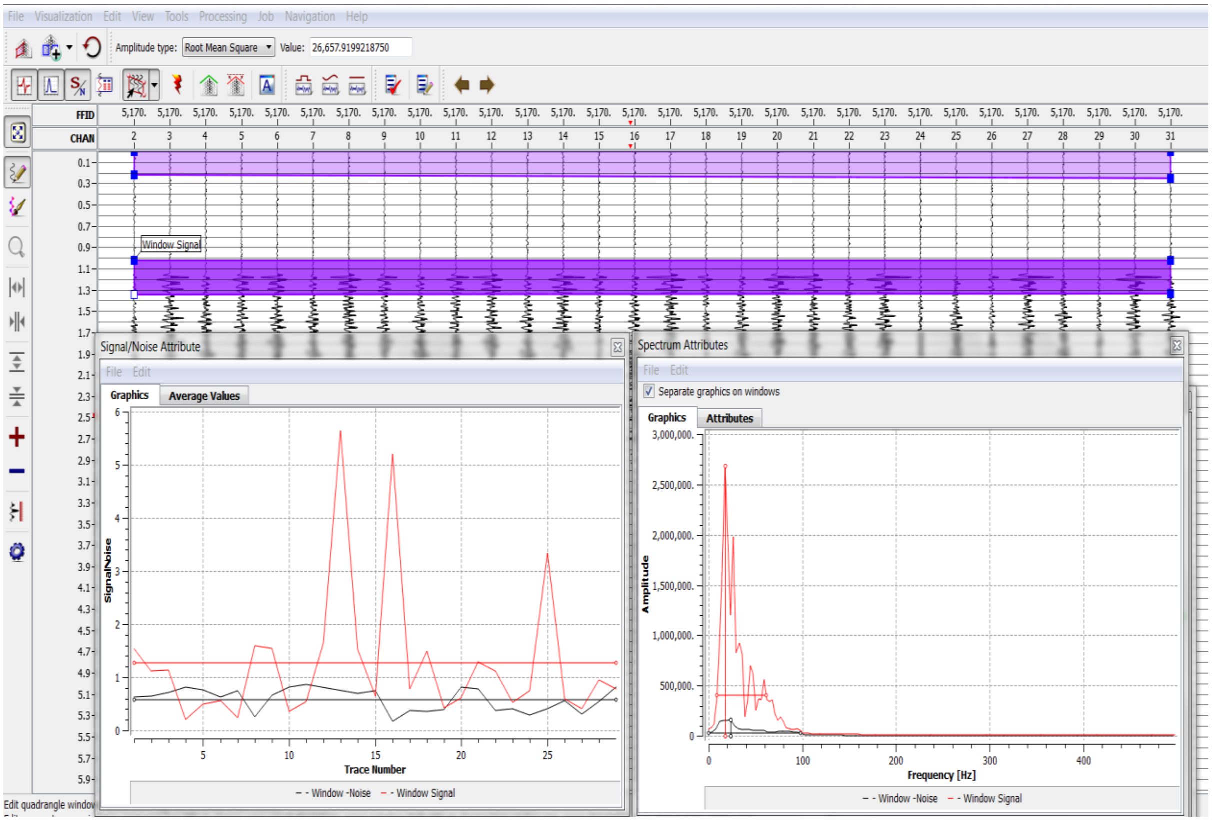
Figure 28. SNR from a land ZVSP with 3C geophones and DAS (T. Daley et al., 2013). Comparison of P-wave signal-to-noise (S/N) ratio for wireline, clamped geophones and tubing-deployed DAS fibre-optic from separate VSP surveys in the same well. Filtered fibre data has a band-pass filter of 5–180 Hz applied to improve (S/N). Different sources were used in the two data sets.

SNR Approach

Another SNR approach (Hatton, et al., 1986) is based on a ratio of the coherent signal energy to the random noise energy. The estimation uses a normalised autocorrelation function (ACF) and a cross-correlation function (CCF) for different traces groups in selected windows by the formula:

$$[S/N] = \left[\frac{[g'_{ij}]_M}{1-[g'_{ij}]_M} \right]^{\frac{1}{2}} \qquad (2)$$

Figure 29 shows a single shot gather with 3C 10 levels tool from a land 3D VSP with a vibroseis source. It helps to select the optimum acquisition parameters in real time and to record high quality data.



Amplitude type: Root Mean Square

Value: 26,657.9199218750

☑ Separate graphics on windows

Figure 29. A single SP with 3C 10 levels tool from a land 3D VSP with a vibroseis source. Z-axis, X-axis and Y–axis (top), SNR (bottom left), the amplitude spectrum (bottom right). QC plots from SeisWin QC (GSD).

SN, Spectrum, Signal Energy Approach

Geophysical Data Systems Ltd. (GSD, Russia) proposes a Quality Control (QC) formula (2) which is based on the weighted sum of signal and noise characteristics:

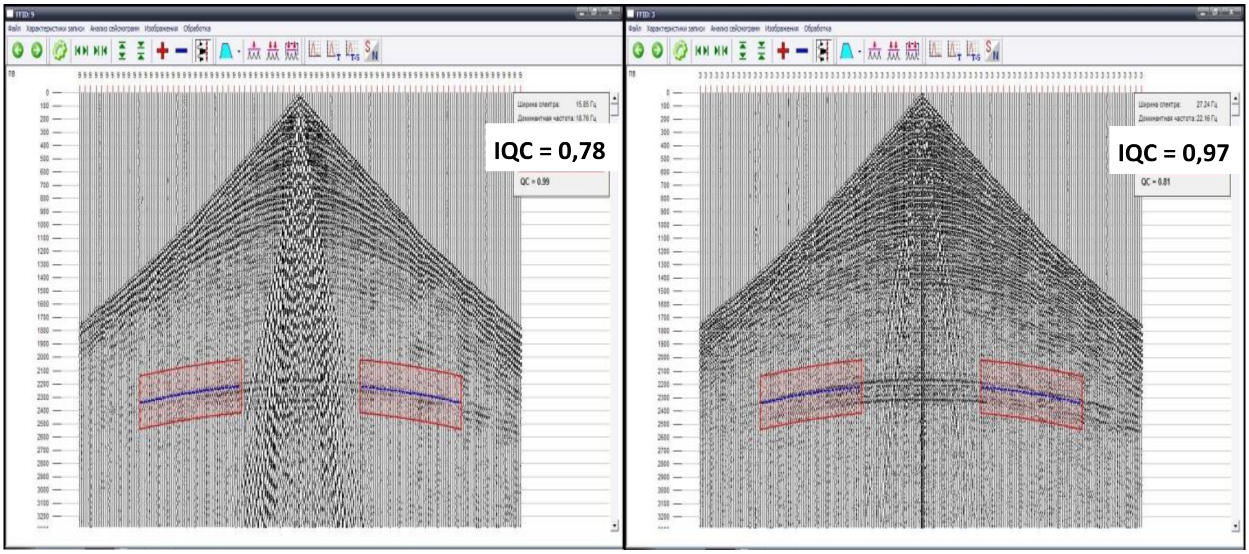
$$QC = \frac{\frac{\text{signal}}{\text{noise}} + \frac{\text{spectrum width}}{60} + \frac{\text{dominant Fr}}{35} + \frac{E_{SP}}{E_{AVG}}}{0.7 + 0.7 + 0.7 + 0.7} * k \qquad (3)$$

where E_{SP} – is the energy characteristic of seismogram; E_{AVG} – is the average energy estimation for a number of seismograms; dominant Fr – a dominant frequency; K – a normalisation coefficient; 0,7 – a normalisation factor to 70% of maximum level. Second and the third terms are dimensionless. A range of the second and the third terms is used in this formula.

The values 60, 35 and “k” characterise parameters of averaged model seismogram, typical for area of work and can be edited by a supervisor or inserted automatically using the statistical analysis results.

Geophysical Data Systems Ltd developed the software package “SeisWin QC”, which implements the mentioned methodology and it is used extensively by servicing and oil companies in Russia, CIS and abroad.

The GSD QC approach helps to make a decision, for the example, when a decreased explosive source depth causes a dominant frequency increase up and the amplitude spectrum becomes wider. At the same time, a signal-to-noise ratio is decreasing. The comparison of seismograms, registered at source depth of 7.5 and 16.5 meters is shown in Figure 30**.** Figure 31 shows the results with the highest QC value corresponding to 16.5 m source depth. For deeper depth QC values do not changed much.



a) b)

Figure 30. A comparison of seismograms with different explosive source depth and a 0.5 kg weight. Where IQC=0.78 in the panel a) – depth 7,5 m; and IQC=0.97 in the panel b) – depth 16,5 m (from Tishenko, 2008).

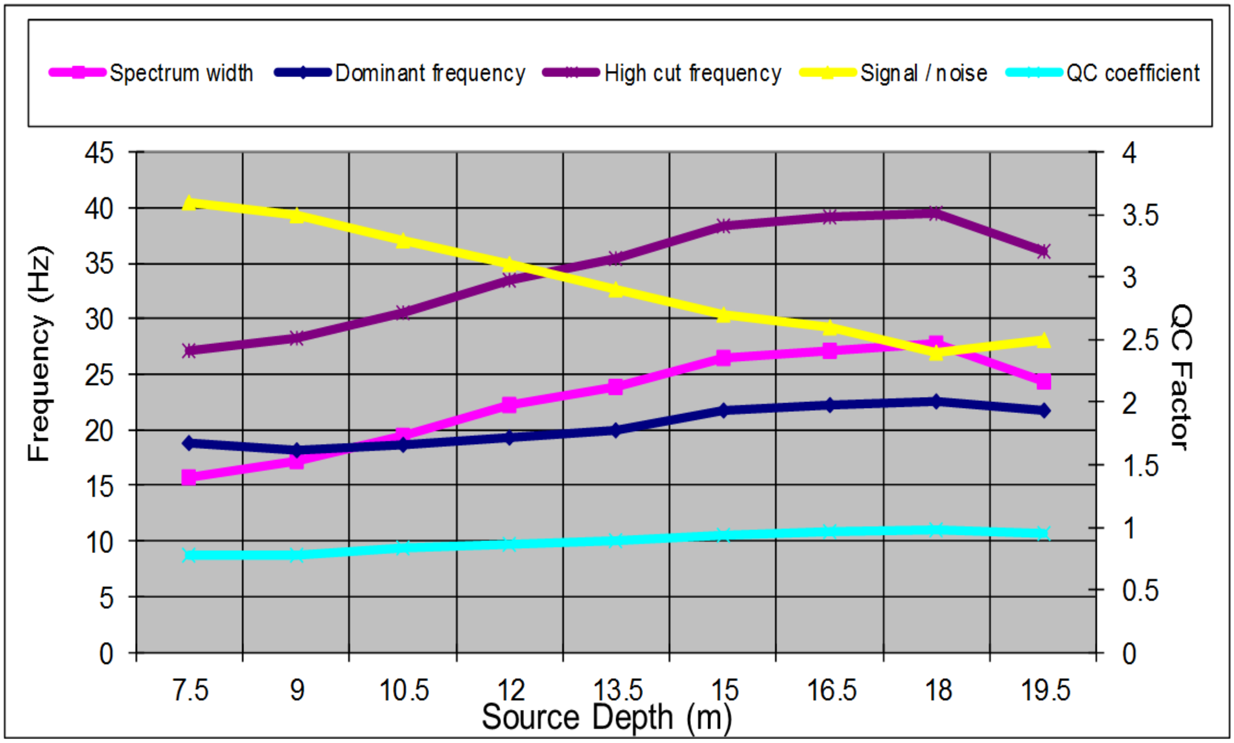


Figure 31. Infield explosive source depth selection using the GSD approach (from Tishenko, 2008).

Time-Amplitude Difference Approach

The arrival times and the amplitudes in a window (min, max, RMS) can be used for the QC purposes to select the good and the bad traces using a user defined threshold. Figure 32 shows the time-amplitude difference analysis results using the repeat shots before stacking for a land VSP survey with a vibroseis source. These results can be used to deselect bad traces using a time-amplitude threshold above a certain level automatically.

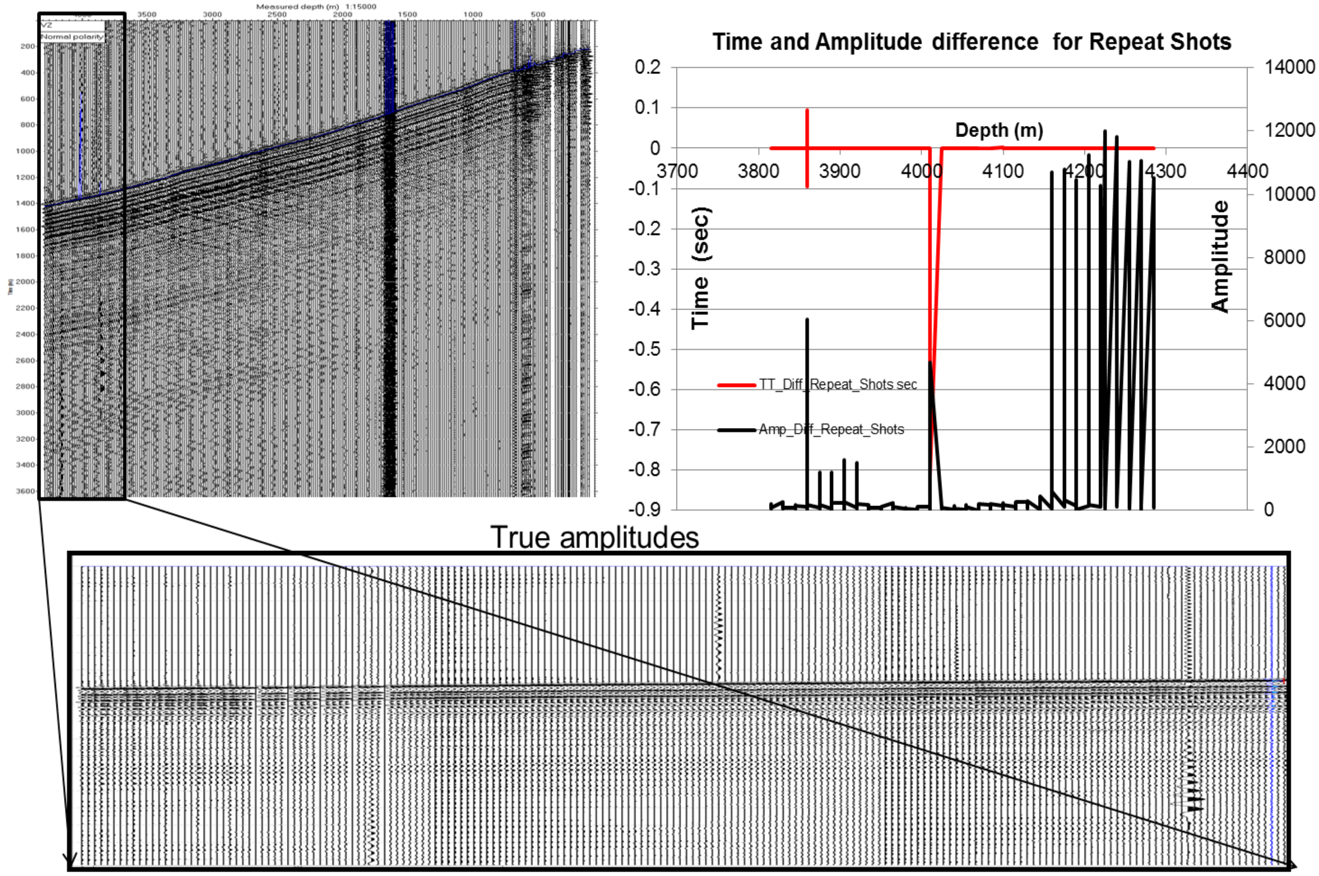


Figure 32. Results of the Time-Amplitude difference analysis using the repeated shots before stacking (Tcherkashnev S.).

Statistical Approaches

A proposed statistical analysis uses the minimum, maximum, average, variance, cumulant amplitude distributions of the recorded seismic traces. These results can be used to separate of the seismic data into good and bad traces.

Figure 33 shows a land VSP survey with a vibroseis source with one VSP shuttle having high amplitudes due to bad anchoring with the borehole. Figure 34 displays the computed mean value of the trace amplitudes (Aver), the coarsened mean (Raver) and the average (Gaver). A standard dispersion and the amplitude level curve taken at 90% are shown in Figure 35. All evaluation curves show picks corresponding to the bad traces and easily deselected using a threshold level. These statistical results can be used in automatic QC analysis.

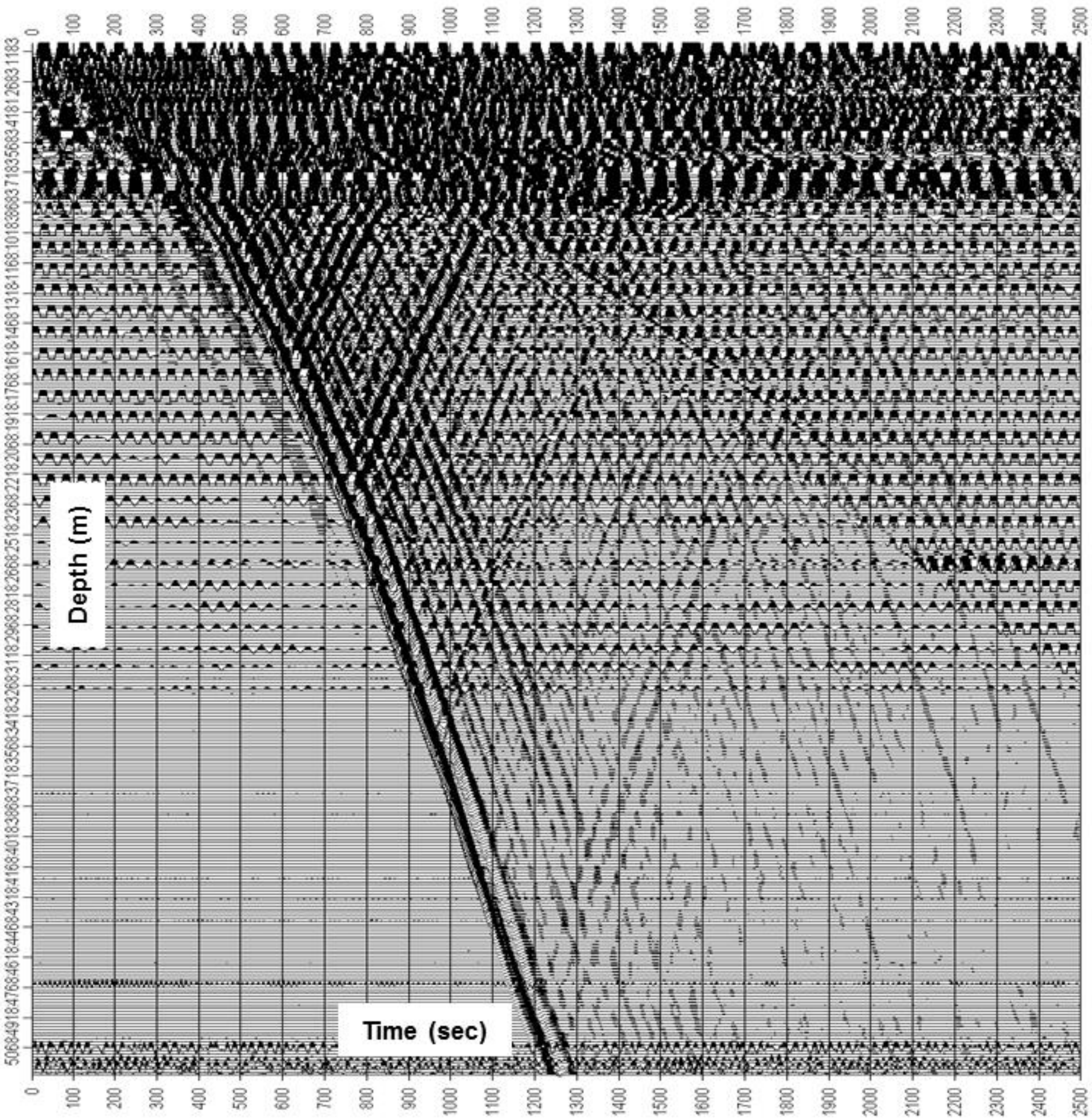


Figure 33. A land vibroseis VSP. One VSP shuttle had the poor coupling with the borehole due to bad anchoring (Tcherkashnev S.).

Figure 36 shows a land VSP survey with a vibroseis source where the data appears to be good quality. However there are the noisy traces above 100m as seen in Figure 37. The computed Aver, Raver, Gaver and the standard dispersion curves can not pick the noisy traces (Figure 38).

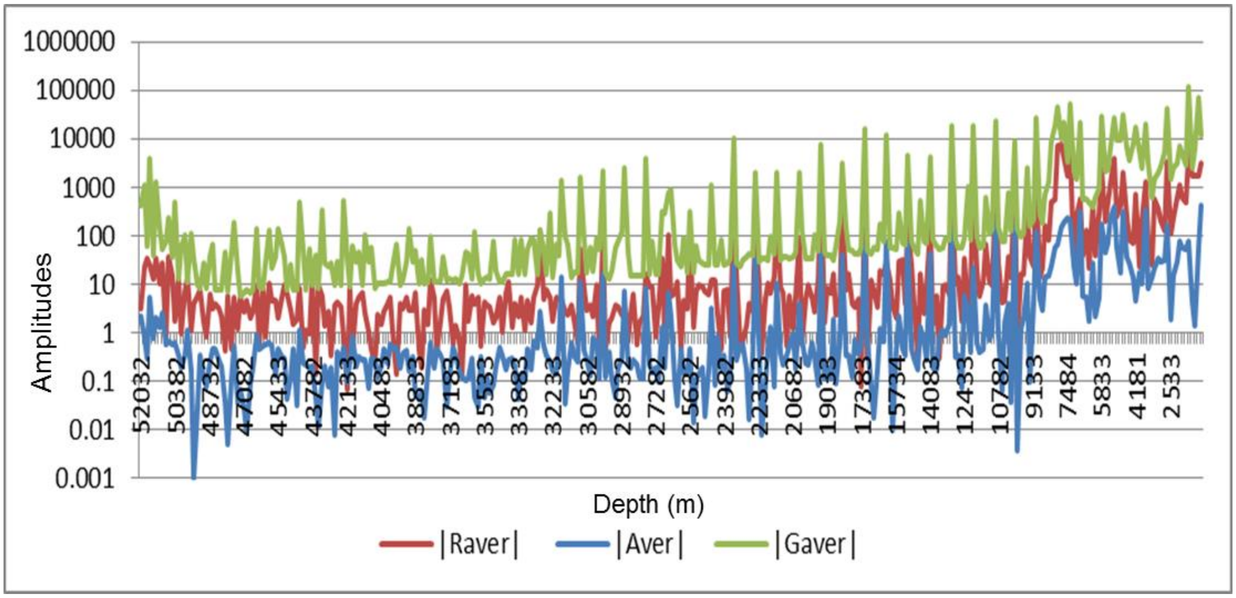


Figure 34. Aver is the mean value of the trace amplitudes. Raver is the coarsened mean. Gaver is the average, determined from the central value of the histogram. All curves show picks corresponding to bad traces (Tcherkashnev S.).

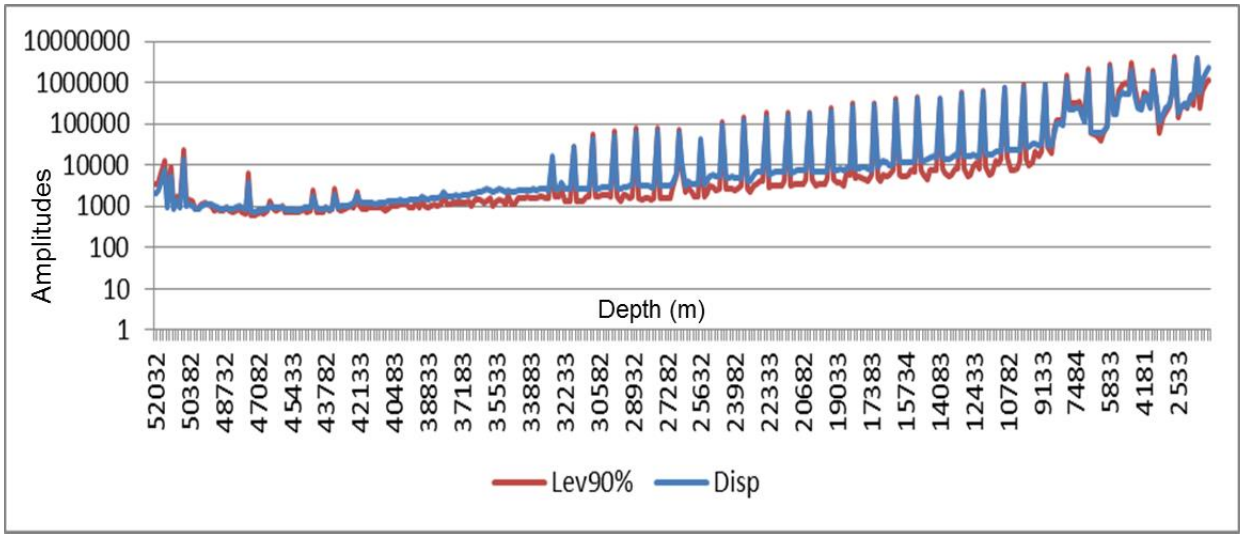


Figure 35. A standard dispersion curve and the amplitude level taken at 90%. All evaluations work equally well. The bad traces are easily selected (Tcherkashnev S.).

Trace differentiation is applied to these computed statistical curves. Trace differentiation works as a filter that passes high frequencies and suppresses low frequencies. Note that the distribution cumulant (bottom panel) at a depth of 100 meters differs significantly from other traces (Figure 39). The distribution cumulant after trace differentiation can be used to select bad traces.

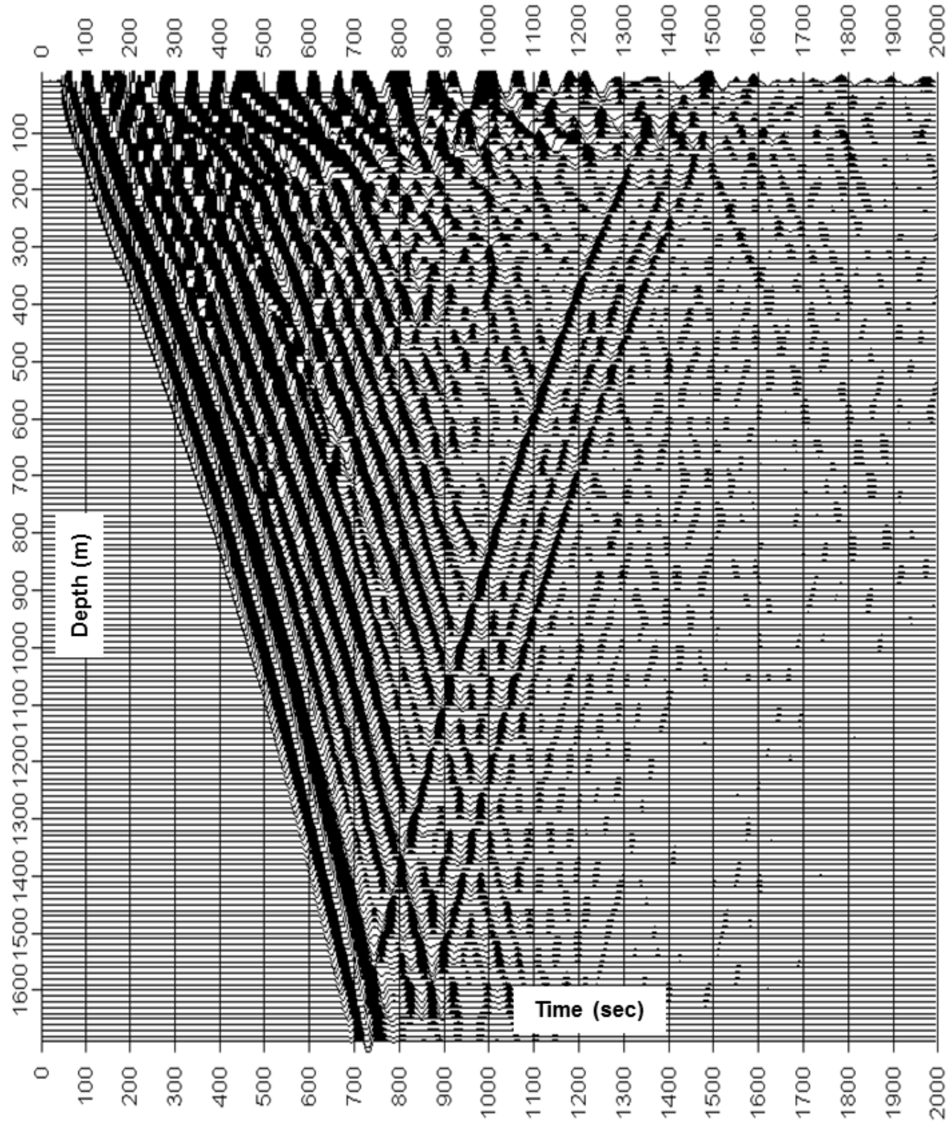


Figure 36. A land vibroseis VSP with good quality data (Tcherkashnev S.).

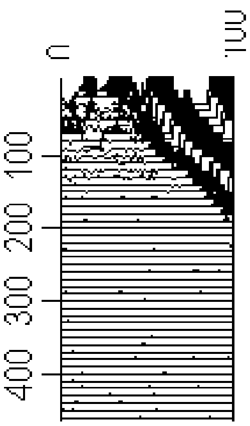


Figure 37. The same data as in Figure 36 after applied gain. Note the noisy traces above 100m (Tcherkashnev S.).

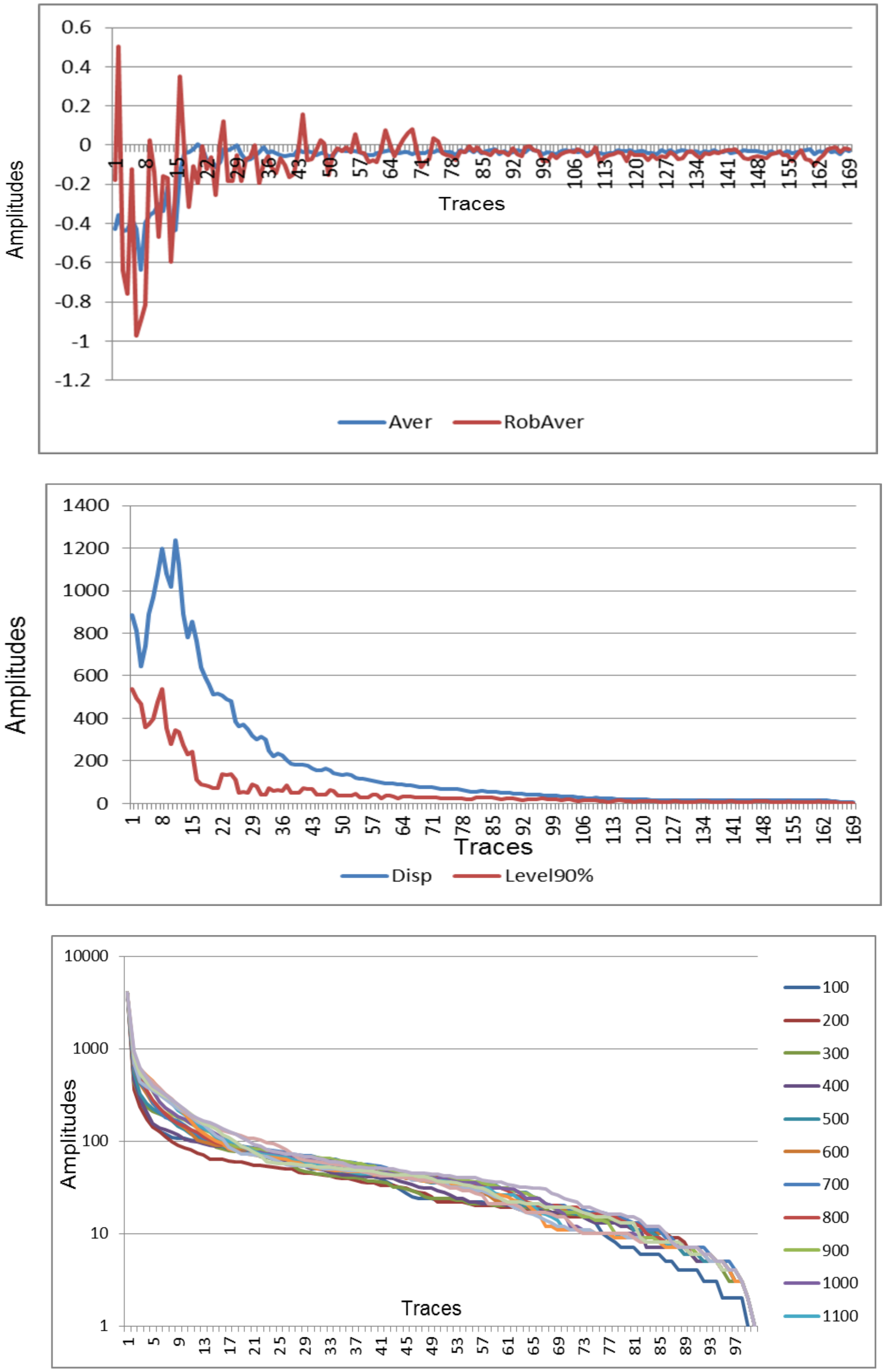


Figure 38. The curves of the mean amplitudes and the coarsened mean amplitudes (top panel). Standard dispersion curves and the amplitude level taken at 90%. (middle panel). The distribution cumulant (bottom panel), constructed for each tenth trace shows that the trace at 100 meters slightly differs from other traces. The detection of bad traces is difficult (Tcherkashnev S.).

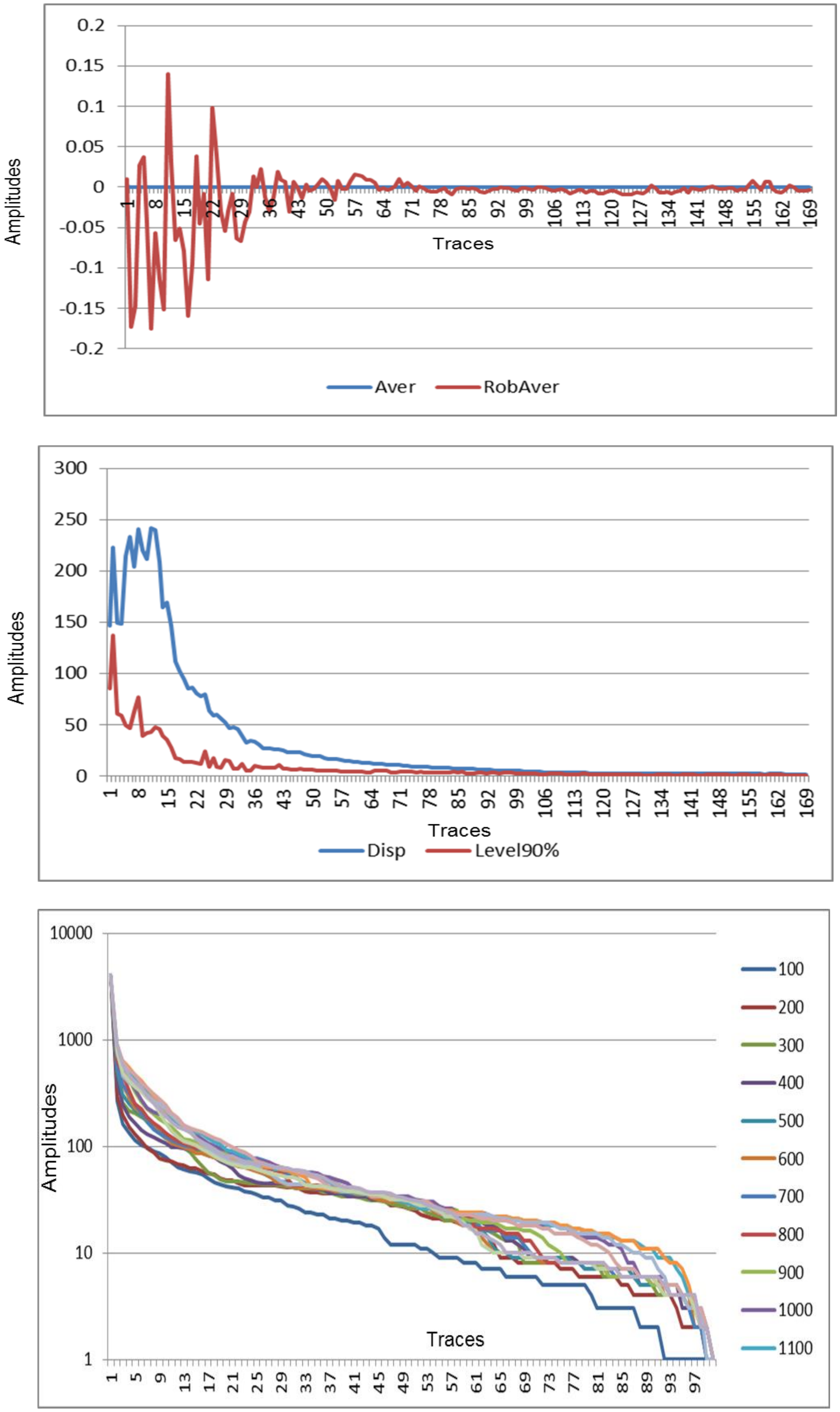


Figure 39. The results after trace differentiation. Note that the distribution cumulant (bottom panel) at a depth of 100 meters differs significantly from other traces (Tcherkashnev S.).

Another example shows a microseismic event in Figure 40. The curves of the mean amplitudes and the coarsened mean amplitudes (Figure 41, top panel) do not detect the microseismic event. However the detection of a microseismic event using Min/Max amplitudes is a simple task (Figure 41, bottom panel).

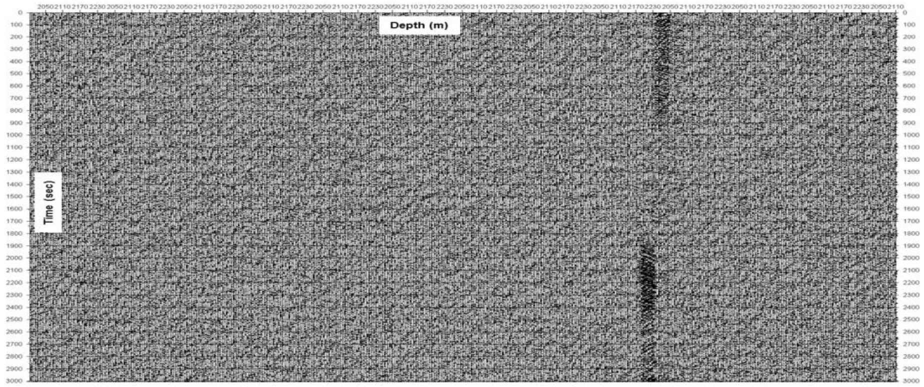


Figure 40. A microseismic event observed during hydraulic frac monitoring (Tcherkashnev S.).

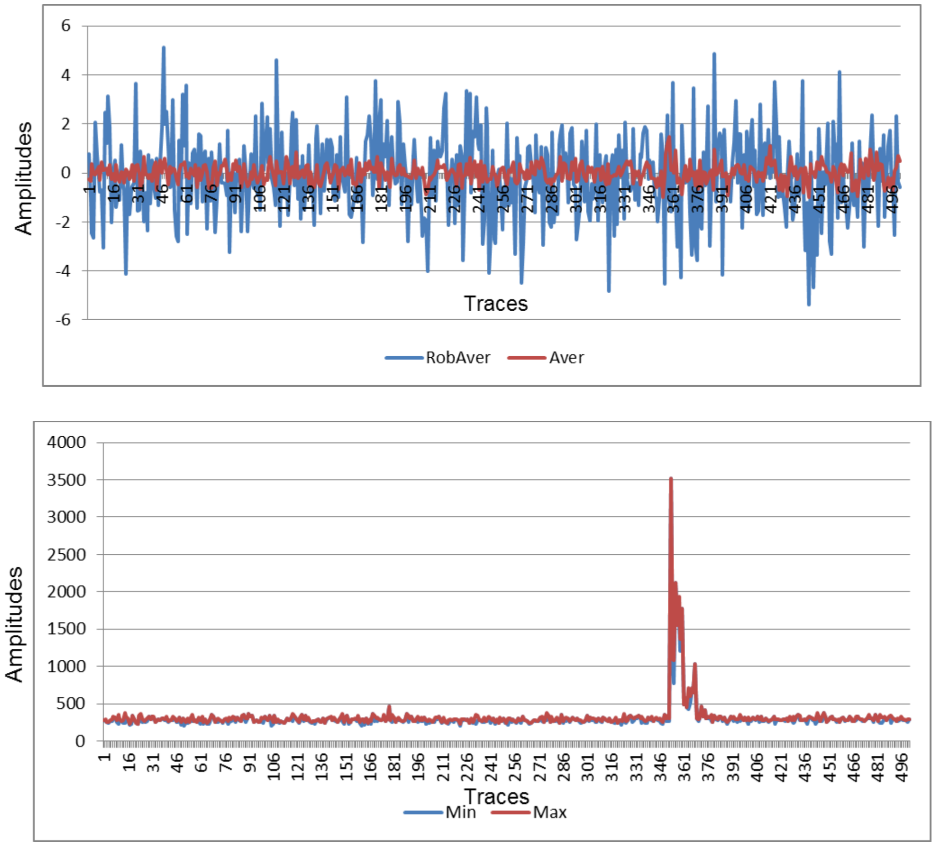


Figure 41. The curves of the mean amplitudes and the coarsened mean amplitudes (top panel). The detection of a microseismic event is difficult. Minimum and maximum amplitudes are shown in the bottom panel (Tcherkashnev S.).

NRMS Attribute Approach

The normalised RMS (NRMS) is the difference between two datasets and used as a quality control measurement for repeatable data (Kragh and Christie 2002). In most cases, the NRMS values are used without considering the signal bandwidth of the data despite publications indicating a dependency of the NRMS value to the data dominant frequency (Calvert, 2005). Equation (3) defines the NRMS metric as the normalised energy of the difference between two seismic traces (base, b and monitor, m):

$$NRMS = 2\frac{RMS\,(b-m)}{RMS\,(b)+RMS\,(m)} \qquad (4)$$

Figure 43 and Figure 44 show the first break transit times, the signal and the noise amplitudes on the surface reference geophone for a land vibroseis ZVSP survey (Figure 42). Note there are significant the transit times and the amplitudes variations between the repeat traces.

The NRMS results for the noisy repeat traces at 2710m and the good traces at 3350 m are displayed in Figure 45. Figure 46 shows the NRMS results for a whole land vibroseis VSP survey. It is difficult to QC and to select bad and good repeat traces using NRMS attributes. The NRMS attributes can be used as a QC indicator showing a general trend.

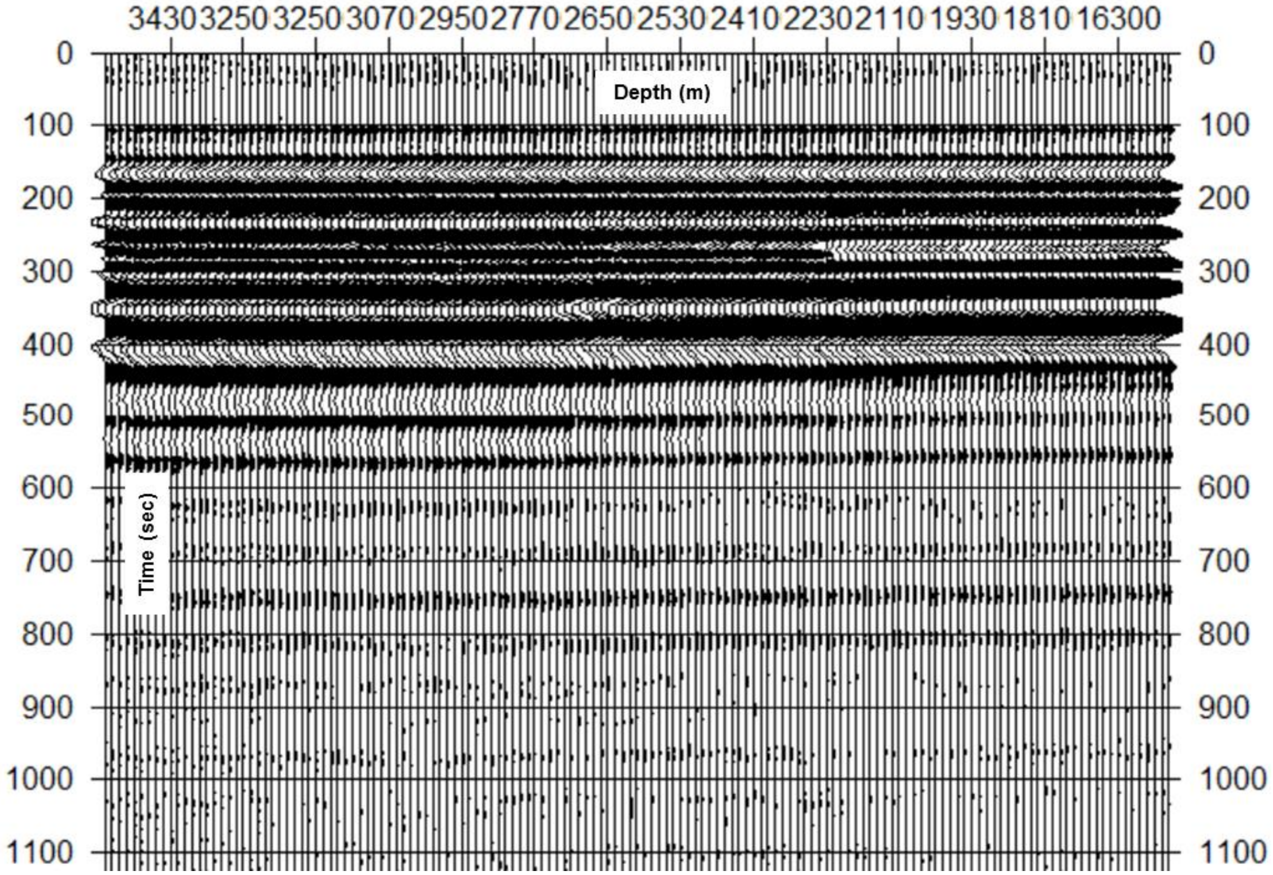


Figure 42. A land vibroseis VSP survey. The surface reference geophone is used to QC vibrator performance (Tcherkashnev S.).

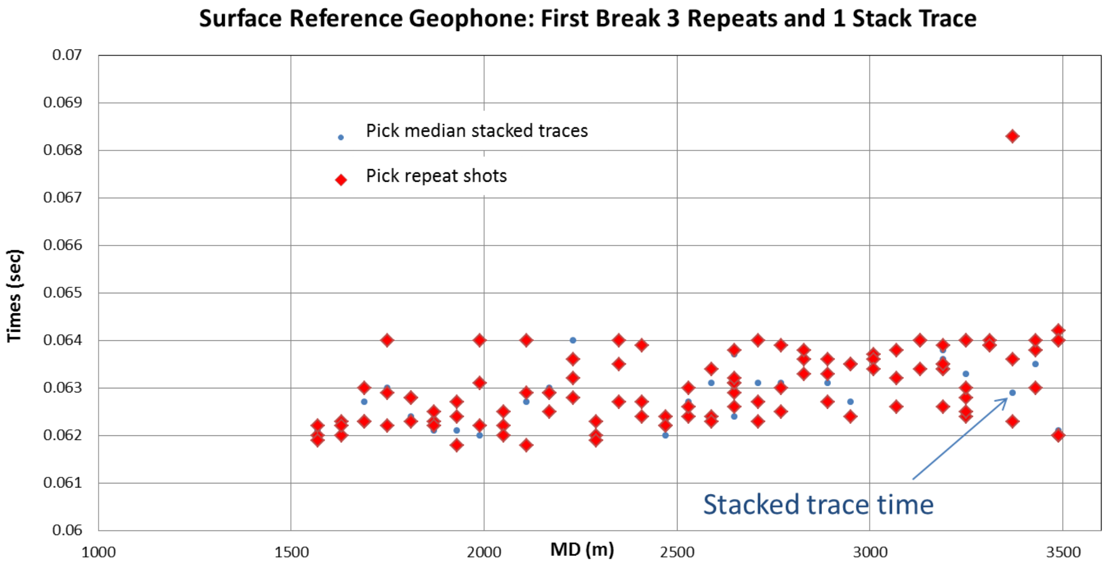


Figure 43. A land vibroseis VSP survey. The surface reference geophone arrival time analysis (Tcherkashnev S.).

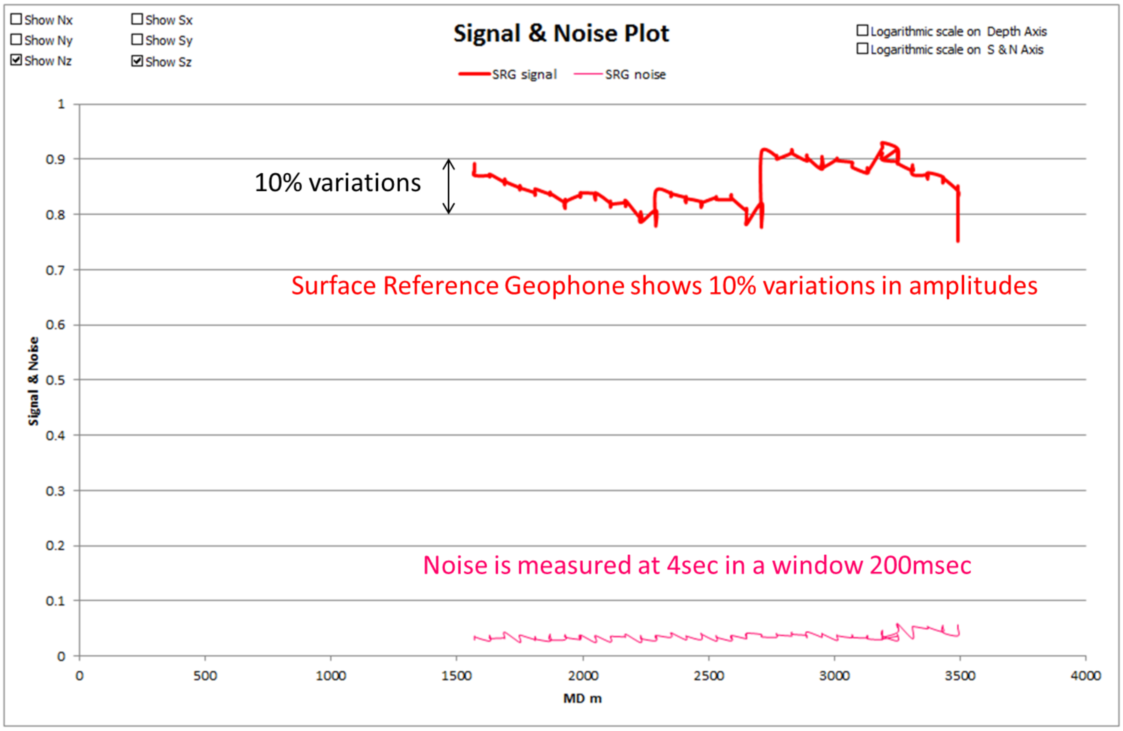


Figure 44. A land vibroseis VSP survey. The surface reference geophone signal and noise amplitude analysis (Tcherkashnev S.).

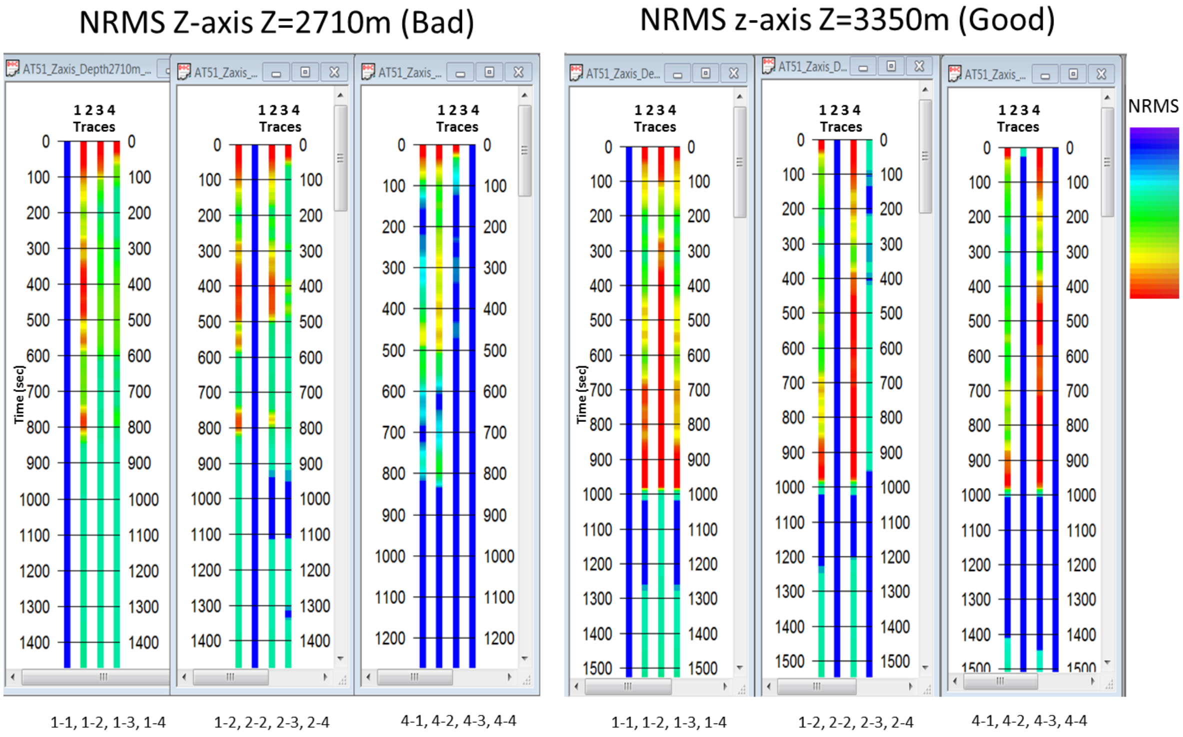


Figure 45. A land vibroseis VSP survey. The NRMS attribute results for the noisy repeat traces at 2710m and the good traces at 3350 m. It is difficult to QC bad and good data using NRMS attributes (Tcherkashnev S.).

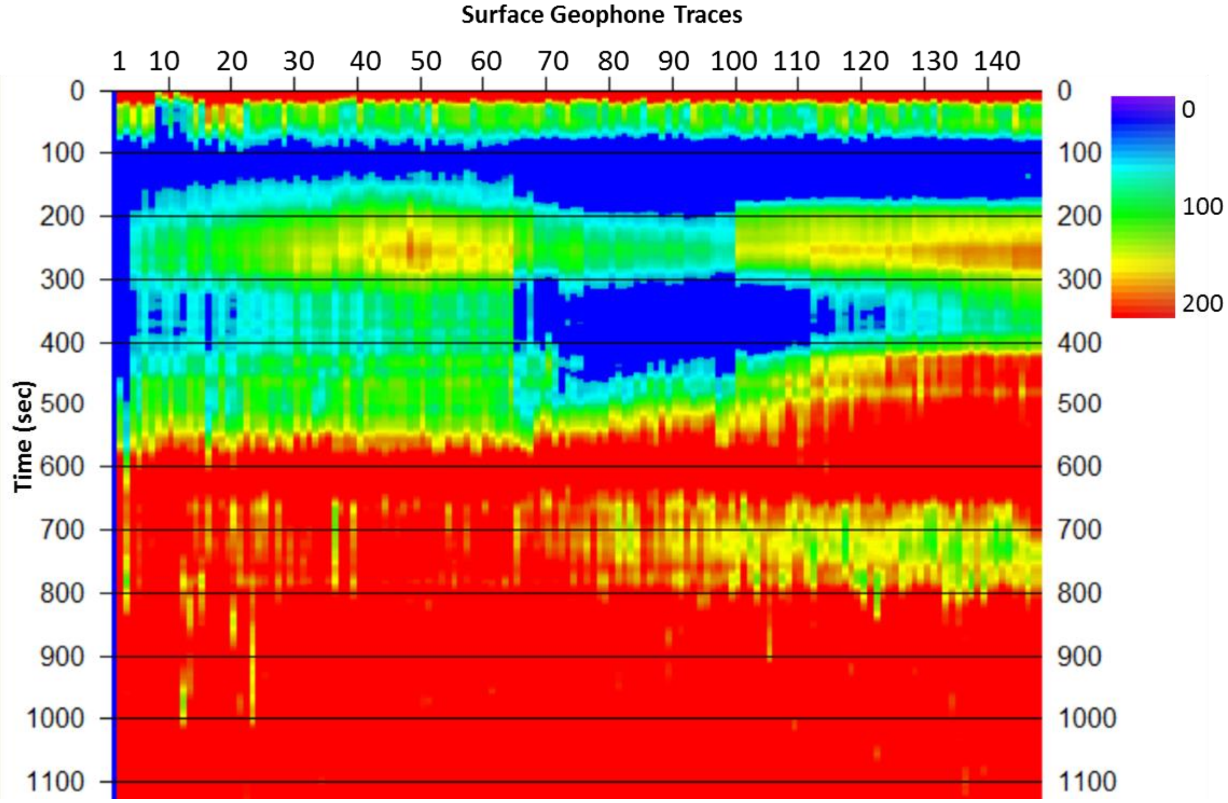


Figure 46. A land vibroseis VSP survey. The NRMS attribute results for all traces. A 1^{st} trace is the reference trace in NRMS estimation (Tcherkashnev S.).

SDR Attribute Approach

Analytical signal-to-distortion ratio (SDR) attribute is a reliable indicator of seismic traces repeatability allowing different acquisition technologies, deployment and processing strategies to be compared (Cantillo, 2012). Figure 47 shows a comparison of NRMS and SDR results for the same data sets. There are two totally different repeatability scenarios with the top panel on the left is poor repeatability and the bottom panel on the left is good repeatability with equal NMRM. However SDR metrics clearly shows the low values (<2) for poor repeatability and the high values (>30-100) for good repeatability scenario.

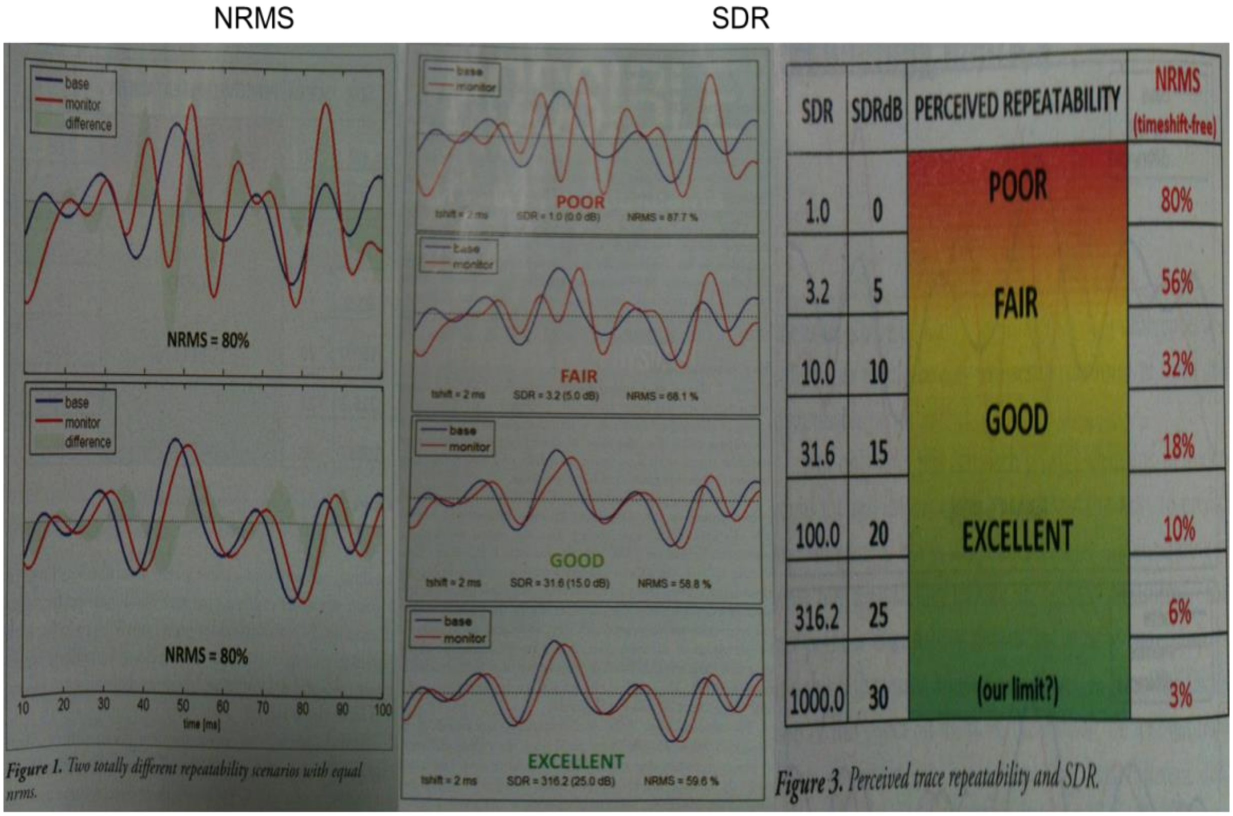


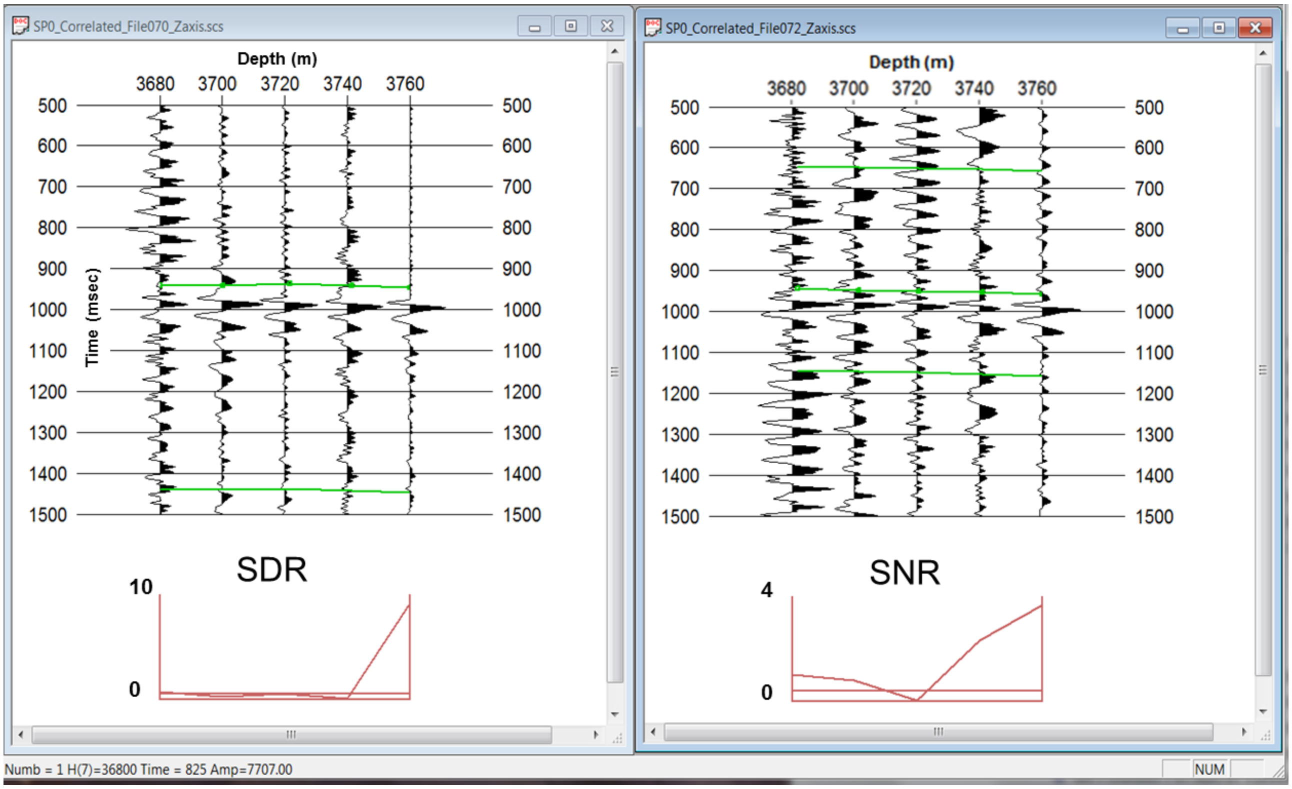
Figure 1. Two totally different repeatability scenarios with equal nrms.

SDR	SDRdB	PERCEIVED REPEATABILITY	NRMS (timeshift-free)
1.0	0	POOR	80%
3.2	5	FAIR	56%
10.0	10		32%
31.6	15	GOOD	18%
100.0	20	EXCELLENT	10%
316.2	25		6%
1000.0	30	(our limit?)	3%

Figure 3. Perceived trace repeatability and SDR.

Figure 47. A comparison of NRMS and SDR results (from Cantillo, 2012).

Another example of NMRS and SDR results for a land vibroseis VSP survey is displayed in Figure 48. The SDR results (left) are computed in VSP QC software indicate good and poor repeatability uniquely than the NRMS results (right).



Numb = 1 H(7)=36800 Time = 825 Amp=7707.00

Figure 48. A land vibroseis VSP survey. The SNR and SDR results using the repeat traces (VSP QC software) (Tcherkashnev S.).

VSP QC Software

A prototyped VSP QC is ongoing software development for quality control analysis. VSP QC software is developed by myself under ASTO Geophysical Consulting Pty. Ltd. (Australia) and has been used for master's thesis. It allows to load SEGY files, plot the waveforms, pick the first break arrival times, calculate signal and noise amplitudes, estimate a phase and static between traces, compute cross correlation coefficients, SNR and SDR attributes and deselect the poor quality data. These results are used by field supervisors from ASTO Geophysical Consulting Pty. Ltd. to evaluate data quality in real time and in post-mortem QC analysis.

Figure 49 shows a main window of the VSP QC software with the computed S/N attribute at the bottom using a land vibroseis ZVSP survey.

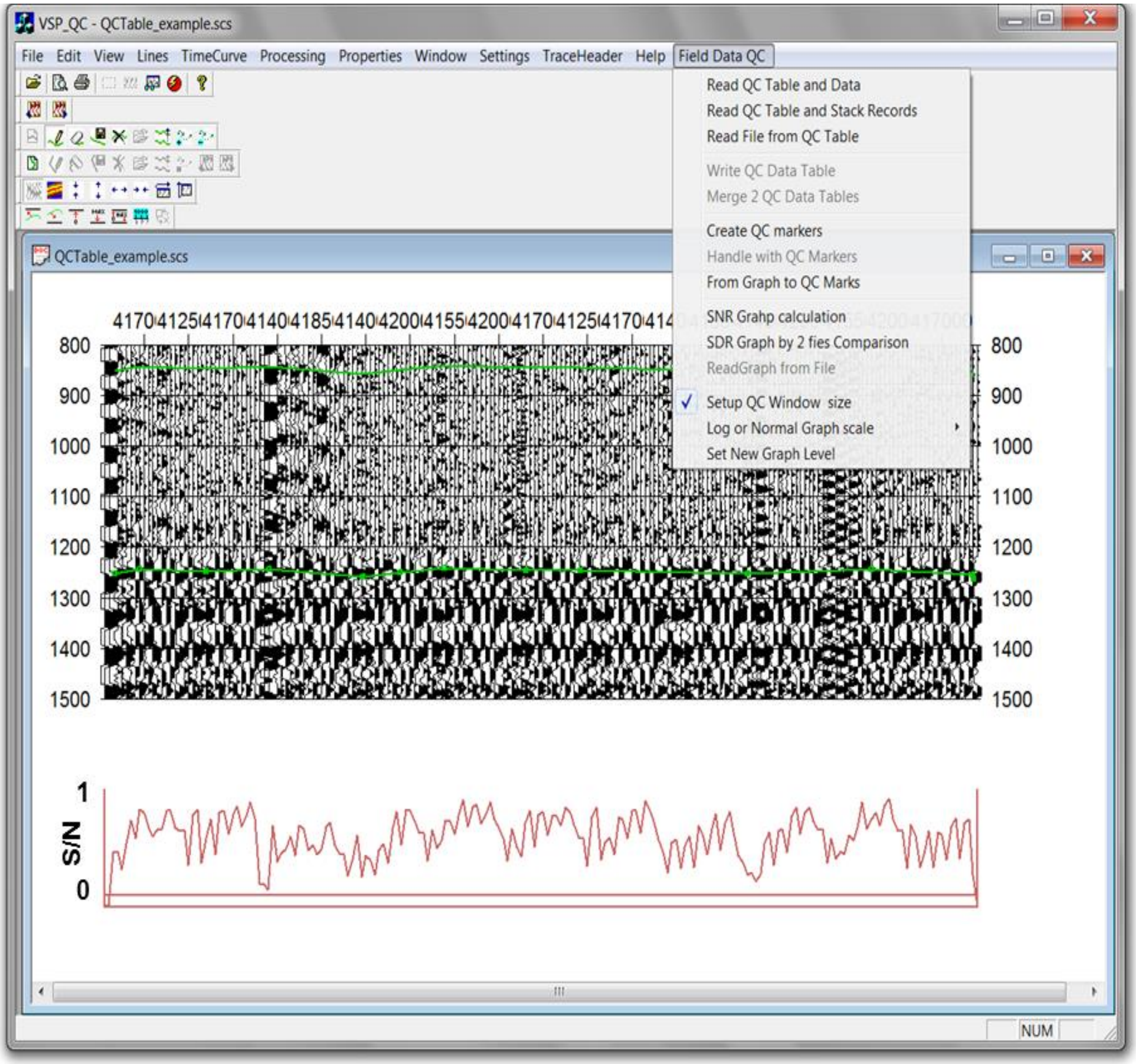


Figure 49. A main window of the VSP QC software (Tcherkashnev S.).

Figure 50 displays the waveforms and the computed S/N attribute for a land vibroseis ZVSP survey. VSP QC outputs a signal and noise amplitude table for QC analysis and selecting bad traces.

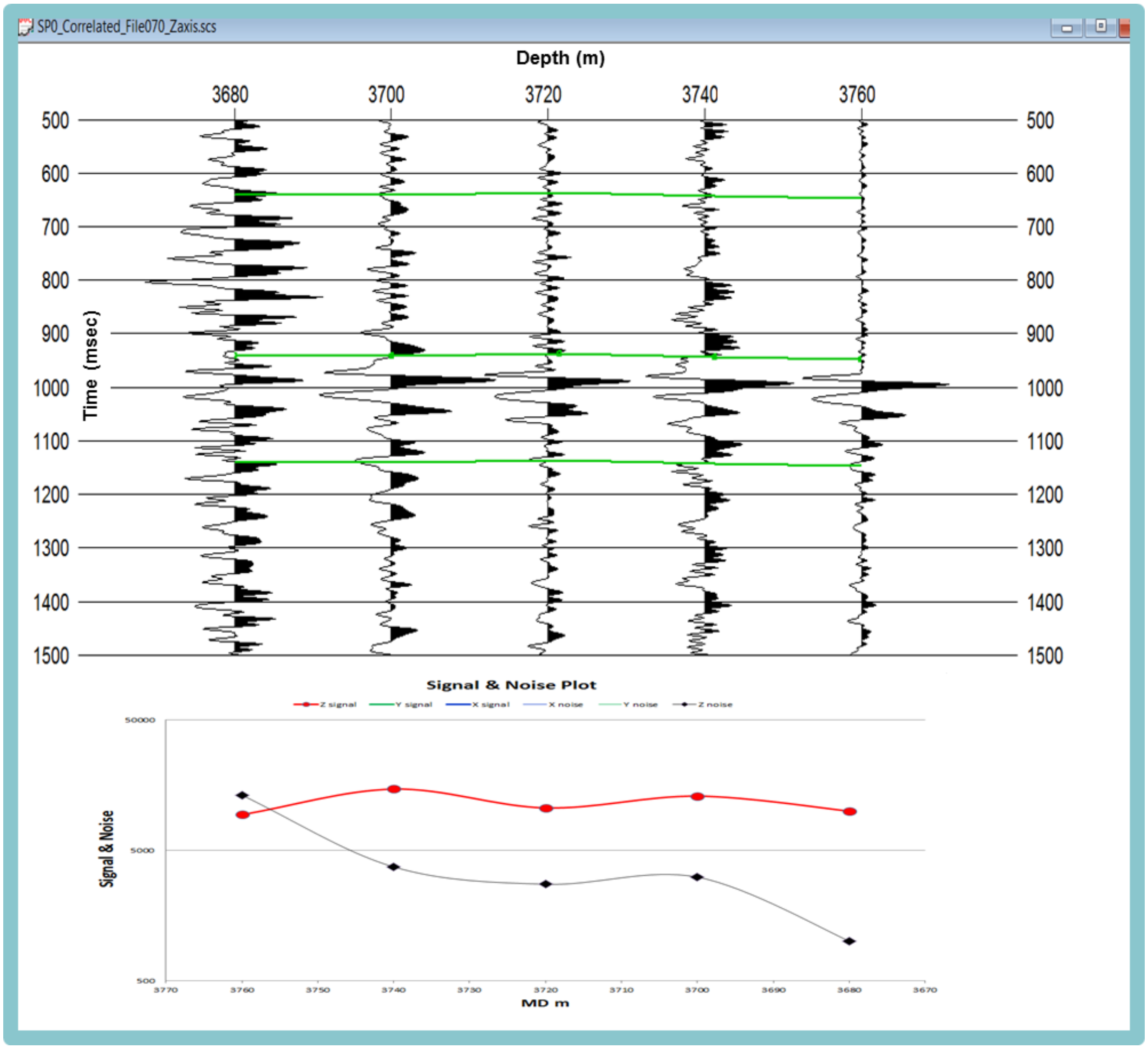
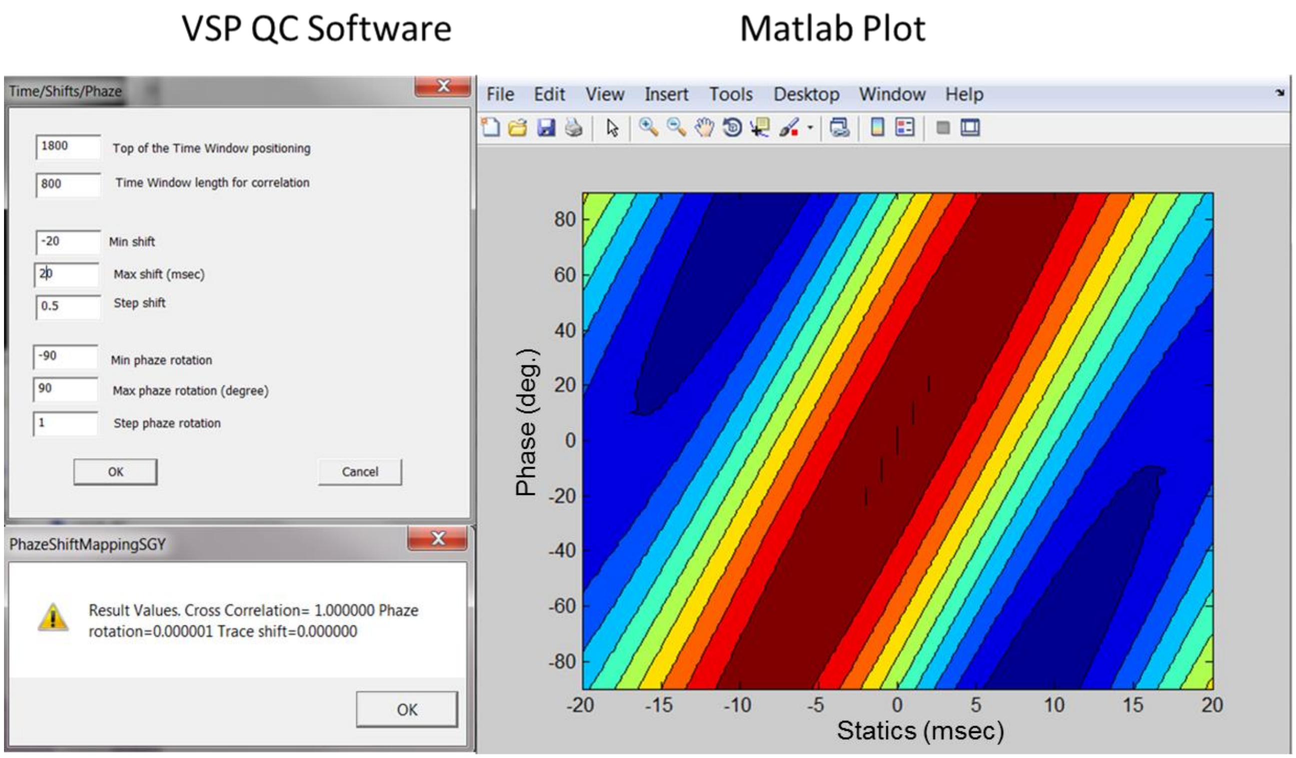


Figure 50. Signal-to noise ratio results from VSP QC software (Tcherkashnev S.).

A computed time difference and a phase shift between surface seismic at a well location and a VSP corridor stack are shown in Figure 51. Matlab is used to crossplot the results. Amplitudes, statics and phase differences between the repeat shots from the surface reference geophone can also be used to compensate for the source variations. Only a limited number of VSP commercial software packages have robust functionalities to compensate for amplitude, time and phase source variations.


VSP QC Software

Matlab Plot

Time/Shifts/Phaze

1800 Top of the Time Window positioning

800 Time Window length for correlation

-20 Min shift

20 Max shift (msec)

0.5 Step shift

-90 Min phaze rotation

90 Max phaze rotation (degree)

1 Step phaze rotation

PhazeShiftMappingSGY

Result Values. Cross Correlation= 1.000000 Phaze rotation=0.000001 Trace shift=0.000000

Figure 51. A phase, static and cross correlation computation (VSP QC) and plotting the results in Matlab (Tcherkashnev S.).

Repeat Shots Analysis

The most common borehole seismic survey is a Zero Offset VSP survey. Usually up to 3-5-7 repeat shots are taken at every tool position (10m - 15m depth interval) as per a VSP acquisition program provided by the client. The repeat shots are recorded in order to improve the data quality during signal processing. It is achieved by removing bad or noisy traces and increasing the signal to noise ratio by stacking. Repeat shot analysis is carried out using the six downhole geophones with eleven repeat shots (Z axis) for a land vibroseis ZVSP survey. Figure 52 shows the repeat traces sorted trace by trace and by a depth index in Figure 53. The eleven repeat shots represent enough information for statistical evaluation purposes. This rich data set is used as an example for repeat shot analysis. Figure 54 and Figure 55 shows the noise and the signal RMS amplitudes for median stacking option (Z-axis).

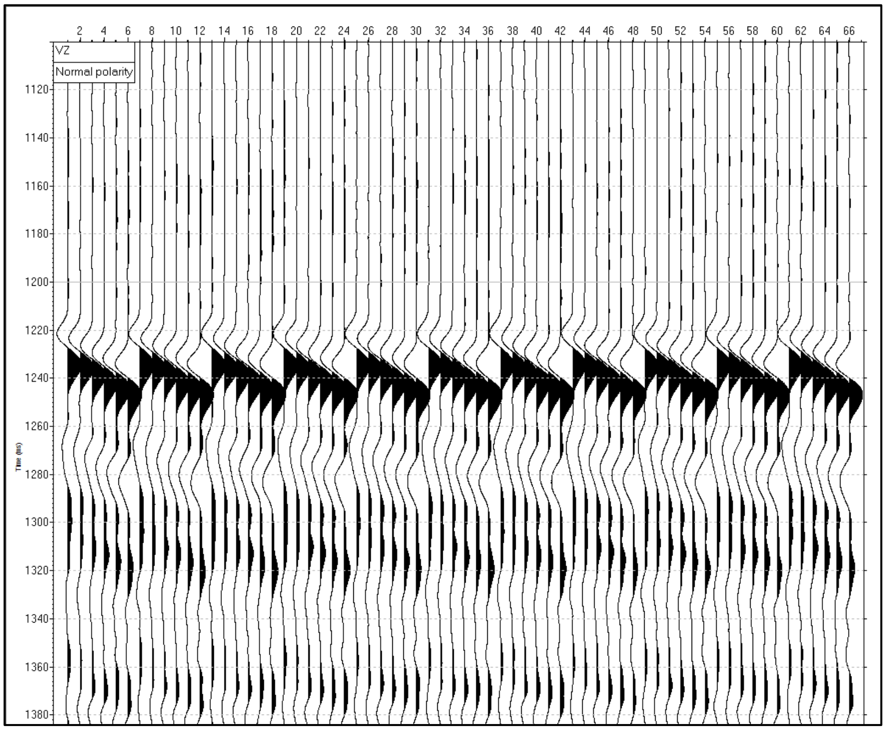


Figure 52. A land vibroseis ZVSP survey (Z axis) with 6 geophones, 11 repeat shots sorted by a trace index (Tcherkashnev S.).

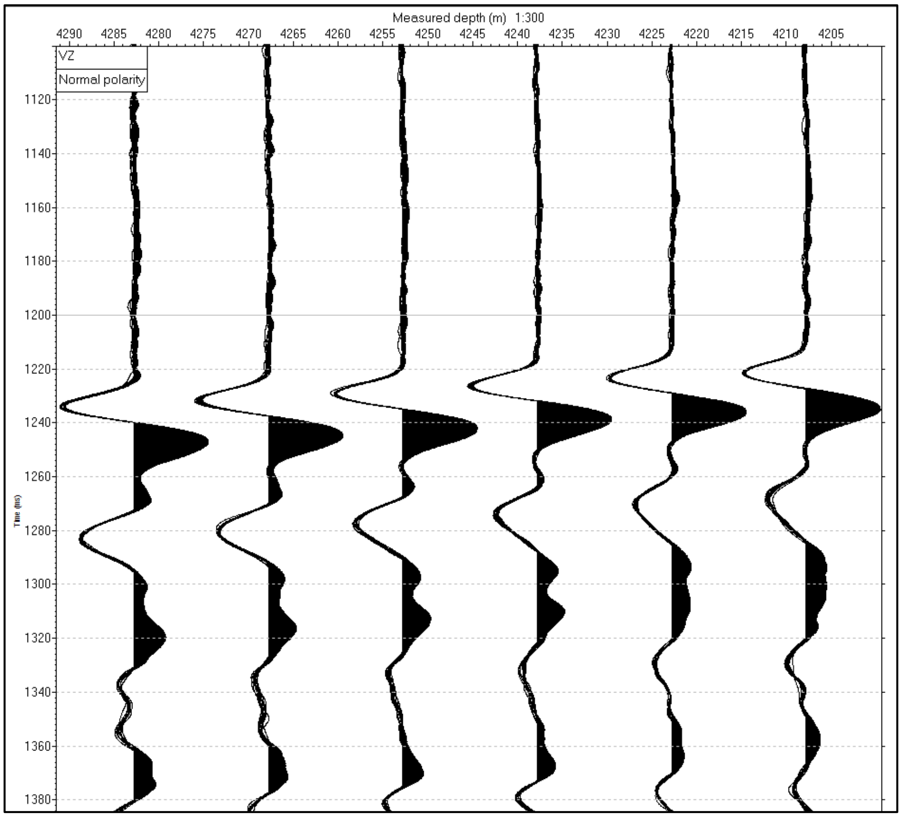
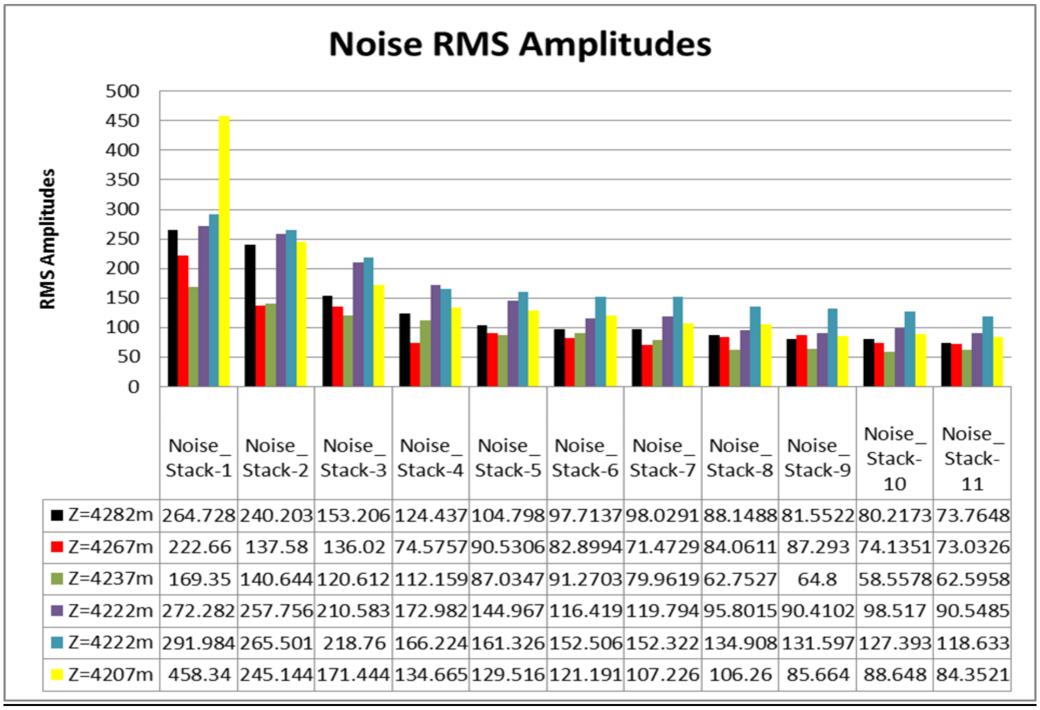
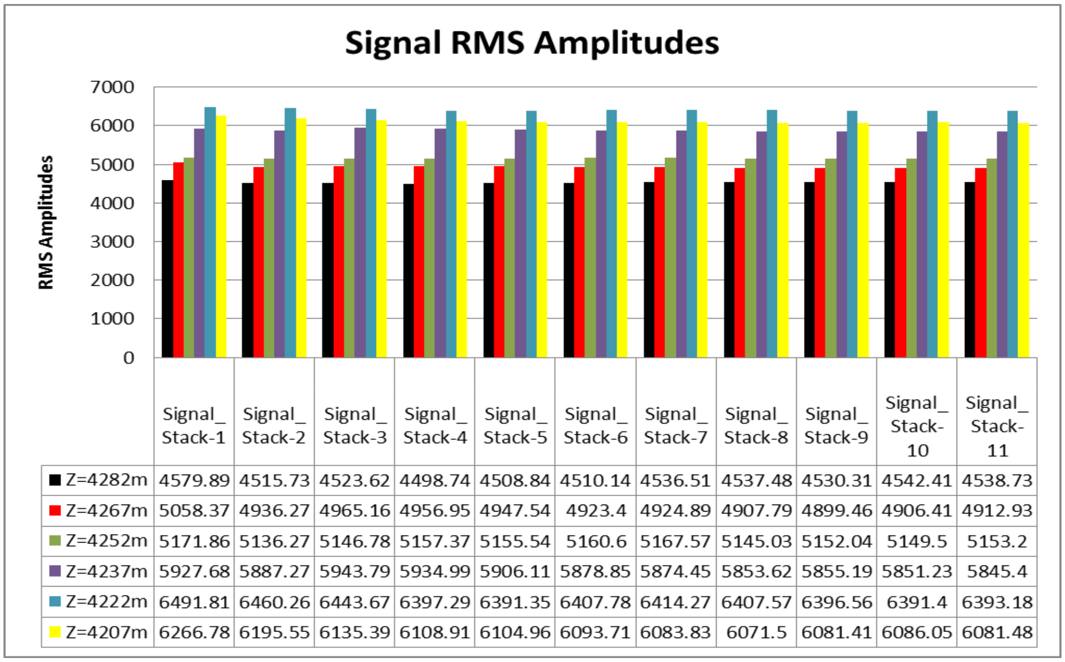


Figure 53. A land vibroseis ZVSP survey (Z axis) with 6 geophones, 11 repeat shots sorted by a depth index (Tcherkashnev S.).



	Noise_ Stack-1	Noise_ Stack-2	Noise_ Stack-3	Noise_ Stack-4	Noise_ Stack-5	Noise_ Stack-6	Noise_ Stack-7	Noise_ Stack-8	Noise_ Stack-9	Noise_ Stack-10	Noise_ Stack-11
■ Z=4282m	264.728	240.203	153.206	124.437	104.798	97.7137	98.0291	88.1488	81.5522	80.2173	73.7648
■ Z=4267m	222.66	137.58	136.02	74.5757	90.5306	82.8994	71.4729	84.0611	87.293	74.1351	73.0326
■ Z=4237m	169.35	140.644	120.612	112.159	87.0347	91.2703	79.9619	62.7527	64.8	58.5578	62.5958
■ Z=4222m	272.282	257.756	210.583	172.982	144.967	116.419	119.794	95.8015	90.4102	98.517	90.5485
■ Z=4222m	291.984	265.501	218.76	166.224	161.326	152.506	152.322	134.908	131.597	127.393	118.633
■ Z=4207m	458.34	245.144	171.444	134.665	129.516	121.191	107.226	106.26	85.664	88.648	84.3521

Figure 54. Noise RMS amplitudes computed in a 100 msec window before First Break (Tcherkashnev S.).

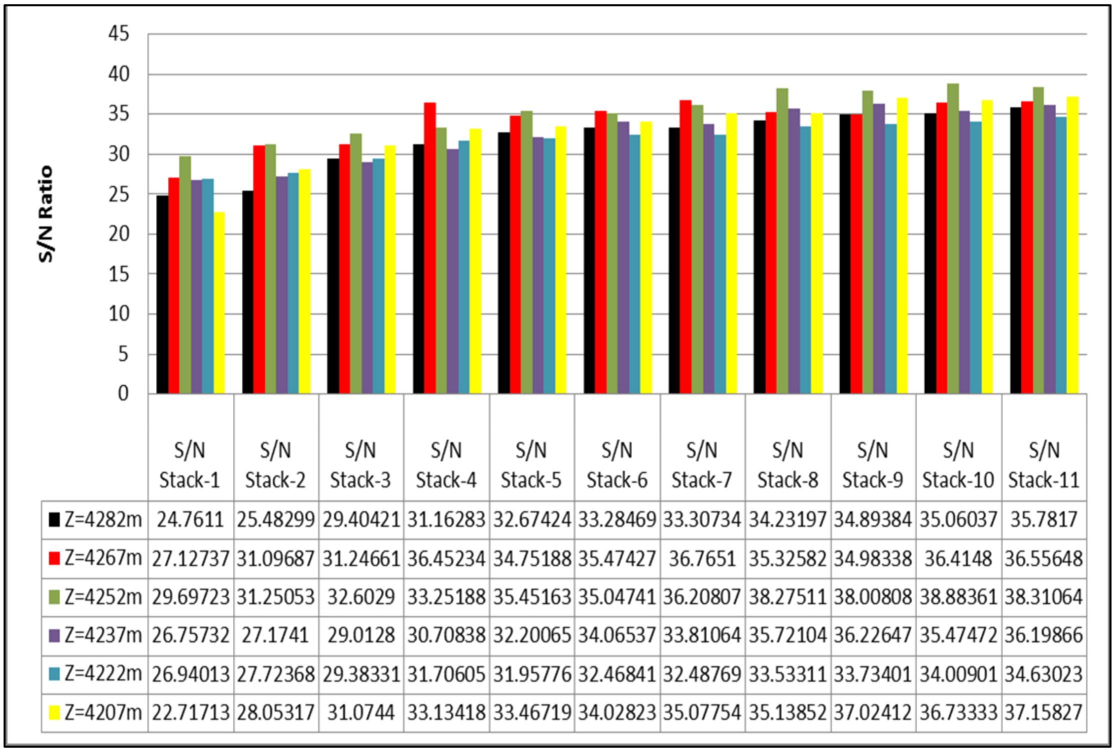


	Signal_ Stack-1	Signal_ Stack-2	Signal_ Stack-3	Signal_ Stack-4	Signal_ Stack-5	Signal_ Stack-6	Signal_ Stack-7	Signal_ Stack-8	Signal_ Stack-9	Signal_ Stack-10	Signal_ Stack-11
■ Z=4282m	4579.89	4515.73	4523.62	4498.74	4508.84	4510.14	4536.51	4537.48	4530.31	4542.41	4538.73
■ Z=4267m	5058.37	4936.27	4965.16	4956.95	4947.54	4923.4	4924.89	4907.79	4899.46	4906.41	4912.93
■ Z=4252m	5171.86	5136.27	5146.78	5157.37	5155.54	5160.6	5167.57	5145.03	5152.04	5149.5	5153.2
■ Z=4237m	5927.68	5887.27	5943.79	5934.99	5906.11	5878.85	5874.45	5853.62	5855.19	5851.23	5845.4
■ Z=4222m	6491.81	6460.26	6443.67	6397.29	6391.35	6407.78	6414.27	6407.57	6396.56	6391.4	6393.18
■ Z=4207m	6266.78	6195.55	6135.39	6108.91	6104.96	6093.71	6083.83	6071.5	6081.41	6086.05	6081.48

Figure 55. Signal RMS amplitudes computed in a 100 msec window after First Break (Tcherkashnev S.).

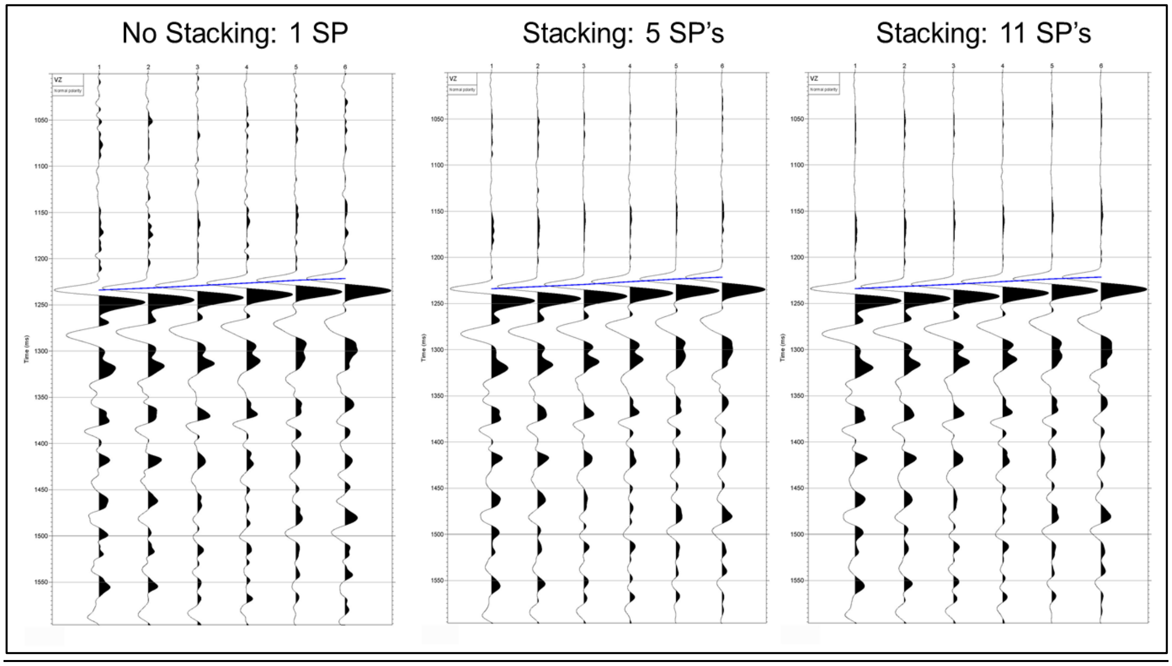
Amplitude analysis indicates that a level of noise stabilises after median stacking three repeat shots (Figure 54). Another important observation is that a level of signal for good repeatable shots is not increased after median stacking (Figure 55). Note that stacking 3 repeat shots increases S/N by 5 dB, stacking 5 repeat shots increases S/N by 7 dB and stacking 11 repeat shots increases S/N by 12 dB (Figure 56). Figure 57 displays the downhole Z-axis waveforms for one shot (left), after median stacking 5 shots (middle) and after median stacking 11 shots (right) with decreasing a level of noise. Figure 58 shows a comparison of one shot versus stacking 11 shots in the time and the frequency domain. Note that a signal before and after stacking has the same level of amplitudes and only the high frequencies are attenuated by median stacking. Figure 58 displays that noise dominant frequency is higher than the dominant frequency of the seismic signal (top panel). Consequently median stacking does improve S/N.

Repeat shot analysis is not carried out for every ZVSP. The common practice is to record 3-5 repeat shots in every VSP survey with airgun and vibroseis. However repeat shot analysis must be done during the evaluation phase before a main VSP survey and included in a logging program.



	S/N Stack-1	S/N Stack-2	S/N Stack-3	S/N Stack-4	S/N Stack-5	S/N Stack-6	S/N Stack-7	S/N Stack-8	S/N Stack-9	S/N Stack-10	S/N Stack-11
■ Z=4282m	24.7611	25.48299	29.40421	31.16283	32.67424	33.28469	33.30734	34.23197	34.89384	35.06037	35.7817
■ Z=4267m	27.12737	31.09687	31.24661	36.45234	34.75188	35.47427	36.7651	35.32582	34.98338	36.4148	36.55648
■ Z=4252m	29.69723	31.25053	32.6029	33.25188	35.45163	35.04741	36.20807	38.27511	38.00808	38.88361	38.31064
■ Z=4237m	26.75732	27.1741	29.0128	30.70838	32.20065	34.06537	33.81064	35.72104	36.22647	35.47472	36.19866
■ Z=4222m	26.94013	27.72368	29.38331	31.70605	31.95776	32.46841	32.48769	33.53311	33.73401	34.00901	34.63023
■ Z=4207m	22.71713	28.05317	31.0744	33.13418	33.46719	34.02823	35.07754	35.13852	37.02412	36.73333	37.15827

Figure 56. S/N for different stacking scenarios (Tcherkashnev S.).


No Stacking: 1 SP

Stacking: 5 SP's

Stacking: 11 SP's

Figure 57. The median stacking results with 1 SP (left), 5 SP's (middle) and 11 SP's (right) (Tcherkashnev S.).

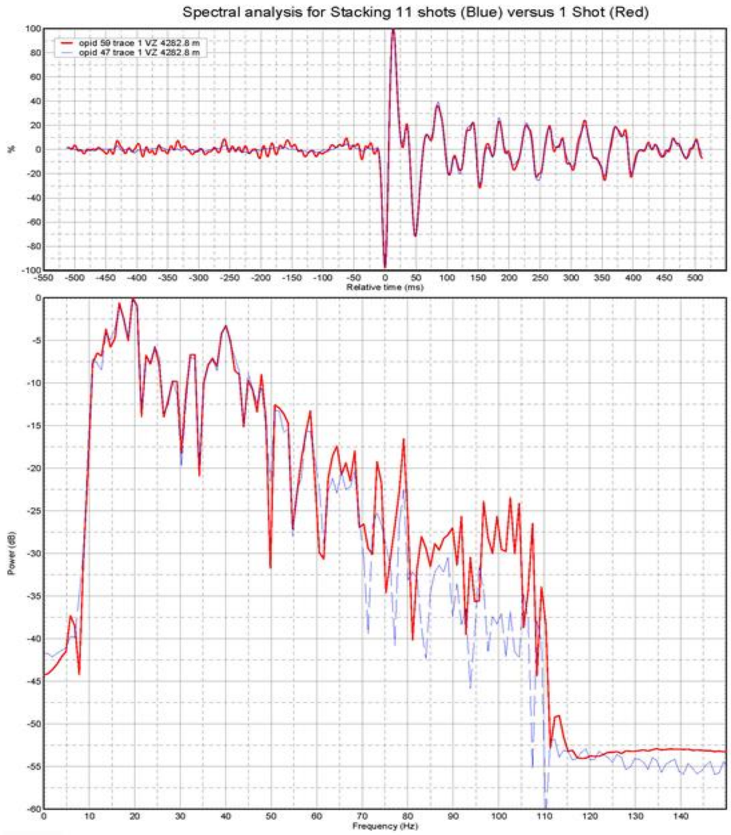

Spectral analysis for Stacking 11 shots (Blue) versus 1 Shot (Red)

Figure 58. Median stacking 11 SP's (blue) versus a 1 SP (red) in time (top) and frequency domain (bottom) (Tcherkashnev S.).

An alternative way of stacking repeat shots to improve S/N is a Quad and a Dual downhole receiver deployment. Avalon Science Ltd (UK) and Sercel (France) recently introduced a Quad and a Dual receiver fitted with two and four geophones per axis. One example shows a Quad and a Dual Geochain receiver (ASR) were deployed within a shallow well. Here, single vibrator sweeps were performed for both sensor types. Comparisons of the correlated traces are shown below in Figure 59. The time domain shows significant increase in correlated pick amplitude with the frequency spectra highlighting an average 5 dB improvement across the signal bandwidth (Figure 60).

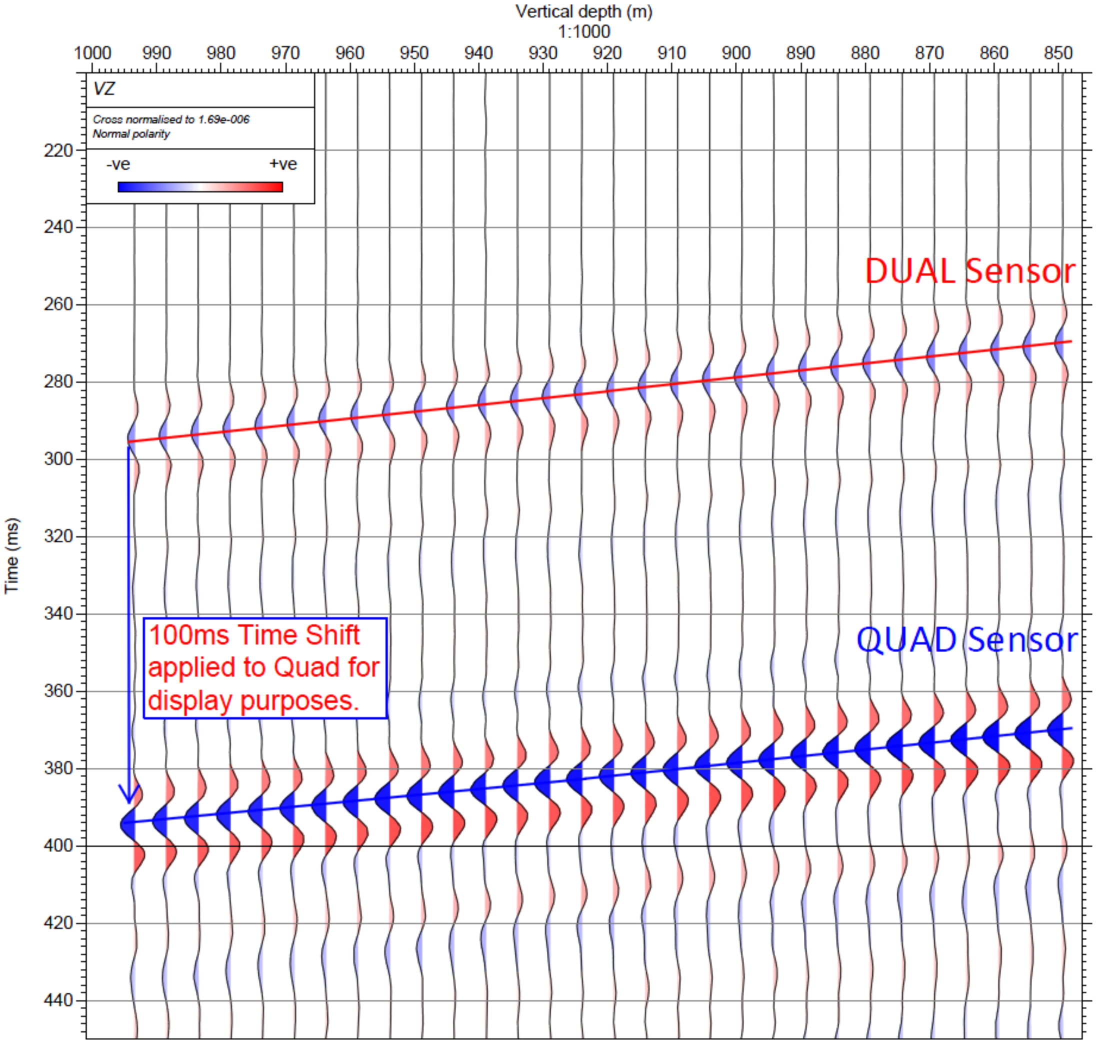


Figure 59. Single sweep downhole Z-axis ASR Dual versus Quad (Courtesy Avalon Science Ltd).

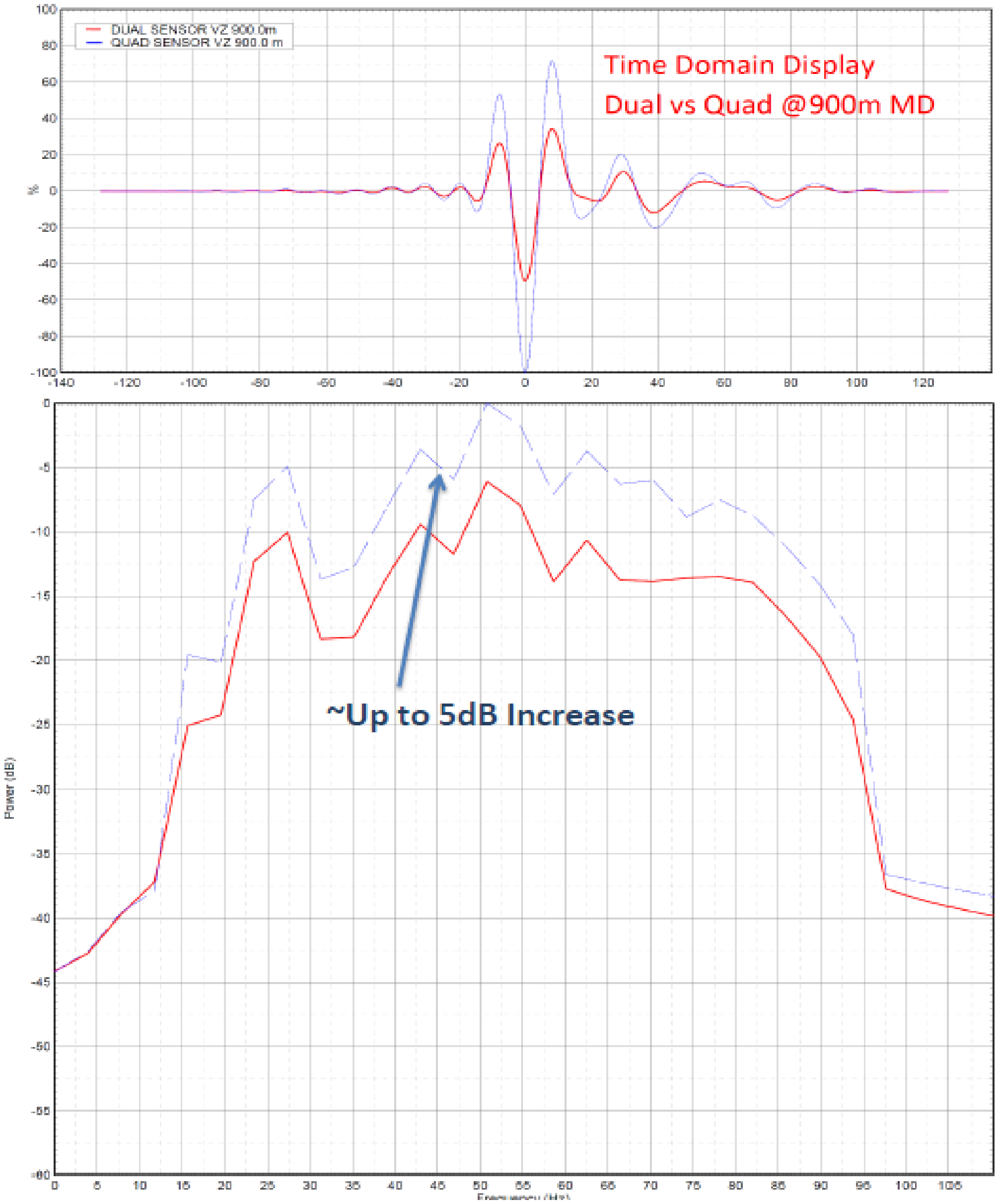


Figure 60. Dual versus Quad response in Time and Frequency domain (Courtesy ASL).

The main conclusions of repeat shot analysis are summarised below.

- Amplitude analysis indicates that a level of noise stabilises after stacking three repeat shots;
- A level of signal for good repeatable shots is not increased after stacking and only the high frequencies are attenuated by stacking;

- Stacking 3 repeat shots increases S/N by 5 dB, 5 repeat shots increases S/N by 7 dB and 11 repeat shots increases S/N by 12 dB;
- Recommend to acquire a VSP survey using a single shot per depth with a Dual or a Quad receiver to improve field acquisition efficiency without compromising data quality and having high S/N.

Acquisition Operation Time Analysis

Statistical analysis of acquisition performance was conducted for two contractors using a land ZVSP survey with a vibrator as shown in Figure 61 and Figure 62. The author has processed these data. Based on this analysis the average acquisition time is between 2:10 and 5:20 minutes for four shuttles with 3-8 repeat shots including data transfer uphole, pre-processing and visual QC analysis. It is interesting to note that time spent on tool anchoring / disanchoring / moving up (green colour) to a next depth position is more than data recording itself (red colour) and it consists of 9:32 – 9:46 minutes. Such QC plots are easy to make and can be used for post-mortem QC analysis to compare the acquisition systems performance and to improve acquisition efficiency. Faster tool deployment, for the example using a magnetic clamping and faster data transmission can reduce total acquisition time and the rig time losses significantly.

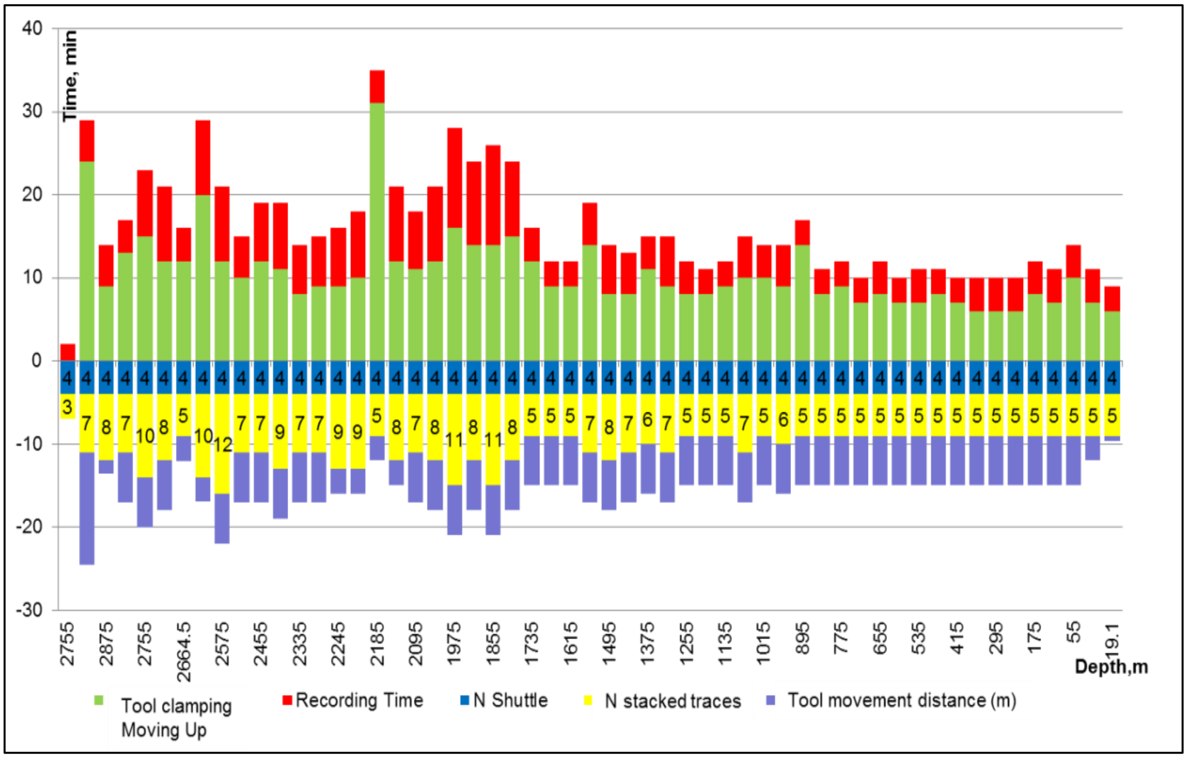


Figure 61. Acquisition Breakdown time for Contractor-1. A land VSP with a vibrator. (Tcherkashnev S.).

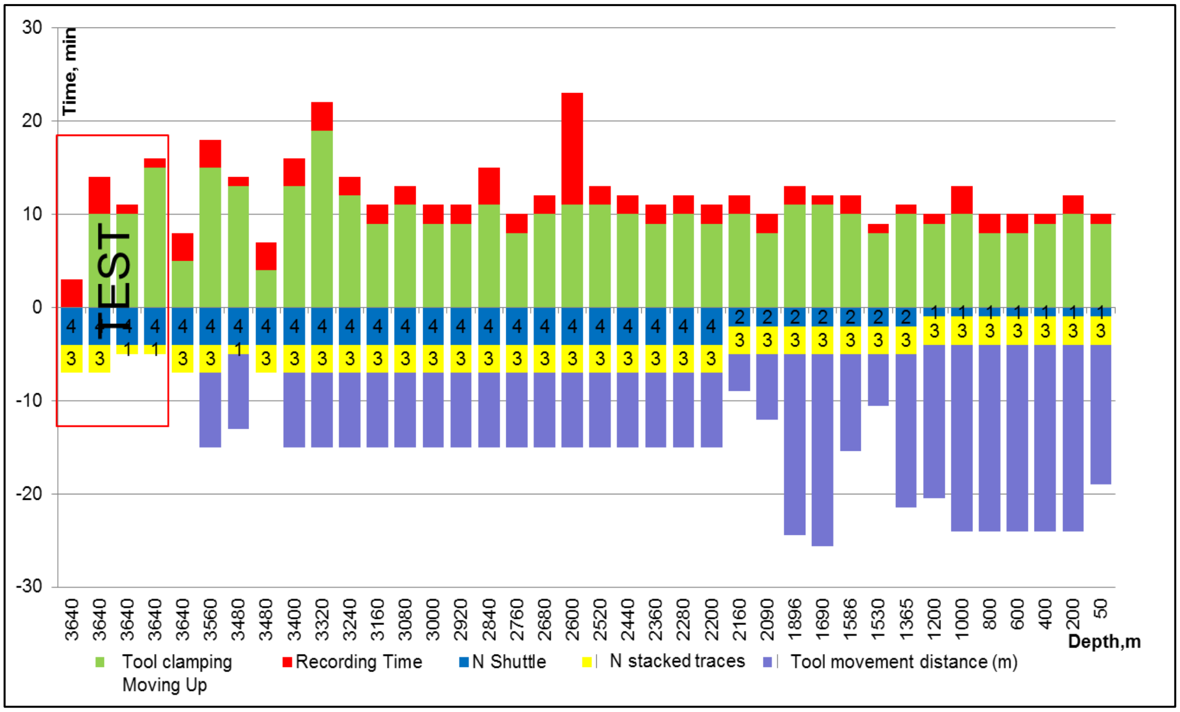


Figure 62. Acquisition Breakdown time for Contractor-2. A land VSP with a vibrator. (Tcherkashnev S.).

Figure 63 shows VSP acquisition breakdown time analysis results from a land VSP job in Kazakhstan. The red column highlights Lost Time due to operation problems. Based on these performance analysis results a client saved $60k by rejecting a contractor invoice which was based on longer crew work schedule. Other benefits on this project were real time QC analysis and onsite processing performed by a supervisor. After this project the client decided to use a dedicated supervisor in future VSP projects.

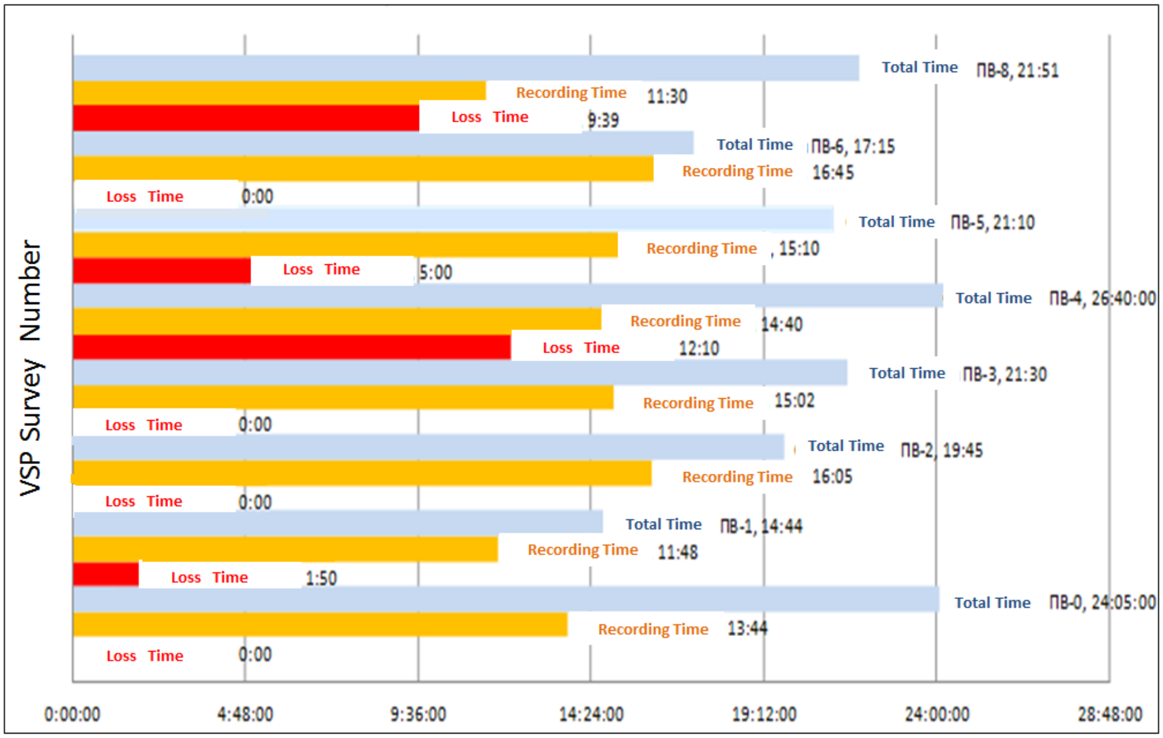


Figure 63. VSP acquisition breakdown time analysis results. Red column highlights Lost Time due to the operation problems (Tcherkashnev S.).

6. Conclusions

VSP data acquisition is highly demanding with respect to equipment type and quality, technical skills including engineering and geophysical specialised knowledge, survey objectives, etc. Because of this it is relatively common that VSP data acquisition is prone to errors and inaccuracies. Identifying the common errors and malpractices in VSP surveys required several years of investigations of numerous case histories. The knowledge acquired allowed me then to propose improvements to the current practice adopted for VSP surveys.

The adopted quality control procedures utilise an advanced method of statistical analysis termed Statistical Process Control (SPC). The proposed quality control approaches are based on the first arrivals and RMS amplitudes of raw repeat shots, signal-to-noise evaluation of stacked data, statistical data analysis and field operation timing analysis derived from the VSP data. The methodology proposed involved the following:

- Standard deviation, Variance of the VSP arrival times and Goodness
- Signal, noise amplitudes and signal-to-noise ratio (SNR)
- Cross correlation coefficients between VSP repeat traces
- Statics and a phase difference between the repeat shots
- Repeatability of VSP traces using Normalised RMS where RMS is root mean square amplitude measured in a window
- Signal distortion ratio (SDR)
- Quality Control Factors as Green (excellent), Yellow (fair), Red (bad) using the computed statistics

The application of the new VSP QC program allowed integration and thorough analysis of borehole seismic, microseismic and DAS data. High correlation was found between several geophysical parameters such as noisy time measurements and dynamic characteristics such as the low signal, the high noise amplitudes and low SNR. There is a good correlation between VSP waveforms showing a low SNR and slowness estimates with a large standard deviation and low Goodness. The Goodness along with the standard deviation curve is a statistical distribution of slowness's and gives a direct indication of how widely distributed the slowness picks are.

The VSP Operation Timing analysis results showed that time spent on tool anchoring / disanchoring / moving up to a next depth position is 2-4 times more than data recording itself. Faster tool deployment, for the example using a magnetic clamping and faster data transmission can reduce total acquisition time and the rig time losses significantly.

Another good finding of the research investigation undertaken by the author is justification of VSP acquisition using a single shot per depth with a Dual or a Quad receiver. This helps to improve field acquisition efficiency without compromising data quality and having high S/N.

The developed BESTQC methodology and VSP QC software can provide cost effective, valuable and comprehensive quality control metrics for clients and service companies to use in order to refine their acquisition methods. These quality control elements will also enable the client to manage risk and make sound decisions based on empirical evidence.

7. References

1. Arroyo, J. L., P. Breton, H. Dijkerman, S. Dingwall, R. Guerra, R. Hope, B. Hornby, R. Jimenez, J. Tulett, S. Leaney, TK. Lim, H. Menkiti, JC. Peach, S. Tcherkashnev, T. Burg, M. Verliac, 2003, Superior Seismic Data from the Borehole: The OilField Review Journal, Schlumberger.

2. Belousov, A. V., Standard assessments of the quality of field seismic material. DEVICES AND SYSTEMS OF EXPLORATION GEOPHYSICS № 03/2011, Russia.

3. Bormann, P., Wielandt E., Seismic Signals and Noise, Chapter 4. 2013.

4. Cantillo, J., Throwing a new light on time-lapse technology, metrics and 4D repeatability with SDR, The Leading Edge, April 2012, Vol. 31, No. 4 : pp. 405-413.

5. Dubrule, O., 1991, Geostatistics for Seismic Data Integration in Earth Model: EAGE DISC 2003.

6. Daley T. M., at al., Field testing of fibre-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring, The Leading Edge, June 2013.

7. Greenwood, A. J., J. C. Dupuis, A. W. Kepic, and M. Urosevic, 2011, Borehole hydrophone acquisition –Some pitfalls and solutions: Borehole Geophysics Workshop, EAGE, 14–17,

8. Frignet B., Hartog A., 2014, Optical Vertical Profiling On Wireline Cable, SPLWA 55th Conference, 2014.

9. Hatton, L., Worthington, M. H., Makin, J. Seismic Data Processing, Book, 1986.

10. Hoover R., 2006, QA/QC and Geophysical Projects: Highway Geophysics – NDE Conference, USA.

11. Krag, E., 2001, Seismic repeatability, normalised rms, and predictability: 71nd Annual International Meeting, SEG, Expanded Abstracts.

12. Krylov, I. B., Notes on the quality of primary seismic material and its estimates, Monography, 2016, Russia.

13. Lansley M. R., 2006, Quality Control in Modern Recording Systems, Benefits Beyond Contract Compliance: 6th International Conference & Exposition on Petroleum Geophysics "Kolkata 2006".

14. Landro, M., 1999, Repeatability issues of 3-D VSP data: Geophysics, 64 (6), pp. 1673-1679.

15. Lensky, V. A., Mamleev, T. S., Danilenko V. N., Borehole Seismic book, VNIIGeoSystem, 2012, Russia.

16. Meunier, J., Daures R., EAGE Vibroseis Workshop, 2008 – Prague, Czech Republic.

17. McNamara, D.E. and R.P. Buland, 2004, Ambient Noise Levels in the Continental United States: Bull. Seism. Soc. Am., 94, 4, 1517-1527.

18. Pevzner, R. L., Urosevic, M., Nakanishi, S., Applicability of Zero-offset and Offset VSP for Time-lapse monitoring - CO2CRC Otway Project Case Study, 72nd EAGE Conference & Exhibition 2010.

19. Schissele, E., E. Forgues, et al., 2009, Seismic repeatability: Is there a limit?, EAGE Amsterdam, 2009, 71st EAGE Conference & Exhibition.

20. Shekhtman, G. A., Vertical Seismic Profiling book, EAGE, 2017, Russia.

21. Shevchenko, A. A., Borehole Seismic book, RGU, 2002, Russia.

22. Tishenko, I. V., A.I. Tishenko, A.A. Zykov, 2008, Quality Control of Surface Seismic Data - Problems and Solutions: EAGE Geomodel Conference & Exhibition, Gelendzik, Russia.

23. Tishchenko I.V., Tishchenko A.I., Zhukov A.A., North-Western Institute of Geology, Lanzhou, CNR, July 2010 Criteria and technique of QC quantitative estimations for seismic field data records.

24. Theys, P., 1991, Log Acquisition and Quality Control.

25. Van Zaanen L., Bona A., Correa J., Dean T., Pevzner R., Tertyshnikov K., 2017, A comparison of borehole seismic receivers, Conference: SEG Technical Program Expanded Abstracts 2017.

26. https://en.wikipedia.org/wiki/Statistical_process_control

Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.

1. ATCE (as SPE 133063PP) in Italy “Evaluating Hydraulic Fracture Effectiveness in a Coal Seam Gas Reservoir from Surface Tiltmetres and Microseismic Monitoring”, Ray Johnson, Jnr., Michael Scott QGC, Brisbane, QLD Australia, Rob Jeffrey, Zuorong Chen, CSIRO Petroleum, Melbourne VIC Australia, C. Vandenborn, Schlumberger Australia Pty. Ltd., S. Tcherkashnev, ASTO Geophysical Consulting Pty. Ltd., Perth, WA, Australia

2. ASEG-2010 conference in Sydney. “Multiple Analysis – A Borehole Seismic Solution” K. Galybin, L. Dahlhaus, Schlumberger, S.Tcherkashnev, ASTO Geophyscial Consulting Pty Ltd.

3. SPE JPT magazine, Technology Focus, Hydraulic Fracturing, March 2011, "Evaluating Hydraulic Fracture Effectiveness in a Coal Seam Gas Reservoir from Surface Tiltmetres and Microseismic Monitoring". Ray Johnson, Jnr., Michael Scott QGC, Rob Jeffrey, Zuorong Chen, CSIRO Petroleum, Australia, C. Vandenborn, Schlumberger, S. Tcherkashnev, ASTO Geophysical Consulting Pty. Ltd., Australia

4. Geomodel-2013, Gelendzik, Russia. “Validation of the geological structure using cross dipole sonic and Walkaway VSP in the Chinarevskoye Field, West Kazakhstan region”. S. Tcherkashnev*, T. Kuptsova, V. Kim (ASTO Geophysical Consulting Pty Ltd), P. Kravetc (JSC «Zaikmunai»), T. Mamleev, (JSC NPF «VNIIGIS», «GITAS»)

5. EAGO-2013, Kaliningrad, Russia. “Walkaway VSP integration with other methods to clarify the geological structure in the Chinarevskoye Field, West Kazakhstan region”. S. Tcherkashnev*, T. Kuptsova, V. Kim (ASTO Geophysical Consulting Pty Ltd), P. Kravetc (JSC «Zaikmunai»), T. Mamleev (JSC NPF «VNIIGIS», «GITAS»)

6. Galperinskie Chtenia-2013, Moscow, Russia. “Integration of 2D Walkaway VSP, cross-dipole acoustics and 3D seismic for refining the geological structure in the Chinarevskoye Field, West Kazakhstan region”. S. Tcherkashnev*, T. Kuptsova, V. Kim (ASTO Geophysical Consulting Pty Ltd), P. Kravetc (JSC «Zaikmunai»), T. Mamleev, (JSC NPF «VNIIGIS», «GITAS»)

7. The 21st international exhibition "OIL, GAS, PETROCHEMICALS", September 3-4, 2014, Kazan, Russia. “Integration of 2D Walkaway VSP, cross-dipole acoustics and 3D seismic for refining the geological structure in the Chinarevskoye Field, West Kazakhstan region”. S. Tcherkashnev*, T. Kuptsova, V. Kim (ASTO Geophysical Consulting Pty Ltd), P. Kravetc (JSC «Zaikmunai»), T. Mamleev, (JSC NPF «VNIIGIS», «GITAS»)

8. The 39th IPA conference, 2015, Jakarta. “Low Frequency Seismic for Hydrocarbon Exploration and Hydraulic Fracturing Monitoring” Shabalin N.Y., Birialtsev E.V., Ryzhov V.A., Feofilov S.A., (Gradient, Russia), Tcherkashnev S.A., Lim T.K., (ASTO Geophysical Consulting Pty. Ltd)

9. ASEG-2016, 25th International Geophysical Conference, Melbourne, Australia. “Mapping of fracture zones and small faults using VSP and Cross Dipole Sonic in Eastern Siberia Carbonate Reservoirs, Yurubchansky Field, Russia” S. Shevchenko* (SIS Exploration), S.Tcherkashnev (ASTO Geophysical Consulting Pty Ltd), M. Kuznetsov (ROSNEFT ESOGC), T. Mamleev (OAO NPP GITAS)

10. EAGO-2016, Carbonate Reservoirs Conference, Moscow, Russia. “Integration of Cross-Dipole Acoustics, Walkaway VSP and 3D Seismic for geological structure mapping of the Yurubchensky gas-condensate field of the Krasnoyarsk Territory” S. Shevchenko (SIS Exploration), S.Tcherkashnev* (ASTO Geophysical Consulting Pty Ltd), M. Kuznetsov (ROSNEFT ESOGC), T. Mamleev (OAO NPP GITAS)

11. Galperinskie Chtenia-2016, Moscow, Russia. “Integration of Cross-Dipole Acoustics, Walkaway VSP and 3D Seismic for geological structure mapping of the Yurubchensky gas-condensate field of the Krasnoyarsk Territory” S. Shevchenko (SIS Exploration), S.Tcherkashnev* (ASTO Geophysical Consulting Pty Ltd), M. Kuznetsov (ROSNEFT ESOGC), T. Mamleev (OAO NPP GITAS)

12. Galperinskie Chtenia-2016, Moscow, Russia.v “Fibre Coherent Reflectometry for Geological and Geophysical Research” S.Tcherkashnev (ASTO Geophysical Consulting Pty Ltd), A.E. Alekseev (OOO Petrofiber)

13. Karotaznik (Well Logging) Journal, Borehole Seismic Technology, December 2016, Russia. “Development of Borehole Seismic Equipment and Technologies in VNIIGIS”, G.G. Safiullin, N.M. Akhmetshin (ZAO NPF SeismoSetService), T.S. Mamleev, A.A. Krusov, V.N. Danilenko (ZAO NPF GITAS), A.G. Bulgarov (OOO NPP IGIS), S.Tcherkashnev (ASTO Geophysical Consulting Pty Ltd), A.E. Alekseev (OOO Petrofiber)

14. Annual Slavneft scientific conference, 2017, Niznevartovsk, Russia. “Integration of Surface Seismic, VSP and LWD for Overpressure Prediction”. A. Mitin* (Weatheford), S. Tcherkashnev (WT & IP consultant)

15. A scientific and technical conference "70 years of scientific research and design of oil and gas fields construction", 2017, Ufa, Russia. “The experience of Walkaway VSP application for Investigation of Oil and Gas Reservoirs ” Danilenko V.N., Mamleev T.S., Sergeev* A.A., Tcherkashnev S.A. (JSC NPF "GITAS")

16. Oil & Gas Journal, Russia, Geology and Geophysics, August 2017, "What are the main advantages and disadvantages of borehole seismic?" S. Tcherkashnev (WT & IP consultant)

17. 80th EAGE Annual Conference and Exhibition 2018, “Integration of cross dipole sonic, Offset VSP and 3D seismic to calibrate a geological model in the Chinarevsky field of the West Kazakhstan region” A. Alzanov, P. Kravetc (JSC « Nostrun Oil&Gaz»), S. Tcherkashnev*, T. Kuptsova, V. Kim (ASTO Geophysical Consulting Pty Ltd)

18. The International G&G Conference and Exhibition: Advanced Exploration and Development Technologies. GeoEurasia 2018, February 5-8, 2018, Moscow, “Fibre optic technology for borehole seismic surveys” S. Tcherkashnev* (ASTO Geophysical Consulting Pty Ltd), A.E. Alekseev (OOO Petrofiber)

19. The International G&G Conference and Exhibition: Advanced Exploration and Development Technologies. GeoEurasia 2018, February 5-8, 2018, Moscow, “New generation of AMC-VSP equipment for borehole seismic surveys” T.S. Mamleev* (ZAO NPF GITAS), S. Tcherkashnev (ASTO Geophysical Consulting Pty Ltd)

20. The International G&G Conference and Exhibition: Advanced Exploration and Development Technologies. GeoEurasia 2018, February 5-8, 2018, Moscow, “Evaluation of the phase spectrum using VSP and Surface Seismic” A.S. Shevchenko* (OOO PetroTrace), S. Tcherkashnev (ASTO Geophysical Consulting Pty Ltd)

21. EAGE Annual Conference and Exhibition 2019, Tumen, Russia, “Modeling and design of walkaway VSP field operations for VTI/TTI anisotropy estimation” I. N. Kerusov (Lukoil-Engineering, LLC), S. A. Tcherkashnev* (Weatherford, LLC), E. A. Blias (Weatherford, LLC), A. V. Mitin (Weatherford, LLC)

22. The International G&G Conference and Exhibition: GeoEurasia 2018, February 5-8, 2019, Moscow, “Analysis of multi-scale VTI anisotropy from seismic, VSP and logs in the Timan-Pechora region” A.U. Andreev (LUKOIL, PJSC) I. N. Kerusov (LUKOIL-Engineering, LLC), S. A. Tcherkashnev* (Weatherford, LLC), E. A. Blias (Weatherford, LLC), A. V. Mitin (Weatherford, LLC)

23. Fifth EAGE Workshop on Borehole Geophysics, 18 -20 November 2019, The Hague, Netherlands “VTI Anisotropy Analysis from 3D Seismic, VSP and Logs in the Timan-Pechora Region” I. N. Kerusov (Lukoil-Engineering, LLC), S. A. Tcherkashnev* (Weatherford, LLC), A. V. Mitin (Weatherford, LLC)

Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.