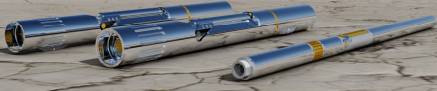


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Borehole Seismic – What's Needed, **What's New,** What's Next.....

.... An Avalon perspective



Press F5 to activate embedded animations 2018 G. Tubridy, W. Wills.

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Geochain / ASR

Contents

- About Avalon
- **What's Needed – a time line**
 - **DEEPER, FASTER, HOTTER, STRONGER... For LONGER!**
- **What's New**
 - Low Noise/High Sensitivity
 - Increased Tools and Recording Options
 - Increased Temperature
 - Increased Pressure
 - High Side Indicator
- **What's Next**
 - The role of Fibre/DAS...Substitute or Supplement?

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About Avalon

Avalon Sciences Ltd (ASL) are based in Somerset UK.

We manufacture down-hole multilevel seismic receivers, sparker sources, recording and processing systems for VSP and MICROSEISMIC surveying.



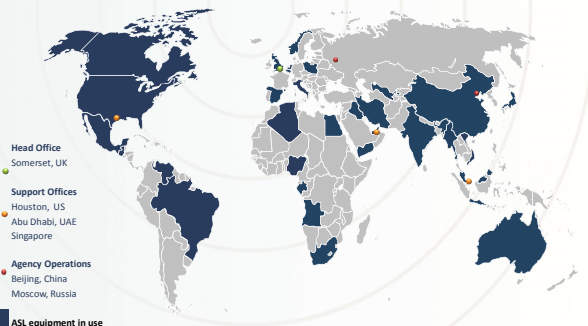
ASL products are designed to deliver the seismic data in the toughest well conditions suitable for short and long term operation

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A Global business

ASL equipment in use



Head Office
Somerset, UK

Support Offices
Houston, US
Abu Dhabi, UAE
Singapore

Agency Operations
Beijing, China
Moscow, Russia

ASL equipment in use

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Brief Overview of the Borehole Seismic Receiver

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SYSTEM OVERVIEW

VSP's traditionally require down-hole multilevel seismic receivers deployed on a wireline from surface within cased and open hole well environments.

- The standard seismic tool consists of a pressure housing hosting a geophone sensor pack, clamping arm mechanism and downhole analogue to digital converter.
- Tools can have a range of diameters and lengths, each with unique coupling mechanisms.



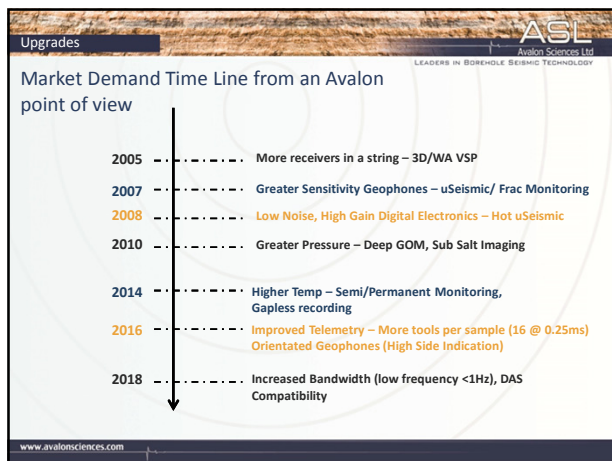
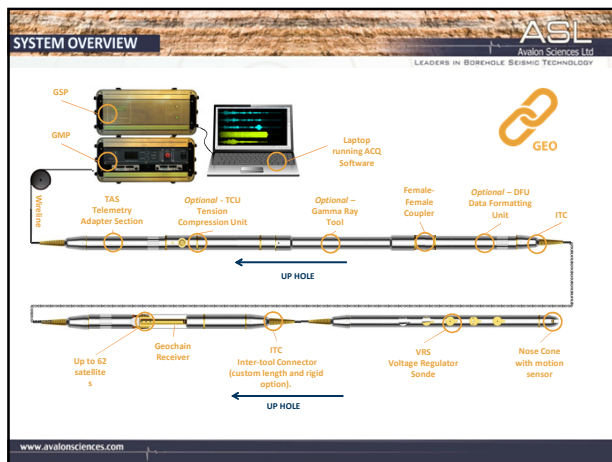
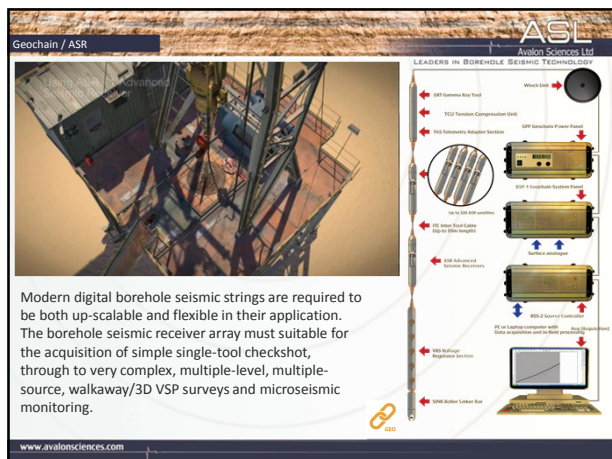
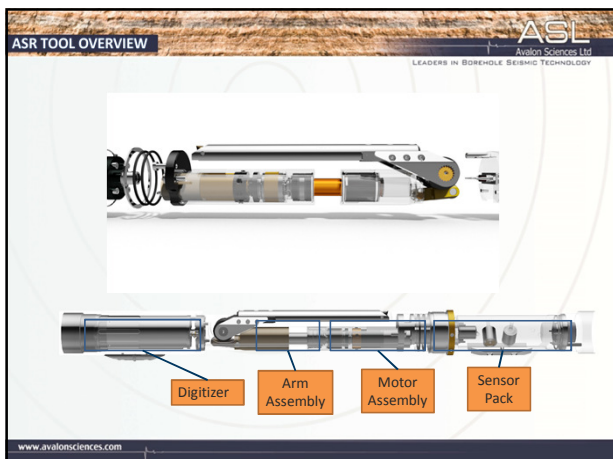
Geochain™ Advanced Seismic Receiver

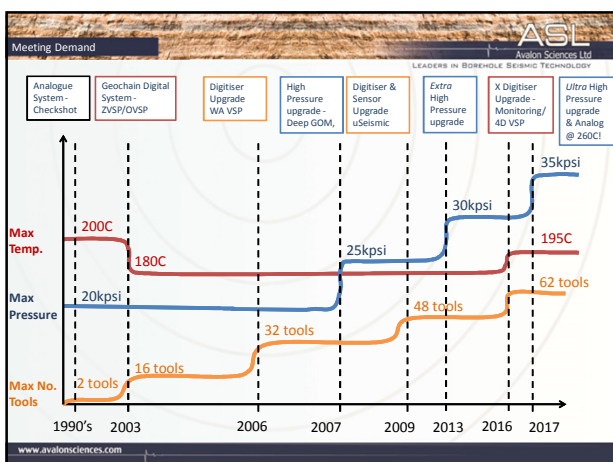
Downhole Advanced Sparker Source

High gain downhole electronics and high speed telemetry systems

GeochainSim™ Receiver

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What's New?

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SURVIVAL UNDER PRESSURE

Ultra High Pressure
35kpsi

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ASR Extra High Pressure (EHP)

Determining quality and integrity of reservoirs that remain below seismic resolution can be achieved if the seismic receiver can be located downhole proximal to the area of interest.

However, at these depths a real technological challenge is presented. In regions such as the Gulf of Mexico these geophone tools need to be designed to function within very hostile borehole environments with temperatures of over 190°C and pressures reaching up to 35,000 psi.

Above - Squashed Titanium pressure housing exposed to 10,000psi, tools now go up to +35,000psi!

New super high strength stainless steel Alloy pressure housing

Composite pressure bulkhead connectors are used throughout.

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ASR Extra High Pressure (EHP)

Deploying such systems is not without risk; much research has been done to ensure the immense borehole fluid pressures (35,000 PSI+) on the deep receivers do not lead to ingress through mechanical seals, resulting in electrical leakage.

High temperature pressure transfer cables that transfer electrical feed through from PDCR to rig

Composites at high temperature, concrete pressure vessel to hold, holding PDCR back on rig

Above - Pressure safeguards are required to ensure insulation of the system from the immense borehole fluid pressures. On the left is an example of pressure bulkhead and seals linking the wireline to a borehole seismic satellite, and the image on the right shows an associated high-temperature, high-pressure test chamber to reconstruct borehole conditions.

Source: Avalon Geosciences

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Downhole Sensor

Geophone Sensor Pack

The individual satellites have different options for sensor packs.

These are usually either **gimballed** mono-directional sensors for deviated wells or **fixed** omni-directional sensors for additional sensitivity.

Data transmitted to surface

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Downhole Sensor

SENSITIVITY

The quality of the geophone receiver therefore plays a fundamental part in how accurately the fracture progression is mapped.

Most seismic geophone sensors have historically been passive analogue devices typically comprising a spring-mounted wire coil moving within magnetic field to induce an electrical signal.

The response of a coil/magnet geophone is proportional to ground velocity.

Data transmitted to surface

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Applications for Microseismic

Sensor Pack:
The response of a coil/magnet geophone is proportional to ground velocity.

Excellent sensor sensitivity is a vital characteristic when trying to pick low-amplitude microseismic arrivals.

Even when deployed in relatively quiet borehole conditions, sensors featuring significant electronic noise (especially at temperature) can be enough to mask a microseismic arrival.

To improve on this signal to noise ratio, technology has evolved to stack the phones within the sensor pack component of a downhole receiver, with the latest technology achieving so far four phones on each component, with 12 in each receiver satellite.

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ASR-227 – Quad Sensor Pack

Main Features

- Ideal for VSP & Microseismic surveys.
- Four geophones per axis.
- Fits standard and high pressure ASR's.
- Greater signal to noise ratio.
- Modular for quick and easy customisation.

Functionality

- Ideal for use with high gain 54dB digitisers.
- Overall sensitivity 86,350 V/m/s at 48°F (20°C).
- Ideal for use with standard, HP and EHP Geochain systems.
- Operating temperature up to 400°F (204°C).

Optimum Orientation	Horizontal
Operational Range	0° to 180° (20m)
Natural Frequency (f _n)	15 Hz ± 5%
Optimum Orientation	15 Hz ± 5% to ± 15%
Operational Range	± 0.120 in. > 306 cm
Coil Excursion @ P	± 0.022 in. > 0.51 cm
Optimum Orientation	250Hz
Operational Range	24000 ± 5% per manufacturer
Resistive	86350 V/m/s ± 5%
Sensitivity	86350 V/m/s ± 5% at 20°C
All Optimum Orientation	0.57 ± 15%
Operational Range	0.57 ± 20% to ± 10%
Open-Circuit Damping	7.9 μg ± 5%
Operational Range	± 0.20%
Distortion	± 0.70%
Optimum Orientation	-40°F to 212°F (-40 to +100°C)
Operational Range	-40°F to 300°F (-40 to +150°C)
Storage Temperature	Weight: 49 gr
Operating Temperature	Diameter: 2.25 cm
Geophone Dimensions:	Height: 2.70 cm (3.00 cm including Terminal)

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ASR Modules

Sensors

GSR ASR Up Hole

- **Fixed**
 - Mono - 1 geophone per axis (ASR Only)
 - Dual - 2 geophones per axis (ASR only)
 - Quad - 4 geophones per axis
 - 15Hz sensor
- **Gimballed**
 - Sensors follow borehole deviation (0-95° C)
 - 10 Hz sensor

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Applications for Microseismic

Sensor Pack: Simple and cost effective to switch over geophones to **QUAD** (4 geophones on each axis, 12 total) to maximise sensitivity. Large Bandwidth <1600Hz for high frequencies.

As the thermal noise (En) output voltage can be expressed as $En = \sqrt{4kTBR}$
(B Boltzmann's constant, kT Temperature, B Bandwidth and R Geophone Resistance).

Then the sensitivity of a typical geophone is effectively doubled when in series whilst only marginally increasing En = Greater S/N at high temperature compared to single phones.

Fig Left - Correlated data from North Belt Well, Texas 2010, acquired by Digital Geochain Borehole Seismic System. Cross normalised seismic trace recorded on Dual Geophones (traces 1 and 3) vs Quad Geophones (traces 2 and 4). The magnitude spectrum shows a ~6 db differential in signal to noise over the recorded bandwidth between the Dual (blue) and Quad (red) sensor packs. Source: Avalon Geosciences

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Downhole Digitization

Downhole Digitizer Module

- This module amplifies and digitizes the geophone signals and transfers the resulting digital data up to the next geophone satellite in the tool chain.
- Requirements for high quality downhole digitization are...
 - **Low Thermal Electronic noise**
 - **High gain**
 - **High Dynamic Range**
 - **Robust at High Temperatures**

Optimising the digital downhole electronics is also a key role for fracture monitoring. If the borehole geophone response has electronic downhole gain applied (54 dB), increasing dynamic range, and a high sample rate (one sample every 1/4ms), it will provide a recording bandwidth of up to 1600 Hz, which is more suited to comprehensively measure the energy content generated by the high-frequency microseisms.

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Downhole Digitization

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Downhole Digitizer Module

- This module amplifies and digitizes the geophone signals and transfers the resulting digital data up to the next geophone satellite in the tool chain.
- Requirements for high quality downhole digitization are....

Market Requirements

- Low Thermal Electronic noise
- High gain
- High Dynamic Range
- Robust at High Temperatures

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Downhole Digitizer Module

- This module amplifies and digitizes the geophone signals and transfers the resulting digital data up to the next geophone satellite in the tool chain.
- Requirements for high quality downhole digitization are....

- Optimising the digital downhole electronics is also a key role for fracture monitoring.
- Borehole seismic tools need to justify their use for all multiple subsurface applications, not just VSP.

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Downhole Digitization

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Downhole Digitizer Module

- This module amplifies and digitizes the geophone signals and transfers the resulting digital data up to the next geophone satellite in the tool chain.
- Requirements for high quality downhole digitization are....

- Being able to switch downhole gain e.g. geophone response has electronic downhole gain applied (54 dB), increases dynamic range.
- When combined with a high sample rate (one sample every 1/4ms), it will provide a recording bandwidth of up to 1600 Hz (0.8x f_{max}), which is more suited to comprehensively measure the energy content generated by the high-frequency microseisms.

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Downhole Digitization

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Electronics for increasingly hostile environments

- Increased operating temperature **195°C (385°F)** have also been introduced through employment of improved vacuum flasking, hermetic seal employment and upgraded active cooling along with upgraded high temperature power supplies. **Analogue system can now go to 260C!**
- For Larger array surveys - Doubles existing Geochain system data rate, allowing up to 60 tools at 1ms sample rate
- Enables continuous recording for microseismic monitoring
- Integrated High Side Indicator
- Selectable Damping and Gain

Downhole Specifications ASB72 32-core/60				
Max. No. of Tools	60	32	16	8
Telemetry	Sample interval	Bandwidth Hz	ASR's	ASR's with DFU
	1.6ms	3000	8	16
	1.0ms	800	16	30
	1ms	400	32	60
	1.0ms	200	48	62
Dynamic Range	>112dB @0dB pre-gain (minimum)			
A/D converter	24-bit Delta-Sigma			
Downhole Gain	42-94dB			
Distortion	<-0.02%			
DC offset	Self-calibrating			
Max data rate	4 Mbits/second			
Min. data rate	256bits/second			

*Used in conjunction with X-TAS and DFU units.

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Improved telemetry = greater receiver spacing options

- Upgraded Intertool telemetry allows for increased tool spacing and aperture. Receivers now capable of up to 200m spacing.
- Appropriate for complex subsalt canopy imaging via WAVSP with tools deployed in both vertical and lateral well components.
- Current large 60 level Geochain tool operations in deep water Gulf of Mexico taking place Q1 2018.

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Pass Through Tool

Enables deployment of two separate arrays within the same well, with no impact on sample rates.

Salt Canopy

Pass Through Tools at 300 ft separation Enable the tool strings to be separated by up to 1600ft

Top Geochain™ String

Bottom Geochain™ String

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High Side Indicator

Tool Orientation

High Side Indicator

- The HSI comprises a set of calibrated internal accelerometers within each X-series GSR and ASR digitizer module so that the following can be monitored downhole...
- Tool Inclination** – Deviation from vertical
- Tool roll** – Clockwise rotation of tool

This will streamline the process for calculating the true component vector from the HSI and well deviation listing for each downhole satellite

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High Side Indicator

- Measures tool roll and inclination for every receiver for full 3-C geophone orientation
- Real time monitor read out and manual capture utility
- Automatic addition of HSI data to MIRF-6 header for each individual record
- Automatic calibration for optimal accuracy at various tool temperatures
- The user can also manually capture the readout for all tools.

Real Time readout for each tool with live status reporting.

Tool Roll Values and Inclination Values displayed during "Tool Monitor" whilst tools are deployed

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High Side Indicator

Geophone Orientation with HSI

- Deviated Well – Fixed Components (HSI Data Provided)
- Z component is vertical
- X component 135°/315° clockwise from arm opening direction (looking downhole)
- Y component 45°/225° clockwise from arm opening direction (looking downhole).
- HSI gives both arm clockwise rotation (RB) angle and inclination from vertical.
- Data is in MIRF-Headers or stand alone hsi.csv manual capture file.

Twig 1 = VZ, Twig 2 = HX, Twig 3 = -HY

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High Side Indicator

HSI 3-C Field Processing Example

Figure Below – ASL Borehole Test Facility RH15 Borehole (Left) oblique well profile view showing survey aperture (1550-2450m MD), red line.

(Right) Borehole receiver string schematic: Geochain 5 level VSP tool combined with gravimeter directional sonde (for fidelity comparison).

The following data was rotated at the Well site to aid QC

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High Side Indicator

HSI 3-C in Field Processing Example

Correlated raw common depth 3C stack plot in true amplitude, as recorded (no rotation applied).

From W. Wills et al, 2017

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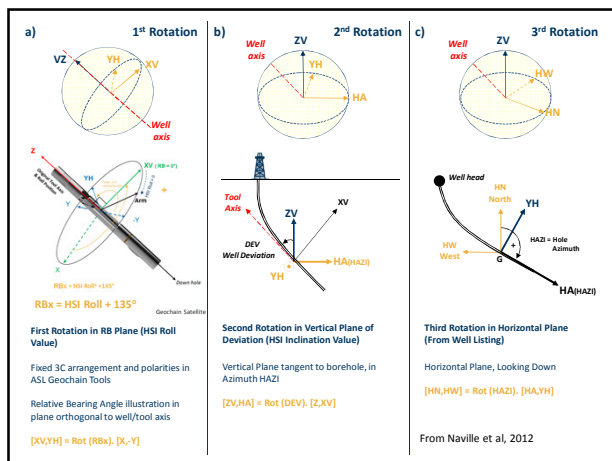
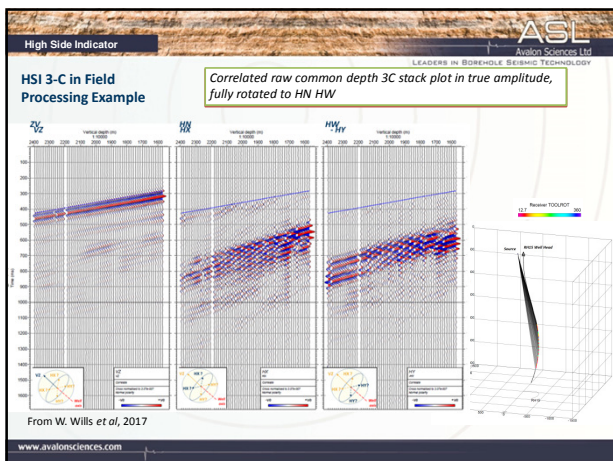
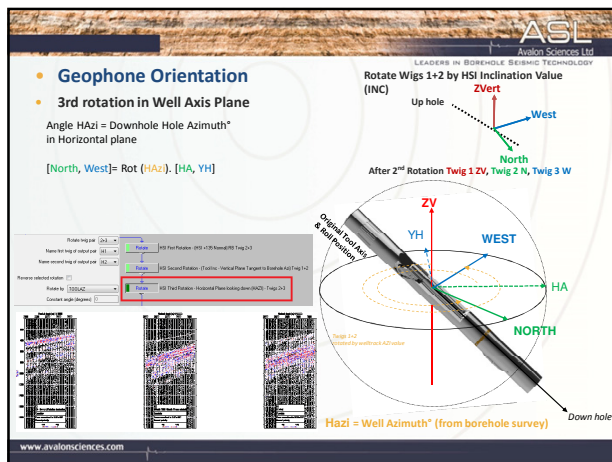
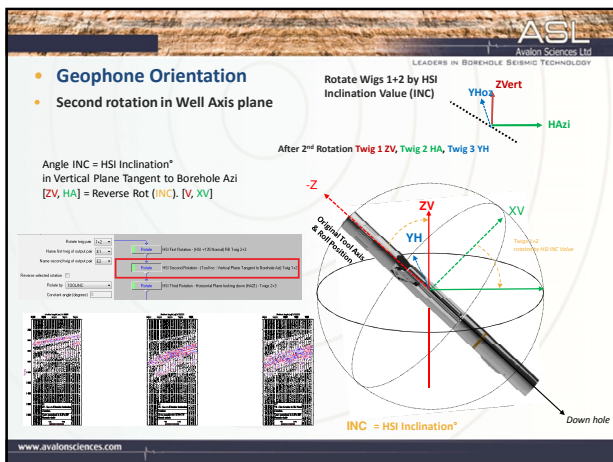
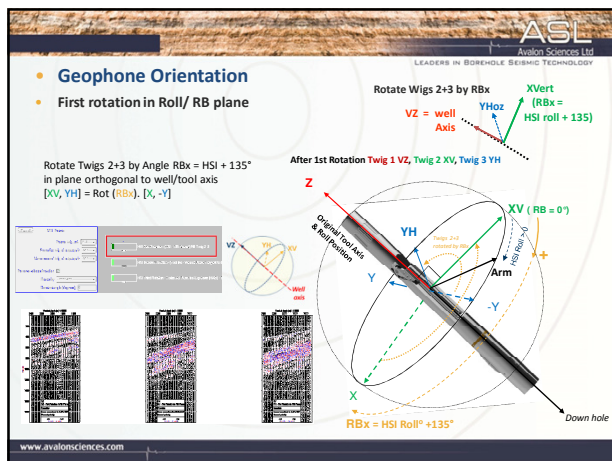
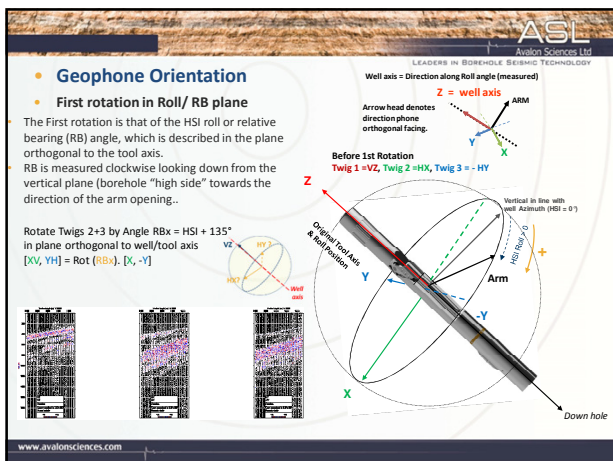
High Side Indicator

HSI 3-C in Field Processing Example

Correlated raw common depth 3C stack plot in true amplitude, Rotated using HSI Relative Bearing Angle (RB)

From W. Wills et al, 2017

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High Side Indicator

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- Orientation of the three components (3C) of a VSP is developed in order to take advantage of the **vector fidelity** of the recorded seismic response of the modern VSP tools, i.e. the identity of the mechanical response to a calibrated seismic pulse received by the VSP tool from any spatial direction.

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High Side Indicator

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- New commercial downhole VSP tool electronics modules implemented with a 3C solid state inclinometer system called a High Side Indicator (HSI), allow measurement of the direction of the pull of gravity and calculates the angles of roll and vertical inclination in each shuttle of a borehole seismic toolstring.

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- By so doing, VSP tool manufacturers expect to
- (a) replace the old-fashioned gimbal settings systems with equivalent or superior solid state electronic solutions for VSP tool orientation, and
- (b) encourage full 3C processing of all downhole datasets, even those acquired within rig source VSP survey geometries.

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What's Next

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High Side Indicator

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Future BHS Technology & Applications

- DAS – Distributed Acoustic Sensing
- Technology for real time, continuous measurements along a fibreoptic cable.
- DAS works by injecting pulse of laser light into optical fibre.
- Localised acoustic field foci leads to tiny strain events which result in back scattered light, which is then sampled back at surface.
- Interrogator at surface can perform a sampled interferometry over the length of the entire fibre typically every 1m over very large band width (~1->50kHz) with a dynamic range of over 120dB.

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DAS– Substitute or Supplement to conventional BHS?

- DAS – Advantages
- Relatively low cost (if suitable *single* mode fibre already installed in well). Excellent bandwidth and sample spacing with depth. Long term deployment.
- DAS - Limitations:
- Many wells not instrumented with fibre. Coupling and sensitivity to borehole noise effects. Lower sensitivity (at present) than traditional sensors. Temperature effects. Only 1 component.
- Going forward: **Hybridization** with 3-C downhole sensors using fibre optic coil phones. DAS to top receiver then high fidelity 3-component sensors clamped to casing/formation.

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FUTURE OF BHS – HYBRIDIZATION OF DAS & CONVENTIONAL PHONES

- From ASL's point of view, combined DAS down to conventional geophones is the next obvious evolutionary application for versatile borehole seismic monitoring.
- When deployed using a combined fibre/conductor wireline, the Geochain-DAS establishes a complete VSP digital seismic solution offering total well coverage from surface without the conventional standalone DAS attributed uncertainties of depth calibration, directionality and noise.
- The system is made up of individual satellites of conventional 3-C ASR/GSR borehole geophones arranged below the DAS integrated wireline.

GeoDAS – Combined Geochain-Distributed Acoustic Sensors

HYBRIDIZATION OF DAS & CONVENTIONAL PHONES

- The GeoDAS arrangement has already been deployed commercially in the Gulf of Mexico to acquire full 3DVSP well coverage with minimal rig time.

Right: Wireline-Fibre combined cable offering Distributed Acoustic Sensing option from surface to top 3-C Geophone

Below: Geochain™ 3-C X-Series 195°C-rated borehole seismic receiver system with inbuilt high side indicator deployed in lower/lateral well section below DAS wireline cable.

GeoDAS – Combined Geochain-Distributed Acoustic Sensors

GeoDAS Identification	• 63 3C Tools below DAS Array
Max Number of Tools	• 63 3C Tools below DAS Array
DAS Cable Length	• >10km
Geop Length	• 1-10m
Max Bandwidth	• 1-1,000Hz
Max Temp	• 195°C
Max Pressure	• 35,000 psi
Control Panels	• GSP & Interrogator

3-Component Borehole Optical Sensors

Borehole Optical Seismic Sensor

New innovation for Avalon Sciences, is a 3-C directional optical sensor, replacing the traditional mass coil transducer. This can then be combined with conventional tool housing using hybrid fibre/electronics or alternatively allowing for systems that are entirely passive downhole. With a continuous temperature rating of 200°C (392°F) and solid mechanical coupling systems very long term deployment is possible.

Ideal 4D VSP & Micro-seismic Monitoring.

Optical phone Main Features

- 3C Fibreoptic Sensors
- Passive Borehole System
- 200°C (392°F) rating
- High Sensitivity
- Low frequency (<1Hz) recording
- Low Noise

Clamped to production tubing/drill pipe

3C Fibreoptic Accelerometers

Sprung Loaded Arm Coupler (motor arm drive option available).

BOSS

Optical Sensors

- The array utilises 3 component optical geophones especially developed by Avalon to cope with hostile deep well conditions.
- These broadband sensors are low noise, extremely sensitive even down to 1 Hz and will operate in any orientation from vertical through to horizontal.

BOSS Specifications

- Max number of tools: • 96
- Dynamic Range: • >100db
- Noise Floor: • <50 ng/√Hz at 100Hz, <500 ng/√Hz at 1 Hz
- Distortion: • <0.01%
- Bandwidth: • 1-1600 Hz
- Sensors: • Omni Directional Fibreoptic Accelerometer
- Max Temp: • 392°F (200°C) *Digital Only
- Max Pressure: • 20,000 psi (1400 bar)
- Projected Lifespan: • 10 years at 302°F (150°C)
- Control Panels: • Interrogator

BOSS

Optical architecture Theory

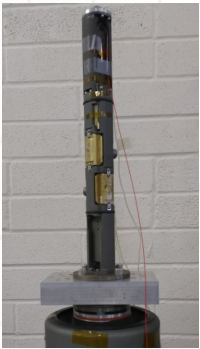
- The system is designed using a combination of wavelength division and time division multiplexing. A total of four lasers is used to interrogate up to 96 sondes.
- The lasers are pulsed with two different frequencies, designed to overlap temporally at the interferometers forming the sensors. The seismic signal is phase-modulated onto the pulses, which are demodulated at the interrogator.
- Pulsed laser modulation allows one laser to interrogate multiple sensors. It also has the added benefit of suppressing environmental noise in surface fibre.
- Fibre Bragg Gratings are not used; instead the sensors are designed to stretch generic fibre according to the seismic signal, changing the optical path length in an interferometer.

Image Source: Matthew Butler, GIPHY

SENSOR THEORY

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- Several Lasers are set up in the surface source panel. Each laser is a narrow band wavelength that is associated with one of the sensors in each return fibre.
- The ASL sensor relies on setting up an optical interferometer at each sensor utilising two legs of fibre with a mirror at the end of each leg.
- Each leg has the same nominal path length. One leg has a fixed light path length, while the other leg passes through the sensor element that varies the path length as the sensor mass moves with vibration.




Right: Avalon 3C Fibreoptic Sensor pack on shaker plate

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SENSOR THEORY

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- The coils of fibre that form the sensor are held in tension by an integral spring.
- The fibre coils are stretched by the moving mass against the tension of the spring.
- When the light reflected from the mirror at the end of each leg combine together back at the Wavelength Division Multiplexer (WDM) they form an interference pattern.
- As the mass moves, this interference pattern changes the phase of the light.



BOSS Carrier array on spool ready for clamping to drill pipe.

— Devine Wells, Tx 2013



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Expandable System -

- The system is fully expandable from a small microseismic 8 level system up to 96 stations for large 3D VSPs.
- The fibreoptic system can also survive more permanent deployment due to metal-to-metal C-rings throughout, meaning it can be considered for life-of field installations.
- The stations are deployed on jointed or coiled tubing as standard with optical wireline as an option. The array can be spaced at just a few meters or at several hundred meters for total well coverage.

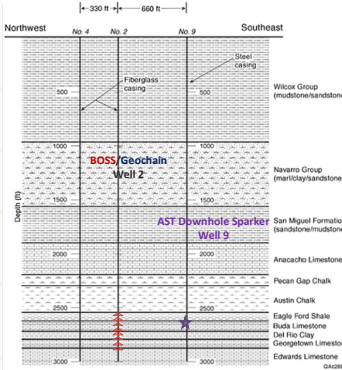
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Field Trial - Devine

Location: Exploration geophysics Laboratory (EGL) Test Site Devine, Texas, USA
 AST Test Well: Test Borehole No. 9
 TD: 3000ft - Vertical
 Casing Size: 6" - Steel Casing
 Well Fluid: Fresh Water
 Wireline: 20,000ft - 7 conductor
 Recording Well: Test Borehole No. 2
 TD: 3000ft - Vertical
 Casing Size: 6" - Fibreglass Casing
 Well Fluid: Fresh Water
 Test Recording Tool: BOSS - Borehole Optical Seismic Sensor - 8 Level Fibre optic Receiver - 50ft Spacing - Sample Interval - 250us
 Comparison Recording Tool: Geochain 4 Level - 50ft Spacing - Sample Interval - 250us




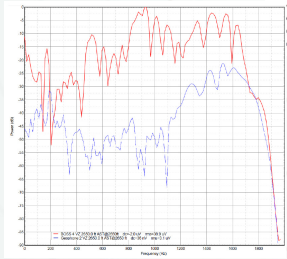
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Field Trial - Devine

Time Domain & Frequency spectra comparing the stacked Geochain response and BOSS for identical downhole sparker shot/receiver geometry of 2650ft source depth/receiver depth.

- This offset gave the strongest S/N for both systems.
- Here the BOSS mean arrival picked S/N is 12.7dB greater than the Geochain
- The BOSS system demonstrates greater frequency content with low end bandwidth (down to 1Hz) compared to Geochain. This was consistent across all BOSS traces. Both systems were able to record to the expected 80% Nyquist frequency for 250us sample rate (1600Hz).

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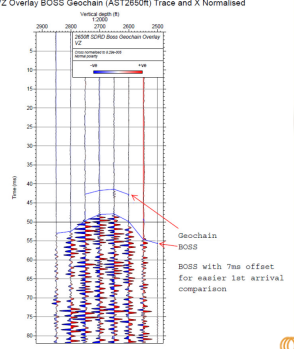
BOSS

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Field Trial - Devine

Cross Well Impulsive Source comparison - Quad Geophone Transducer

- The Devine test was able to demonstrate that the BOSS system had a superior sensitivity and signal to noise ratio compared to our standard geophone transducers.
- Even at their most contiguous performance, the BOSS sensors boasted a minimum 11dB improvement in S/N with an extended bandwidth down to 1 Hz compared to the Geochain roll off at <15Hz.



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- **DAS Hybrid to Geochain/Optical phones**
- **Increased robustness for hostile wells (ROI)**
- **Measurement of sensor orientation even with rig source VSP**
- **Dynamic Range for both microseismic/monitoring and high energy VSP**
- **Instant velocity model calibration with DAS hybrid above 3-C sensors**
- **Modular upgrade with backwards compatibility to future proof and take advantage of new BHS technology**

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- **GOING FORWARD: Industry Demands!**
- **Push for lower frequency – It's all about the low frequency (>1Hz) – Optical Phone & DAS**
- **Increased Sensitivity and Noise Immunity – Multiple Phones / High Vector Fidelity**
- **Deeper, hotter for longer! A permanent application – Regulation for post fracture/reservoir stimulation operations (months – years after well operations).**

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Thank you for listening



**ASL & Leeds University -
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