Workshop for Gravitational Wave detection on the Moon

Silixa Overview

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SILIXA actionable insight

Outline

- Introduction
- Distributed Optical Fibre Sensing
- Carina Sensing with Engineered Constellation Fibre
- Advantages of Carina Sensing System
- Environmental Monitoring Applications

SILIXA actionable insight

Who are we

We are the global leading independent provider of fibre optic-powered data solutions.

Our suite of integrated distributed fibre optic technologies (DAS, DSS & DTS), provides ultra-high-definition data sets that solve mission critical measurement challenges in the Alternative Energy, Mining, Environmental & Earth Sciences, Infrastructure and Oil & Gas sectors.

Our dedicated domain specific teams use their expertise to deliver world class real-time data solutions. These enable our clients to gain actionable insight into their assets and systems to increase efficiency, prevent loss, reduce operational costs and extend lifespans.

Alternative Energy	Mining	Environmental and Earth Sciences	Infrastructure	Oil and Gas

SILIXA actionable insight

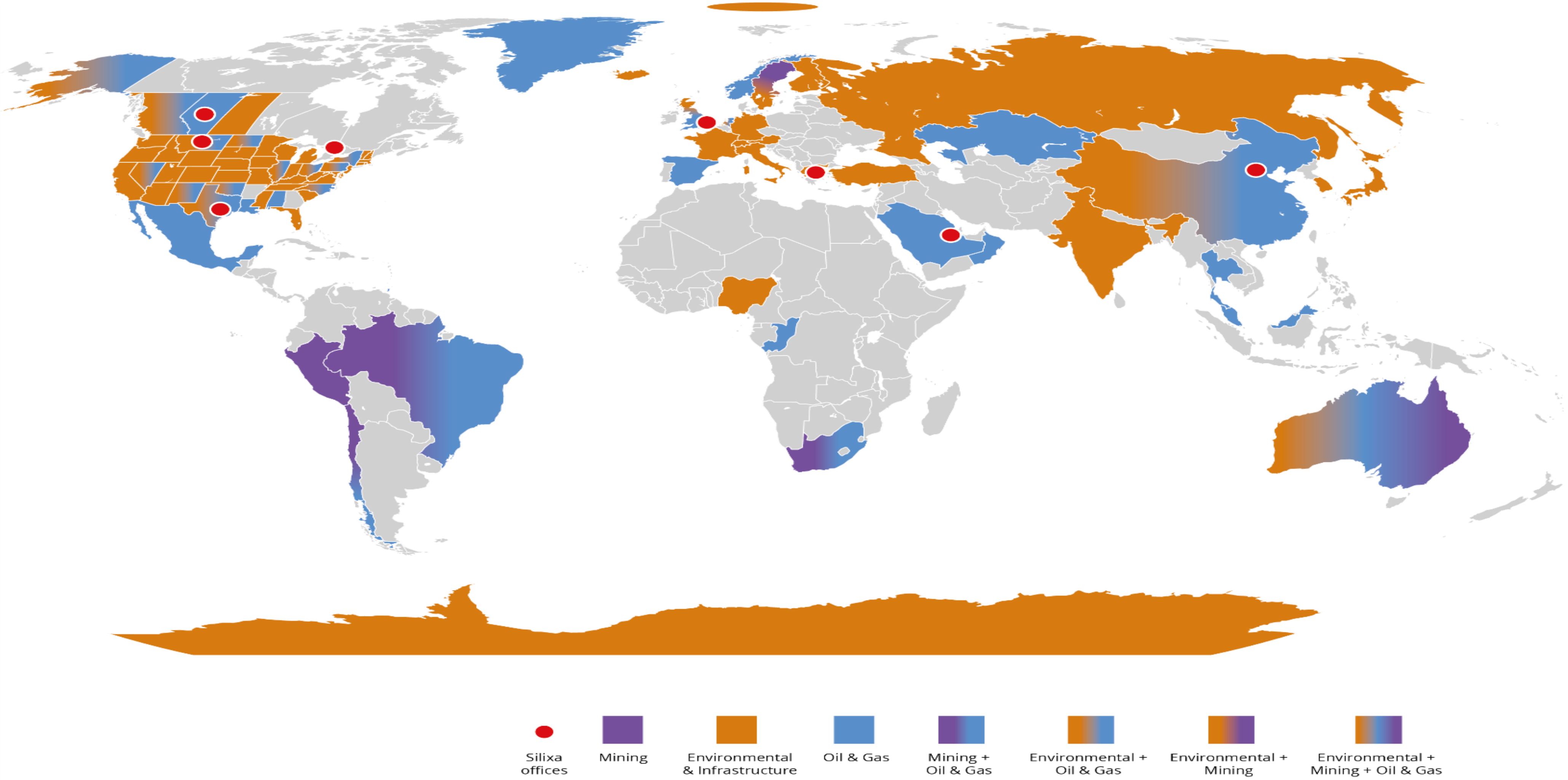
Silixa at a Glance

Institute of Physics Innovation Award 2015

World Oil Award for The Best Deepwater Technology 2020

World Oil Award for New Horizons Idea 2020

Queen's Award for Innovation: Enterprise 2021



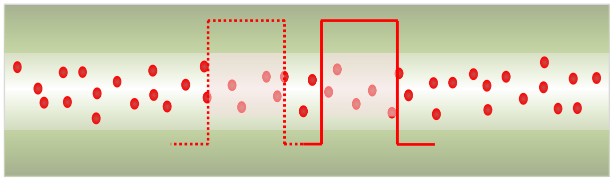
14 Years with No Loss Time Injury

Distributed Optical Fiber Sensing Technology

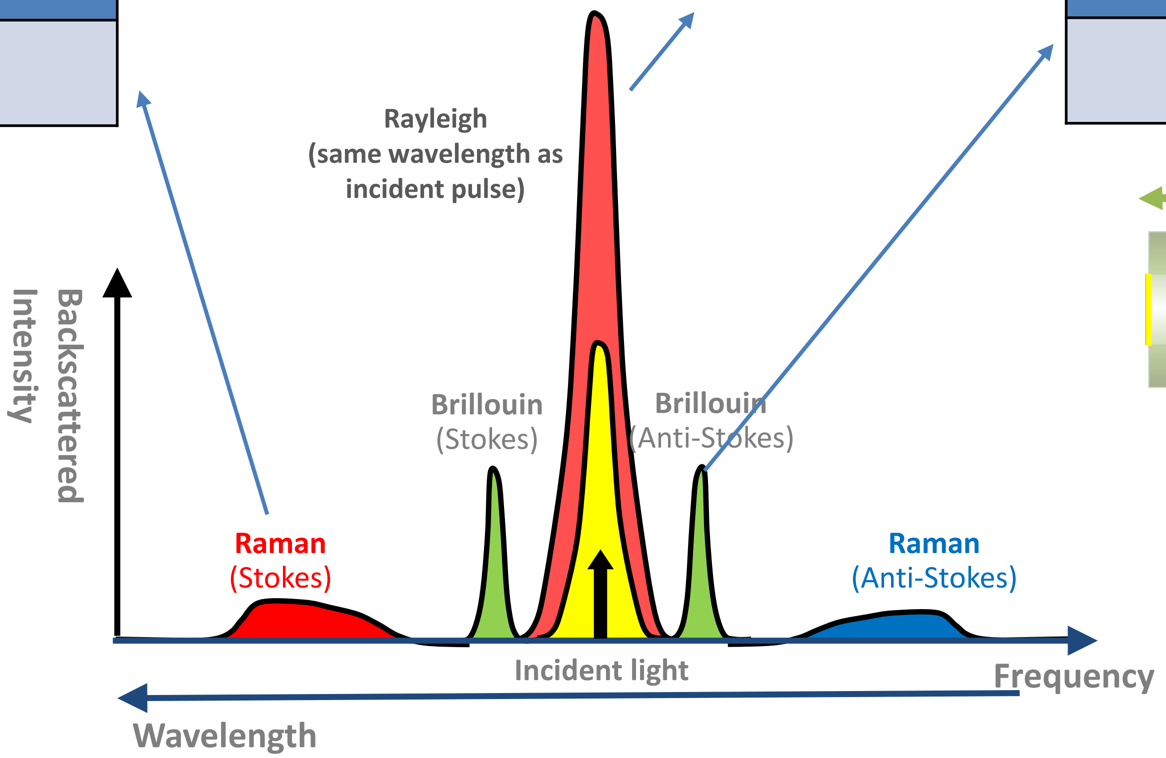

MK2 Ultima	MK2 XT
Temperature (DTS) 0.01ºC Resolution	


IDAS v2	Carina v3
Acoustics (DAS) >120dB Dynamic range	

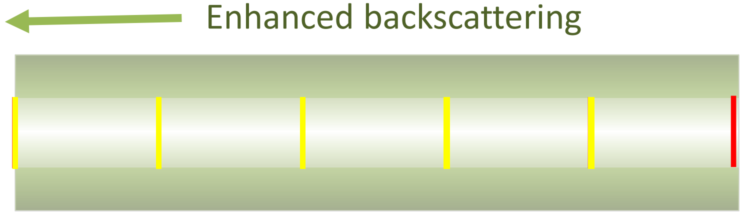

Carina DSS	Fiber Ruler
Strain (DSS) 1 με Resolution	



Standard fibre



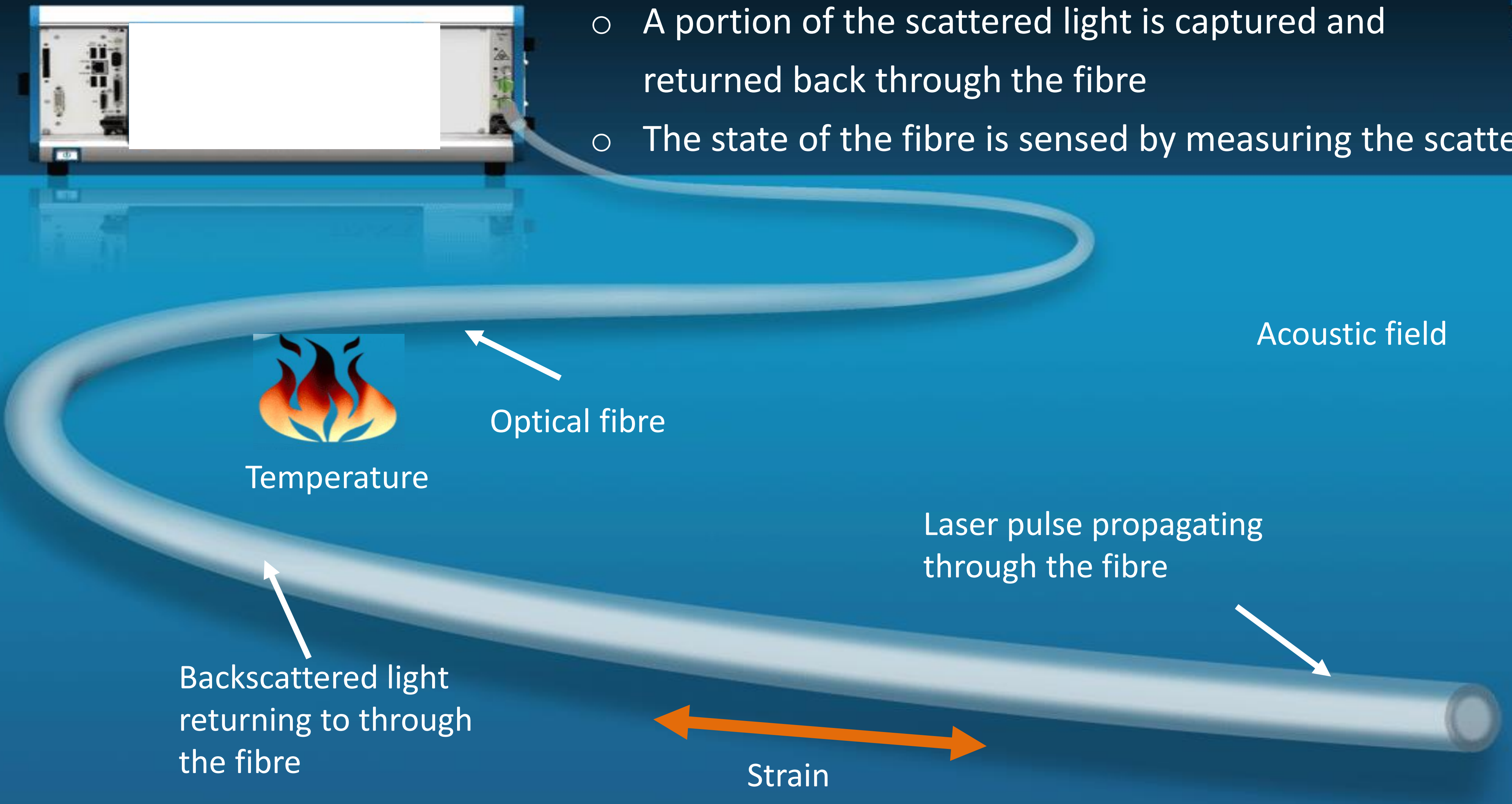
Enhanced backscattering



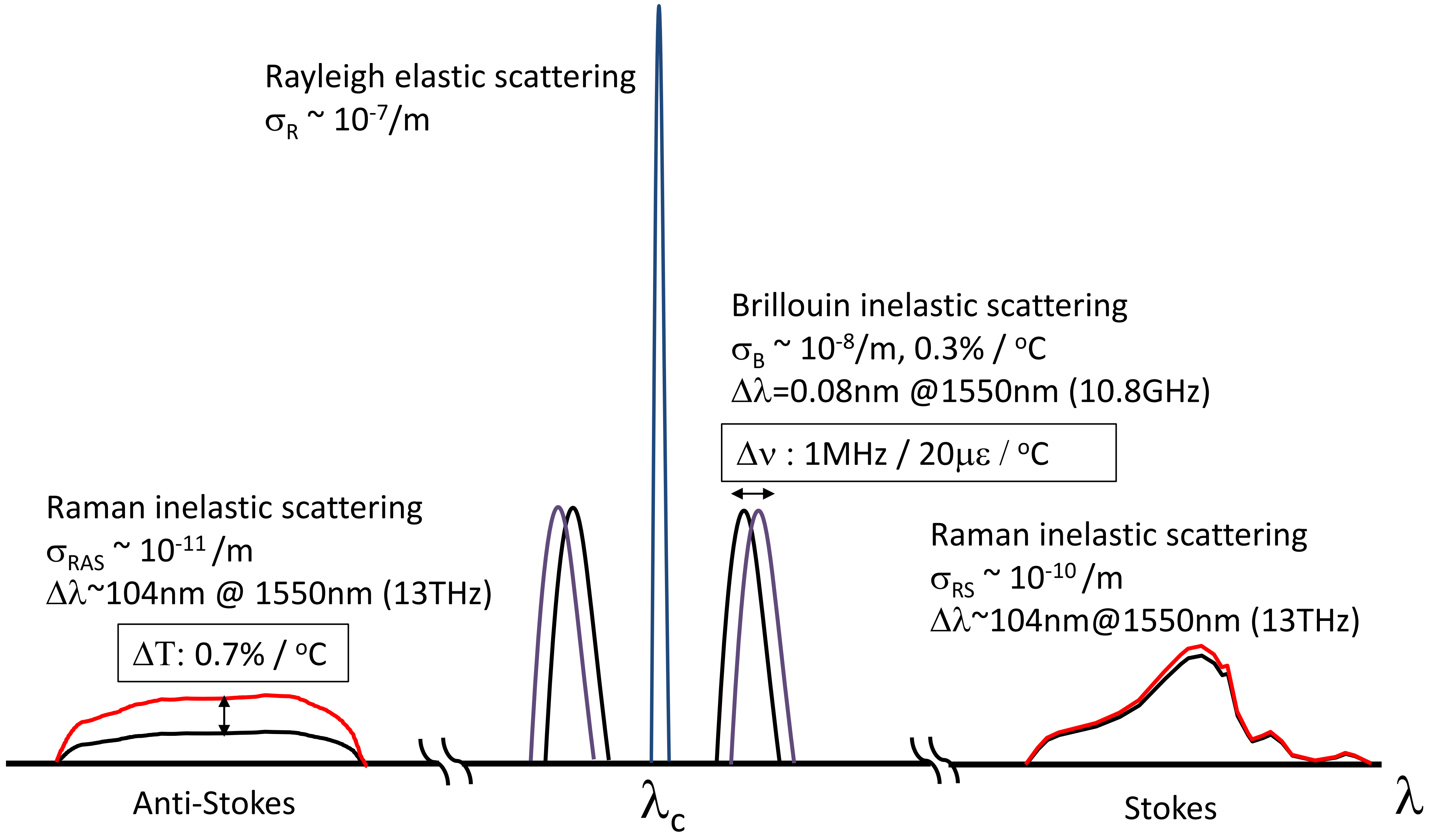
Engineered Fibre
US Patent No. US 10,883,861 B2
EP Patent No. 3265757

[redacted]

- A laser pulse launched in to the fibre
- Laser pulse propagates through the fibre
- Light undergoes a number of scattering process
- A portion of the scattered light is captured and returned back through the fibre
- The state of the fibre is sensed by measuring the scattered light



Backscatter spectrum

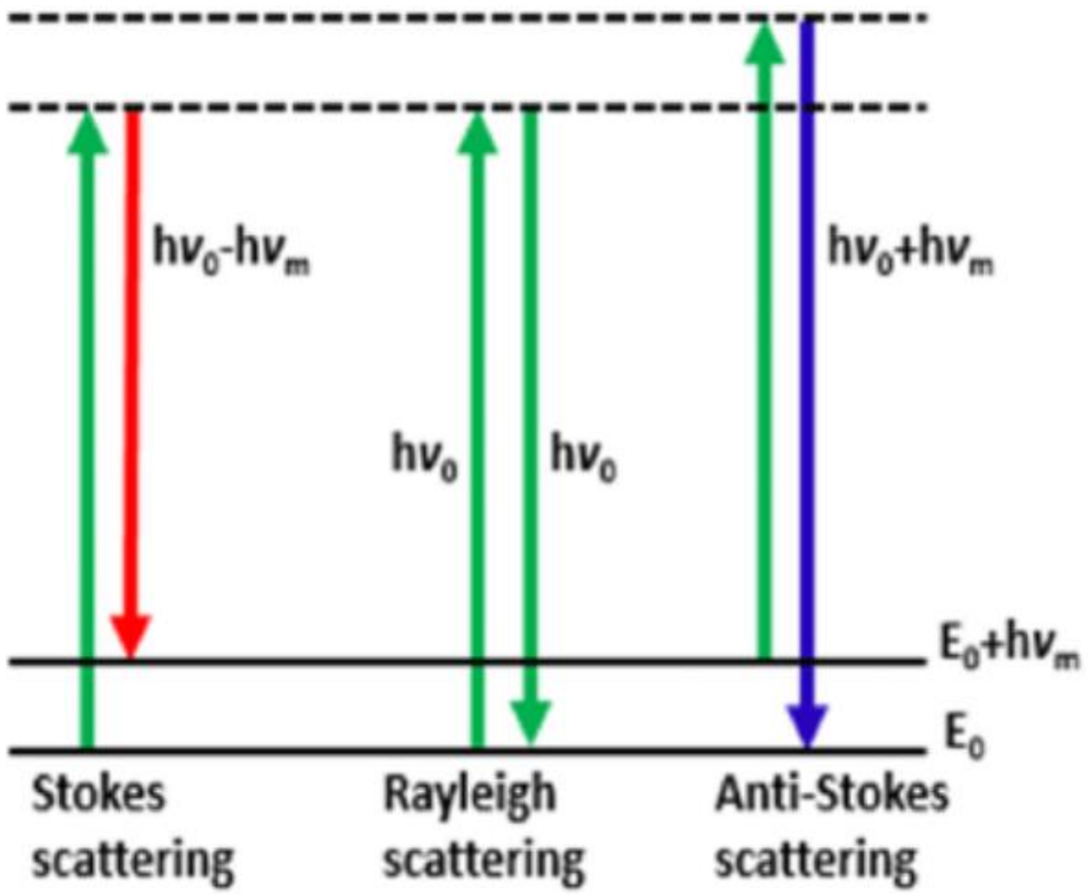


Elastic and in-elastic Scattering

In-elastic scattering
Lower energy
down-shifted frequency

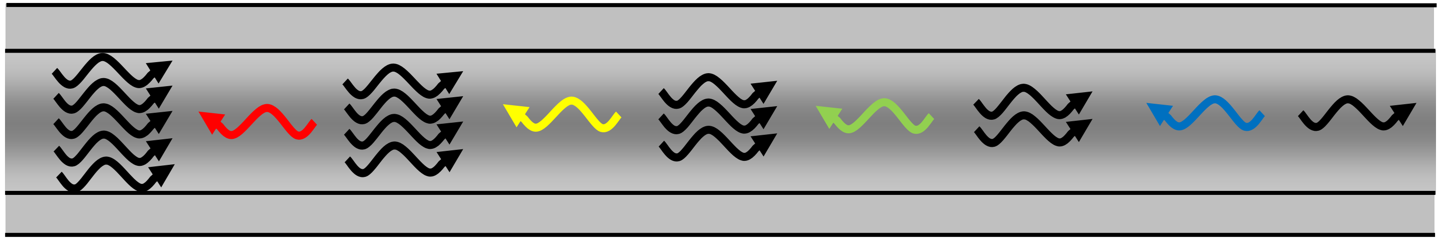
Elastic scattering
same frequency

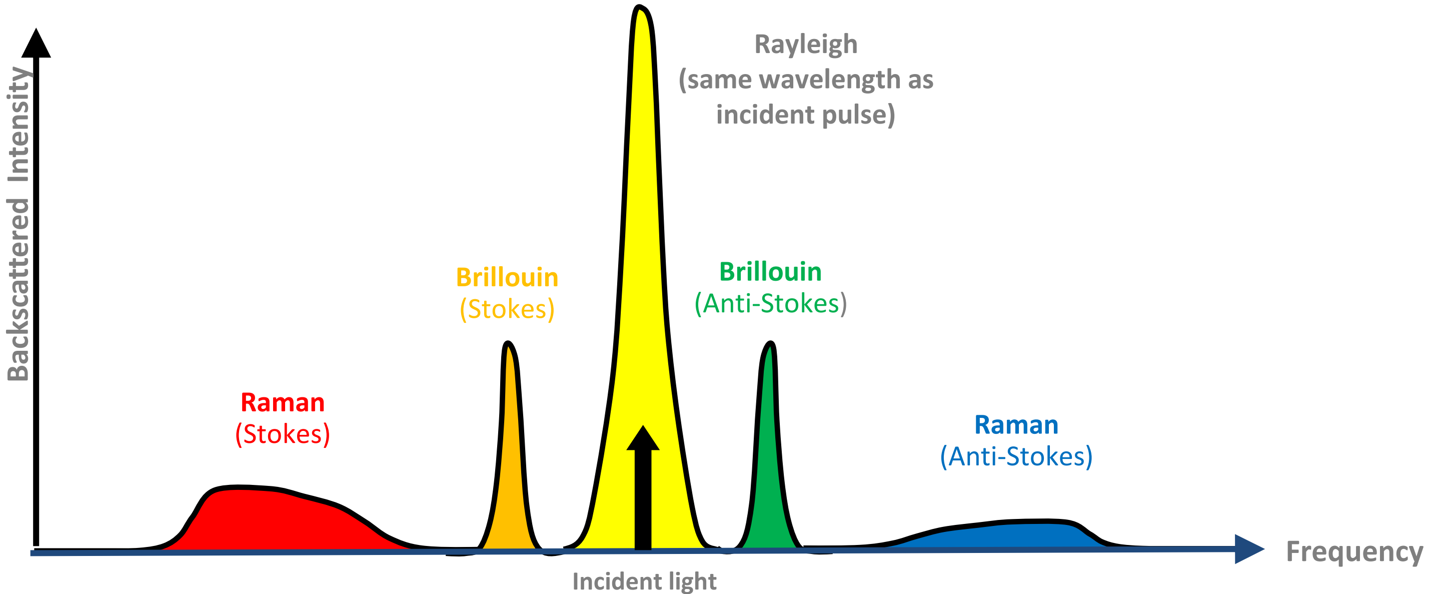
In-elastic scattering
Higher energy
up-shifted frequency



Optical fibre scattering

- There are three types of light scattered in an optical fibre: **Rayleigh**, which has the same frequency as the source light; **Brillouin**, which has a small frequency shift and **Raman** which has a larger frequency shift
- Rayleigh scattering acts like a weak mirror (it is the same scattering that makes the sky blue)
- Brillouin and Raman light are generated by an interaction between the source light and natural vibrations in the glass

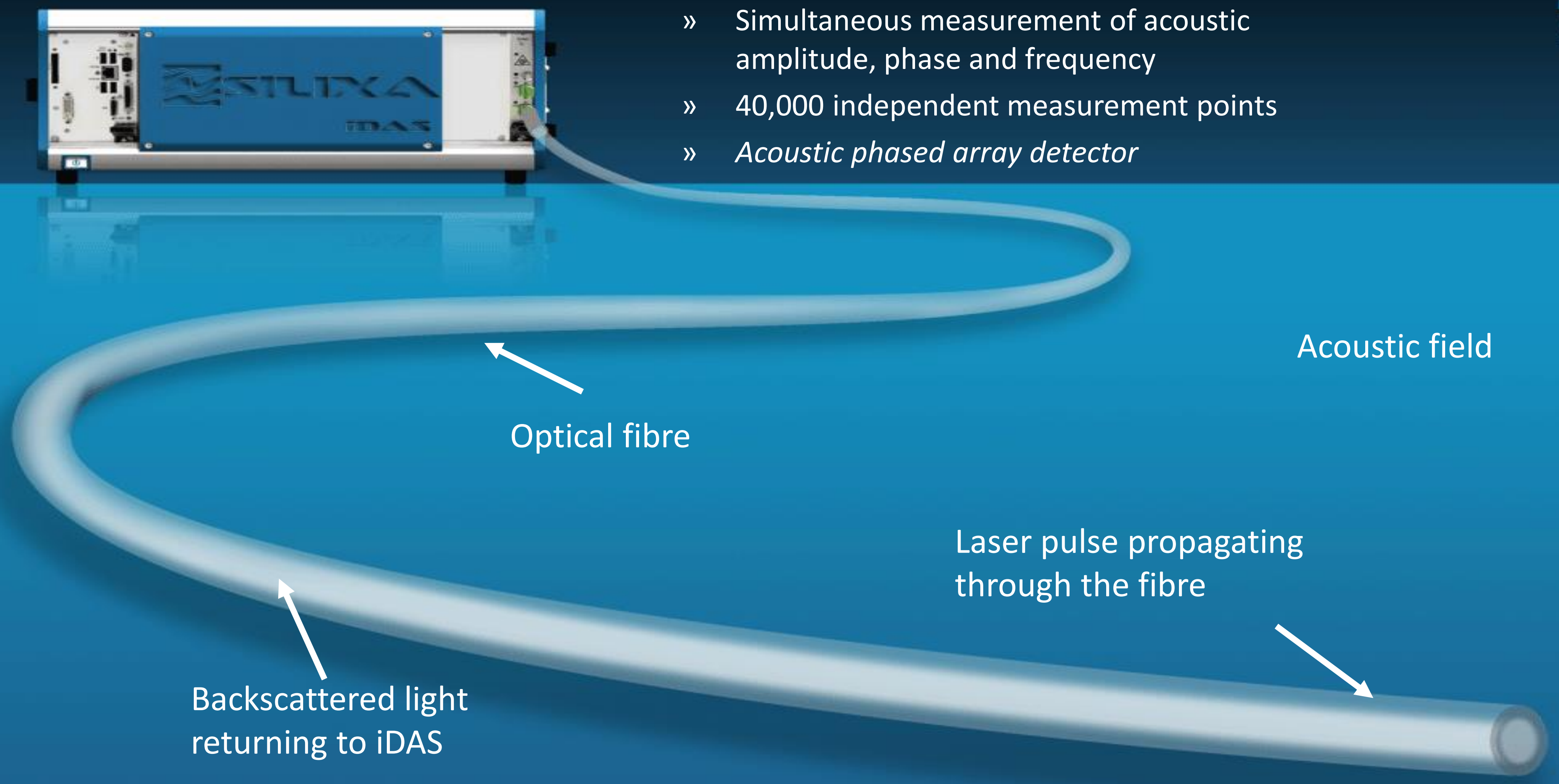




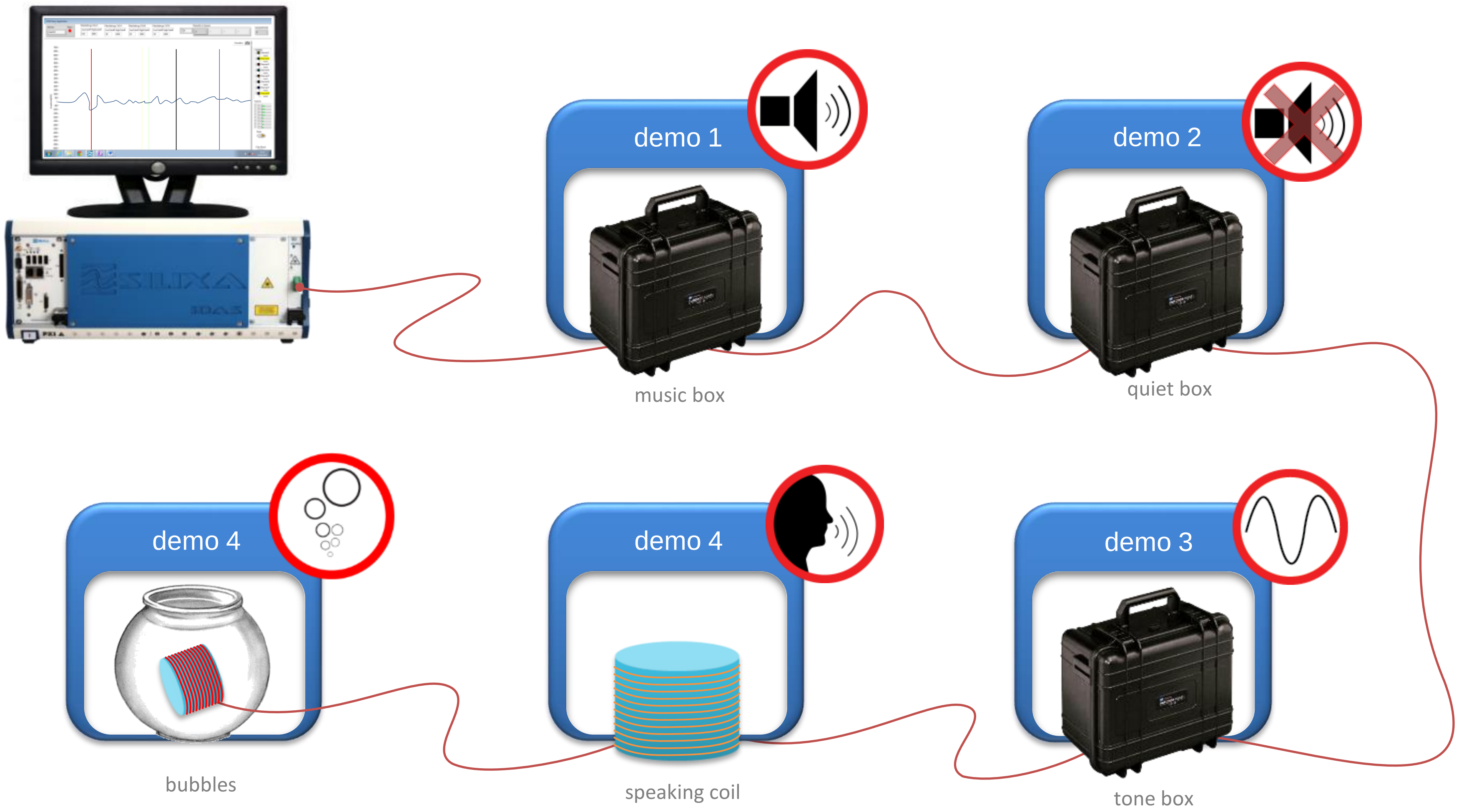
iDAS

intelligent Distributed Acoustic Sensor

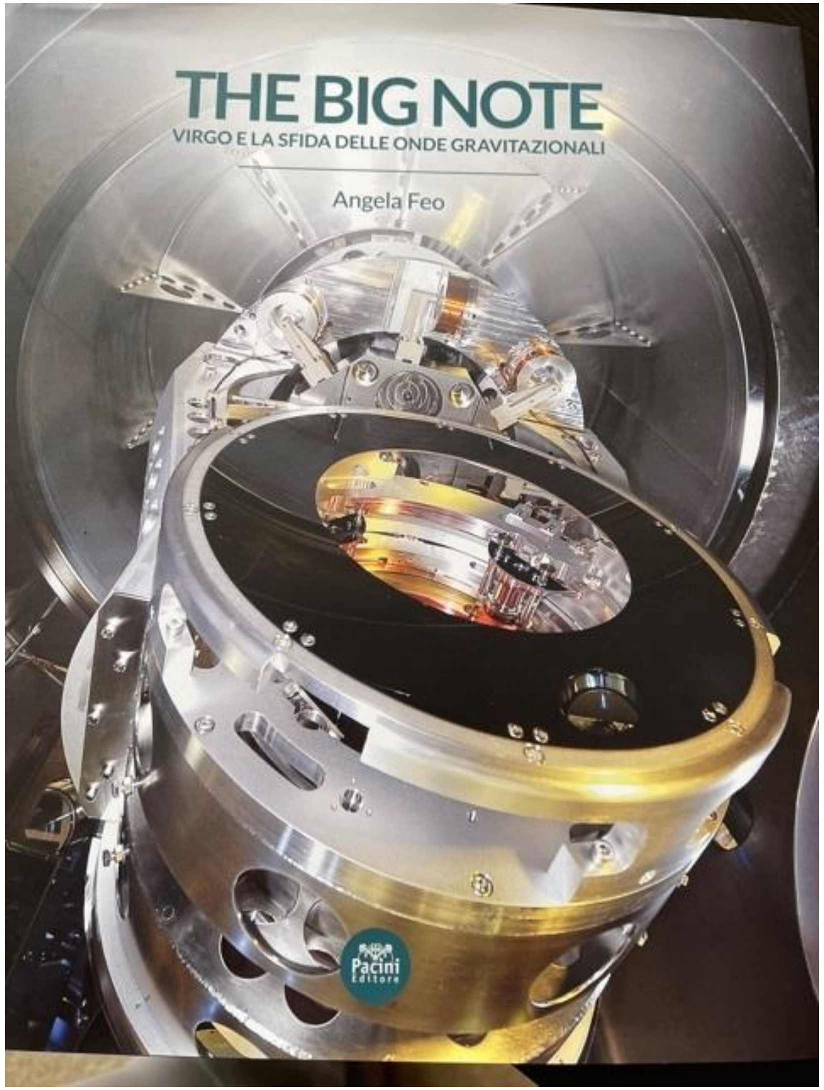
- Simultaneous measurement of acoustic amplitude, phase and frequency
- 40,000 independent measurement points
- *Acoustic phased array detector*

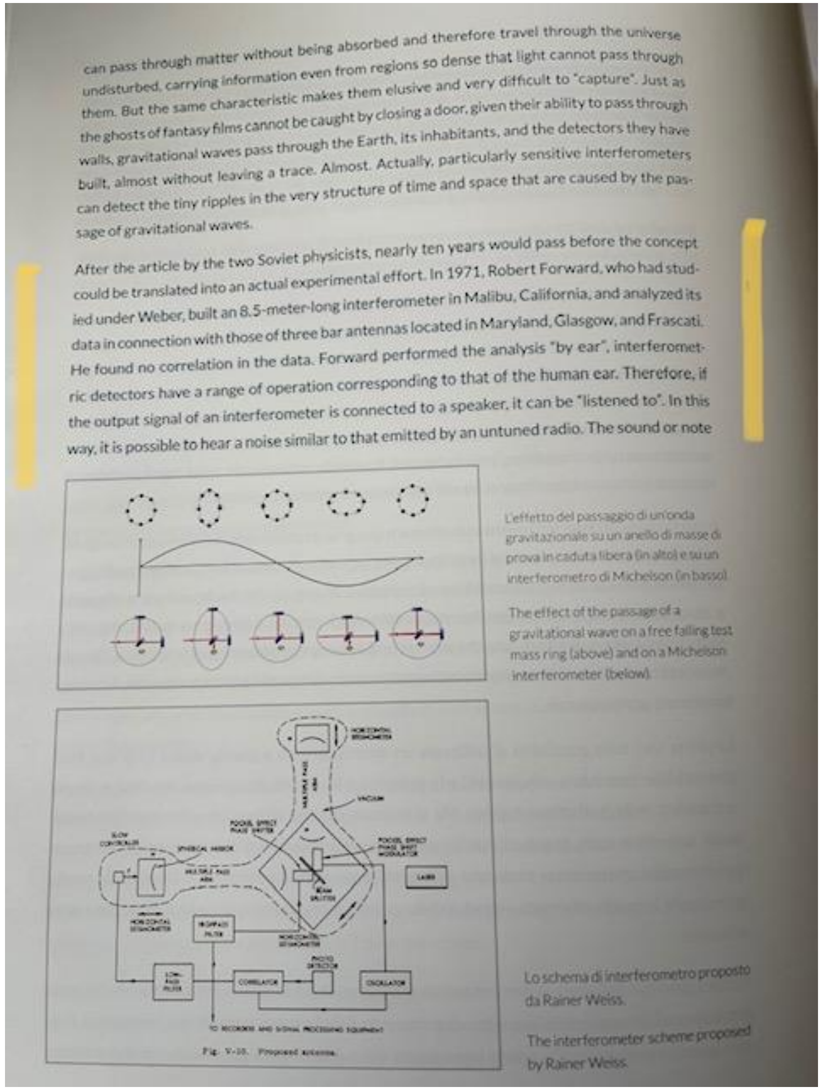


DAS - Listening to True Acoustics



The Big Note Connection





can pass through matter without being absorbed and therefore travel through the universe
undisturbed, carrying information even from regions so dense that light cannot pass through
them. But the same characteristic makes them elusive and very difficult to "capture". Just as
the ghosts of fantasy films cannot be caught by closing a door, given their ability to pass through
walls, gravitational waves pass through the Earth, its inhabitants, and the detectors they have
built, almost without leaving a trace. Almost. Actually, particularly sensitive interferometers
can detect the tiny ripples in the very structure of time and space that are caused by the pas-
sage of gravitational waves.

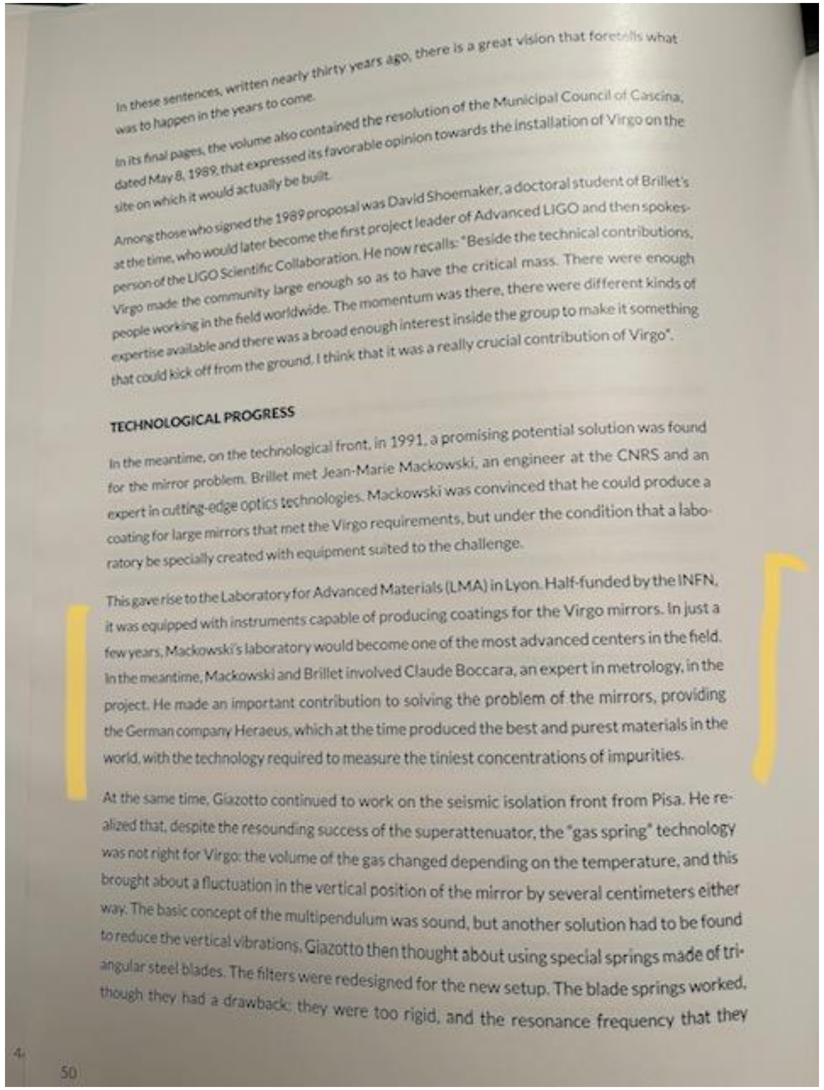
After the article by the two Soviet physicists, nearly ten years would pass before the concept
could be translated into an actual experimental effort. In 1971, Robert Forward, who had stud-
ied under Weber, built an 8.5-meter-long interferometer in Malibu, California, and analyzed its
data in connection with those of three bar antennas located in Maryland, Glasgow, and Frascati.
He found no correlation in the data. Forward performed the analysis "by ear", interferomet-
ric detectors have a range of operation corresponding to that of the human ear. Therefore, if
the output signal of an interferometer is connected to a speaker, it can be "listened to". In this
way, it is possible to hear a noise similar to that emitted by an untuned radio. The sound or note

L'effetto del passaggio di un'onda gravitazionale su un anello di masse di prova in caduta libera (in alto) e su un interferometro di Michelson (in basso).

The effect of the passage of a gravitational wave on a free falling test mass ring (above) and on a Michelson interferometer (below).

Lo schema di interferometro proposto da Rainer Weiss.

The interferometer scheme proposed by Rainer Weiss.



In these sentences, written nearly thirty years ago, there is a great vision that foretells what was to happen in the years to come.

In its final pages, the volume also contained the resolution of the Municipal Council of Cascina, dated May 8, 1989, that expressed its favorable opinion towards the installation of Virgo on the site on which it would actually be built.

Among those who signed the 1989 proposal was David Shoemaker, a doctoral student of Brillet's at the time, who would later become the first project leader of Advanced LIGO and then spokes-person of the LIGO Scientific Collaboration. He now recalls: "Beside the technical contributions, Virgo made the community large enough so as to have the critical mass. There were enough people working in the field worldwide. The momentum was there, there were different kinds of expertise available and there was a broad enough interest inside the group to make it something that could kick off from the ground. I think that it was a really crucial contribution of Virgo".

TECHNOLOGICAL PROGRESS

In the meantime, on the technological front, in 1991, a promising potential solution was found
for the mirror problem. Brillet met Jean-Marie Mackowski, an engineer at the CNRS and an
expert in cutting-edge optics technologies. Mackowski was convinced that he could produce a
coating for large mirrors that met the Virgo requirements, but under the condition that a labo-
ratory be specially created with equipment suited to the challenge.

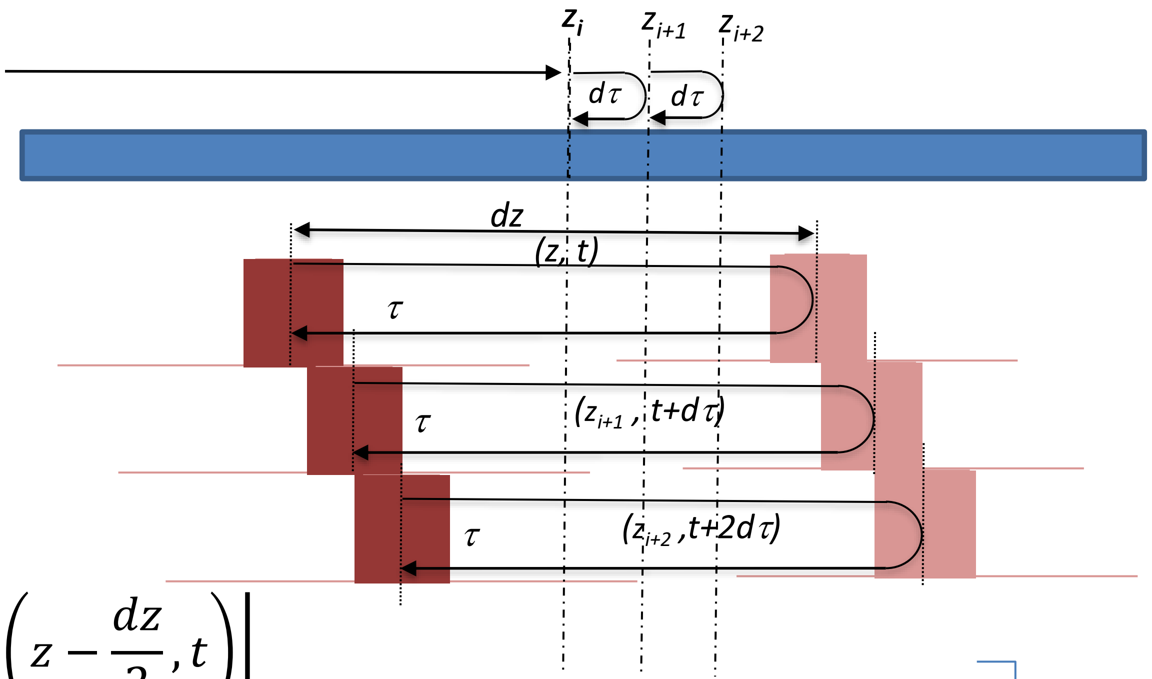
This gave rise to the Laboratory for Advanced Materials (LMA) in Lyon. Half-funded by the INFN,
it was equipped with instruments capable of producing coatings for the Virgo mirrors. In just a
few years, Mackowski's laboratory would become one of the most advanced centers in the field.
In the meantime, Mackowski and Brillet involved Claude Boccara, an expert in metrology, in the
project. He made an important contribution to solving the problem of the mirrors, providing
the German company Heraeus, which at the time produced the best and purest materials in the
world, with the technology required to measure the tiniest concentrations of impurities.

At the same time, Giazotto continued to work on the seismic isolation front from Pisa. He re-alized that, despite the resounding success of the superattenuator, the "gas spring" technology was not right for Virgo: the volume of the gas changed depending on the temperature, and this brought about a fluctuation in the vertical position of the mirror by several centimeters either way. The basic concept of the multipendulum was sound, but another solution had to be found to reduce the vertical vibrations. Giazotto then thought about using special springs made of tri-angular steel blades. The filters were redesigned for the new setup. The blade springs worked, though they had a drawback: they were too rigid, and the resonance frequency that they

50

What are we measuring?

spatial distance, gauge length	$dz = (\tau.c)/(2.n)$
effective refractive index	n
Sampling interval	$d\tau$
time sample rate	dt
position along the fibre	z_i
dynamic displacement	$u(z, t)$



Integrating

$$\left[u\left(z+\frac{dz}{2},t+dt\right)-u\left(z-\frac{dz}{2},t+dt\right)\right]-\left[u\left(z+\frac{dz}{2},t\right)-u\left(z-\frac{dz}{2},t\right)\right]$$

$z_{i+1} = [z_i + (d\tau.c)/(2.n)]$

$z_{i+2} = [z_{i+1} + (d\tau.c)/(2.n)]$

25cm

fibre strain rate $\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z}\right)$

Definition of DAS (SEAFOM MSP-02)

A system including an interrogator and optical fiber sensor that measures dynamic strain signals at acoustic frequencies at any point along the fiber, as well as the means to process and archive the interrogation information.

Geophone Equivalent Particle Velocity

Relating strain ε to particle motion v

where C is the seismic wave propagation velocity

$u(z,t) = u(\varphi)$ Displacement wave function

$\varphi = (t_0 + t \pm z/c)$ Propagating in time and space with speed c

$v = \frac{\partial u}{\partial t} = \frac{\partial u}{\partial \varphi}$ Particle motion

$\varepsilon = \frac{\partial u}{\partial z} = \pm 1/c \, \frac{\partial u}{\partial \varphi}$ Strain rate

$\boxed{c\,\varepsilon = \pm v}$ Relating strain to particle motion

- Data can be converted to Geophone equivalent particle velocity
- The response of DAS at a given location is similar to the Geophone response
- DAS is single component and not triaxial, but does benefit for a large measurement array

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Strain rate conversion

Optical phase shift

$$\boldsymbol{strain\ rate\ (nanostrain/second) = 115(nm)\ x\ DAS\ values\ x\ \frac{sampling\ freq\ (Hz)}{spatial\ res\ (m)}}$$

strain and change in refractive index
through Photo-elastic effect

$$A_0 = \frac{\lambda}{4\pi\, n_{eff} K_{\varepsilon}} = 115nm \qquad \lambda = 1550nm,\ n_{eff} = 1.468 \quad K_{\varepsilon} = 0.73$$

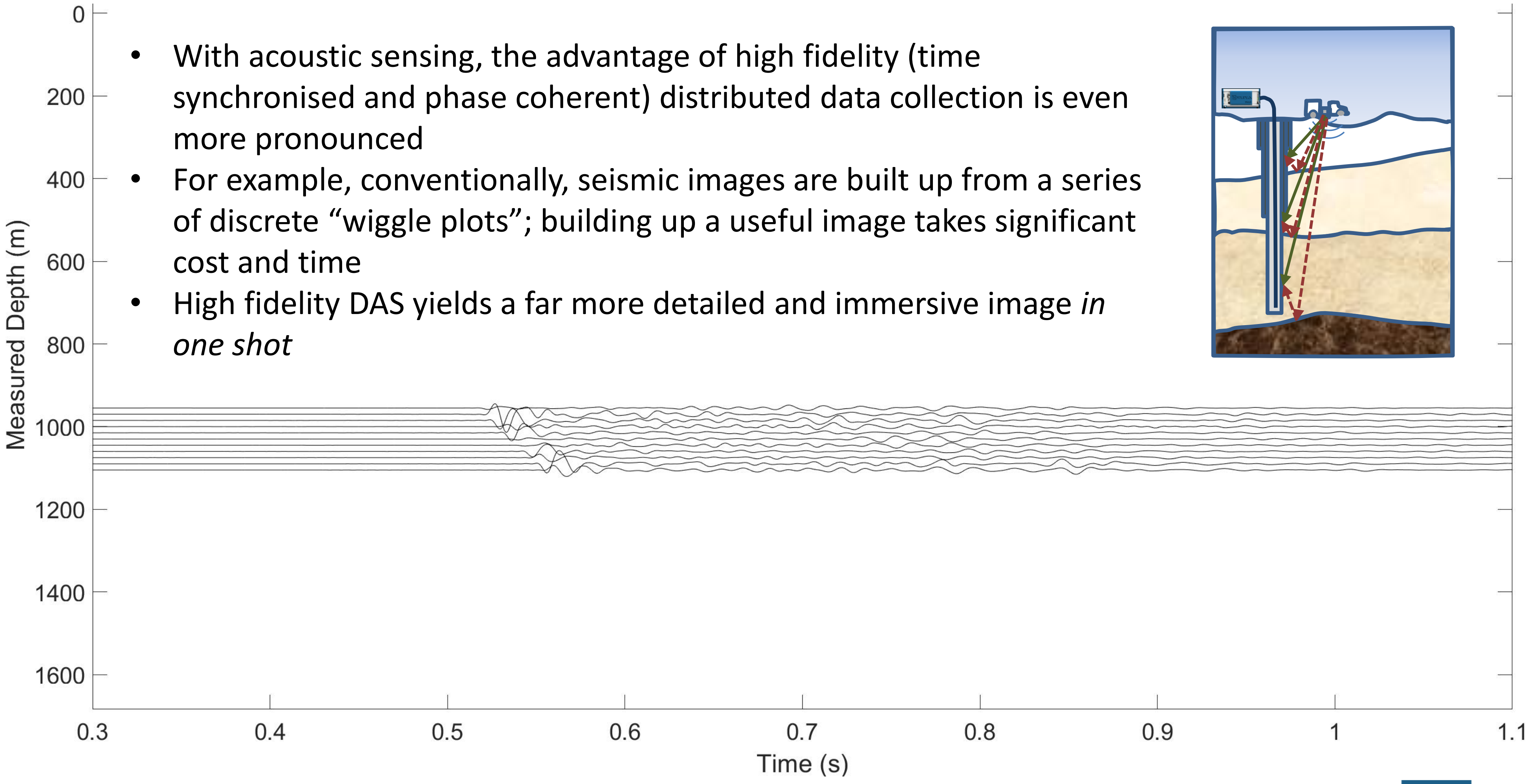
Strain rate (in nanostrain/second) = 11,500 x DAS Value

Spatial resolution 10m
Sample frequency is 1kHz (1ms samples)

(see SEAFOM MSP-02 Document)

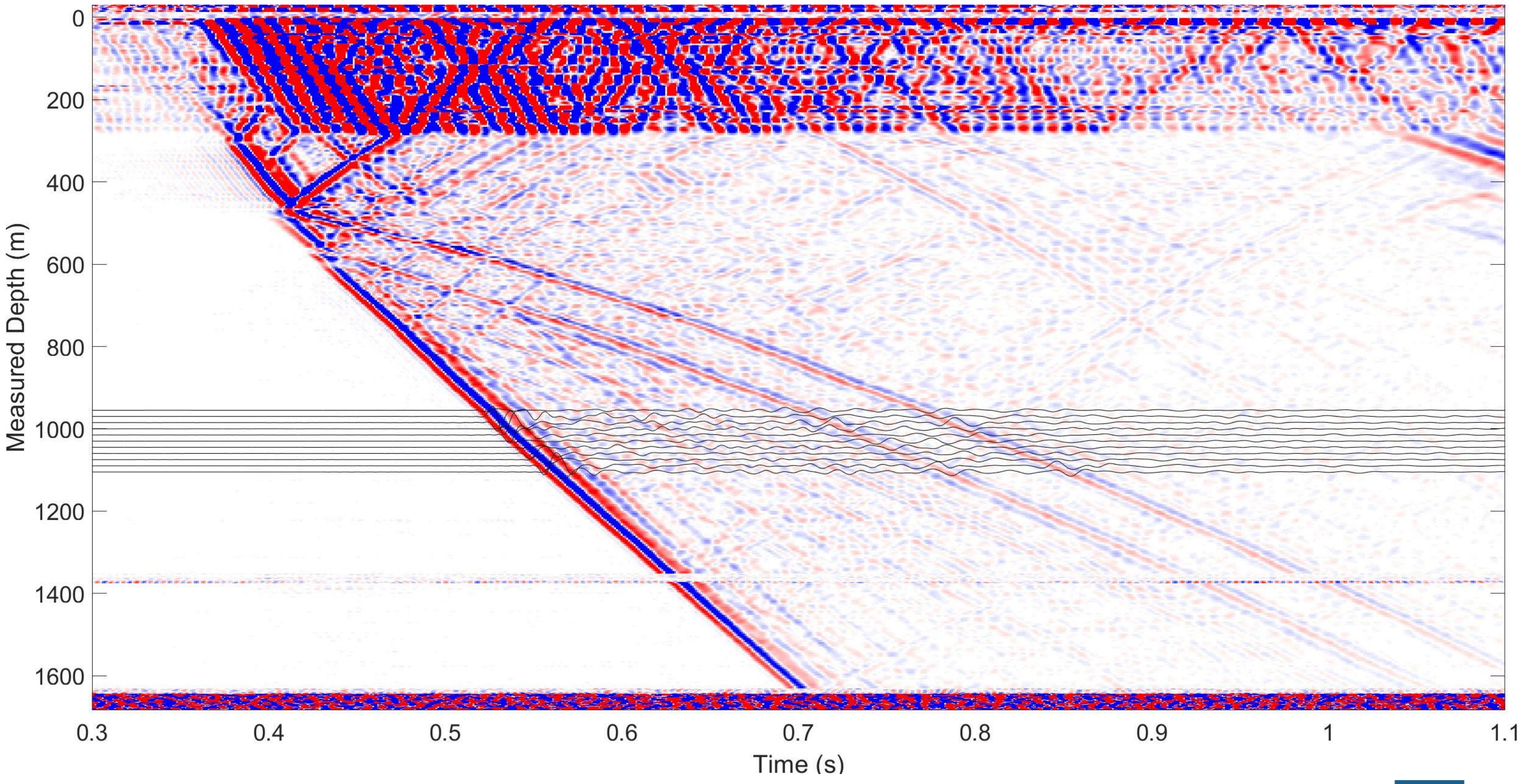
The advantage of true distributed measurements

- With acoustic sensing, the advantage of high fidelity (time synchronised and phase coherent) distributed data collection is even more pronounced
- For example, conventionally, seismic images are built up from a series of discrete “wiggle plots”; building up a useful image takes significant cost and time
- High fidelity DAS yields a far more detailed and immersive image *in one shot*



Confidential

The advantage of true distributed measurements

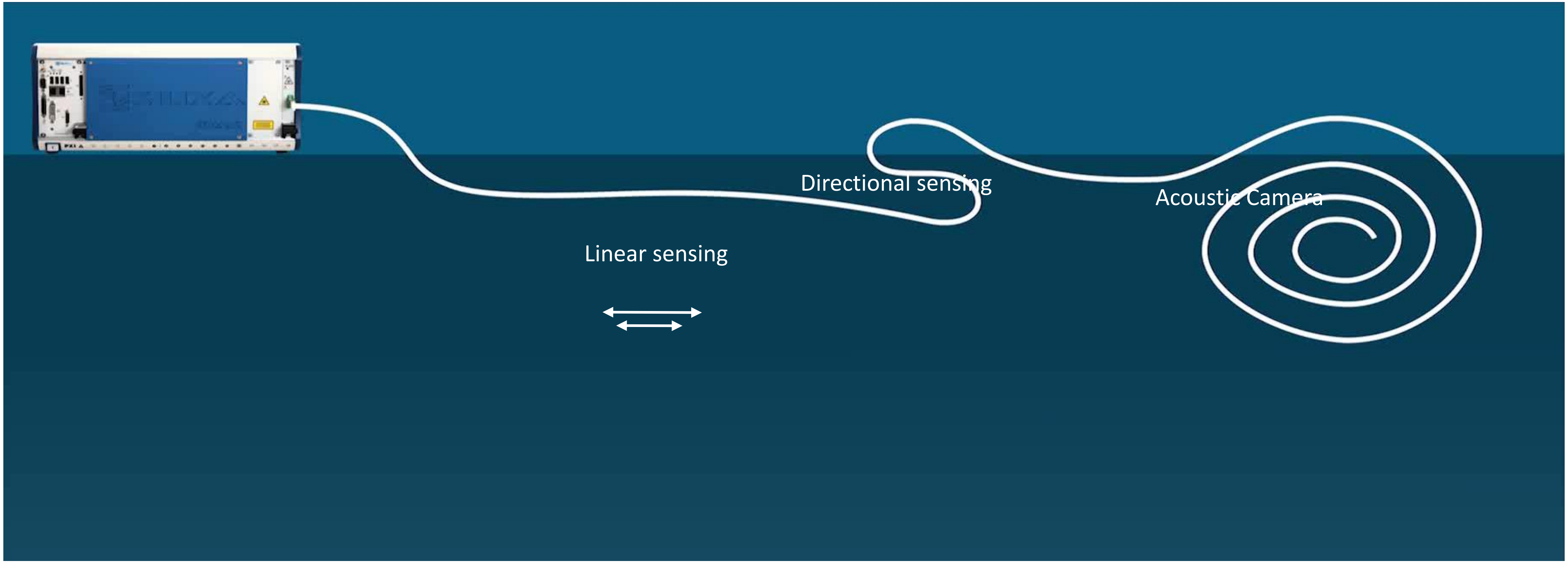


Confidential

actionable insight

Acoustic Imaging

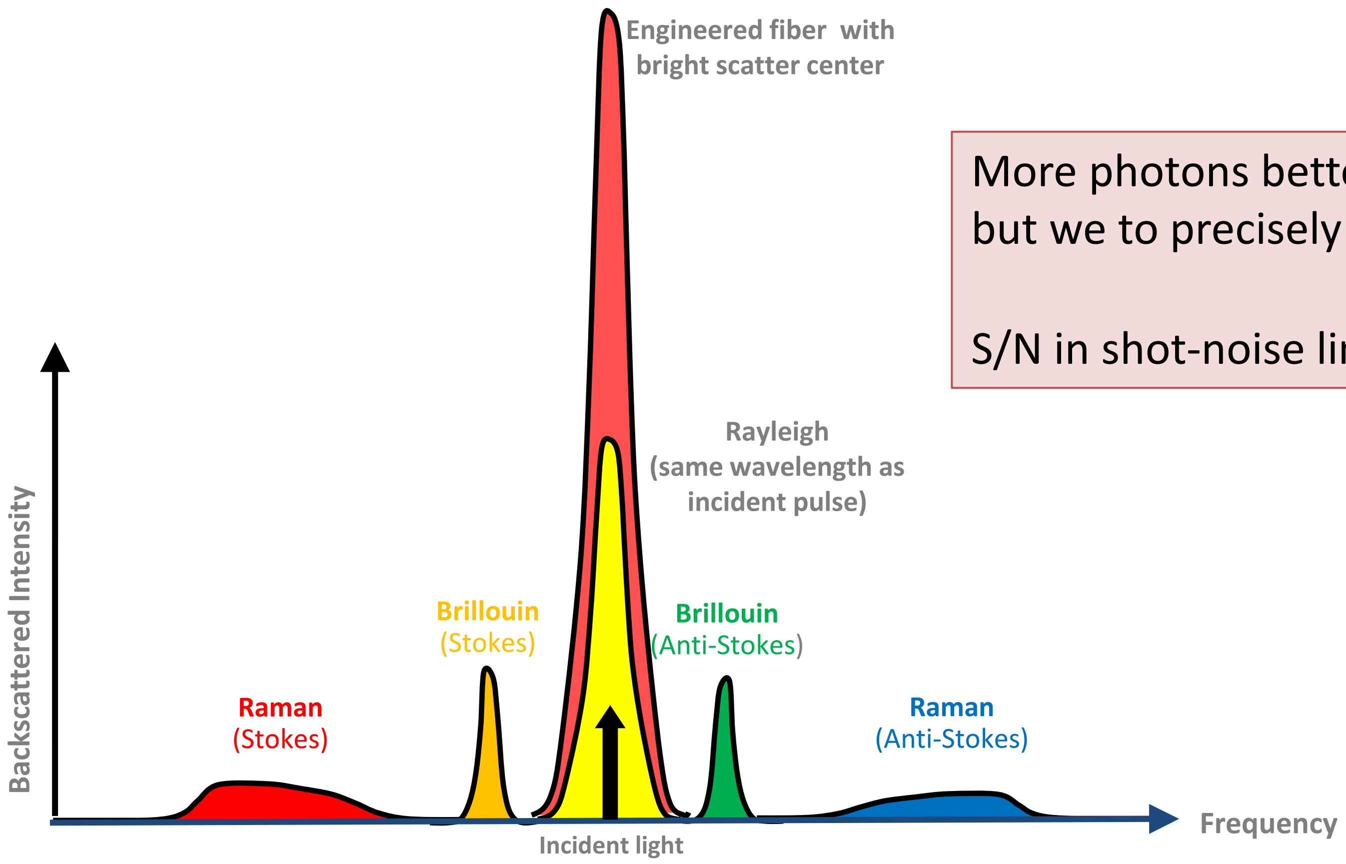
- The fibre can be arranged to modify its frequency response and directionality
- The fibre can be configured as an acoustic lens / camera (Beamforming)
- Strain vector camera



5
sense the difference

Optical fibre scattering mechanisms – Engineered Fiber

With engineered Constellation fiber we introduce bright scatter centres to efficiently reflect the light returning back through the fiber (x100) without introducing significant loss along the fiber

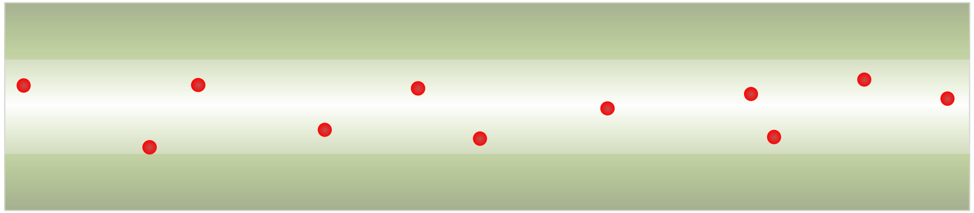


More photons better Signal-to-noise ratio but we to precisely control the phase

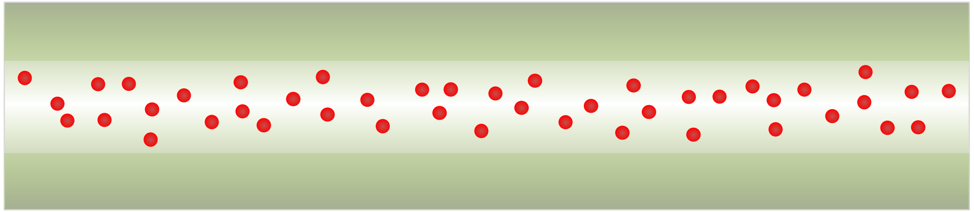
S/N in shot-noise limit $\longrightarrow \sqrt{N}$

Enhancing optical fibers

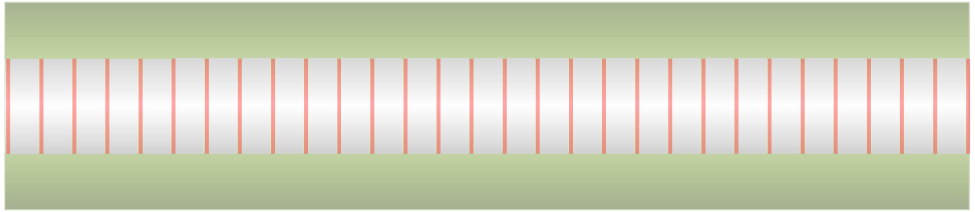
- **Standard fiber** – worst for signal, best for loss; uncontrolled phase relationship causes SNR variation (fading), which is an issue in some interrogator architectures



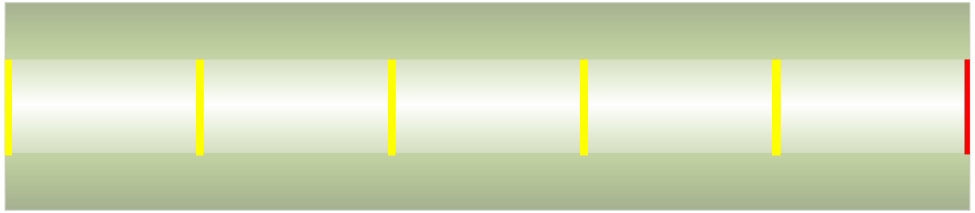
- **Highly doped fiber** – higher signal, but significantly higher loss increase



- **Continuous enhanced fiber** – much higher signal; reasonable losses but still uncontrolled phase relationship from multiple scatterers means there is a limit how the extra light can be effectively used



- **Engineered Constellation fiber** – much higher signal, reasonable losses and distinct scattering locations give control of the optical signal amplitude and phase: with a highly precision interrogator, the extra light can be used to reduce the noise floor



US Patent Appl. No. 2018/0045543
EP Patent No. 3265757

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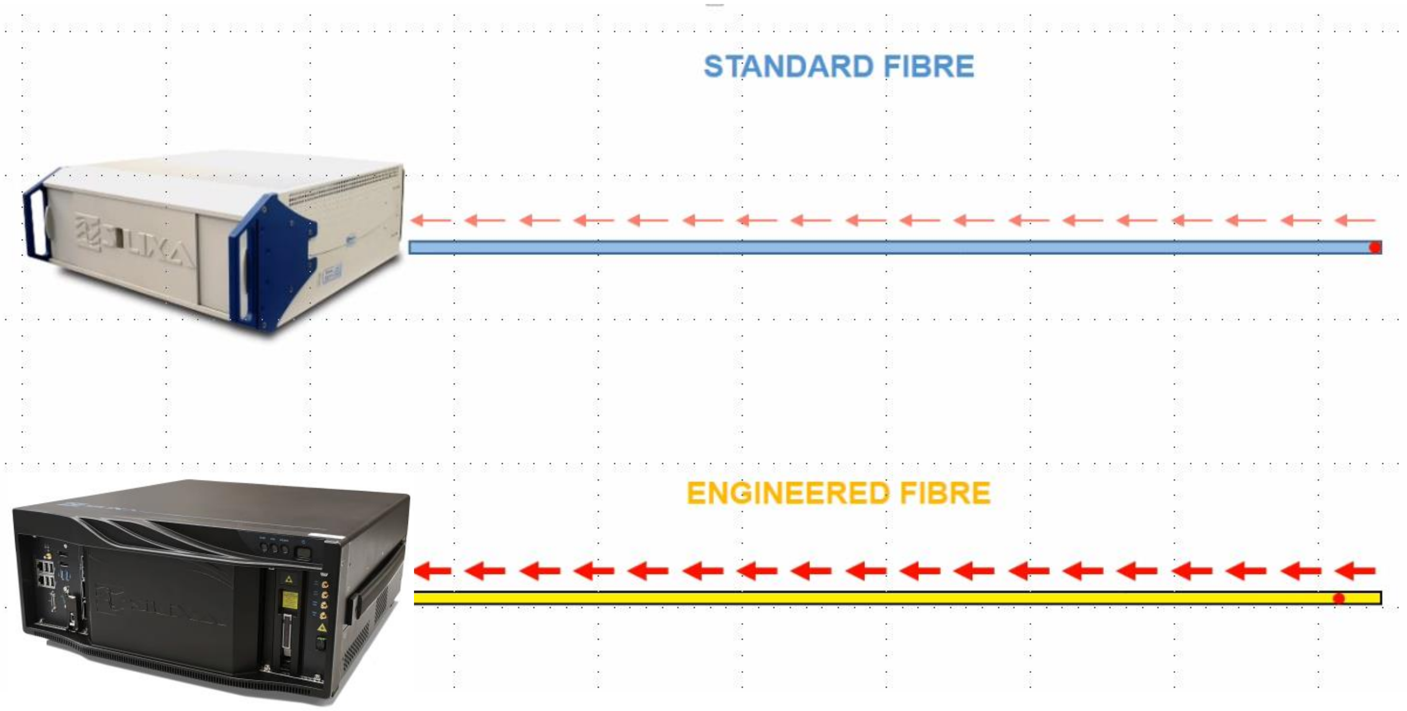
Constellation - engineered fibre optic sensing

- A distributed sensor noise floor is governed by how much light is returned from the optical fiber
- We want low loss fiber – to achieve *long range*, but high scattered fiber – to get *more signal*
- This apparent contradiction is overcome by engineering bright scatter centers along the fiber
- Typically, 20dB (100x) more light is generated than from standard fibre
- Using a matched interrogator translates this to a step change acoustic noise floor improvement of 20dB (100x)



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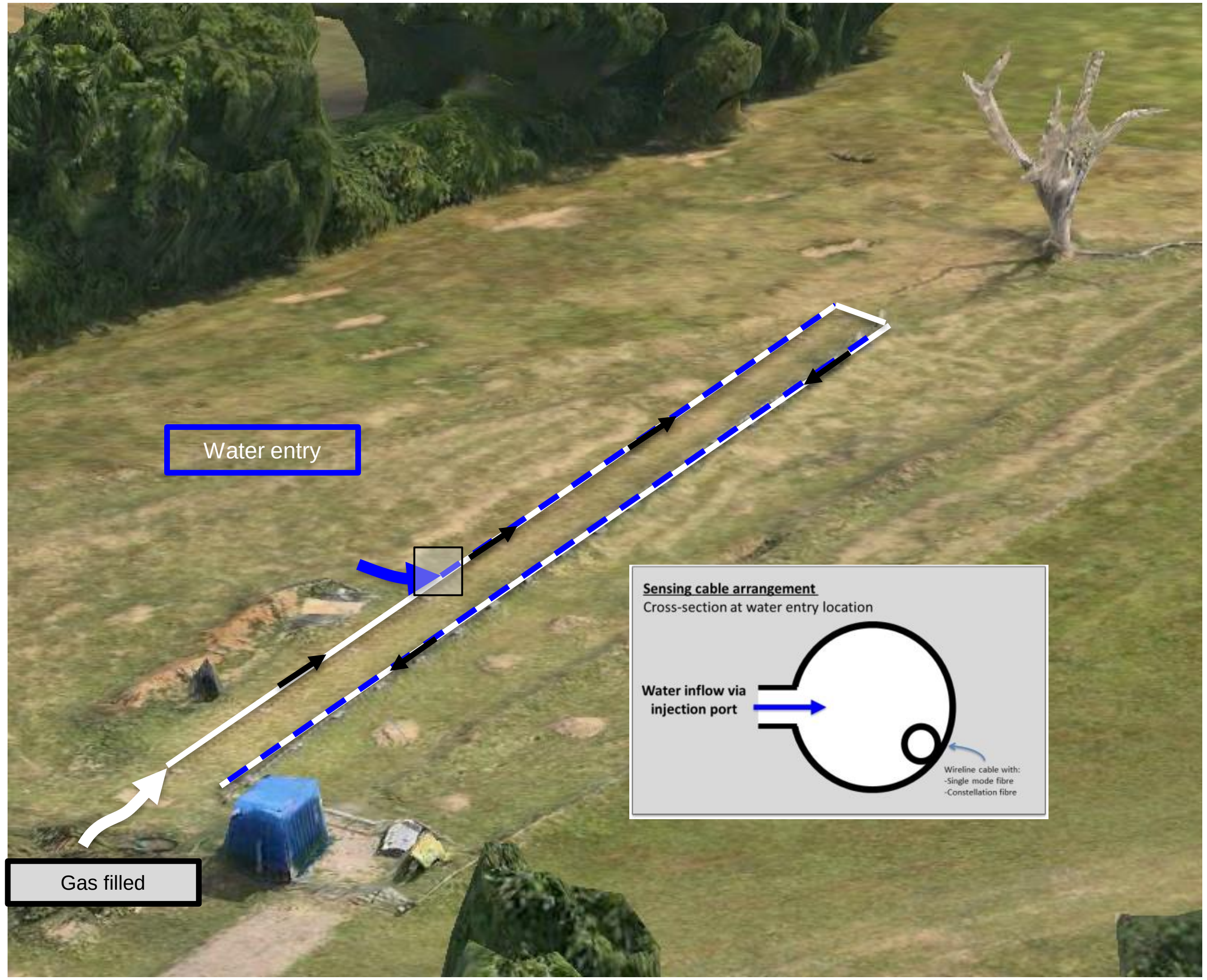
sense the difference

Engineered Constellation fiber advantages

- Higher signal to noise
- Fine spatial resolution
- Lower source energy/fewer shots
- Better depth correlation
- Wider dynamic range
- Wider Aperture
- High-performance low frequency response
- Increased loss tolerance
  - Long-offset subsea applications

Higher signal to noise performance - Complete Clarity



	Background noise	Water noise
DAS		
EAS		
	Sound of Silence	Complete Clarity

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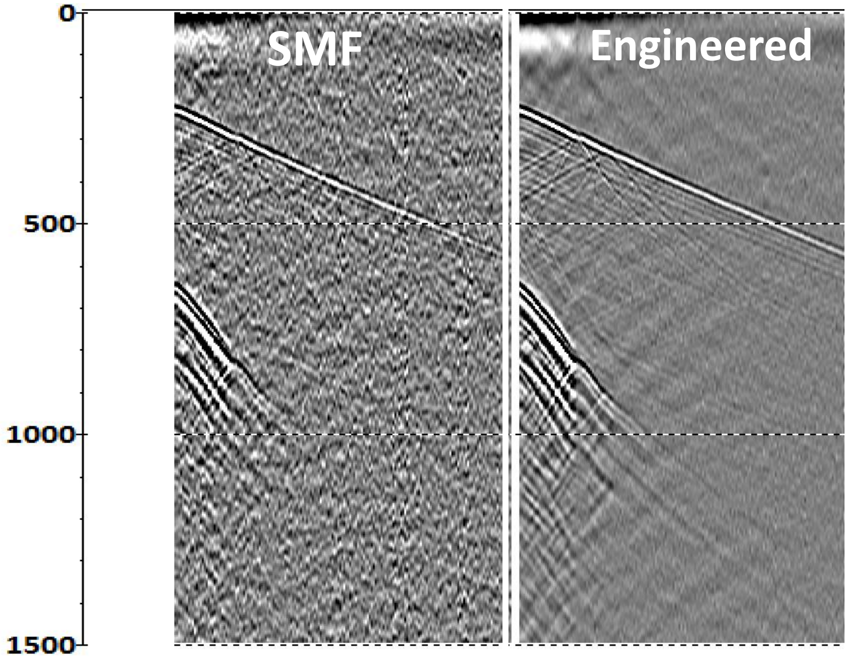
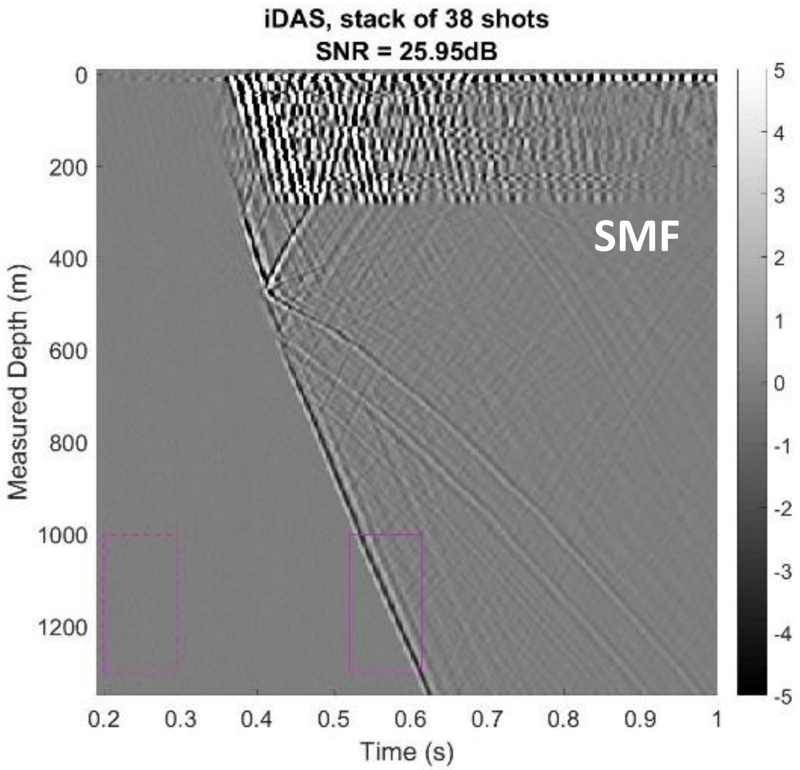
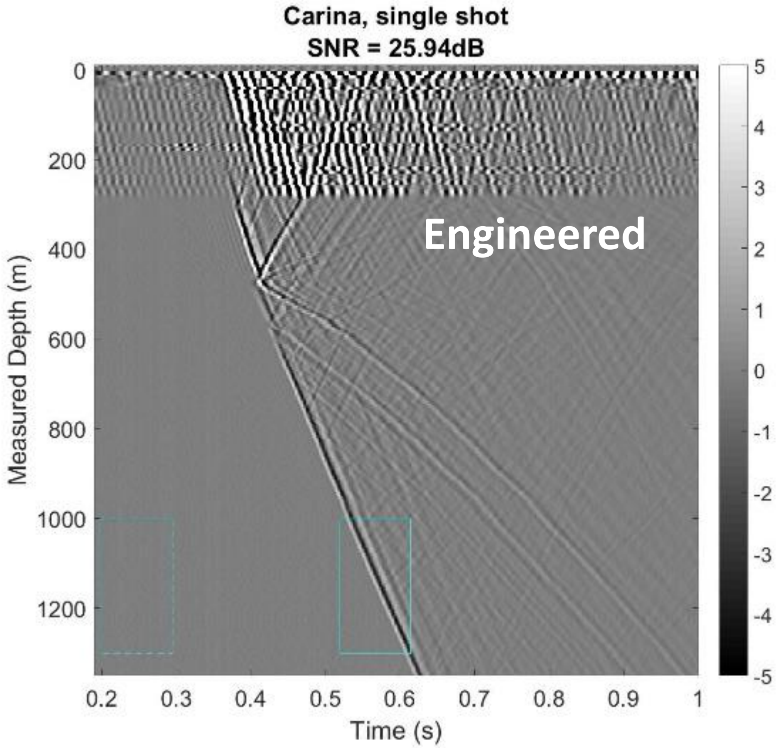
VSP comparison

Higher
Signal to noise

Lower source effort



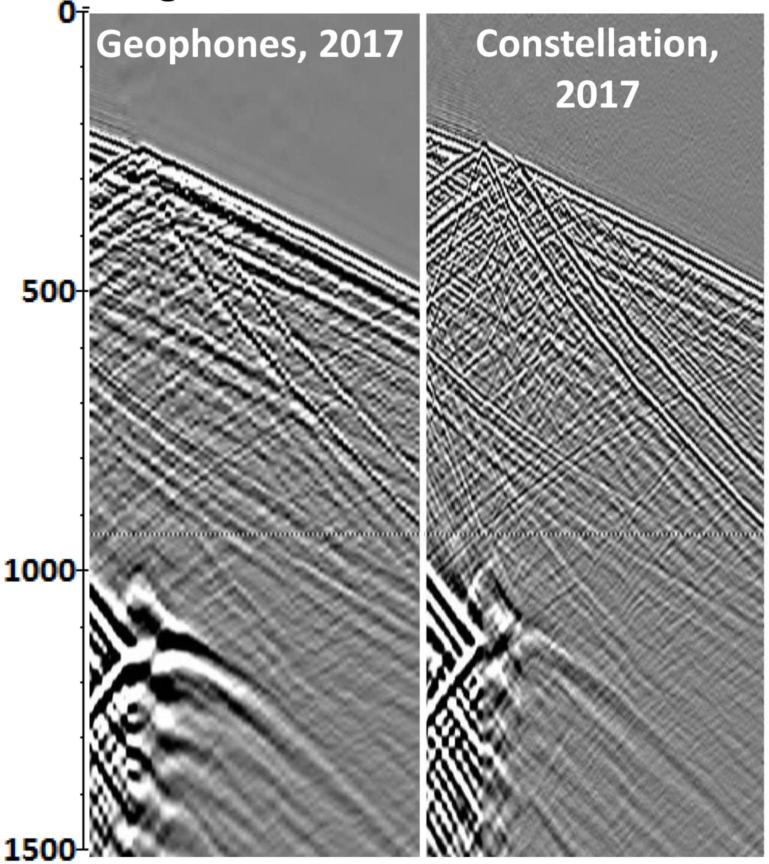




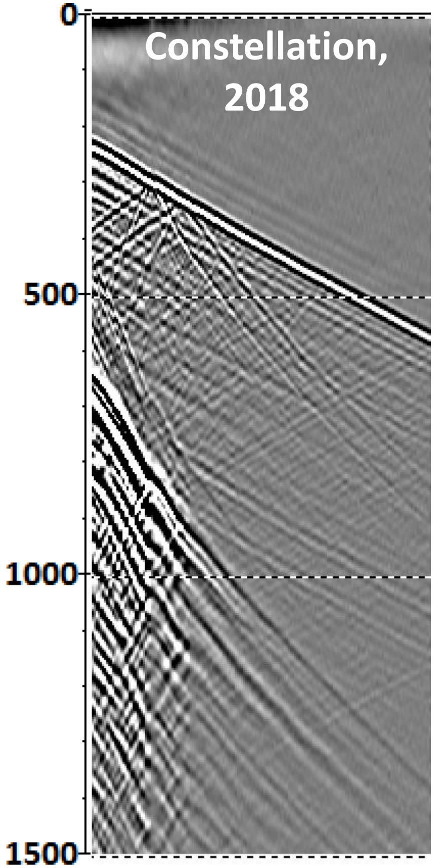
Reduced source energy

- Constellation performance allows large, expensive, manned sources to be replaced with autonomous, small, permanent sources

Large vibe source



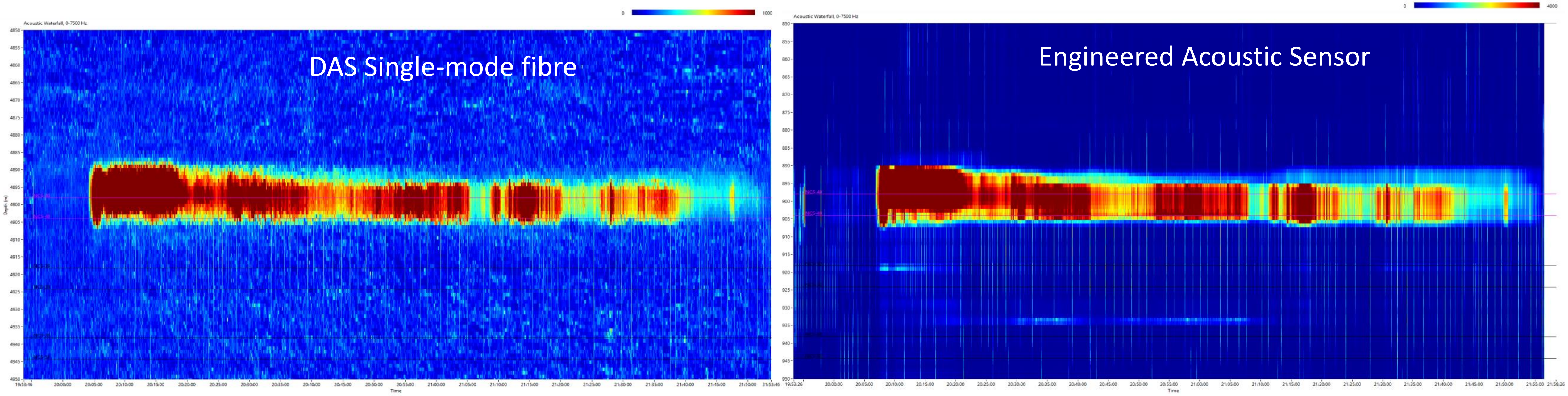
Small stationary orbital vibe source



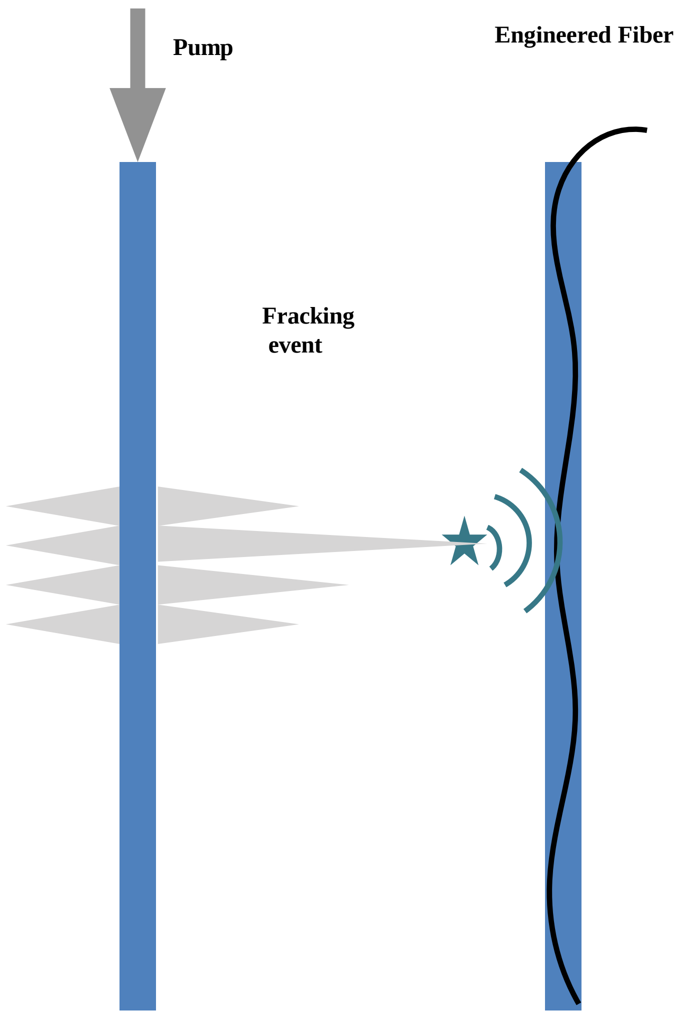
High cost, high environmental impact, non-continuous → Low cost, low environmental impact, continuous

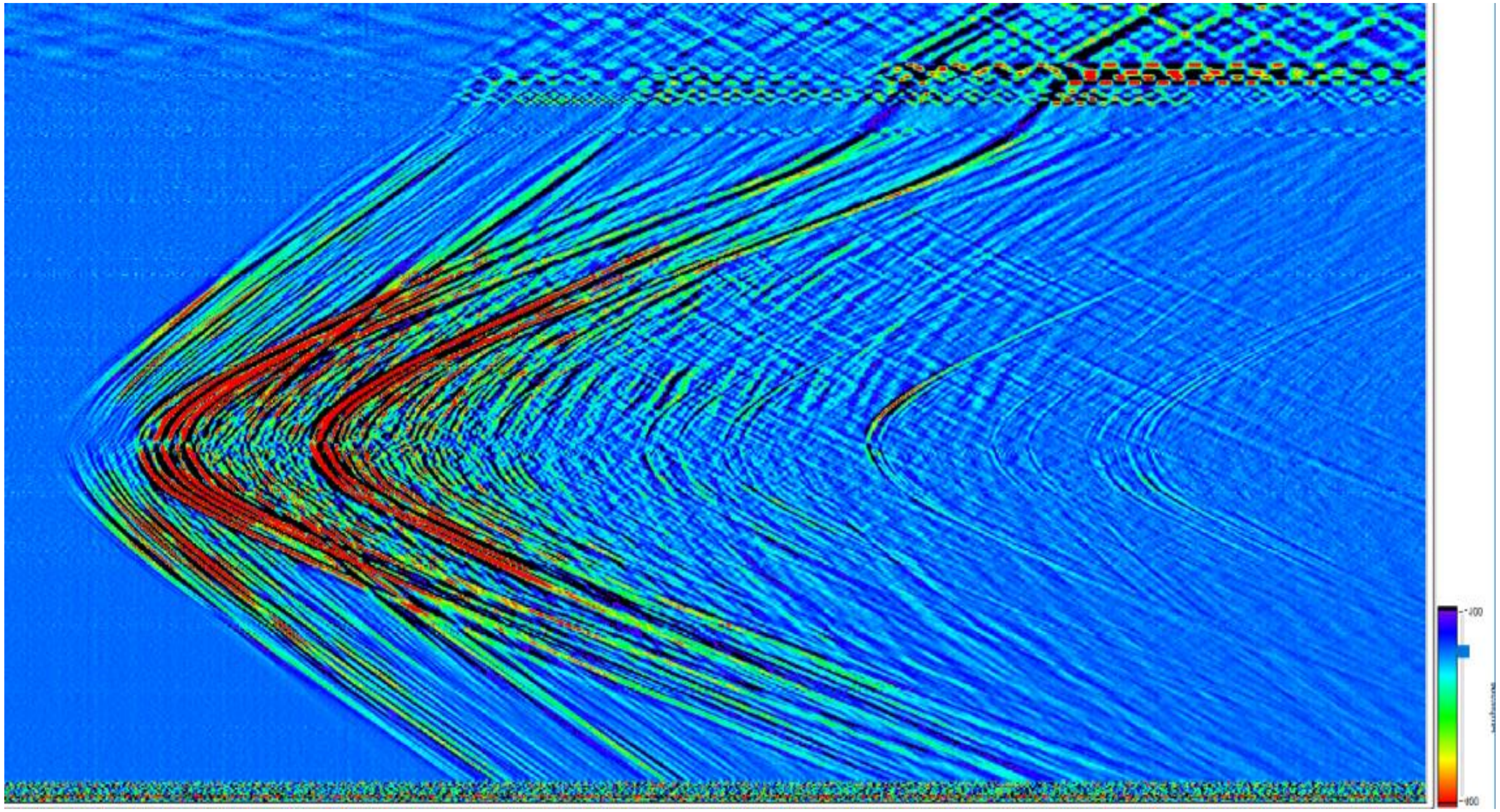
Wide dynamic range

Fracture monitoring in the treatment well



Wide aperture microseismic event detection





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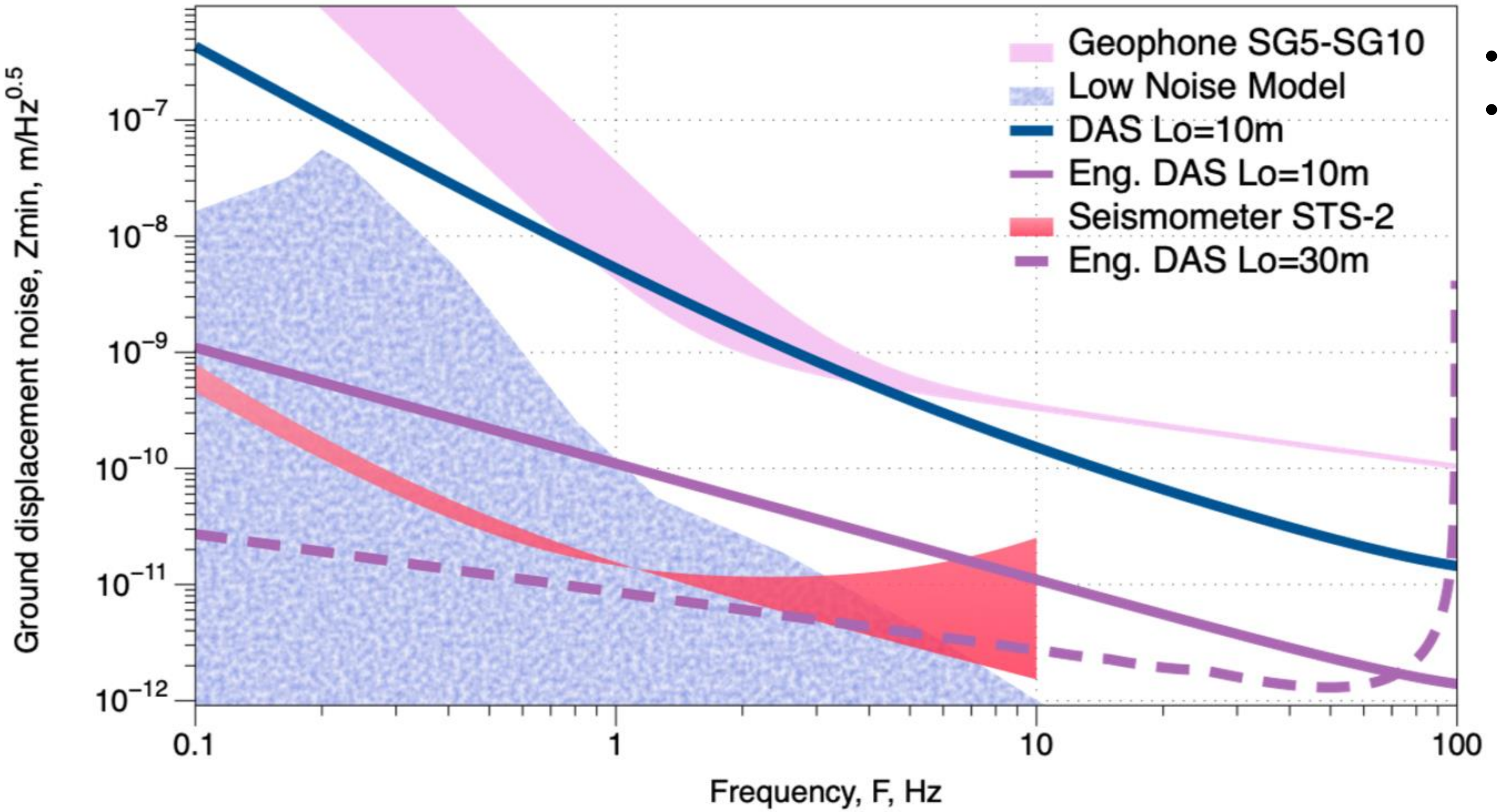
Enhanced Low-frequency sensitivity

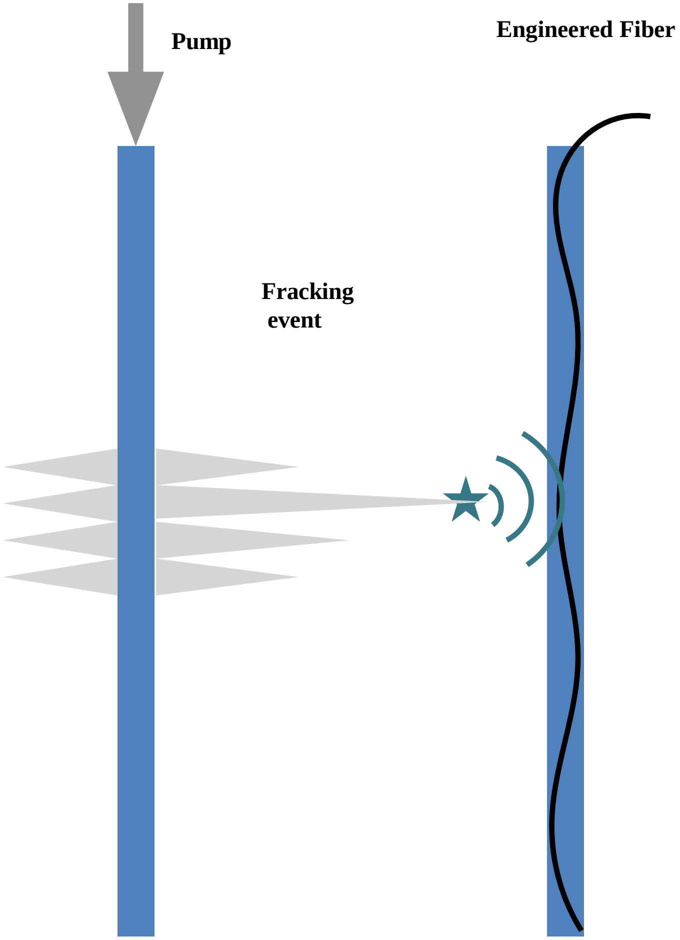


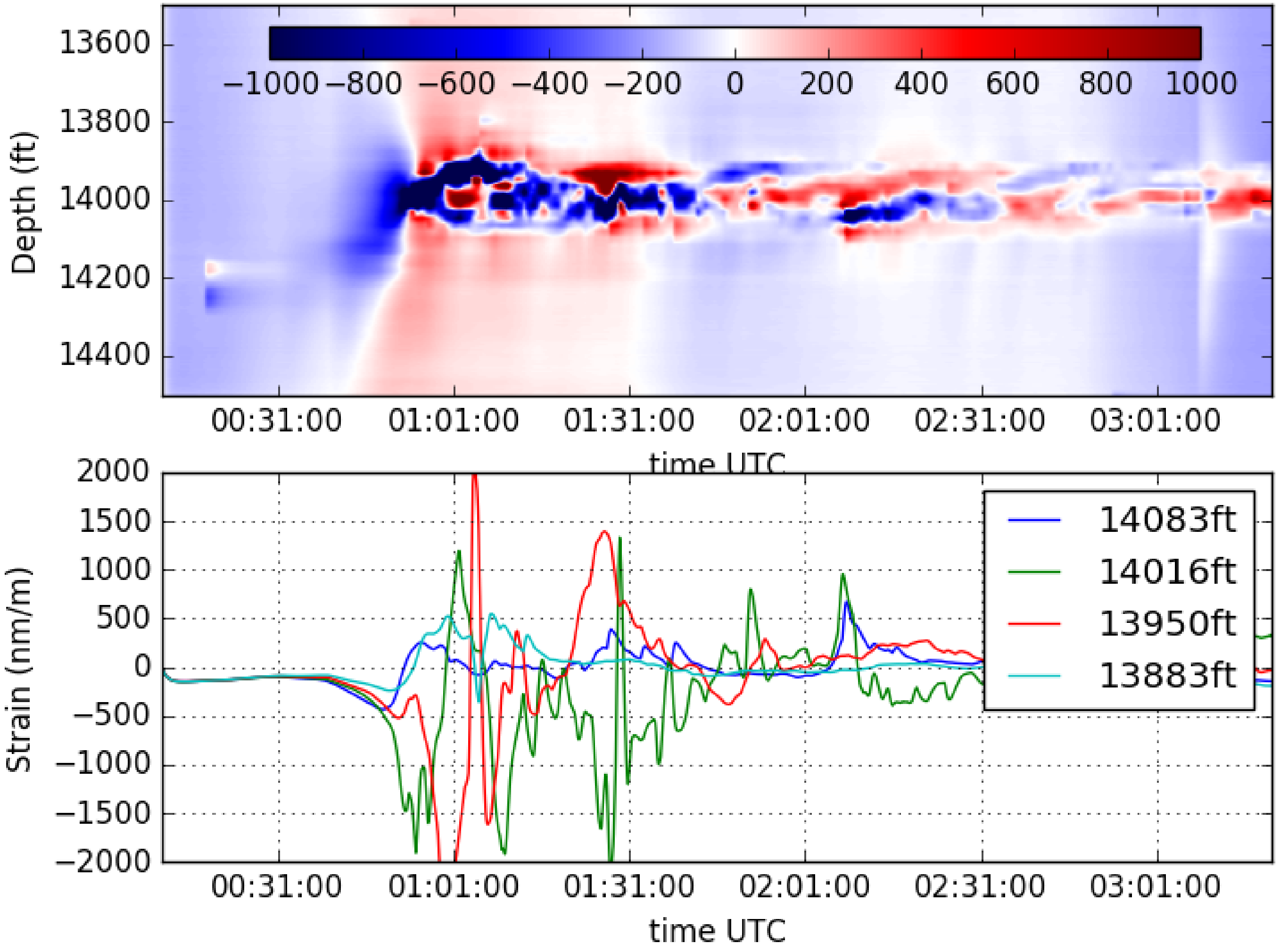
- 10km Array
- 10^{-13} with 10m array spacing

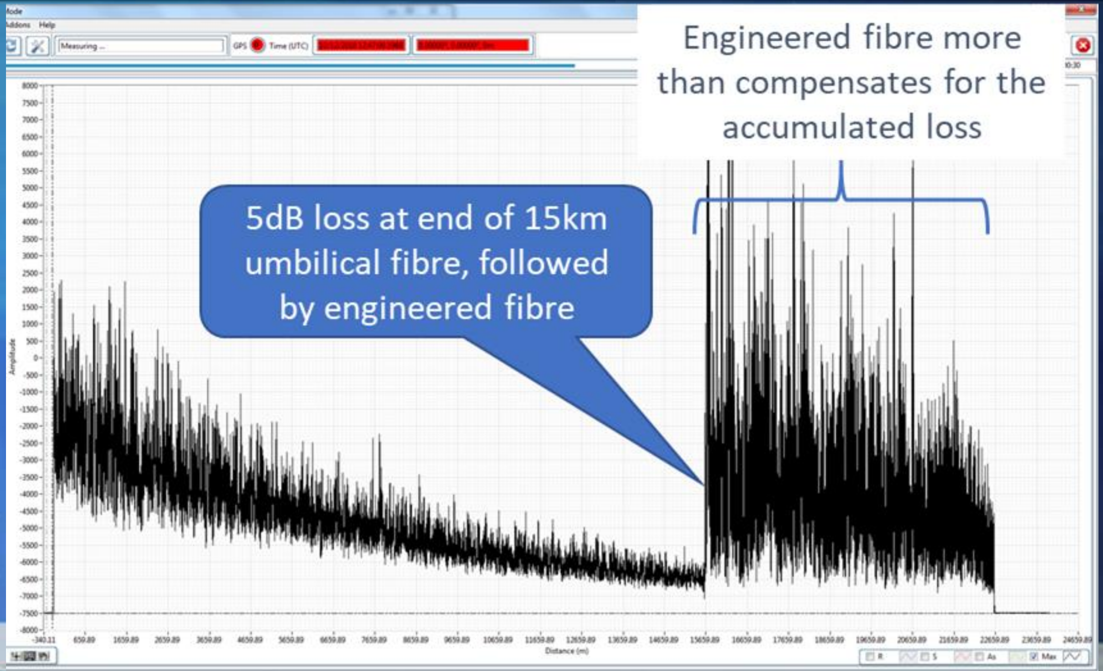
Synthetise an optimum low frequency antenna that is also not confined to a linear configuration

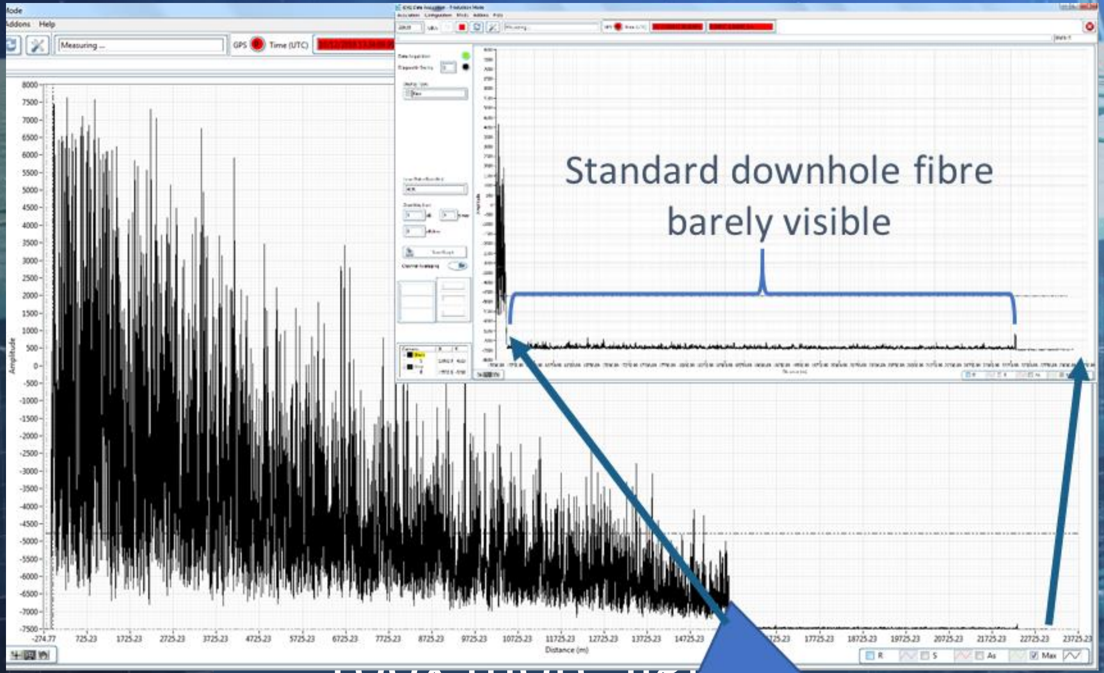
actionable insight

Enhanced Low-frequency strain









BP Atlantis system demonstration 6th Feb. 2020

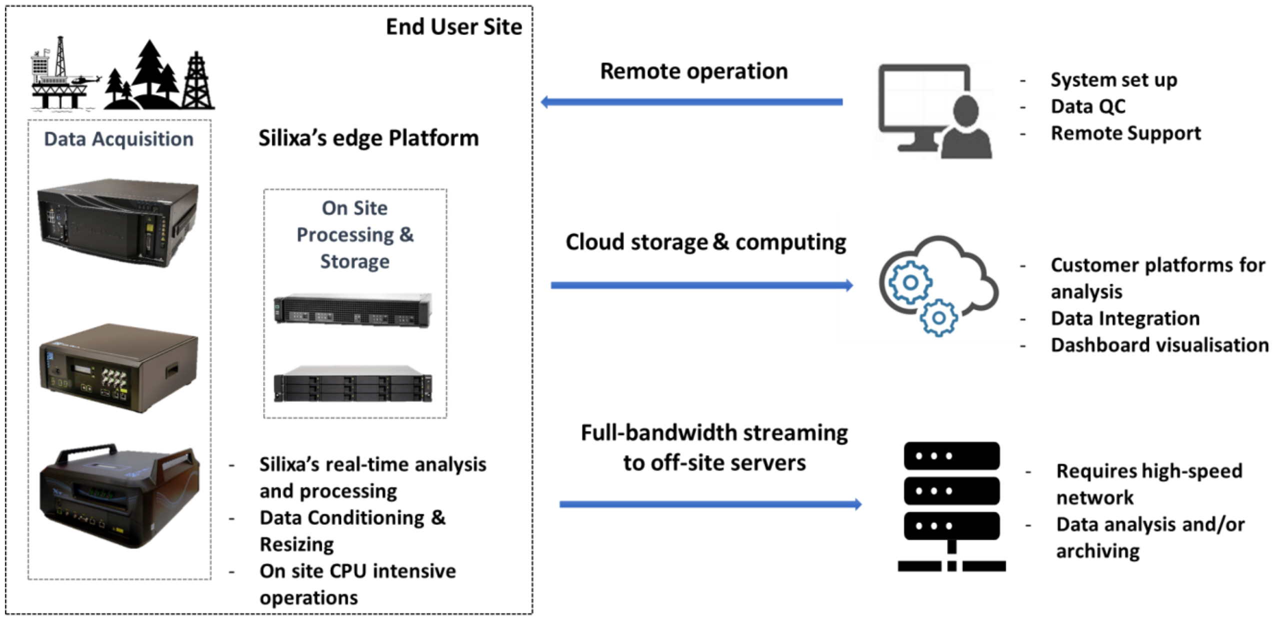
Carina® CarbonSecure™ Summary

Solution

- Distributed Temperature Sensing
- Distributed Acoustic Sensing
- Distributed Strain Sensing
- Structural Faulting
- Induced Seismicity
- Well Integrity
- Plume Migration
- Cap Rock Integrity

Carina® CarbonSecure™

Real time, on line, modular, monitoring platform.



Benefits

- Cost Effective Solution
- Suitable Onshore or Offshore Operations
- Large Spatial Coverage
- Continuous Monitoring or On Demand
- Capable of Remote Operation
- Low Energy Consumption
- Low cost of ownership
- Minimum impact to the Environment
- Long lifetime

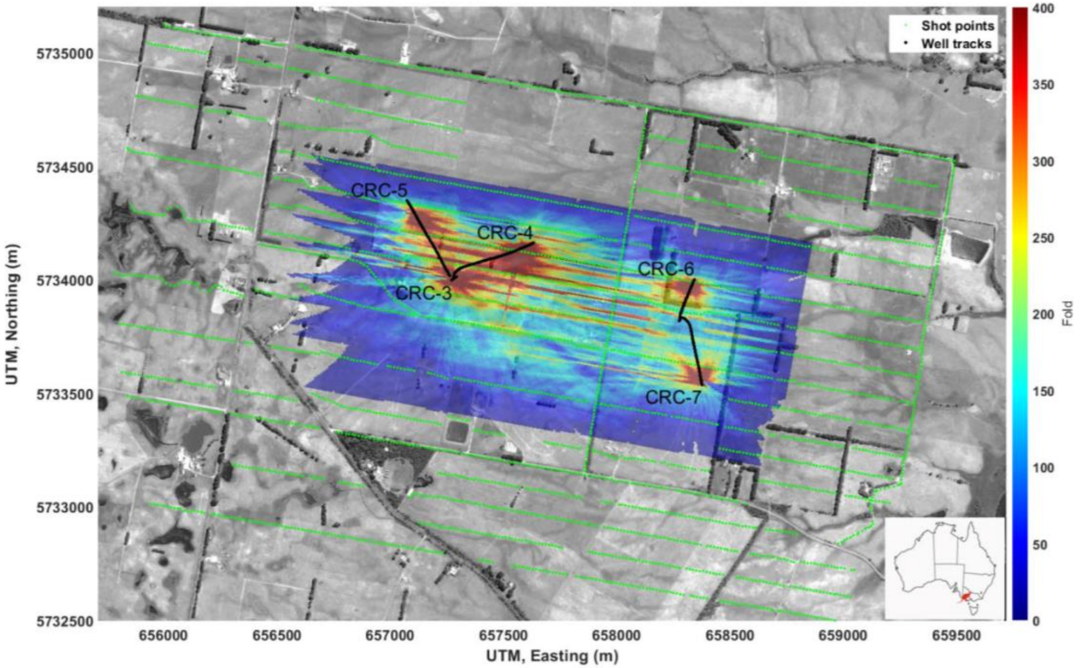
Carina® CarbonSecure™ Silixa's Solution for Safe & Economic Storage of Co2

- **Carina ® Sensing System is the core of the most cost effective permanent monitoring solution because of the 100x improvement in SNR.**
- **Complete solution** built on 3 integrated distributed optical measurements in one cable, DAS, DTS & DSS.
- Addresses current **Pain Points**
  - Wellbore and caprock integrity
  - Plume mapping
  - Induced seismicity
  - Long step-out distances up to 150km
  - Cost
- Carina CarbonSecure **delivers**:
  - Verification the amount of CO_2 being stored underground
  - Understanding of CO_2 distribution underground
  - Provides assurance of long–term storage integrity
  - Minimizes environmental impact.
  - Gives lower life-cycle costs

CO2CRC Otway project, VA, Australia

Reducing the *cost* of CO_2 *monitoring* by tens to hundreds of millions of dollars over the life of a commercial project and *further development* of CCUS programs

- Onshore CUS in rural area
- 15,000 tonnes CO_2 injection by 2022 at 2.1 km
- Need to reduce environmental footprint
- 2014 first optical fibre cable installed
- 5 wells now equipped with the Carina Sensing System
- Additional helically wound surface fibre optic cables
- Over 40 km of optical fibre installed (2020)
- Multiple low impact/low cost SOV's
- Capable of remote passive or continuous monitoring



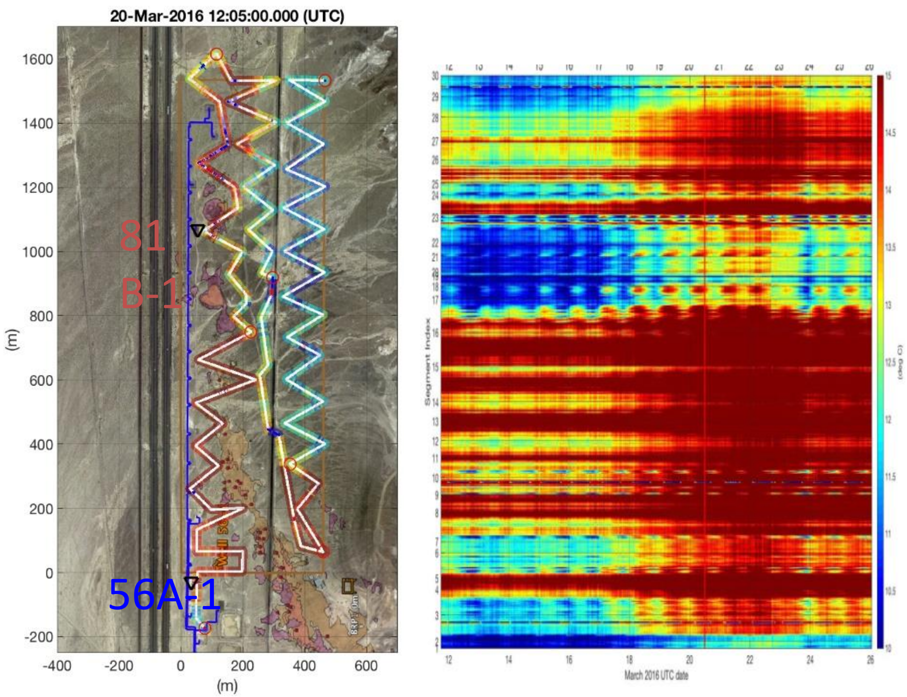
Optimal solution for surveillance of CO_2 Sequestration

(EAGE Workshop on Fibre Optics Sensing for Energy Applications)

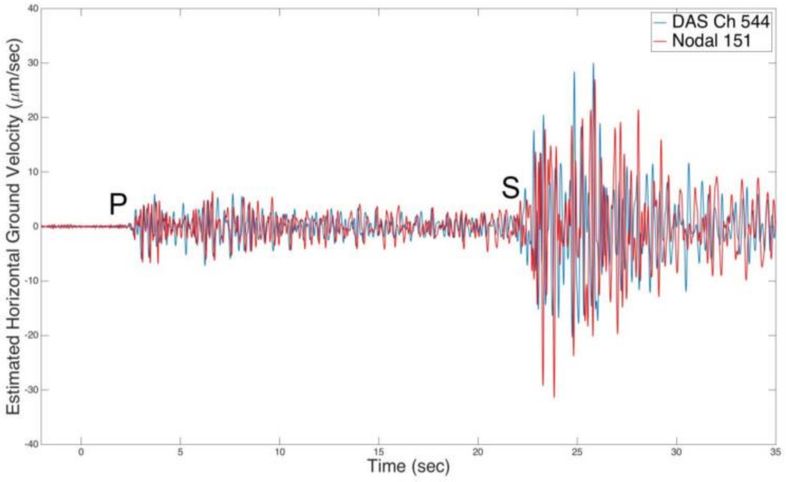
POROTOMO -Brady Hot Springs

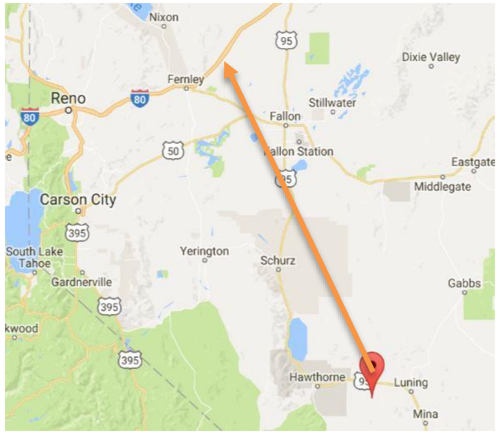
DAS and DTS were recorded continuously over 15 days while a series of changes to pumping and injection were made.

- DAS and DTS data were collected using a single cable with multiple optical fibers
- Horizontal/Trenched
  - ~8,500 m buried cable length
  - Buried 1 m
  - Sample spacing 1 m (DAS and DTS)



(modified from Miller et al., 2018)





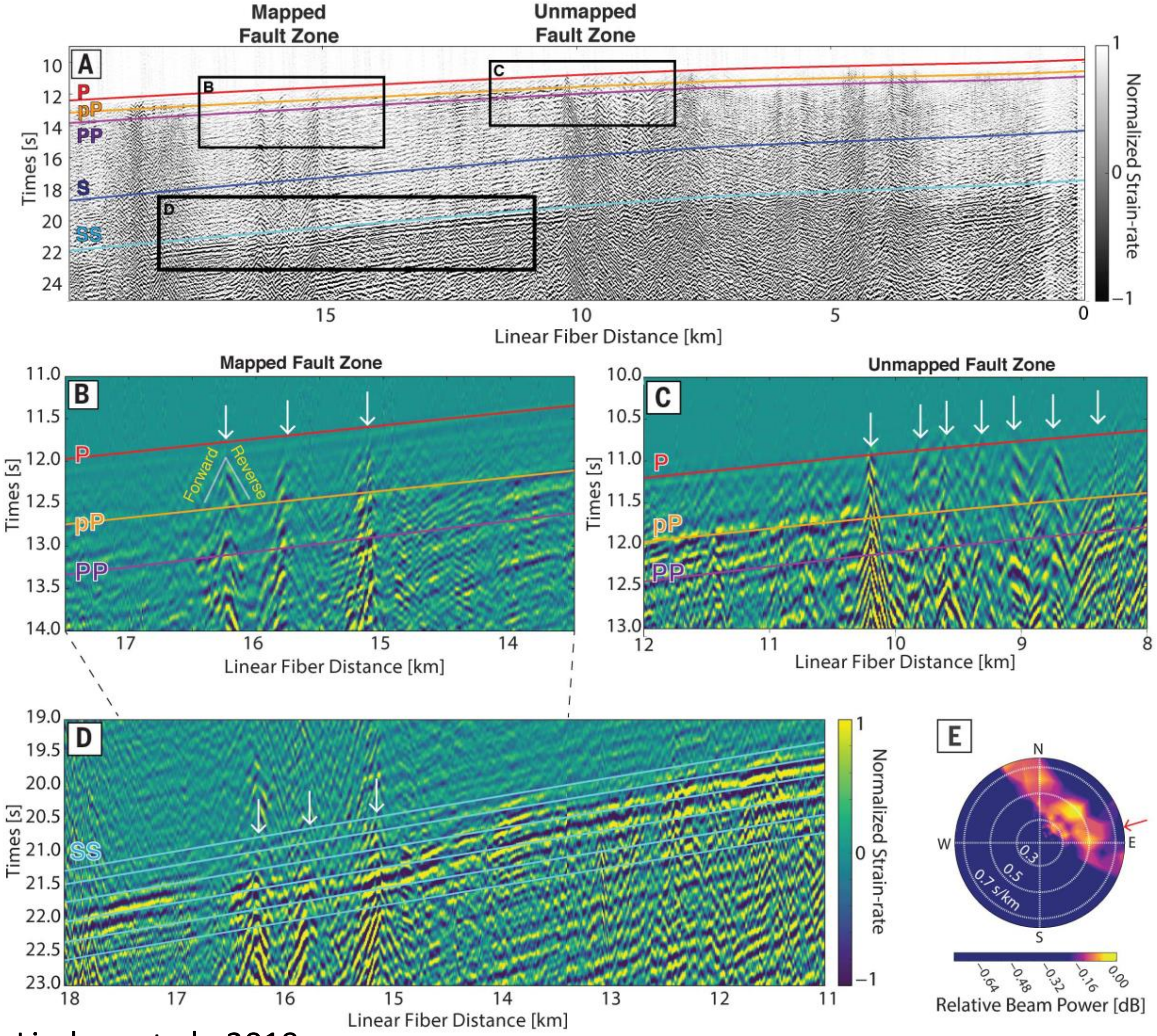
4.3 earthquake that occurred near Hawthorne, Nevada.

Time series of ground motion as recorded by DAS and a co-located Nodal seismometer.
(modified from Feigl et al., 2017).

actionable insight

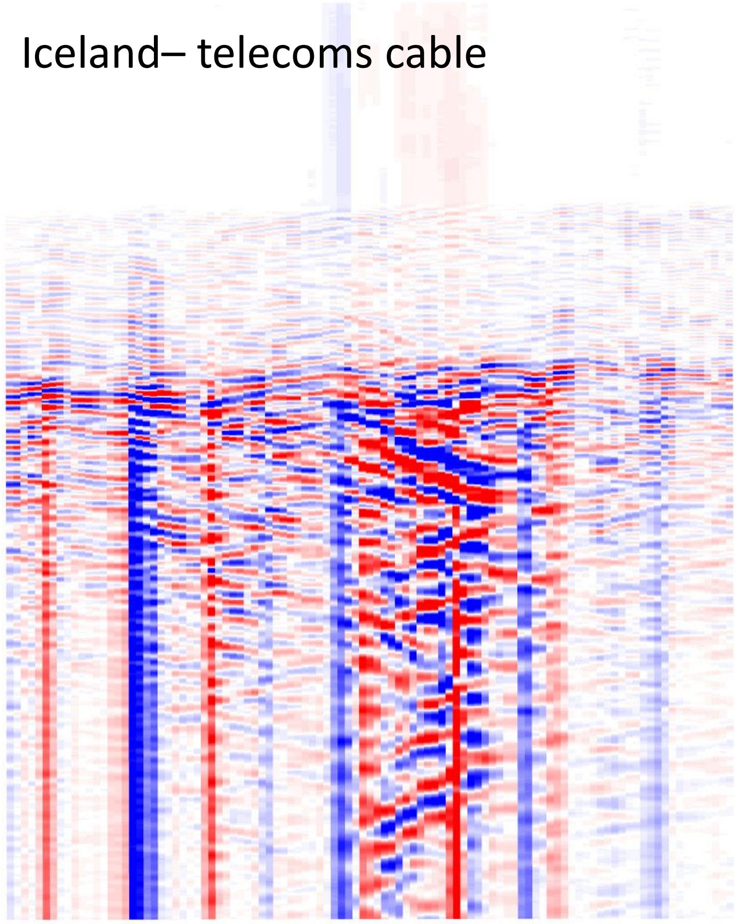
Case Studies– Mapping fault zones

Monterey Bay, California – offshore science cable



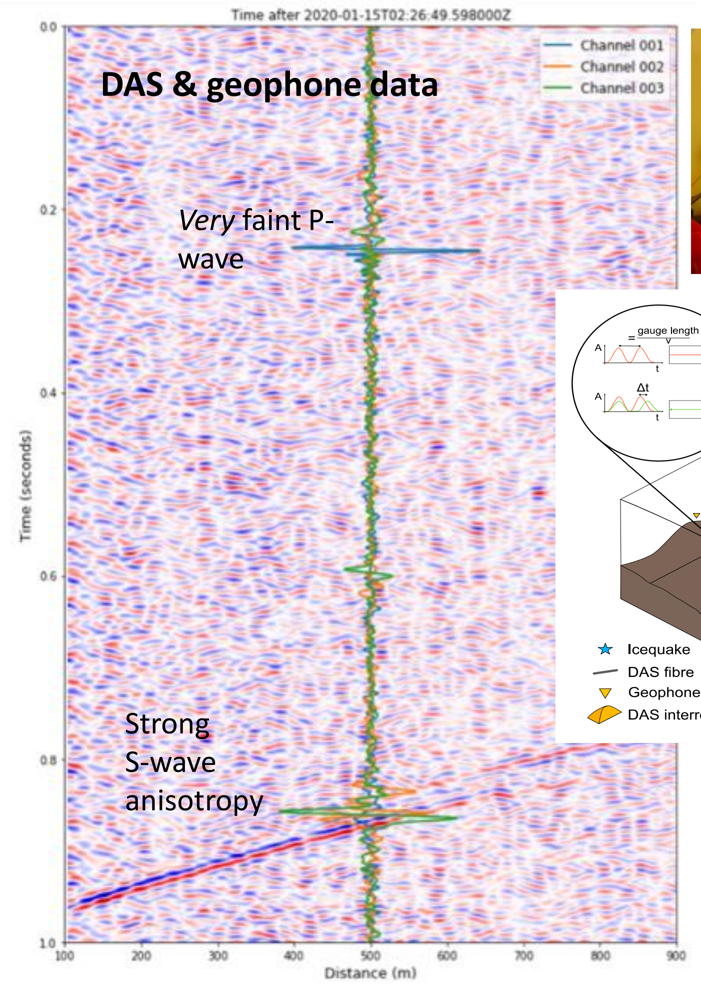
Lindsay et al., 2019

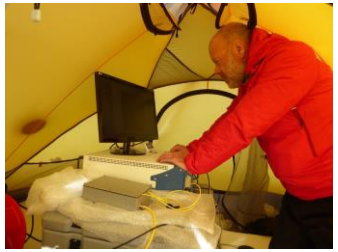
Iceland– telecoms cable

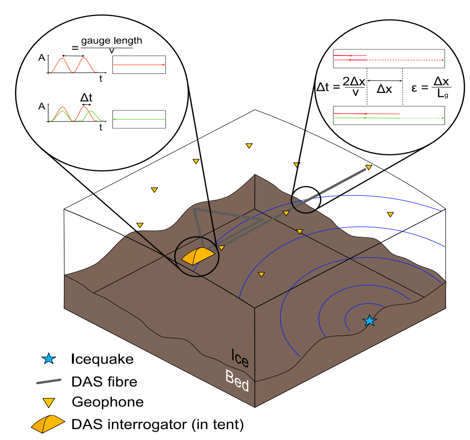


Jousset et al., 2018

Microseismic, standard SM fibre, surface – Icequakes



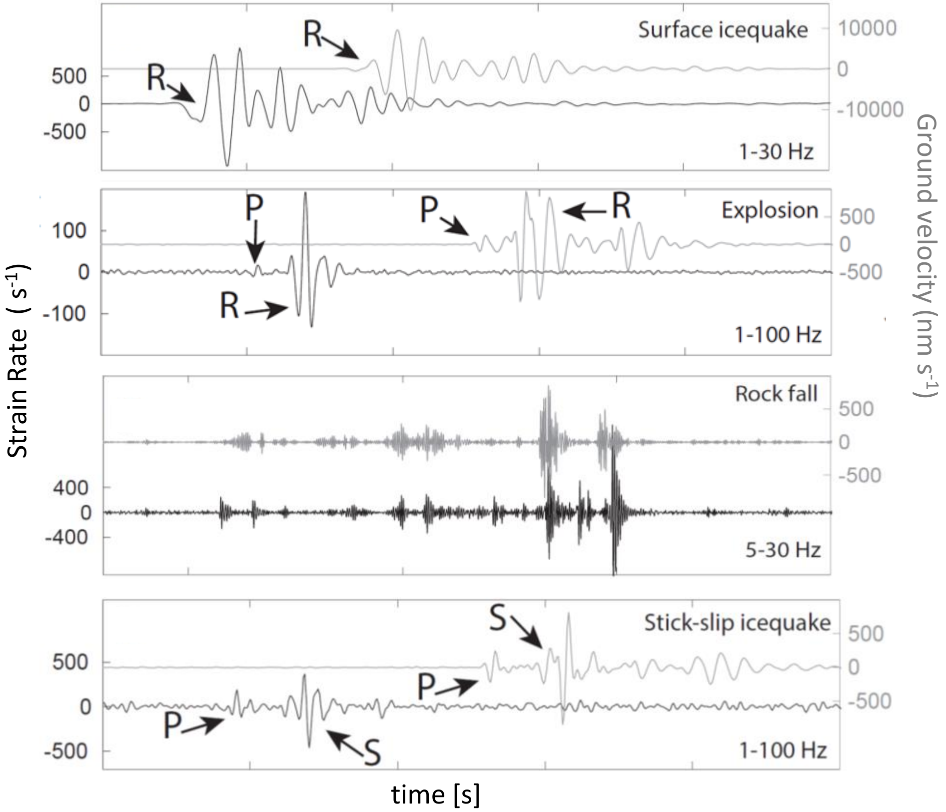


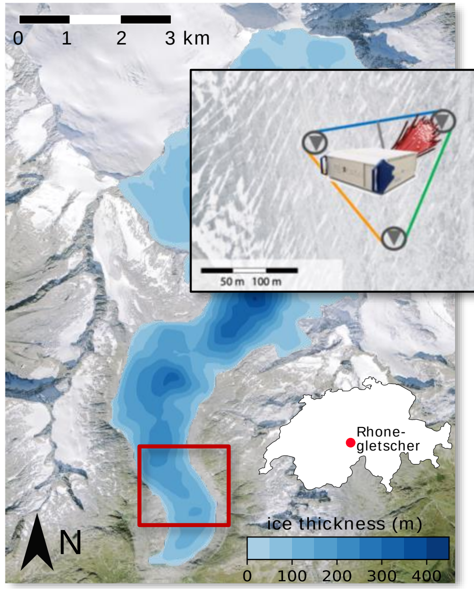


Images courtesy of Mike Kendall & Tom Hudson (University of Oxford); Antony Butcher (University of Bristol)

Rhone Glacier

- 8km surface trenched cable
- Flow velocity 35 m/y
- Ice thickness 200m





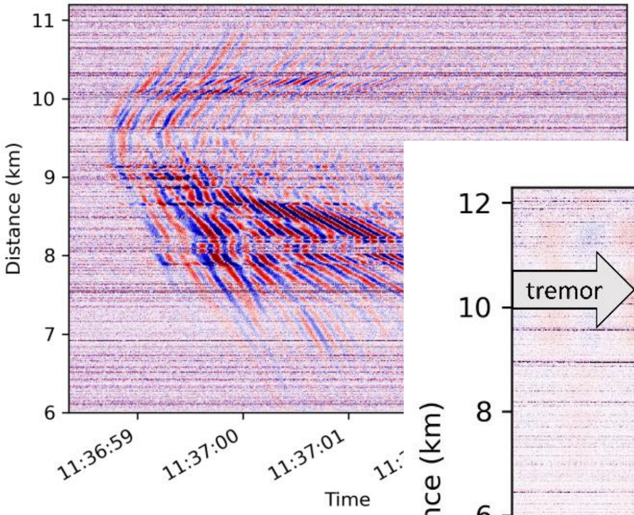
co-located channels

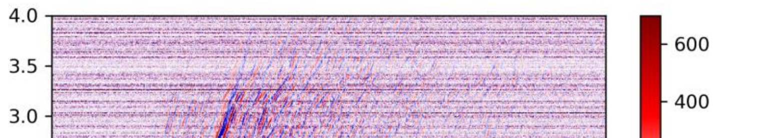
- DAS strain rate [10^{-9} s^{-1}]
- seismometers [nm s^{-1}]

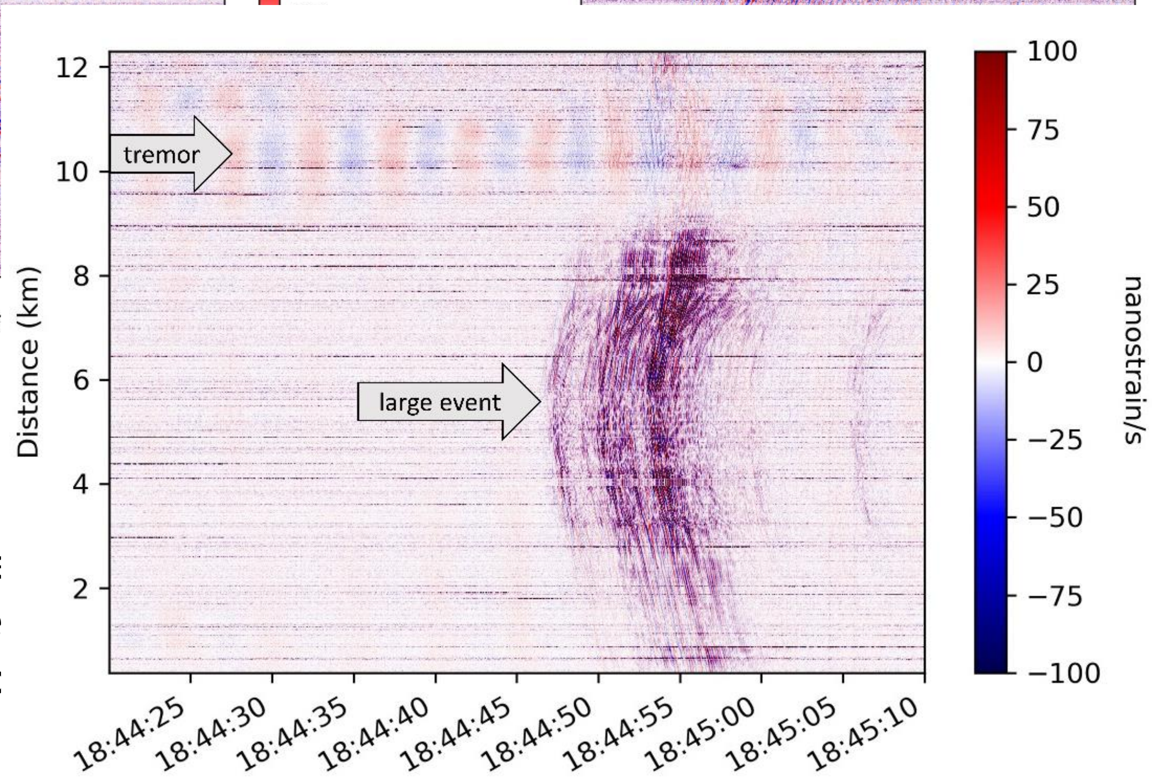
Images courtesy of Andreas Fichtner (ETH) and from Walter et al. 2020

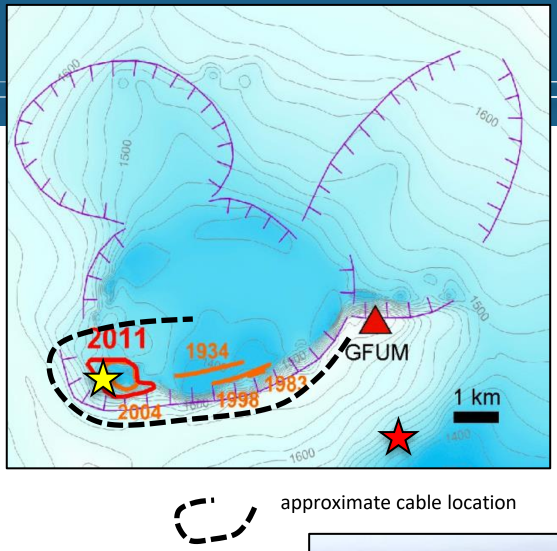
Understanding Volcanoes

Grímsvötn volcano, Iceland - 13km surface trenched cable









14 April 2021 ☆

- intermediate-fre
- possibly surface
- complex wavefc
- strong focusing
- location near lar

z)

Images courtesy of Andreas Fichtner (ETH)

SILIXA actionable insight

Geotechnical Monitoring Solutions

DTS (temperature)

Passive or Active Seepage Detection

- Seepage flow monitoring
- Water level

DSS (strain)

Subsidence and Deformation Monitoring
- Identification of locations with deformation
- Dam/levee breach detection

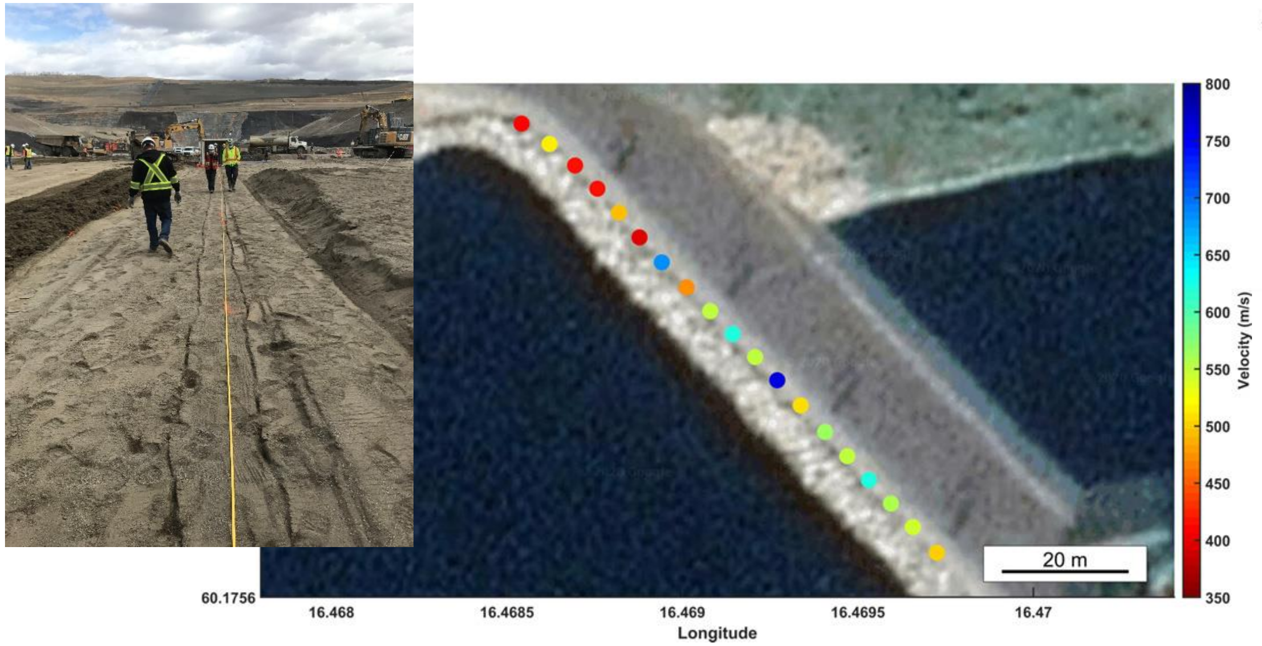
DAS (acoustic)

Subsurface Tomography / Imaging
- Material property changes
  - Density
  - Saturation

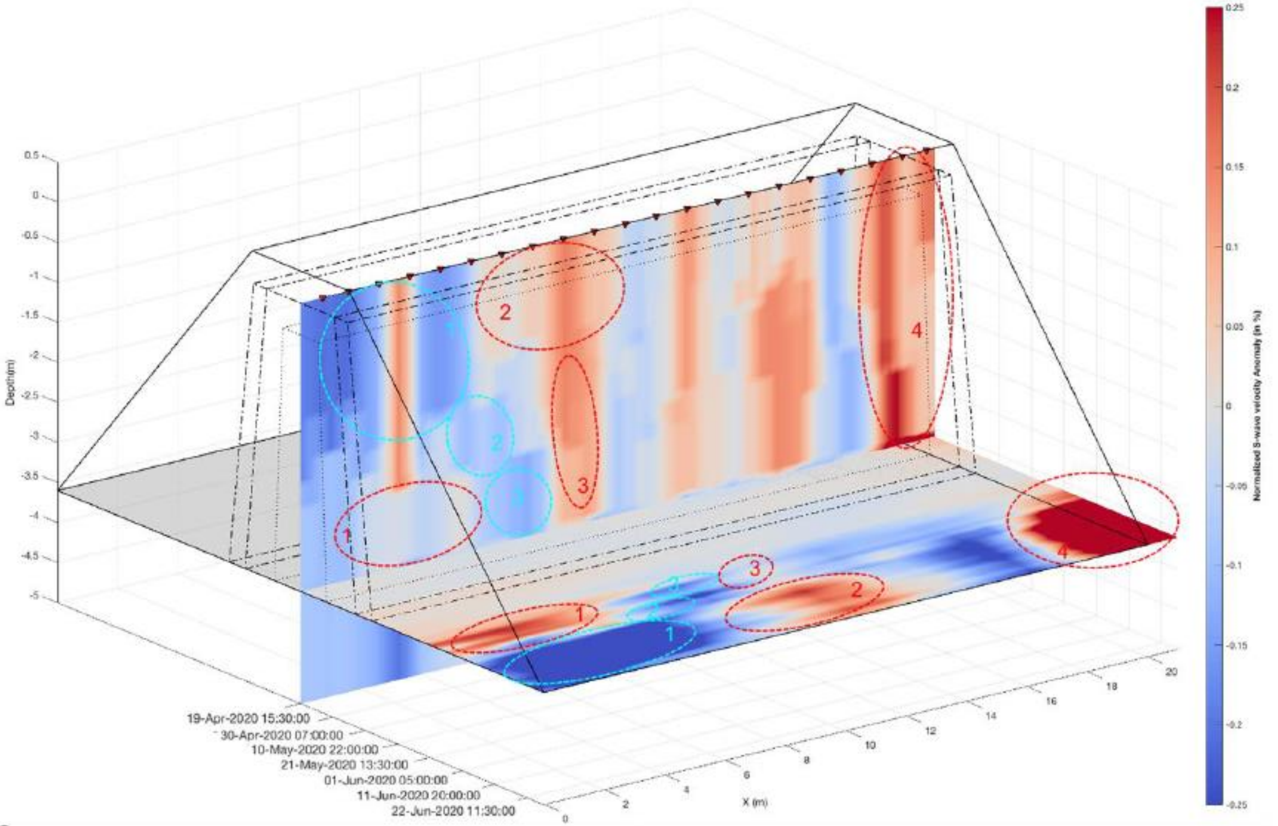
Microseismicity monitoring

Ambient noise seismic interferometry

- Small scale & large dams
- Imaging & monitoring
- Body-waves, surface waves, coda waves
- Cables buried at crest & in dam – permanent installations
- Gauge length comparison



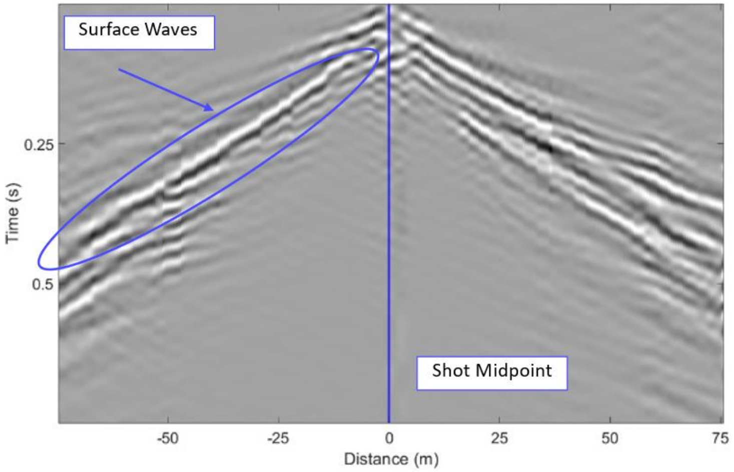
Body wave velocities

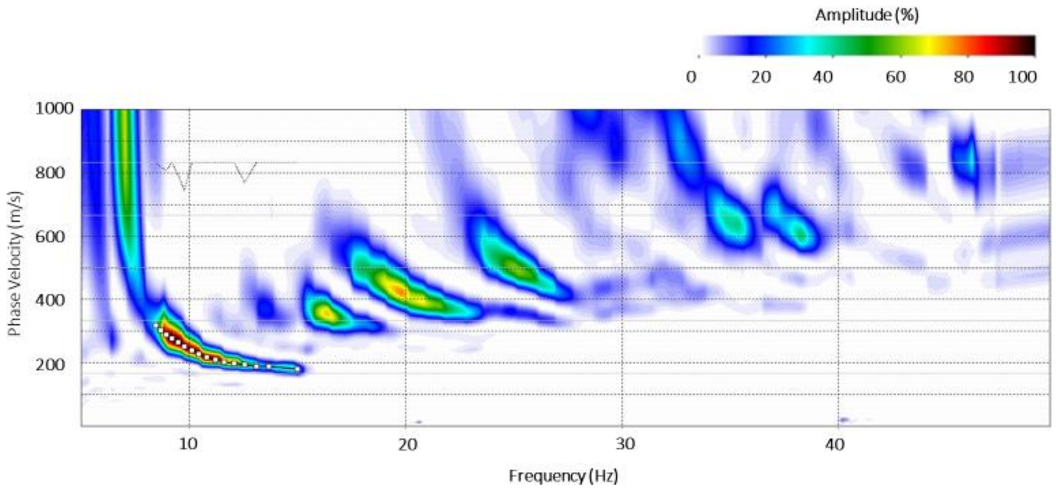


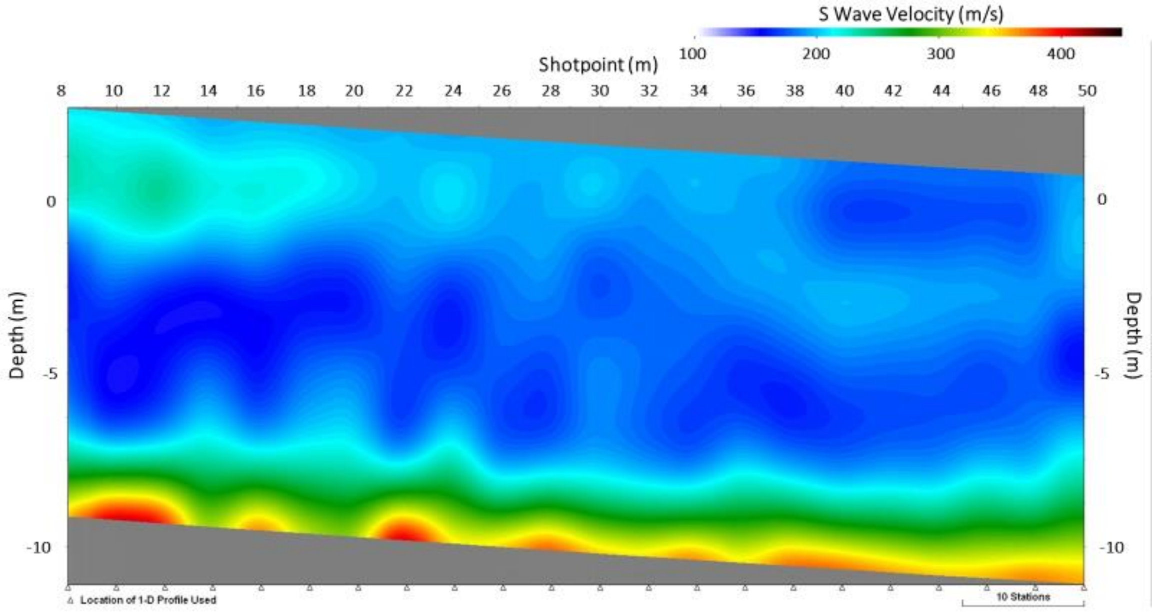
Coda wave imaging & monitoring

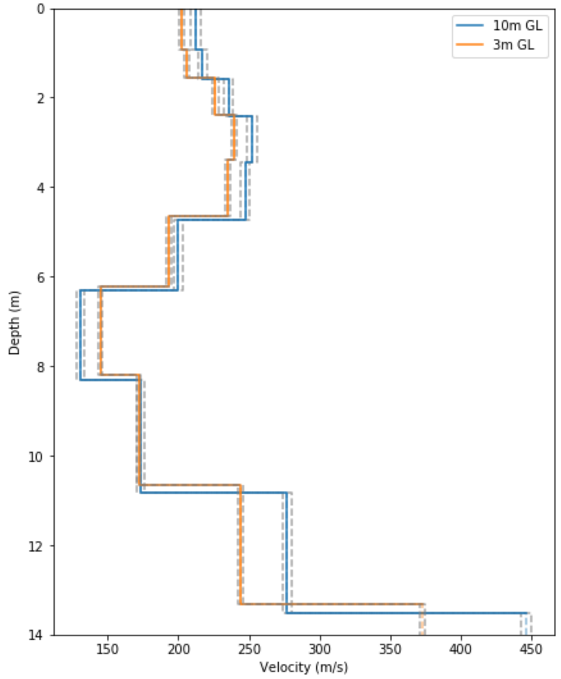
Active MASW

- Gauge length comparison
- 100s m survey length without large field team









SILIXA actionable insight

Thank you for listening!
Any questions?