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SPE International Aberdeen Section

Fiber-Optic Sensing for Field Development
Asset Integrity & Optimization Workshop

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Aberdeen, UK

Field Validation of MagiQ's GeoLite Three-Component Optical Seismic Sensor Array in a Borehole Deployment

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Dr. J.B.U. Haldorsen

MagiQ Technologies

The industry clearly needs a fiber-optic three-component acoustic sensor

This talk is about GeoLite, one such sensor…

Presentation Overview

- Why Vector Sensors?
- Why Fiber-Optic Sensors?
- GeoLite 3C Architecture
- Laboratory & Field Validation (2025)
- Sensor Coupling & Angular Precision
- Deployment Options
- Conclusions

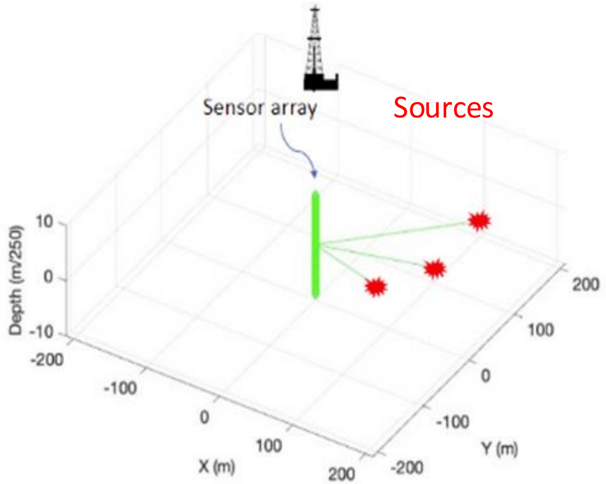
Why Vector Sensors?

Hint: Single component sensors cannot measure the direction of tool motion…

Spatially Dense 1C vs. Sparse 3C Sensors

Model	Raw Synthetic Data	image Section	Conclusions

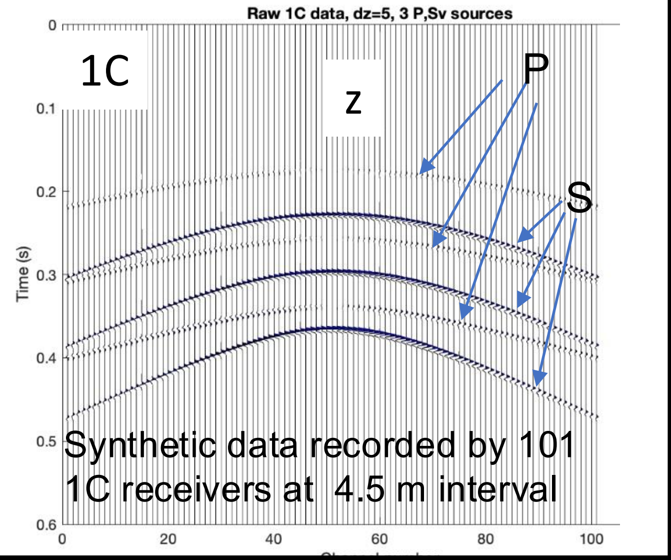
Model



- Simple Isotropic Model
  Vp = 2750 m/s
  Vs = 1588 m/s
- Three sources at different distances generate P & Sv wave modes

Haldorsen, SEG 2023

Raw Synthetic Data



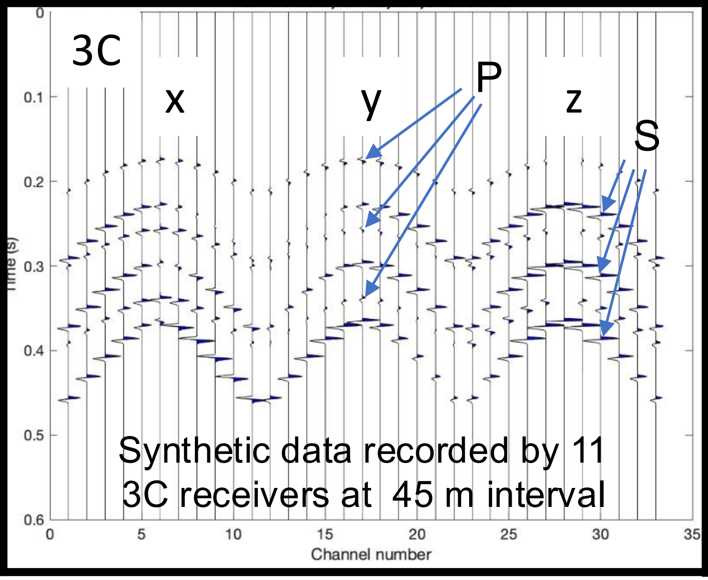
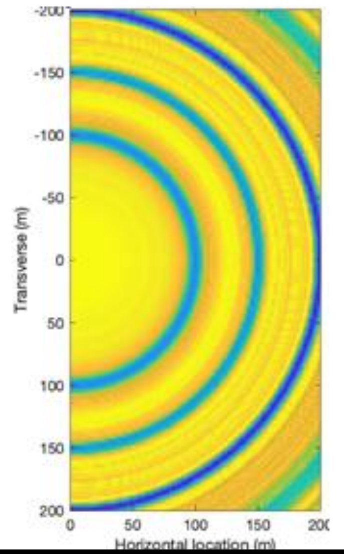
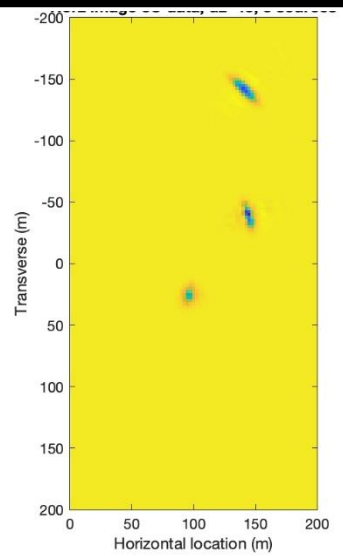


image Section





Conclusions

Dense single-axis sensors

Depth is well-determined

Distance is well-determined

Azimuth is not determined

Sparse 3C sensors

Depth is well-determined

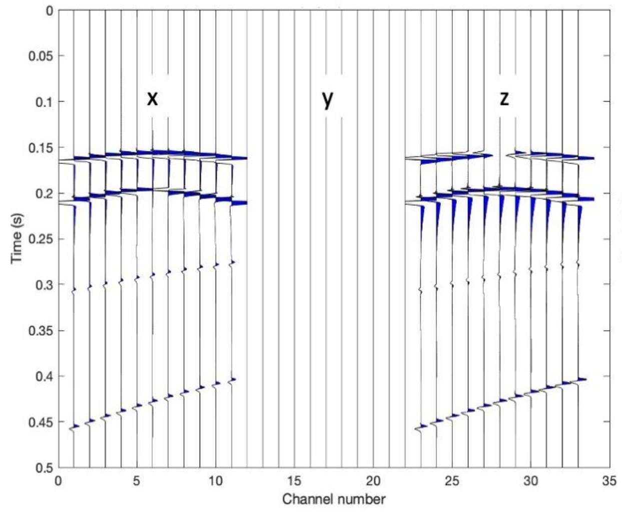
Distance is well-determined

Azimuth is well-determined

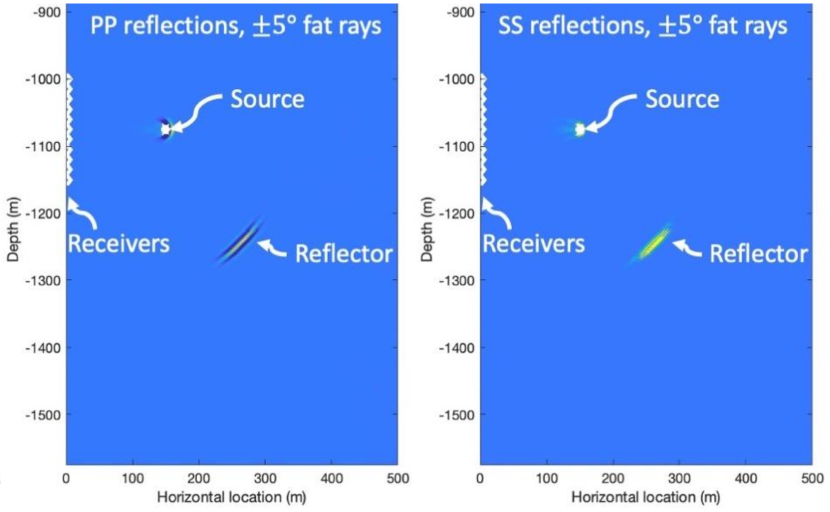
Imaging with 3C Sensors

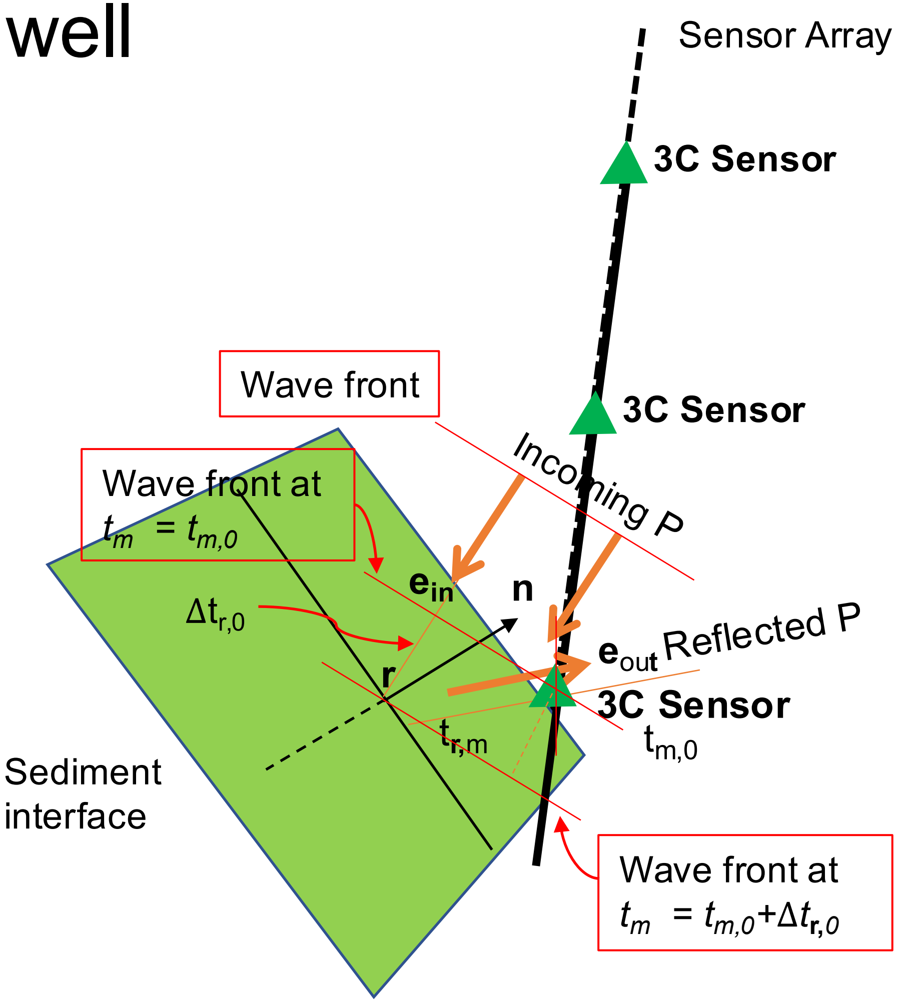
- 3C sensors enable 3D imaging around the well
- No prior source knowledge required
- Passive imaging with microseismicity

Synthetic 3C Data



P- and S-Wave Reflection Formation Images





Haldorsen, SEG 2022, Workshop

Haldorsen, Jahren, 2020, Geophysics, **85**, 3, pp. 1MJ-Z13

Why Fiber-Optic Seismic Sensors?

- Fiber-optic sensors outperform electrical sensors in harsh borehole environments

Wider bandwidth

Data successfully acquired from 0.1 to 20,000 Hz

Longer Lifetime

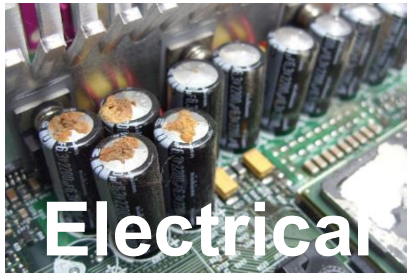
Eliminate downhole electronics

Higher Temperature

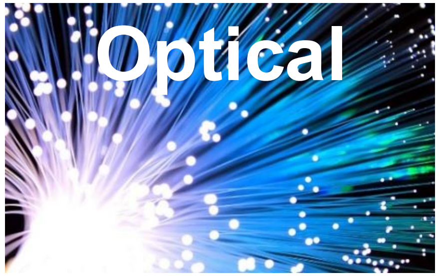
Tested to 300C

Cost effective

Maintenance-free and combinable with DAS



Industrial Direction



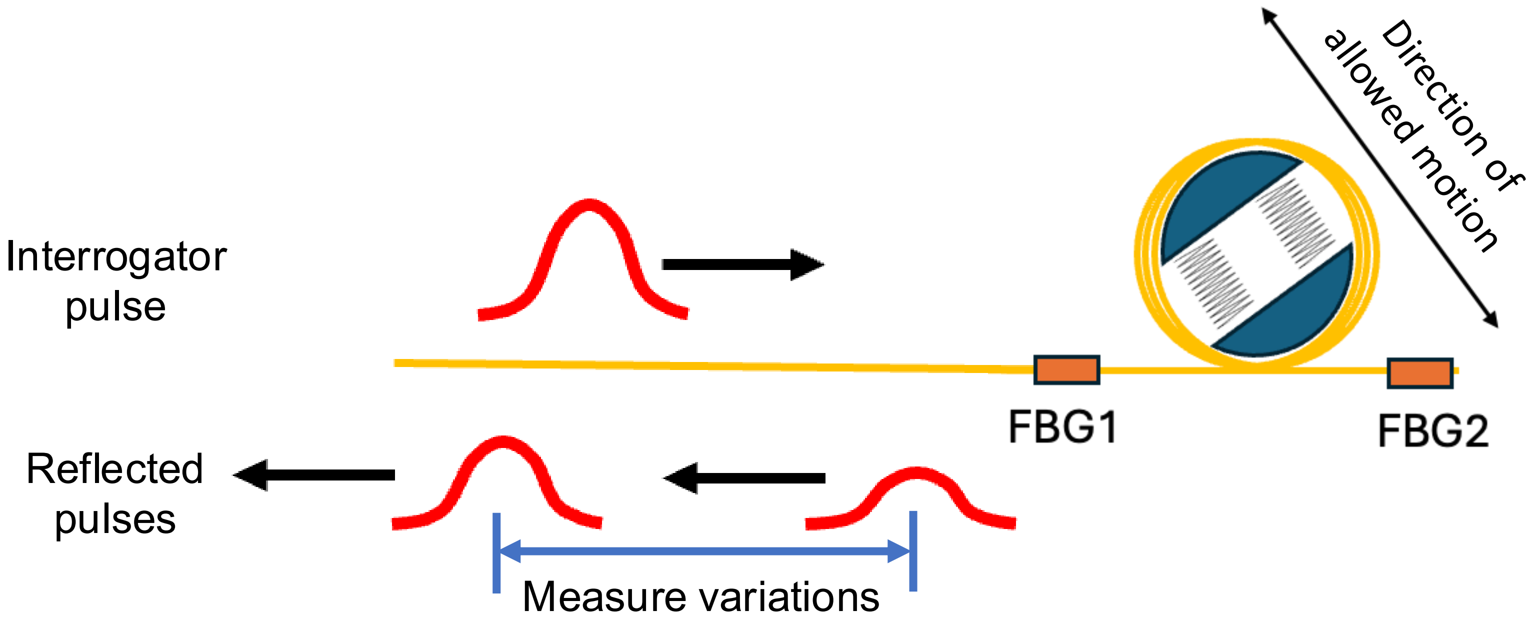
GeoLite

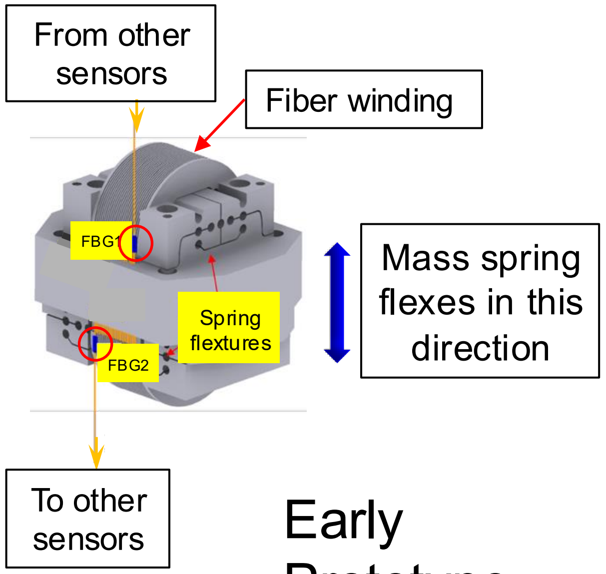
A Fiber-Optic Three-Component Accelerometer

A Directional Sensor

Fiber-Optic Directional Accelerometer

- By winding the optical fiber around a mass-spring that is free to extend in only one direction, we can make a directional sensor
- The fiber stretch across the spring is measured by interferometry of laser light reflected from two Fiber Bragg Gratings (FBG)
- When the fiber length changes, the optical phase changes proportionally



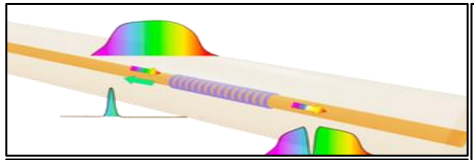


Early Prototype

The Three-Component Sensor

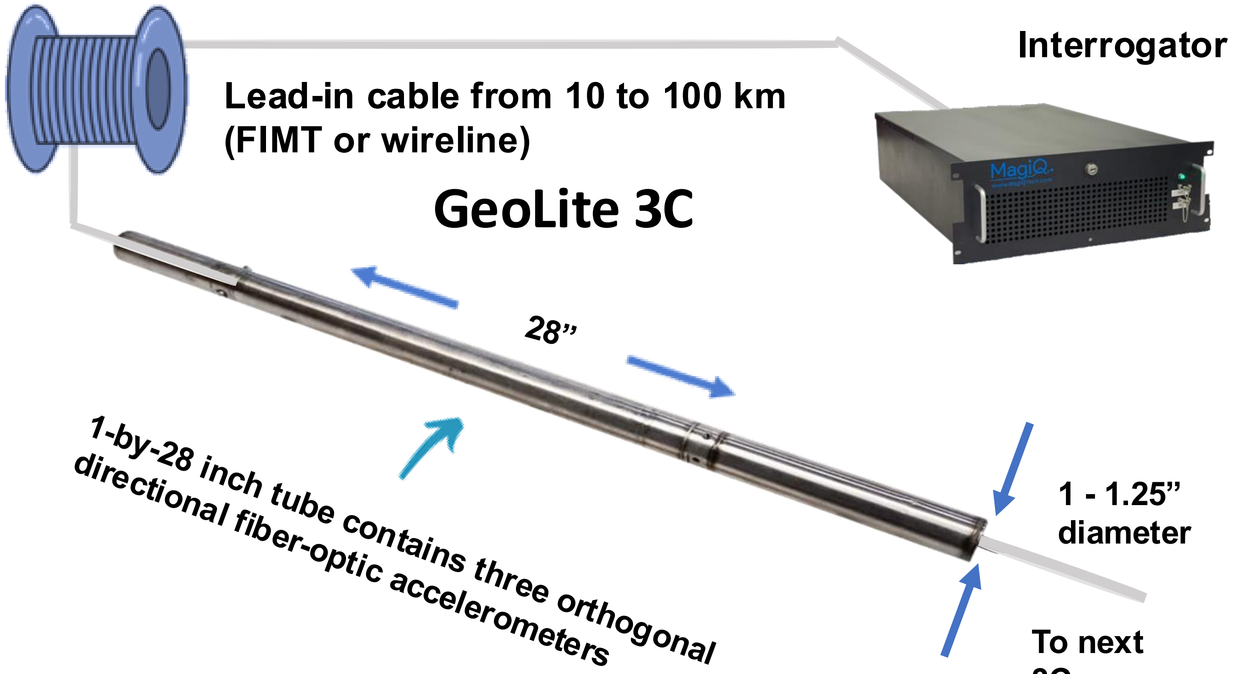
- The **GeoLite 3C Sensor** consists of three fiber-wound mass-springs arranged in mutually orthogonal directions
- The process is managed by the **GeoLite Interrogator**

Mass Spring → Fiber Bragg Gratings → Optical Accelerometer



- FBGs are inscribed into fiber to reflect a particular wavelength of light and transmits all other

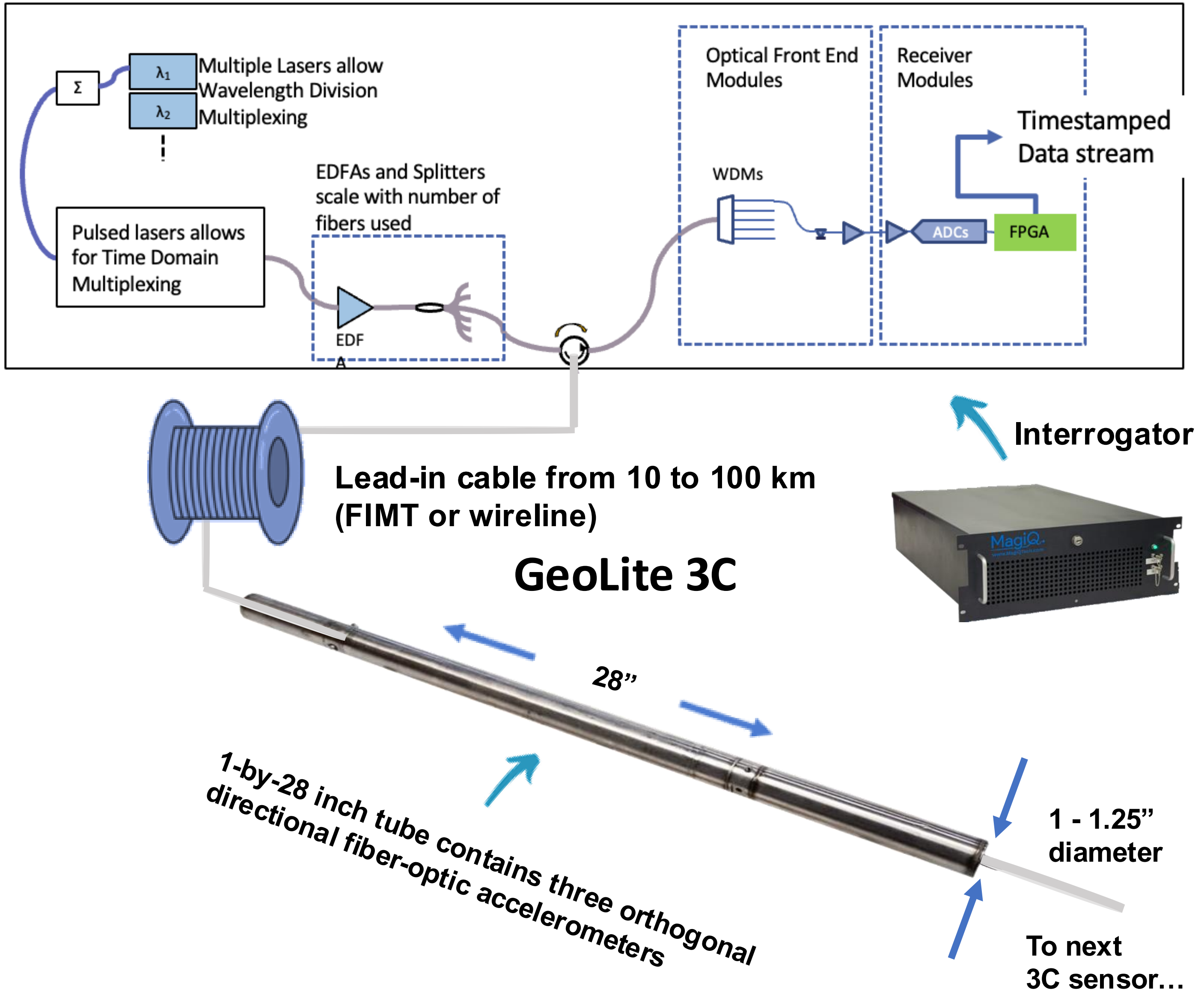
- Seismic waves causes vibrations in mechanical springs in the sensor
- Fiber wound around the spring stretches with the spring in proportion to force and acceleration
- Laser interferometry measures *changes* in the length of the fiber



Haldorsen et al., The Leading Edge, 2021

System Architecture

- The **GeoLite Interrogator** allows a large number of channels by using both
  - Wavelength Division Multiplexing (WDM)
  - Time Division Multiplexing (TDM)
- The unique optical layout and interrogation method avoids
  - noise from interrogator and lead-in cable
  - problems related to laser polarization



Haldorsen et al., The Leading Edge, 2021

Validation

Laboratory measurements confirm:

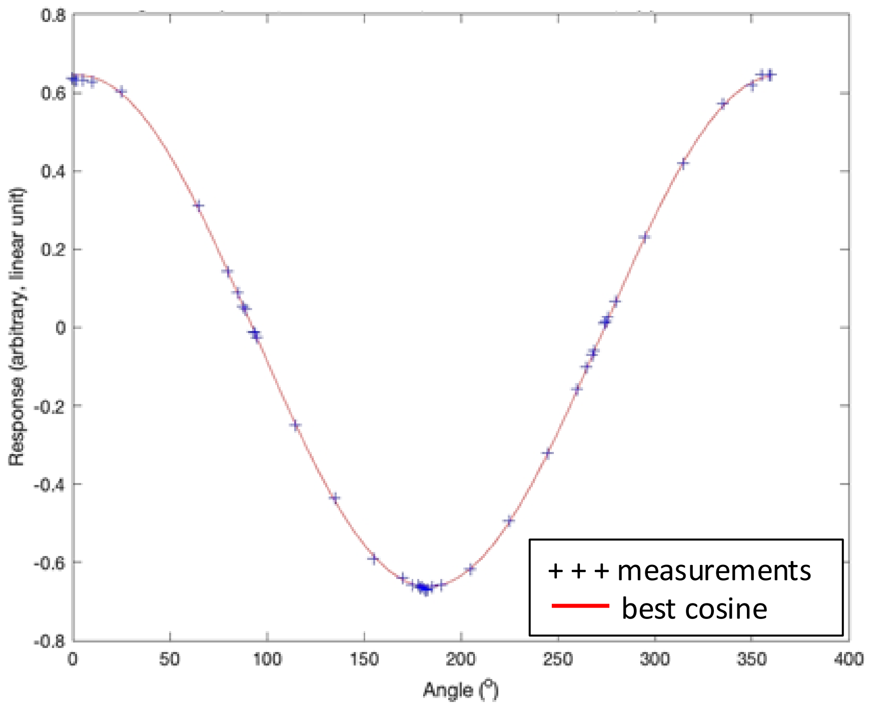
- Angular precision 0.5°
- No measurable phase delay or distortion

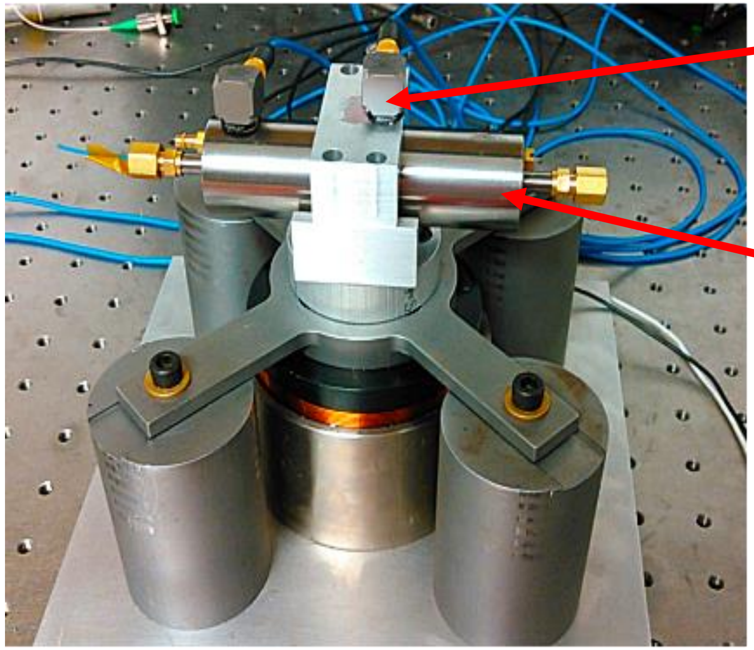
Directional Precision

GeoLite Fiber-Optic Accelerometer

- The deviations between the GeoLite response and an ideal cosine indicate an **angular precision 0.5°**, **cross-axis rejection 41 dB**

Angular precision **0.5°**



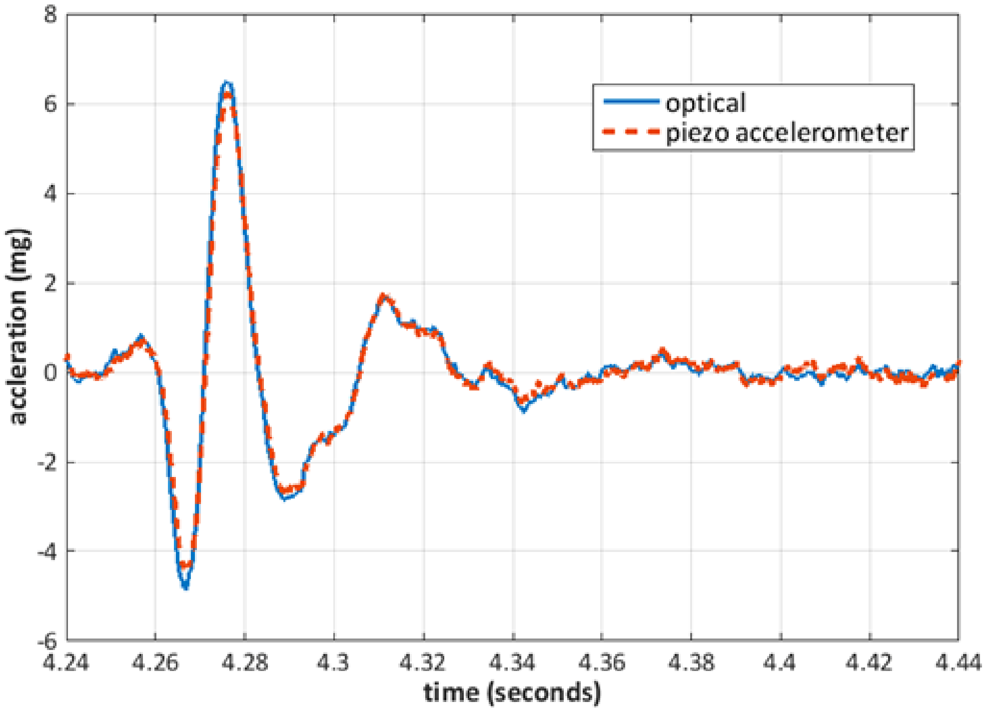


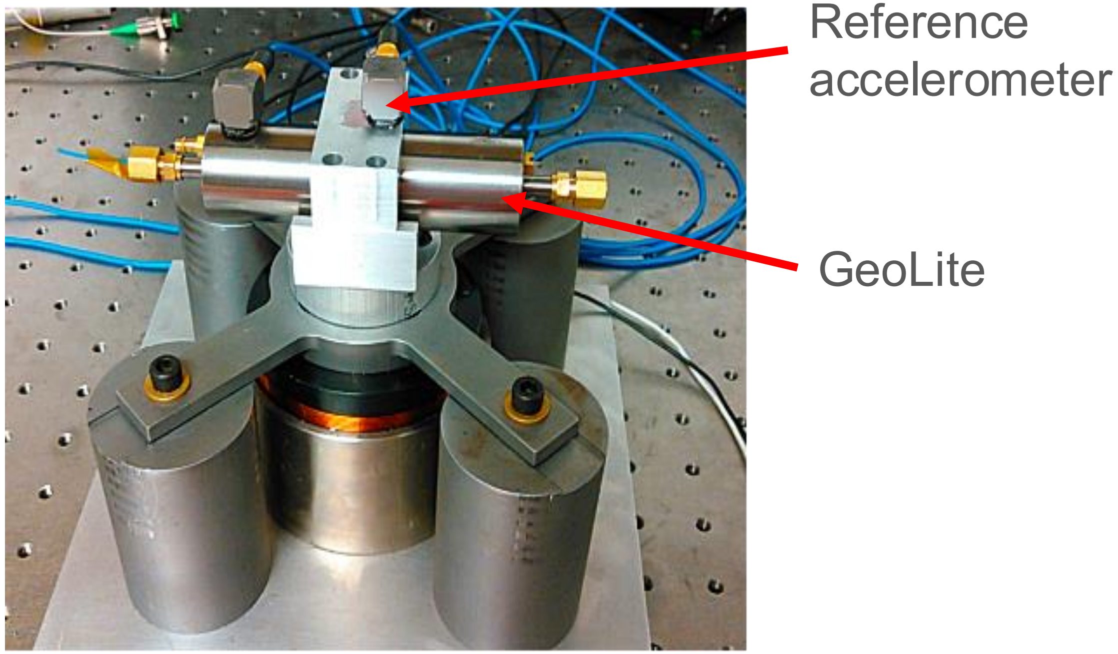
Haldorsen et al., The Leading Edge, 2021

Linear Accuracy

GeoLite Fiber-Optic Accelerometer

- Optical and piezo-electric sensor responses overlap closely, confirming excellent linearity across the full dynamic range
- No measurable phase delay or distortion





Haldorsen et al., The Leading Edge, 2021

Field Data (2025)

How accurately can 3C field data tell the direction towards a microseismic source?

- Mechanical coupling between the sensor and the formation is a major contributor to directional uncertainty in field data

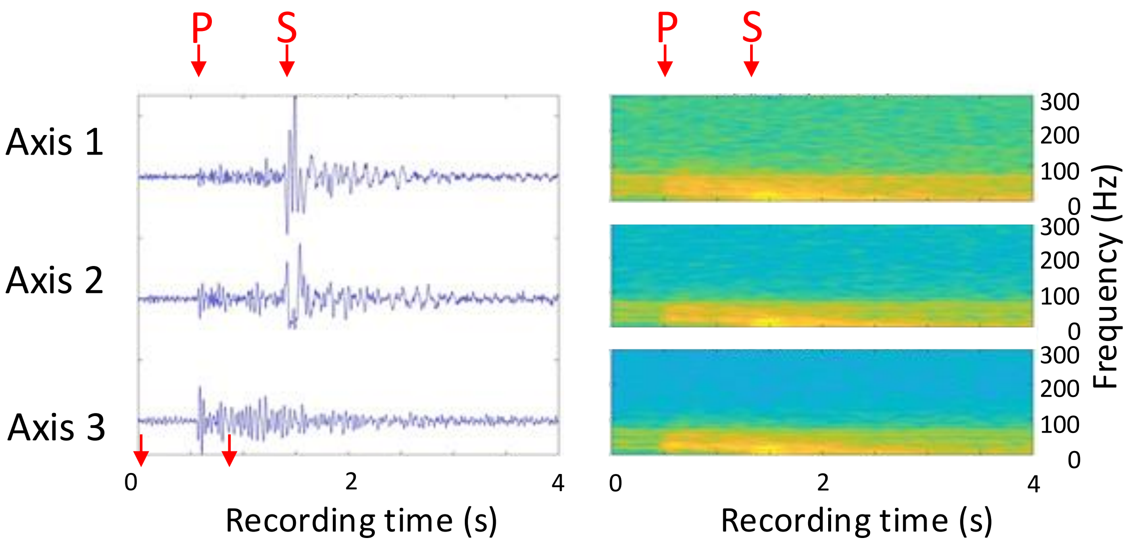
Field Data, July 2025

- VSP data in a well operated by HighPeak Energy near Big Spring, Texas
- Using a Vibroseis source
  - 6 Walkaround VSP surveys
  - 2 Zero-offset VSP surveys
  - 2 Near-offset VSP surveys
  - 4 nights of passive listening
- Using GeoLite 3C fiber-optic accelerometers:
  - 1¼” OD
  - Sensitivity: ≥ 1000 rad/g
  - Bandwidth: 0.1 – 1,000 Hz
  - Angular precision $\approx 0.5°$

Microseismic Event 10:33:06 (UTC), M_w=-0.2

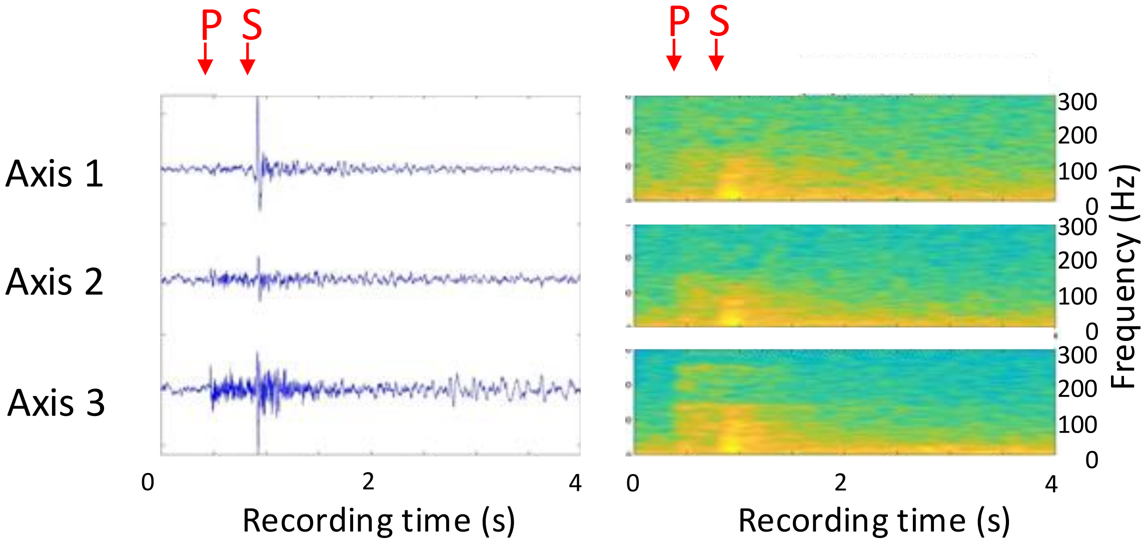
- The P–S delay for the surface sensor is approximately twice that of the borehole sensor, indicating roughly twice the source distance

SensorEra Sensor at Surface



- **P-wave up to 80 Hz**
- **S-wave up to 15 Hz**

MagiQ GeoLite at 3000 ft Depth



- **P-wave up to 270 Hz**
- **S-wave up to 150 Hz**

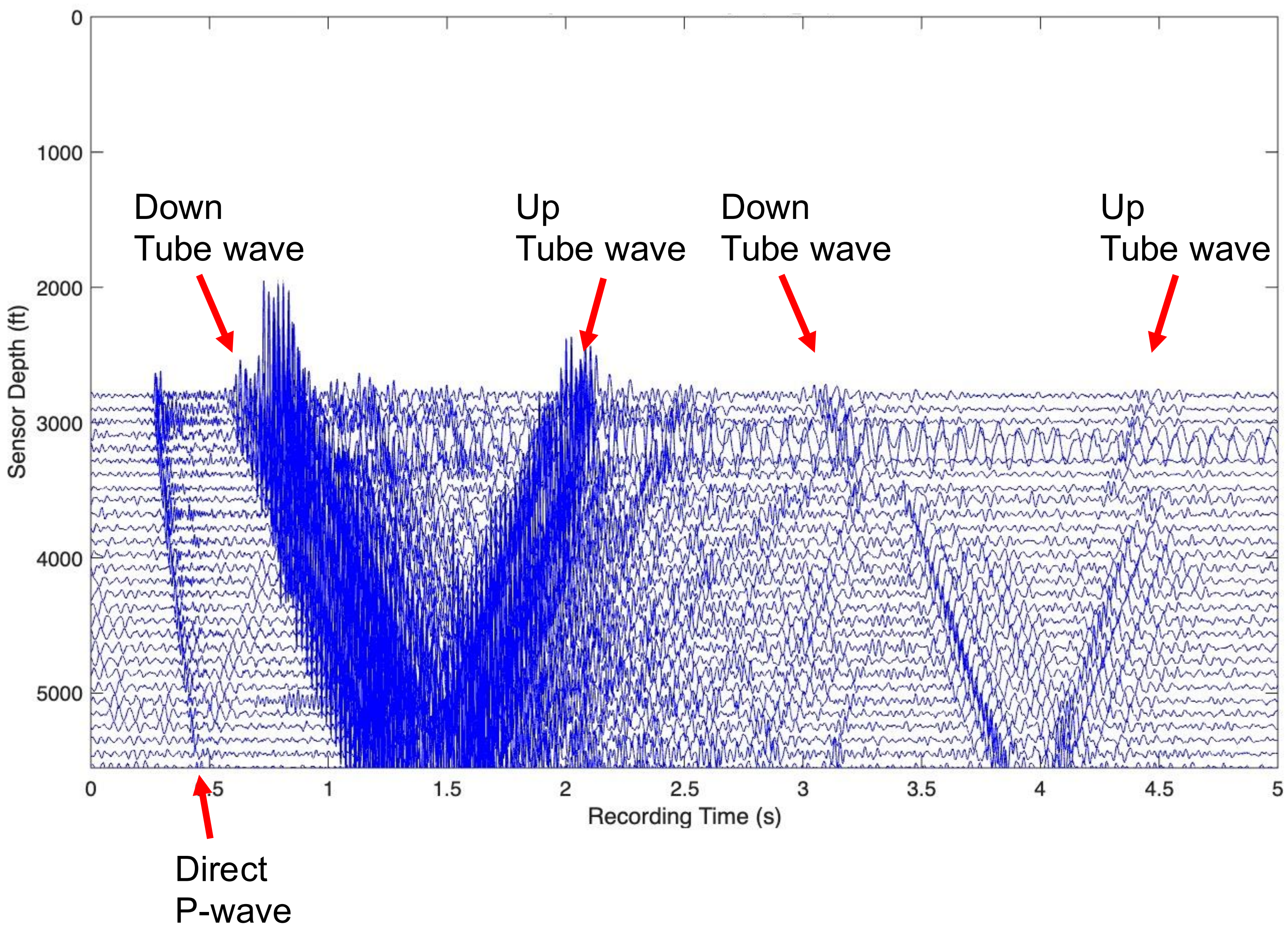
Sensor Coupling & Angular Precision

Angular precision in field data is primarily controlled by mechanical coupling

Source Offset 125 ft

Correlated and Stacked VSP Data

- The overwhelming feature is the tube wave – a pressure wave traveling in the fluid-filled well
- The strong tube-wave response indicates that the fluid motion moves the sensor node
  - This indicates that **the coupling of the sensor to the well casing may be weak**



Source Offset 125 ft, Close-up

Correlated and Stacked VSP Data

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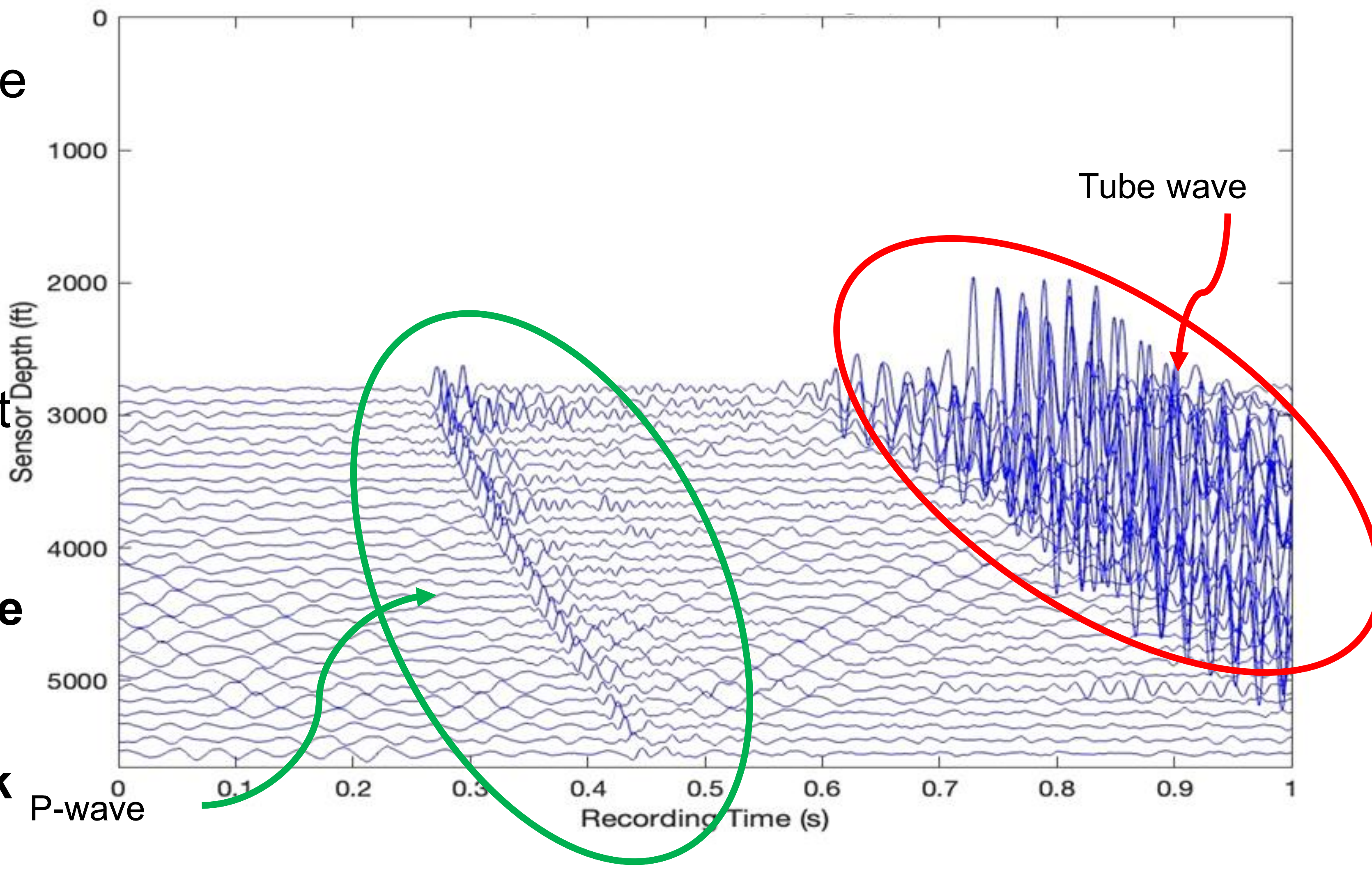
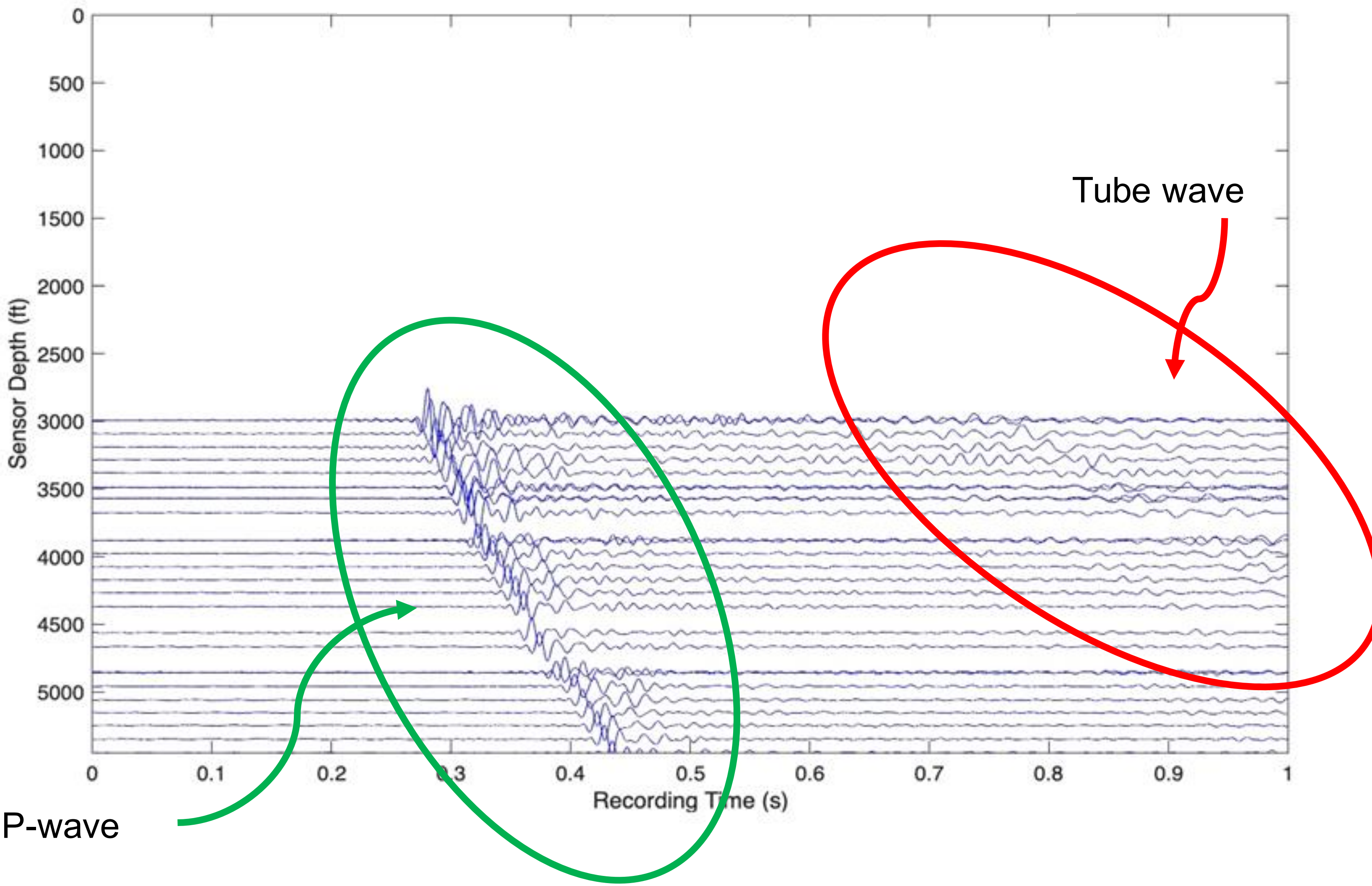


Source Offset 900 ft, Close-up

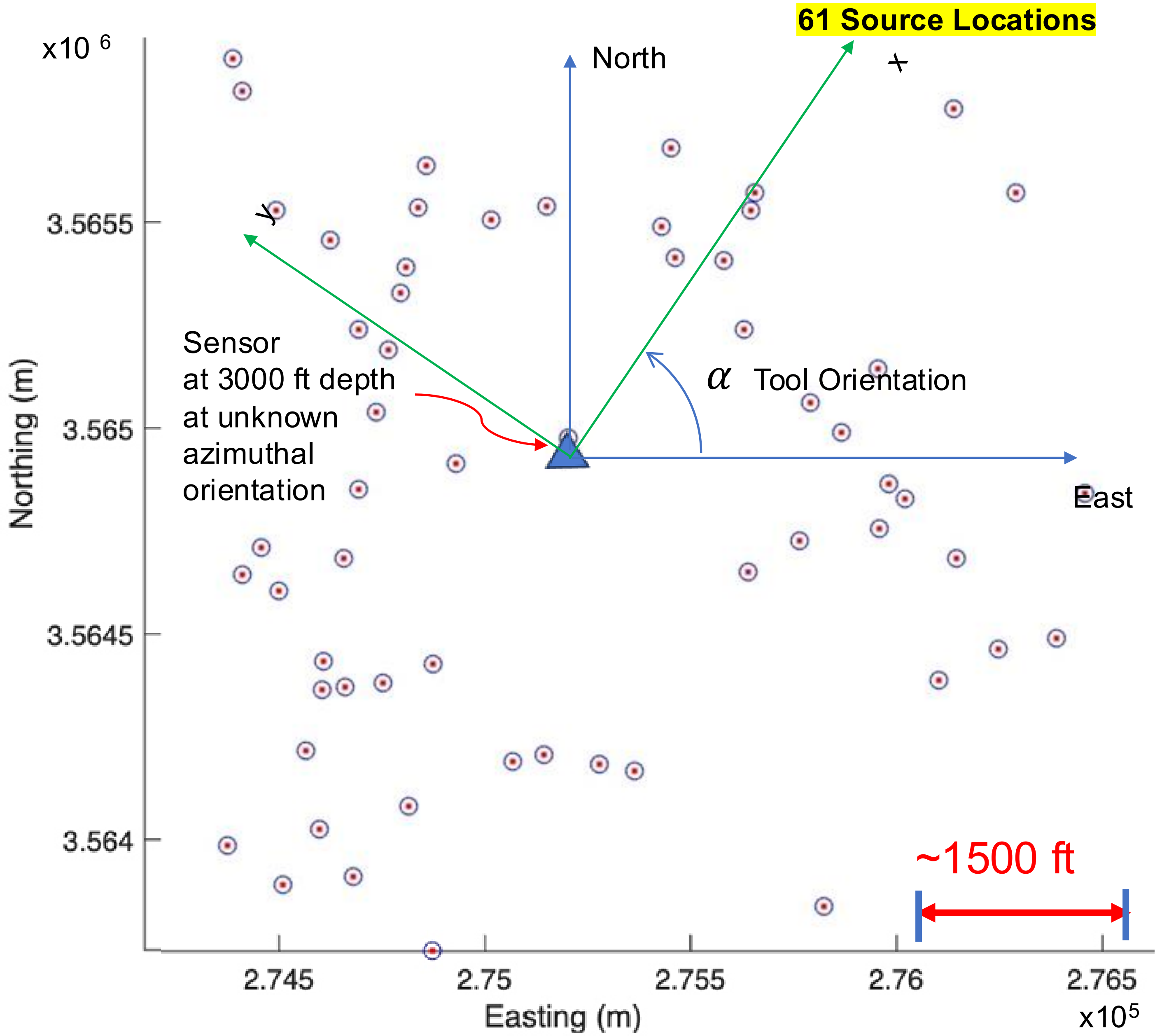
Correlated and Stacked VSP Data

- P-wave dominates – the tube wave is hardly visible
- However, keep in mind that the coupling of the sensor node to the well casing has not changed – and a weak coupling may compromise the angular accuracy of the data…



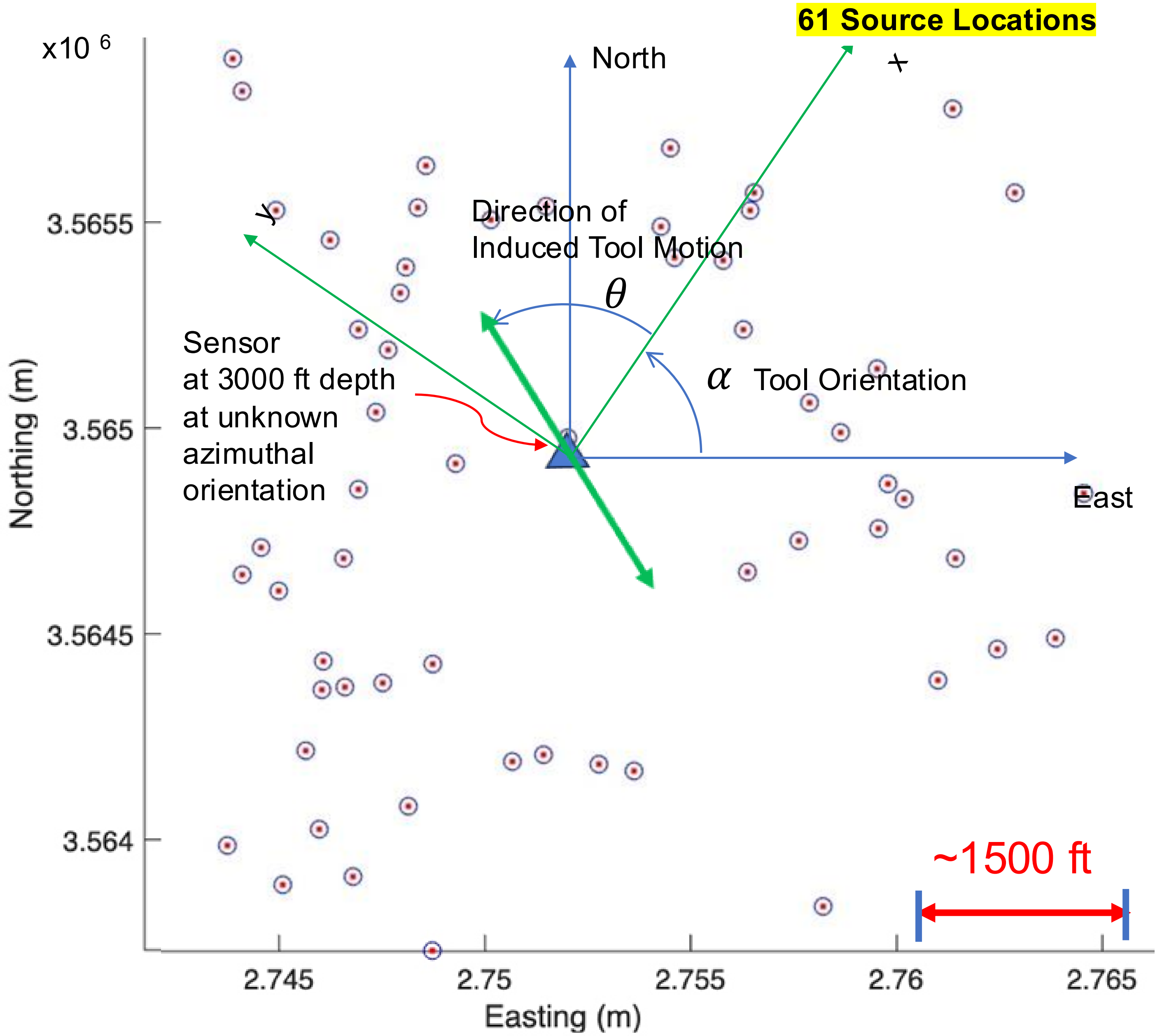
Walkabout VSP Source Points

- 61 source locations distributed over a surface of about 1.5 square miles
- The well head is at the blue triangle at the center of the plot
- The sensor is about 3000 ft below the well head



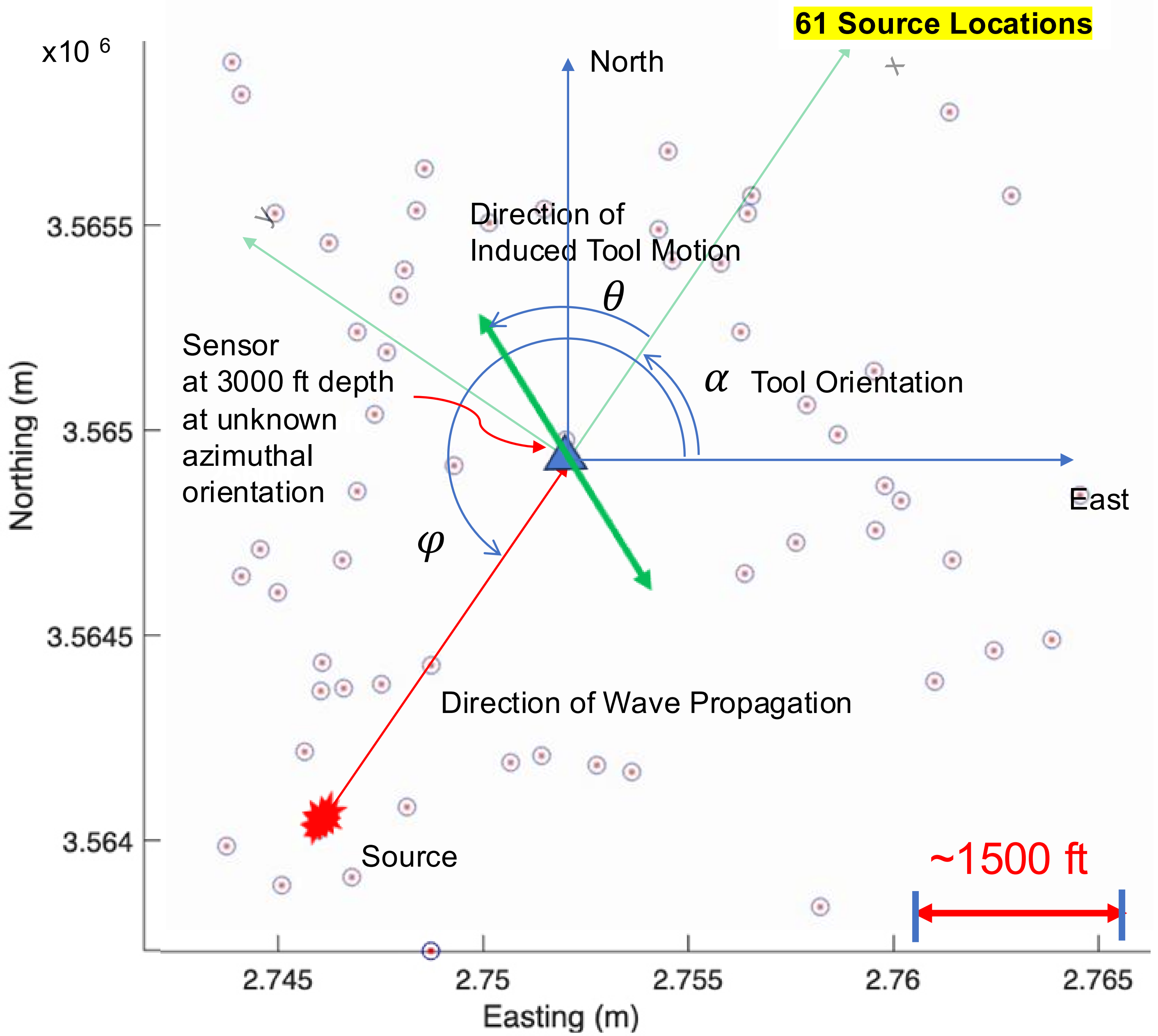
Direction of Induced Tool Motion

- The P-wave induces tool motion that is linearly polarized along the propagation direction
- The reference frame for the recorded tool motion is not known



Induced Tool Motion → Source Location

- The tool motion induced by the P-wave should match the azimuth to each known source location
- The tool orientation is estimated by using a least-squares process that minimizes the deviation between measured P-wave polarization and known source azimuths.



Least-Squares Process

The horizontal components of the data for shot n are proportional to $\cos\theta_n$ and $\sin\theta_n$

$$\begin{bmatrix} x_n(t) \\ y_n(t) \end{bmatrix} = d(t)\begin{bmatrix} \cos\theta_n \\ \sin\theta_n \end{bmatrix}$$

The horizontal polarization of the data is

$$\theta_n = atan2[y_n(t), x_n(t)]$$

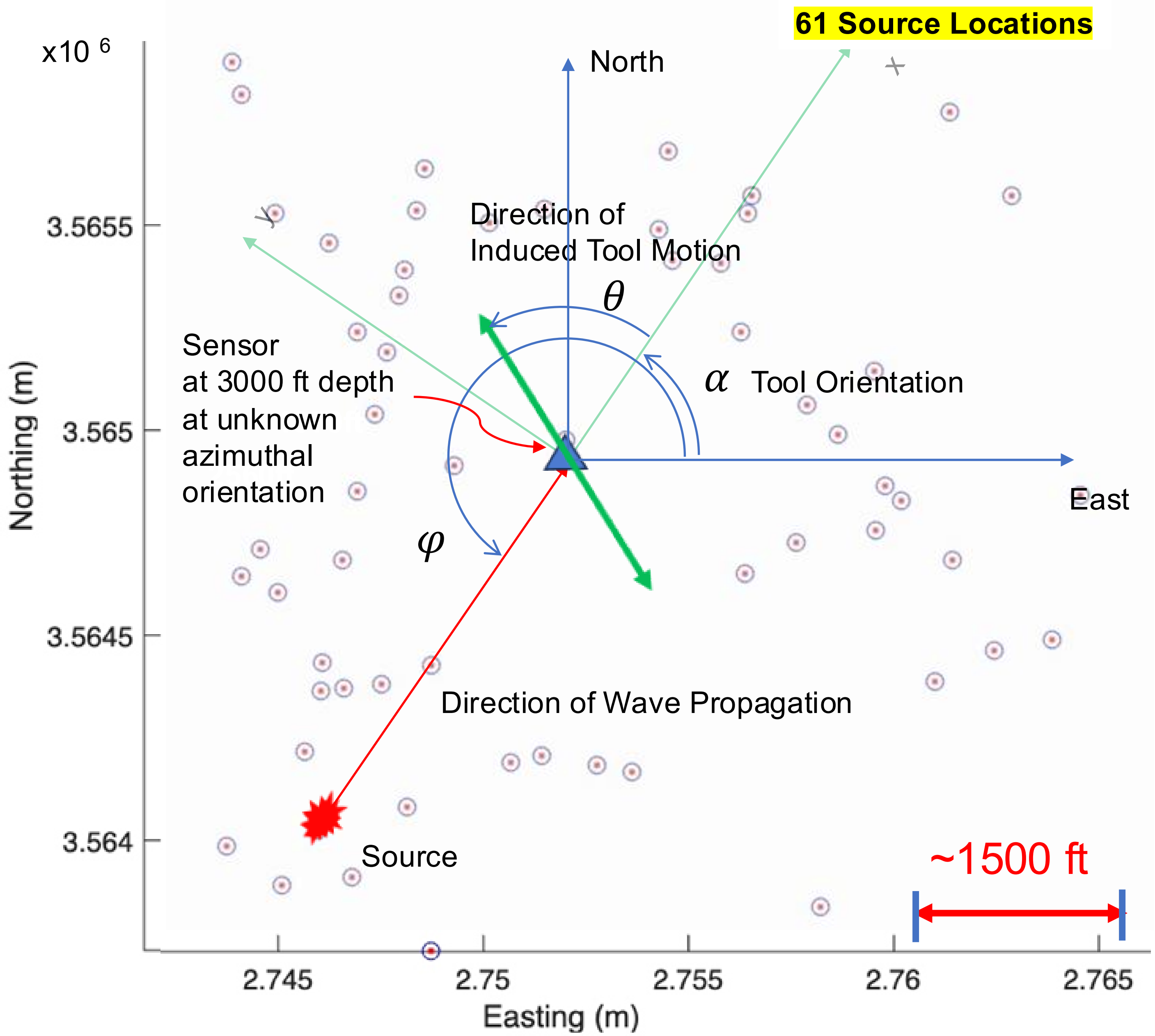
Using φ for the azimuth angle to the source, we find the single rotation operator

$$\mathrm{R}(\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}$$

that minimizes the average squared differences between the rotated data and the direction to the source

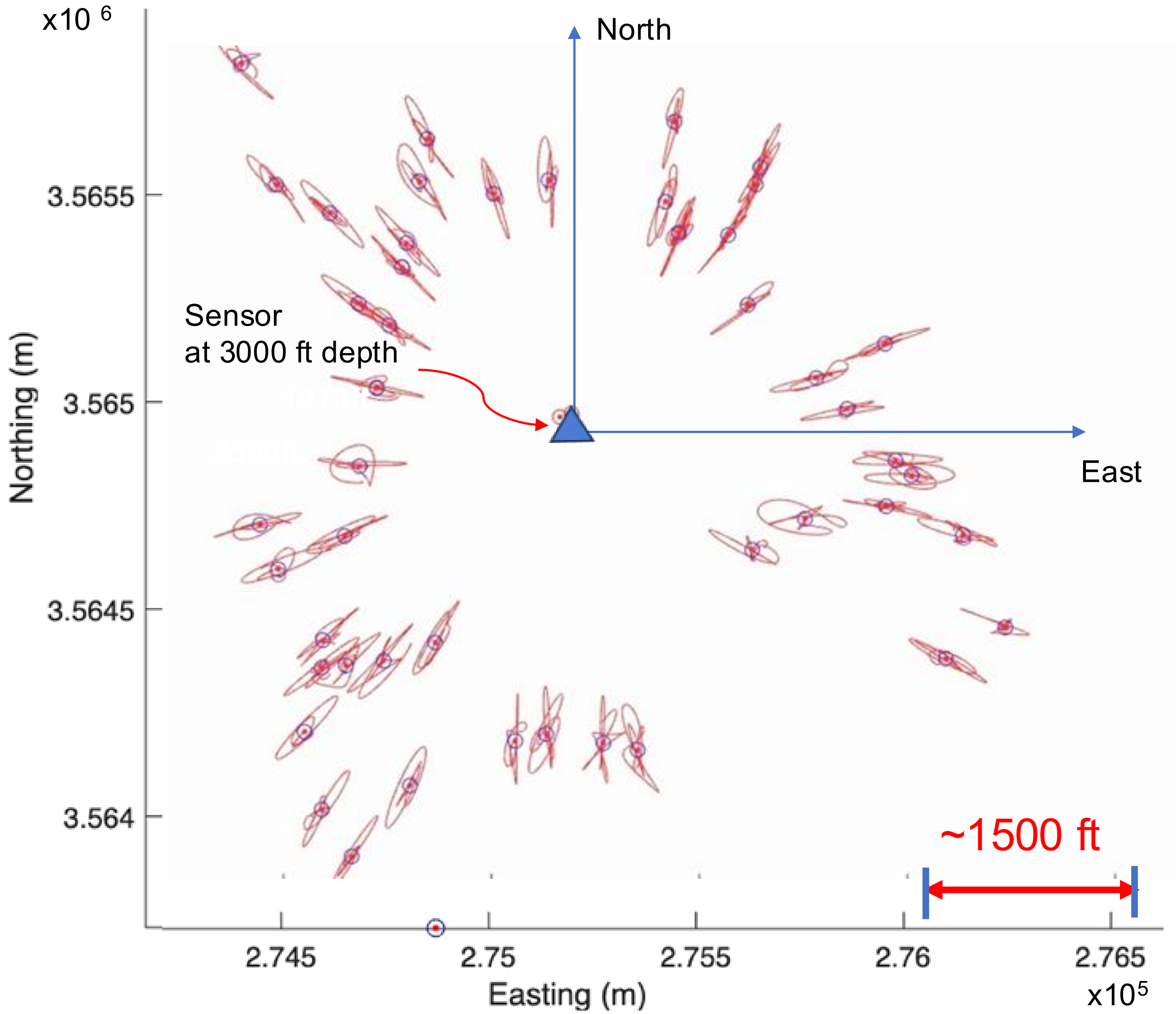
$$\chi^2(\alpha) = \frac{1}{N}\sum_{n=1}^{N}\left|\mathrm{R}(\alpha)\begin{bmatrix} \cos\theta_n \\ \sin\theta_n \end{bmatrix} - \begin{bmatrix} \cos\varphi_n \\ \sin\varphi_n \end{bmatrix}\right|^2$$

The angle α is an estimate of the orientation angle of the tool



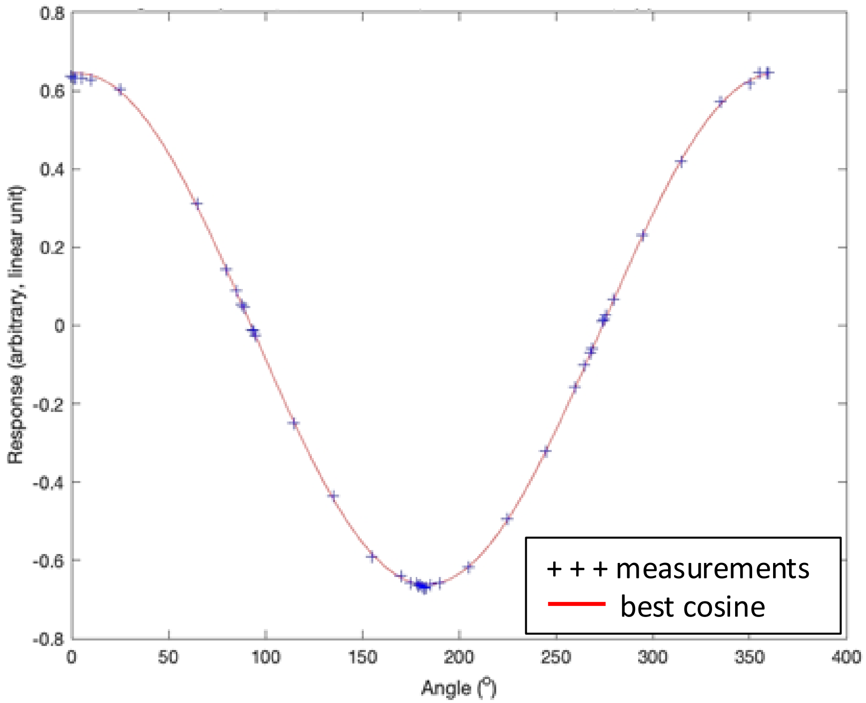
True Direction of Induced Tool Motion

- Tool x-axis pointing at $\alpha = 63°$
- I plot the induced tool motion at each source location with reference to true North
- Induced motion mostly linear - pointing at well head
- Average ratio of radial-to-transverse energy is 25:1, corresponding to angular spread of $12°$



Sensor Coupling Defines Angular Precision

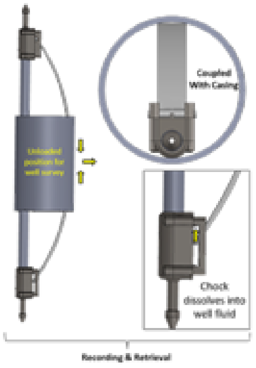
- A 3C sensor records tool motion
- Main factors contributing to tool motion:
    1) motion of the rock
    2) coupling of the tool to the rock
    3) precision of the tool
- **GeoLite angular precision is $\mathbf{0.5°}$**
- Contributions from local variations in geology may be from 2° to 5°
- The majority of 12° spread can be attributed to **the acoustic coupling of the sensor to the borehole wall**

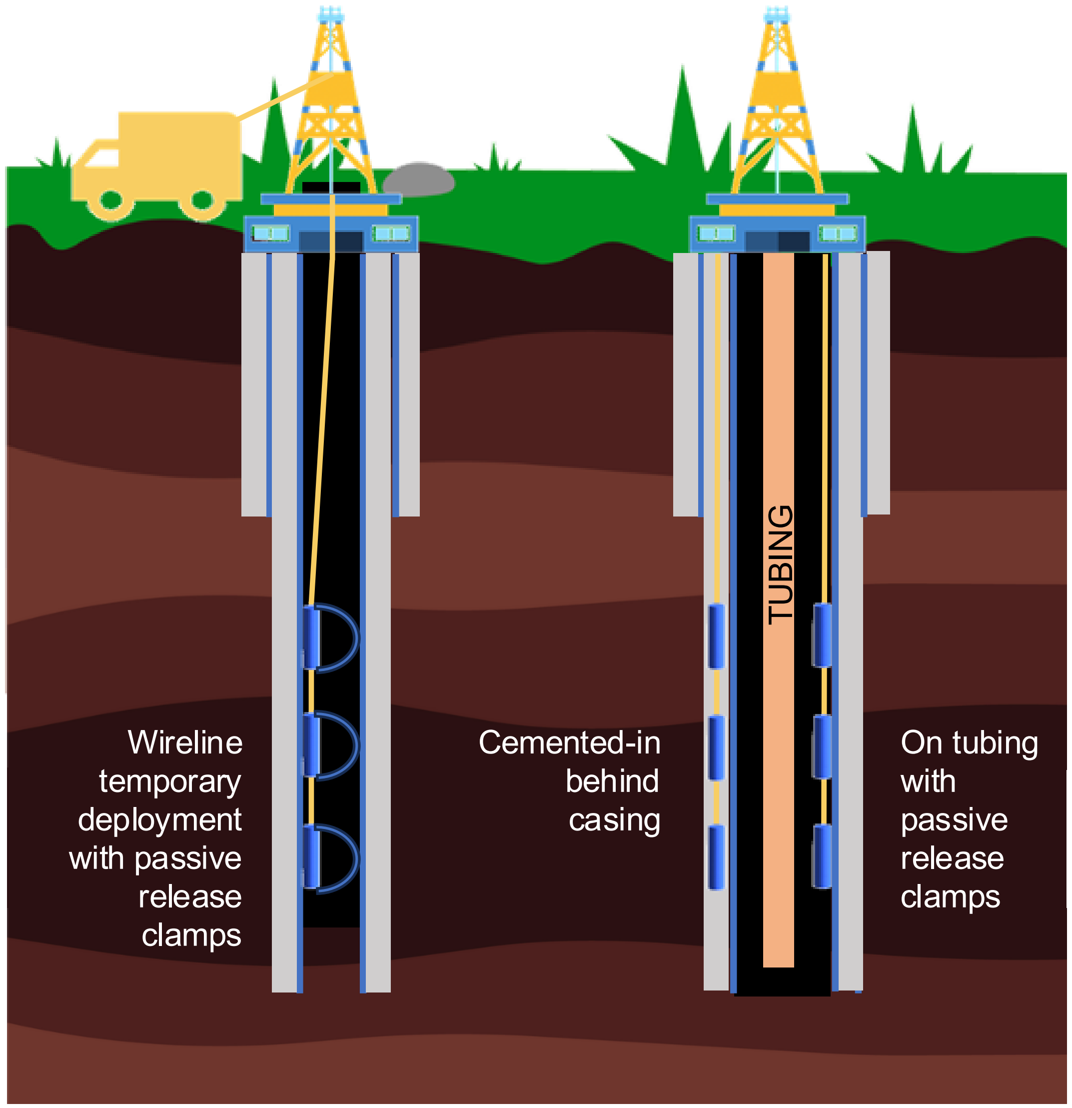


GeoLite angular precision is $\mathbf{0.5°}$
(from Slide 11)

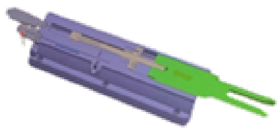
Deployment Options

Wireline/Tubing Clamp:
Loaded bow spring released with dissolvable chock

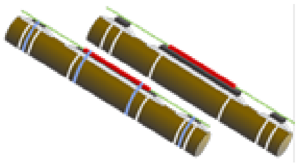




Tubing Clamp:
TotalEnergies' Spider Clamp (SEG 2021)



Tubing Clamp:
MagiQ's swellable/ dissolvable combo

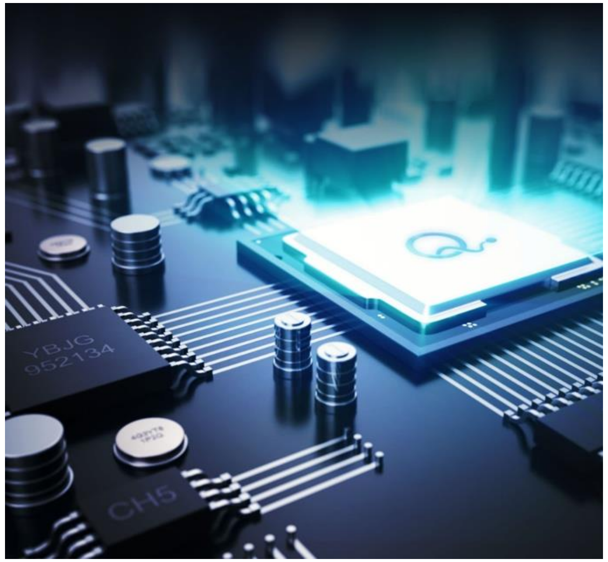


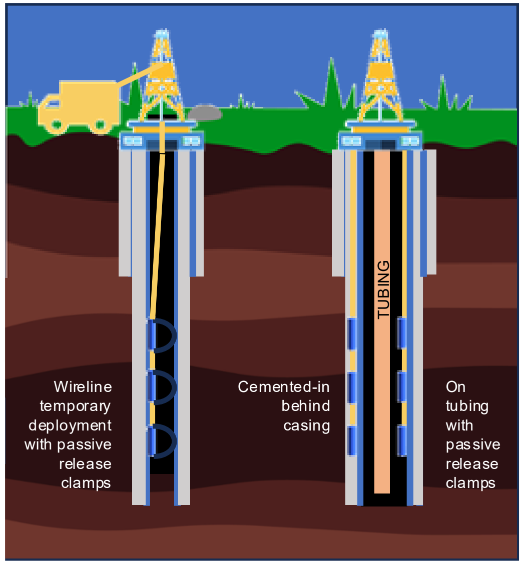
- **Seismic sensors need to be securely coupled to the borehole wall**
- No downhole electronics
  - Passive release mechanism is required
- Wireline applications
  - Locked bow spring
- Longer-term monitoring
  - Tubing clamps using a burst-disk actuated system
  - Combination of swellable and dissolvable materials

Conclusions

GeoLite Fiber-Optic Accelerometer

- GeoLite delivers true vector seismic measurements in harsh borehole environments — and removes the fundamental azimuthal ambiguity of DAS





Acknowledgements:

We like to thank the management teams of TotalEnergies, HighPeak Energy, and MagiQ Technologies for their continued support for the development of GeoLite

Thank You!