

Advances in rotational seismic measurements

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Agenda

- What is rotational seismic?
- Rotational sensor technologies
- Concept and status of the SMHD sensor

Motivation

- Rotational motion is a significant, often neglected aspect of earth motion
 - Provides promising new capabilities, but
 - Measurement technology has been limited, and
 - Field datasets, to date, remain sparse and scattered
- The U.S. Department of Energy (DOE) and Applied Technology Associates (ATA) have built and are deploying a new generation of prototype sensors to help validate rotational seismic utility



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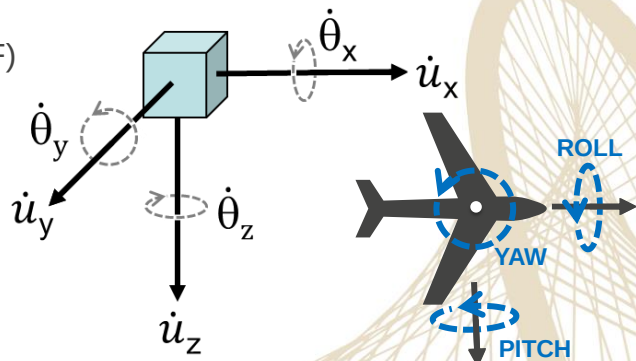
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What is rotational seismic?

- A measurement of missing degrees-of-freedom of motion
- Six-degree-of-freedom (6-DoF) motion of an element of earth includes:
 - Linear particle motion (3-DoF)
 - Angular rotation (3-DoF)
- We typically only measure linear motion



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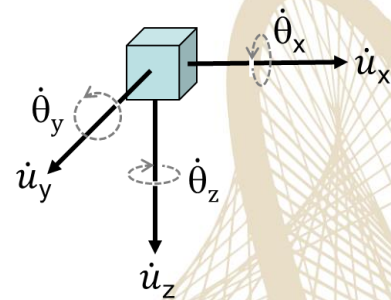
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What is rotational seismic?

- A measurement of wavefield spatial structure
 - Involves spatial gradient of linear motion
 - Rotation equates to the vector curl of the infinitesimal displacement vector, u

$$\begin{bmatrix} \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} \equiv \frac{1}{2} \nabla \times \underline{u} = \frac{1}{2} \begin{bmatrix} 0 & -\partial_z & \partial_y \\ \partial_z & 0 & -\partial_x \\ -\partial_y & \partial_x & 0 \end{bmatrix} \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix}$$



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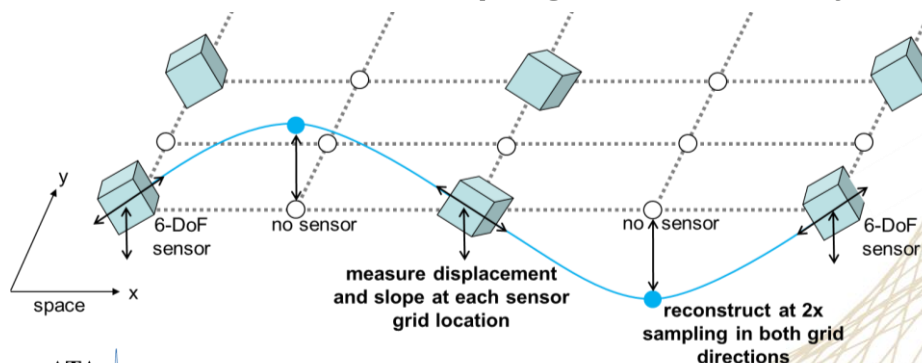
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What is rotational seismic?

- A way of increasing effective sampling
 - As a spatial derivative, adding rotational sensors **increases effective sampling** for seismic arrays



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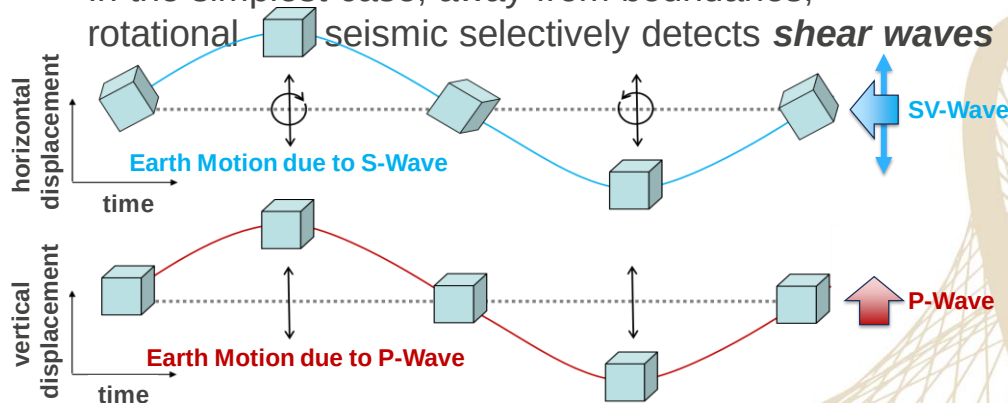
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What is rotational seismic?

- A way of discriminating shear waves
 - In the simplest case, away from boundaries, rotational seismic selectively detects **shear waves**



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What is rotational seismic?

- A **single receiver** ability to calculate:
 - Local shear wave phase velocity
 - Shear wave angle of arrival

Based on measurements of linear acceleration, $\ddot{u}$, and angular rotation rate, $\dot{\theta}$

$$\text{local shear velocity, } V_s = \frac{|\ddot{u}|}{|\dot{\theta}|}$$

$$\text{propagation direction, } \hat{n} = \frac{\ddot{u} \times \dot{\theta}}{|\ddot{u} \times \dot{\theta}|}$$

Subject to a factor of 2 dependent on boundary conditions



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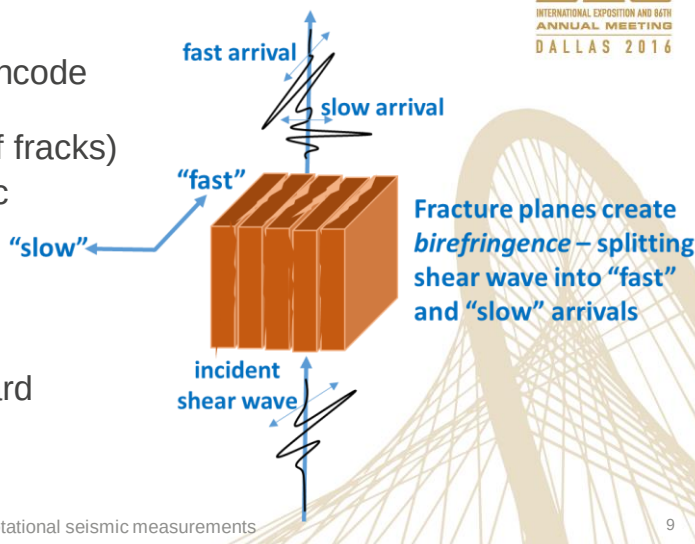
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What is rotational seismic?

- A new field for research
 - Shear wave splitting may encode rock information of interest (structure and orientation of fracks)
 - Observed rotational seismic motion is known to exceed predictions in some cases, motivating new models in earthquake seismology
 - Relates to earthquake hazard (building torsional motion)



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Rotational sensor technologies



Sensor Type	Physical Principle	Example	General Aspects
Ring Laser	Optical Sagnac interference	Wettzell facility, Germany	Fixed site installation; extremely low noise
IFOG	Optical Sagnac interference	iXBlue BlueSeis-3A	"Portable"; low noise at low frequencies
MEMS Gyro	Vibratory Coriolis gyroscope	Gladiator C150Z	Portable; high noise; low size, weight, power, cost
Differential Linear	Differenced linear geophones	Rotaphone	"Portable"; low noise at mid frequencies
Electrokinetic	Electrokinetics	Eentech R-1, R-2 Mettech METR-3	"Portable"; low noise at mid frequencies
SMHD	Magnetohydrodynamics	ATA Proto-SMHD	"Portable"; low noise at mid to high frequencies

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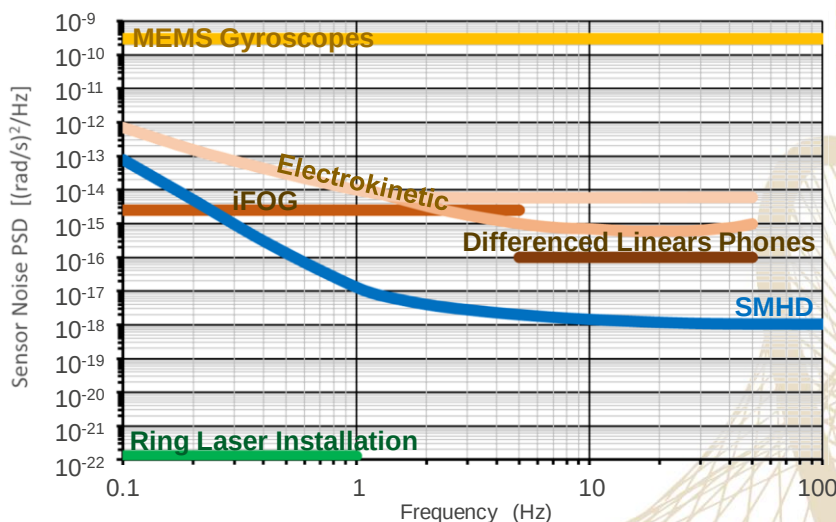
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Rotational sensor technologies



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ANNUAL MEETING
DALLAS 2016

- Noise Floor Comparison
 - MEMS
 - “Portable”
 - Stationary



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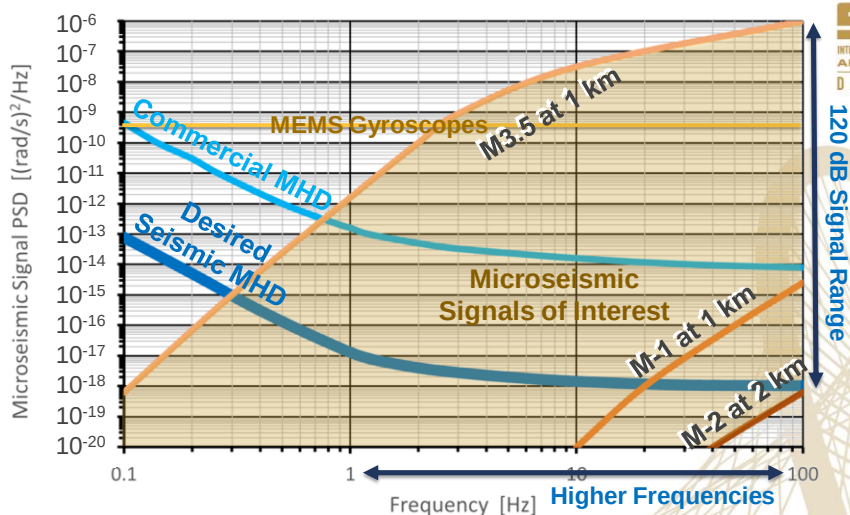
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Rotational sensor technologies



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- Expected microseismic signal levels
- Motivate:
 - Bandwidth
 - Dynamic range
 - Downhole form factor



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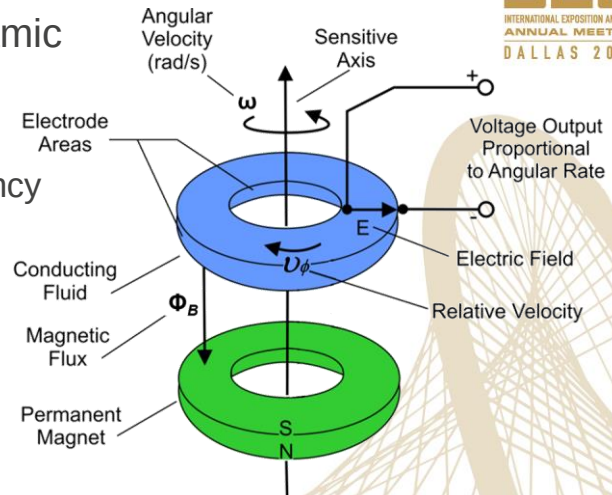
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Concept and status of the SMHD sensor

- Seismic Magnetohydrodynamic (SMHD) sensing principle
 - Senses **angular rate**
 - Ideal for mid and high frequency
 - Small enough to fit downhole
 - Simple, robust construction
 - Unit to unit consistency
 - Large dynamic range
 - Tailorable



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Concept and status of the SMHD sensor

- 13 single axis prototypes exist (13 Proto-SMHDs)

Proto-SMHD Characteristics	
Size	133mm $\varnothing$ x64mm (5.2" $\varnothing$ x2.5")
Weight	3.9 kg (8.6 lb)
Power	< 0.35 Watt (+/-15 VDC)
Bandwidth	1 – 100 Hz (nominal)
Sensitivity	2,000 V/(rad/s) (adjustable)
Range	± 5 mrad/s at ± 10 V (not limited by sensor)
Noise	4 (nrad/s)/ $\sqrt{\text{Hz}}$ at 1 Hz



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Concept and status of the SMHD sensor



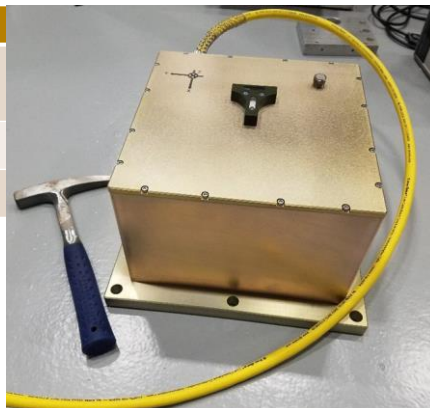
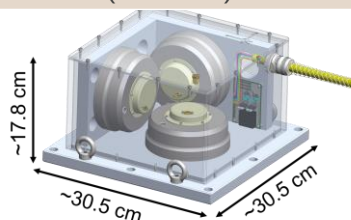
- 3 triaxial sets exist (3 Proto-SMHD Triad Boxes)

Proto-SMHD Characteristics	
Size	305mm x 305mm x 178 mm (12"x12"x8.25")
Weight	24.5 kg (54 lb)
Power	< 2.0 Watt (+12 VDC)

Prototype Box

- Field Packaging
- Orthogonal Axes
- Rigid

First Mode > 100 Hz



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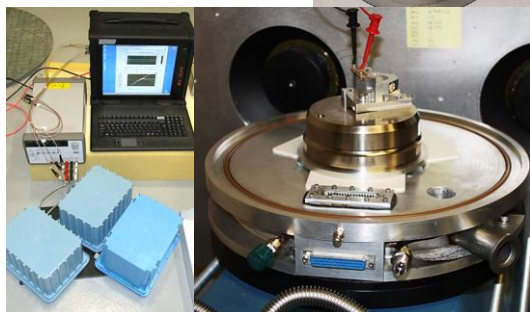
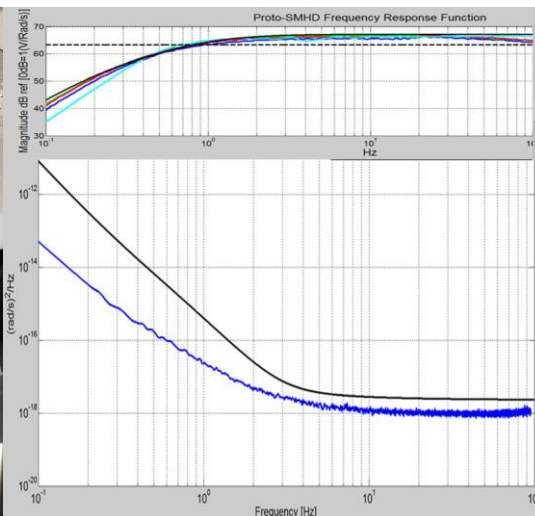
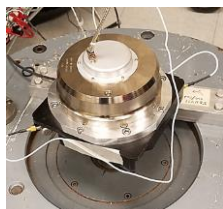
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Concept and status of the SMHD sensor

- Sensor Test
 - Sensitivity
 - Noise



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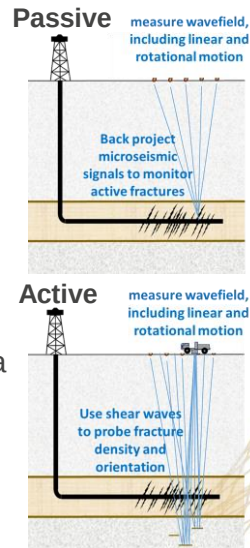
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Concept and status of the SMHD sensor

- Initial field deployments
 - Seismic background observation
 - Shear selectivity test
 - Active shear wave reflection survey
 - Potential deployment requests
 - Albuquerque Seismological Laboratory
 - Passive aftershock monitoring in Oklahoma
 - Active seismic frack monitoring experiment
 - Global Seismic Network site



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Summary

- The U.S. Department of Energy (DOE) and Applied Technology Associates (ATA) have built a new generation of rotational seismic sensors
- Prototypes are available now to support experiments that help validate the utility of rotational seismic measurements

Acknowledgement and Disclaimer

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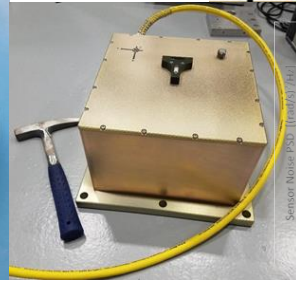
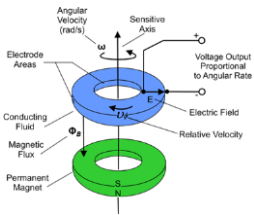
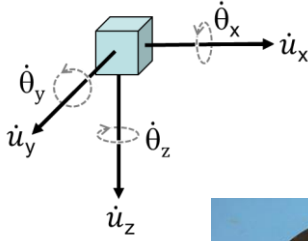
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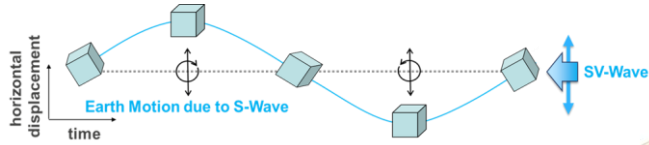
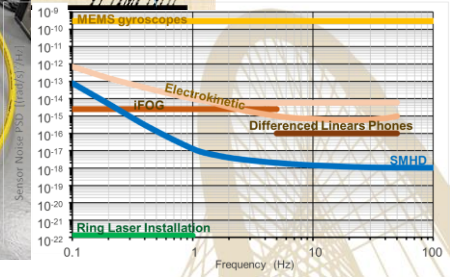
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Questions?



measure wavefield,
including linear and
rotational motion

Back project
microseismic
signals to monitor
active fractures



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