ATA Applied Technology Associates

SEG INTERNATIONAL EXPOSITION AND 86TH ANNUAL MEETING DALLAS 2016

Advances in rotational seismic measurements

Robert Pierson and Darren Laughlin

Applied Technology Associates (ATA)

Robert Brune

Consultant

Agenda

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

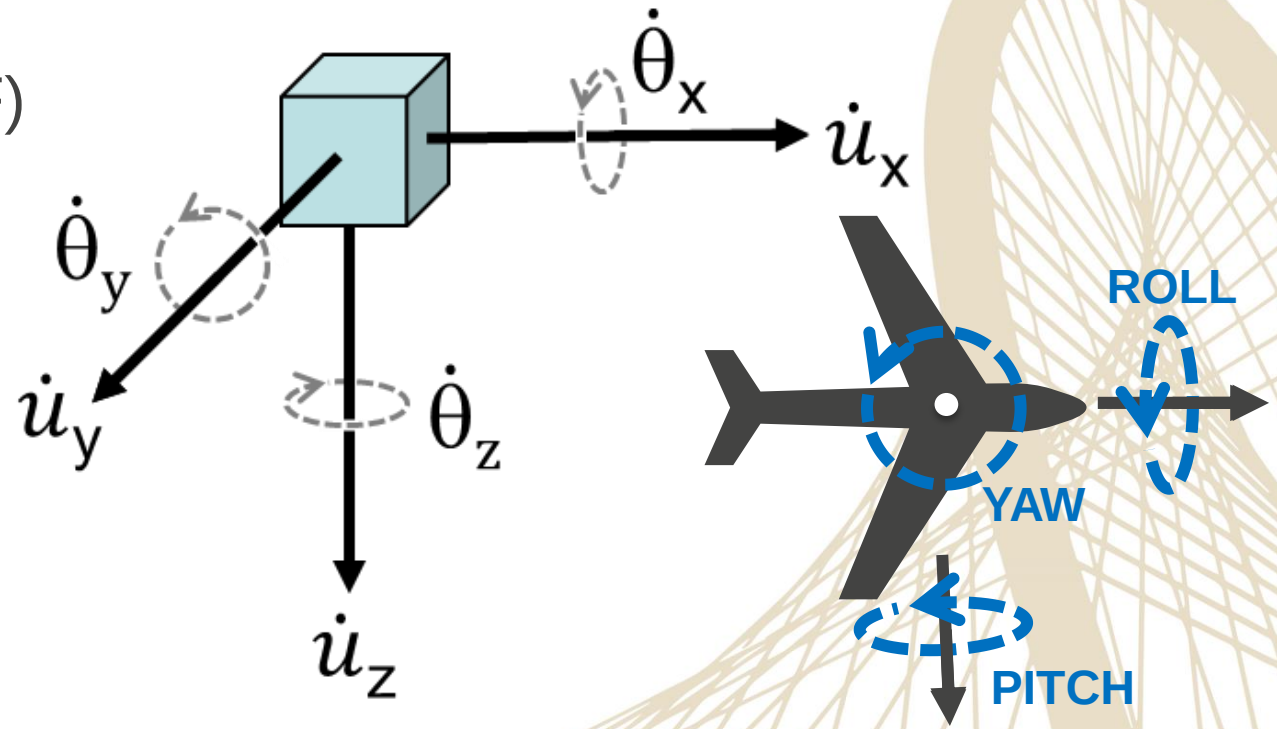
Motivation

- 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

What is rotational seismic?

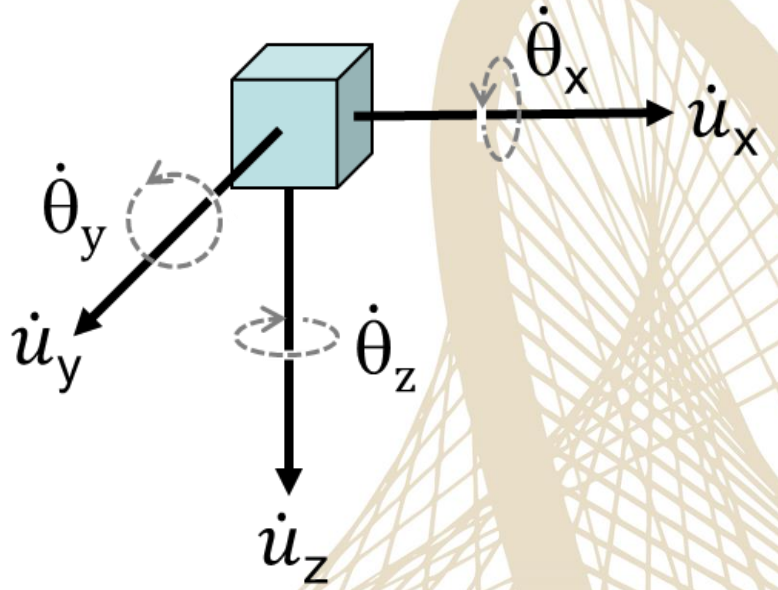
- A measurement of missing degrees-of-freedom of motion
- Six-degree-of-freedom (6-DoF) motion of an element of earth includes:
  - Linear particle motion (3-DoF)
  - Angular rotation (3-DoF)
- We typically only measure linear motion



What is rotational seismic?

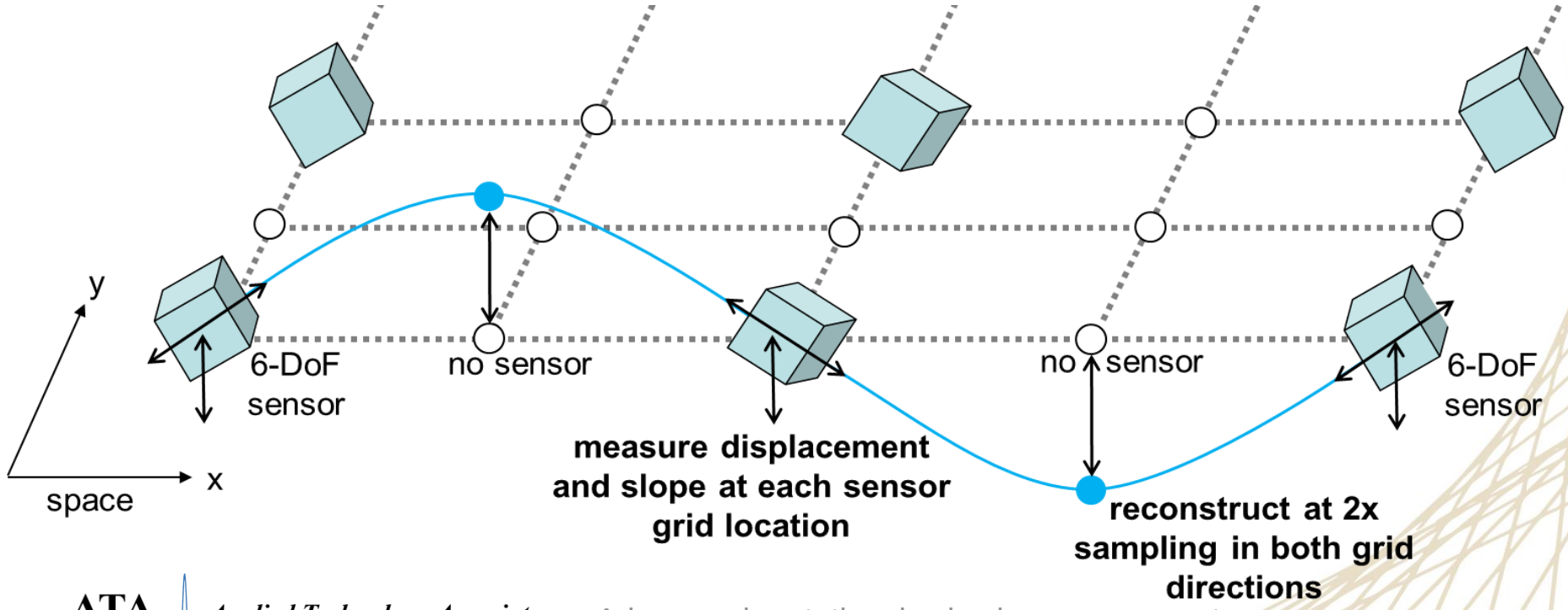
- A measurement of wavefield spatial structure
  - Involves spatial gradient of linear motion
  - Rotation equates to the vector curl of the infinitesimal displacement vector, u

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



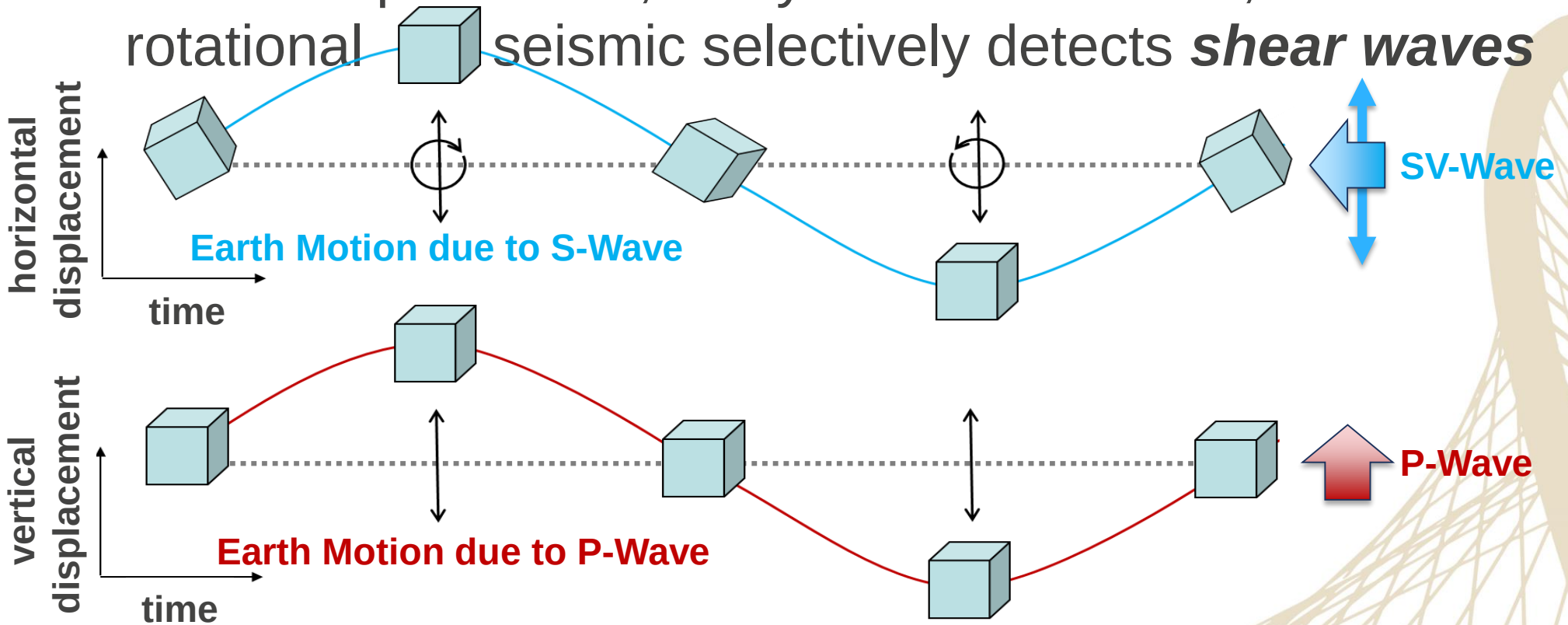
What is rotational seismic?

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



What is rotational seismic?

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



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, $\dot{\theta}$

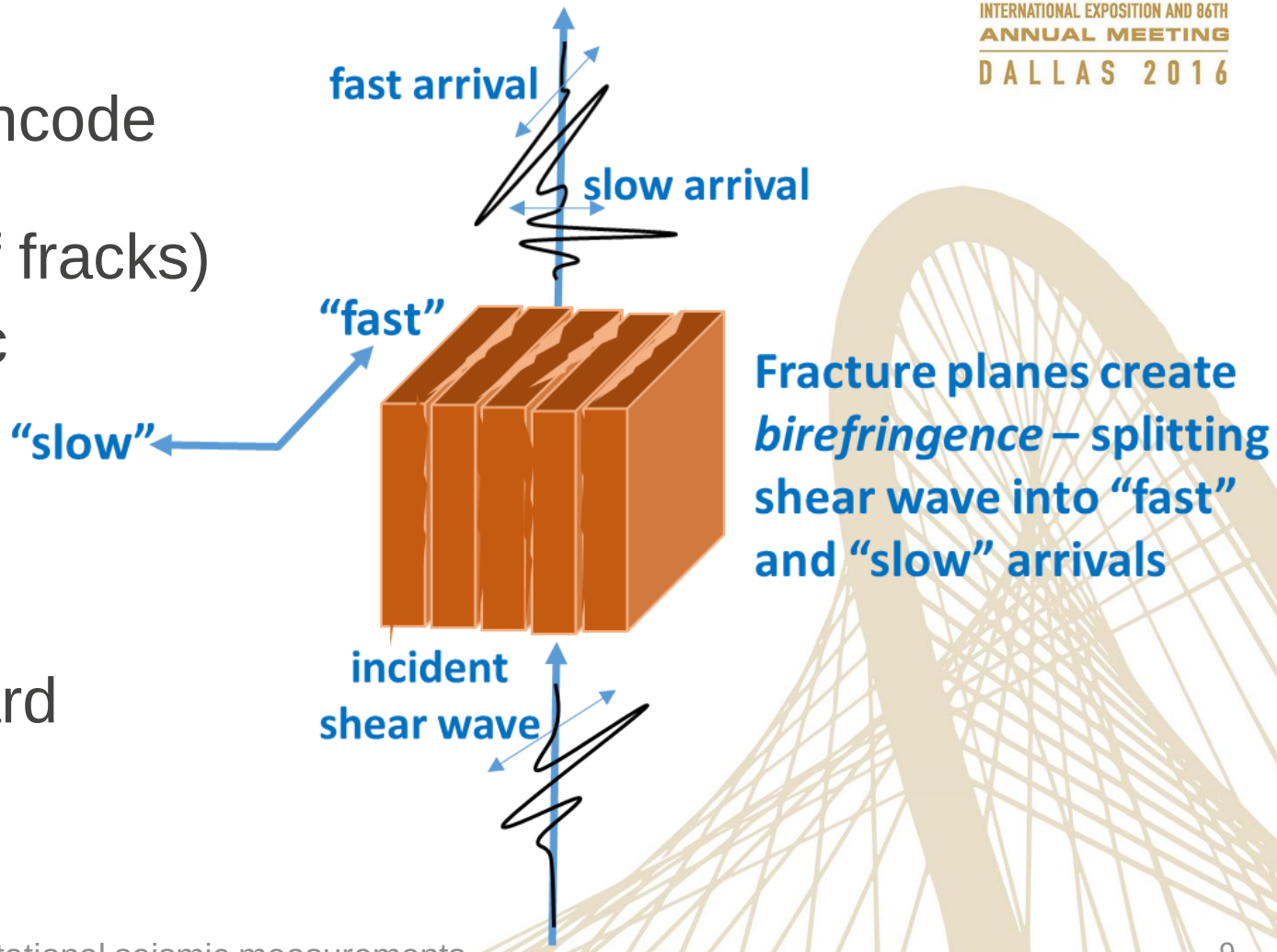
$$\boldsymbol{local\ shear\ velocity}, V_s = \frac{|\ddot{\boldsymbol{u}}|}{|\dot{\boldsymbol{\theta}}|}$$

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

Subject to a factor of 2 dependent on boundary conditions

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)

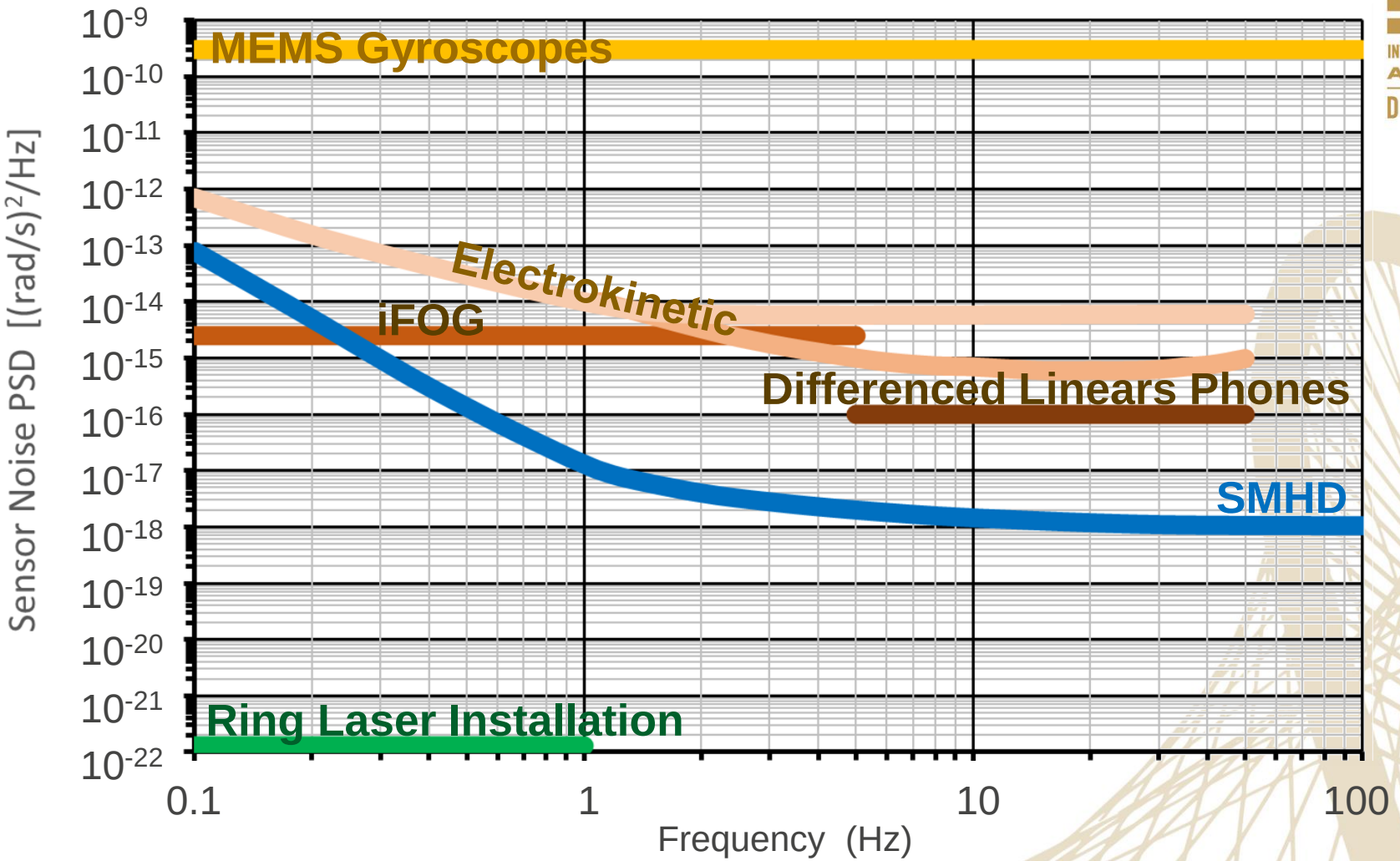


Rotational sensor technologies

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

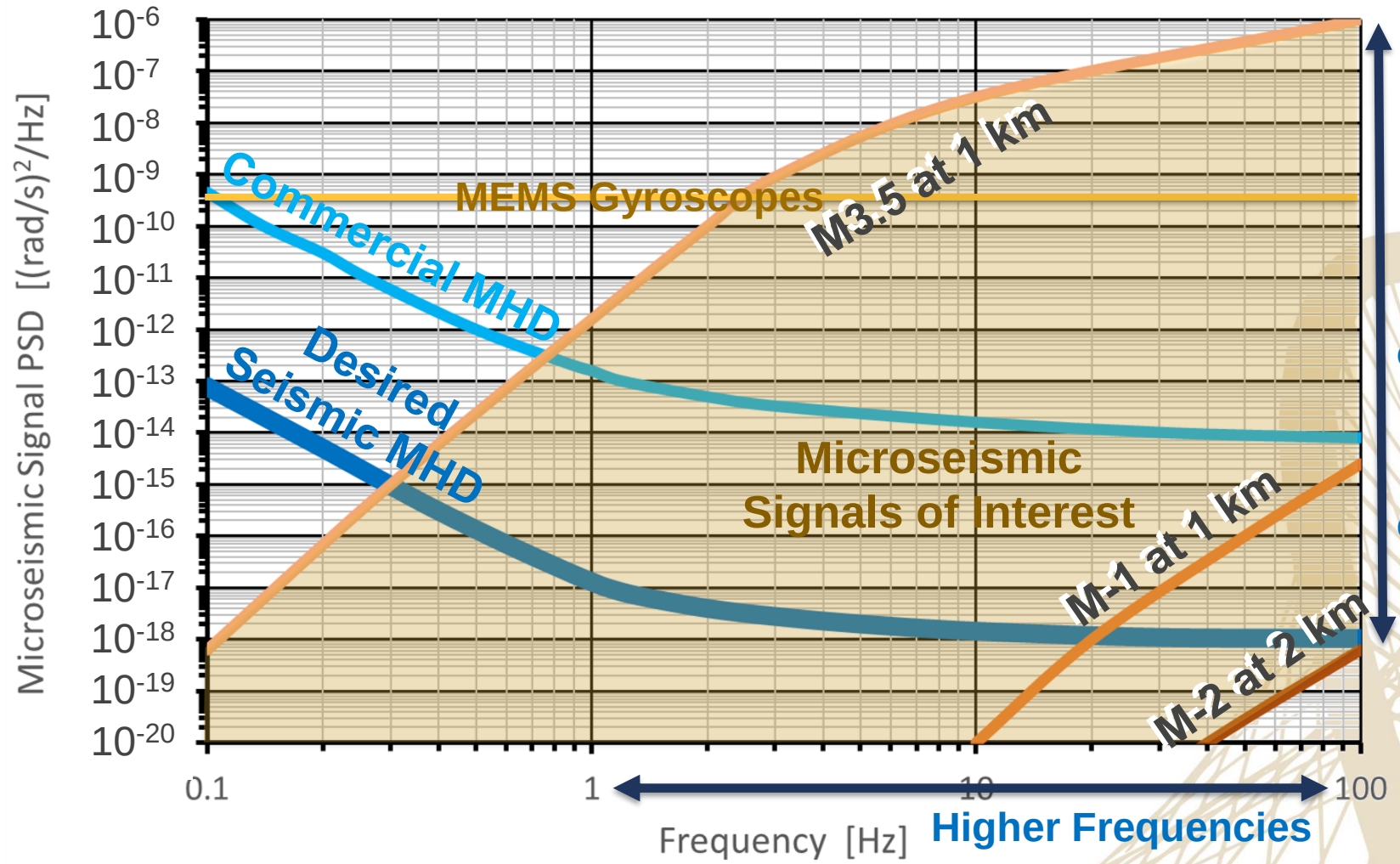
Rotational sensor technologies

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



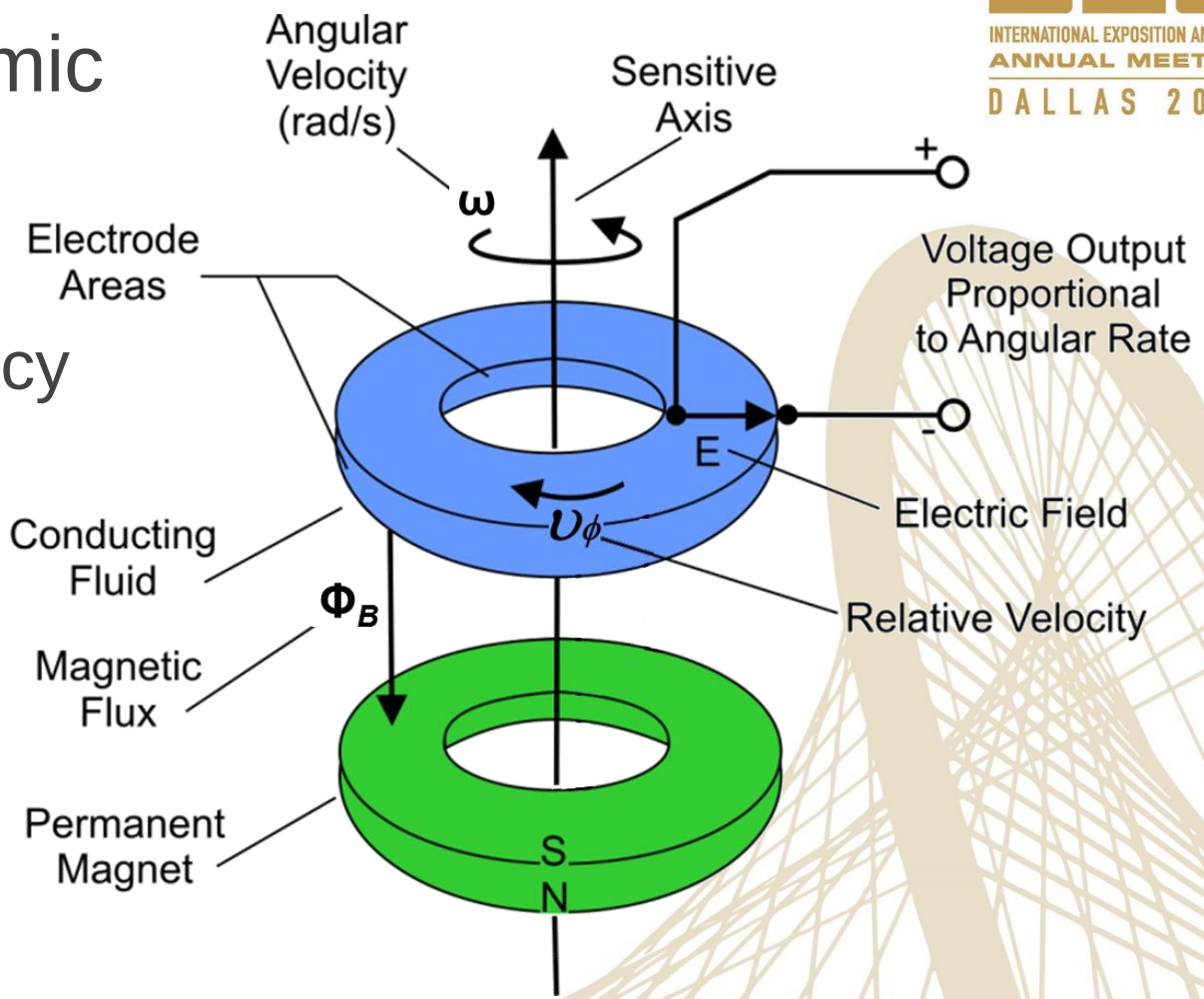
Rotational sensor technologies

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



Concept and status of the SMHD sensor

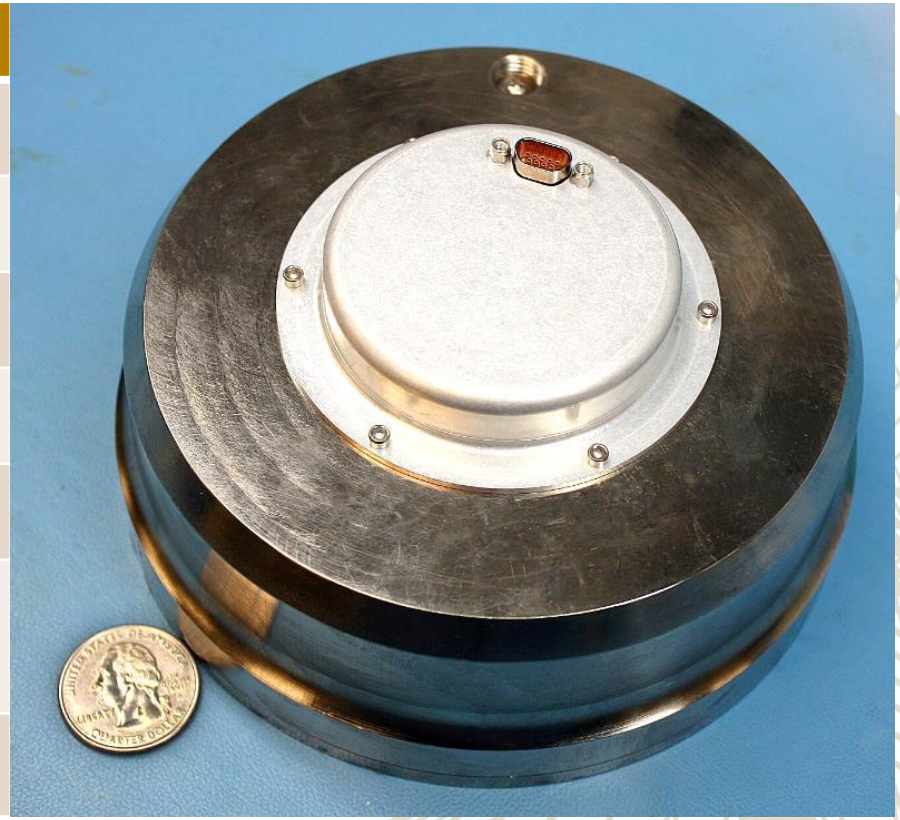
- Seismic Magnetohydrodynamic (SMHD) sensing principle
  - Senses **angular rate**
  - Ideal for mid and high frequency
  - Small enough to fit downhole
  - Simple, robust construction
  - Unit to unit consistency
  - Large dynamic range
  - Tailorable



Concept and status of the SMHD sensor

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

Proto-SMHD Characteristics	
Size	133mm∅x64mm (5.2”∅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)/$\sqrt{Hz}$ at 1 Hz



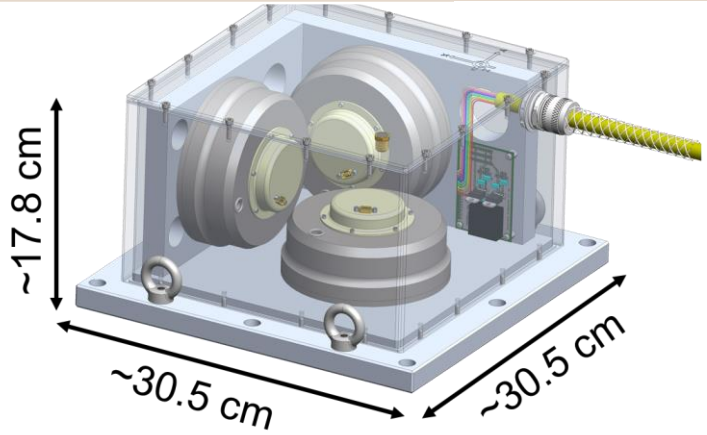
Concept and status of the SMHD sensor

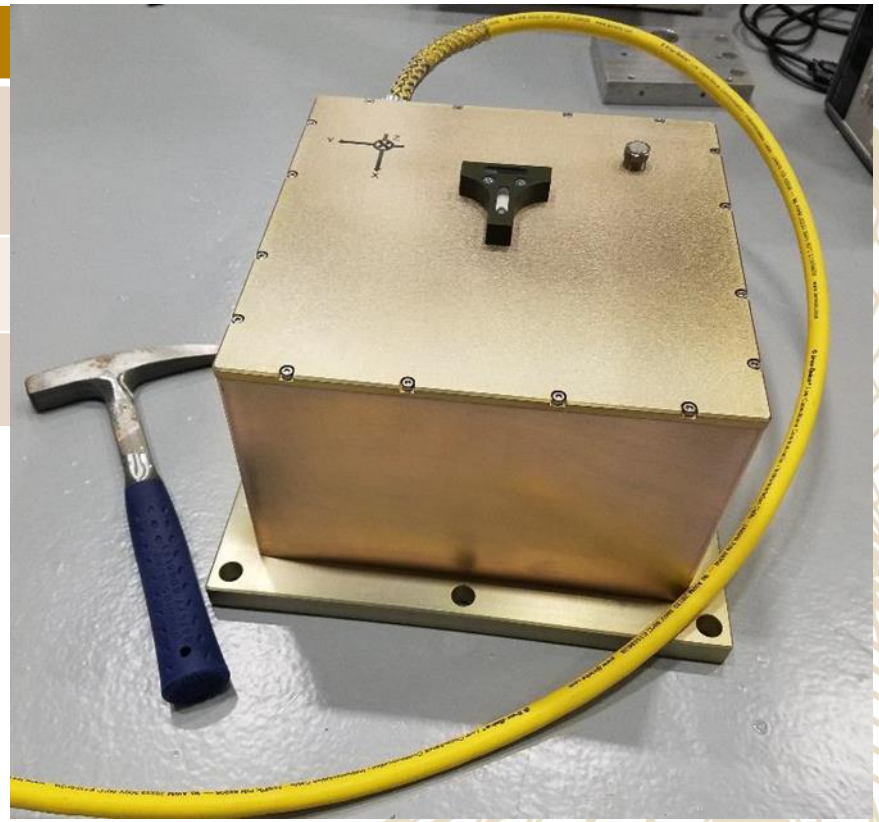
- 3 triaxial sets exist (3 Proto-SMHD Triad Boxes)

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

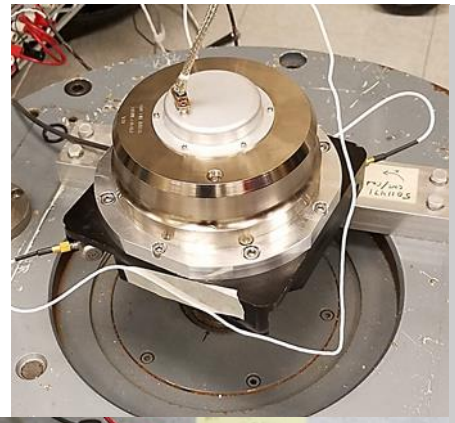
First Mode > 100 Hz

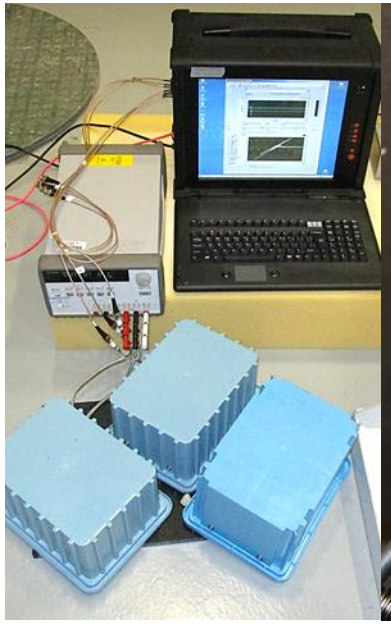


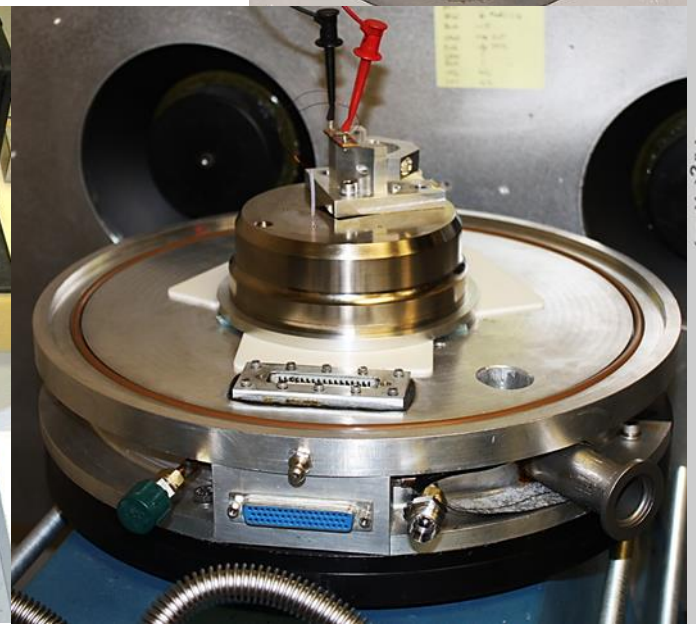


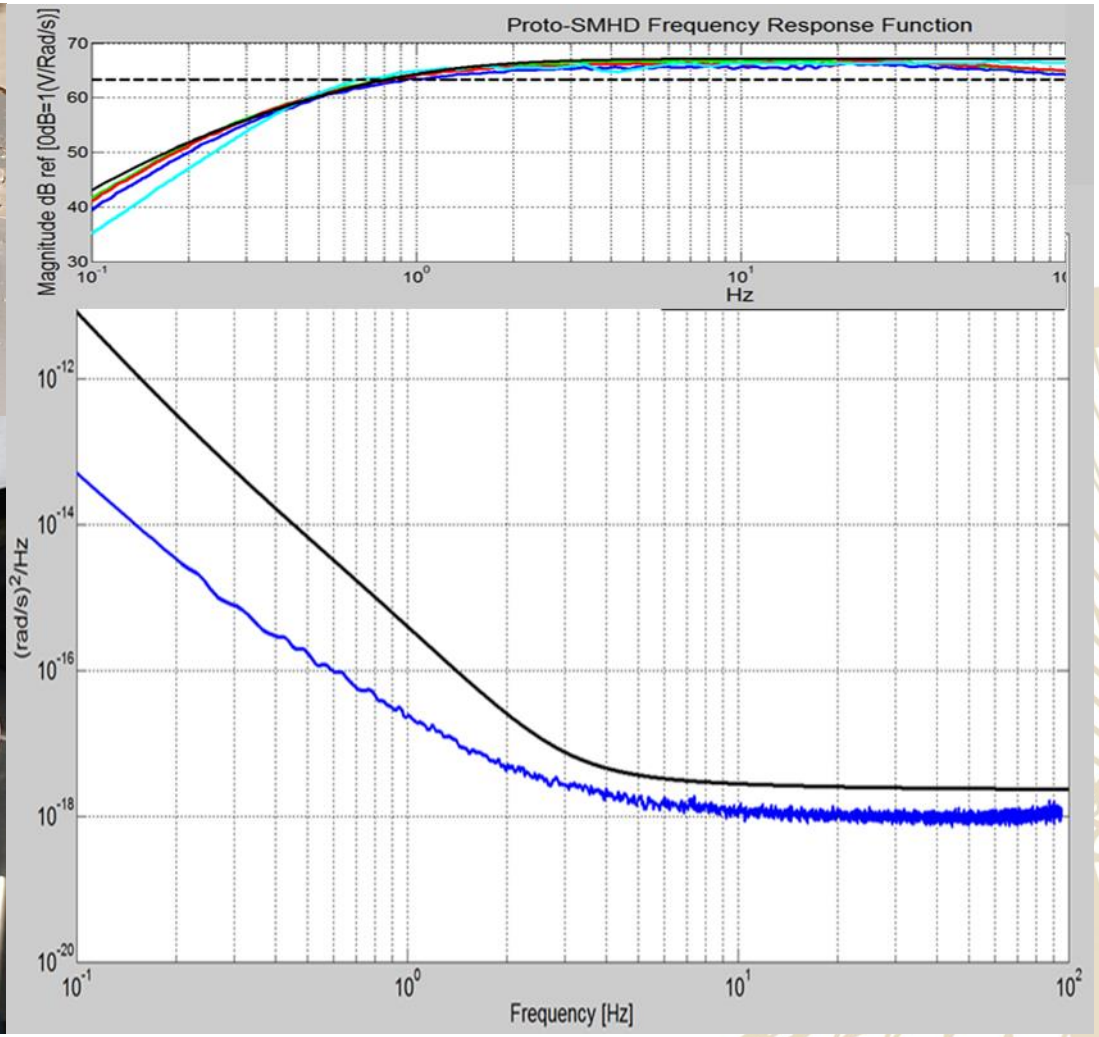
Concept and status of the SMHD sensor

- Sensor Test
  - Sensitivity
  - Noise



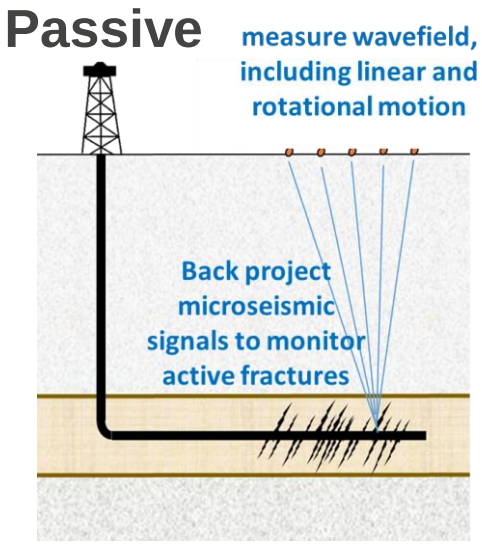


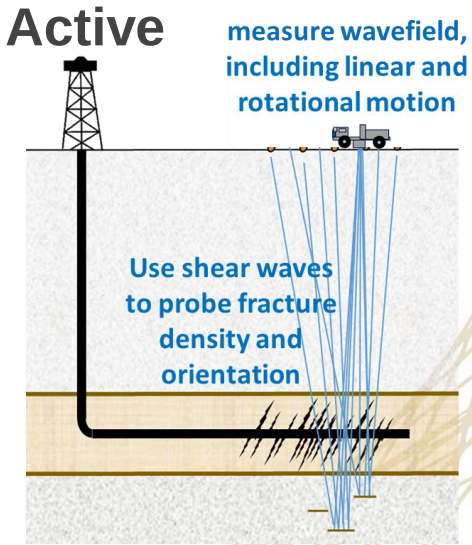




Concept and status of the SMHD sensor

- 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





Summary

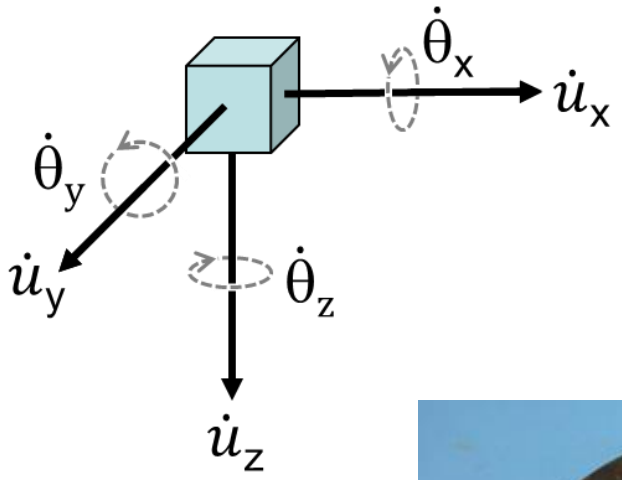
- The U.S. Department of Energy (DOE) and Applied Technology Associates (ATA) have built a new generation of rotational seismic sensors

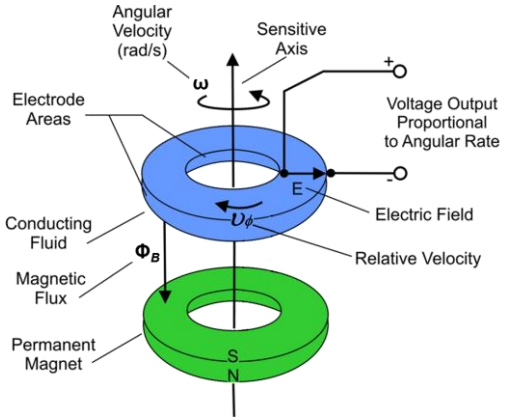
- Prototypes are available now to support experiments that help validate the utility of rotational seismic measurements

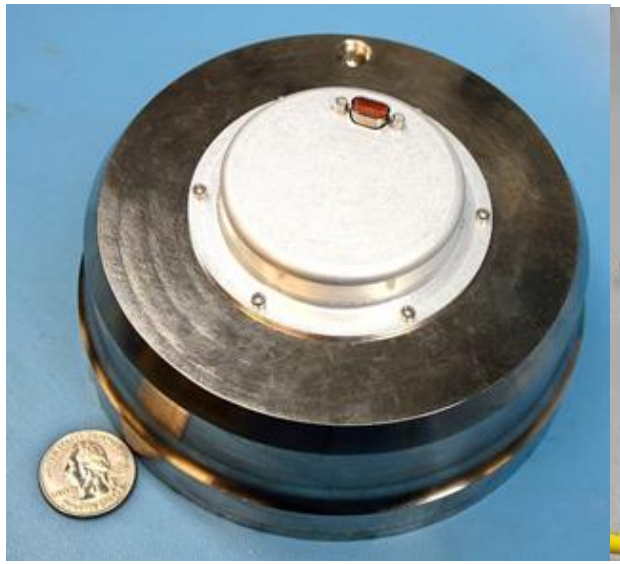
Acknowledgement and Disclaimer

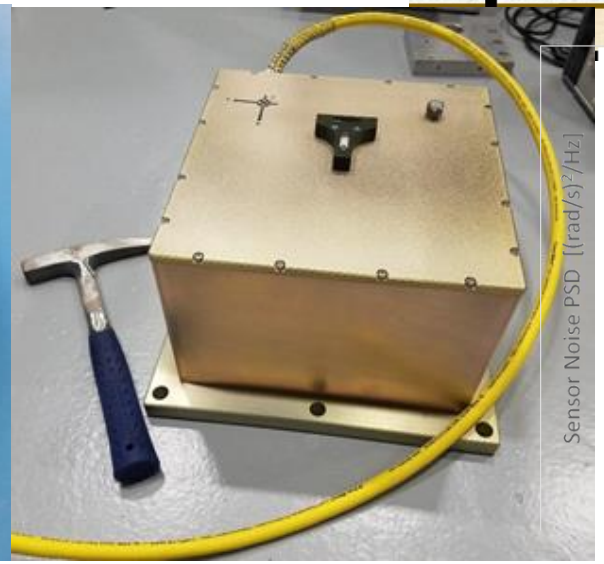
This material is based upon work supported by the U.S. Department of Energy under Award Number EE0005511. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

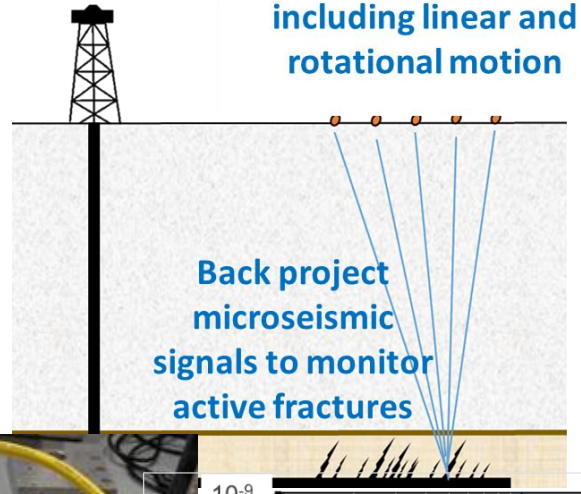
Questions?

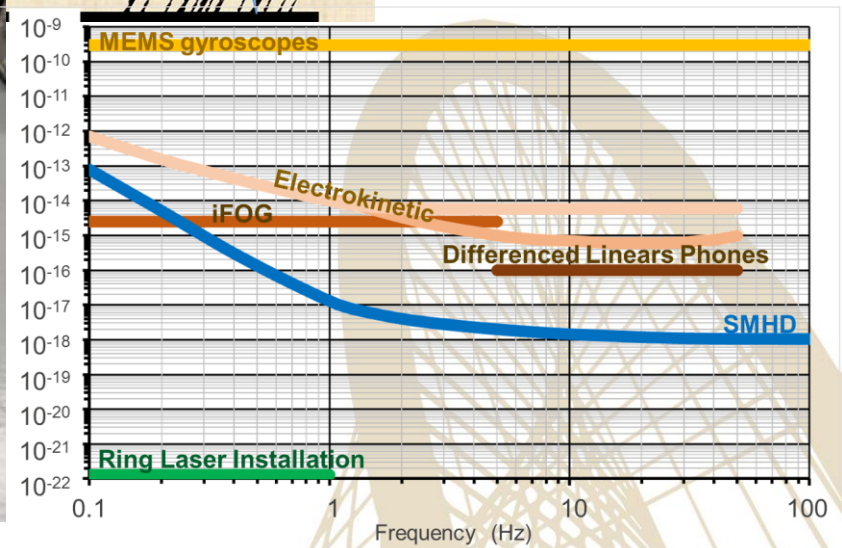

$\dot{\theta}_x$
$\dot{u}_x$
$\dot{\theta}_y$
$\dot{u}_y$
$\dot{\theta}_z$
$\dot{u}_z$

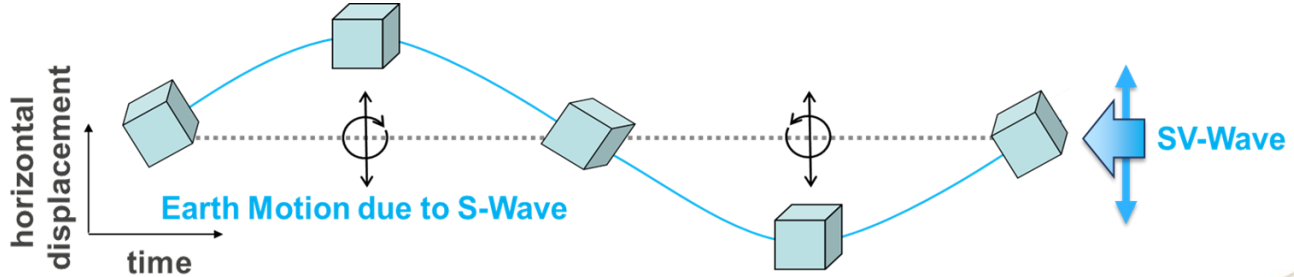

Angular Velocity (rad/s)
Sensitive Axis
Electrode Areas
Voltage Output Proportional to Angular Rate
Electric Field
Relative Velocity
Conducting Fluid
Magnetic Flux
Permanent Magnet
ω
E
S
N






measure wavefield, including linear and rotational motion
Back project microseismic signals to monitor active fractures


MEMS gyroscopes
Electrokinetic
iFOG
Differenced Linears Phones
SMHD
Ring Laser Installation
Sensor Noise PSD [(rad/s)²/Hz]
Frequency (Hz)
0.1
1
10
100


horizontal displacement
time
Earth Motion due to S-Wave
SV-Wave