Quartz Seismic and Pressure Sensors

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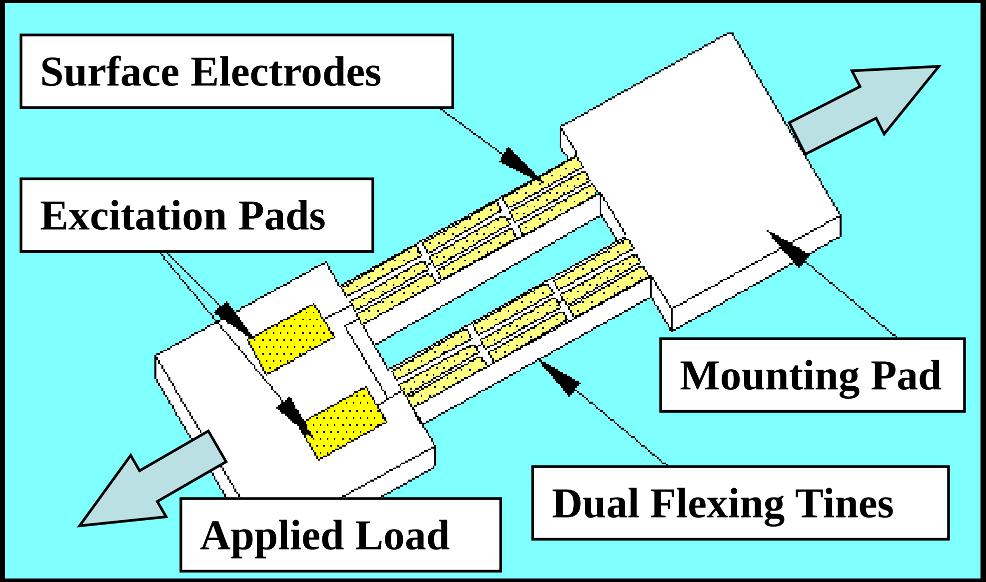
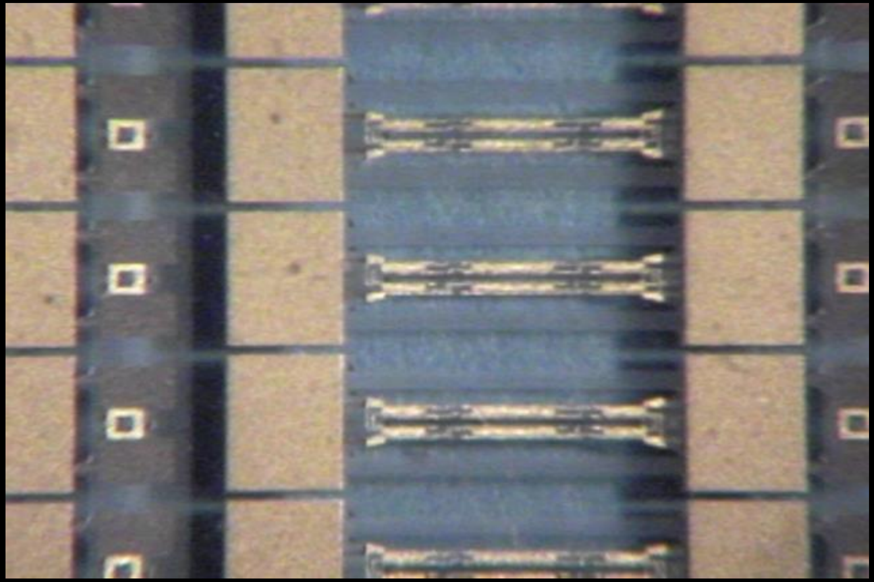
8/29/2024

Resonant Quartz Crystal Technology

Double-Ended Tuning Fork Force Sensors

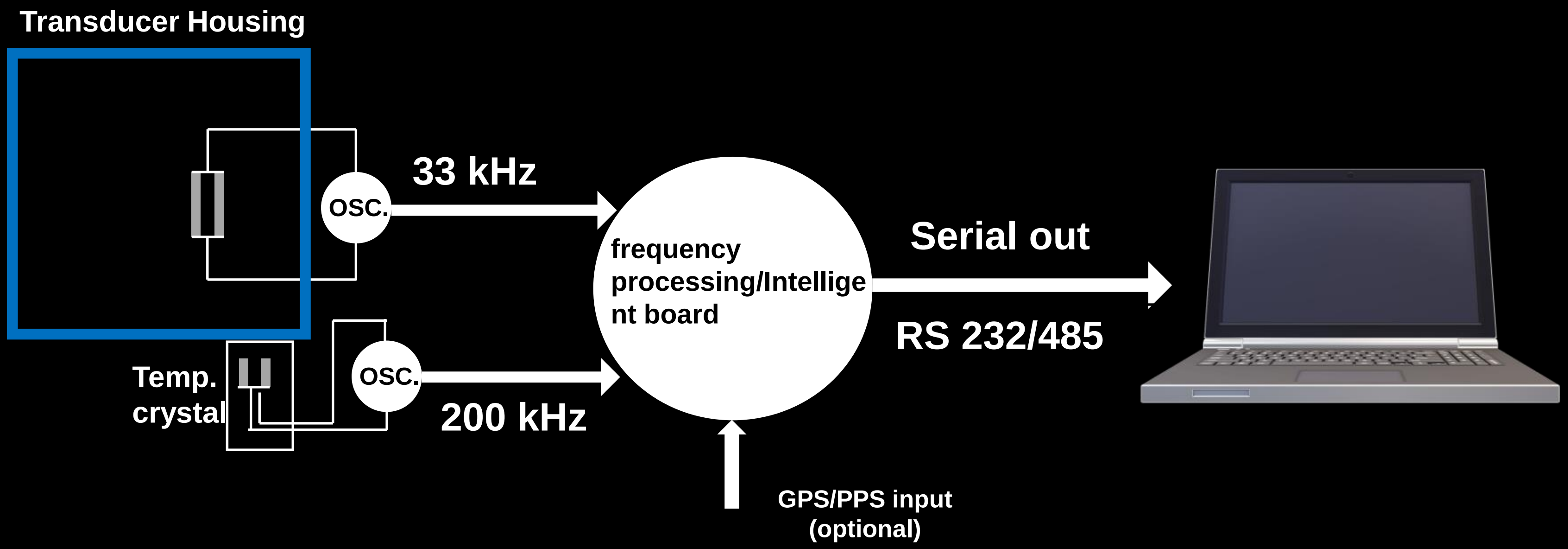




- Quartz crystal resonates in dual-ended tuning fork mode. Frequency of the mode depends on the force/stress on the tines.

- Force measurement is converted to a frequency/period measurement. Longer measurement leads to an increasingly better resolution: Resolution (noise) ∝ 1/T (as opposed to noise ∝ 1/√T for analog/voltage measurements) until thermal noise is reached.

Data Acquisition



- Force/Acceleration is sensed as a change in frequency of quartz crystal resonators. +/- 10% change in frequency is the nominal Full-Scale (FS) range of the sensors.

- Frequency is measured in a microprocessor using a stable reference oscillator and IIR filters* with resolution of parts per Billion (PPB) in a second. Processing delays < 1 ms.

- Outputs are in serial format and can be synchronized to external clocks using GPS/PPS input.

- Typical power consumption ~ 5 mW (sensor) + 200 mW (board)

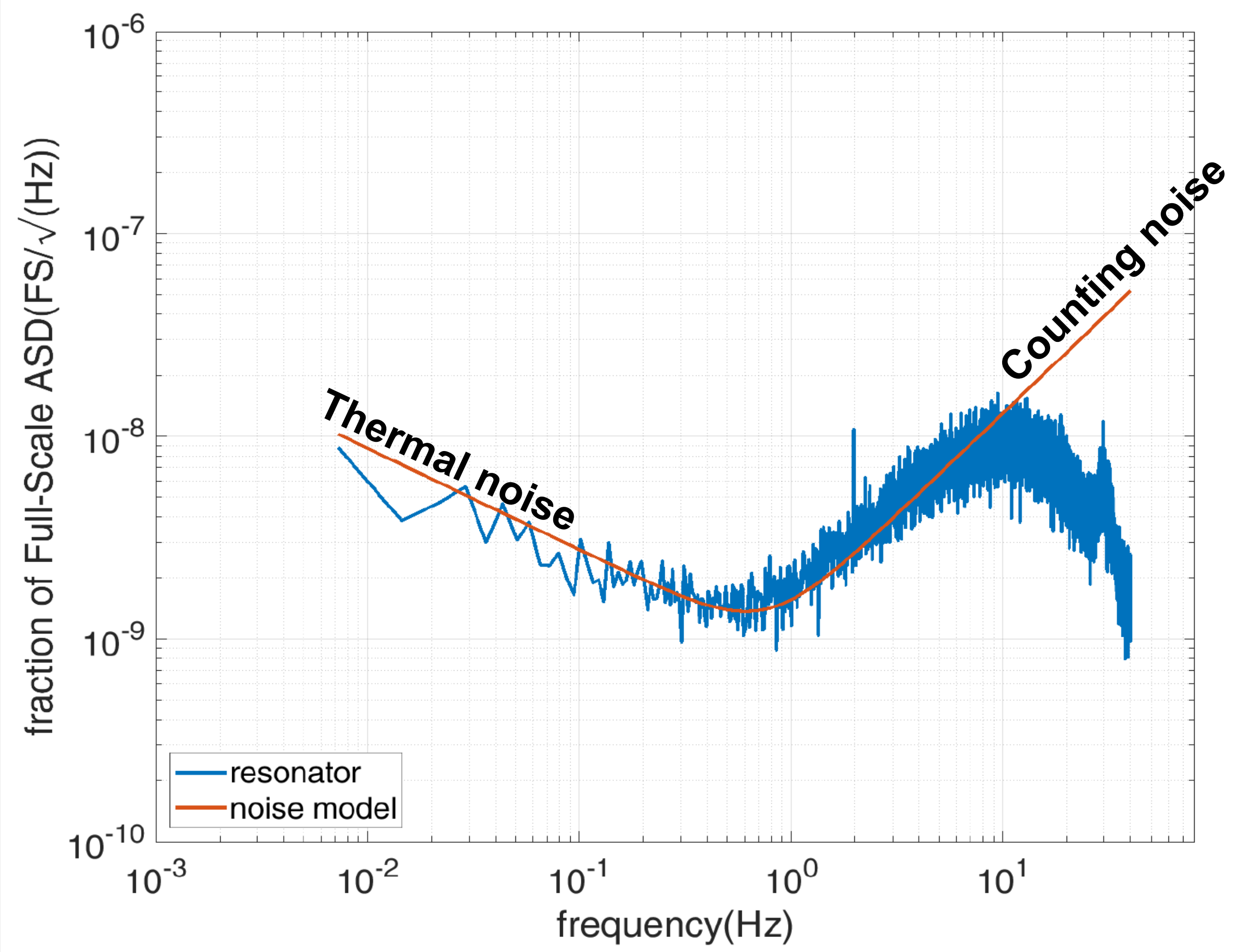
***Webb and Nooner (2016):** https://doi.org/10.1175/JTECH-D-15-0114.1

Transducer
-raw frequency output

Transmitter
-Rs 232/485 output

Absolute pressure sensors ranging from 16 psia to 40 kpsia and gauge pressure sensors from 2 to 200 psi.

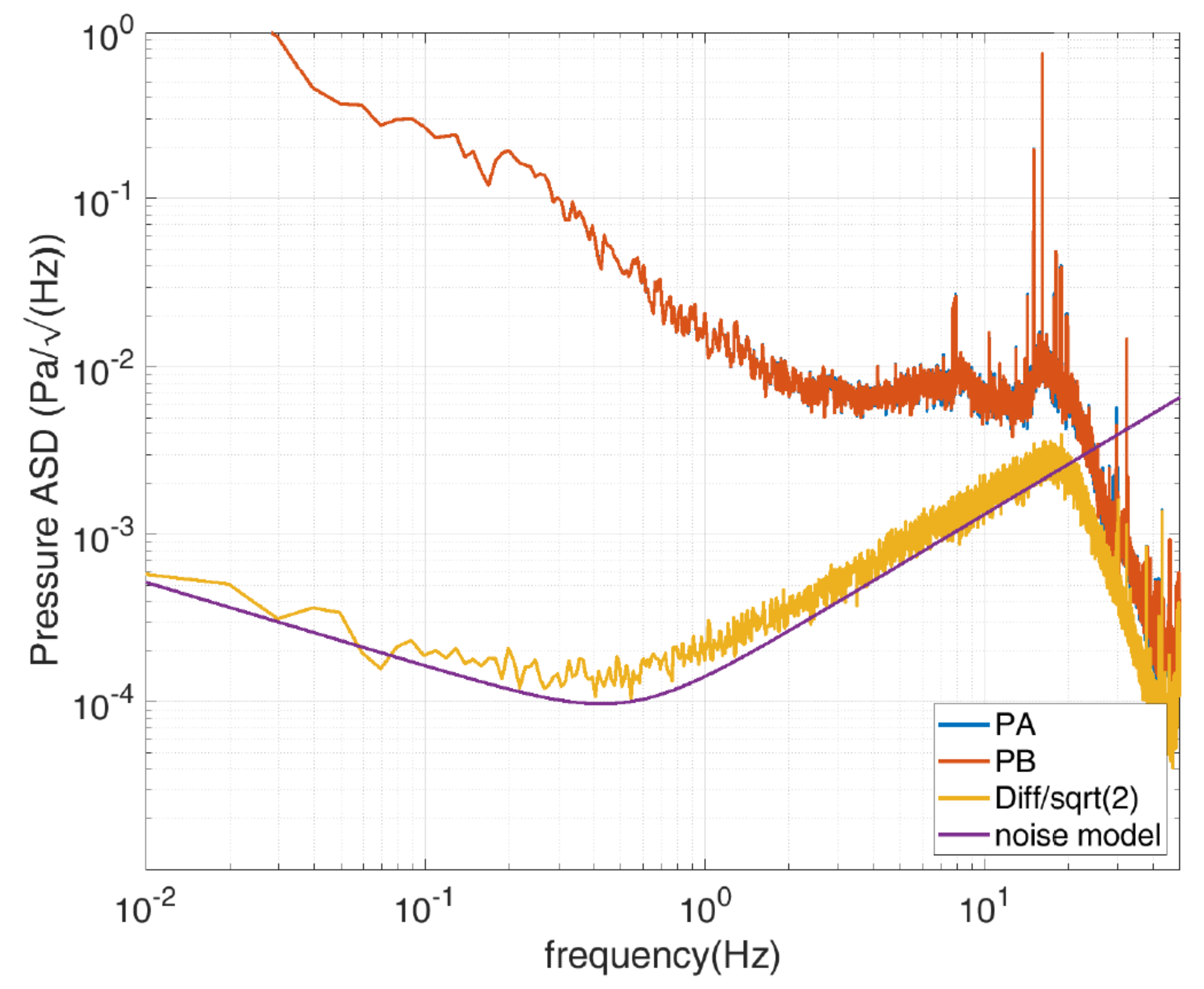
Noise floor of Resonator



Noise of a quartz sensor (in physical units) scales with the Full-Scale range of that sensor.
For example:
noise of 1000 psia sensor at 1 Hz = $1.7 \times 10^{-9} \times 1000$ = 1.7×10^{-6} psi/rt(Hz)

Infrasound Barometers for Seismo-Acoustic Measurements

Sensor Noise Floor



First Acoustic Detection of an Earthquake from Balloons

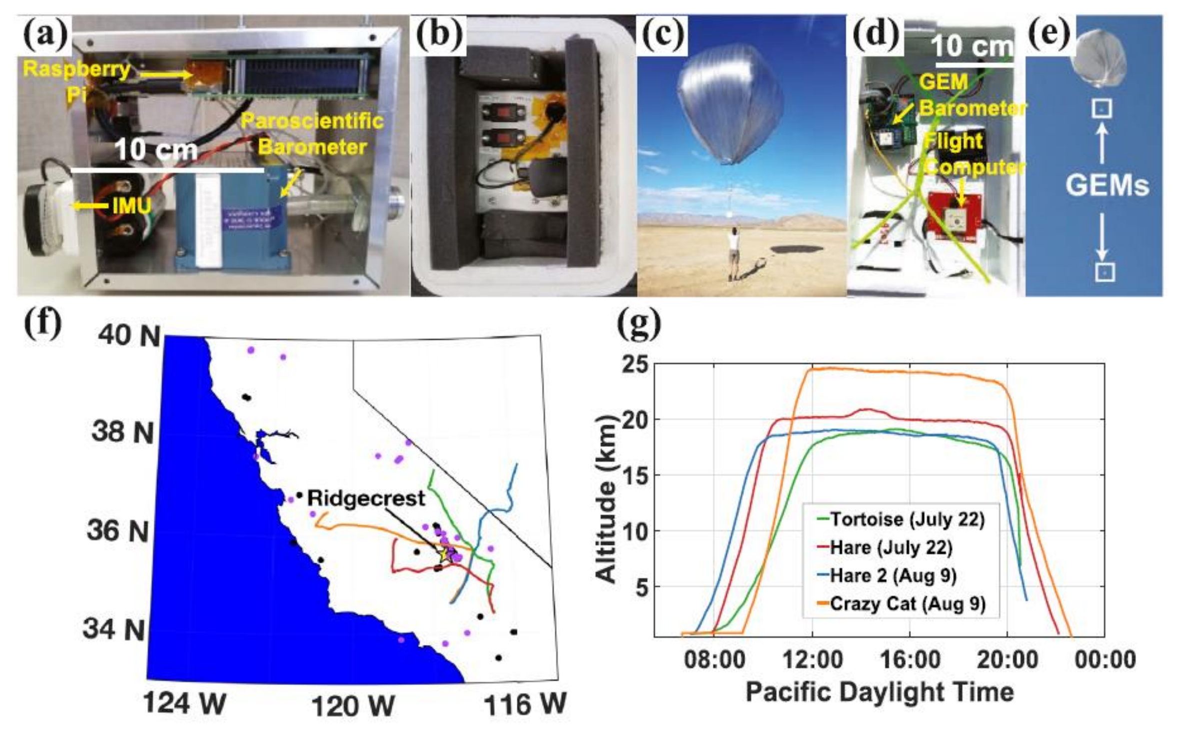
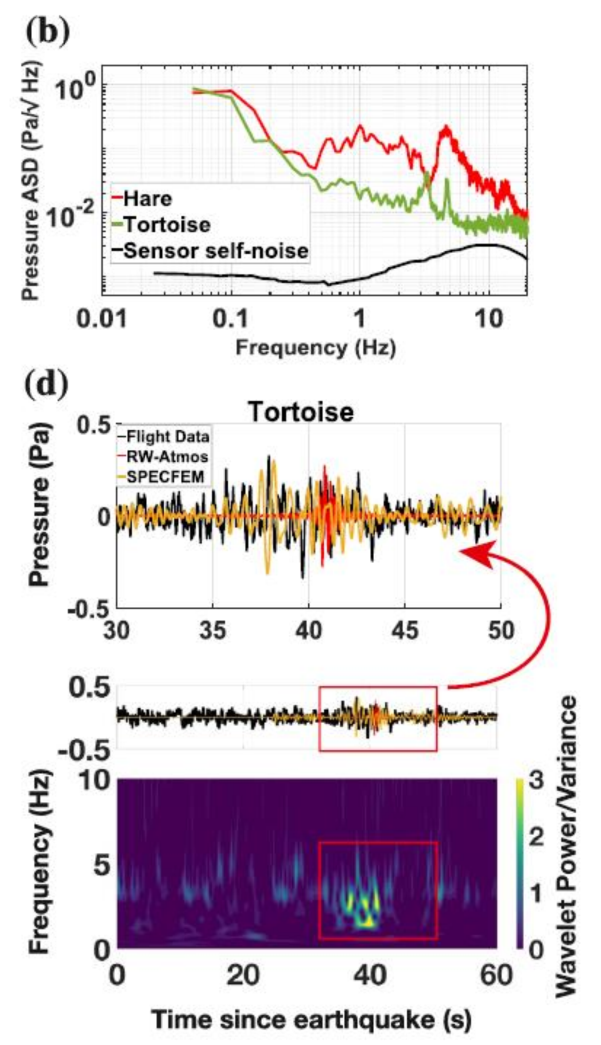


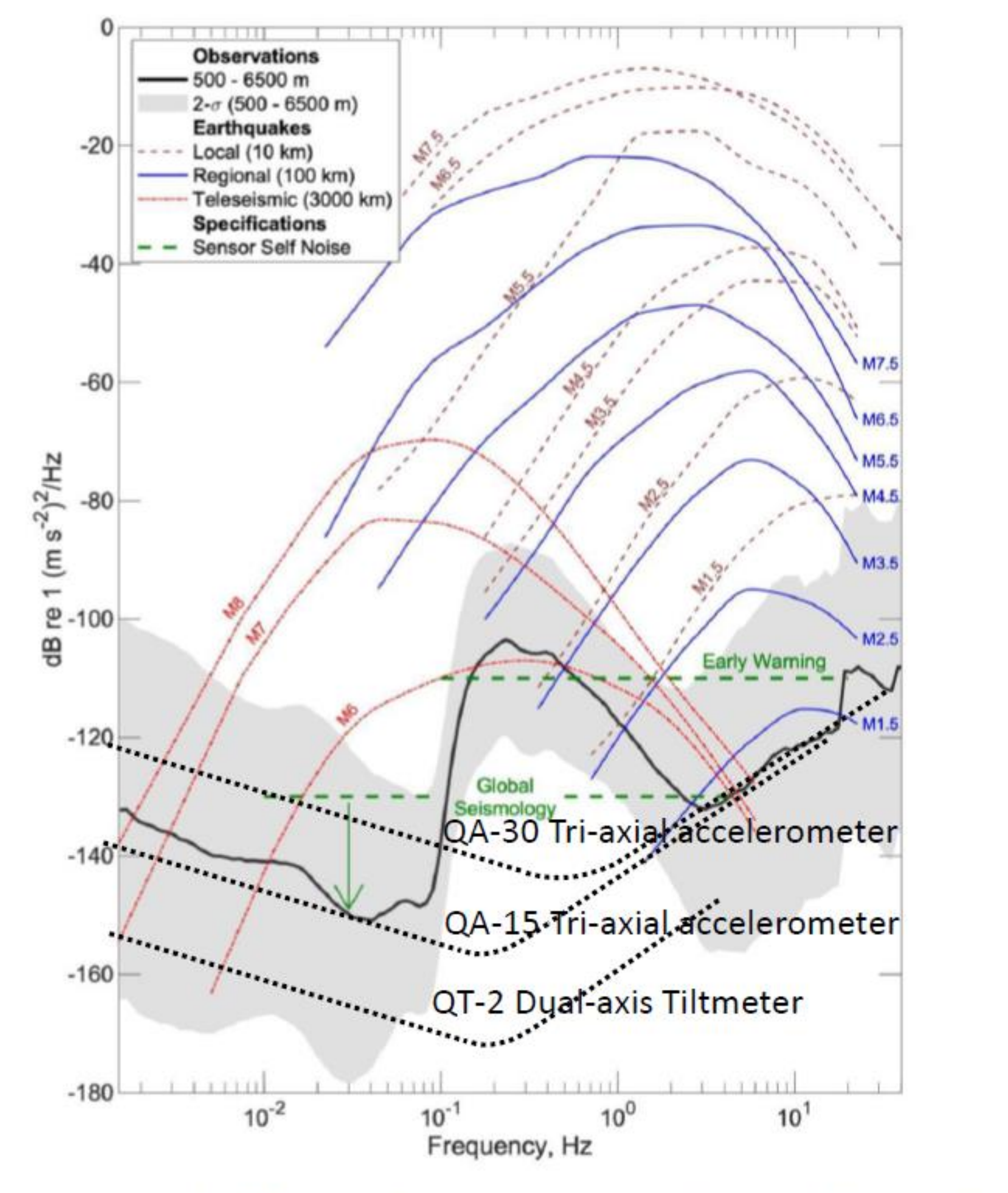
Figure 1. The Ridgecrest balloon experimental campaign. (a) Sensor package for Tortoise, Hare, and Hare 2 balloons, "IMU" stands for Inertial Measurement Unit (b) Sensor packaged for flight, (c) Launch of the Hare balloon, (d) Sensor package for the CrazyCat balloon, (e) CrazyCat balloon with two sensor packages on a 36-m tether, (f) and (g), The trajectory and altitude profile of the balloons. Hare and Tortoise balloons flew on July 22, 2019, whereas Hare 2 and CrazyCat flew on August 9, 2019. Earthquakes with $M_w \geq 1.5$ occurring during the July 22 campaign are shown as black dots, and those on August 9 are shown as magenta dots. Stratospheric wind velocities exhibited strong altitude dependence on these days, leading to the divergence in trajectories of balloons launched from the same location.



The First Detection of an Earthquake From a Balloon Using Its Acoustic Signature, Geophysical Research Letters, Volume: 48, Issue: 12, First published: 28 June 2021, https://doi.org/10.1029/2021GL093013

New Seismic Sensors

Modeled noise



*noise floor overlaid on plot from Howe et al., Frontiers in Earth Science (2022), doi: 10.3389/feart.2021.775544

QA30 and QA15 Triaxial Accelerometer

QA15 Tri-axial Accelerometer

Property	QA15	QA30
Full-scale range	±1.5-g	±3-g
Noise level	<3-ng/√Hz at 0.1 Hz	<10-ng/√Hz at 1 Hz
Size	1.88” OD X 3.5” HT	1.2” OD X 2.6” HT
Power (transducer)	3.6 mW (typical) at 3.6V DC	3.6 mW (typical) at 3.6V DC
Power (intelligent board)	223 mW (typical) at 3.6V DC	223 mW (typical) at 3.6V DC
Temperature range	-2°C to 50°C (calibrated)	-2°C to 50°C (calibrated)
Resonant frequency	~25 Hz	>200 Hz

BENEFITS

High range – will not saturate (clip)

Compact & Omni-directional – easy to deploy

Low self-noise – high resolution over broad spectrum

Low Power Consumption – extended deployment times

Excellent stability – long-term geodetic monitoring

Eliminates need for multiple seismic instruments to cover the full seismic spectrum

APPLICATION AREAS

Geodesy
Seismology
Oceanography
Volcanology & Gravimetry
Carbon Capture & Sequestration
Boreholes + Cabled, Remote, & Mobile Platforms

QT-2 Dual-axis Tiltmeter

QT-2 Tilt meter

Property	QT2
Full-scale range	±0.17-g (±10°)
Noise level	<0.4-ng/√Hz at 0.1 Hz
Size	1.75” OD X 6” HT
Power (transducer)	3.6 mW (typical) at 3.6V DC
Power (intelligent board)	223 mW (typical) at 3.6V DC
Temperature range	-2°C to 40°C (calibrated)
Resonant frequency	~6 Hz

BENEFITS

High range – will not saturate (clip)

Compact & Omni-directional – easy to deploy

Low self-noise – high resolution over broad spectrum

Low Power Consumption – extended deployment times

Excellent stability – long-term geodetic monitoring

APPLICATION AREAS

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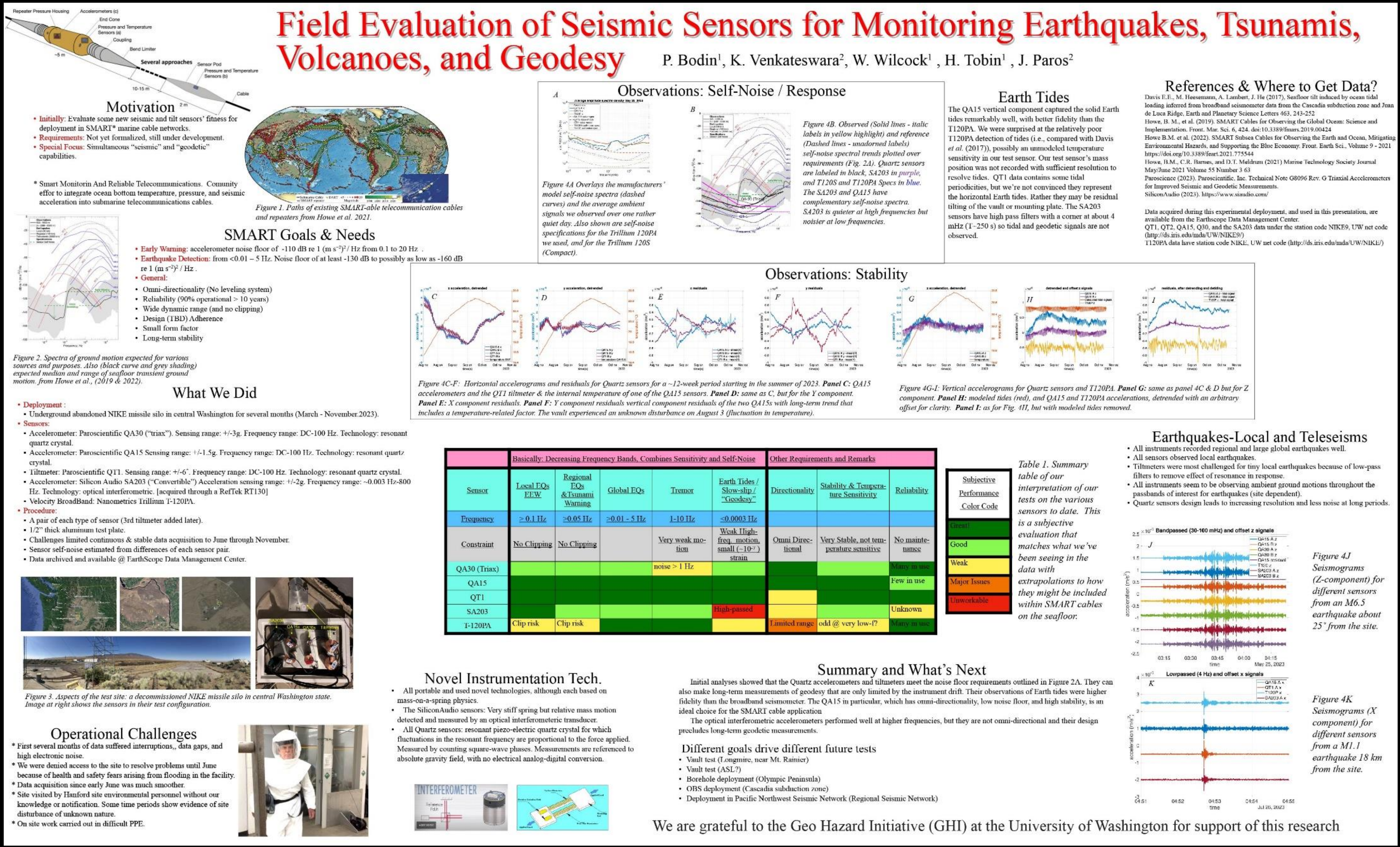
Boreholes + Cabled, Remote, & Mobile Platforms

Vault Testing by Univ. of WA



Field Evaluation of Seismic Sensors for Monitoring Earthquakes, Tsunamis, Volcanoes, and Geodesy

P. Bodin[1], K. Venkateswara[2], W. Wilcock[1] , H. Tobin[1] , J. Paros[2]

Motivation

- **Initially**: Evaluate some new seismic and tilt sensors' fitness for deployment in SMART* marine cable networks.
- **Requirements**: Not yet formalized, still under development.
- **Special Focus**: Simultaneous "seismic" and "geodetic" capabilities.

* Smart Monitorin And Reliable Telecommunications. Comunity effor to integrate ocean bottom temperature, pressure, and seismic acceleration into submarine telecommunications cables.

Figure 1. Paths of existing SMART-able telecommunication cables and repeaters from Howe et al. 2021.

SMART Goals & Needs

- **Early Warning**: accelerometer noise floor of -110 dB re 1 $(m\,s^{-2})^2$ / Hz from 0.1 to 20 Hz .
- **Earthquake Detection**: from <0.01 – 5 Hz. Noise floor of at least -130 dB to possibly as low as -160 dB re 1 $(m\,s^{-2})^2$ / Hz .
- **General**:
  - Omni-directionality (No leveling system)
  - Reliability (90% operational > 10 years)
  - Wide dynamic range (and no clipping)
  - Design (TBD) Adherence
  - Small form factor
  - Long-term stability

Figure 2. Spectra of ground motion expected for various sources and purposes. Also (black curve and grey shading) expected median and range of seafloor transient ground motion. from Howe et al., (2019 & 2022).

What We Did

- **Deployment** :
  - Underground abandoned NIKE missile silo in central Washington for several months (March - November.2023).
- **Sensors**:
  - Accelerometer: Paroscientific QA30 ("triax"). Sensing range: +/-3g. Frequency range: DC-100 Hz. Technology: resonant quartz crystal.
  - Accelerometer: Paroscientific QA15 Sensing range: +/-1.5g. Frequency range: DC-100 Hz. Technology: resonant quartz crystal.
  - Tiltmeter: Paroscientific QT1. Sensing range: +/-6˚. Frequency range: DC-100 Hz. Technology: resonant quartz crystal.
  - Accelerometer: Silicon Audio SA203 ("Convertible") Acceleration sensing range: +/-2g. Frequency range: ~0.003 Hz-800 Hz. Technology: optical interferometric. [acquired through a RefTek RT130]
  - Velocity BroadBand: Nanometrics Trillium T-120PA.
- **Procedure**:
  - A pair of each type of sensor (3rd tiltmeter added later).
  - 1/2" thick aluminum test plate.
  - Challenges limited continuous & stable data acquisition to June through November.
  - Sensor self-noise estimated from differences of each sensor pair.
  - Data archived and available @ EarthScope Data Management Center.

Figure 3. Aspects of the test site: a decommissioned NIKE missile silo in central Washington state. Image at right shows the sensors in their test configuration.

Operational Challenges

* First several months of data suffered interruptions,, data gaps, and high electronic noise.
* We were denied access to the site to resolve problems until June because of health and safety fears arising from flooding in the facility.
* Data acquisition since early June was much smoother.
* Site visited by Hanford site environmental personnel without our knowledge or notification. Some time periods show evidence of site disturbance of unknown nature.
* On site work carried out in difficult PPE.

Observations: Self-Noise / Response

Figure 4A Overlays the manufacturers' model self-noise spectra (dashed curves) and the average ambient signals we observed over one rather quiet day. Also shown are self-noise specifications for the Trillium 120PA we used, and for the Trillium 120S (Compact).

Figure 4B. Observed (Solid lines - italic labels in yellow highlight) and reference (Dashed lines - unadorned labels) self-noise spectral trends plotted over requirements (Fig. 2A). Quartz sensors are labeled in black, SA203 in purple, and T120S and T120PA Specs in blue. The SA203 and QA15 have complementary self-noise spectra. SA203 is quieter at high frequencies but noisier at low frequencies.

Earth Tides

The QA15 vertical component captured the solid Earth tides remarkably well, with better fidelity than the T120PA. We were surprised at the relatively poor T120PA detection of tides (i.e., compared with Davis *et al.* (2017)), possibly an unmodeled temperature sensitivity in our test sensor. Our test sensor's mass position was not recorded with sufficient resolution to resolve tides. QT1 data contains some tidal periodicities, but we're not convinced they represent the horizontal Earth tides. Rather they may be residual tilting of the vault or mounting plate. The SA203 sensors have high pass filters with a corner at about 4 mHz (T~250 s) so tidal and geodetic signals are not observed.

References & Where to Get Data?

Davis E.E., M. Heesemann, A. Lambert, J. He (2017), Seafloor tilt induced by ocean tidal loading inferred from broadband seismometer data from the Cascadia subduction zone and Juan de Luca Ridge, Earth and Planetary Science Letters 463, 243-252
Howe, B. M., et al. (2019). SMART Cables for Observing the Global Ocean: Science and Implementation. Front. Mar. Sci. 6, 424. doi:10.3389/fmars.2019.00424
Howe B.M. et al. (2022). SMART Subsea Cables for Observing the Earth and Ocean, Mitigating Environmental Hazards, and Supporting the Blue Economy. Front. Earth Sci., Volume 9 - 2021 https://doi.org/10.3389/feart.2021.775544
Howe, B.M., C.R. Barnes, and D.T. Meldrum (2021) Marine Technology Society Journal May/June 2021 Volume 55 Number 3 63
Paroscience (2023). Paroscientific, Inc. Technical Note G8096 Rev. G Triaxial Accelerometers for Improved Seismic and Geodetic Measurements.
SiliconAudio (2023). https://www.siaudio.com/

Data acquired during this experimental deployment, and used in this presentation, are available from the Earthscope Data Management Center.
QT1, QT2, QA15, Q30, and the SA203 data under the station code NIKE9, UW net code (http://ds.iris.edu/mda/UW/NIKE9/)
T120PA data have station code NIKE, UW net code (http://ds.iris.edu/mda/UW/NIKE/)

Observations: Stability

Figure 4C-F: Horizontal accelerograms and residuals for Quartz sensors for a ~12-week period starting in the summer of 2023. ***Panel C:*** *QA15 accelerometers and the QT1 tiltmeter & the internal temperature of one of the QA15 sensors.* ***Panel D:*** *same as C, but for the Y component.* ***Panel E:*** *X component residuals.* ***Panel F:*** *Y component residuals vertical component residuals of the two QA15s with long-term trend that includes a temperature-related factor. The vault experienced an unknown disturbance on August 3 (fluctuation in temperature).*

Figure 4G-I: Vertical accelerograms for Quartz sensors and T120PA. ***Panel G:*** *same as panel 4C & D but for Z component.* ***Panel H:*** *modeled tides (red), and QA15 and T120PA accelerations, detrended with an arbitrary offset for clarity.* ***Panel I:*** *as for Fig. 4H, but with modeled tides removed.*

	Basically: Decreasing Frequency Bands, Combines Sensitivity and Self-Noise					Other Requirements and Remarks		
Sensor	Local EQs EEW	Regional EQs &Tsunami Warning	Global EQs	Tremor	Earth Tides / Slow-slip / "Geodesy"	Directionality	Stability & Temperature Sensitivity	Reliability
Frequency	> 0.1 Hz	>0.05 Hz	>0.01 - 5 Hz	1-10 Hz	<0.0003 Hz			
Constraint	No Clipping	No Clipping		Very weak motion	Weak High-freq. motion, small (~10^{-7}) strain	Omni Directional	Very Stable, not temperature sensitive	No maintenance
QA30 (Triax)	🟢	🟢	🟢	🟨 noise > 1 Hz	🟢	🟩	🟢	🟩 Many in use
QA15	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟢 Few in use
QT1	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩
SA203	🟩	🟢	🟢	🟢	🟥 High-passed	🟨	🟢	🟨 Unknown
T-120PA	🟨 Clip risk	🟨 Clip risk	🟩	🟩	🟨	🟧 Limited range	🟨 odd @ very low-f?	🟩 Many in use

Subjective Performance Color Code
🟩 Great!
🟢 Good
🟨 Weak
🟧 Major Issues
🟥 Unworkable

Table 1. Summary table of our interpretation of our tests on the various sensors to date. This is a subjective evaluation that matches what we've been seeing in the data with extrapolations to how they might be included within SMART cables on the seafloor.

Earthquakes-Local and Teleseisms

- All instruments recorded regional and large global earthquakes well.
- All sensors observed local earthquakes.
- Tiltmeters were most challenged for tiny local earthquakes because of low-pass filters to remove effect of resonance in response.
- All instruments seem to be observing ambient ground motions throughout the passbands of interest for earthquakes (site dependent).
- Quartz sensors design leads to increasing resolution and less noise at long periods.

Figure 4J Seismograms (Z-component) for different sensors from an M6.5 earthquake about 25˚ from the site.

Figure 4K Seismograms (X component) for different sensors from a M1.1 earthquake 18 km from the site.

Novel Instrumentation Tech.

- All portable and used novel technologies, although each based on mass-on-a-spring physics.
- The SiliconAudio sensors: Very stiff spring but relative mass motion detected and measured by an optical interferometeric transducer.
- All Quartz sensors: resonant piezo-electric quartz crystal for which fluctuations in the resonant frequency are proportional to the force applied. Measured by counting square-wave phases. Measurements are referenced to absolute gravity field, with no electrical analog-digital conversion.

Summary and What's Next

Initial analyses showed that the Quartz accelerometers and tiltmeters meet the noise floor requirements outlined in Figure 2A. They can also make long-term measurements of geodesy that are only limited by the instrument drift. Their observations of Earth tides were higher fidelity than the broadband seismometer. The QA15 in particular, which has omni-directionality, low noise floor, and high stability, is an ideal choice for the SMART cable application

The optical interferometric accelerometers performed well at higher frequencies, but they are not omni-directional and their design precludes long-term geodetic measurements.

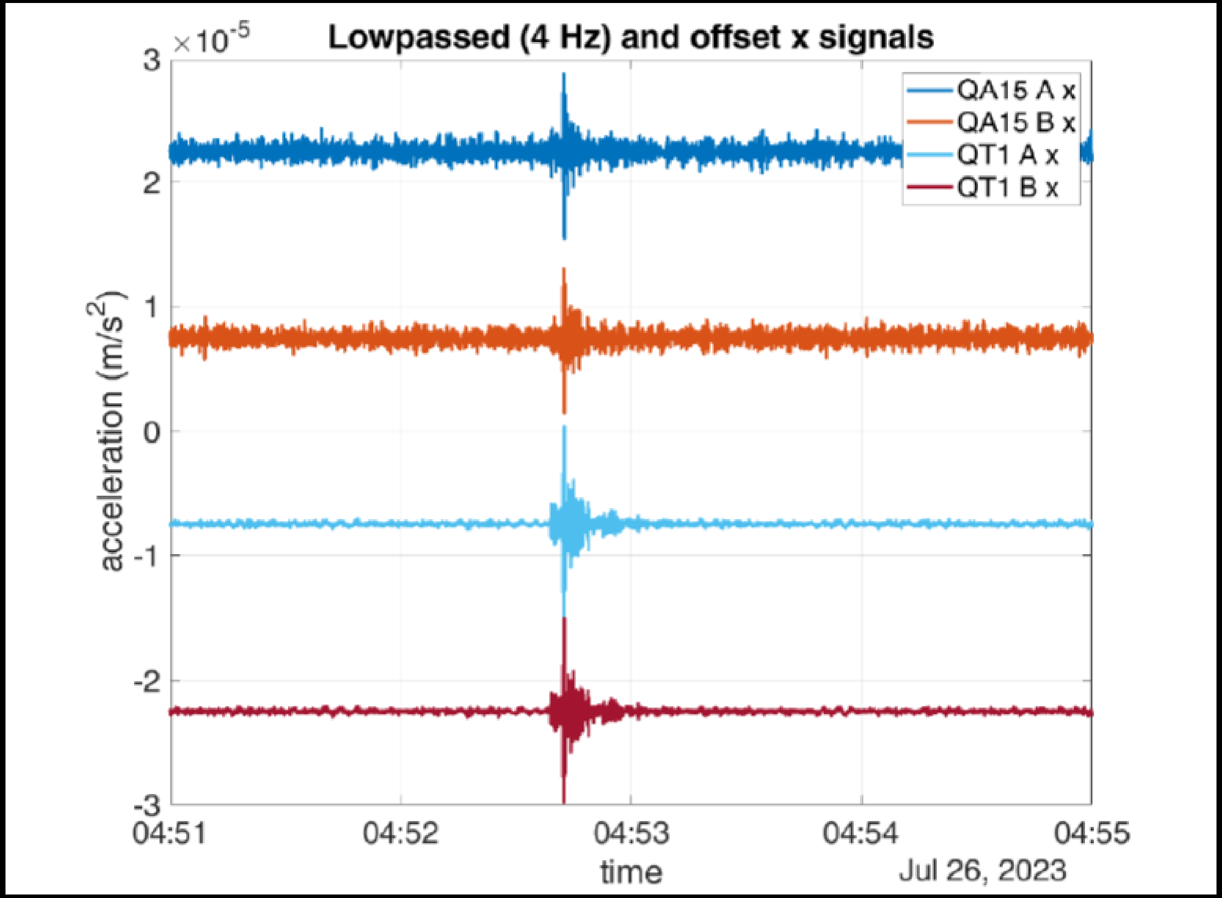
Different goals drive different future tests

- Vault test (Longmire, near Mt. Rainier)
- Vault test (ASL?)
- Borehole deployment (Olympic Peninsula)
- OBS deployment (Cascadia subduction zone)
- Deployment in Pacific Northwest Seismic Network (Regional Seismic Network)

We are grateful to the Geo Hazard Initiative (GHI) at the University of Washington for support of this research

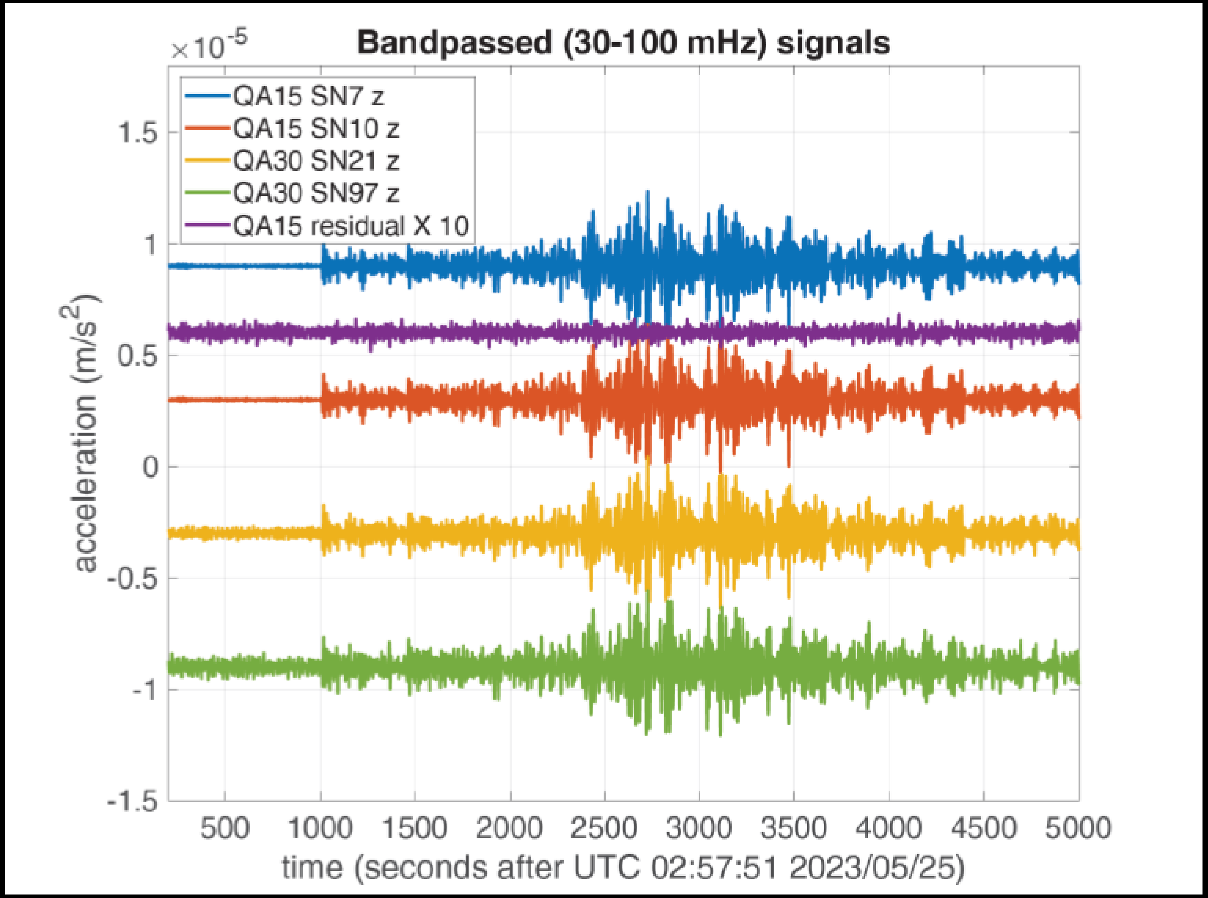
University of Washington Vault Tests – Earthquake Signals

Local M1.1 Earthquake about 40-km away



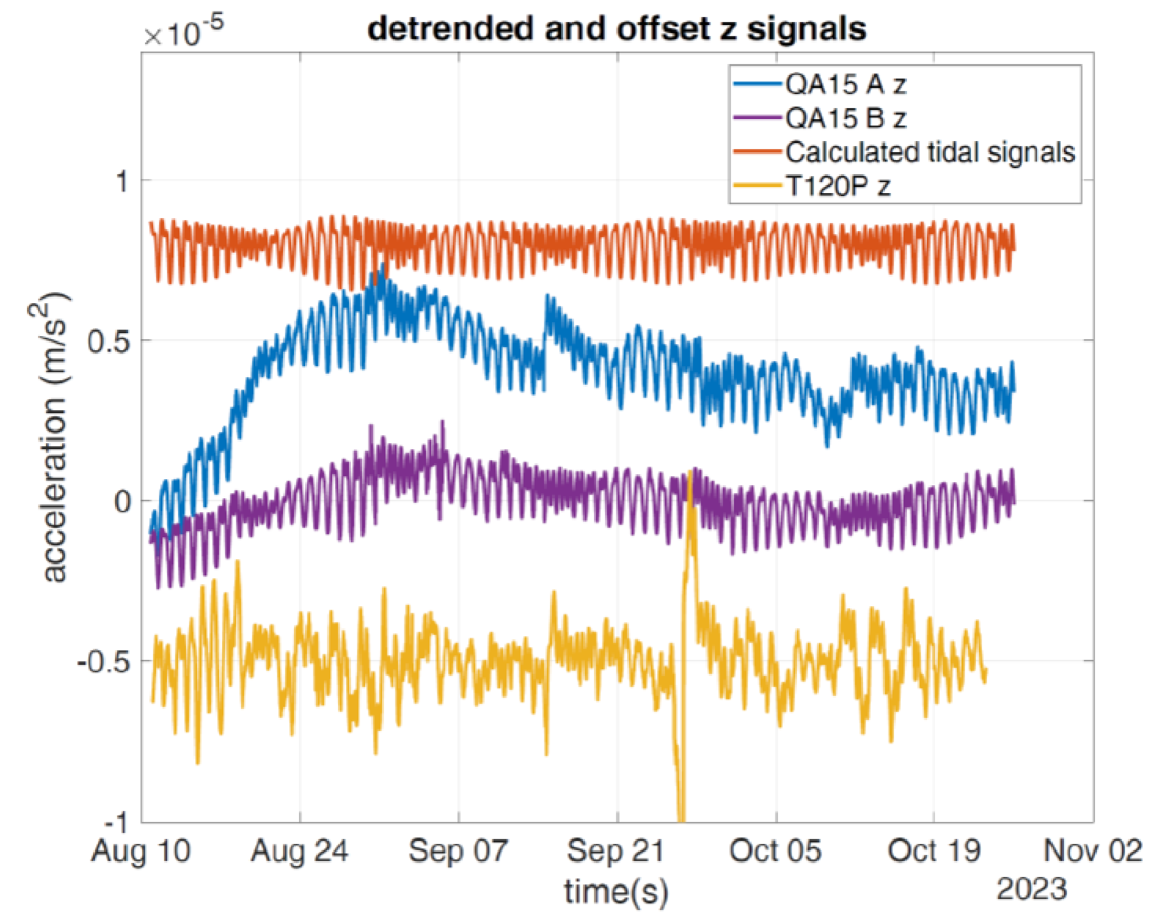
Ability to detect short-duration local signals…

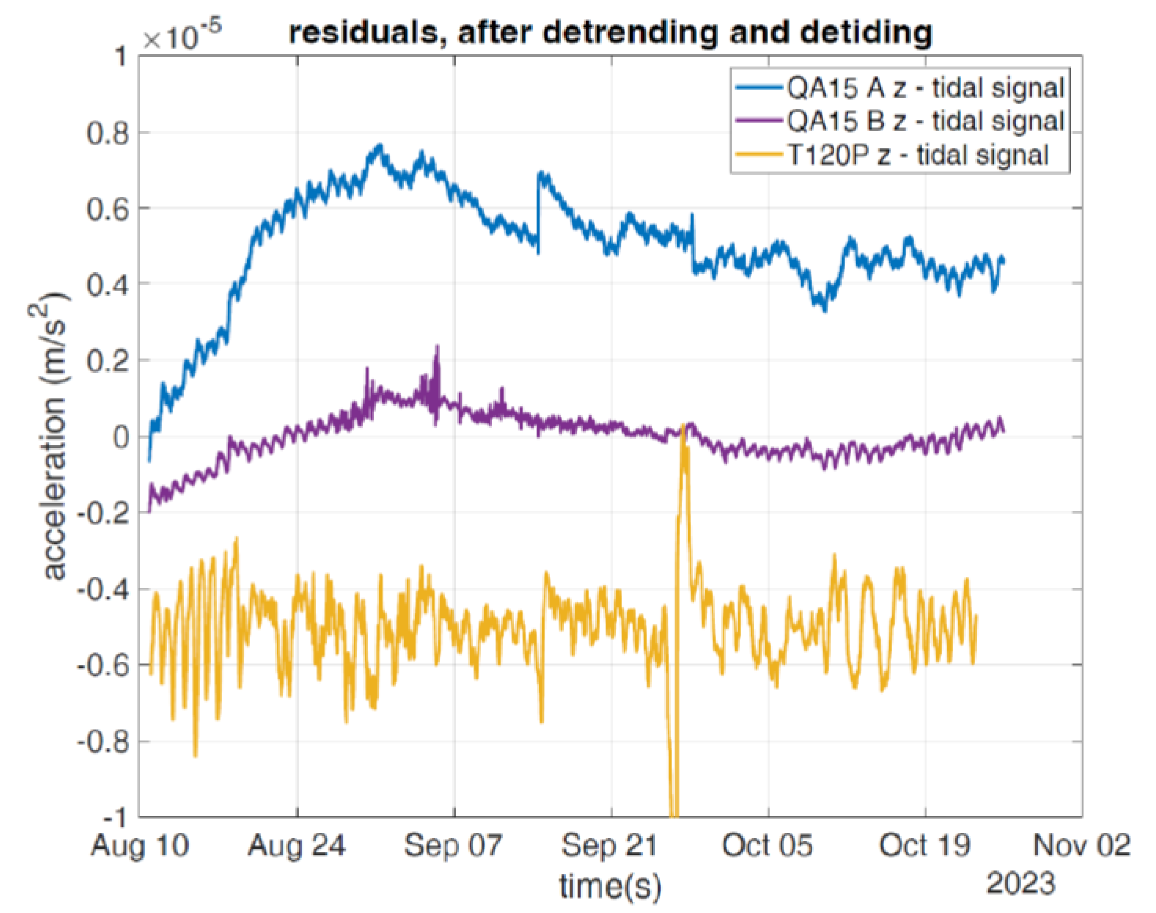
M6.5 EQ in Panama - May 25, 2023



…and long-duration tele-seismic signals with no distortion

University of Washington Vault Tests – Earth Tides



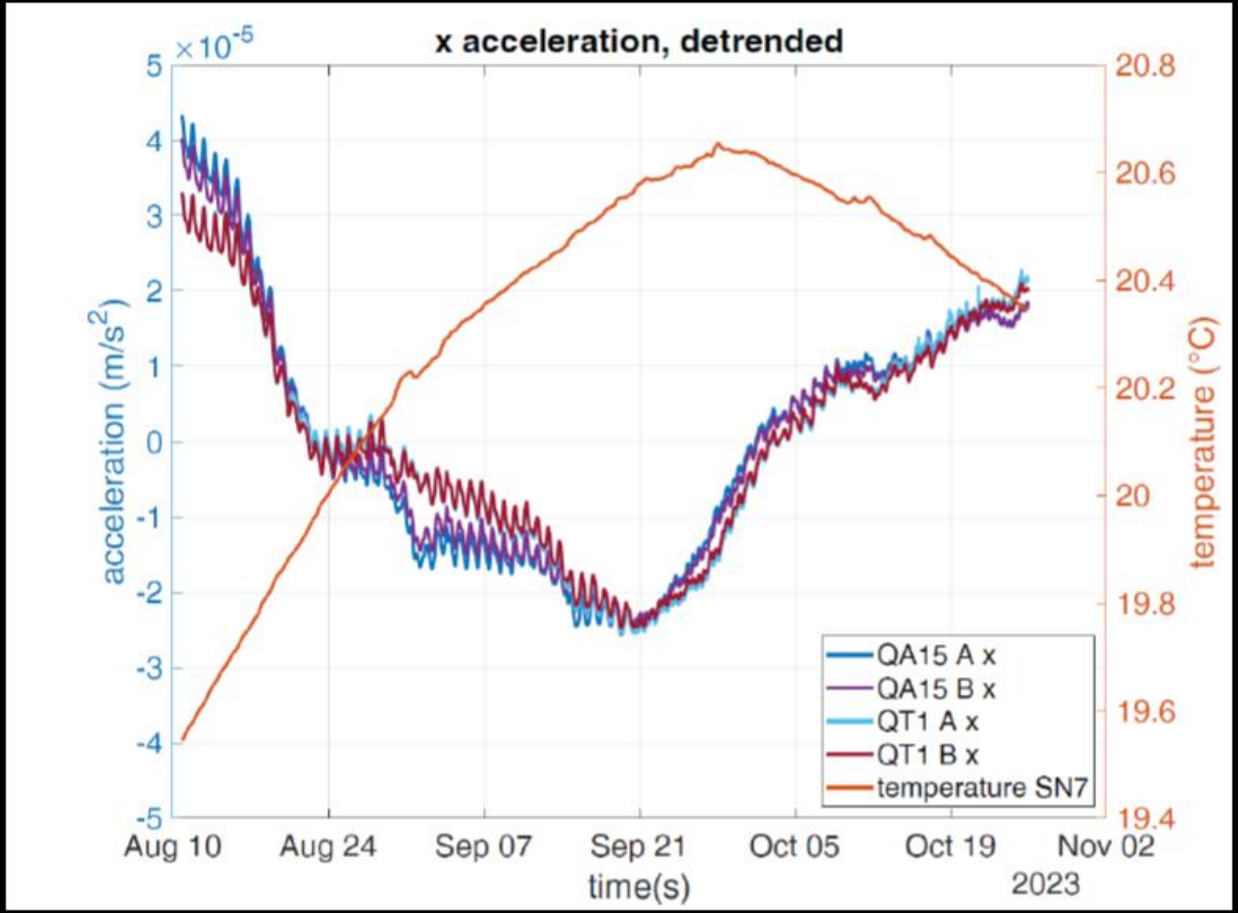


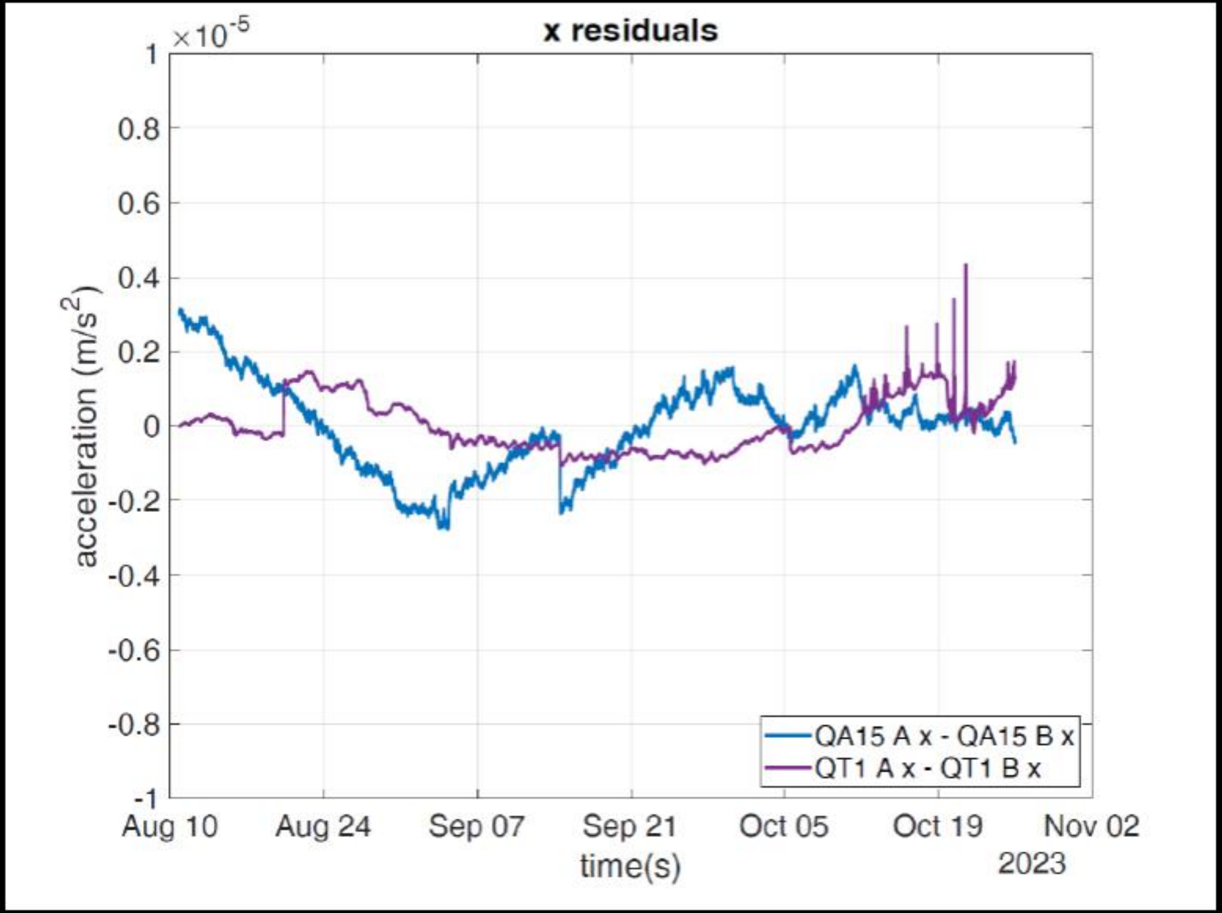
Better resolution of tidal acceleration than a broadband (lower temperature sensitivity & better long-term stability)

UW vault test - Long term tilt

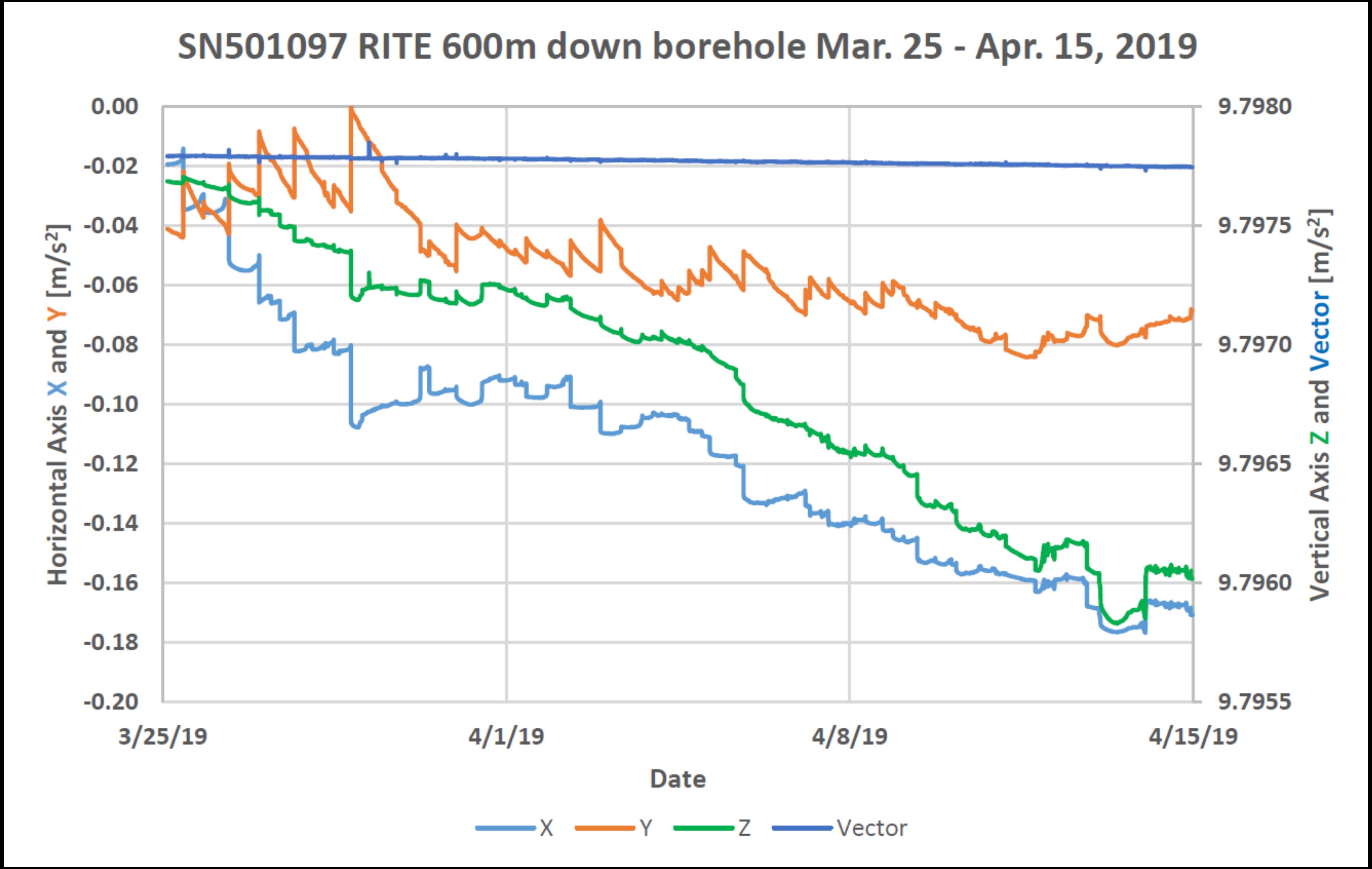
Platform and/or floor was tilting by
many microradians over several months

Tilt agreement good to a fraction
of a microradian between all sensors



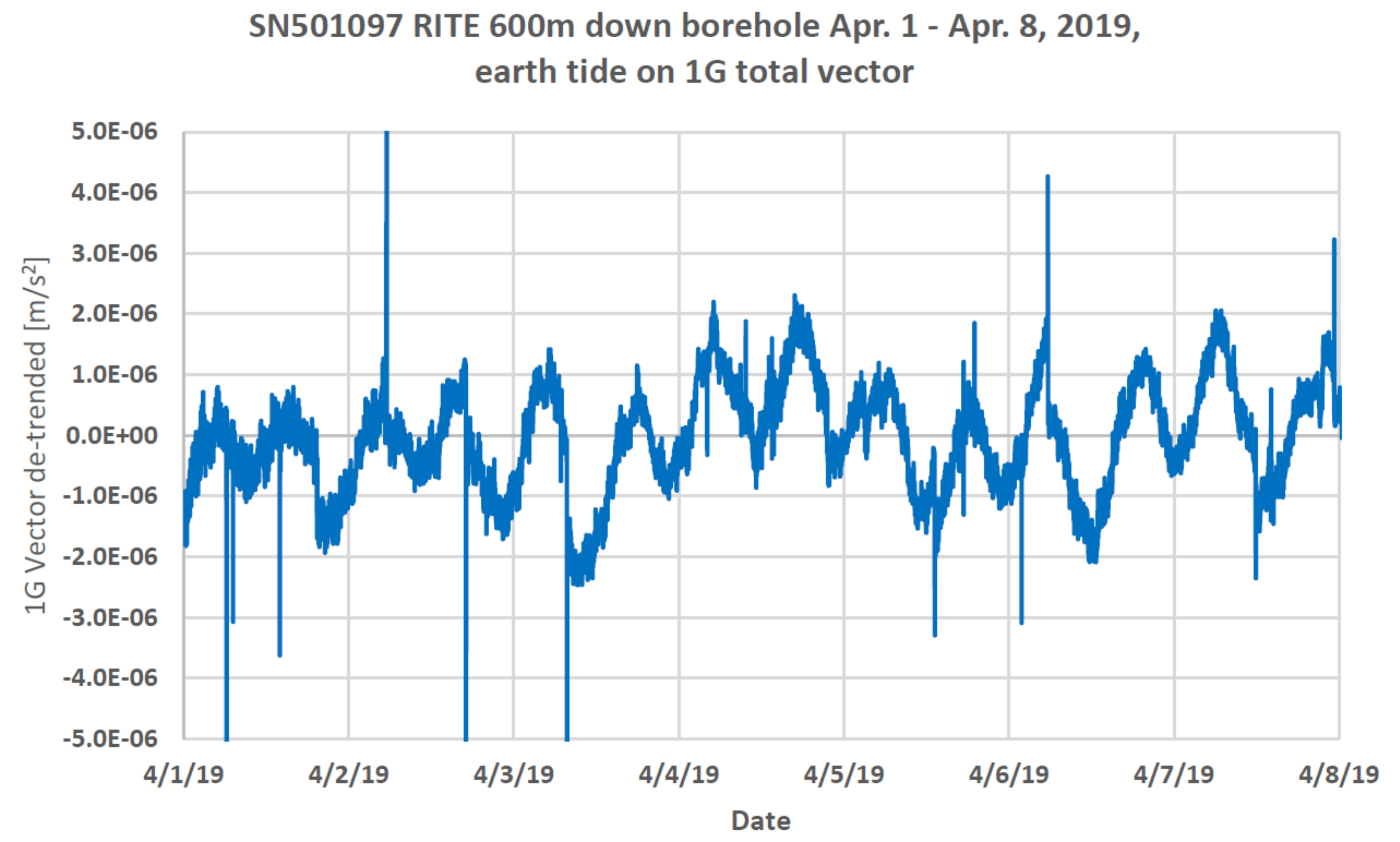


Borehole Data with QA30



Data provided by RITE: Dr. Ziqiu Xue, Dr. Tsutomu Hashimoto

Borehole Data with QA30

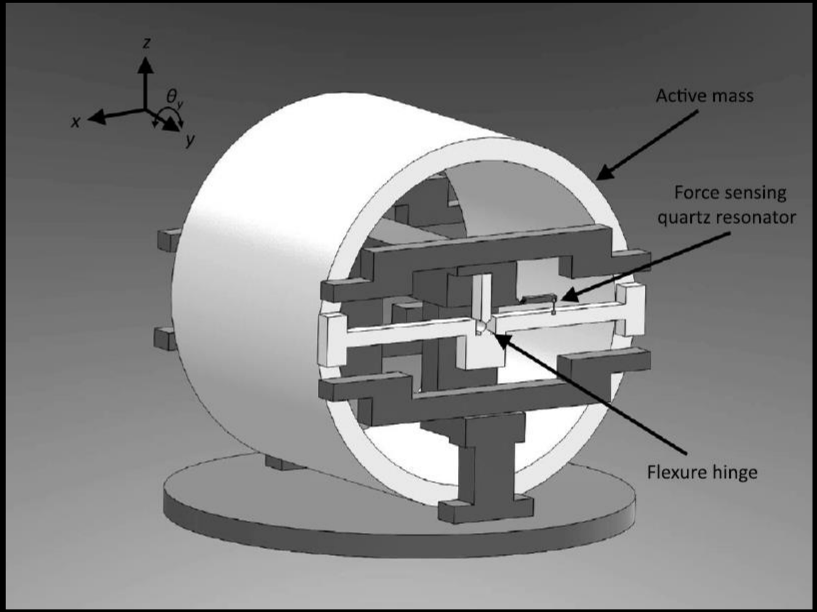


Data provided by RITE: Dr. Ziqiu Xue, Dr. Tsutomu Hashimoto

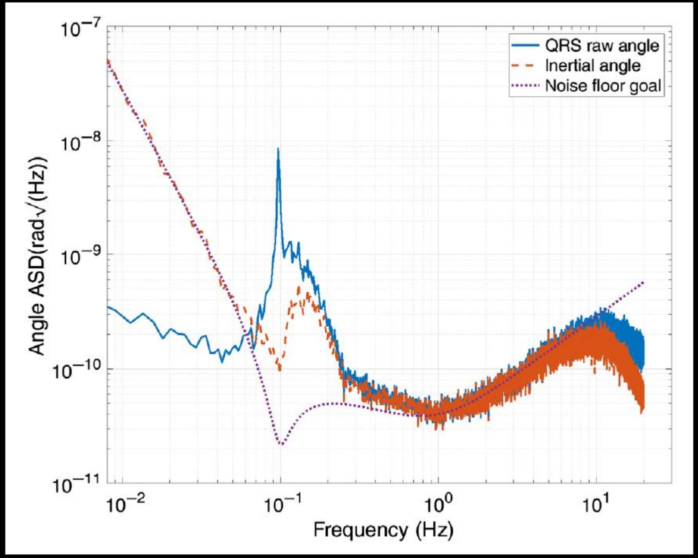
Quartz Rotation Sensor

Quartz Rotation Sensor (QRS)

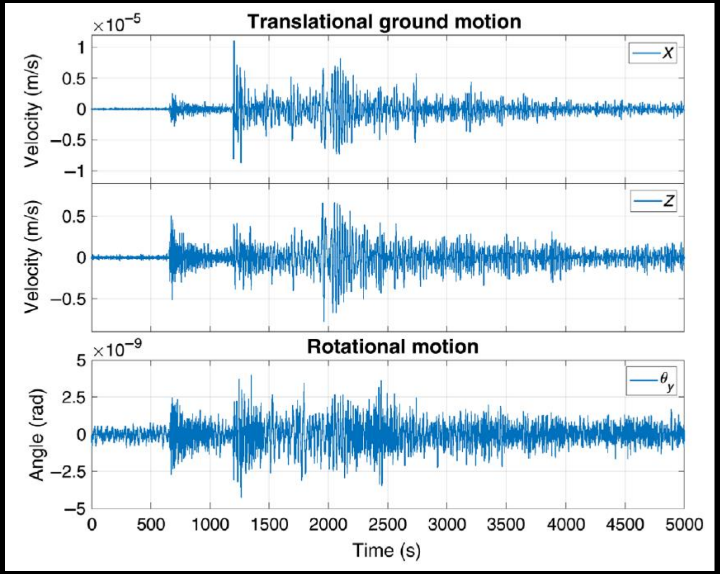
Design



Noise



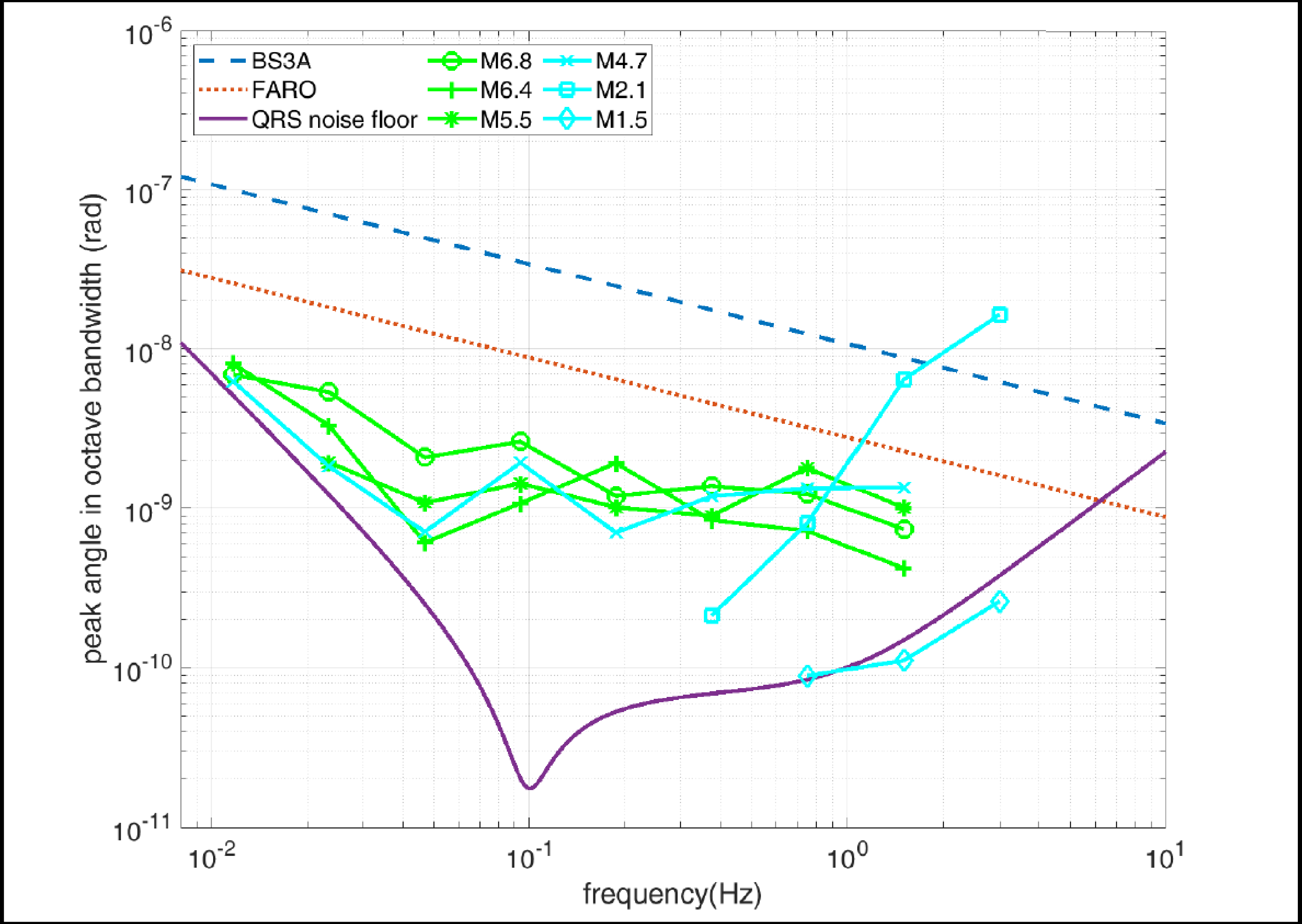
Teleseismic signals



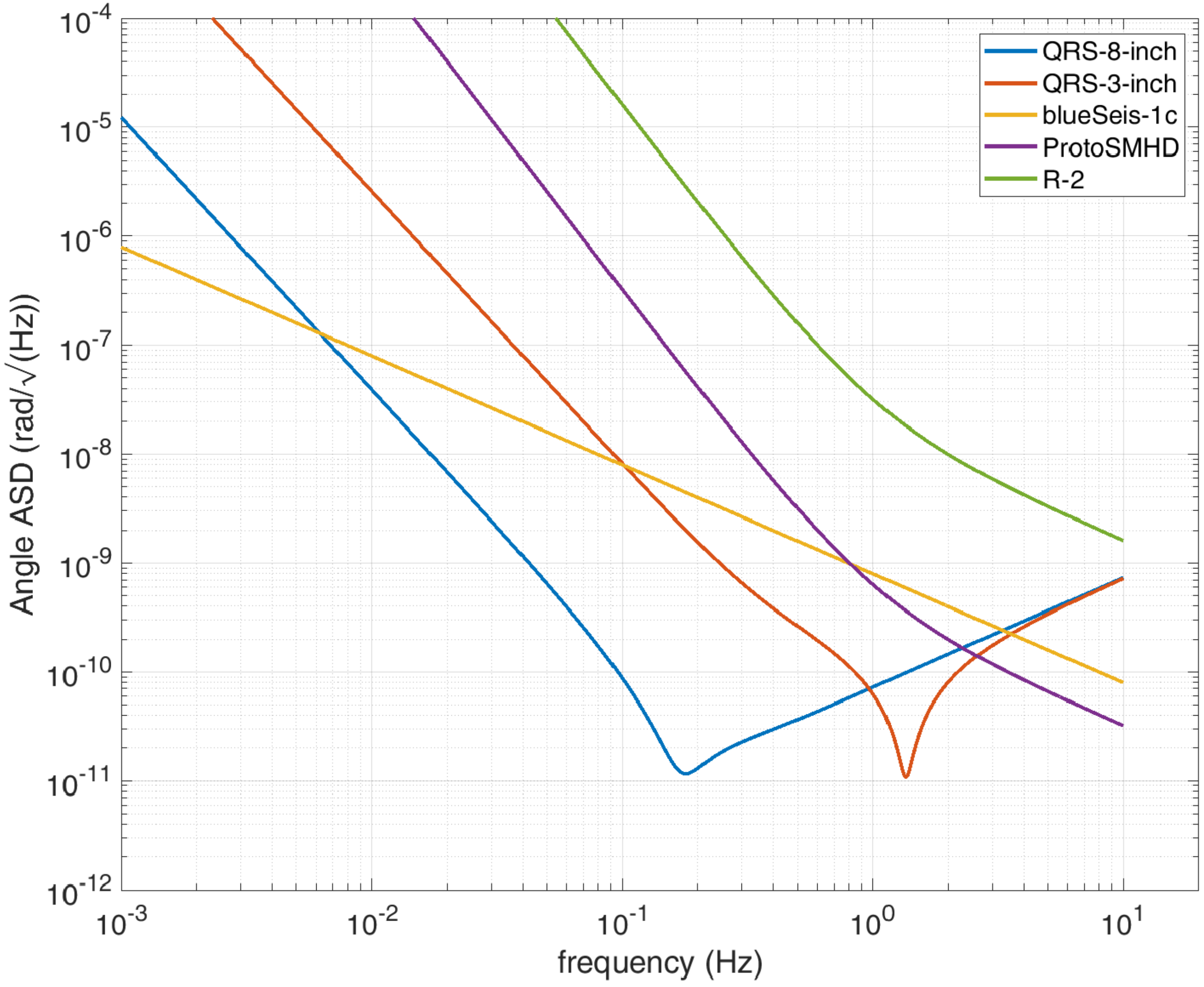
QRS is an angular accelerometer with a long period (~10 s) and a center of mass aligned closely with the pivot, which makes it insensitive to linear acceleration.

Rotational Seismology with a Quartz Rotation Sensor. Seismological Research Letters 2021;; 93 (1): 173–180. doi: https://doi.org/10.1785/0220210171

QRS comparison



Size vs Sensitivity



Summary

Quartz seismic and pressure sensors offer:

- **High sensitivity/Low noise floors**
- **Large dynamic range**
- **High stability – DC sensitivity**
- **Low power**
- **Small size**
- **High accuracy (.008% - 0.05%)**

Paroscientific History

- Founded in 1972 by Jerome Paros after a decade of research on digital force sensors
- Manufactured over 165,000 pressure and seismic sensors for the last 52 years in our facility in Redmond, WA.
- Worldwide reputation for high-quality, high-performance pressure instruments
- Technology applied to many different market areas including Metrology, Aerospace, Meteorology, Physical Oceanography, Tsunami sensing, etc.