LIGO

# Precision Mechanical Rotation Sensors for Terrestrial Gravitational Wave Observatories

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Final Exam

May 2020

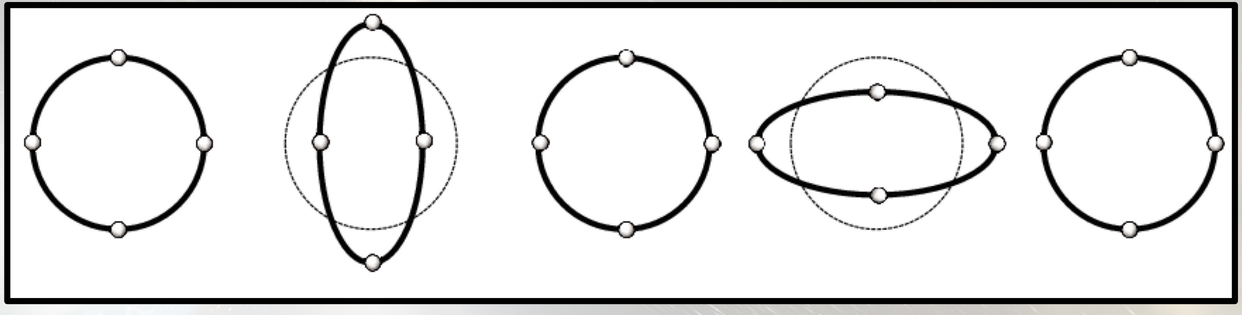
# Outline

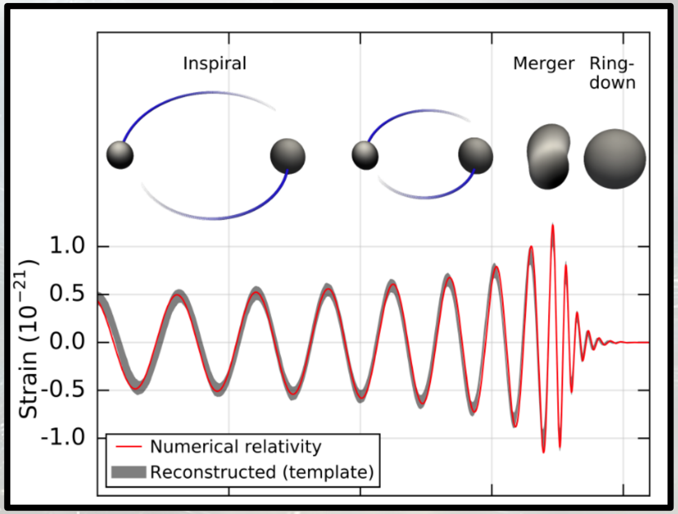
- LIGO
  - LIGO overview
  - aLIGO seismic isolation
- Beam Rotation Sensor (BRS)
  - Tilt contamination
  - BRS overview
  - Installation
  - Duty cycle improvements
- Compact Beam Rotation Sensor (cBRS)
  - Current rotational problems
  - cBRS overview
  - Projected improvement

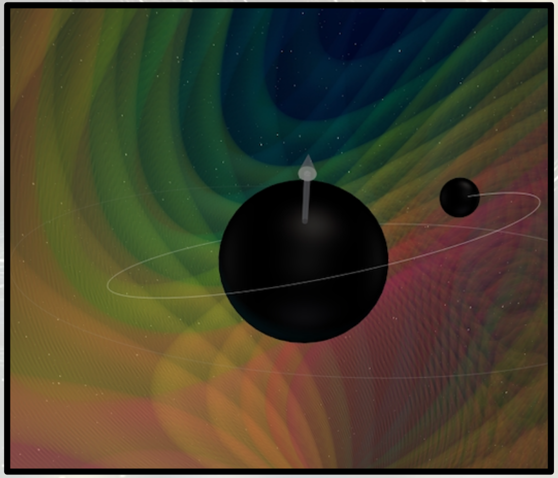
# LIGO
# Laser Interferometer Gravitational-Wave Observatory

# Gravitational Waves

- Ripples in space-time
- Emitted by cataclysmic astrophysical events
- First direct detection by LIGO in 2015
- Only source seen so far has been compact binary mergers

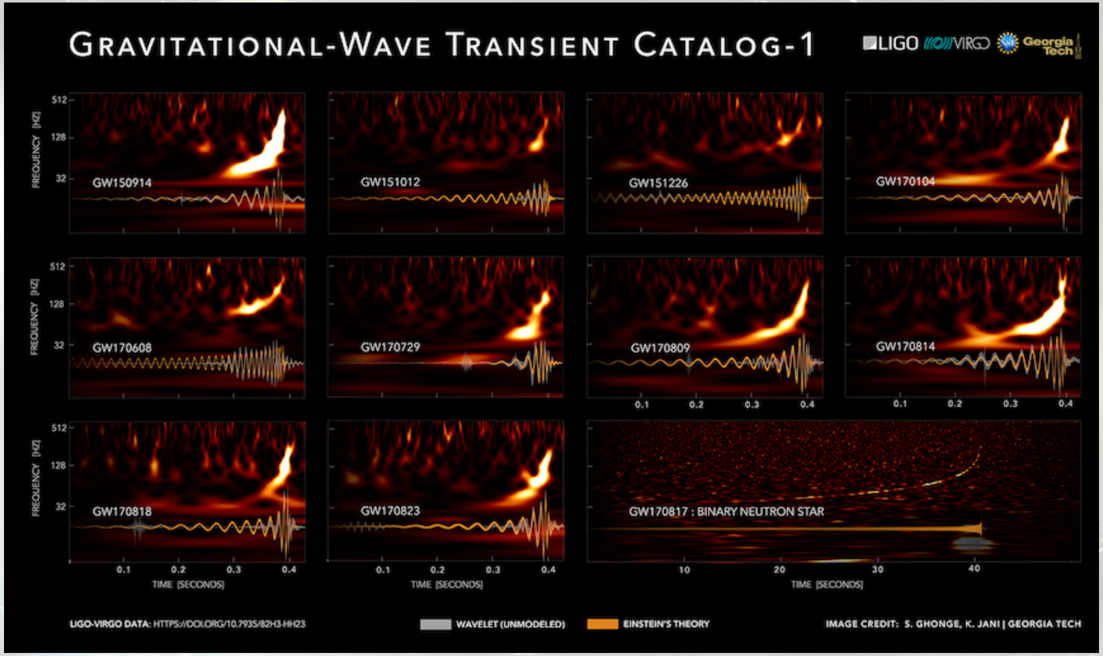




# Gravitational Waves

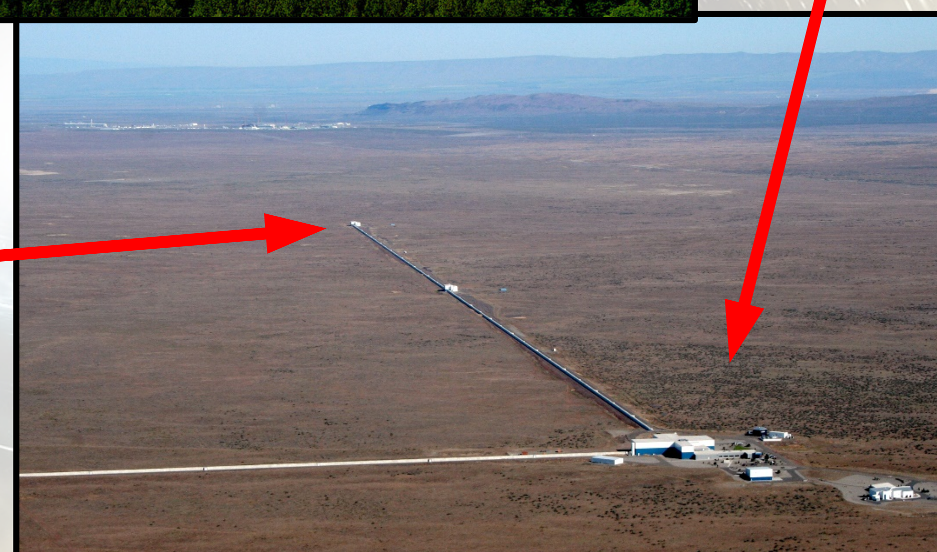
- 13 confirmed detections (2 BNS, 11 BBH)
- 54 significant candidates
- Led to many important insights
  - Origin of heavy elements
  - Neutron star matter
  - Black hole populations
  - Modifications of general relativity
  - Expansion of the universe (Hubble constant)



# LIGO

- Interferometric gravitational wave observatory
- Two observatories: Livingston, LA Hanford, WA

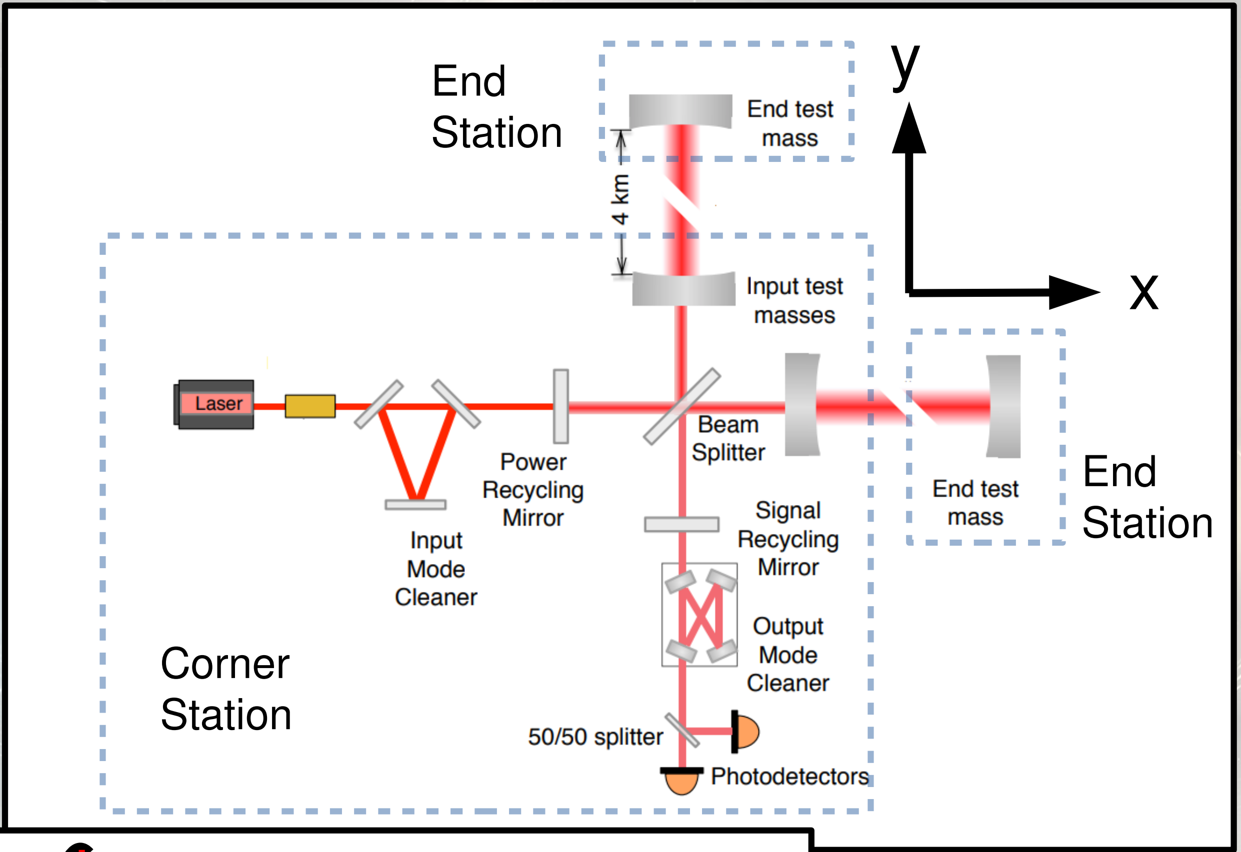
Corner Station

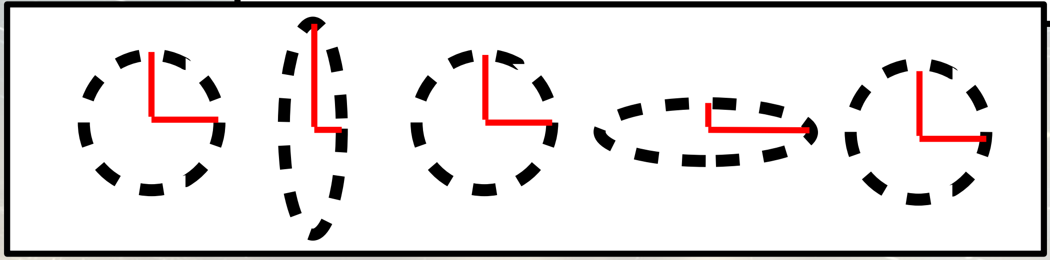


End Station

# LIGO

- Dual-recycled Fabry-Perot Michelson Interferometer
- Measures differential strain between the two arms
- “Locked” = optics held in optimal alignment

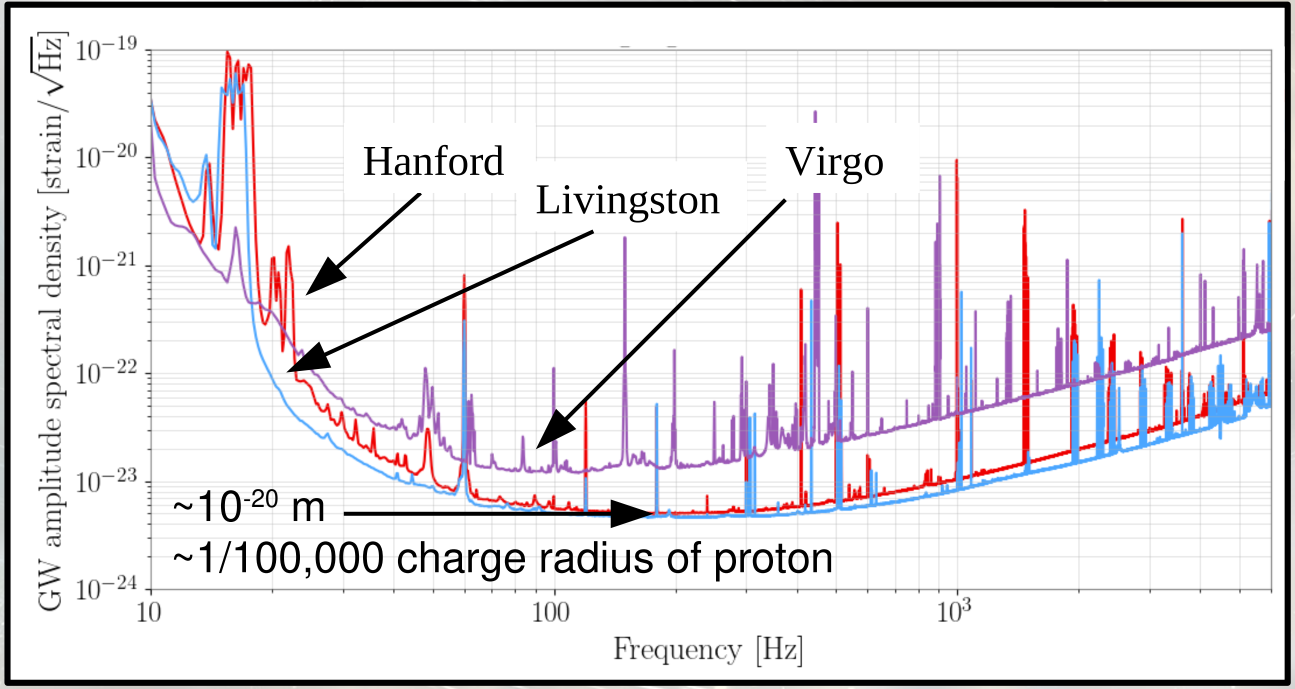


# LIGO

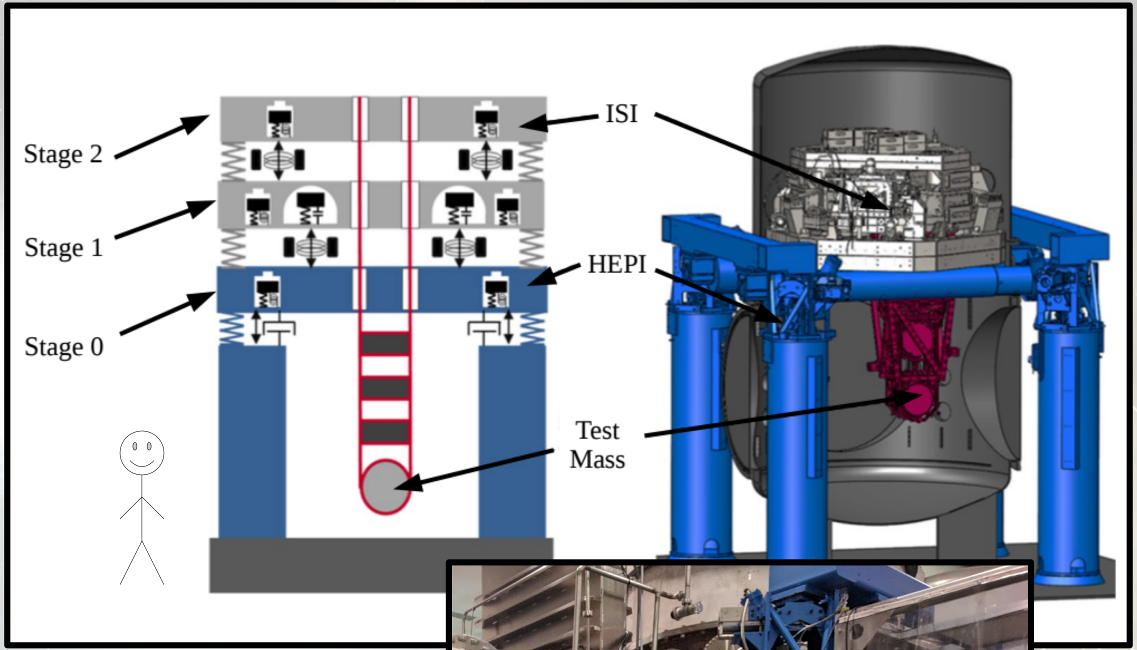
- Measures differential strain between the two arms
- Sensitive to GW from ~20 Hz- 6 kHz
- Limited by quantum mechanics above ~200 Hz
- Control noise dominates below ~40 Hz

strain $h = \frac{\Delta L}{L}$ length (4 km)



# LIGO Seismic Isolation

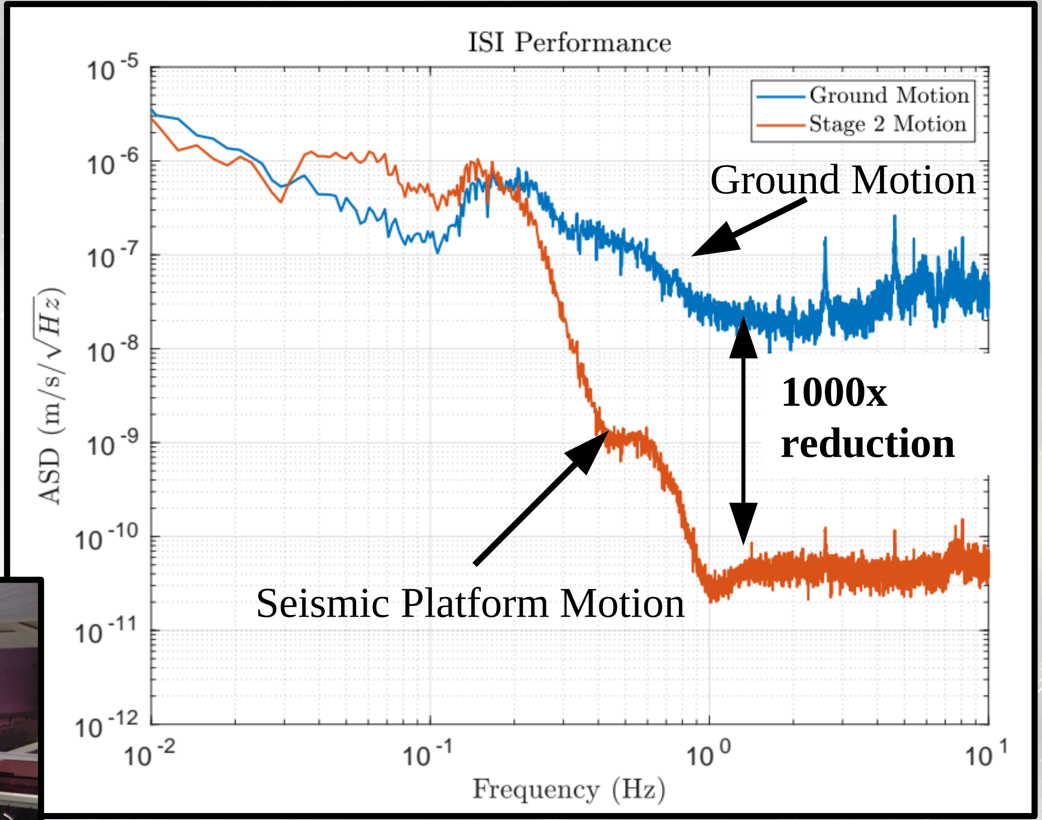
- Multi-layer seismic isolation
- First layer (blue): hydraulic external pre-isolation (HEPI)
- Second layer (gray): internal seismic isolation (ISI), a two stage active isolation
- Third layer (red): quadruple pendulum, four stage passive isolation

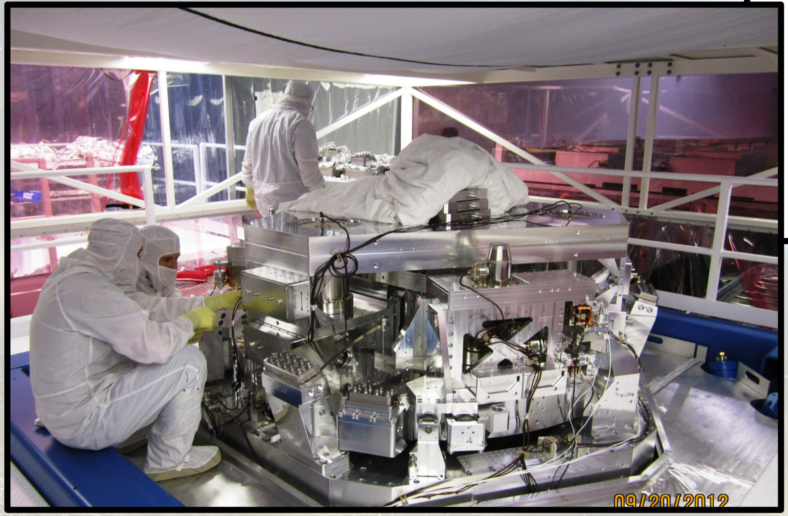



LIGO

# Internal Seismic Isolation

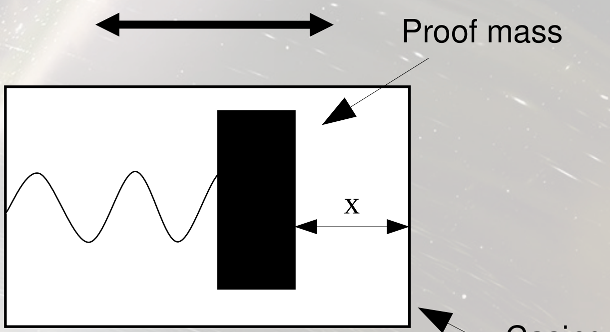
- Dual stage isolation
- Isolates all 6 degrees of freedom
- Suspended tables driven with magnetic actuators

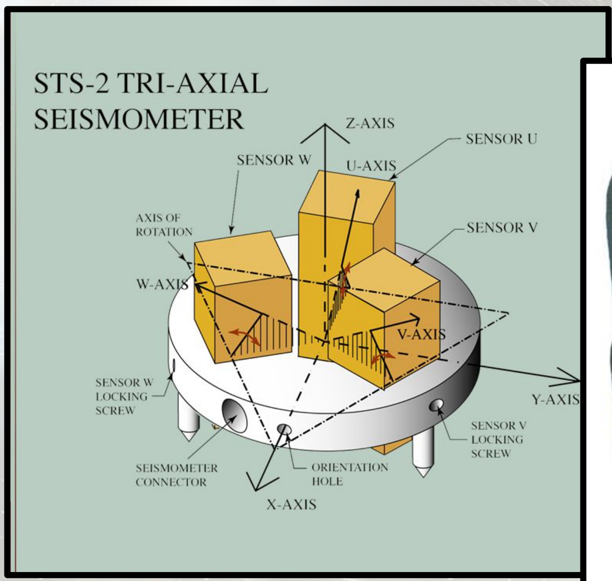


# Seismometer Basics

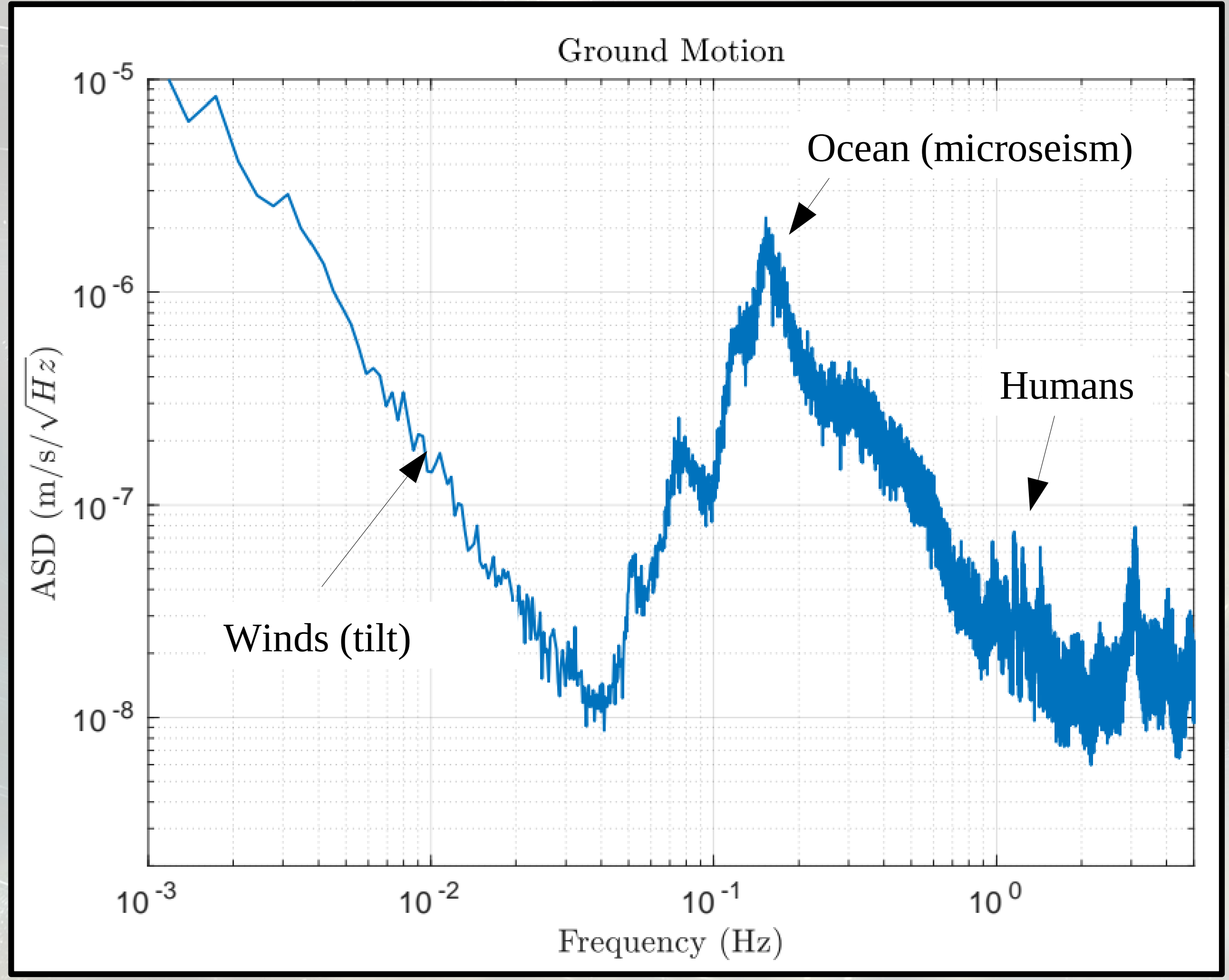
- Seismometers are simple low frequency spring mass systems
- Above the resonant frequency (~8 mHz) the casing moves while the mass stays stationary
- Measurement noise rises significantly below the resonance




# Seismic Spectra

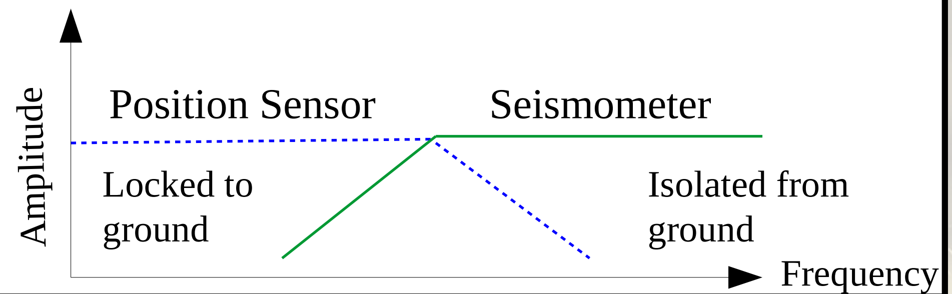
- Seismic motion is naturally excited across all frequencies
- Ocean driven peaks are largest ambient feature (“microseism”)
- Low frequency dominate by tilt contamination

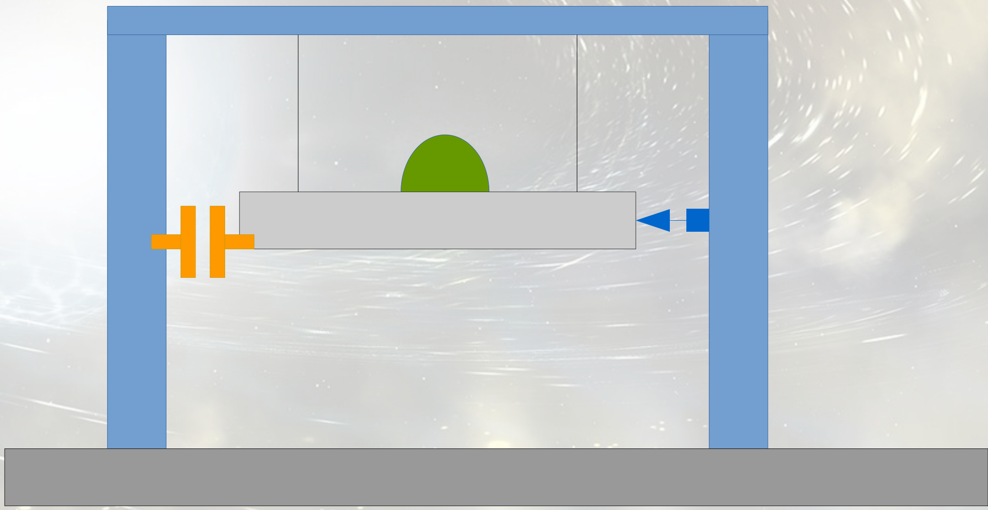


# Simple Seismic Isolation

- Isolate the platform by driving seismometer signal to zero with feedback
- Real seismometers have low frequency noise
- “Blend” a position sensor (low frequency) and the seismometer (high frequency) together
- Position sensor measures distance between ground and platform

$$x_{control} = F_{HP} \cdot x_{platform} + F_{LP} \cdot (x_{platform} - x_{ground})$$

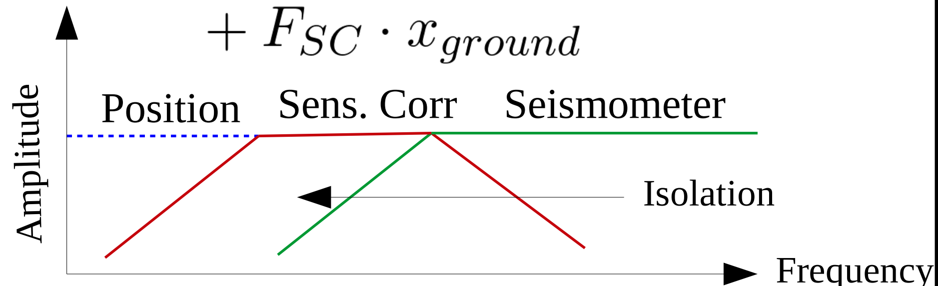


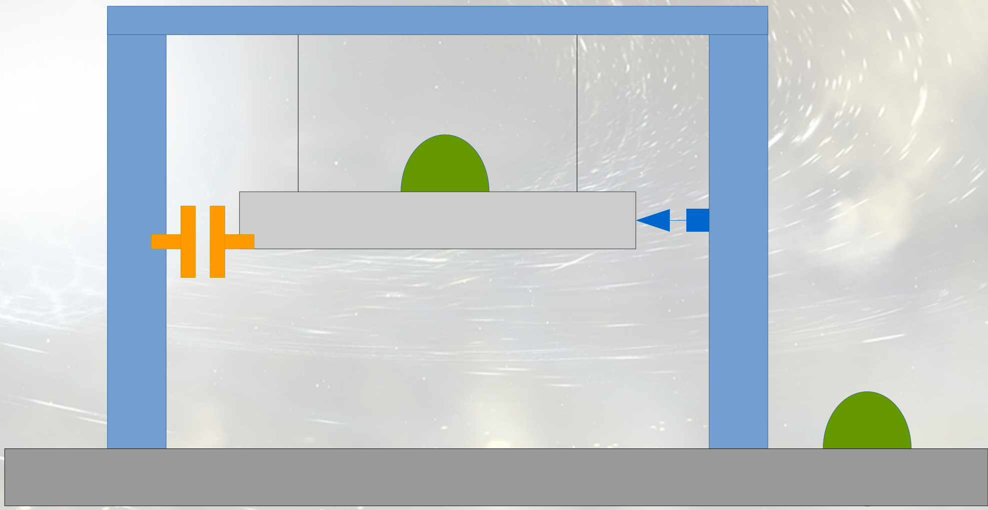



# Sensor Correction

- No isolation where position sensor is used
- Push this frequency lower by adding a ground seismometer
- Corrects for the ground contribution to the position sensor (sensor correction)

$$x_{control} = F_{HP} \cdot x_{platform} + F_{LP} \cdot (x_{platform} - x_{ground}) + F_{SC} \cdot x_{ground}$$



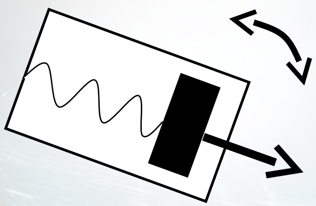
# BRS
# Beam Rotation Sensor

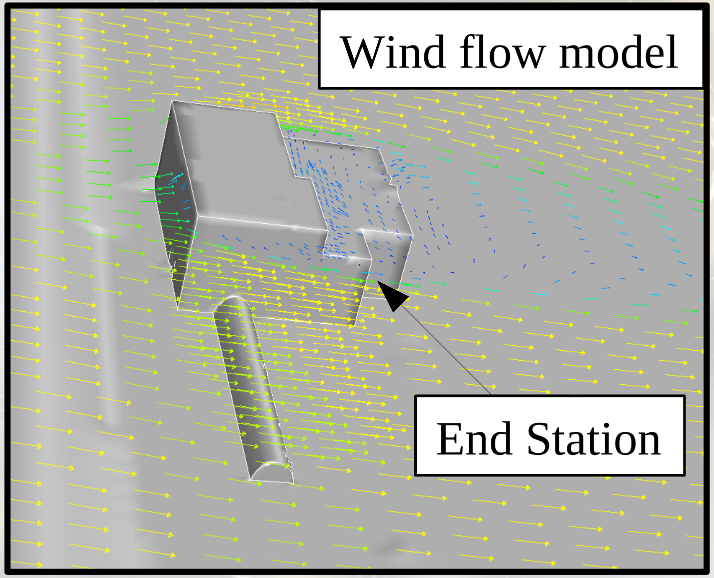
# Tilt Contamination

- If a seismometer is tilted then the mass feels a force due to gravity
- Adds spurious signal which dominates at low frequencies
- Deformation of the building's concrete slab is the main source of tilts at the observatories

$$a = \ddot{x} = g \cdot sin(\theta)$$

$$x_{seis}(\omega) = x_{ground}(\omega) - \frac{g}{\omega^2}\theta(\omega)$$

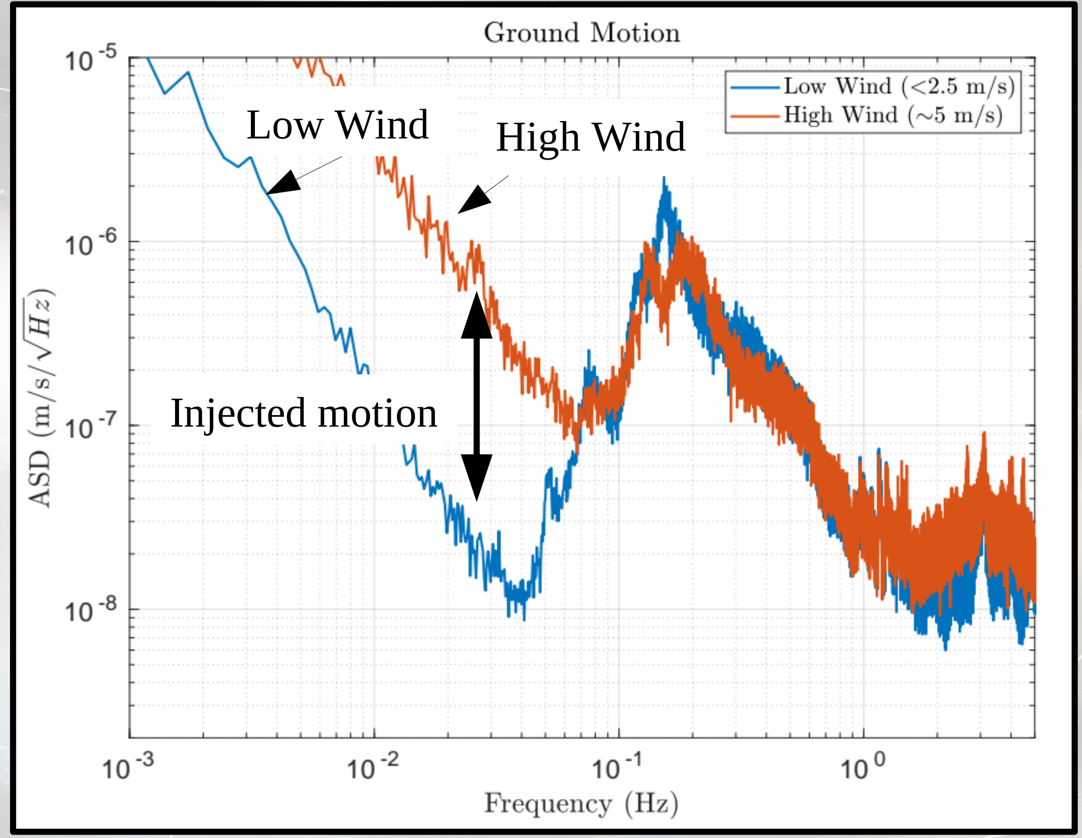





Modeling done by Elyssa Hofgard at Stanford

# Tilt Contamination

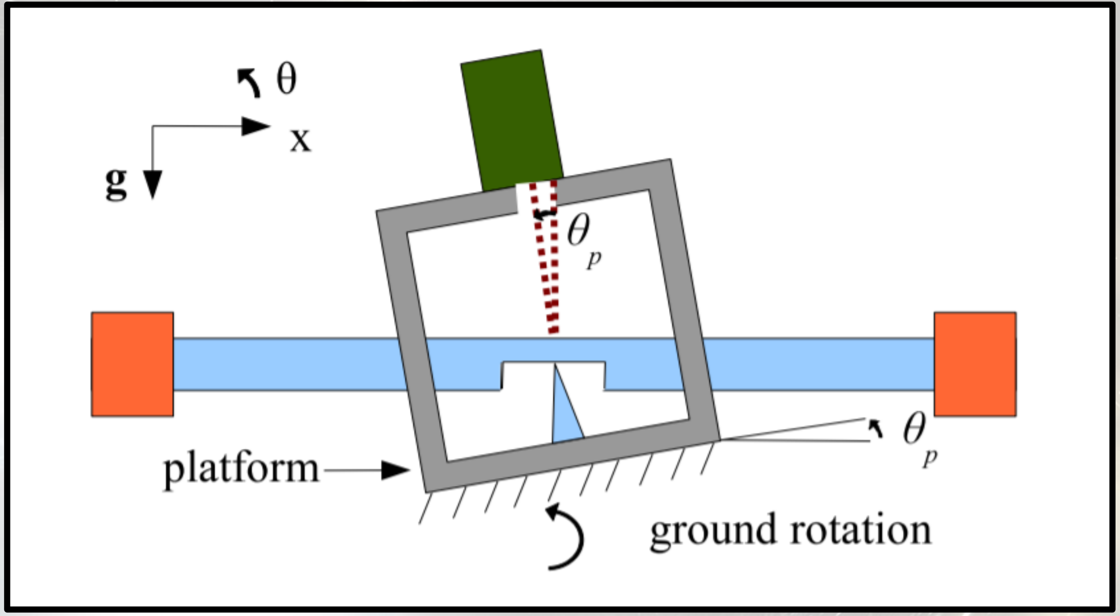
- If wind dominates then we inject motion onto platform
- Limits our ability to isolate at low frequency
- Solve by measuring tilt and subtracting




$$x_{seis}(\omega) = x_{ground}(\omega) - \frac{g}{\omega^2}\theta_{wind}(\omega) + \frac{g}{\omega^2}\theta_{meas}(\omega)$$

# Beam Rotation Sensor

- Same concept as a seismometer but with rotations
- Angle between casing and beam readout by autocollimator
- Above resonance response to displacement is proportional to δ
- Beam suspended close to center-of-mass

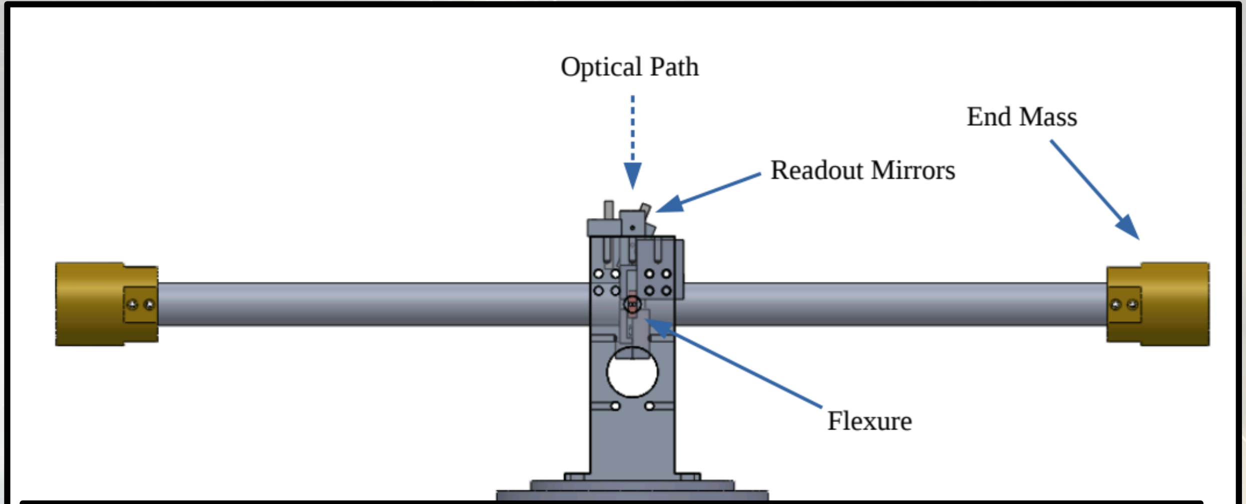


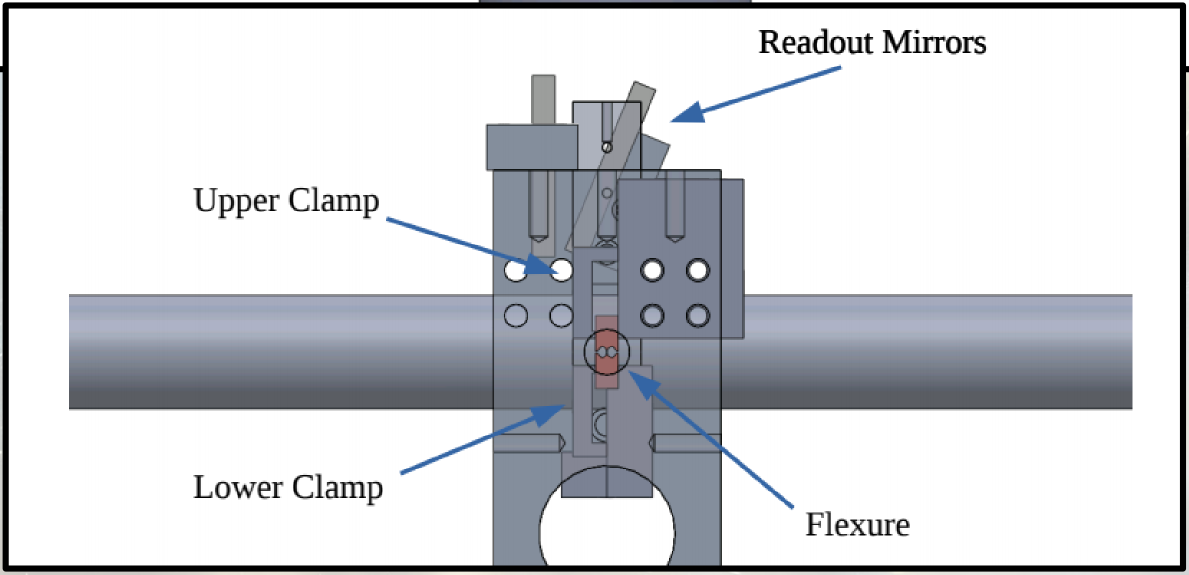

$$\text{response to displacement} = \frac{M\delta}{I}$$

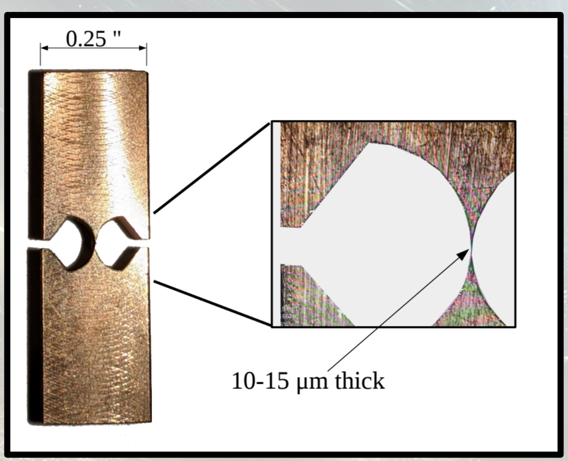
$$\delta = \text{vertical distance between center-of-mass and pivot point}$$

# Beam Rotation Sensor

- 1-m long beam hung from 10-15 μm-thick flexures with 3-8 mHz resonance
- δ as low as 0.5 μm corresponding to 1 μrad/m above 10 mHz

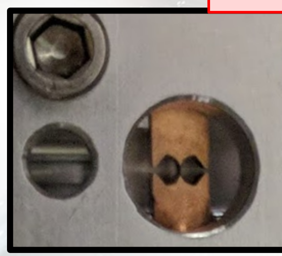


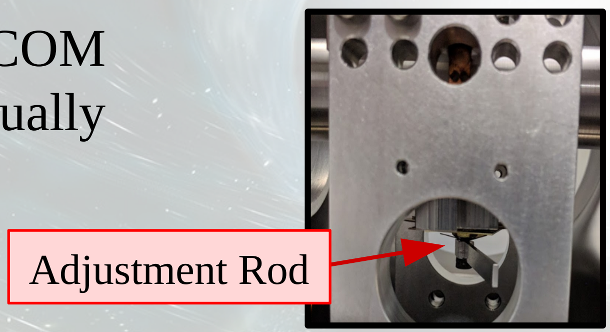



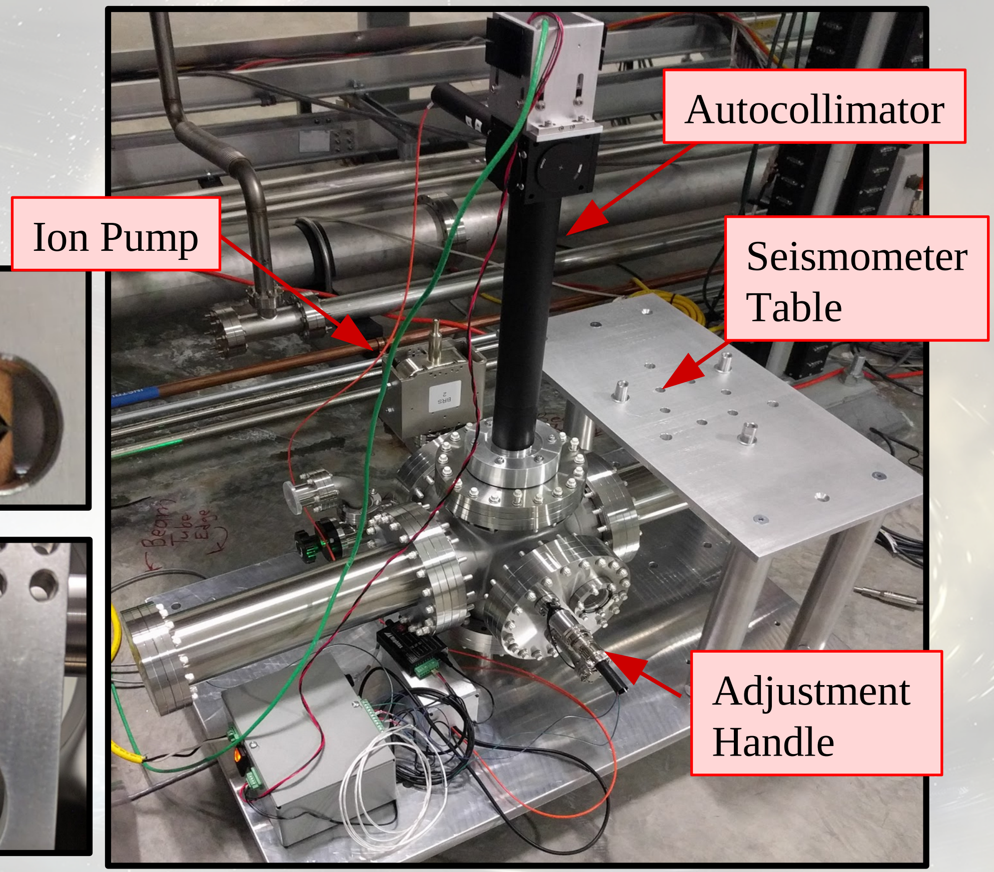



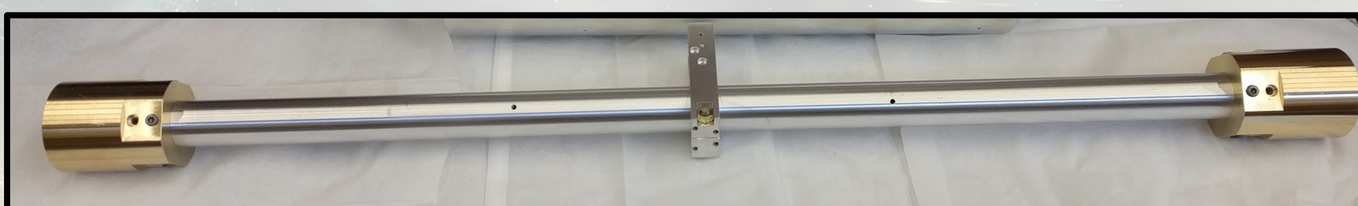
# Beam Rotation Sensor

- ~ 0.3 nrad/√Hz sensitivity at 0.1 Hz
- Held at high vacuum
- Surrounded by thermal insulation
- Horizontal COM adjusted manually



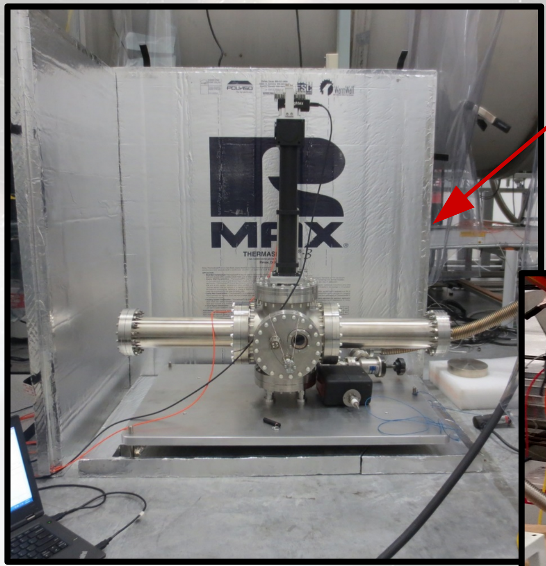


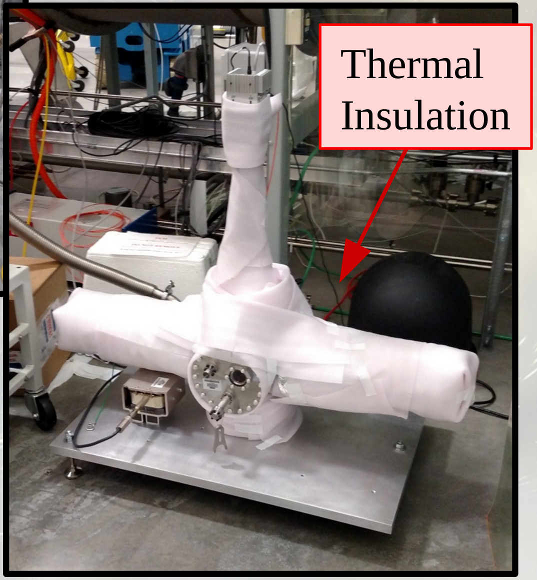



# Hanford BRSs

- Two BRSs installed at Hanford between the first (O1) and second (O2) observing runs (April 2016)
- One at each end-station correcting the translation along the direction of the interferometer arm
- Low tilt location was found at the corner station



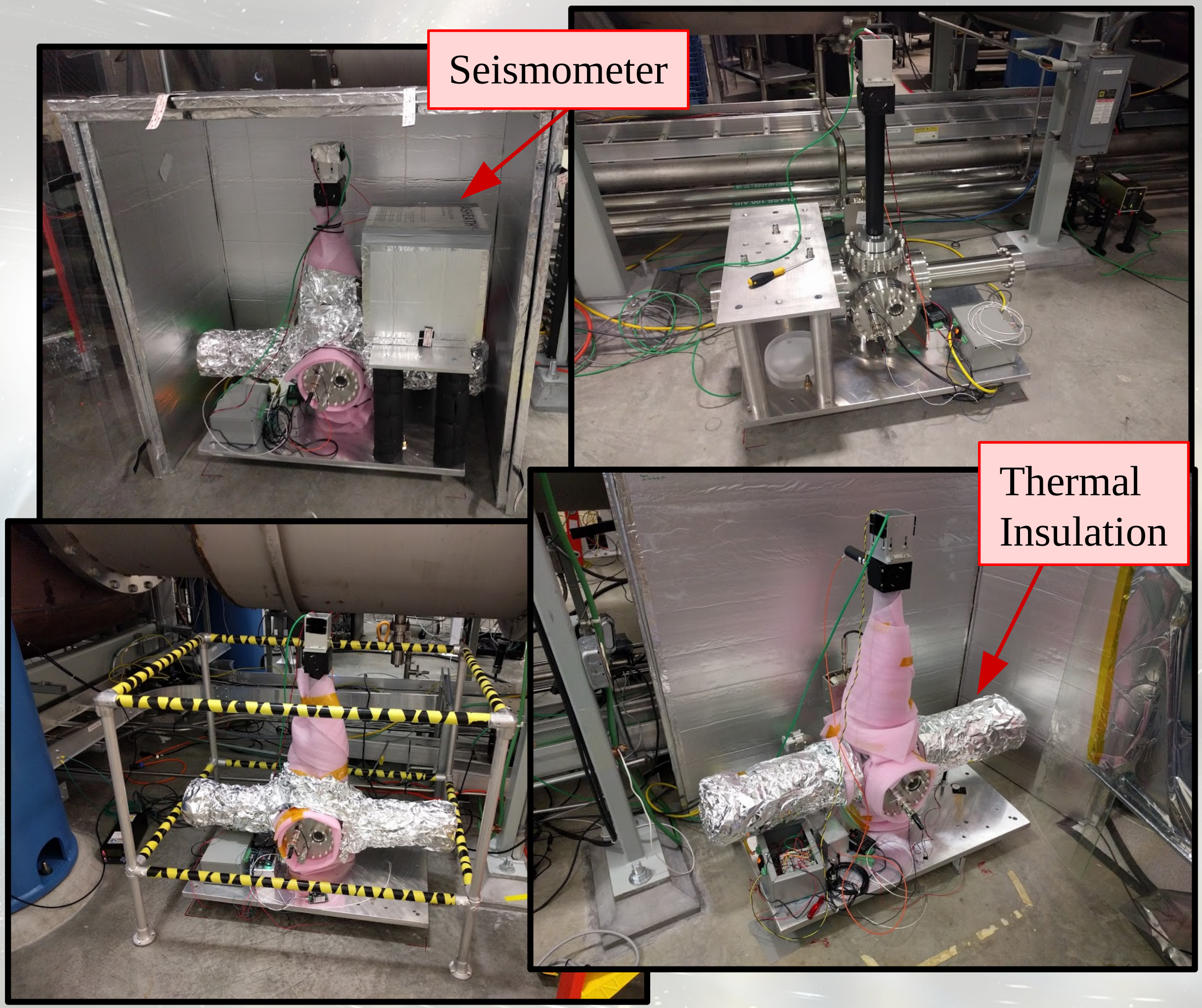
Thermal Insulation Box



Thermal Insulation

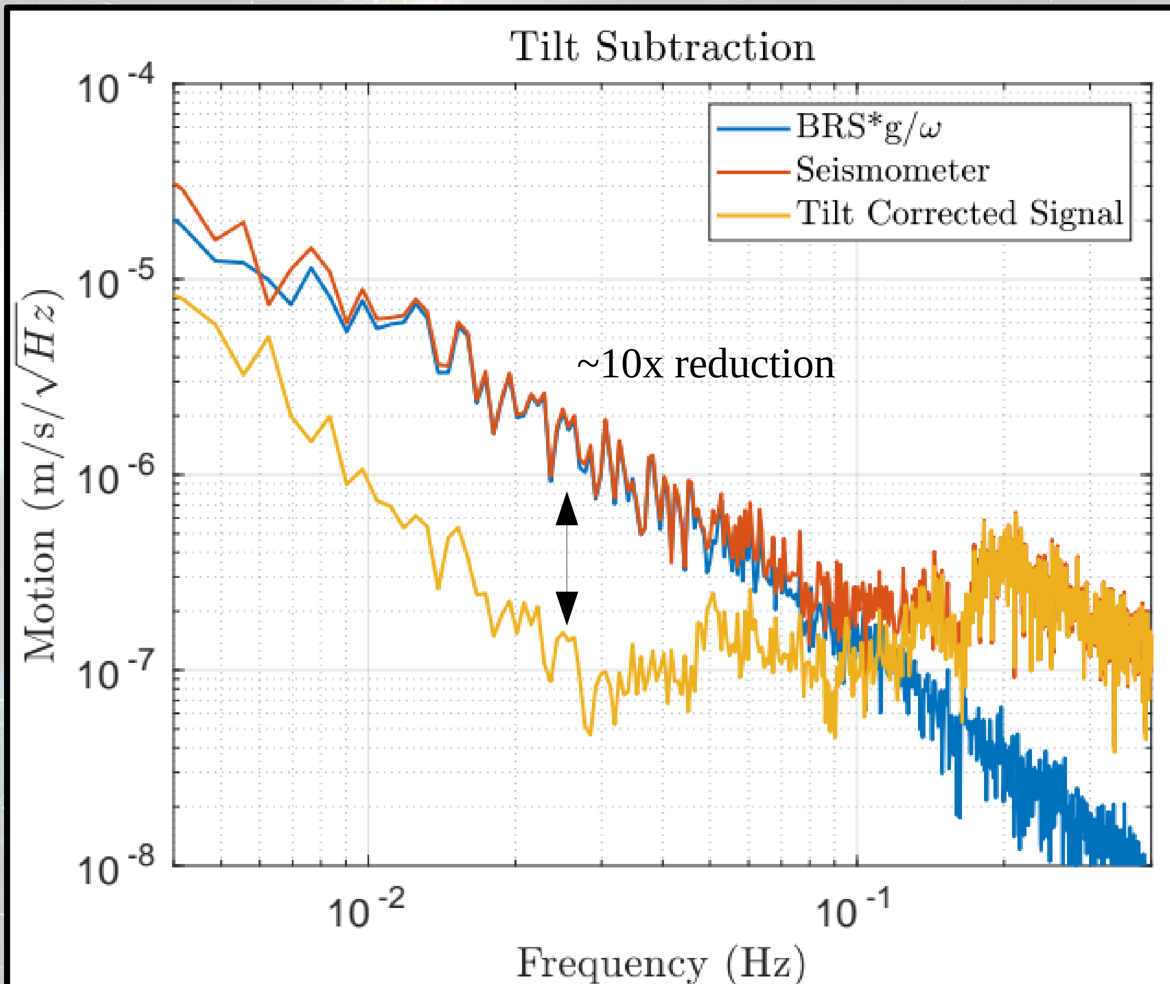
# Livingston BRSs

- Since the Hanford devices worked well Livingston also wanted BRSs
- No low tilt location so we needed four, one at each end and two at corner
- Installed between O2 and O3 (Feb – May 2018)



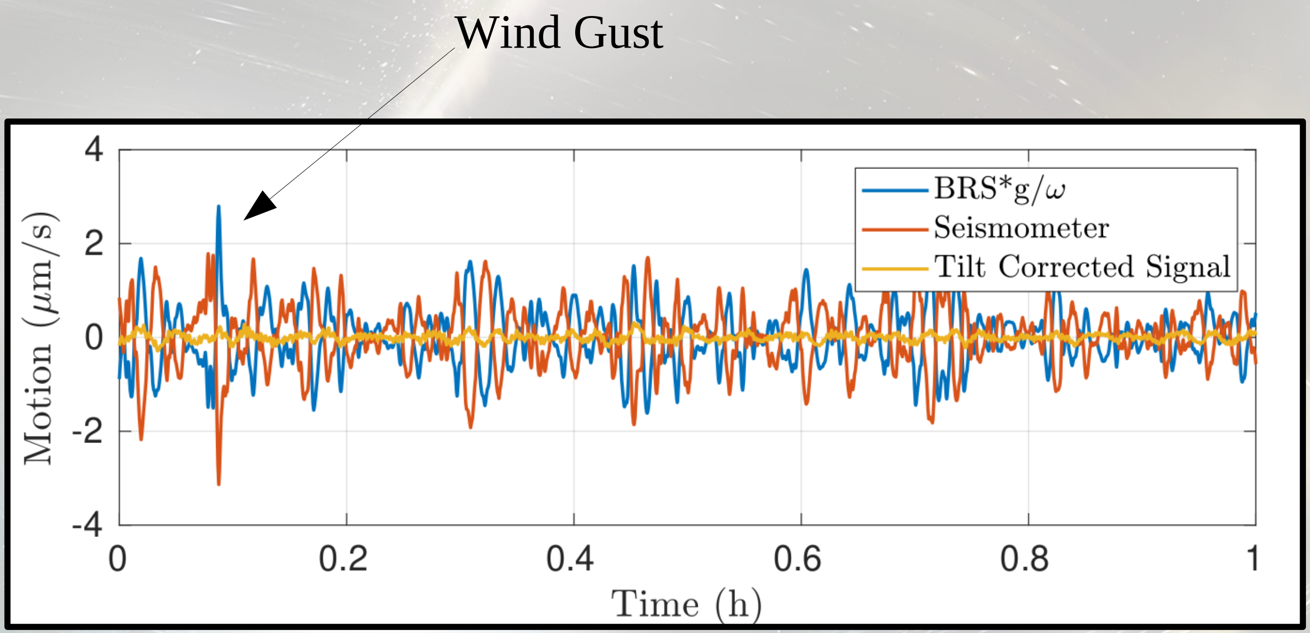
# Tilt Subtraction Results

- Subtracted signal used for sensor correction
- >60 mHz is dominated by microseism
- Subtraction between 8 mHz and 60 mHz
- Up to a factor of ~10 reduction



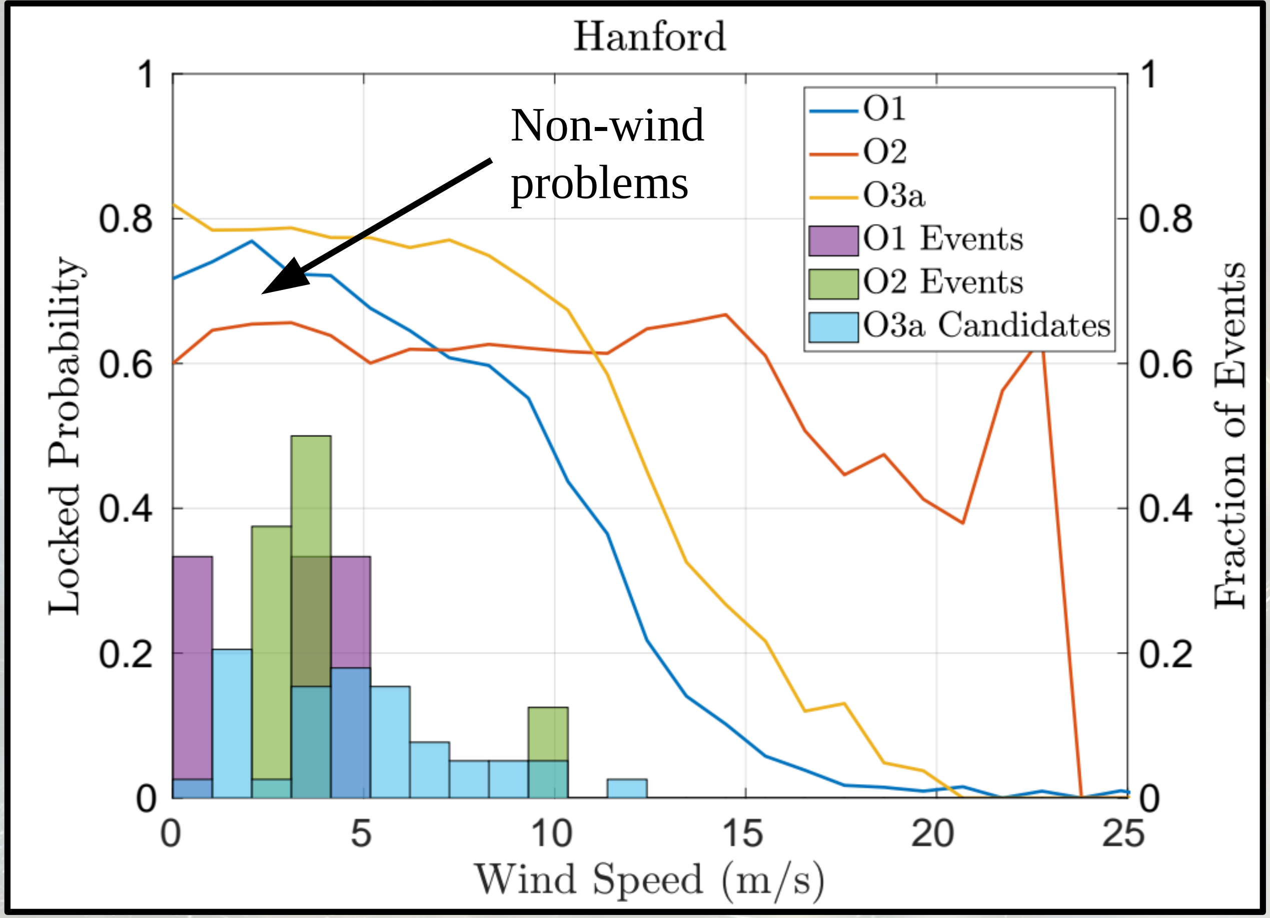
# Tilt Subtraction Results

- Tilt subtraction removes transients due to wind gusts
- Gusts can knock the interferometer out of lock
- Subtracted signal used for sensor correction



# Duty Cycle Improvements

- Between O1 and O2: +13.1 observing days per year
- Low wind speed performance affected by other problems (earthquakes, maintenance, etc)



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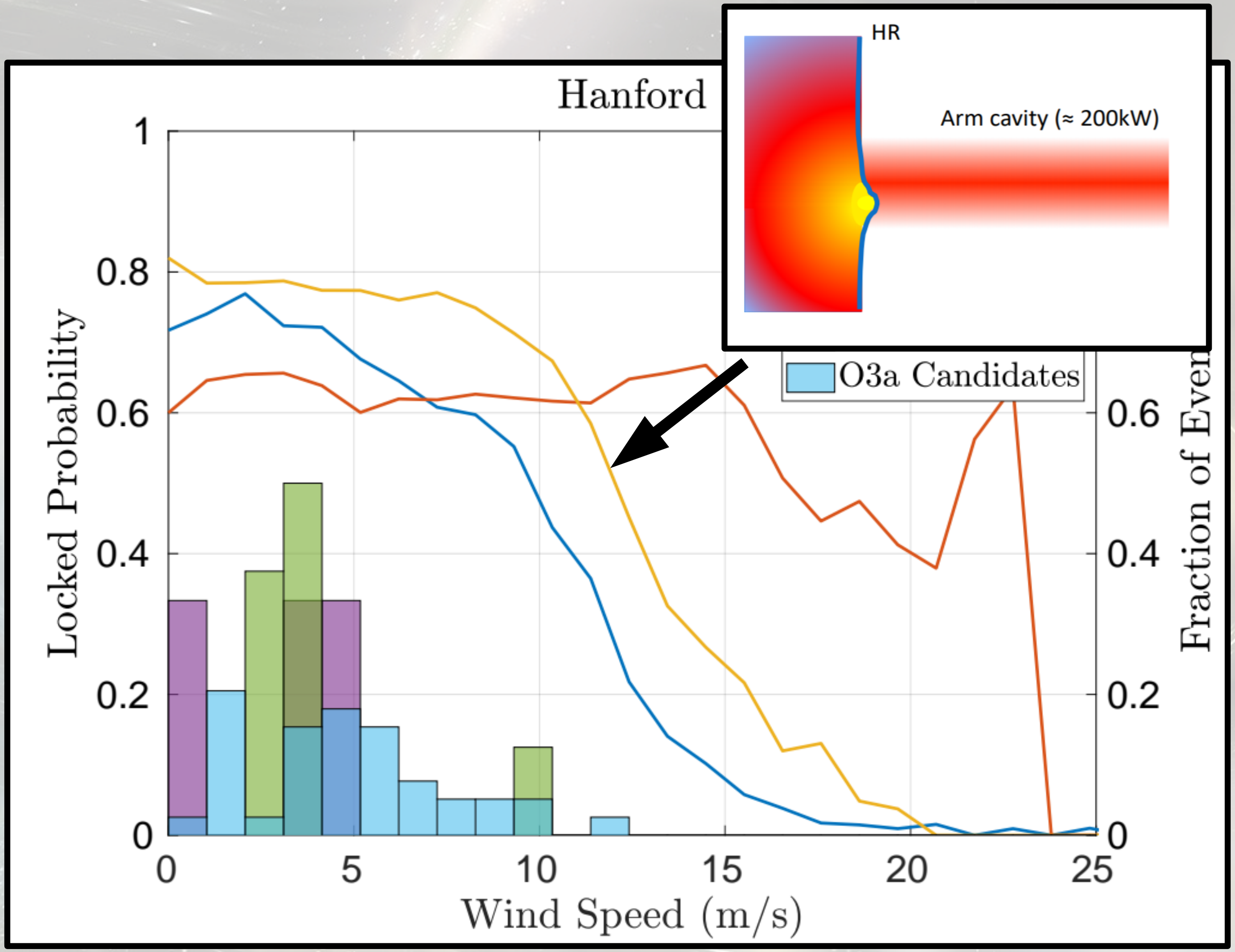
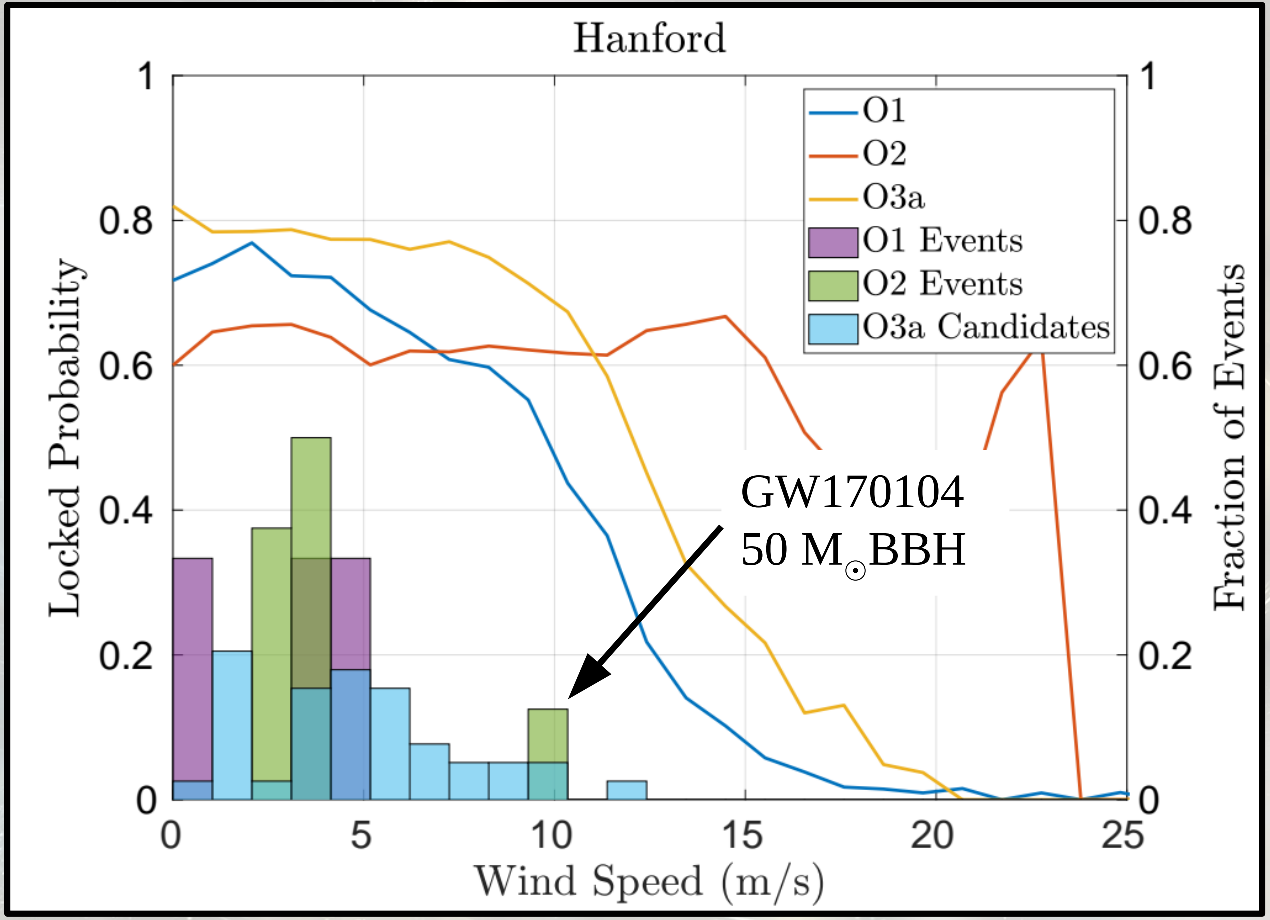
# Duty Cycle Improvements

- Beam spot was off center during O3a to avoid point absorbers
- Point absorbers deform mirror and degrade performance
- Off center beam spot couples makes the system more susceptible to isolation performance



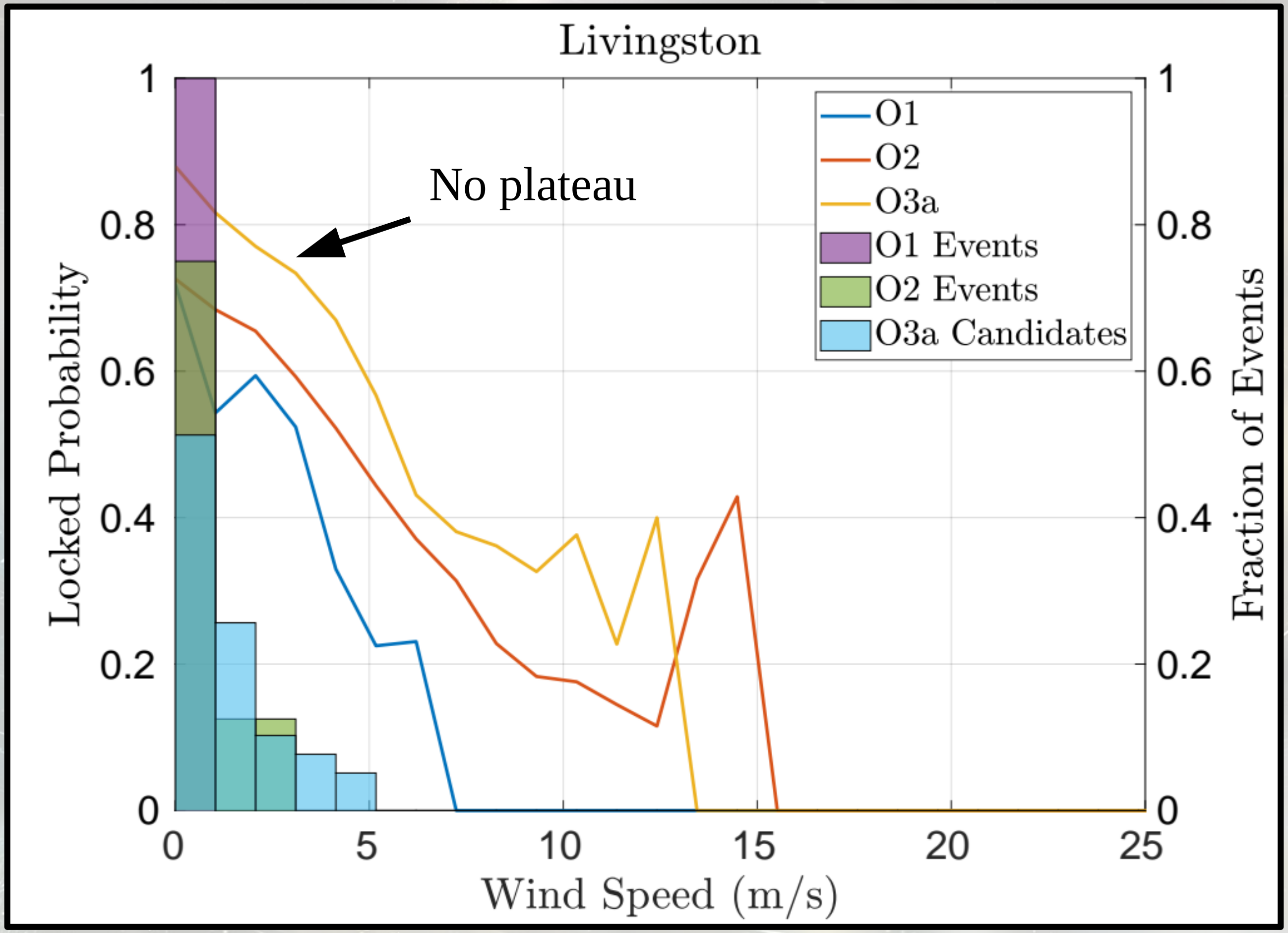
# Duty Cycle Improvements

- GW170104 measured at wind speeds of 10 m/s (29% more likely)
- Multiple O3 events observed above 5 m/s (30-40% more likely)



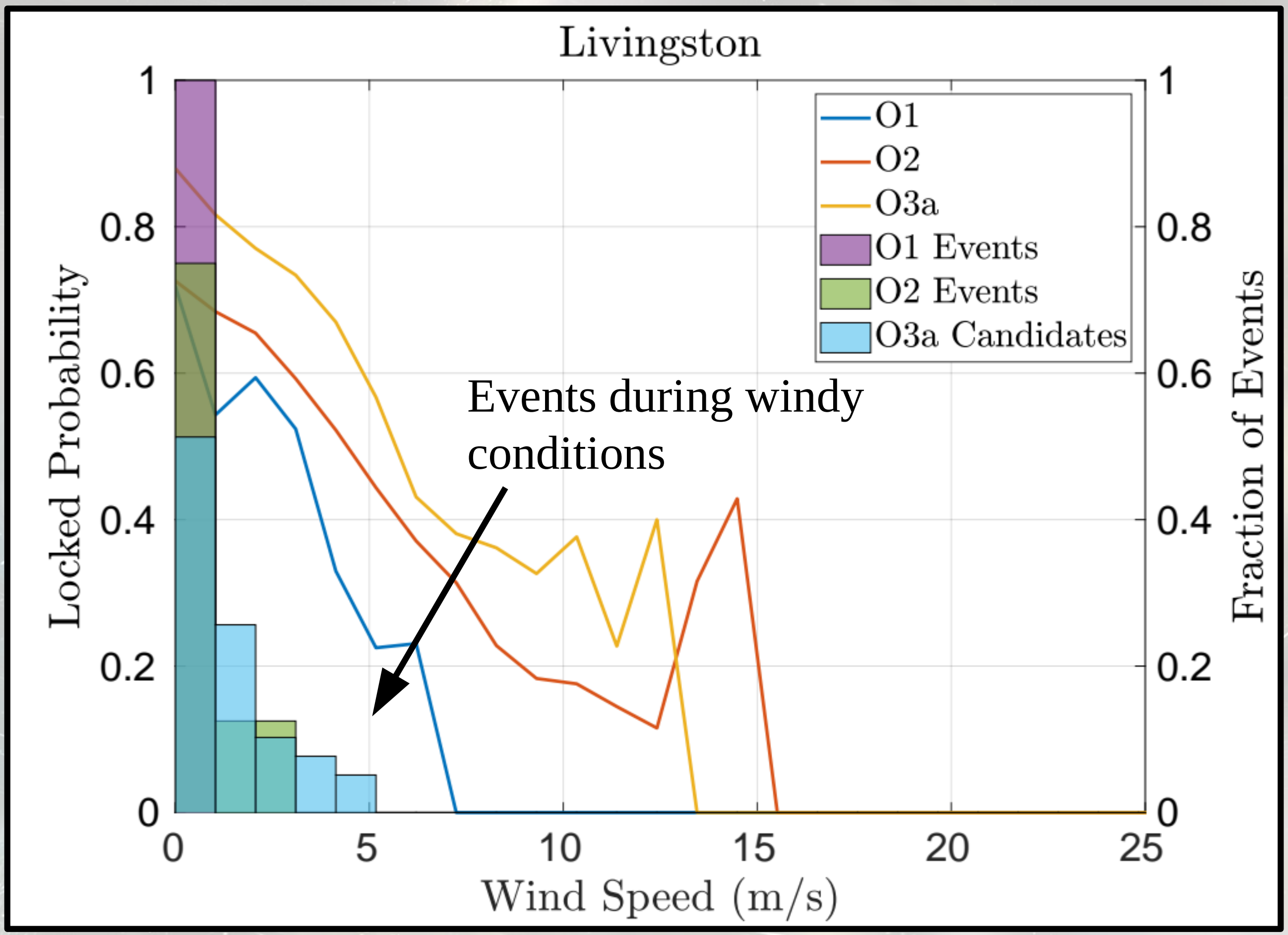
# Duty Cycle Improvements

- Between O1 and O2 single seismometer implemented for corner station sensor correction
- Livingston has softer ground = more response to wind
- In the forest = less windy than Hanford



# Duty Cycle Improvements

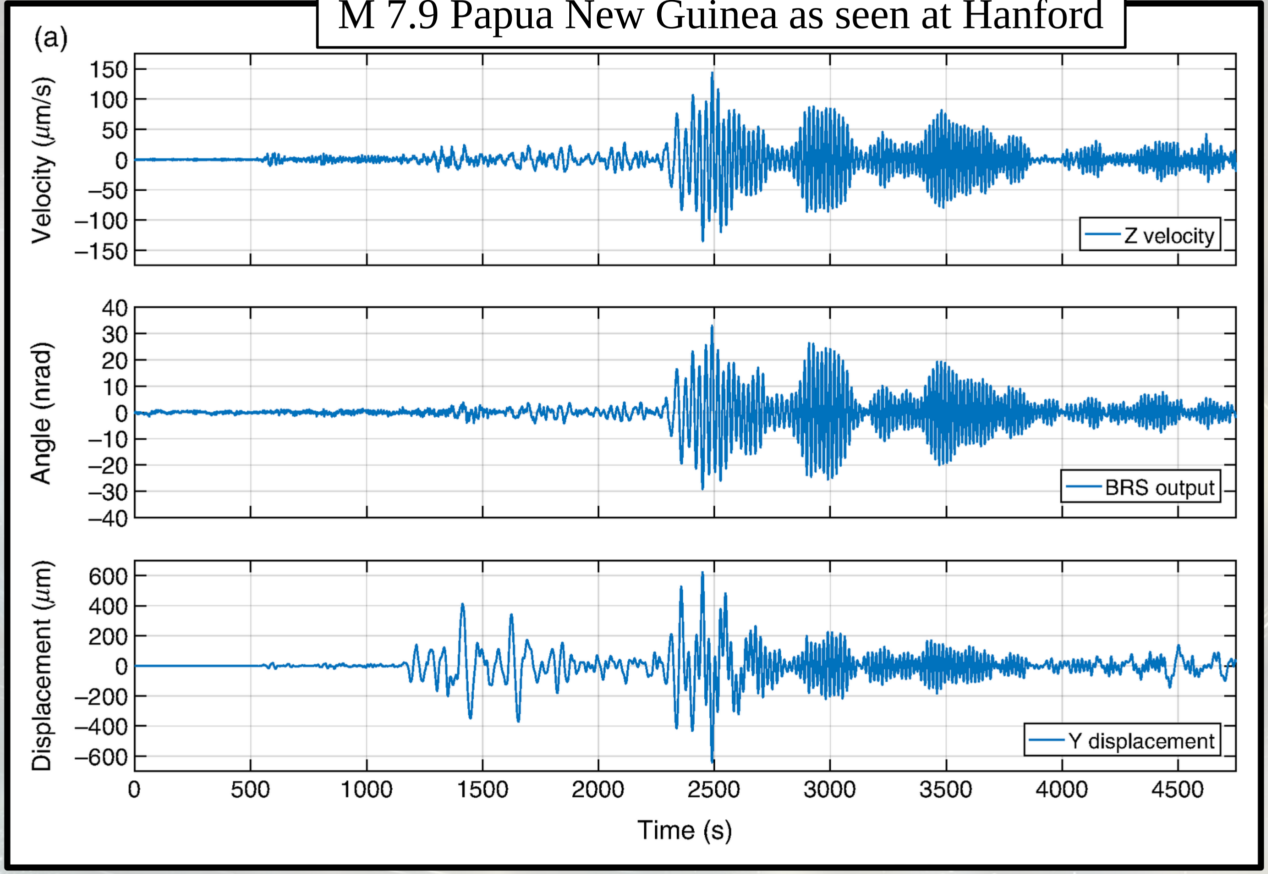
- Between O2 and O3a: +6.9 observing days per year
- Still falls off with wind speed
- Events observed above 2.5 m/s (~30% more likely)



# Seismology

- Unique measurements of seismic waves
- Single point seismic phase velocity measurements
- Can probe density profiles at a single location

M 7.9 Papua New Guinea as seen at Hanford



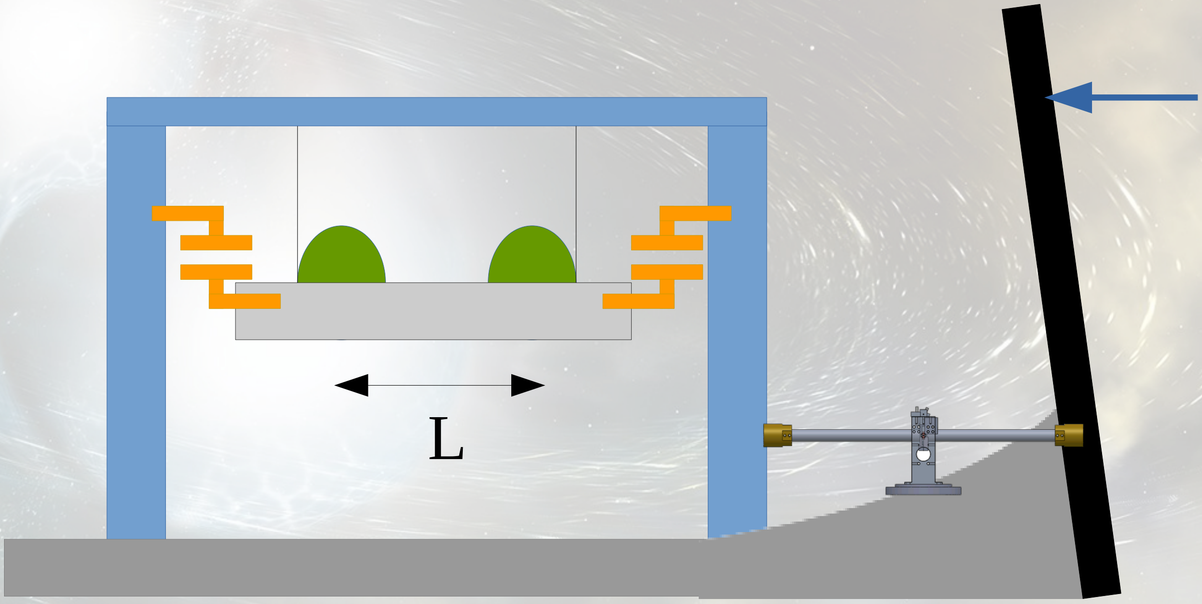

Low-Frequency Tilt Seismology with a Precision Ground-Rotation Sensor. M. P. Ross, K. Venkateswara, C. A. Hagedorn, J. H. Gundlach, J. S. Kissel, J. Warner, H. Radkins, T. J. Shaffer, M. W. Coughlin, P. Bodin. Seismological Research Letters (2017) 89 (1): 67-76.

# cBRS
# Compact Beam Rotation Sensor

# Back to Seismic Isolation

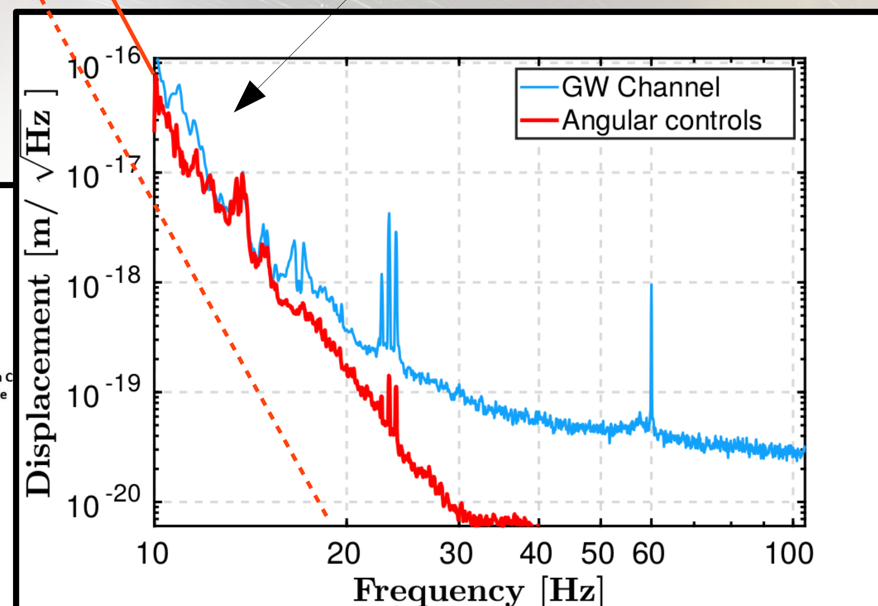
- Existing rotation sensors are pairs of vertical sensors
- Assumes no differential motion between the sensors other than tilt
- Sensors have rising noise at low frequency
- Can't use ground sensor because tilt is location dependent

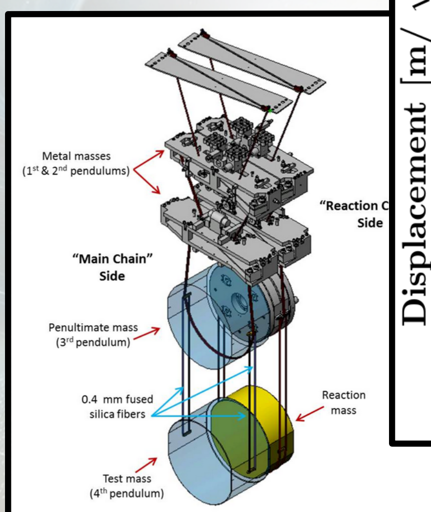
$$\theta = \frac{z_1 - z_2}{L}$$



# Angular Control Noise

- Angular motion must be <1 nrad RMS
- Angular control system removes residual motion at low frequency
- Each pendulum stage has actuators
- Sensor noise is low-passed to decrease leakage into GW band
- Currently too much motion to not have leakage

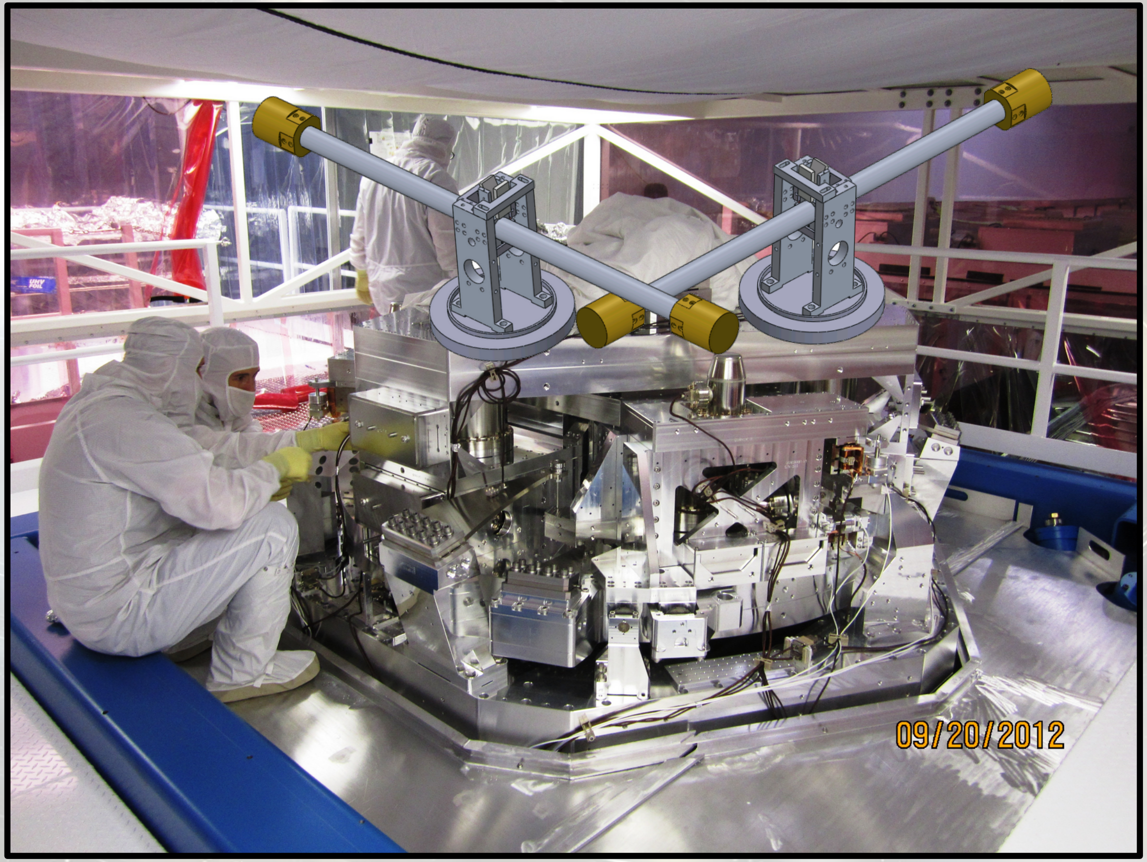



Noise budget by Anamaria Effler at LIGO Livingston Observatory

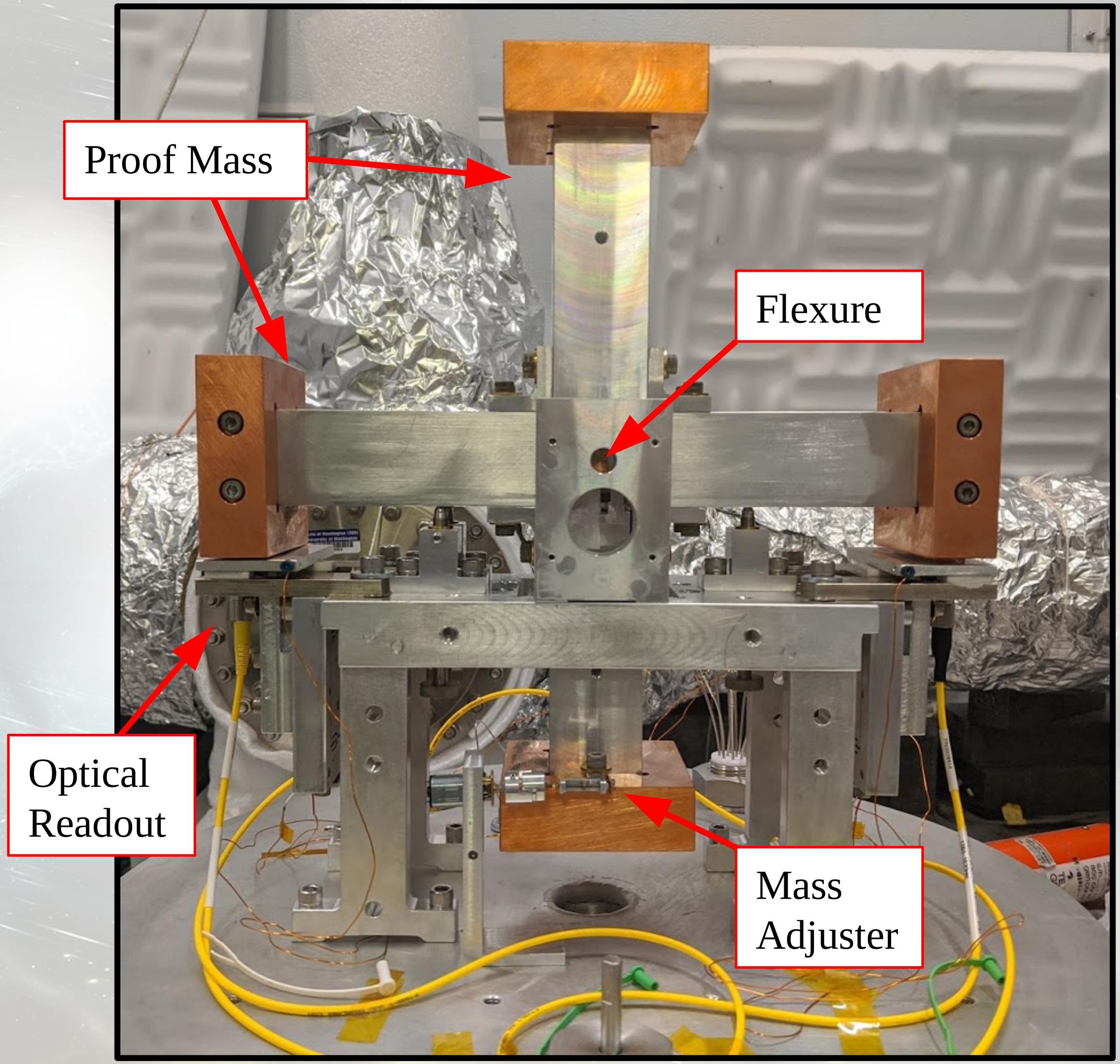
# BRS on Platform

- To improve current system we'd like to put BRSs on-platform
- Current version too big and not suited for application



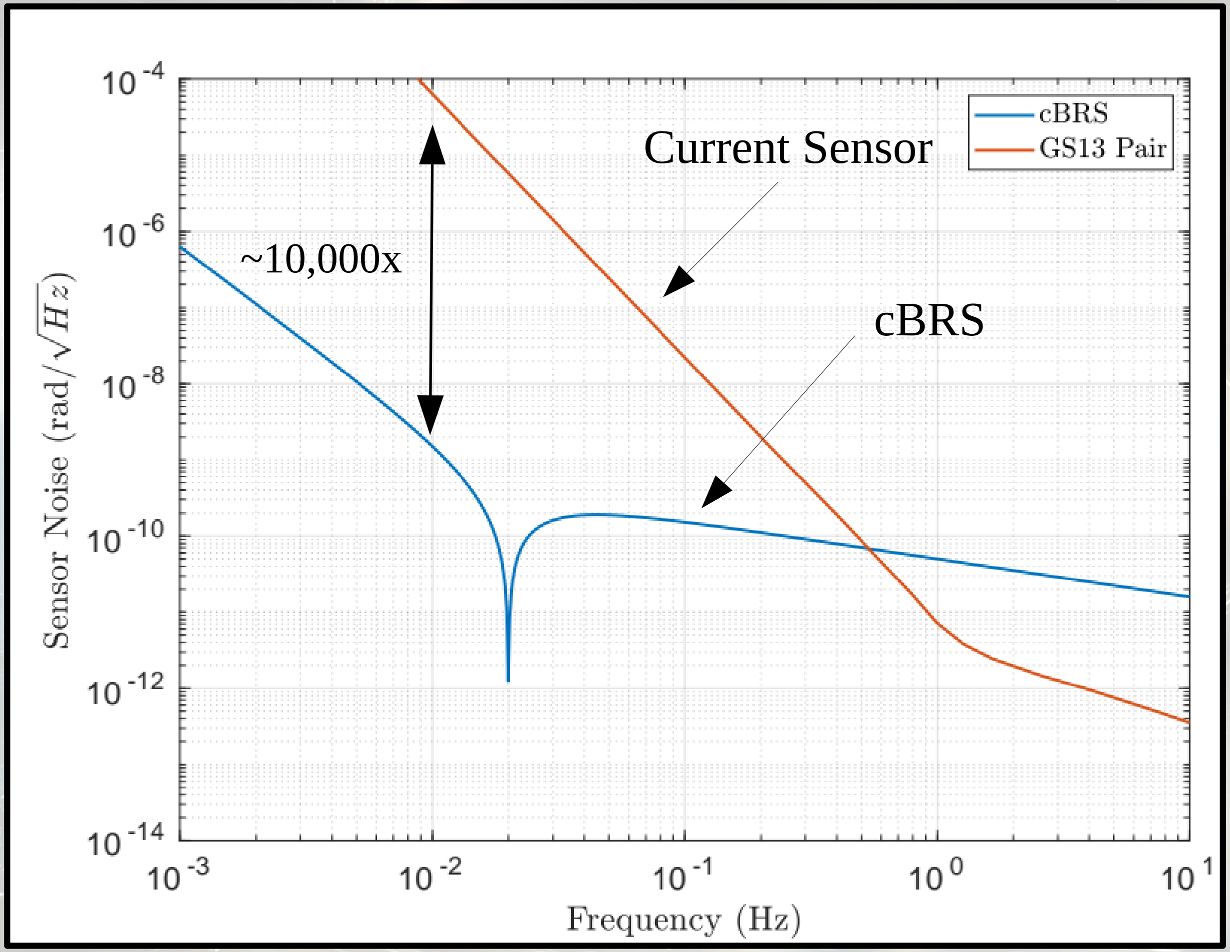
# cBRS

- Same concept as the BRS, only smaller
- 30-cm long beam hung from 10-15 µm thick flexure with 50 mHz resonance
- Cross decreases coupling to gravity gradients
- Can be housed in independent vacuum bell jar



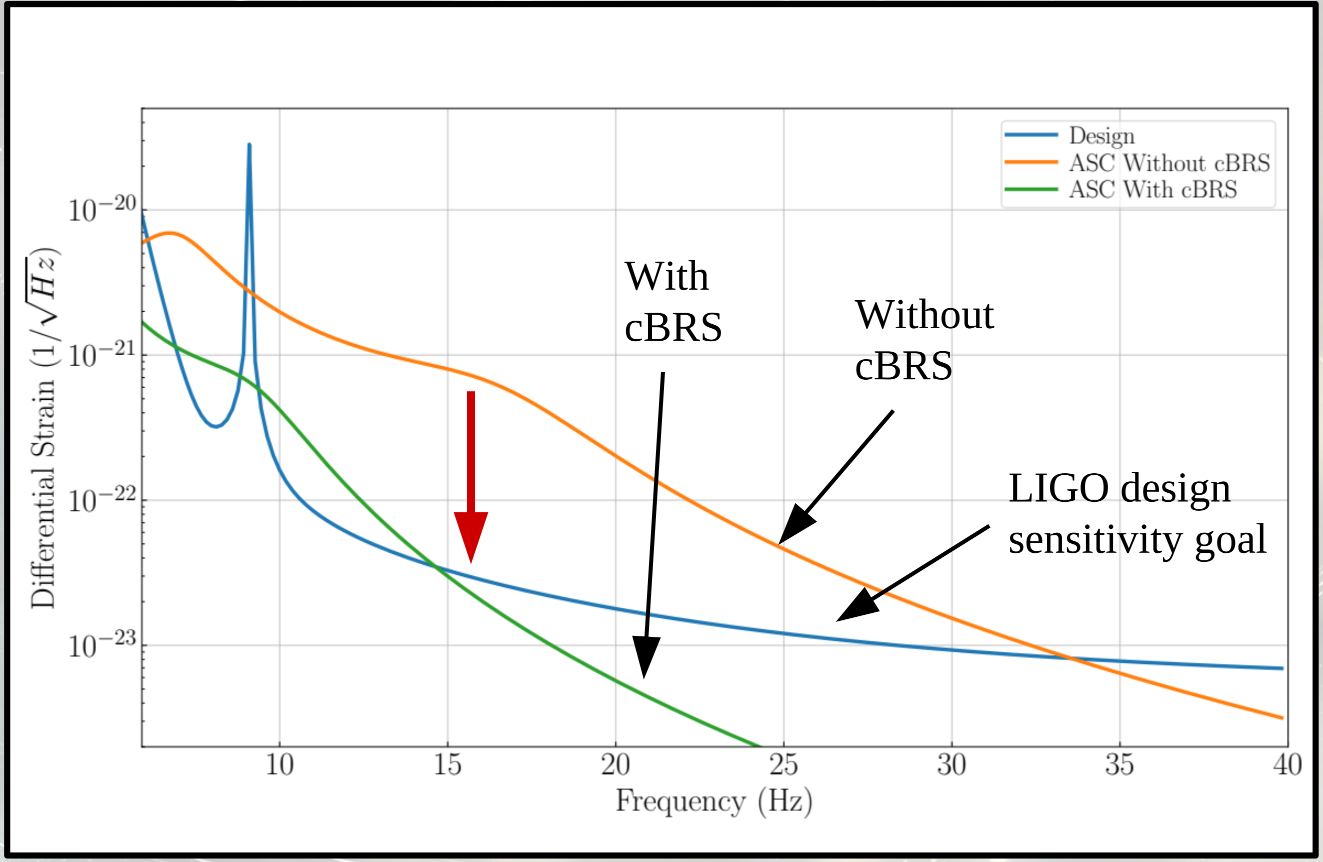
# cBRS vs Seismometer Pair

- Current sensor is pair of GS13 seismometers separated by 1 meter
- Lower noise at frequencies less than 0.5 Hz
- Can be blended with seismometer to use cBRS at low frequency and seismometer at high



# Projected Angular Control Improvements

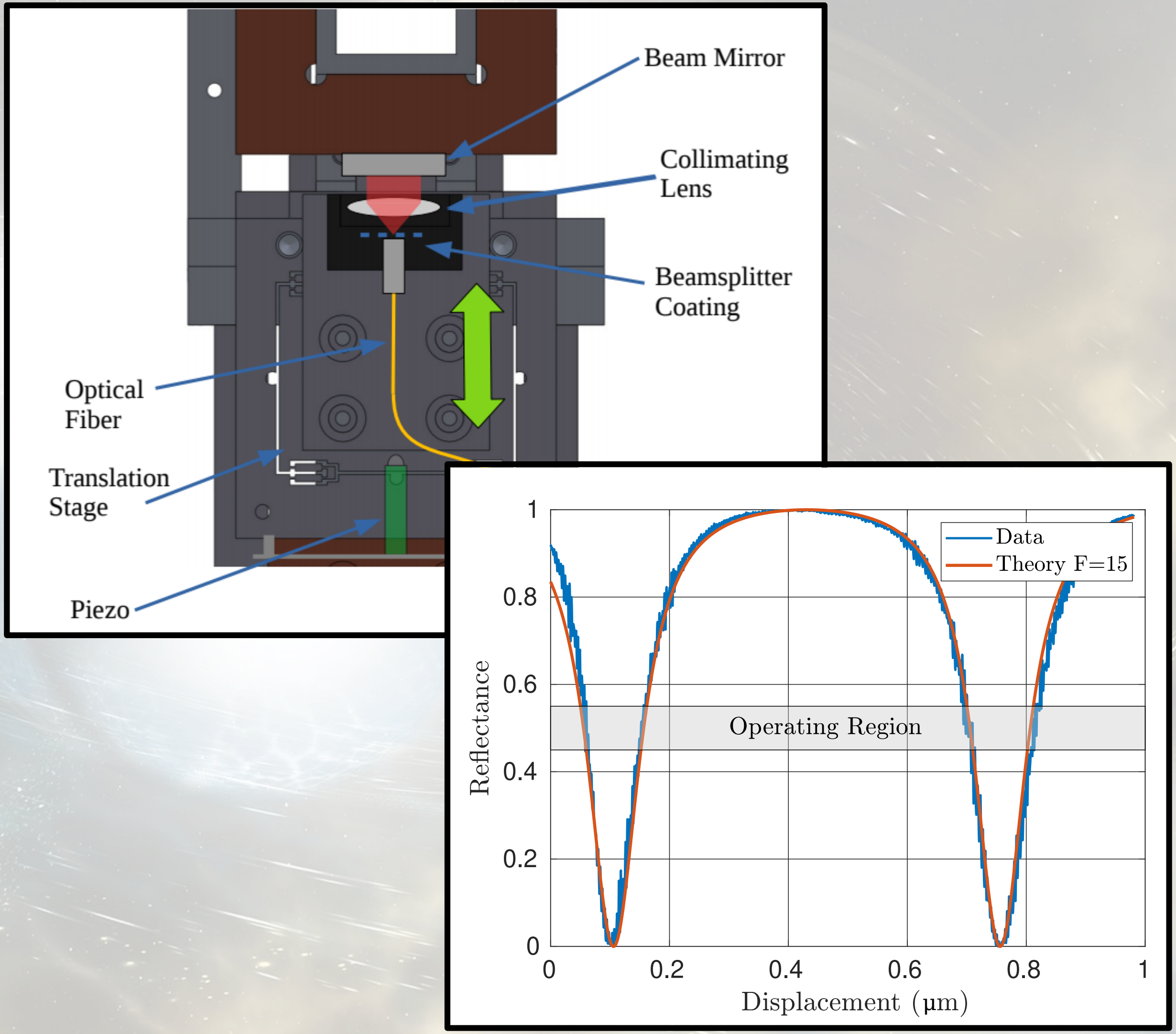
- Better rotation sensor equals better seismic isolation at ~0.1 Hz
- Better seismic isolation allows lower gain angular controls
- Decreases angular control noise in strain readout
- True performance estimates require detailed model




Model originally developed by Hang Yu, Caltech

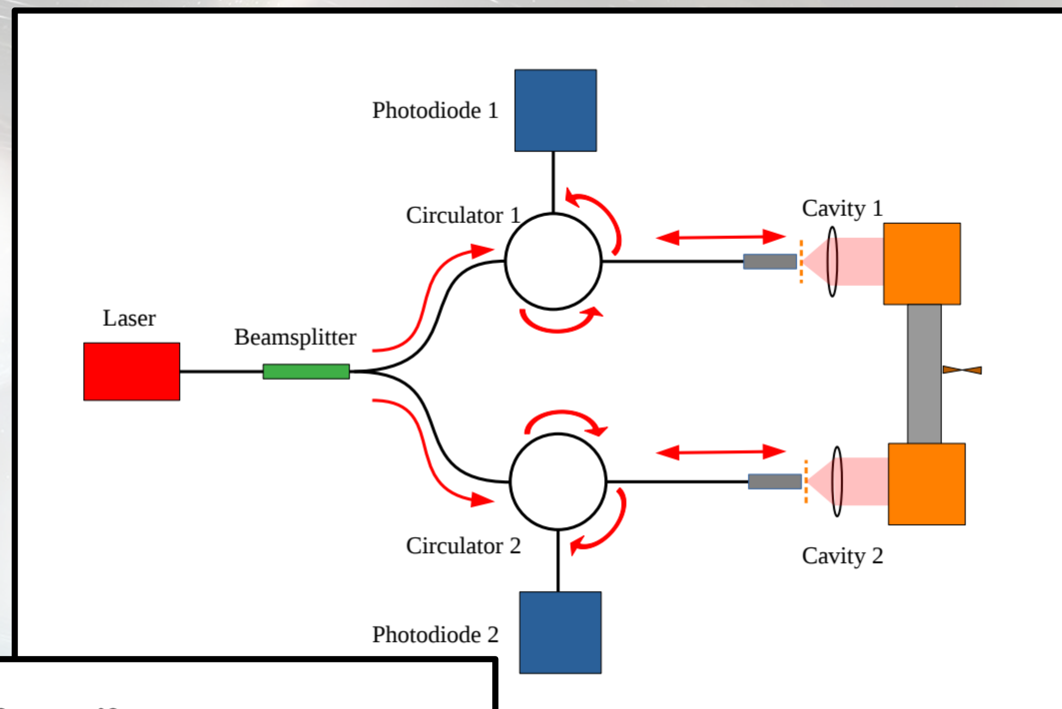
# cBRS Readout

- Fiber interferometer readout
- ~30 prad/√Hz sensitivity at 10 Hz
- Reflectance of Fabry-Perot cavity is fed back to piezo
- Holds the cavity length constant allowing linear readout
- Self-calibrating



# cBRS Readout

- Circulator separates out the ingoing and outgoing beams
- Two readouts are deployed to allow for common noise subtraction




Angle of Beam

Frequency Noise

$$\Delta\theta = 2\theta_s + (x_1 - x_2)\delta_\lambda/\lambda^2 + n_1 - n_2$$

$$\Sigma\theta = (x_1 + x_2)/L + (x_1 + x_2)\delta_\lambda/\lambda^2 + 2n_c + n_1 + n_2$$

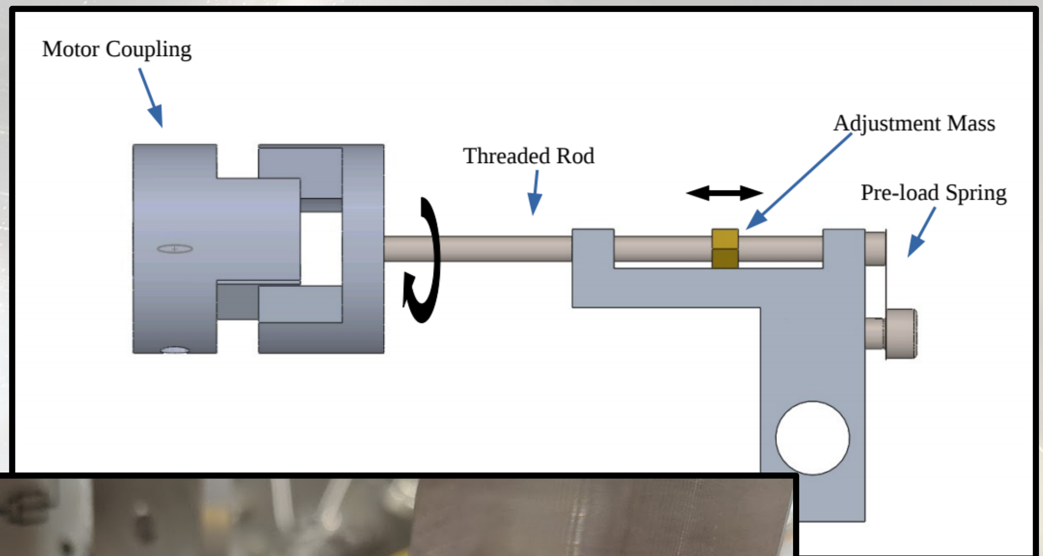
Cavity Length

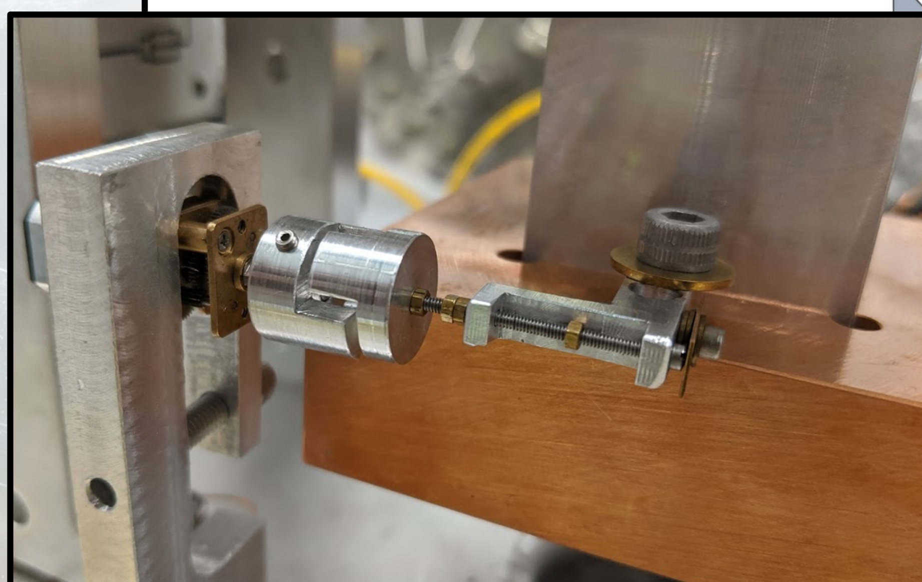
Frequency Noise

Common Noise

# Mass Adjuster

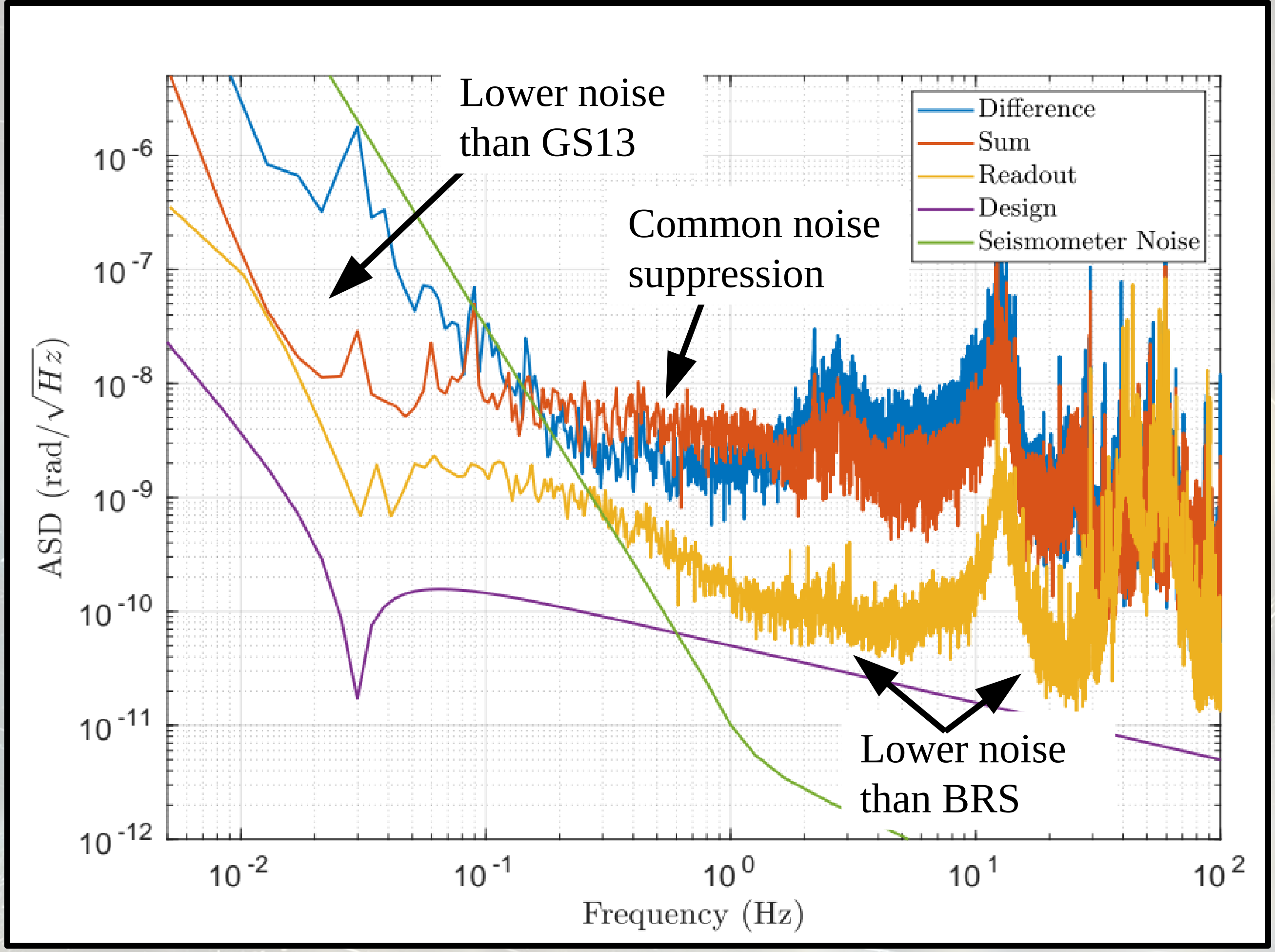
- Horizontal center of mass must be adjusted periodically
- To work on platform mass adjustment must be remote and automated
- Wires running to the beam would be stiffer than flexures
- Motor can be decoupled by rotating backwards



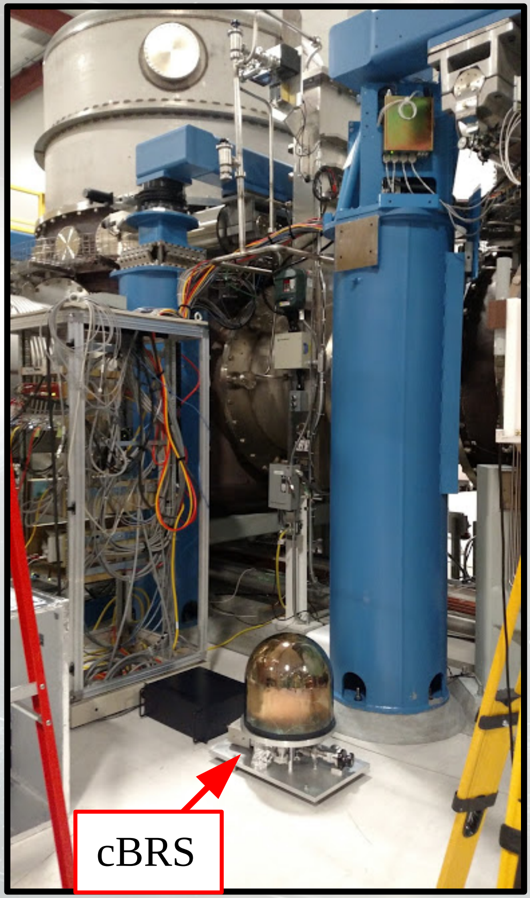
# Prototype Performance

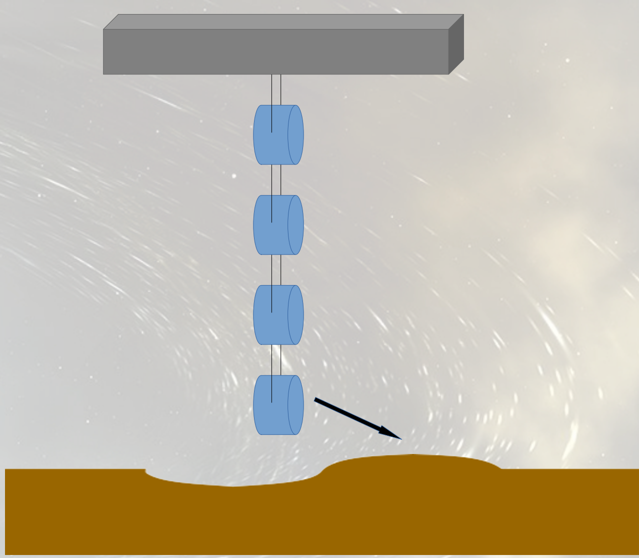
- ~100x lower noise than current sensor at 40 mHz
- Readout noise is lower than BRS above 1 Hz
- ~12 Hz peak due to table resonance
- Noise hunting will resume once we can return to the lab



# Newtonian Noise Study

- Deployed at Hanford to study gravitation coupling between seismic waves and test mass (Newtonian noise)
- Ran for most of O2 and observed ground tilt coupling with GW channel
- Ideal sensor for future cancellation schemes



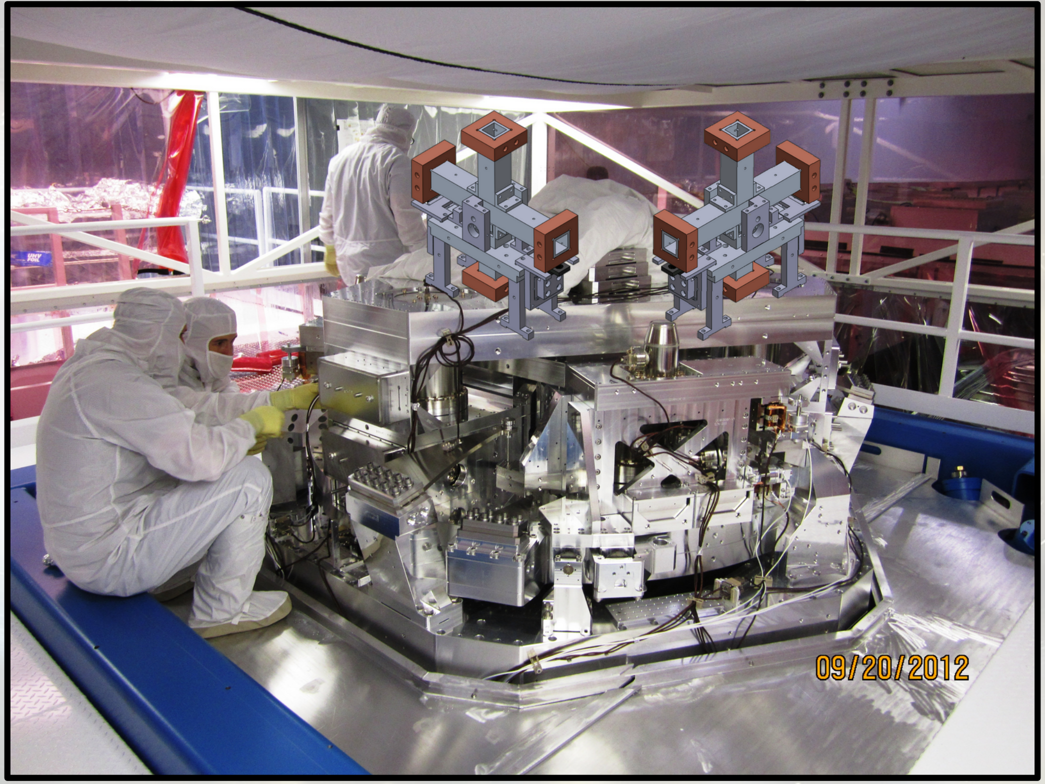



Implications of Dedicated Seismometer Measurements on Newtonian-Noise Cancellation for Advanced LIGO
M. W. Coughlin, J. Harms, J. Driggers, D. J. McManus, N. Mukund, M. P. Ross, B. J. J. Slagmolen, and K. Venkateswara
Phys. Rev. Lett. 121, 221104 – Published 28 November 2018

LIGO

# Future Research

- Eliminate noise sources in cBRS (after pandemic ends)
- Install on test isolation platform (~ year)
- Roll out to both sites (hopefully for O4)
- Detect more gravitational waves (the future)



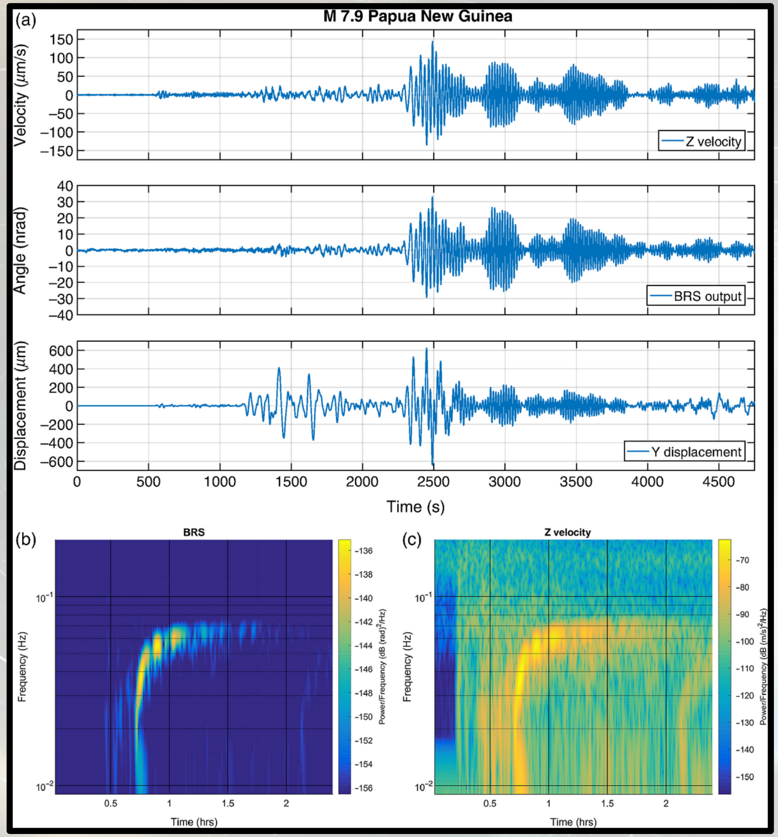
# Conclusions

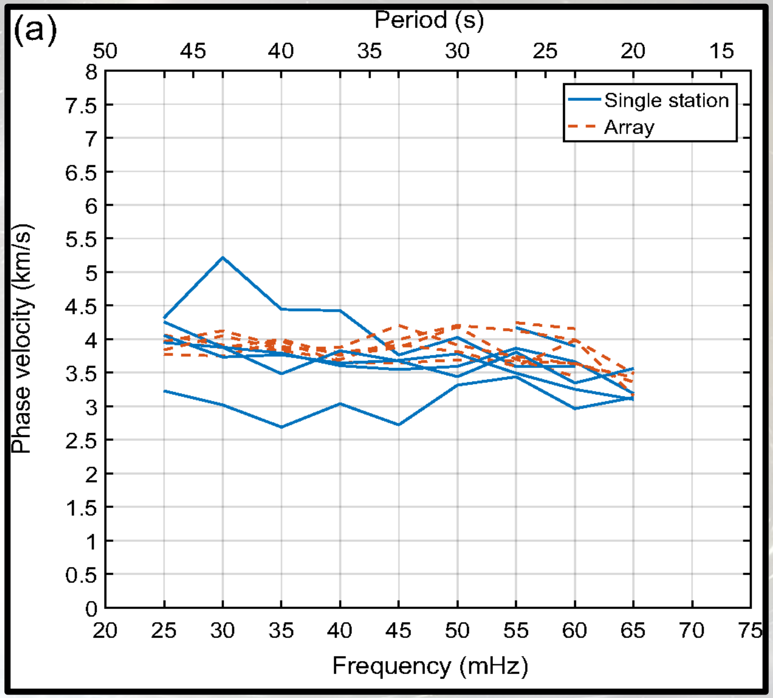
- We developed, constructed, and deployed six BRSs
- These allow the observatories to run during high winds and improved GW detection
- cBRS prototyped and almost ready to be installed on test platform
- Has the capability to significantly decrease LIGO’s low frequency noise
- Applied these sensors to seismology and Newtonian-noise subtraction

# Thank You

- Special thanks to Krishna Venkateswara for leading this research
- My committee members especially Jens Gundlach
- The entire Eöt-Wash group especially Charlie Hagedorn
- The LIGO Seismic team especially Brian Lantz and Jeff Kissel
- Arnaud Pele, Eyal Schwartz, Jim Warner, Hugh Radkins
- CENPA and Physics machine shops
- CENPA
- NSF and DOE

# Seismology

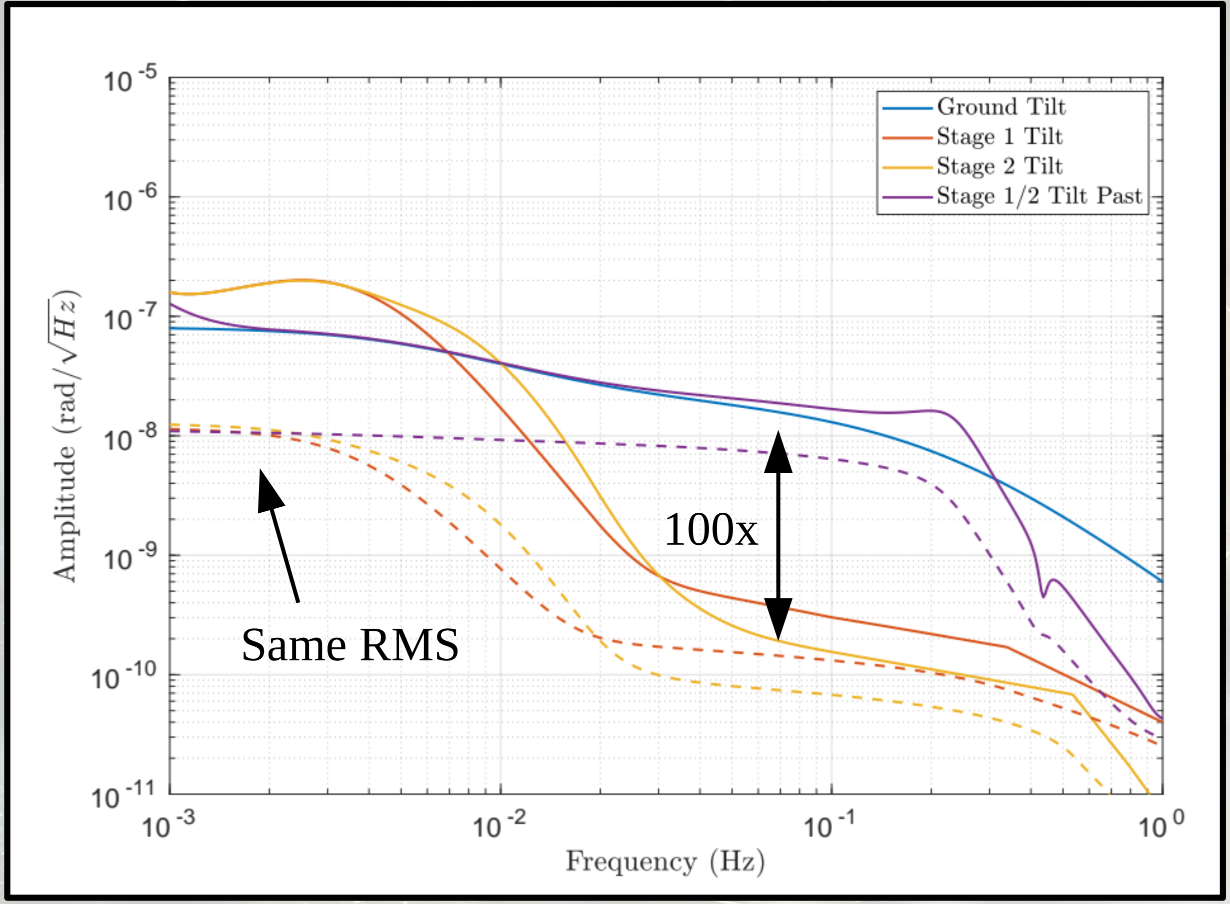



Low-Frequency Tilt Seismology with a Precision Ground-Rotation Sensor. M. P. Ross K. Venkateswara C. A. Hagedorn J. H. Gundlach J. S. Kissel J. WarnerH. Radkins T. J. Shaffer M. W. Coughlin P. Bodin. Seismological Research Letters (2017) 89 (1): 67-76.

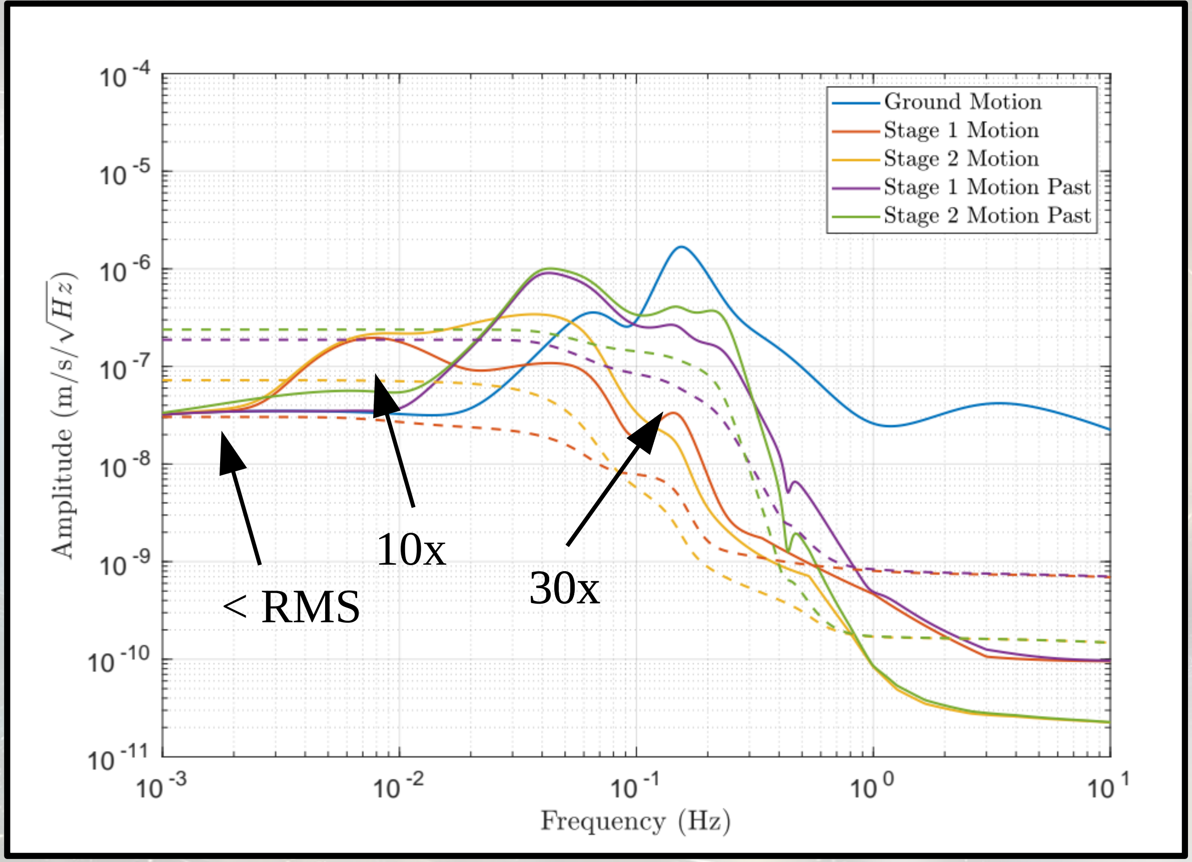
# Projected Tilt Improvements

- Modeled isolation performance with cBRS on-platform
- Simplified 2 degree of freedom model
- Significant decrease in rotation from 10 mHz to 1 Hz
- Same low frequency RMS motion as the past



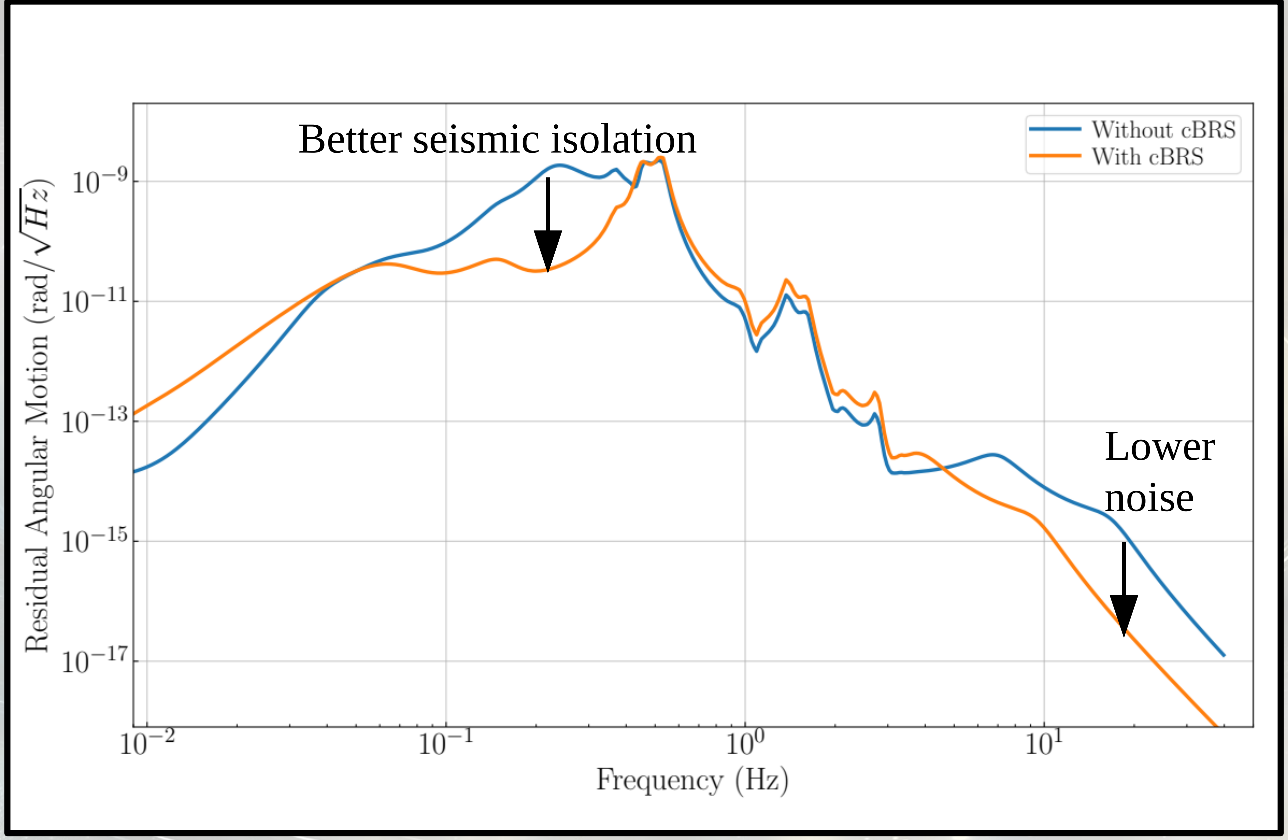
# Projected Translation Improvements

- Better tilt control equals less tilt contamination of platform seismometers
- Improved performance above 20 mHz
- Factor of 3-30 improvement at microseism
- Increased motion at ~10 mHz
- Decreased RMS



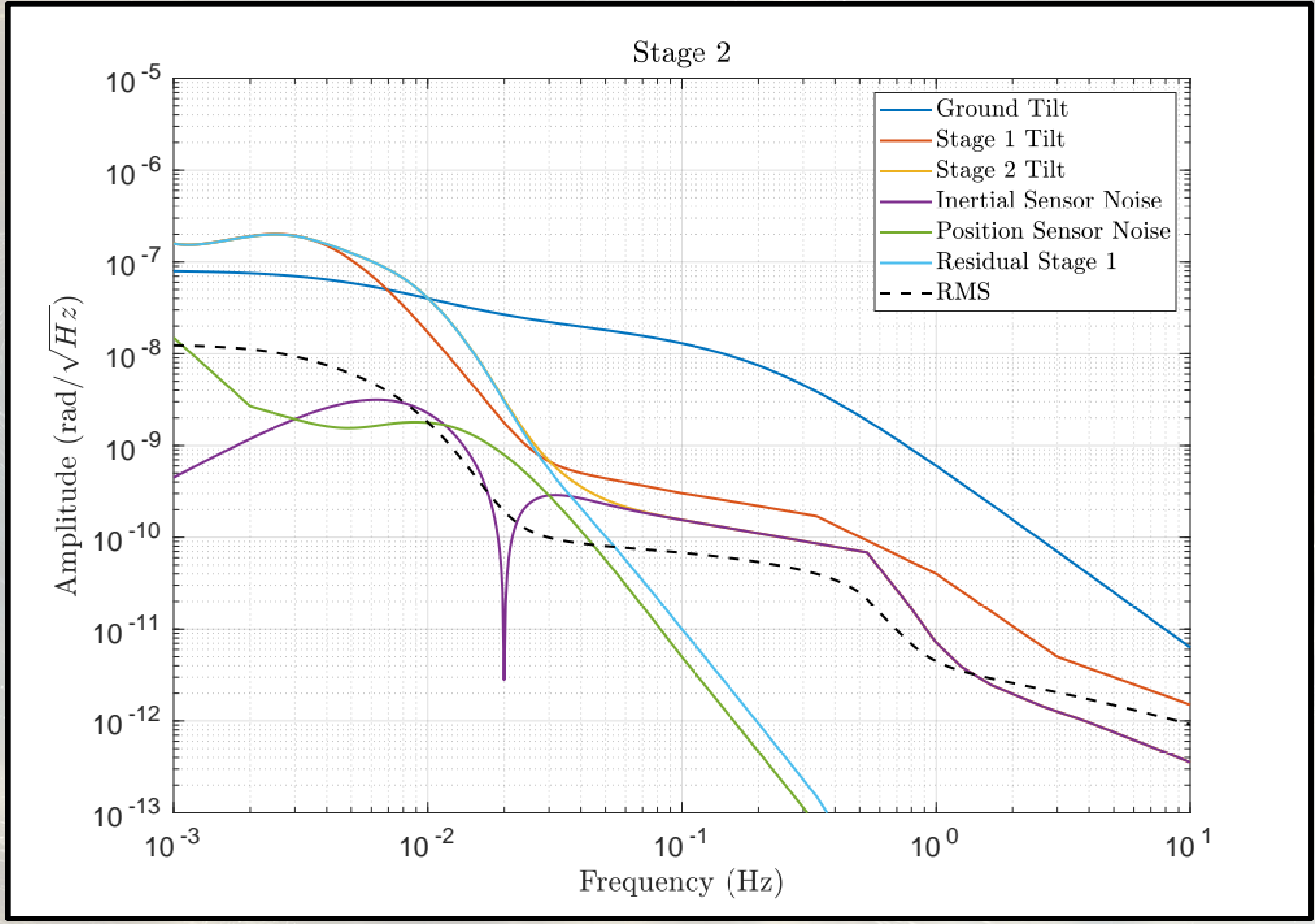
# Projected Angular Control Improvements

- Angular control loops can be retuned with better seismic isolation
- Modified simple angular control model to estimate performance
- Decrease gain yields same RMS motion of ~1 nrad

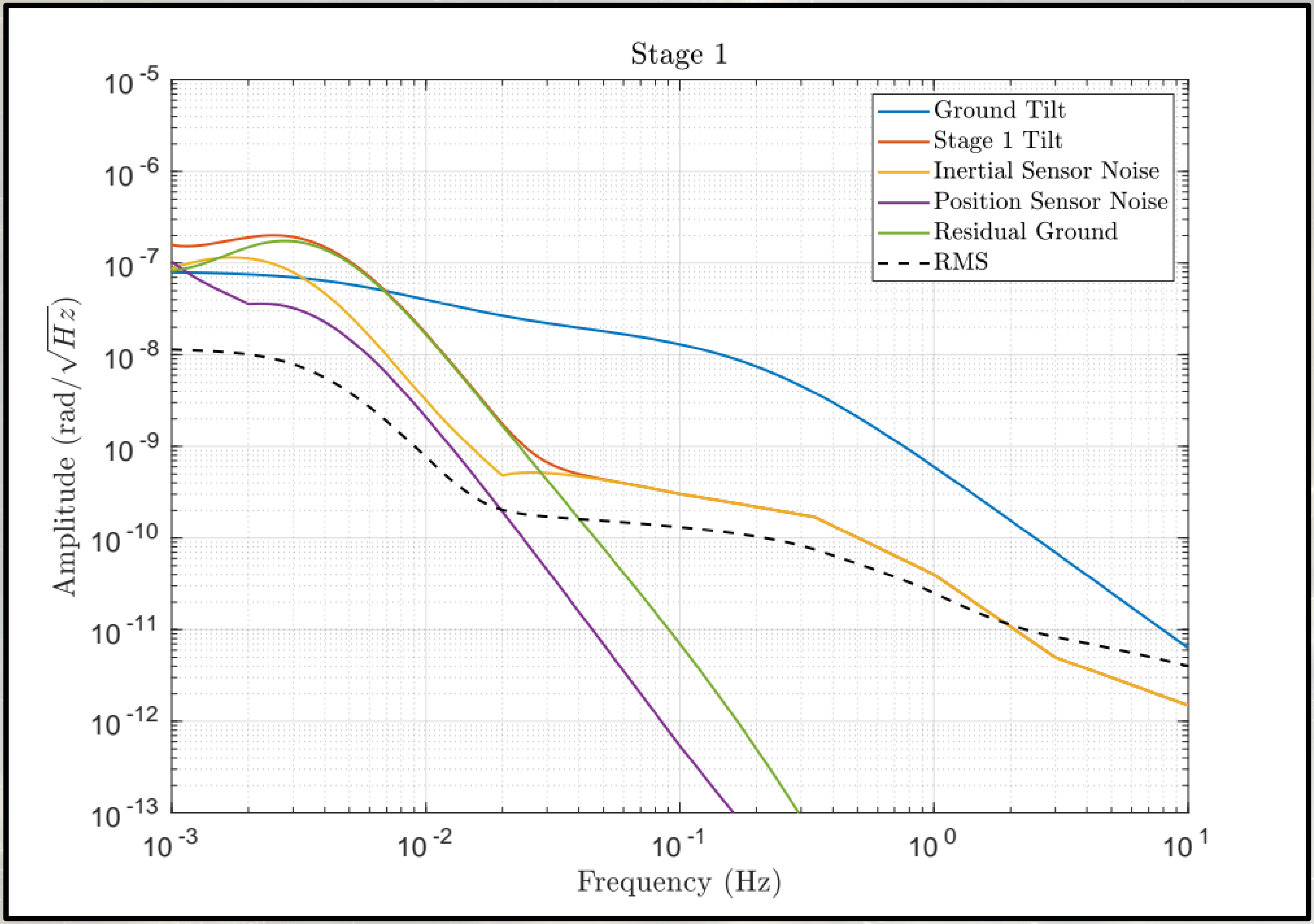



Model originally developed by Hang Yu, Caltech

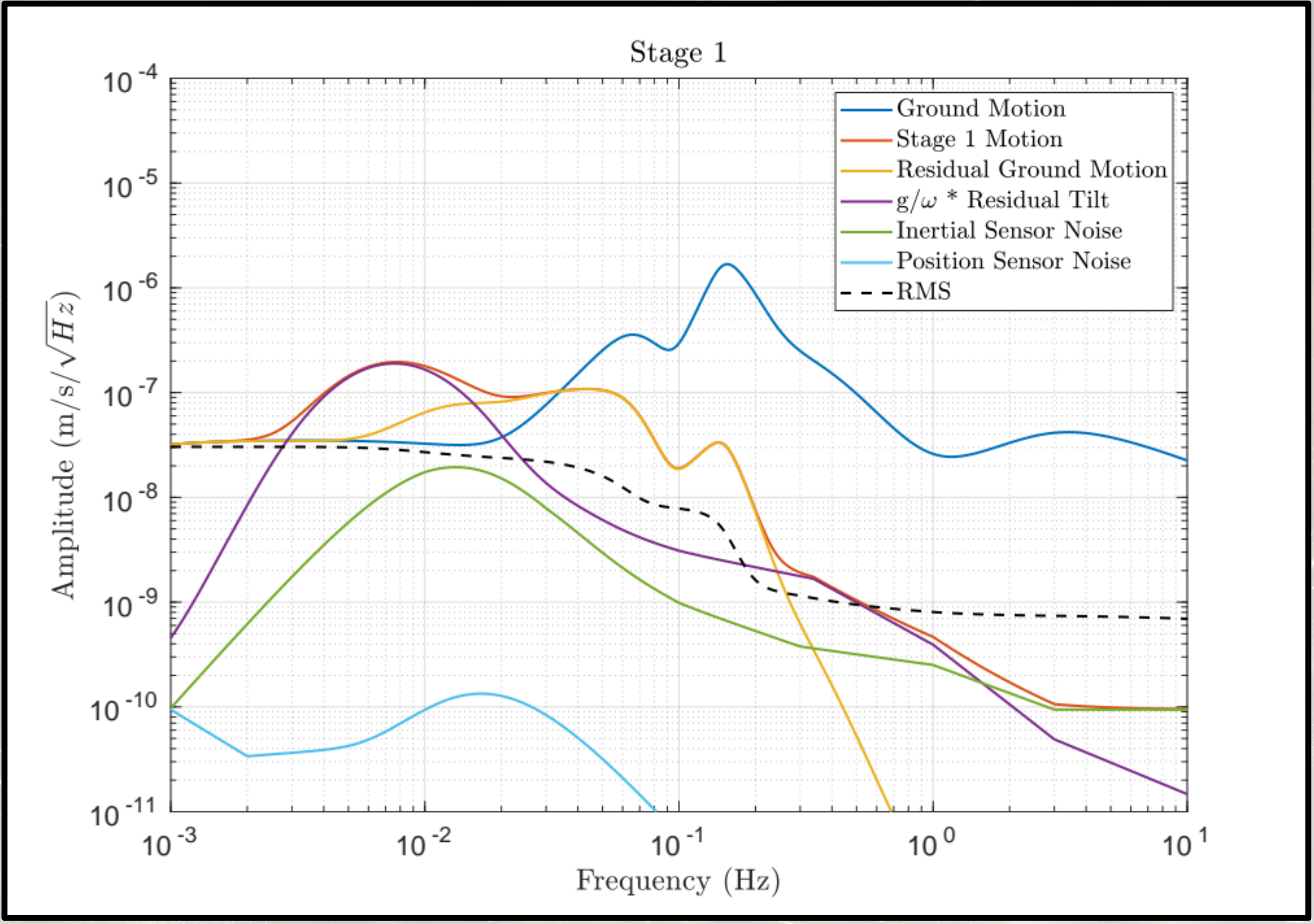
# Projected Tilt Improvements



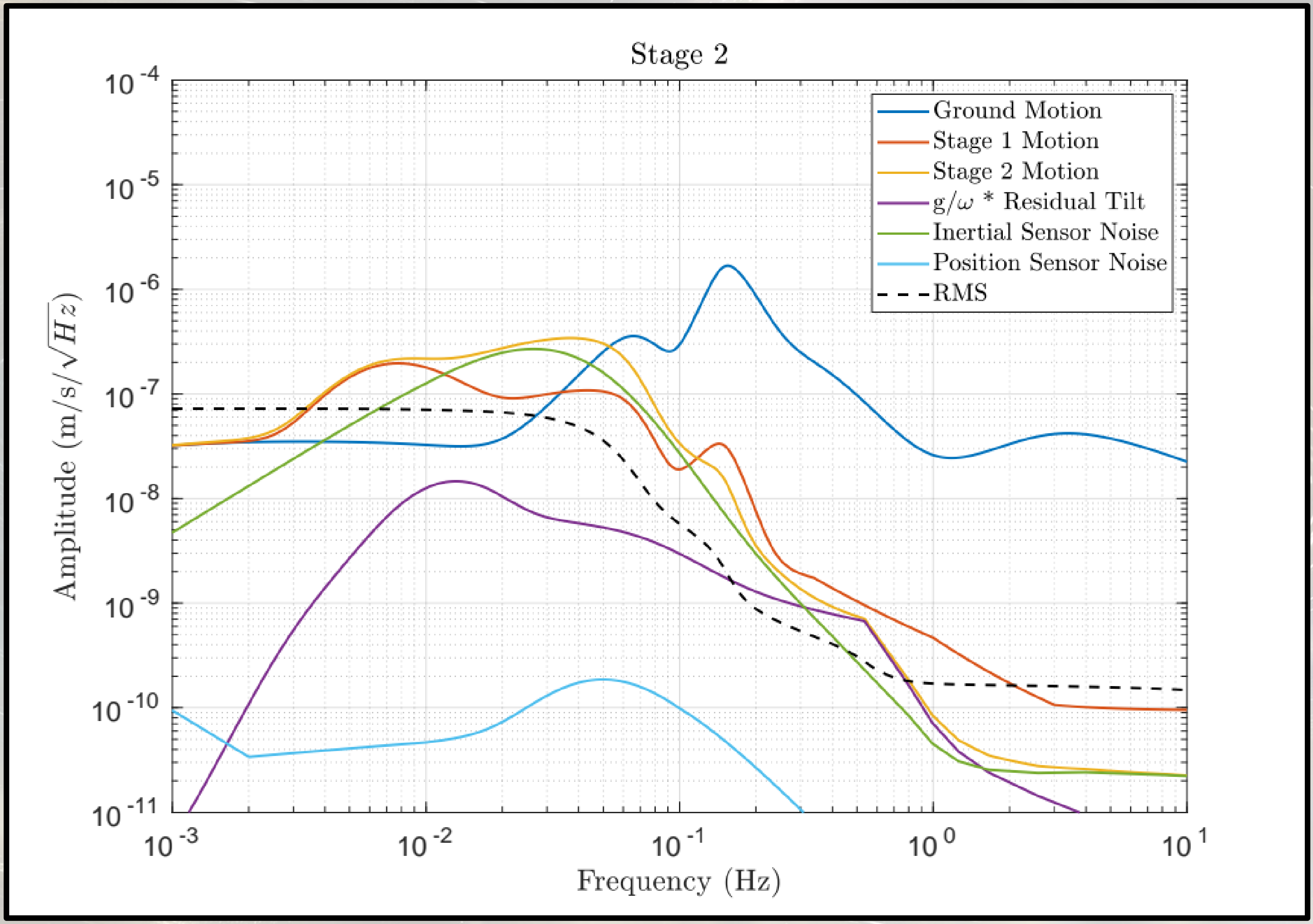
# Projected Tilt Improvements



# Projected Translation Improvements



# Projected Translation Improvements



# Duty Cycle Improvements