# LIGO/VIRGO Earthquake studies and controls configuration

## GWADW 2015 – Controls Workshop

G1500652
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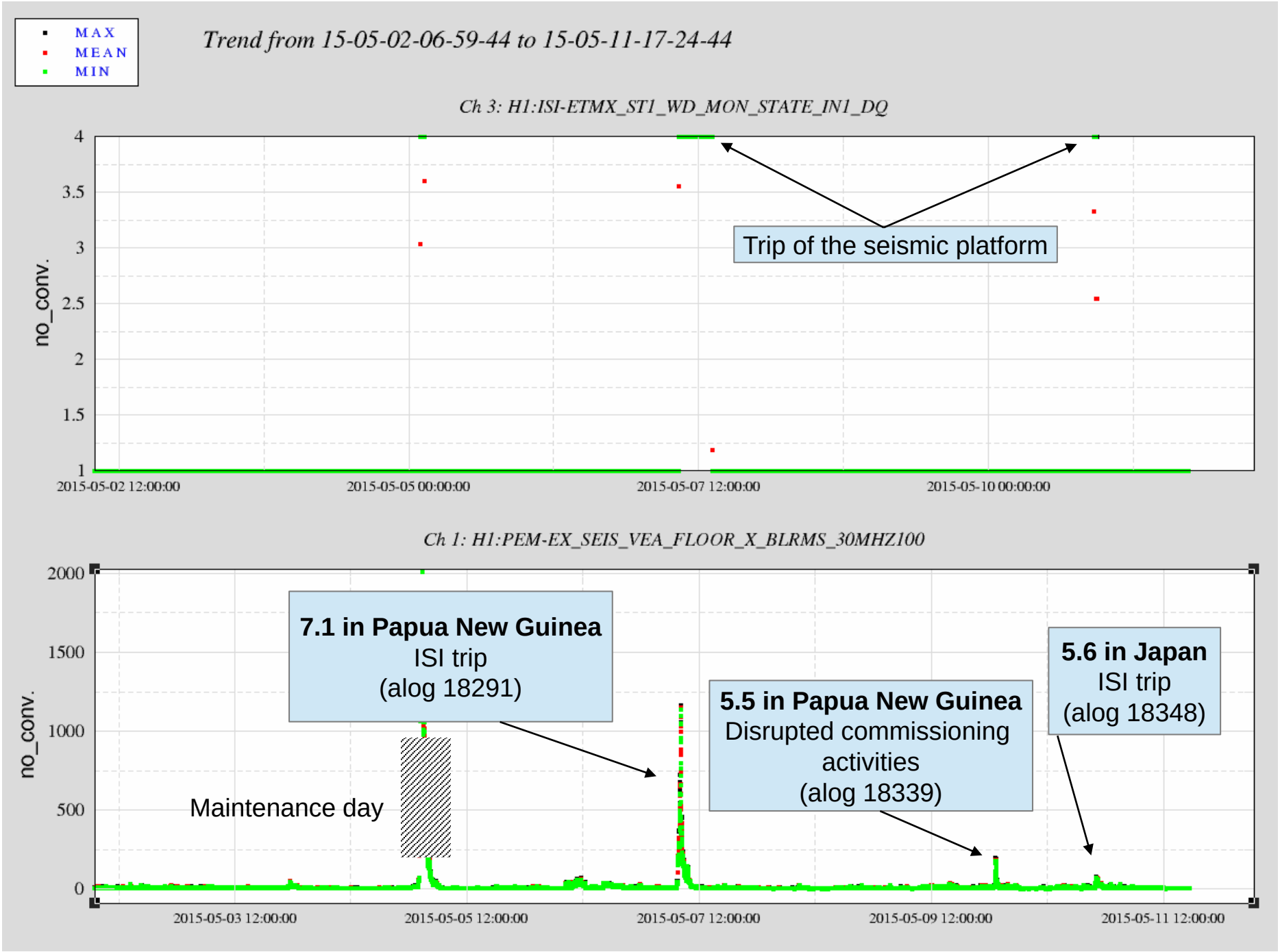
# Quick glance at LHO EX



# Introduction

- LIGO → 3 earthquakes related issues in 10 random days.
- VIRGO → “Couples of unlocks per week” according to commissioners.

- Earthquakes change the ground motion behavior, disrupt commissioning activities

→ **it is an issue**

I.Earthquake characterization

a)Tonga Earthquake (June 2014)

b)Tilt or no tilt? (Nicaragua, October 2014)

II.Seismic platform behavior during earthquakes

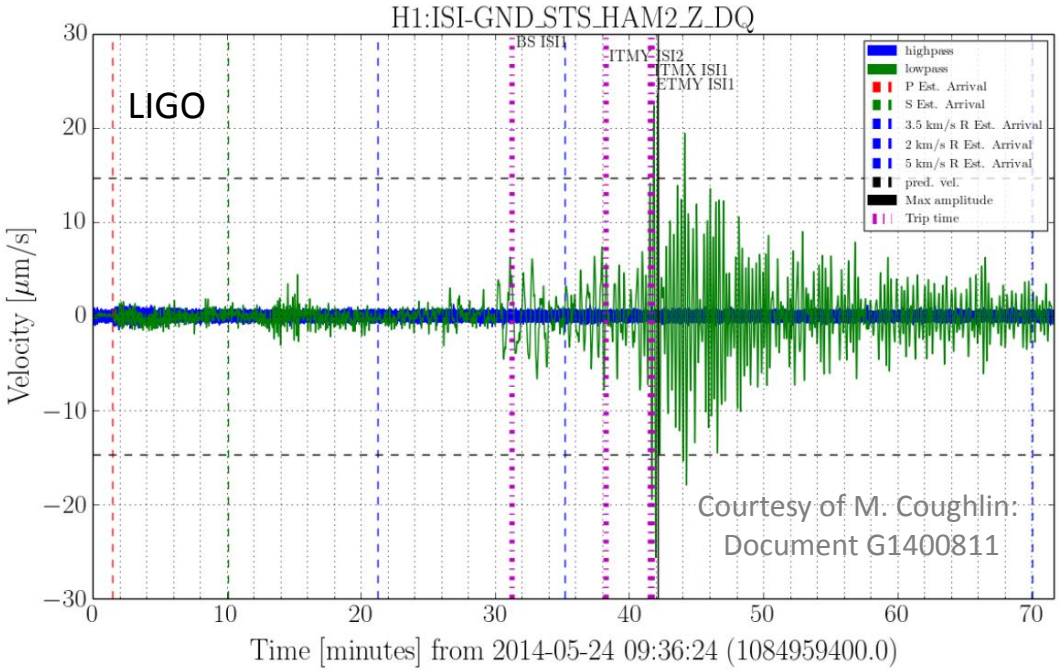
III. Strategy

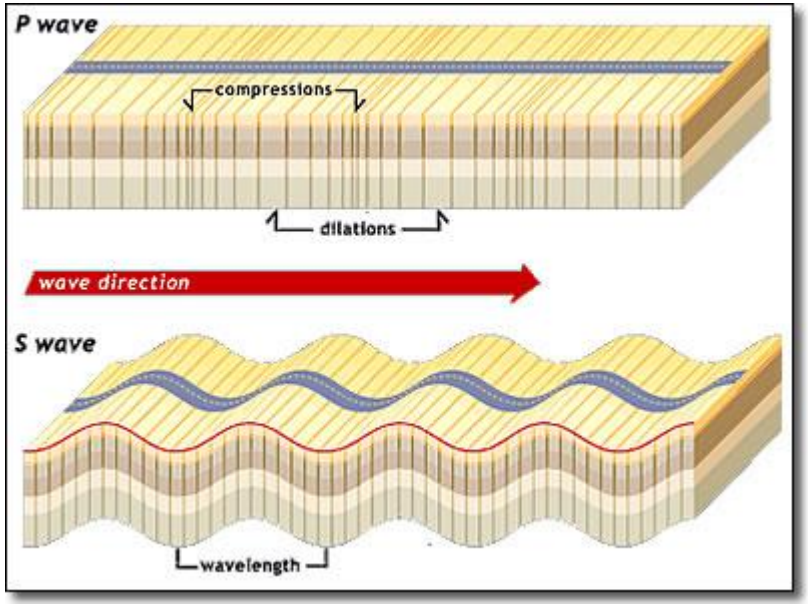
a)Earthquake monitor

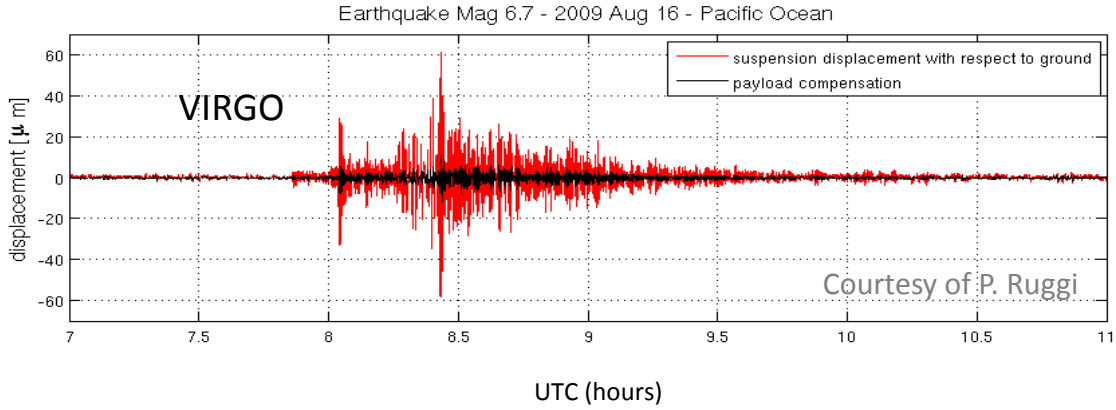
b)Possible controls configurations

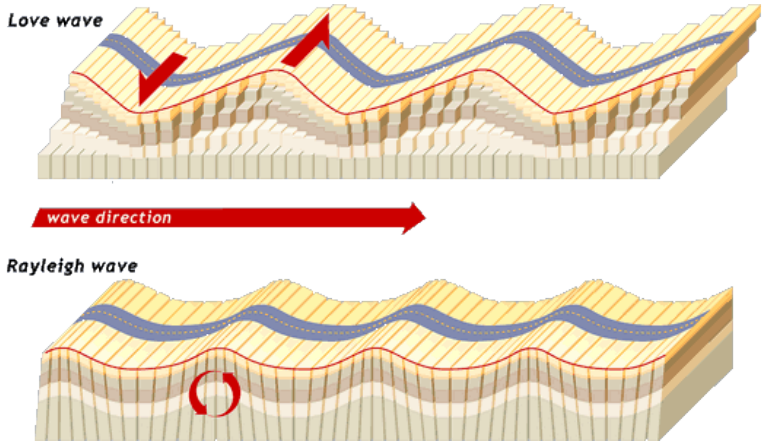
IV.Future/Conclusion

# Typical time series of ground motion during earthquake



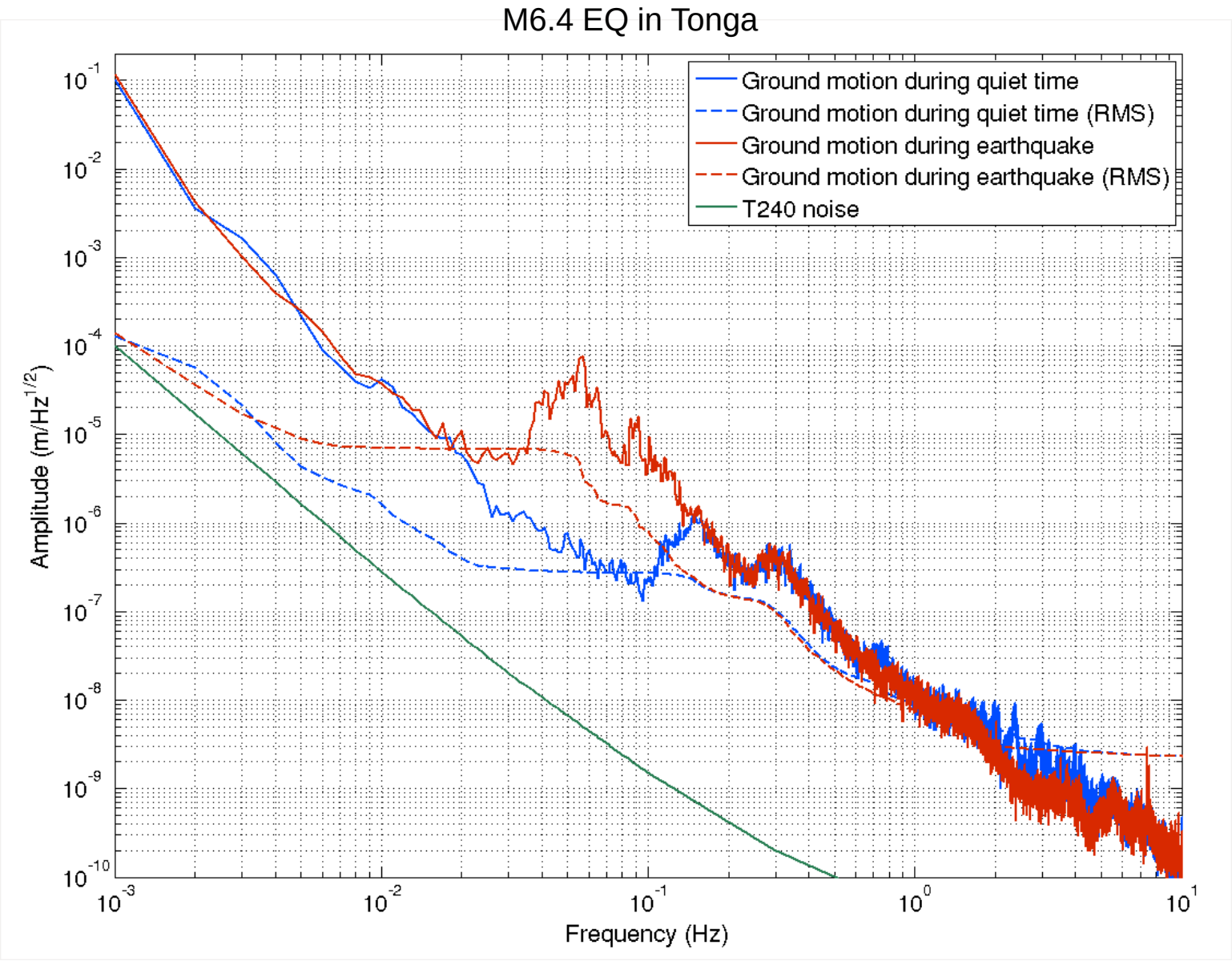



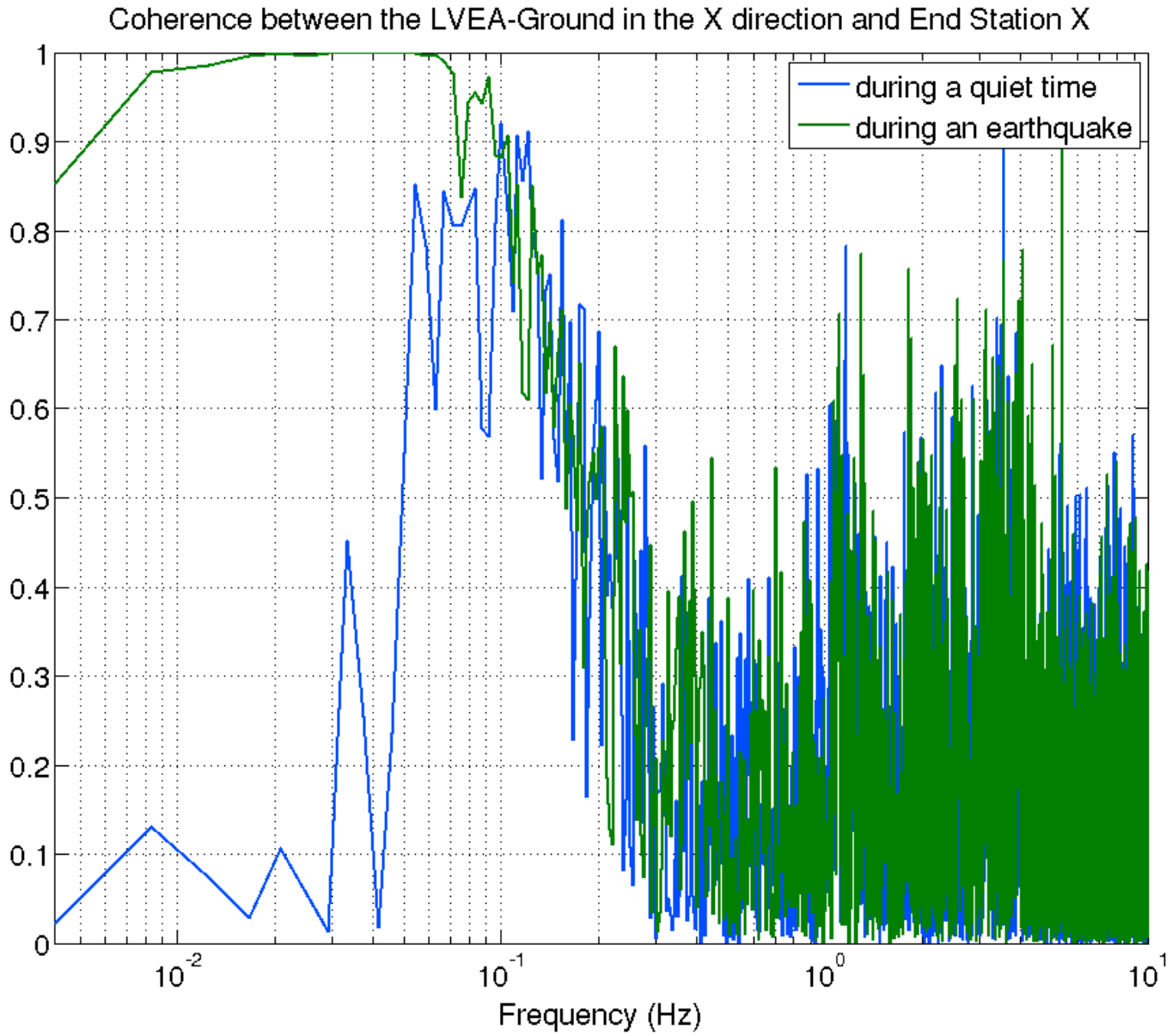

1. Similar ground behavior LIGO/VIRGO

# ASD of LLO-LVEA Ground motion in the X direction




2. Amplification of the ground motion by a factor of ~100 below 150mHz

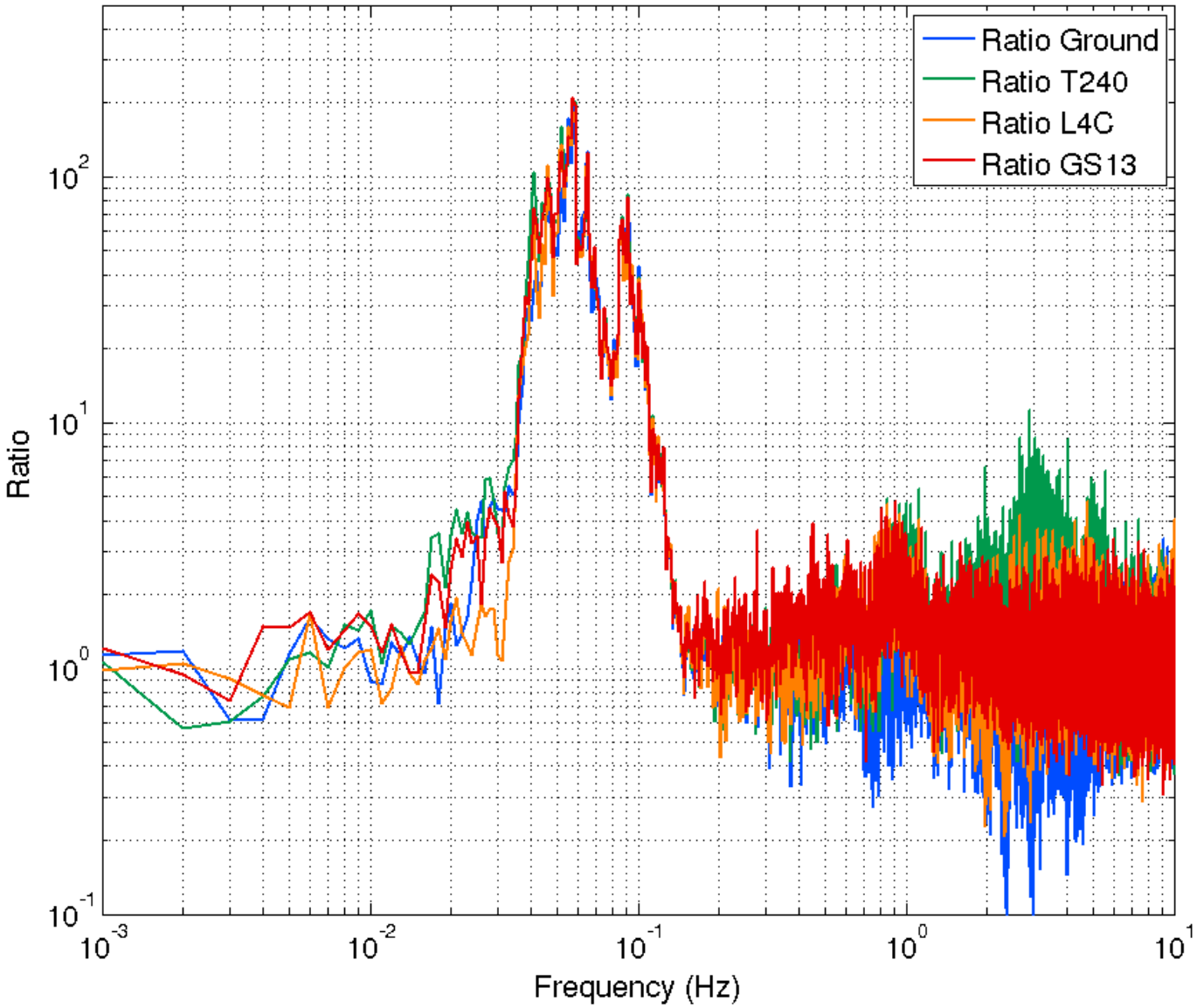
# Coherence between stations




3. Common amplification between the stations

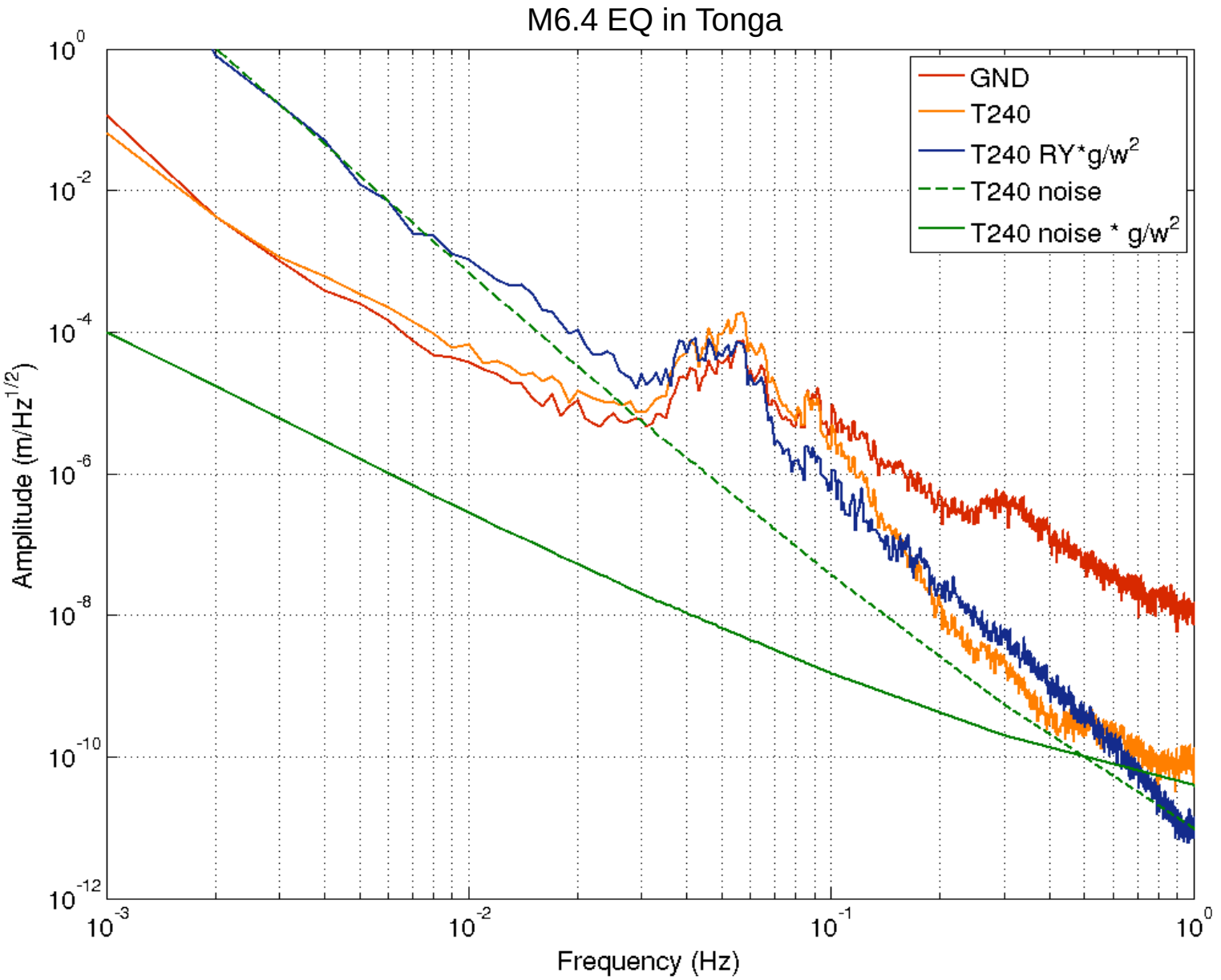
# Ratio of the ASDs

M6.4 EQ in Tonga



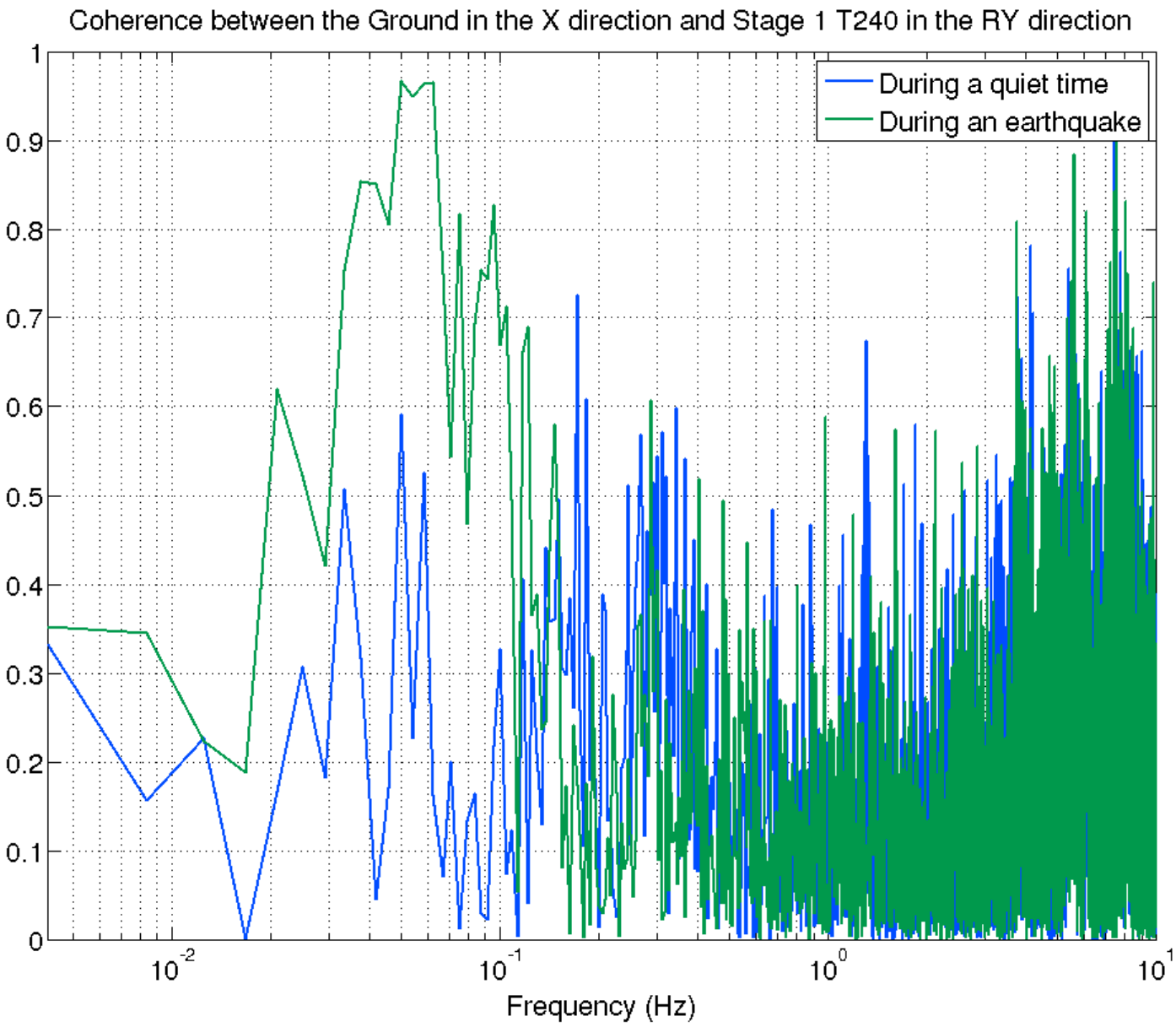

4. Same amplification seen on the platform. The platform is linear.

# Tilt or not tilt?

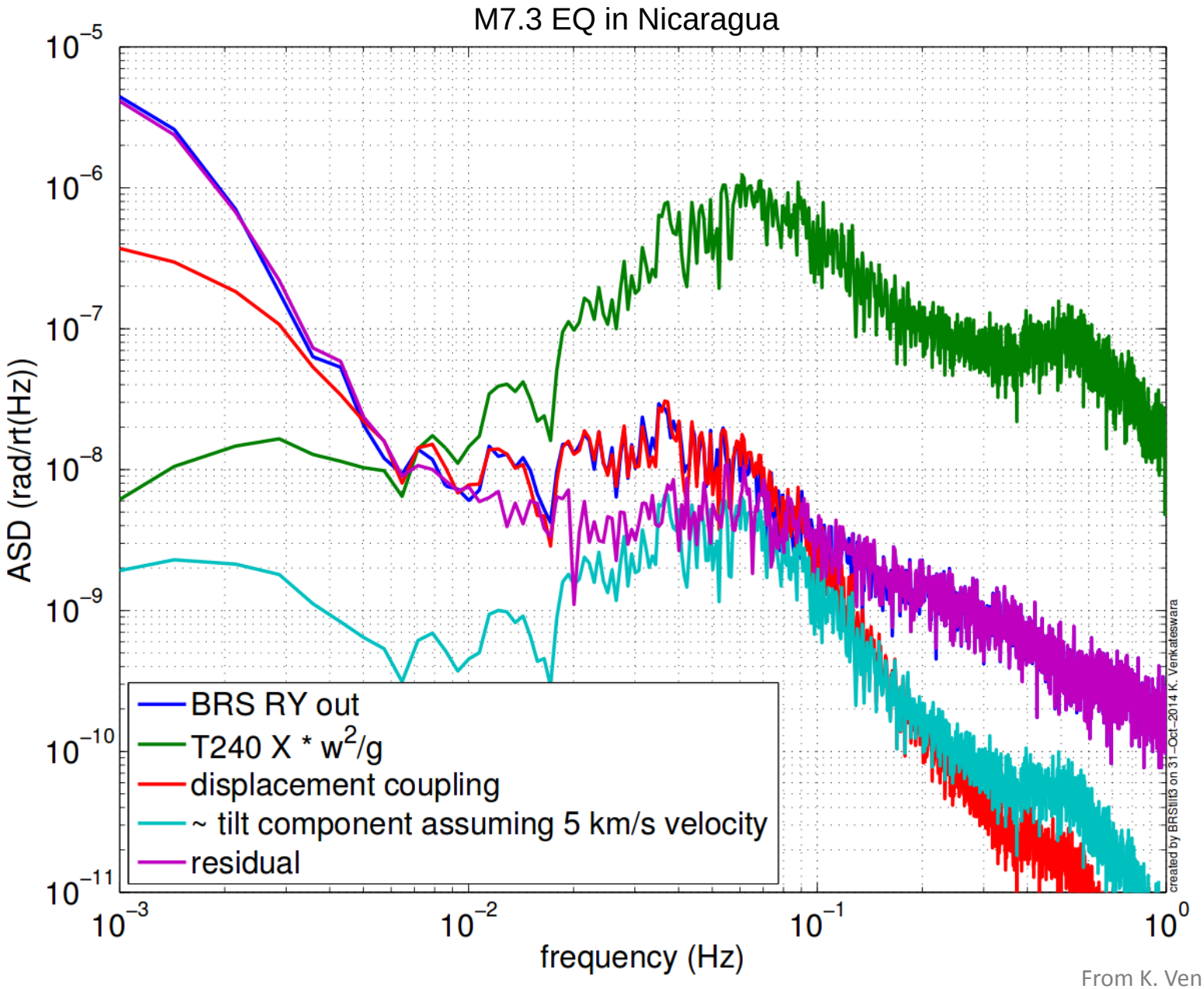



5a. A fair fraction of the amplification is induced by tilt

# Coherence between translation and rotation



# Tilt or not tilt?




From K. Venkateswara: alog 14766

5b. Earthquake creates pure translation

# Earthquakes consequences

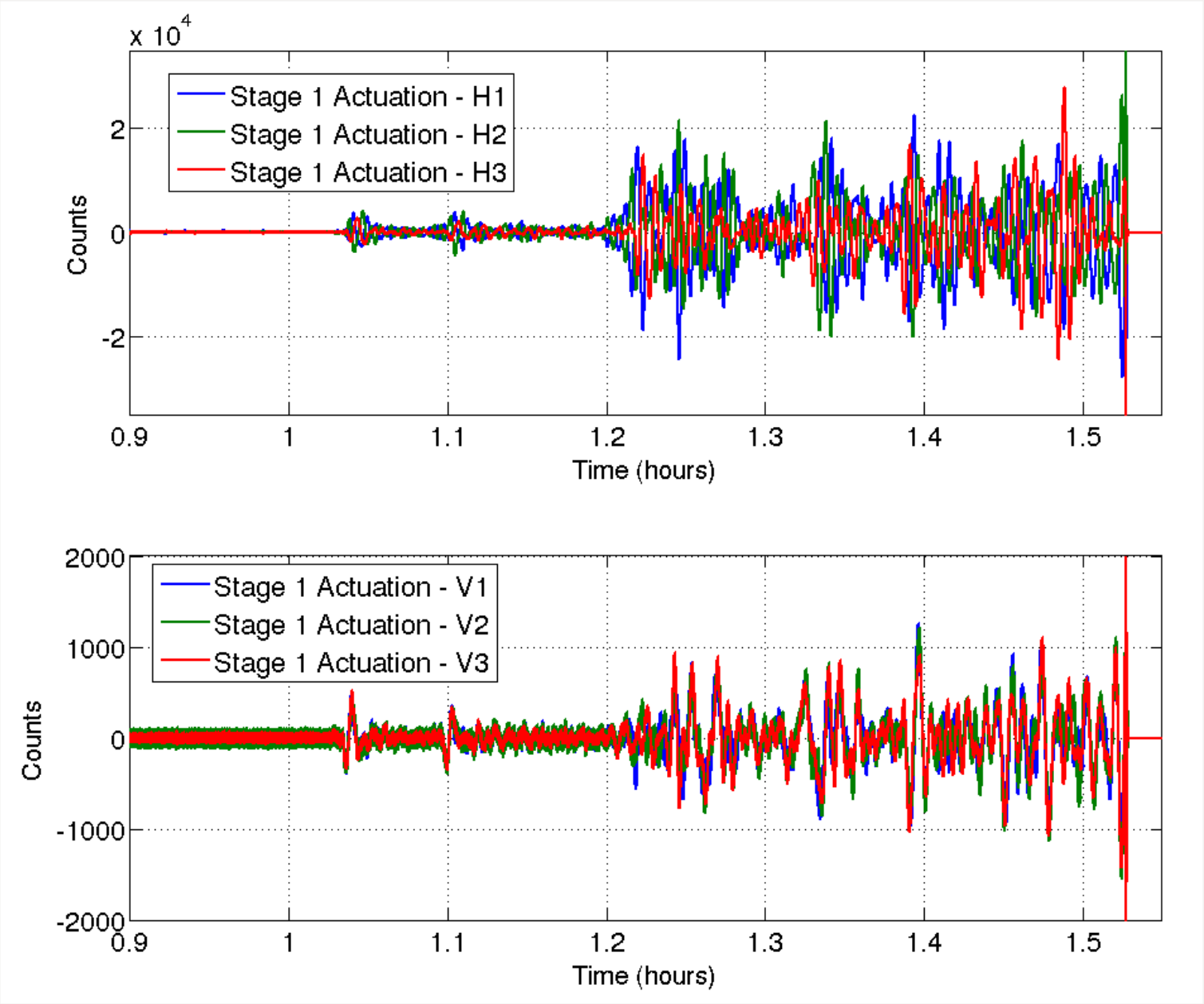
Earthquake characterization:

- Similar behavior LIGO/VIRGO
- Amplification of the ground motion below 150mHz
- The seismic platforms follow the ground at those frequencies
- Unclear if the motion created by earthquakes is mostly tilt or translation (depends on the earthquakes?). More analysis work needed.

Consequences:

- The seismic platforms are most likely to trip
- Platform trips occur on S-wave arrivals, or a combination of S-waves and surface waves
- Trips are almost always actuator based (**horizontal direction**)

# Platform trips




~30 minutes between the beginning of the EQ and the trip → time for reaction!

# Earthquake monitor

- Earthquake monitor developed by J. Harms and M. Coughlin.
- Developed in python.

- Two purposes:
  - estimate the arrival time of P-waves and S-waves
  - estimate the maximum amplitude of the event

- Estimate arrival times based on preliminary reference earth models (PREM)[1]
- Precision of 1-2 seconds

- Estimate amplitude based on experimental results (data from LHO during S5)
- Ended up with a 'semi-physical' equation that works for LHO

(1) Dziewonski, Adam M., and Don L. Anderson. "Preliminary reference Earth model." Physics of the earth and planetary interiors 25.4 (1981): 297-356.

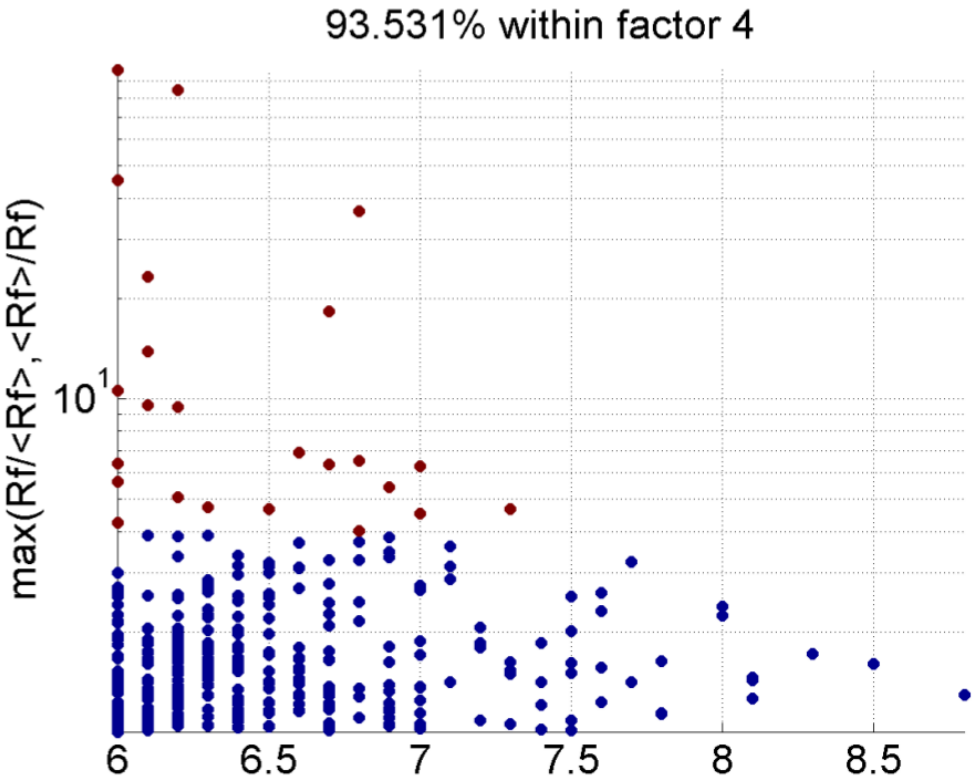
- Using equation (1), can predict the amplitude of an event by a factor of 4 (outliers are data issues)

# M = magnitude
# r = distance [km]
# h = depth [km]

# Rf0 = Rf amplitude parameter
# Rfs = exponent of power law for f-dependent Rf amplitude
# Q0 = Q-value of Earth for Rf waves at 1Hz
# Qs = exponent of power law for f-dependent Q
# cd = speed parameter for surface coupling [km/s]
# ch = speed parameter for horizontal propagation [km/s]
# rs

# exp(-2*pi*h.*fc./cd), coupling of source to surface waves
# exp(-2*pi*r.*fc./ch./Q), dissipation

fc = 10**(2.3-M/2)
Q = Q0/(fc**Qs)
Af = Rf0/(fc**Rfs)




*Comparison of fit to measurements at LHO*

Courtesy of M. Coughlin:
Document G1400811

(1) $$R_f = 10^{-3} * M * Af * e^{-2*pi*h*h*fc/cd} * e^{-2*pi*r*fc/ch/Q} / r^{rs}$$

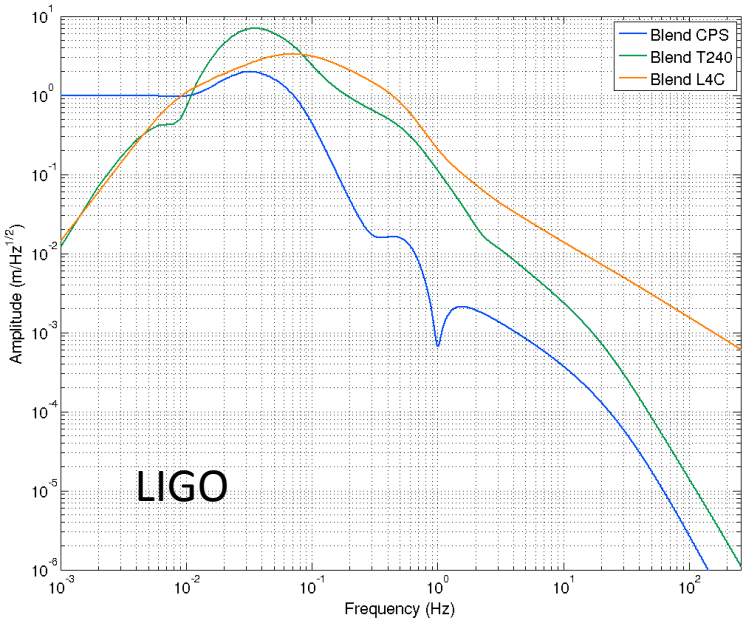
# Controls strategies

- Reducing the digital gain and increasing the analog gain of the actuators
- Two approaches

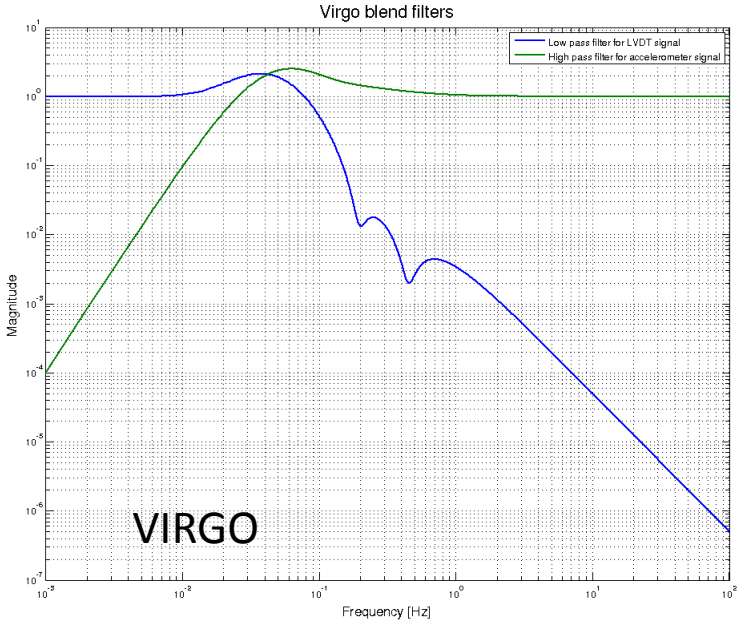
Increase the blend frequency (decrease control authority) to not actuate on the common ground displacement

Decrease the blend frequency (increase control authority) to exploit the extra motion created by the earthquake

If translation signal: decrease blend frequency on horizontal DOFs
If tilt signal: decrease blend frequency on rotational DOFs




Current blend frequency ~45mHz

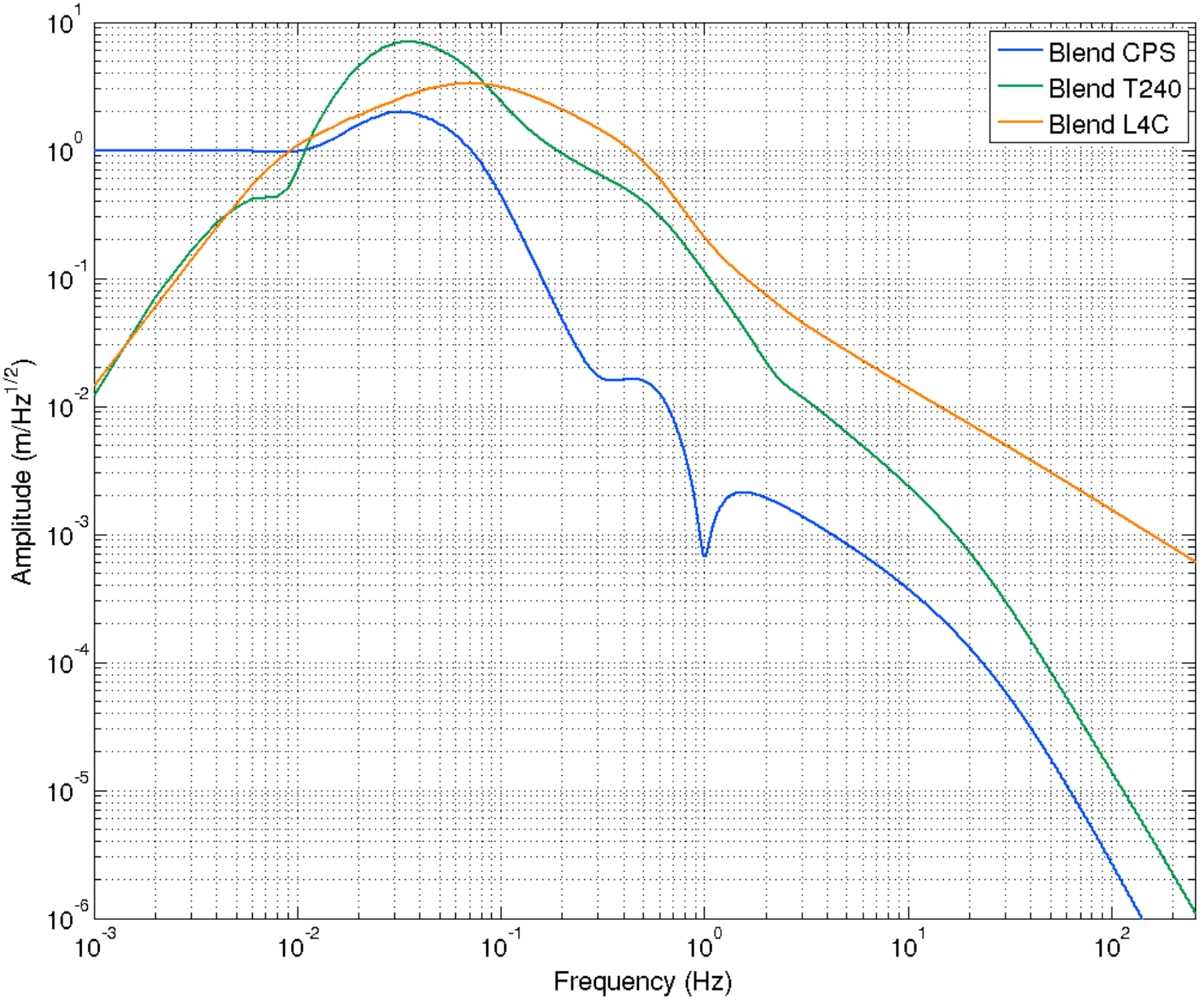


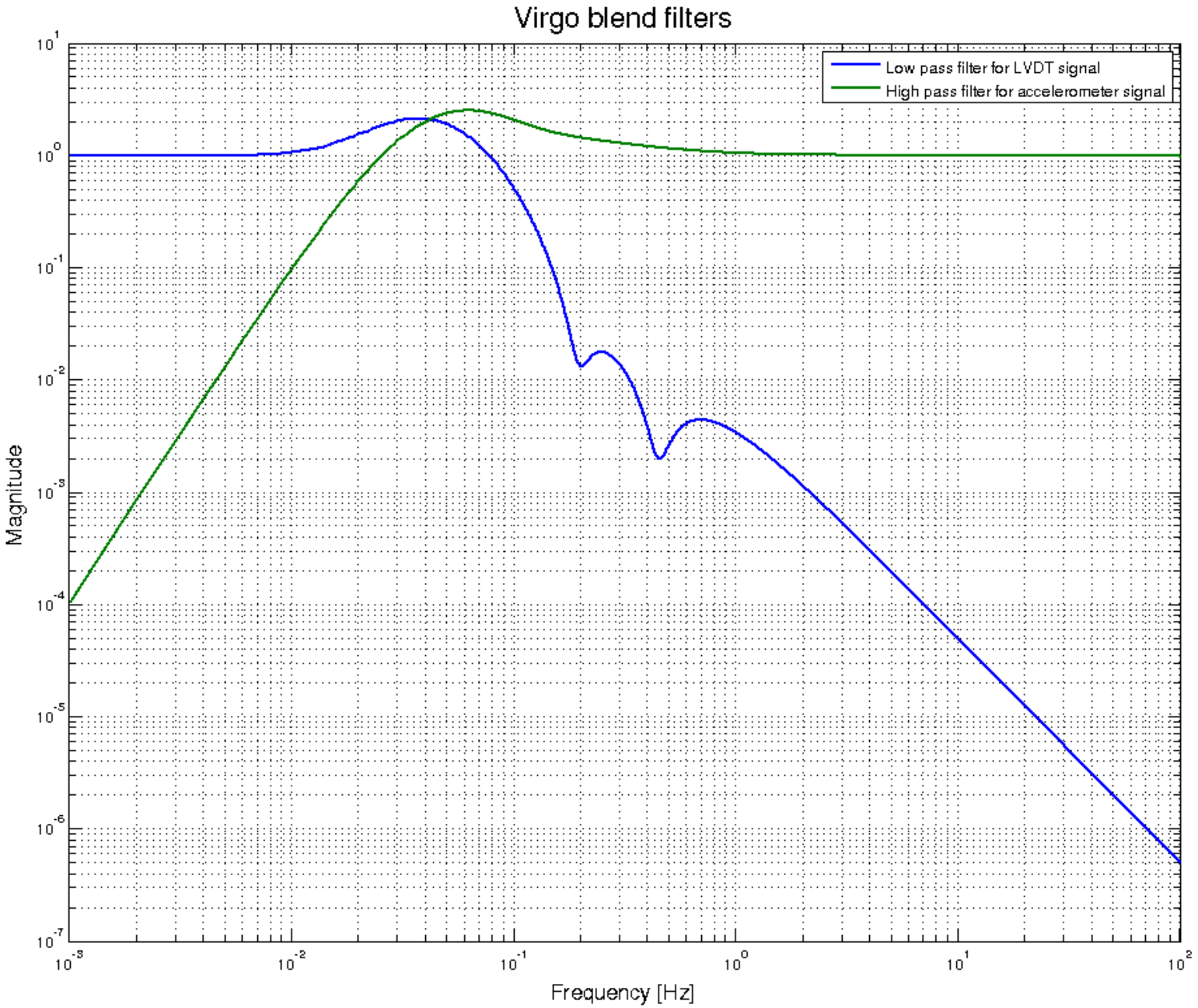
# Conclusion/Future work

- More analysis work is needed (repeatability, tilt, …). Each earthquake is different? Which earthquake (magnitude, location, …) could we react on?
- The viability of the Earthquake monitor needs to be tested outside LHO (MIT tests)
- An “earthquake blend” could be developed and tested at MIT (VIRGO?)
- Distant future: automatic configuration switching with the guardians

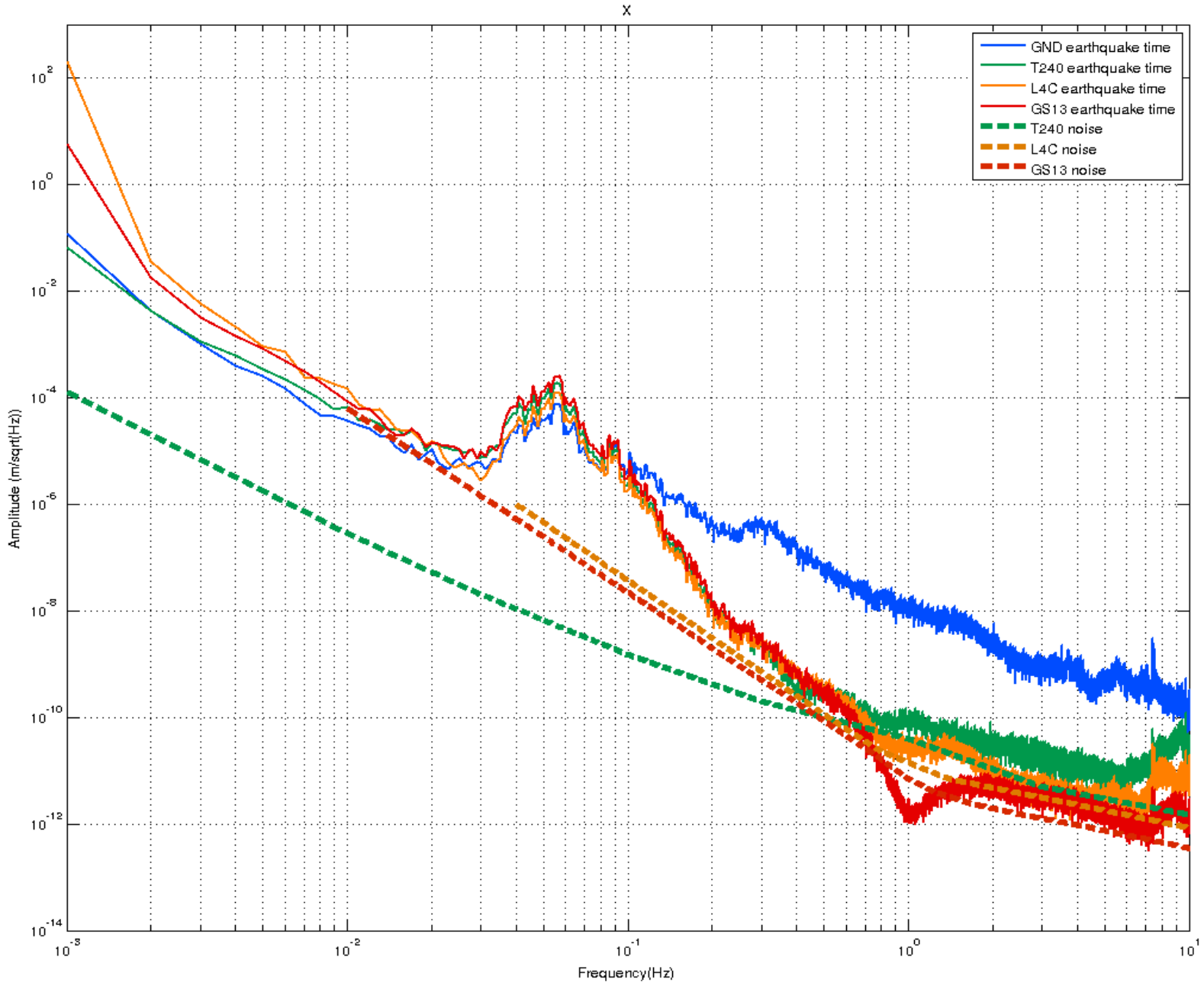
Thank you for your attention

Extra-slides

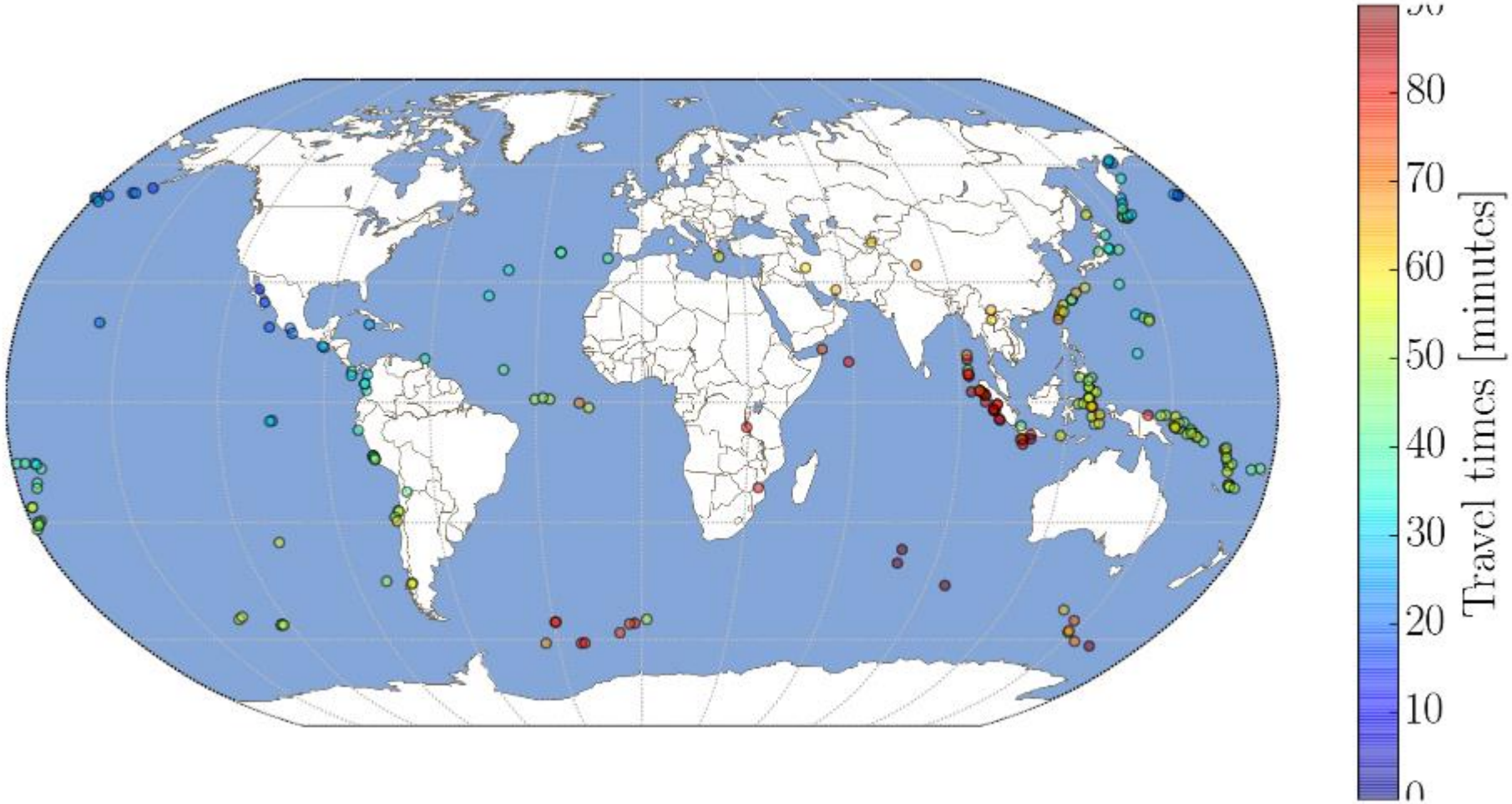

Blend CPS
Blend T240
Blend L4C
Amplitude (m/Hz^1/2)
Frequency (Hz)
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-3
10^-2
10^-1
10^0
10^1
10^2


Virgo blend filters
Low pass filter for LVDT signal
High pass filter for accelerometer signal
Magnitude
Frequency [Hz]
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-3
10^-2
10^-1
10^0
10^1
10^2

# Earthquake in Tonga



# Earthquake monitor



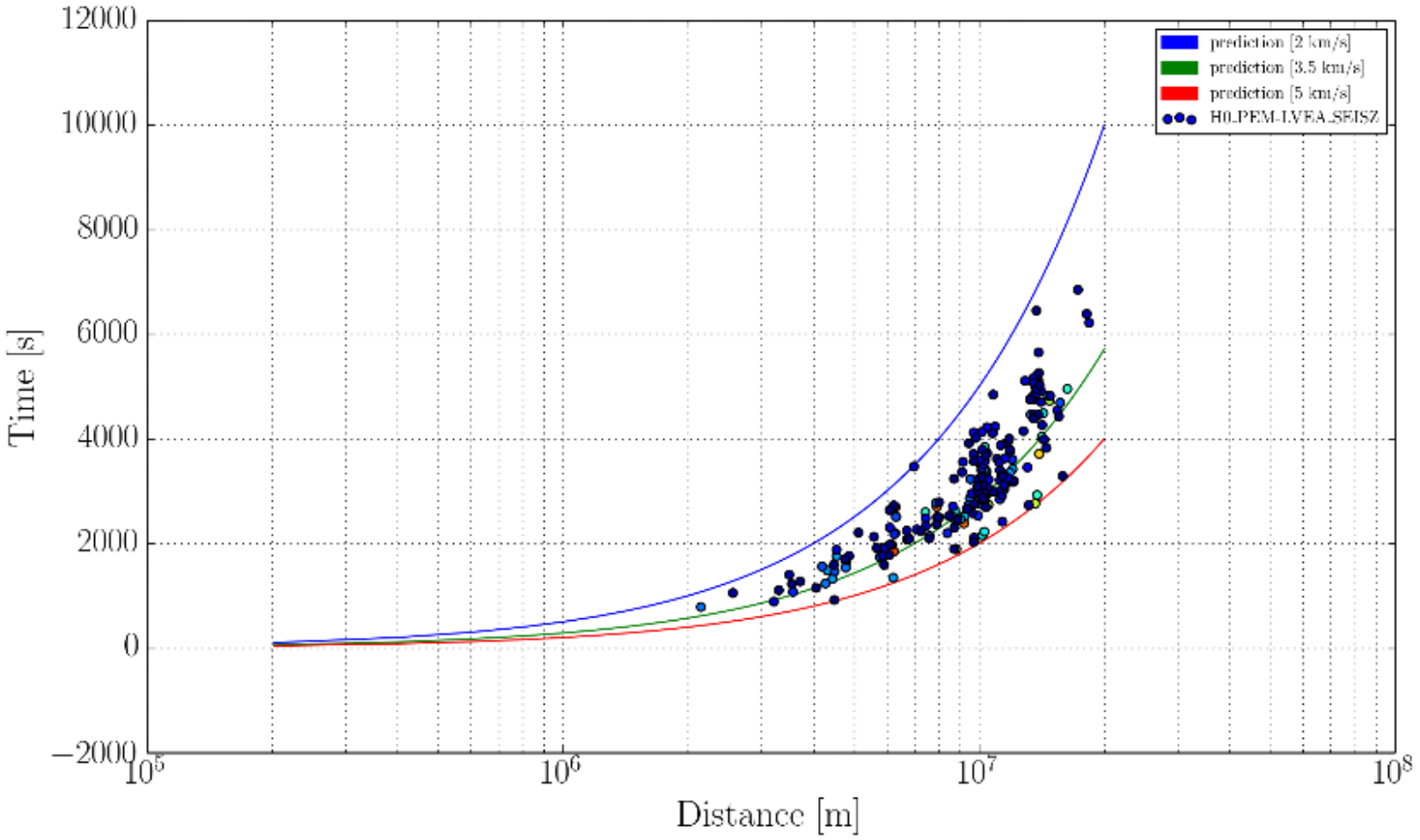

Travel times of peak seismic waves at LHO during S5

Courtesy of M. Coughlin: Document G1400811

# Earthquake monitor

Take the amplitude the peak low-passed time-series of the seismometer data between 2 and 5 km/s

Wave velocities slightly below 3.5 km/s on average

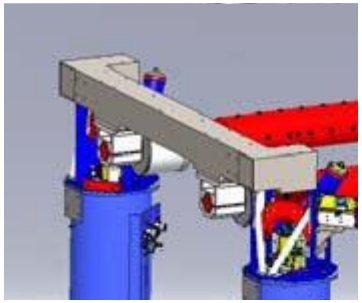


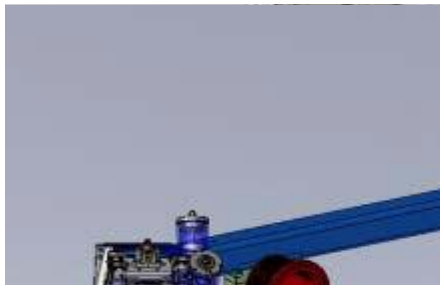

Courtesy of M. Coughlin: Document G1400811

# Status

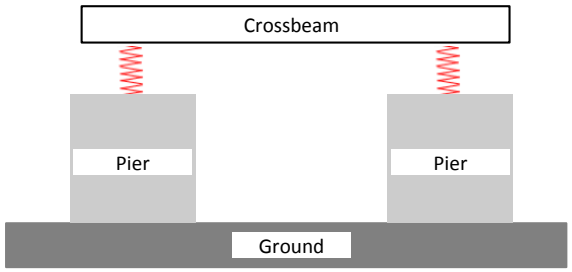
## HAM-HEPI/BSC-HEPI

Hydraulic External Pre Isolator (33 units)





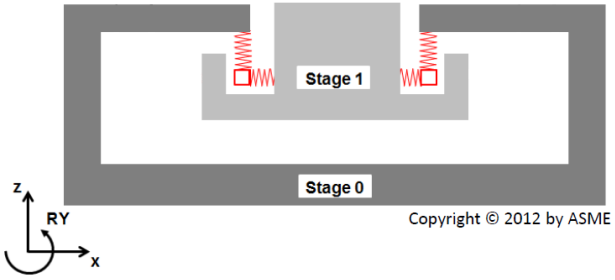
- Out of vacuum
- Hydraulically actuated
- Not much passive isolation (highly damped)
- Provides positioning and DC alignment
- Provides active isolation between ~0.1Hz and 10 Hz




## HAM-ISI

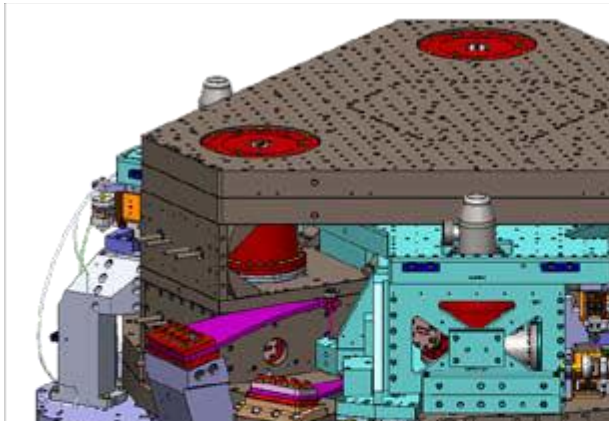
Single Stage Internal Seismic Isolator (15 units)

- In vacuum
- Electromagnetically actuated
- Single stage of passive isolation (above ~1.8Hz)
- Provides positioning and DC alignment
- Provides active isolation between ~0.1Hz and 350Hz

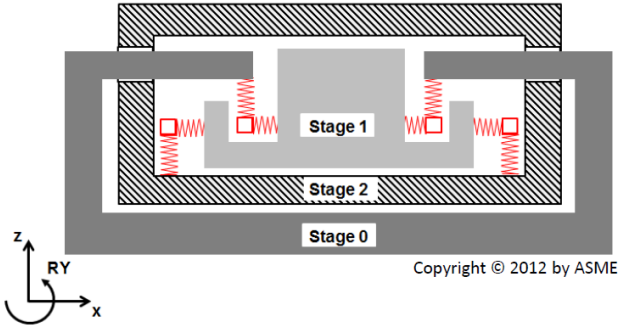



## BSC-ISI

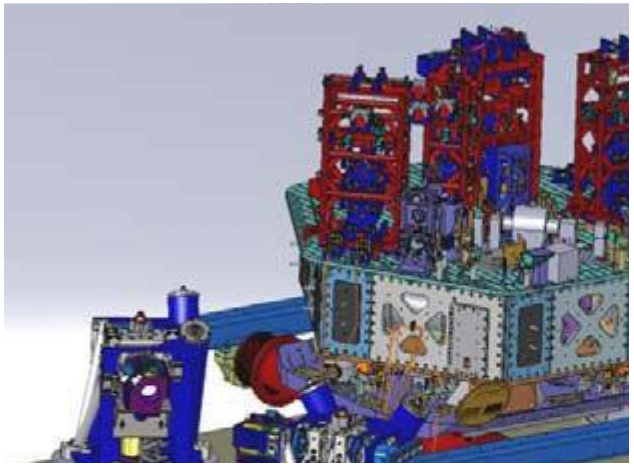
Two-Stages Internal Seismic Isolator (15 units)

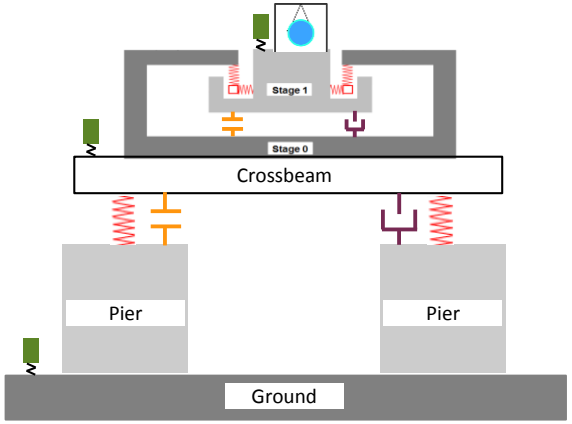


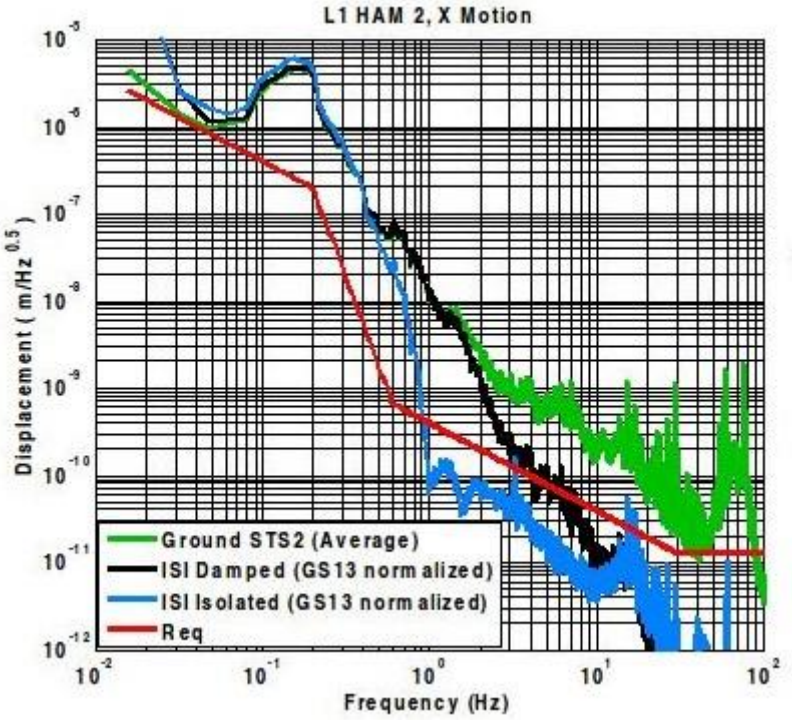
- In vacuum
- Electromagnetically actuated
- Two stages of passive isolation (above ~7Hz)
- Provides positioning and DC alignment
- Provides active isolation between ~0.1Hz ar

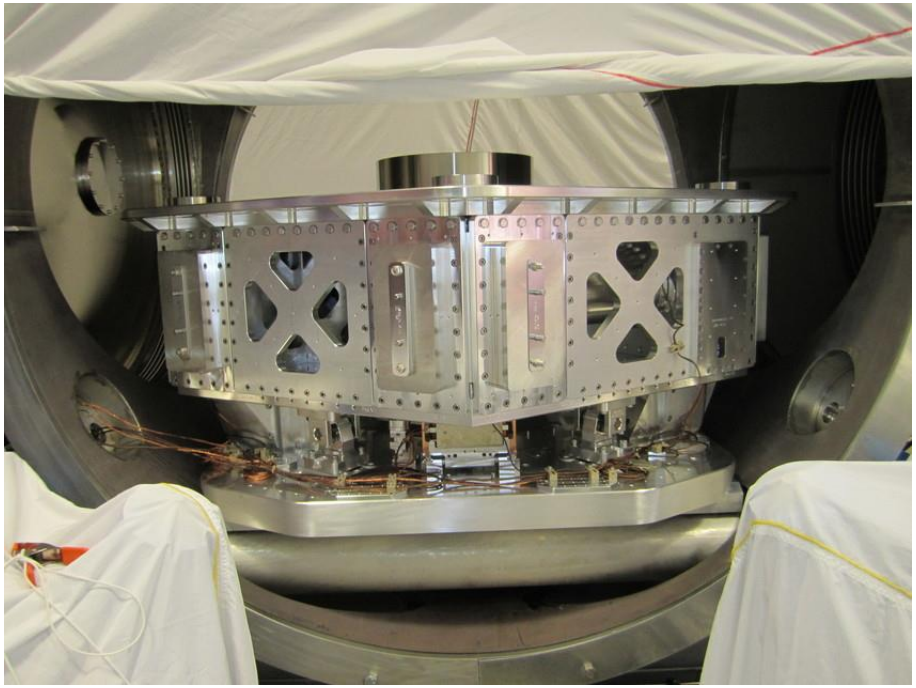


## HAM Chamber Layout & Configuration



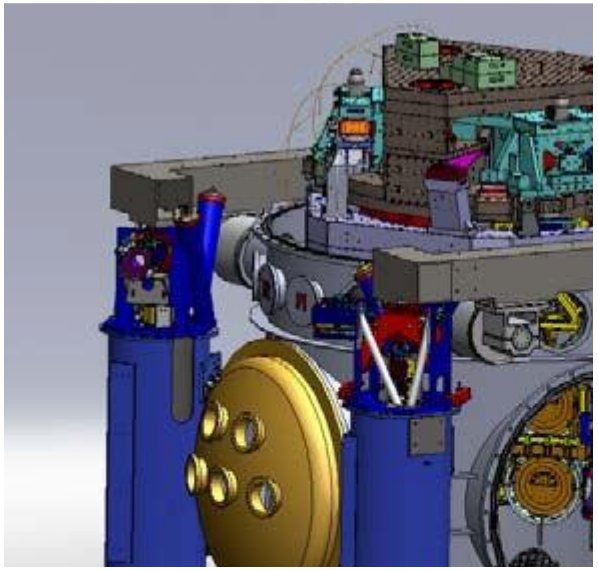


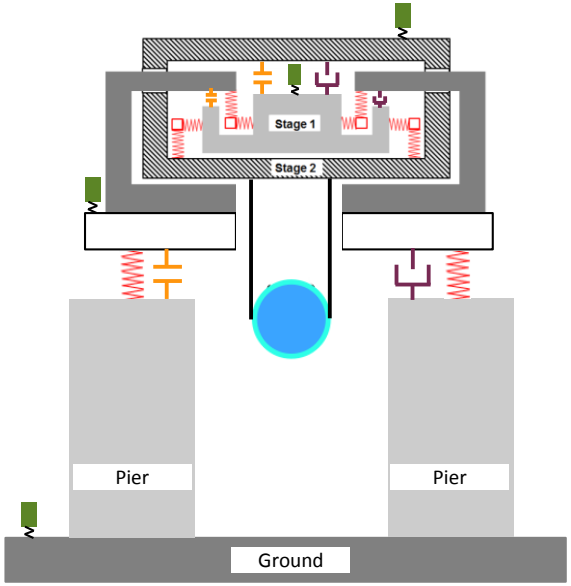



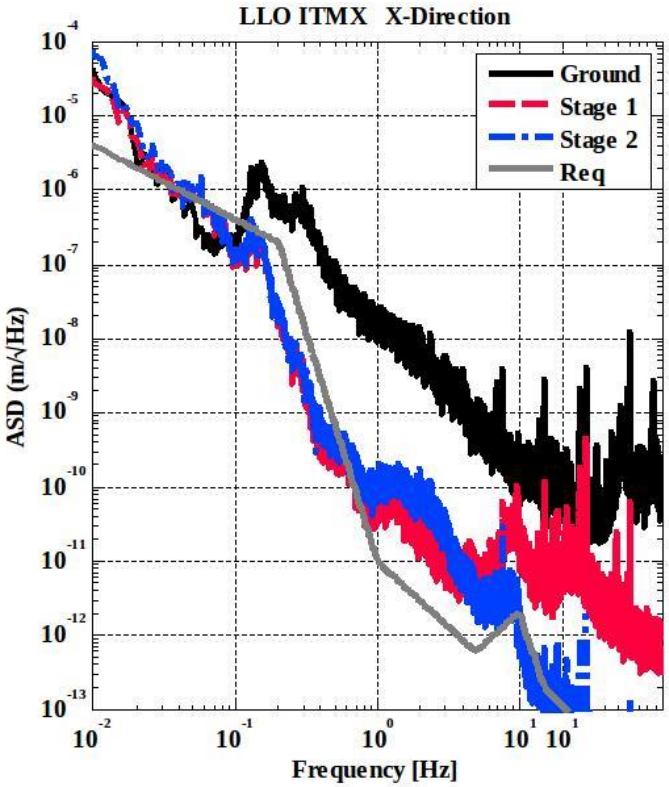



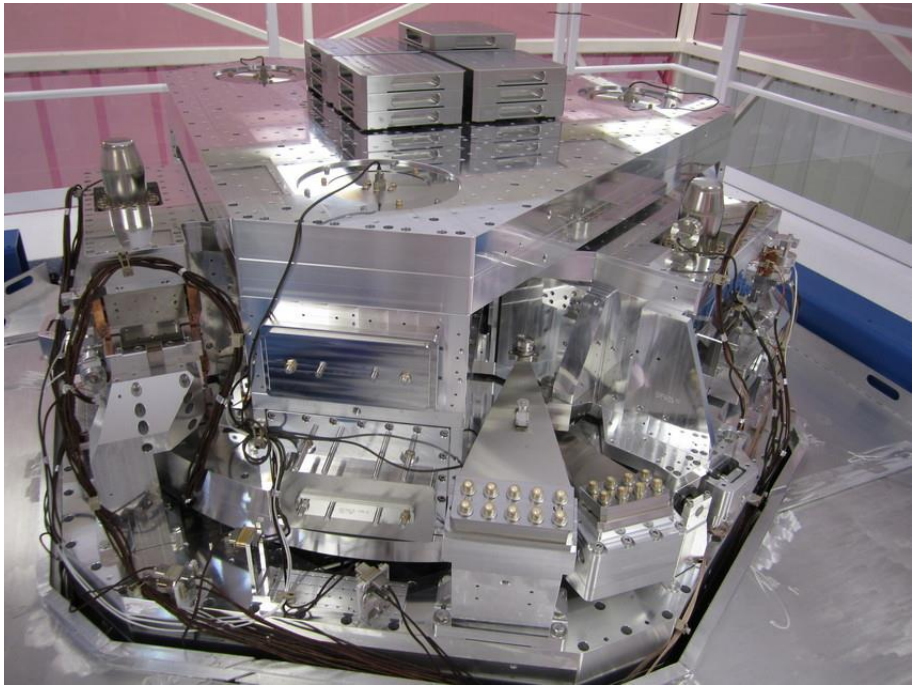
# Status

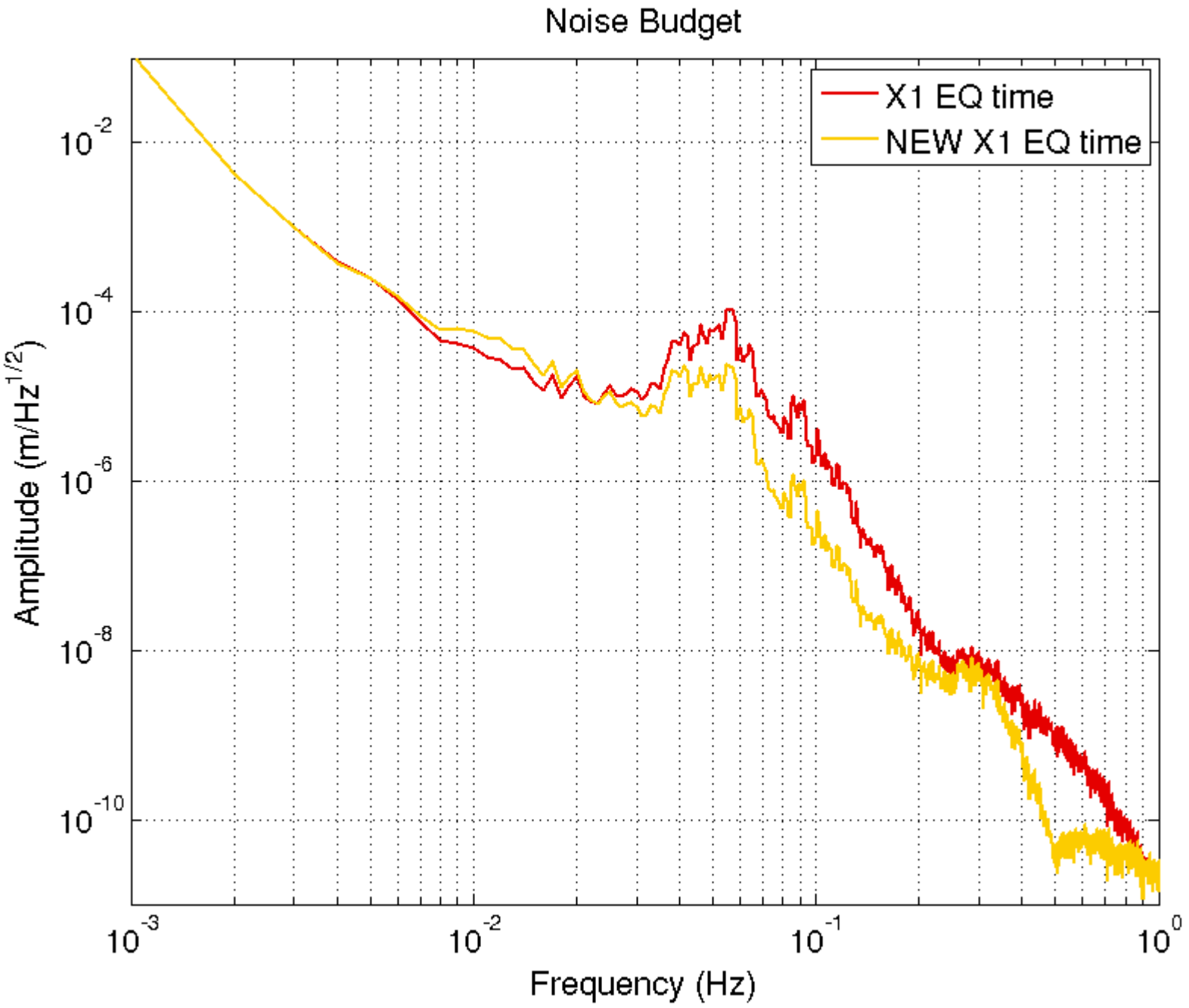
## BSC Chamber Layout & Configuration






Noise Budget
X1 EQ time
NEW X1 EQ time
Amplitude (m/Hz^1/2)
10^-2
10^-4
10^-6
10^-8
10^-10
10^-3
10^-2
10^-1
10^0
Frequency (Hz)

# Status

- **All the units have been installed and commissioned at both sites**