LIGO

IMPROVING FREQUENCY STABILIZATION FOR THE AUXILIARY LASER

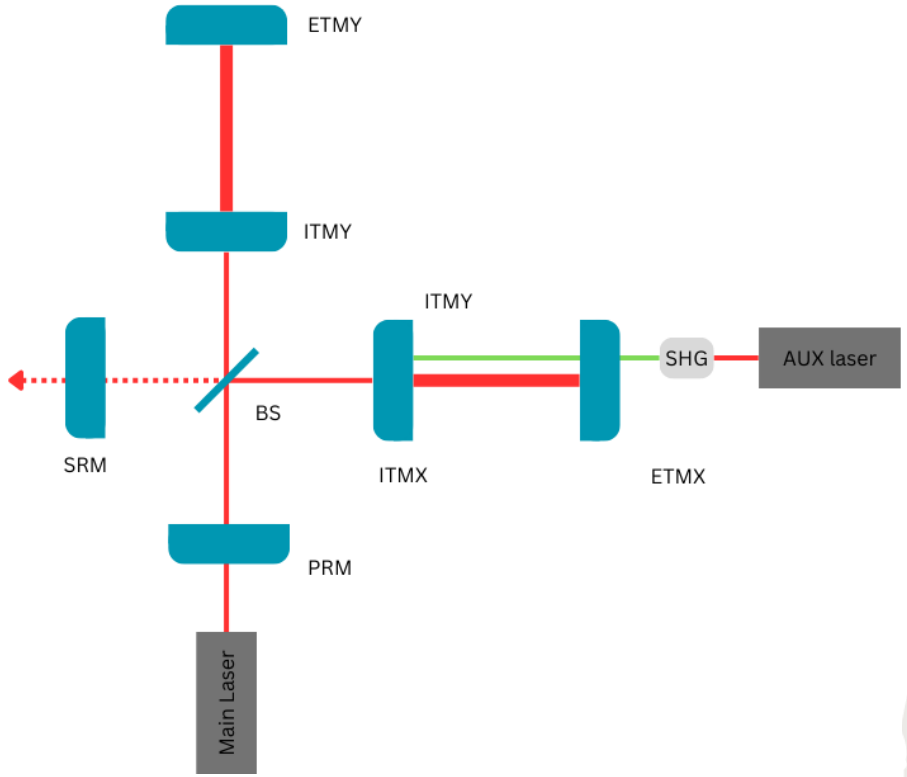
Reuben S Mathew

Mentors: Radhika Bhatt, Rana Adhikari, Paco

LIGO

THE 40M LIGO LAB

- 1:100 scale model of the 4km long LIGO observatories
- Testbed for improvements to the detector
- Run smaller scale experiments
- Michelson interferometer with Fabry Perot cavities and power recycling mirrors
- Multiple degrees of freedom to sense and control
  - Differential arm length
  - Common arm length
  - Michelson
  - Power recycling cavity length
  - Signal recycling cavity length

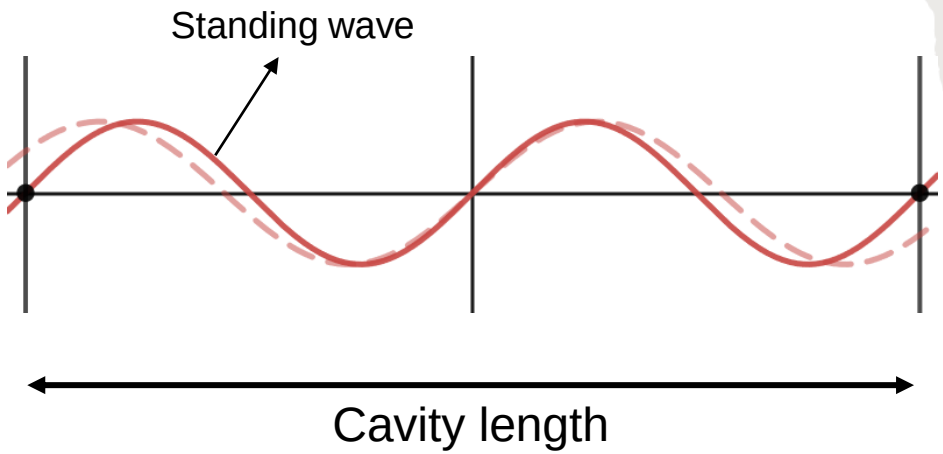


Overview of the interferometer, with AUX laser

LIGO

ARM LENGTH STABILIZATION

- Reference auxiliary (AUX) green (532nm) laser locked to arm cavity
- The wavelength of laser should resonate with the cavity length
- Transmission maximum when locked
- Cavity length integer multiple of half wavelength

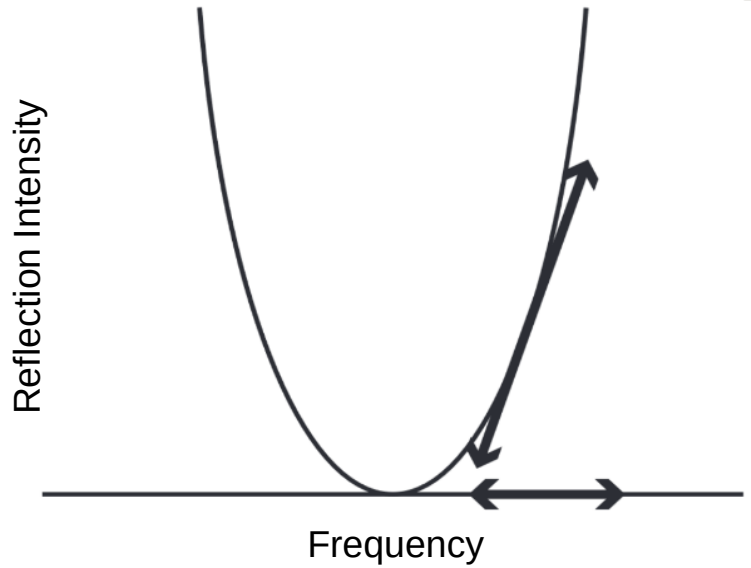


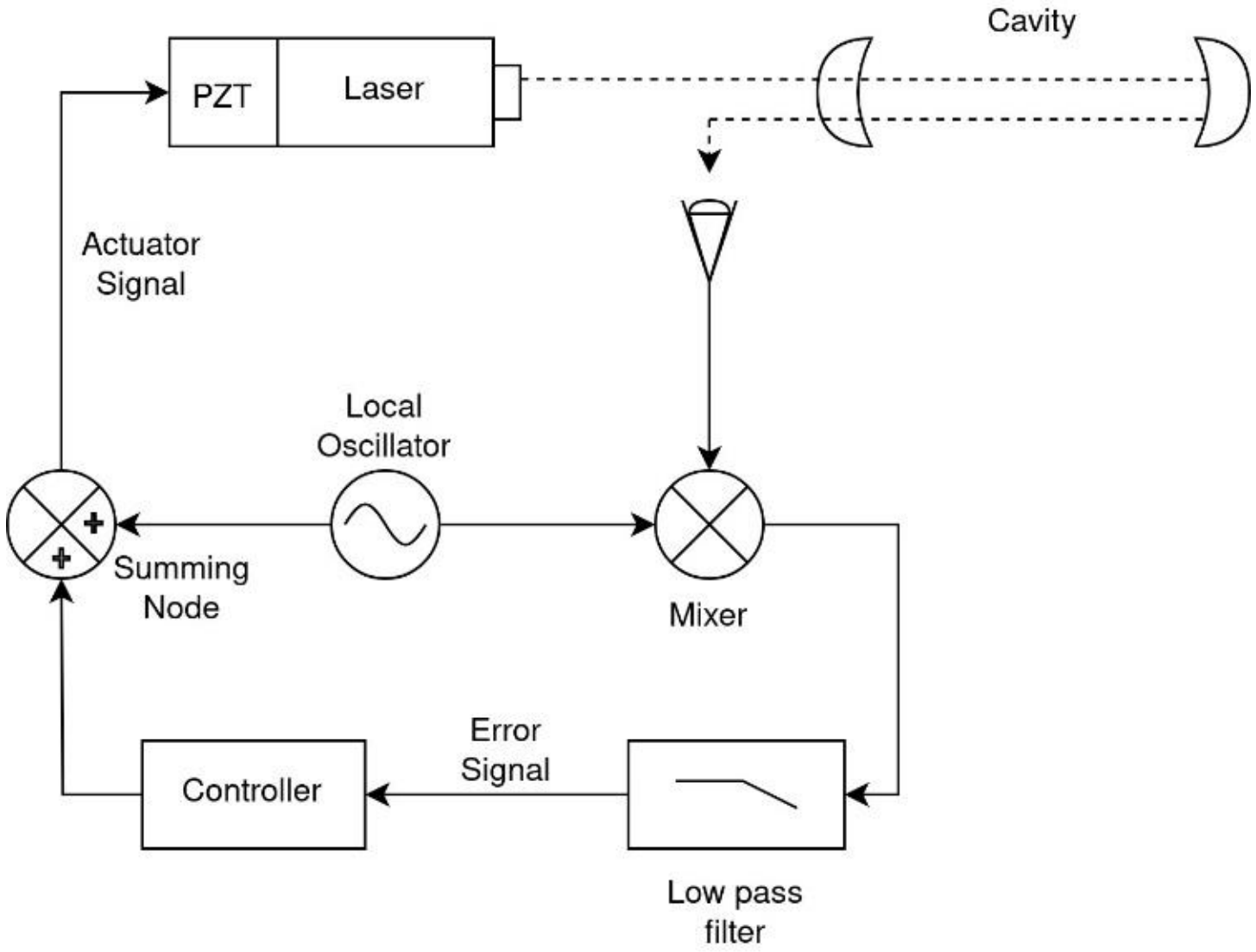
- Track arm cavity length
- Used as reference to lock arm cavity to main laser (IR) (1064nm)
  - Sum with AUX green SHG IR
  - Beat note error signal for main laser locking
- **Better stabilization of AUX laser ⇒ Better stabilization of cavity arm length**

LIGO

AUX LASER LOCKING – POUND DREVER HALL (PDH) METHOD

- Lock the laser to cavity by adjusting laser frequency
- Track change in cavity length by keeping track of change in frequency
- Sense the reflectivity, use as error signal to adjust frequency
- Reflected light is an even error signal, can't say which side of resonance
  - Take derivative of intensity
  - Move frequency up and down to see which direction intensity changes
  - Modulate frequency, pass output through mixer and low pass filter – error signal!
  - Cavity noise measured with error signal
  - Piezoelectric on laser adjusts frequency by changing length of resonant cavity
- **PDH locking method gives odd error signal**





AUX laser locking schematic

LIGO

GOAL OF THE PROJECT

- Currently the 40m uses an analog universal PDH (uPDH) box to lock the green laser
- Improve the current analog uPDH box with a digital implementation
- Improve **performance** of controller
  - faster lock and reduced noise
  - Add resonant gain filters to aid calibration of detector
- Achieve **better control** over filter, filter switching, new filters can be implemented easily, new **features**
- AUX laser dominates beat note noise in 10Hz-2kHz range – aim to improve noise reduction in this range – more focus in this range
- Increase unity gain frequency, broader frequency range which system can respond to

Complete PDH Setup at XEND

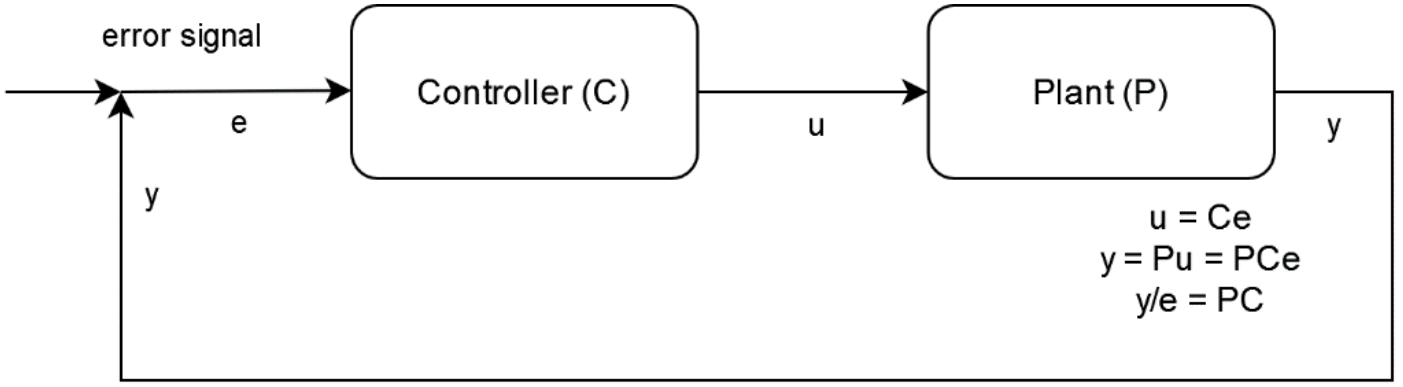
Analog uPDH box at 40m XEND

Moku:Go

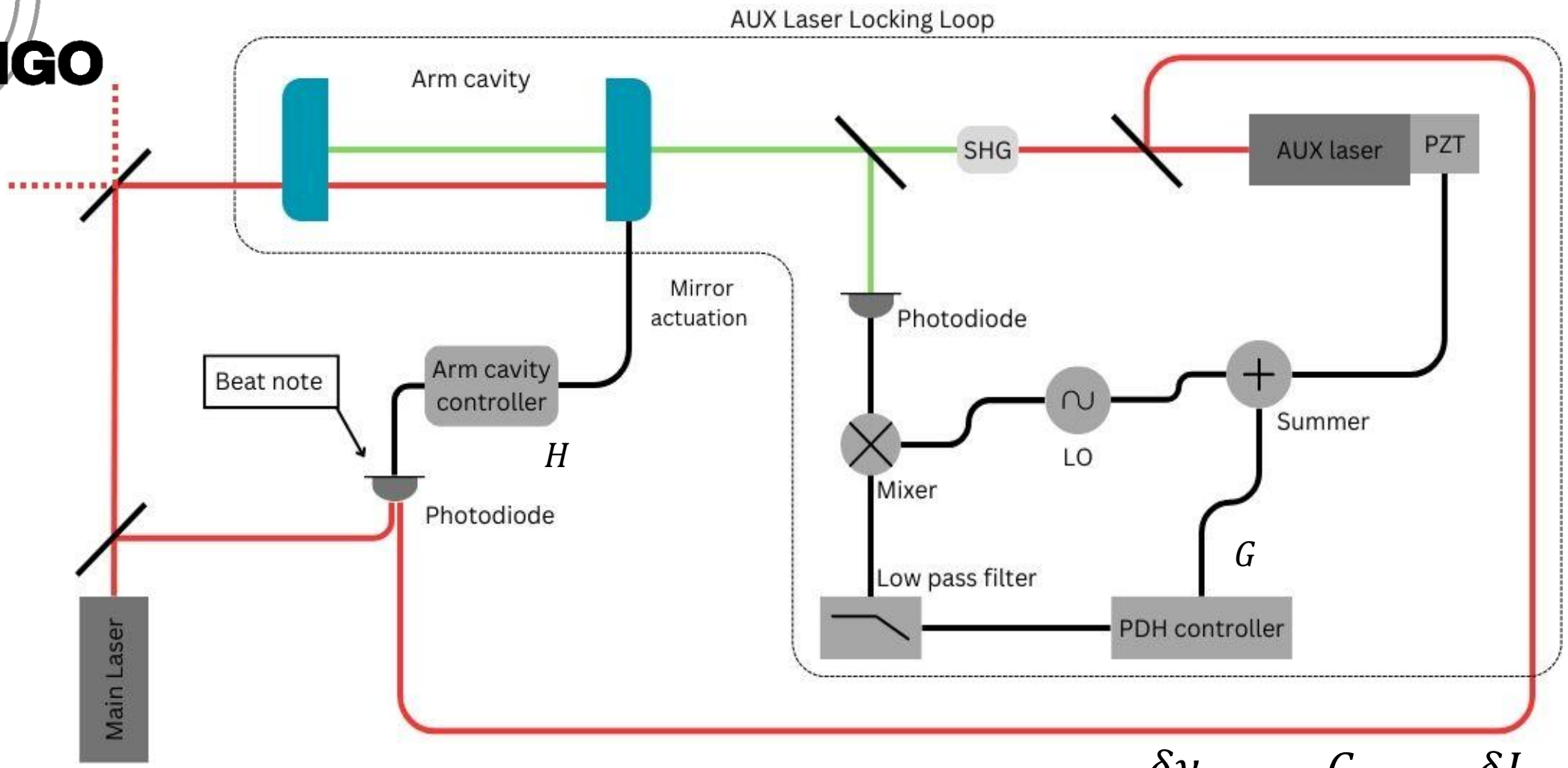
LIGO

CHARACTERIZING FEEDBACK LOOP

- **Open loop transfer function** of feedback loop
  - Algebraic product of transfer function of individual blocks of system
  - Inject disturbance into error signal and measure signal just before and after injection point (frequency response)
  - Measure **performance**, stability margins
  - Used to fit model parameter
  - Excitation injected with loop closed
- Moku:Go frequency response analyzer tool to calculate frequency response
- Transfer function of analog uPDH box
  - Used to fit poles and zeroes for model parameter and test initial digital controller



Simple block diagram for a feedback loop



Overview of ALS system

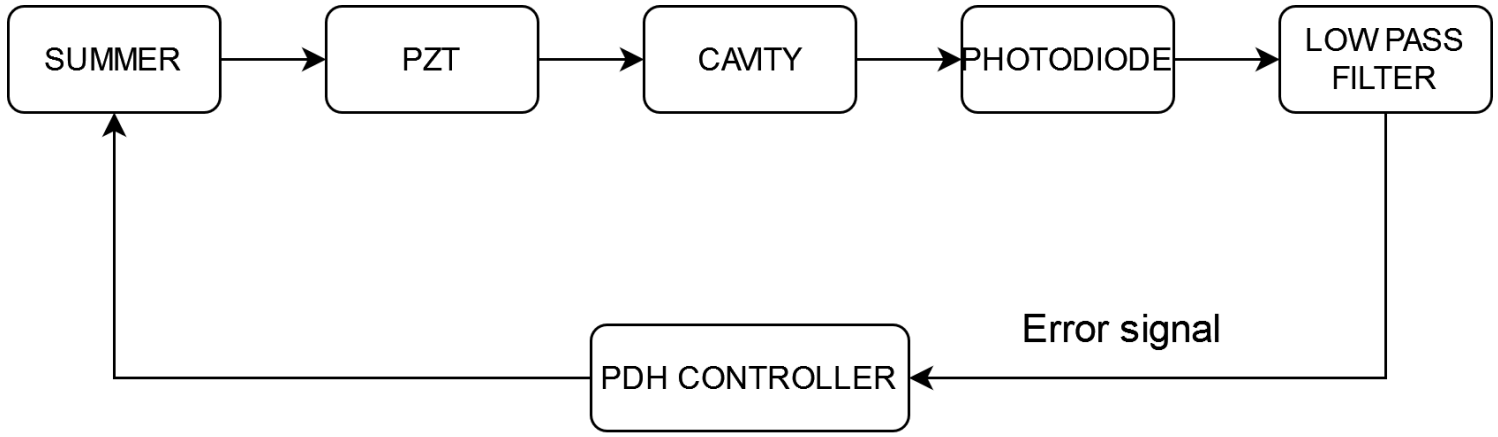
$$\frac{\delta \nu_g}{\nu_g} = \frac{G_{ol}}{1 - G_{ol}} * \frac{\delta L_x}{L_x}$$

$$\frac{\delta L_x}{L_x} = \frac{H_{ol}}{1 - H_{ol}} * \frac{\delta \nu_m}{\nu_m}$$

LIGO

MODELLING OF SYSTEM

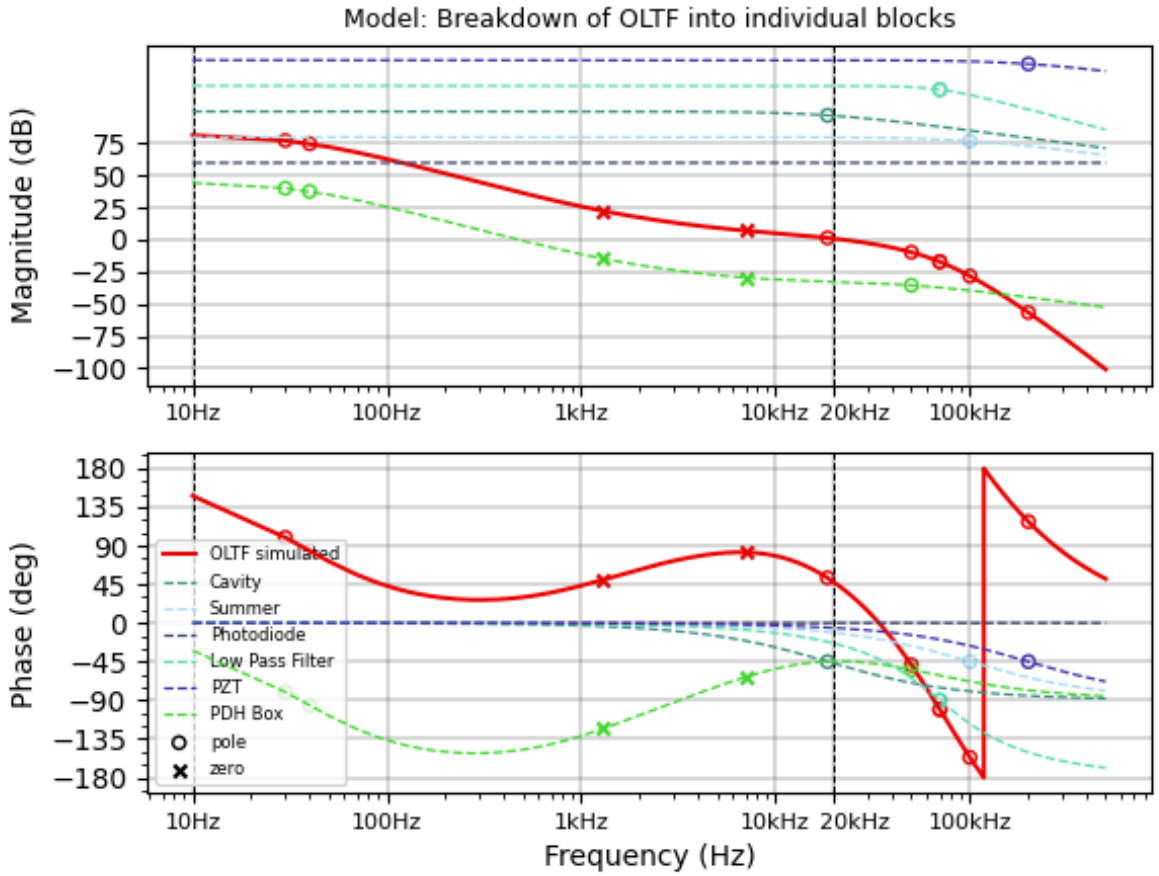
- Python controls library, model blocks of plant as transfer function
- Use measured open loop and uPDH box transfer function along with poles and zeroes from Gautam Venugopalan's thesis to model
- Chains the blocks together using control library, find open loop, closed loop transfer function, stability margins
- **Use this model to test performance and stability margins of new PDH controllers by just plugging its values into the system**

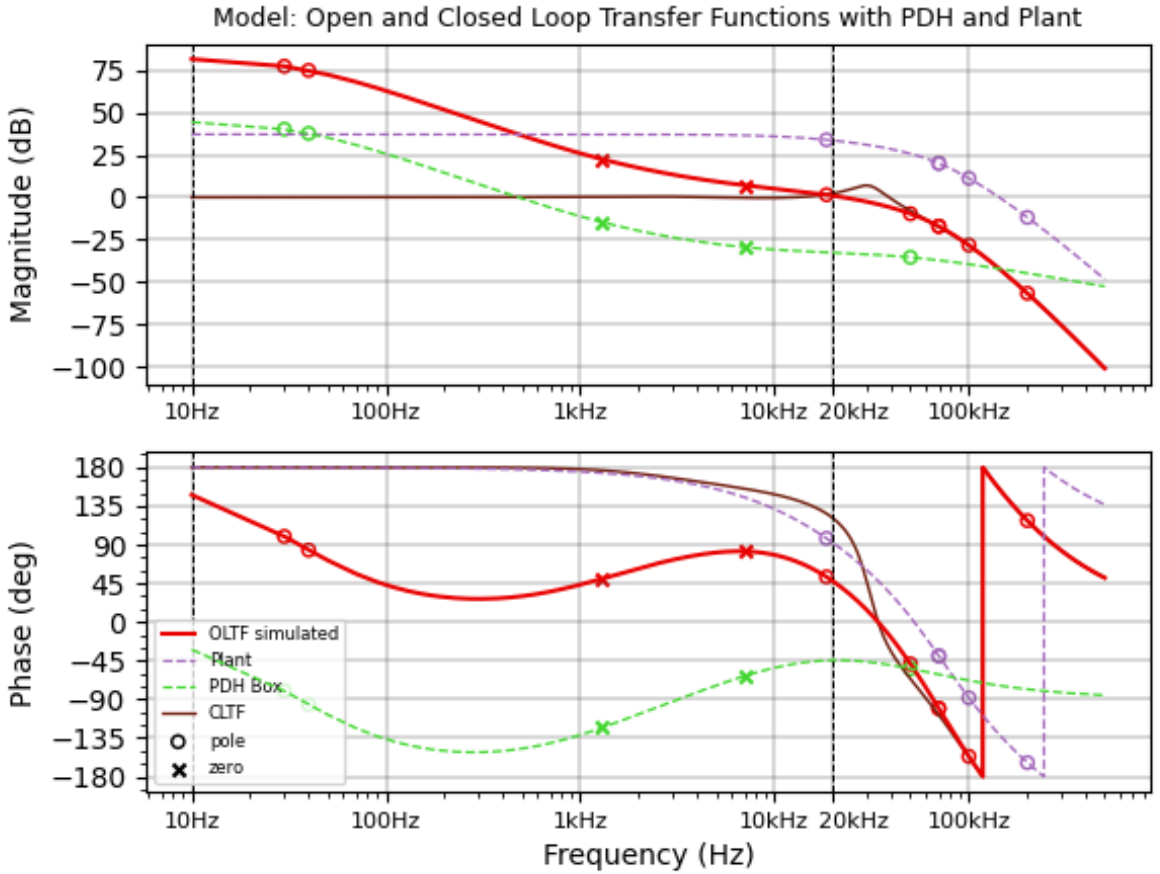


Block diagram of control loop

LIGO

BODE PLOTS OF MODELLED SYSTEM

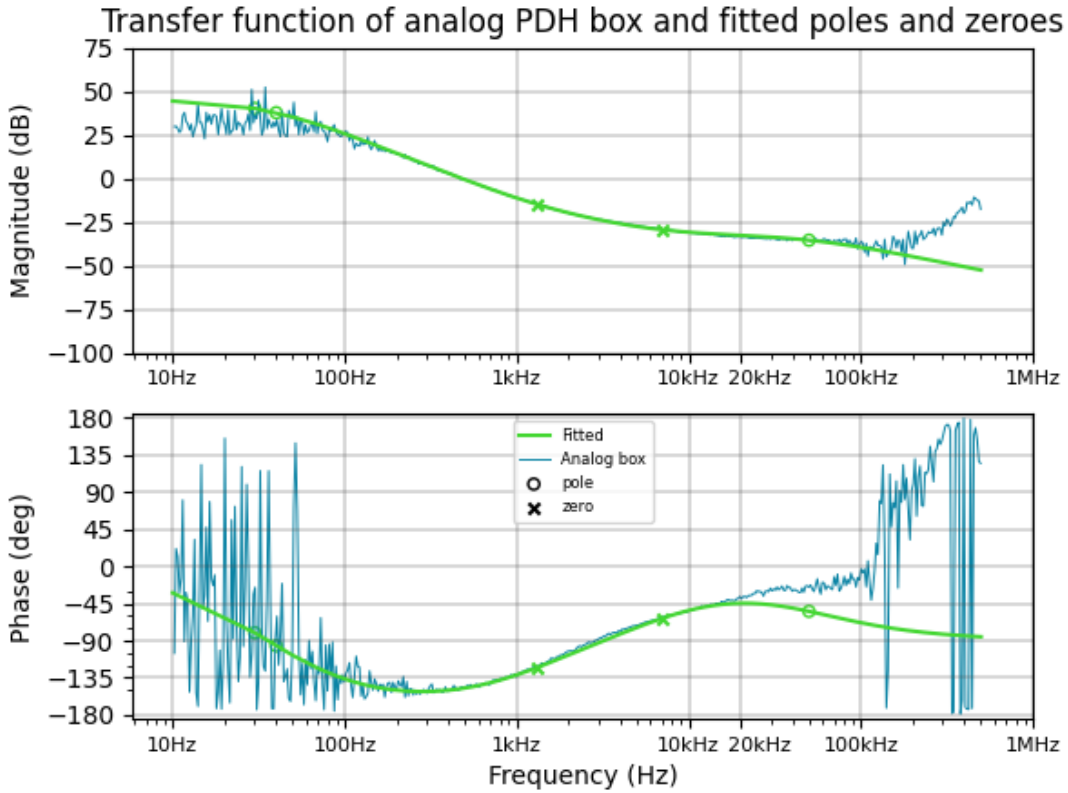


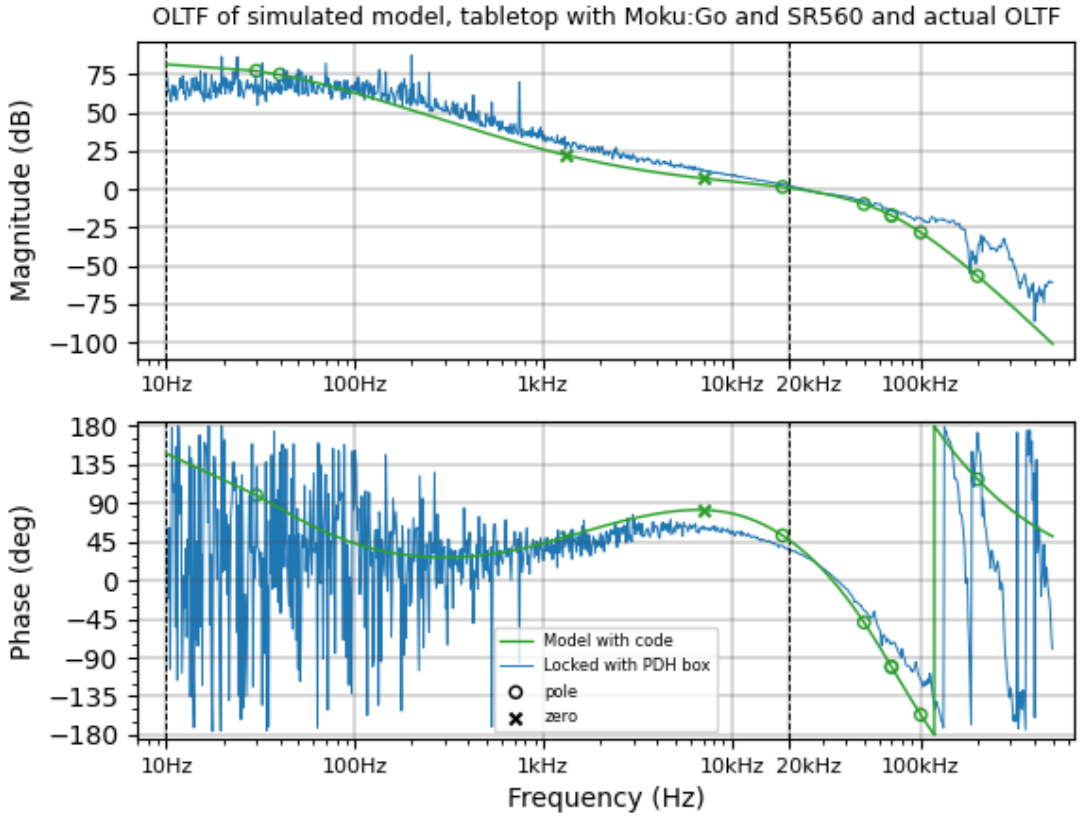


- Low frequency characteristics dominated by PDH controller
- Better PDH controller design to improve low frequency performance

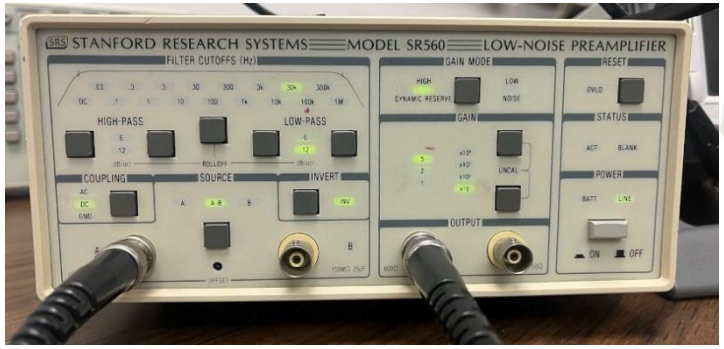
LIGO

COMPARISON BETWEEN MEASURED AND MODELLED SYSTEM



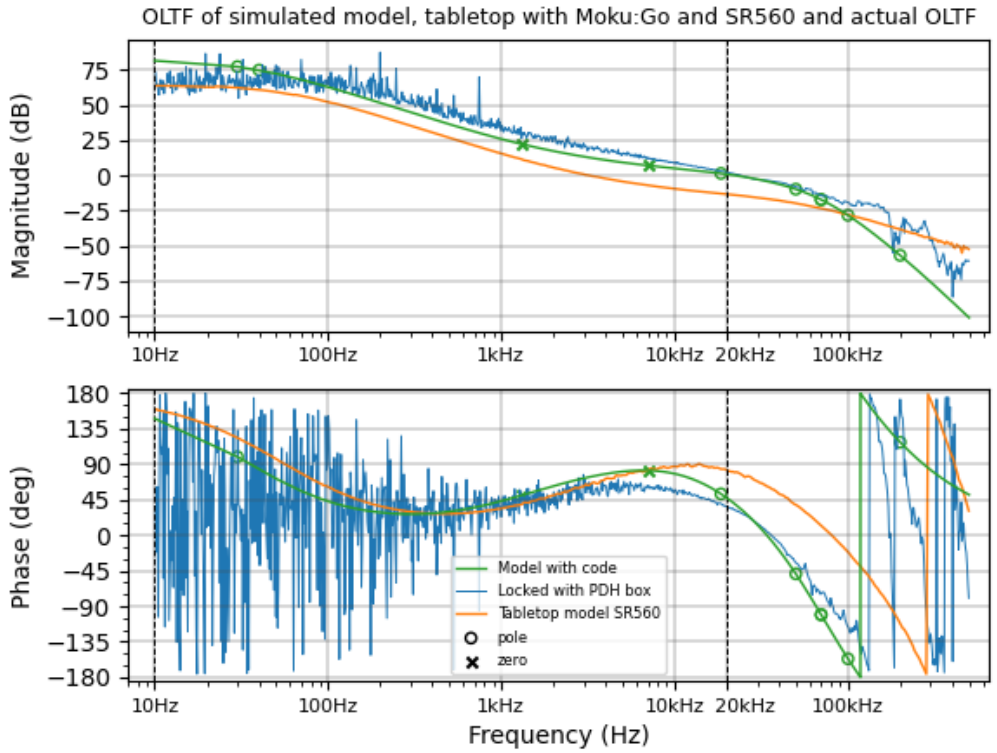


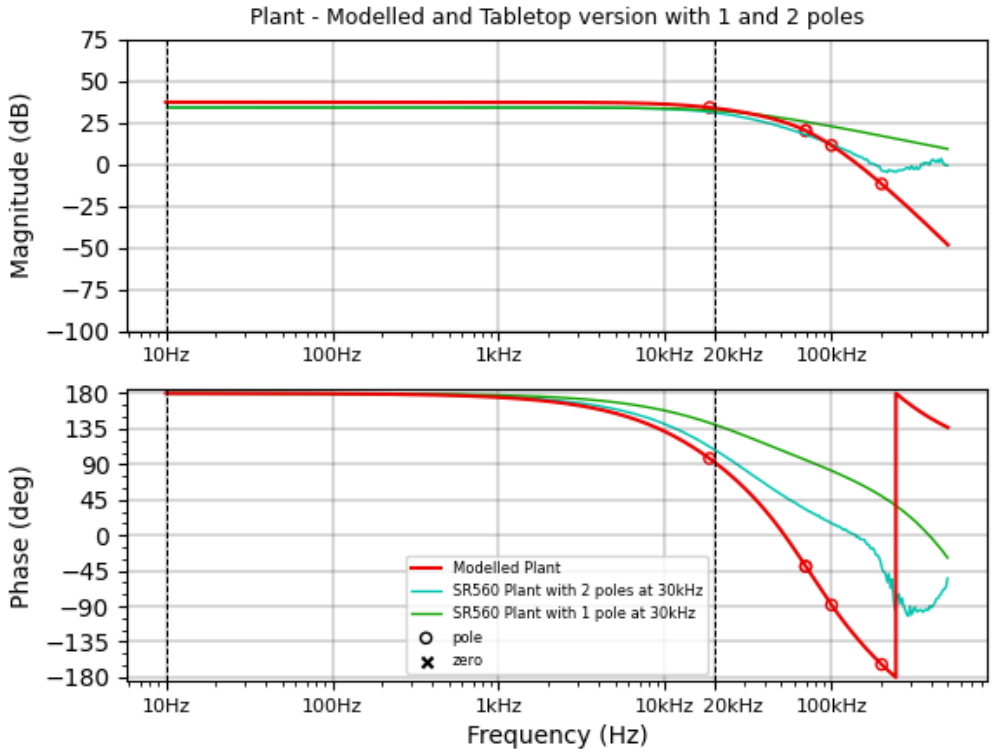
TABLETOP CAVITY



SR560 Preamplifier

- Use an SR560 preamplifier to simulate poles of system
- Two poles at 30kHz, similar transfer function of modelled plant
- Deviation due to not enough poles to count for all components



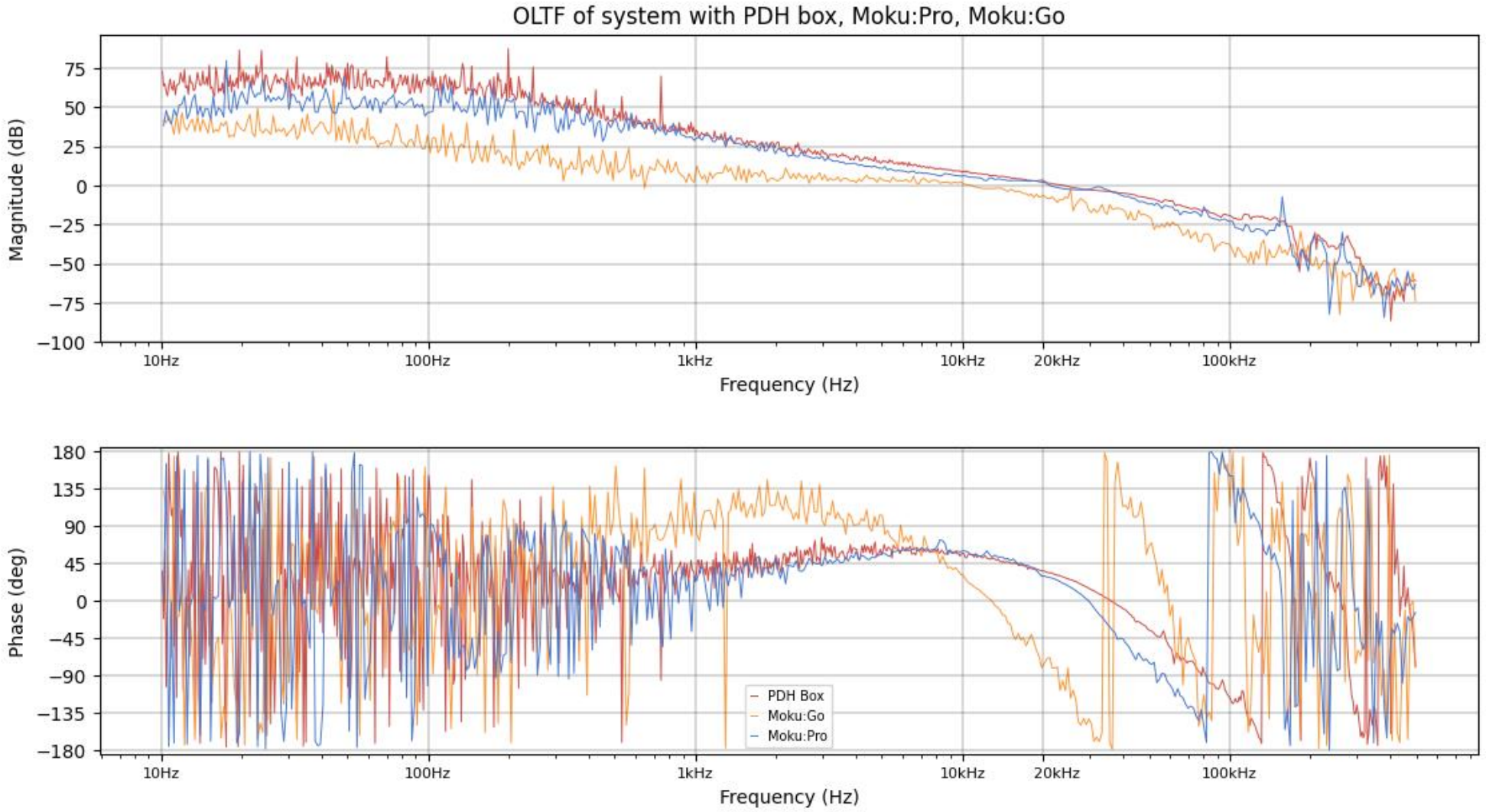


LIGO

DIGITAL CONTROLLER IMPLEMENTATION

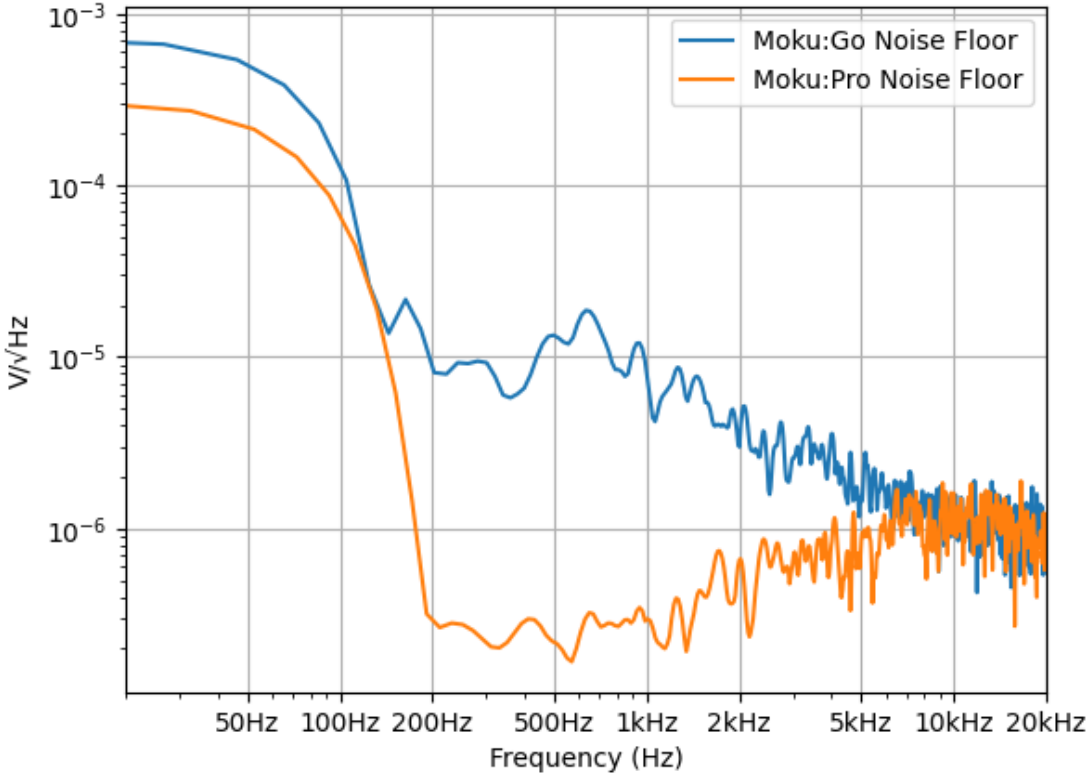
- Moku:Go/Moku:Pro supports custom filters
- Input Zero, Poles, Gain (ZPK) values, use code written by Anchal and Radhika to convert to second order section file readable by Moku
- Start by implementing fitted ZPK values on analog box
- OLTFs taken and compared
- Able to lock using digital filter
- Moku:Pro was most similar to uPDH box. Moku:Go had significantly lower bandwidth

LIGO

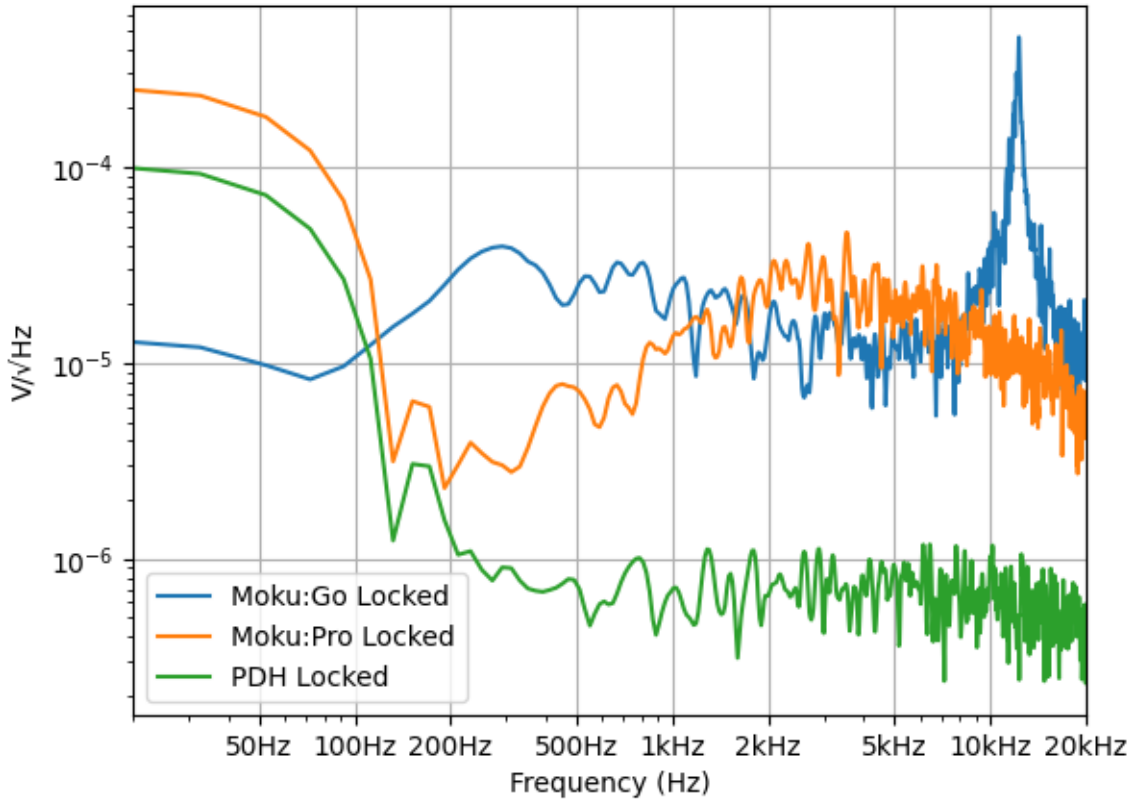

OLTF of system with PDH box, Moku:Pro, Moku:Go
Magnitude (dB)
75
50
25
0
−25
−50
−75
−100
10Hz
100Hz
1kHz
10kHz
20kHz
100kHz
Frequency (Hz)
Phase (deg)
180
135
90
45
0
−45
−90
−135
−180
PDH Box
Moku:Go
Moku:Pro
10Hz
100Hz
1kHz
10kHz
20kHz
100kHz
Frequency (Hz)

LIGO

NOISE COMPARISONS



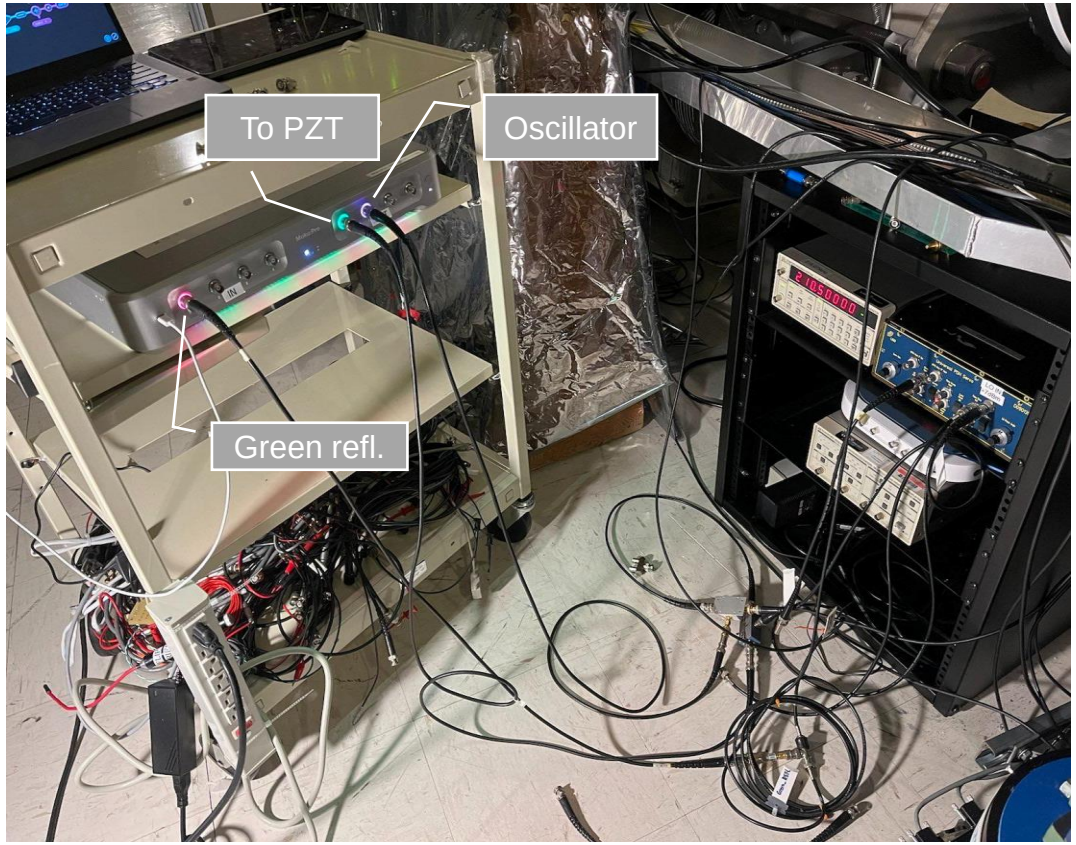
Noise floor comparison between Moku:Go and Moku:Pro



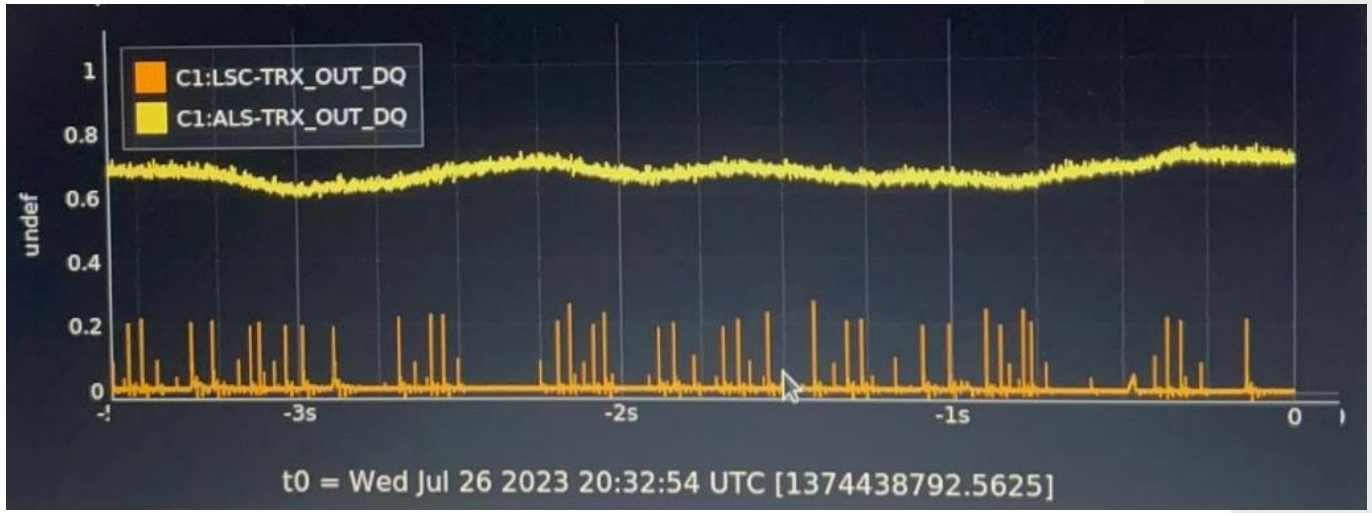
Error signal noise comparison

- Moku:Pro has lower noise floor
- When locked, the uPDH box has lower noise, could be improved with better digital controller design?

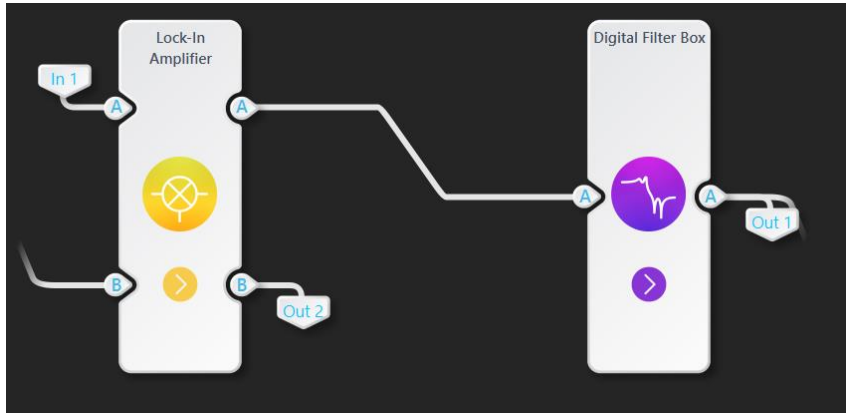
LIGO



Setup completely replacing uPDH box

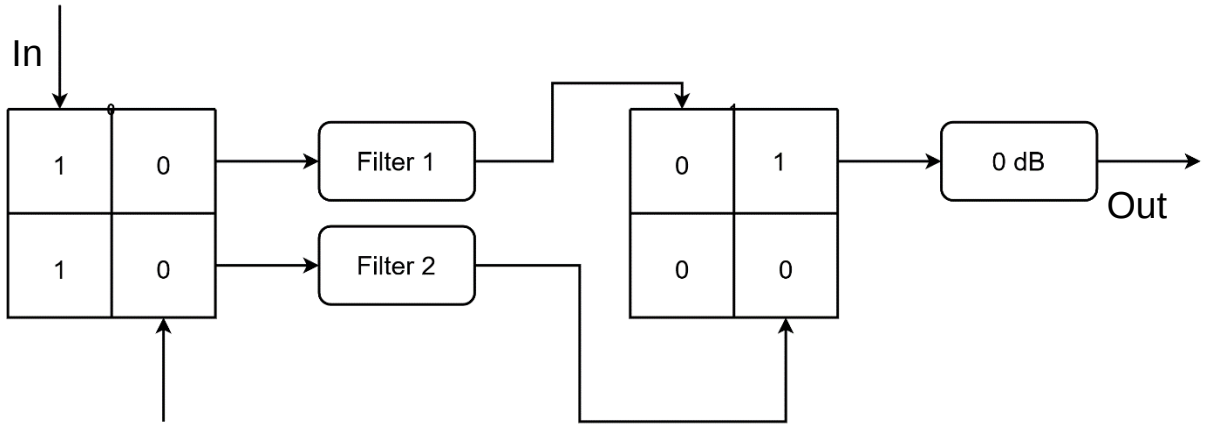


Transmission output when locked

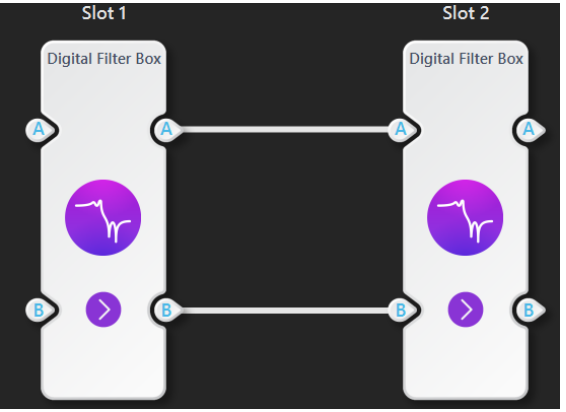


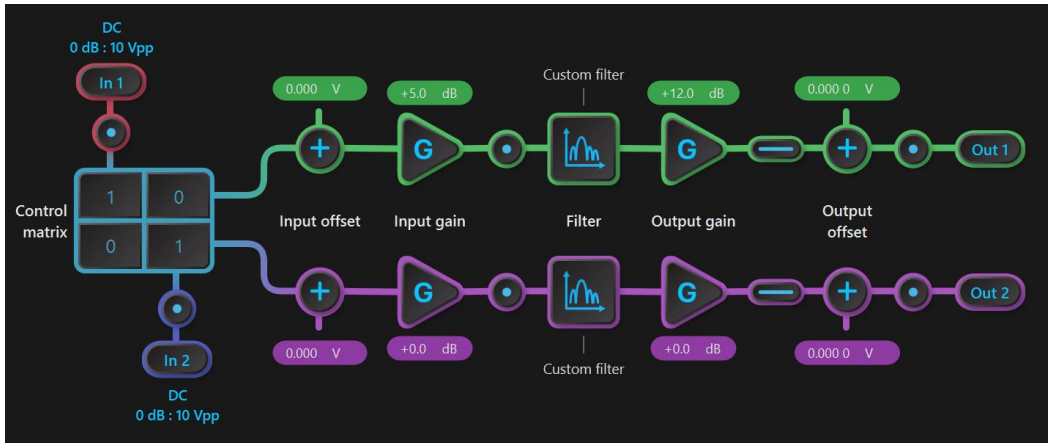
Moku:Pro multi instrument mode

FURTHER SCOPE



- Implement two filters
  - One designed to acquire lock fast
  - Other designed to hold lock strong once acquired
  - Have two parallel filter, and change output matrix to toggle between them\
  - No output matrix – only input matrix
    - Use two sets of filter banks
    - Changing filter banks breaks continuity of signal
    - Changing input matrix maintains continuity of signal
    - Setting filter banks, changing input matrix done through Pymoku API
    - Input reflected signal, detect if lock broken (high reflection), switch between filters

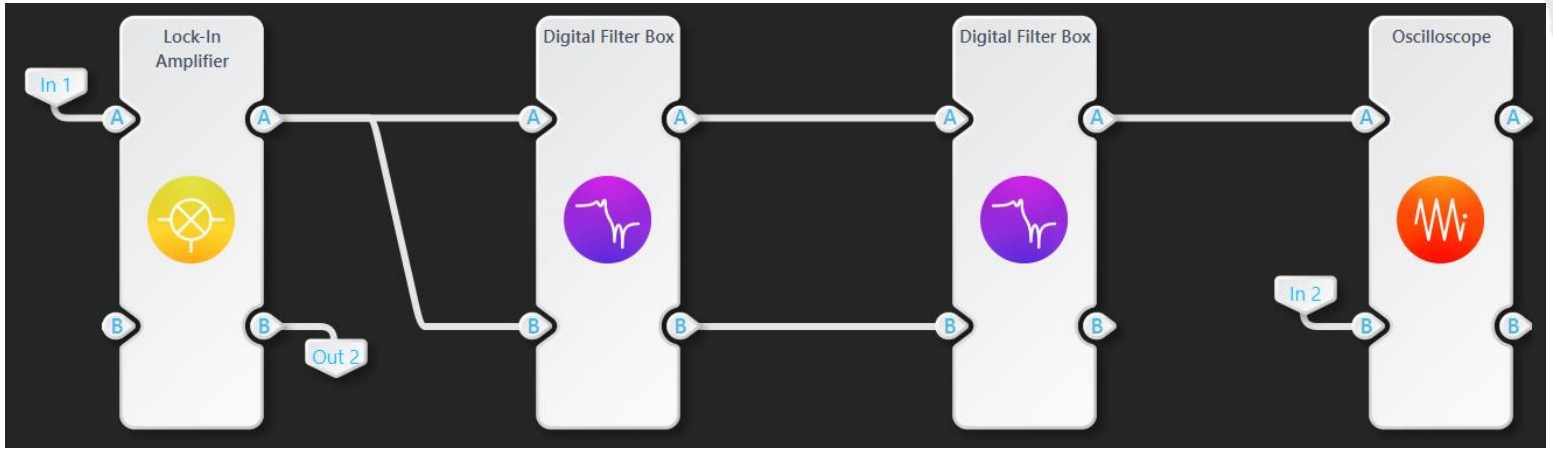




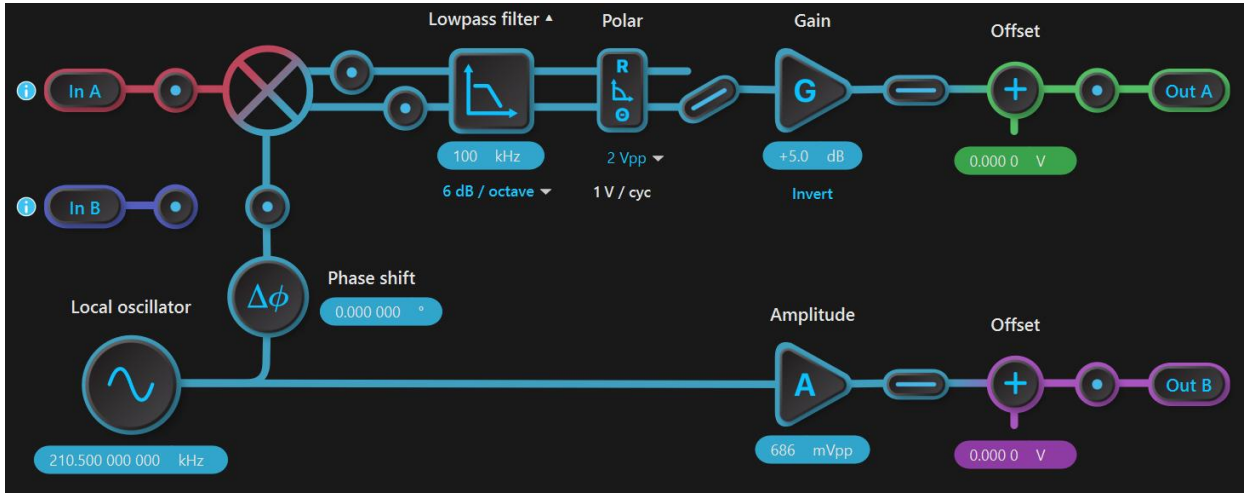
Moku digital filter GUI

LIGO

- Completely replace analog box
  - Use Moku to provide modulation, demodulation, parallel filters, lock sensing



Moku setup for an all in one locking system



Low pass filter schematic

LIGO

SUMMARY

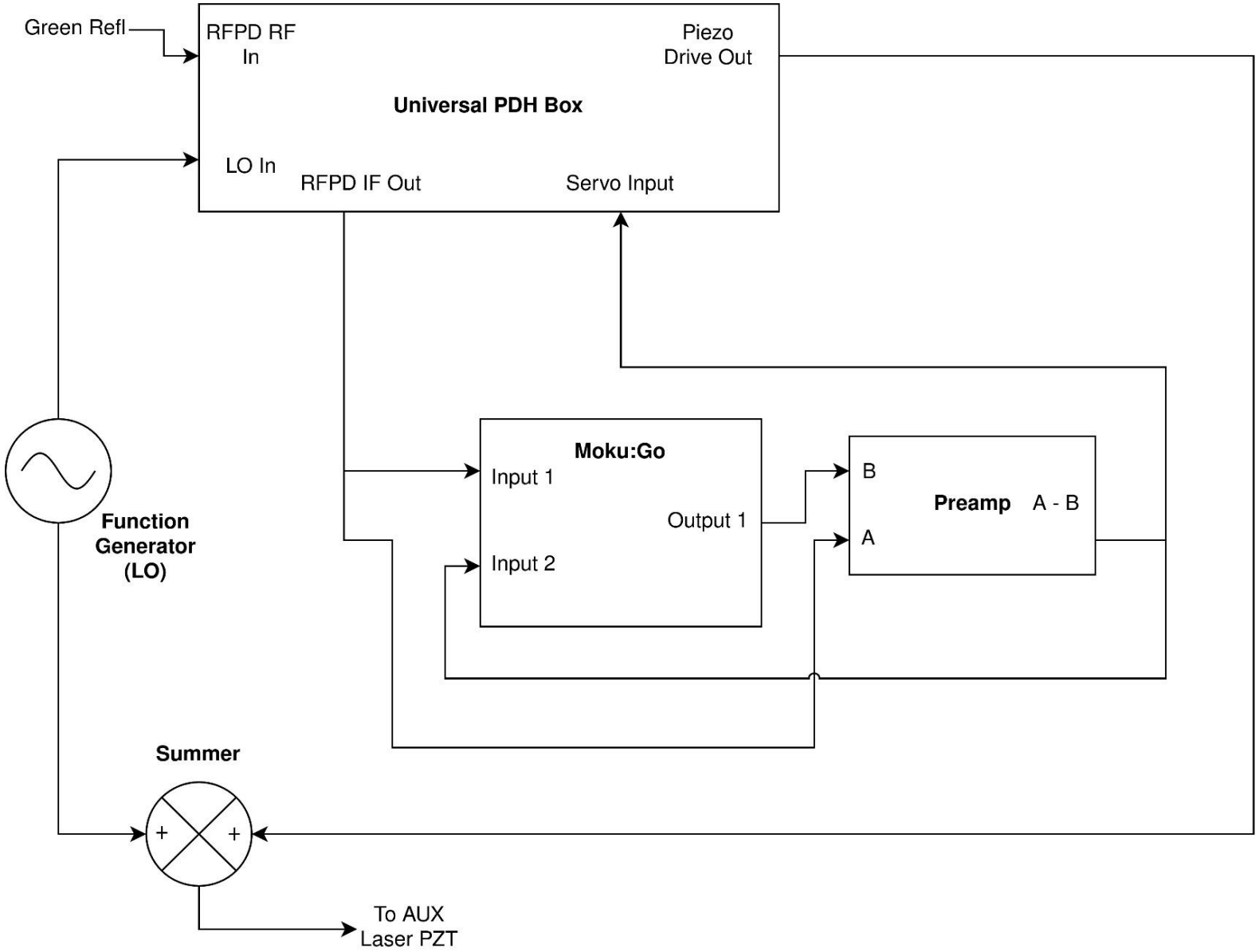
- Use a digital controller to replace the current analog controller
  - Reduce AUX laser noise contribution to ALS beat note in 10Hz-20kHz range
  - Add resonant gain filters for better calibration
- Modelled system
- Tabletop simulation of cavity poles
- Basic locking with digital controller
- Optimal controller design (Could not complete due to time and interferometer constraints)
- Scripts to automatically switch filters and reacquire lock when broken
- Complete replacement of uPDH box is possible

LIGO

THANK YOU

ACKNOWLEDGMENTS

- My mentors : Radhika Bhatt, Rana Adhikari, Paco
- The 40m gang : JC, Koji, Yuta, Yehonathan, Mayank
- My alma mater : National Institute of Technology, Calicut
- NSF REU, LIGO SURF, Caltech SFP, Alan
- Friends and family



Setup to measure OLTF of system