Development of Photon Calibrator for Hardware Injection Test

Yu-Kuang Chu
2018 Oct. 25

outline

- Introduction
- Hardware Injection through Photon Calibrator
- Signal Generating System (Digital Control System)
- Noise reduction through De-Whitening Filter
- Validation of Injection Channel
- Discussion and Future Works

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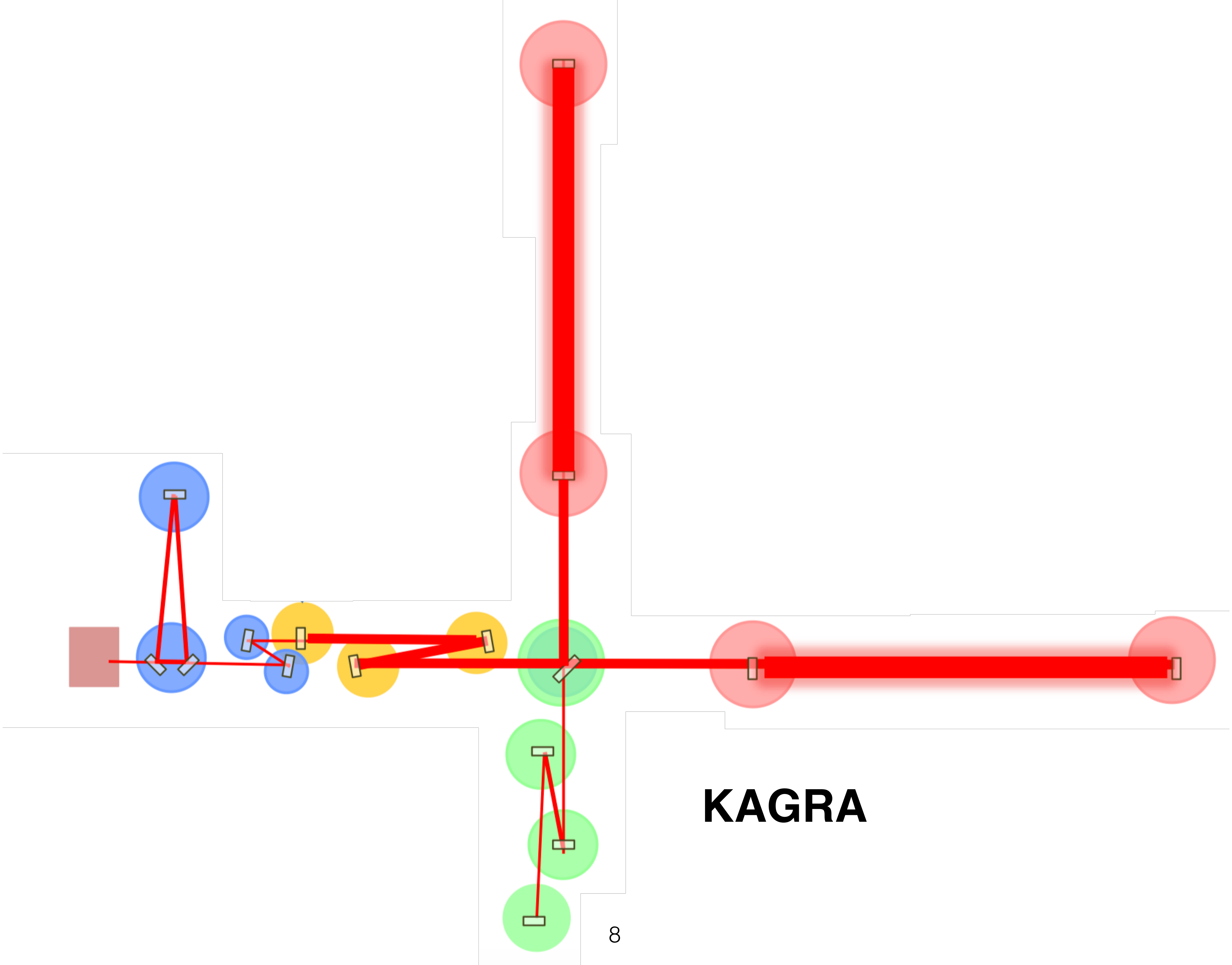
What is Hardware Injection Test?

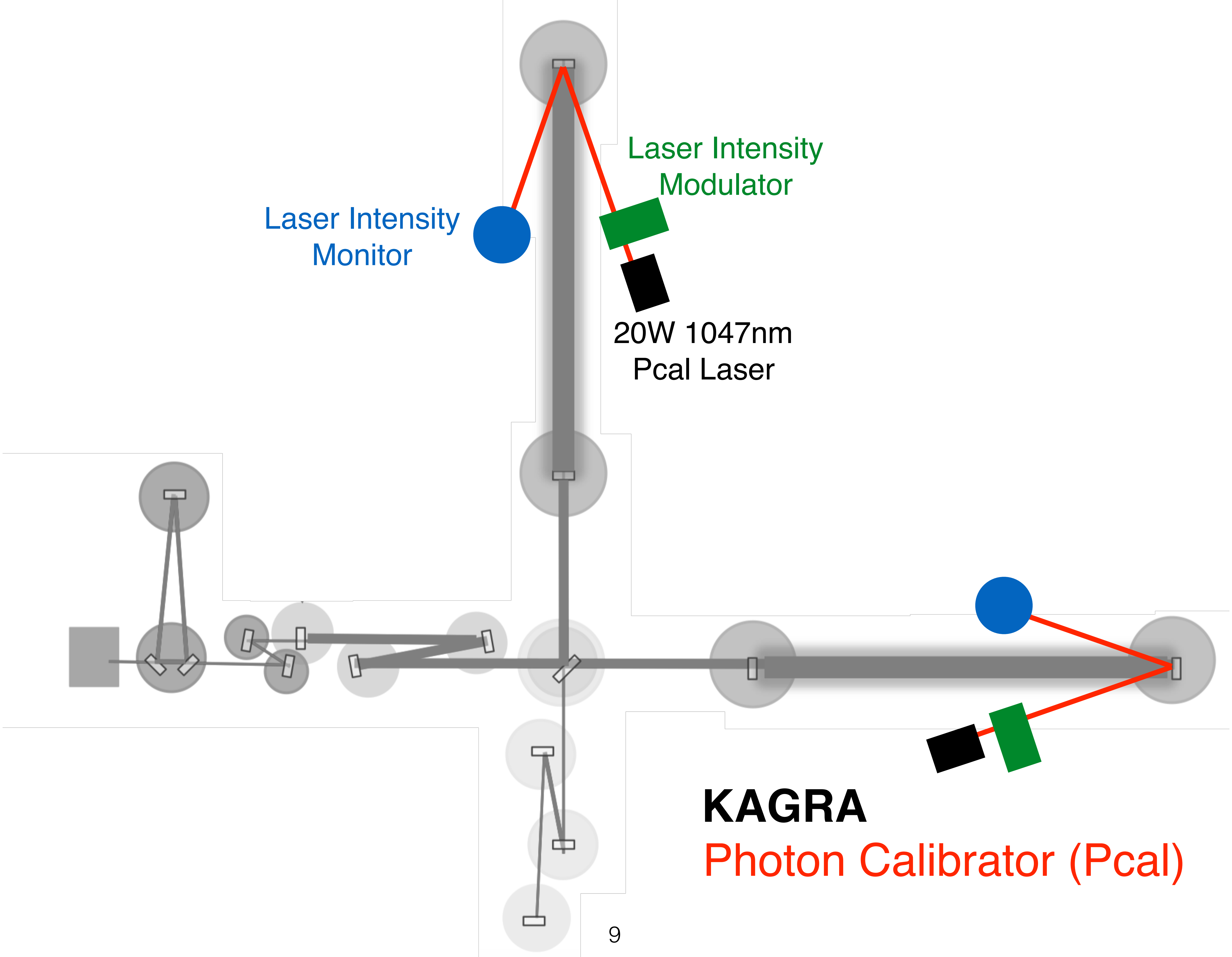
Hardware injection test is a **process to verify the performance of interferometer by sending sample signals into interferometer**. Ideally, we should prepare some real gravitational waves as test signals. But it is practically hard to generate large enough artificial gravitational waves that are detectable by current technology.

Therefore, instead of generating gravitational waves, people mimic the effect of celestial gravitational waves by **displacing the mirror according to the simulated gravitational waveforms**, changing arm length correspondingly, comparing the optical readout in the main interferometer, thereby checking the response of their interferometer.

What is Photon Calibrator(PCal)?

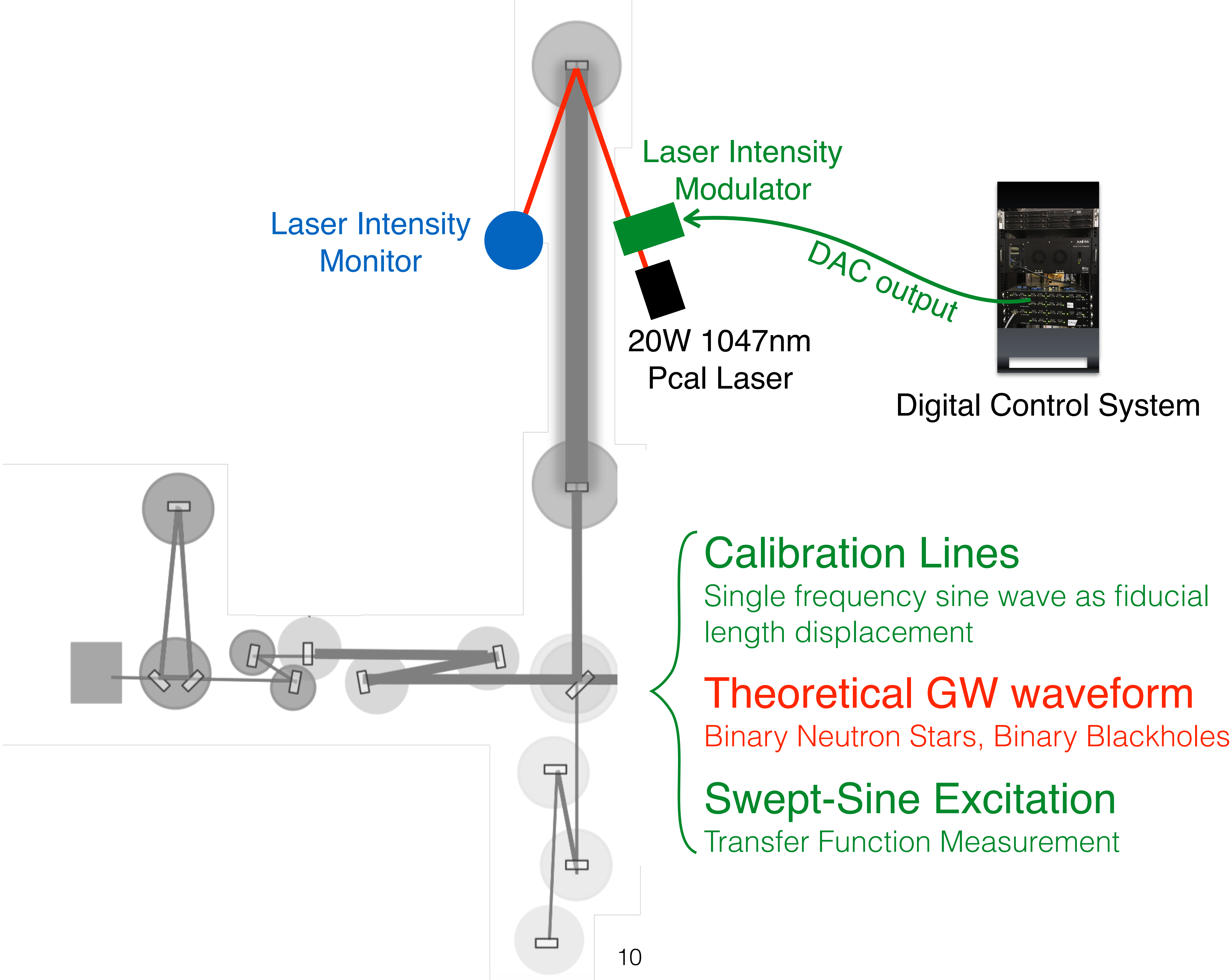


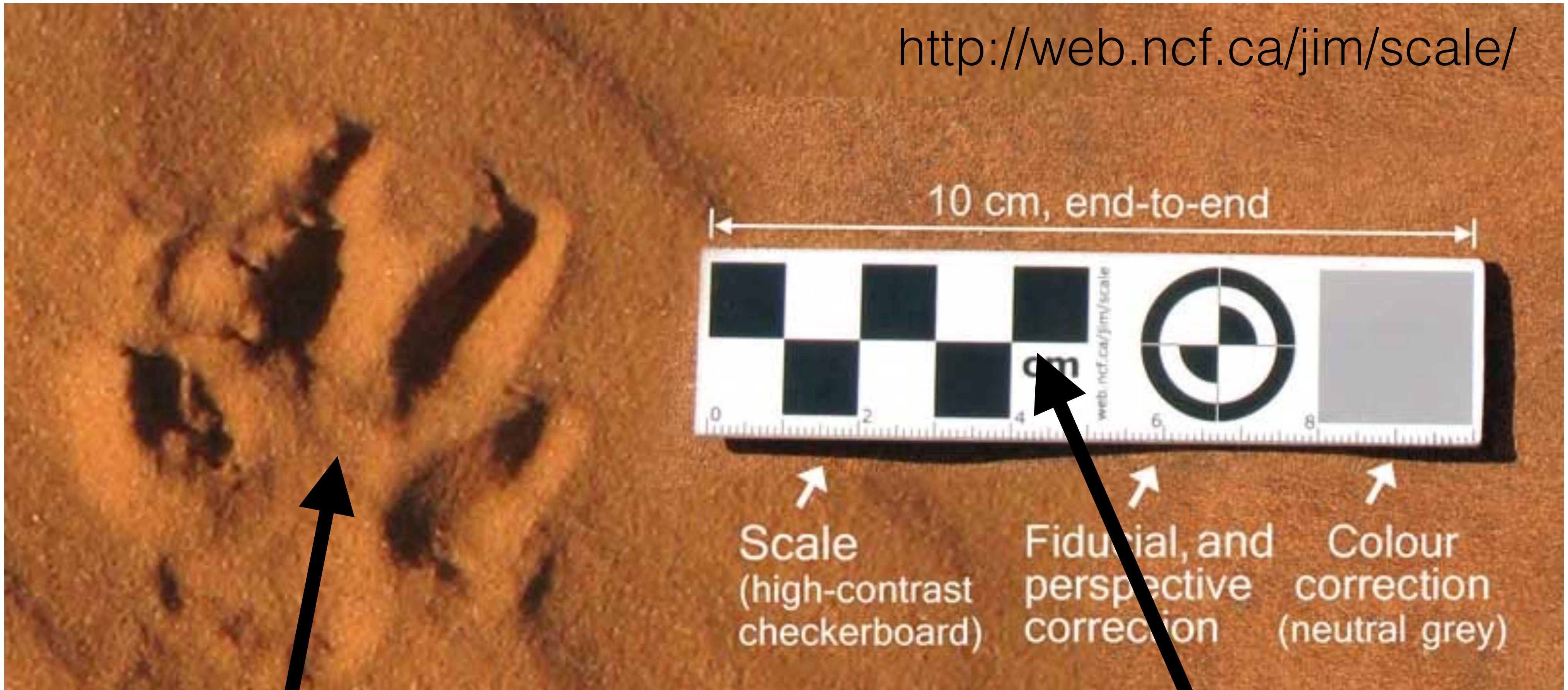
KAGRA



KAGRA

Photon Calibrator (Pcal)


Laser Intensity Monitor
Laser Intensity Modulator
DAC output
20W 1047nm Pcal Laser
Digital Control System
Calibration Lines
Single frequency sine wave as fiducial length displacement
Theoretical GW waveform
Binary Neutron Stars, Binary Blackholes
Swept-Sine Excitation
Transfer Function Measurement



Interferometer readout generated by gravitational wave signal **(GW signal)**

Interferometer readout generated by Mirror displacement due to Photon Calibrator **(Calibration Lines)**

Interferome adout
generated by
gravitational wave signal
(GW signal)

Interferometer readout
generated by Mirror
displacement due to
Photon Calibrator
(Calibration Lines)

History of Photon Calibrators

D. A. Clubley *et al.*, “Calibration of the **Glasgow 10 m prototype** laser interferometric gravitational wave detector using photon pressure,” Phys. Lett. A 283, 85 (**2001**).

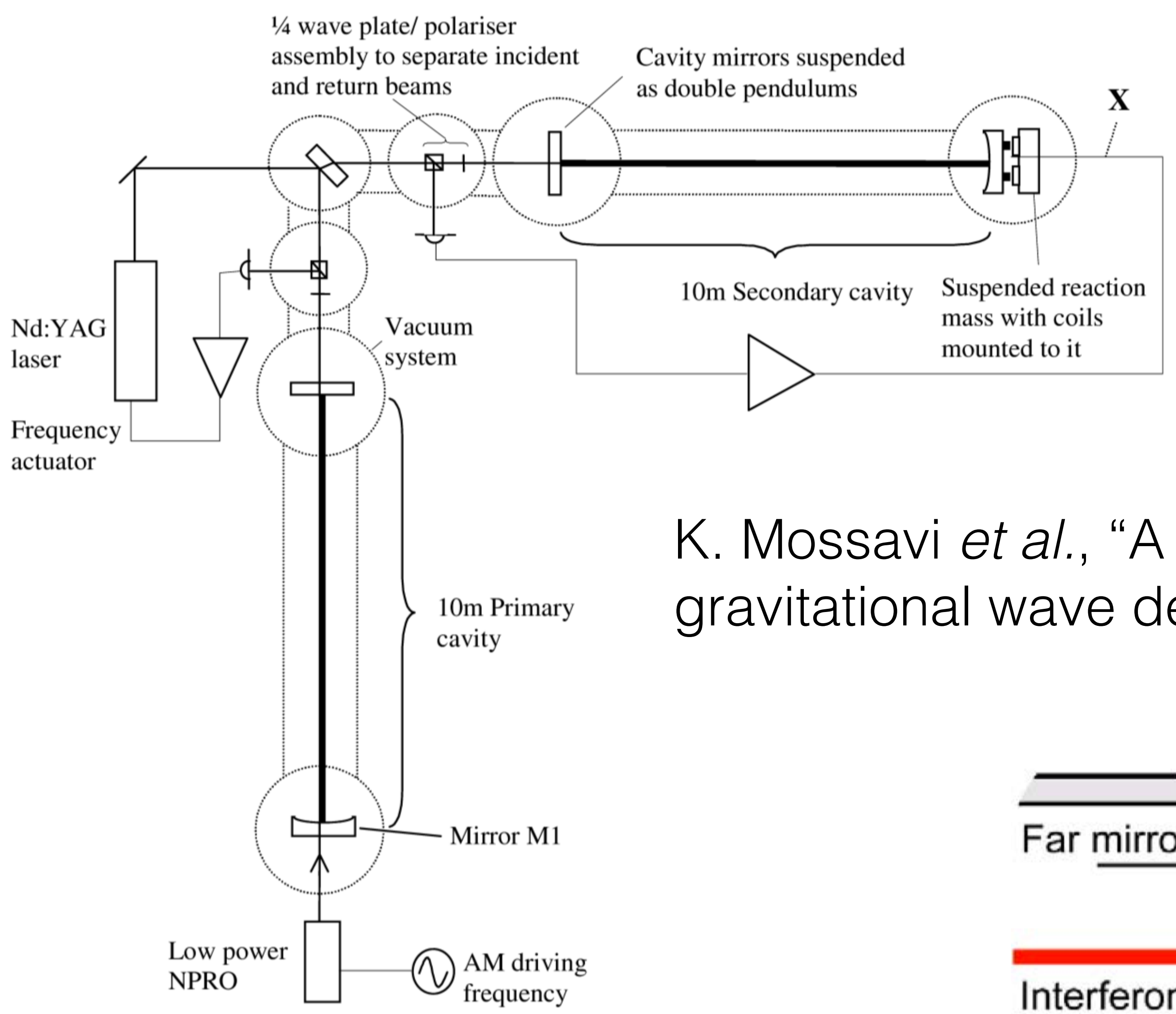


Fig. 1. A schematic of the Glasgow prototype gravitational wave detector. Frequency stabilisation scher

K. Mossavi *et al.*, “A photon pressure calibrator for the **GEO600** gravitational wave detector,” Phys. Lett. A 353, 1 (**2006**).

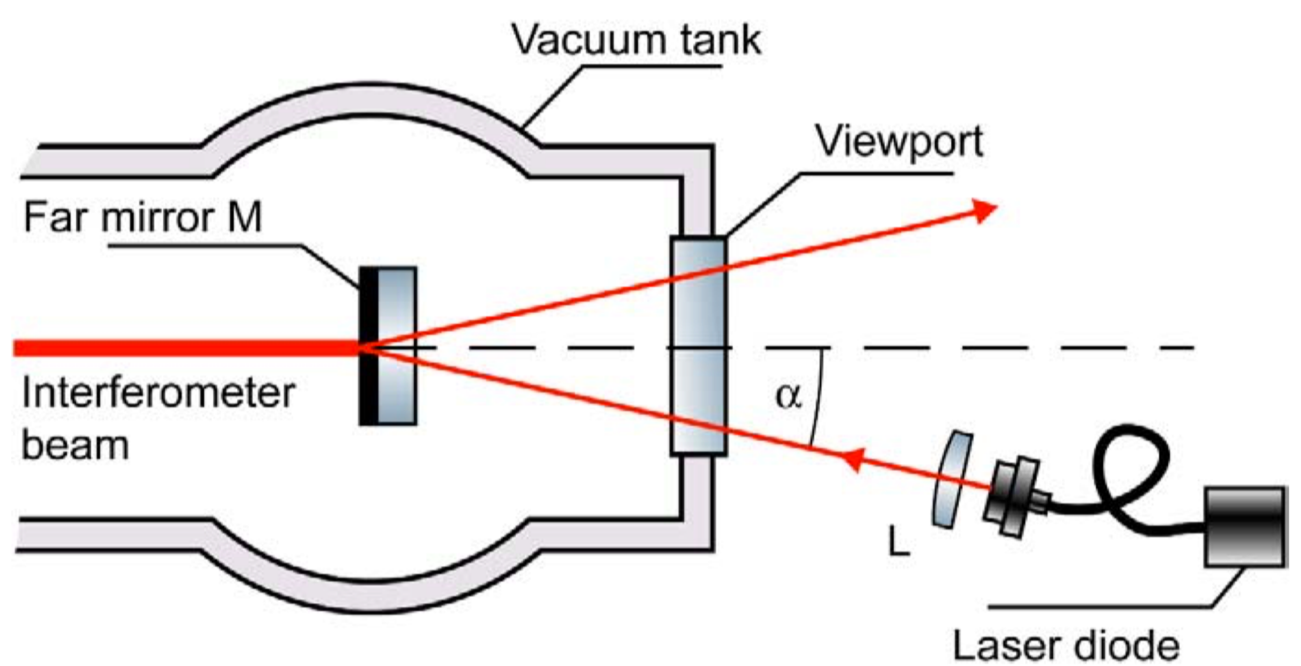


Fig. 1. Experimental arrangement for measurements with the photon calibrator. M: Far mirror in the north building of the GEO 600 detector. Illumination of this mirror with light from the laser diode produces a differential arm-length change that is measured at the main output of the interferometer.

S. Hild et al., “Photon pressure induced **test mass deformation** in gravitational wave detectors,” Classical Quantum Gravity 24, 5681–5688 (**2007**)

Badan M A, Landry M, Savage R and Willems P (**2009**) Analyzing **elastic deformation** of test masses in LIGO LIGO doc. T0900401

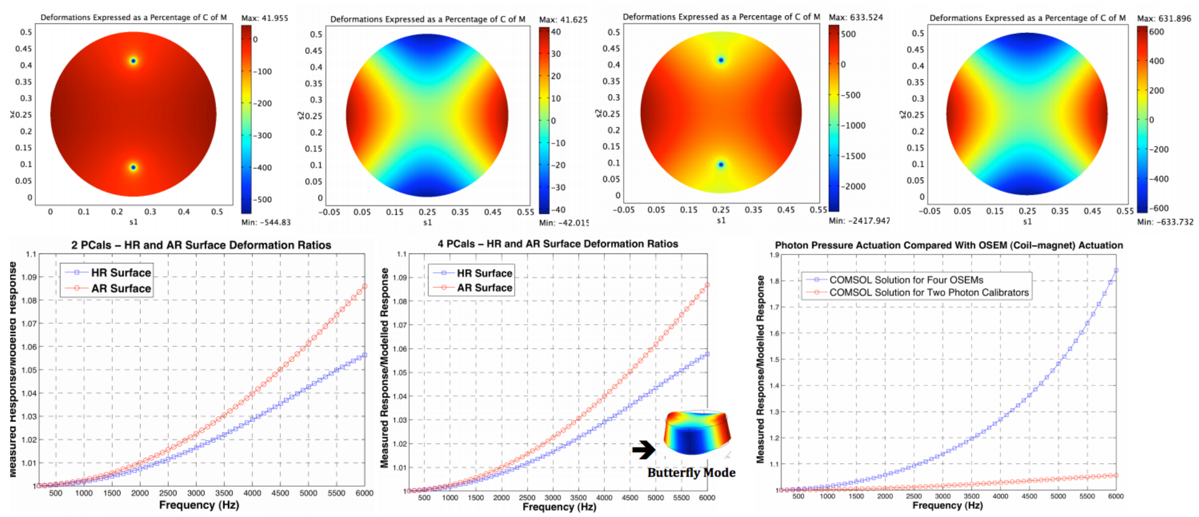
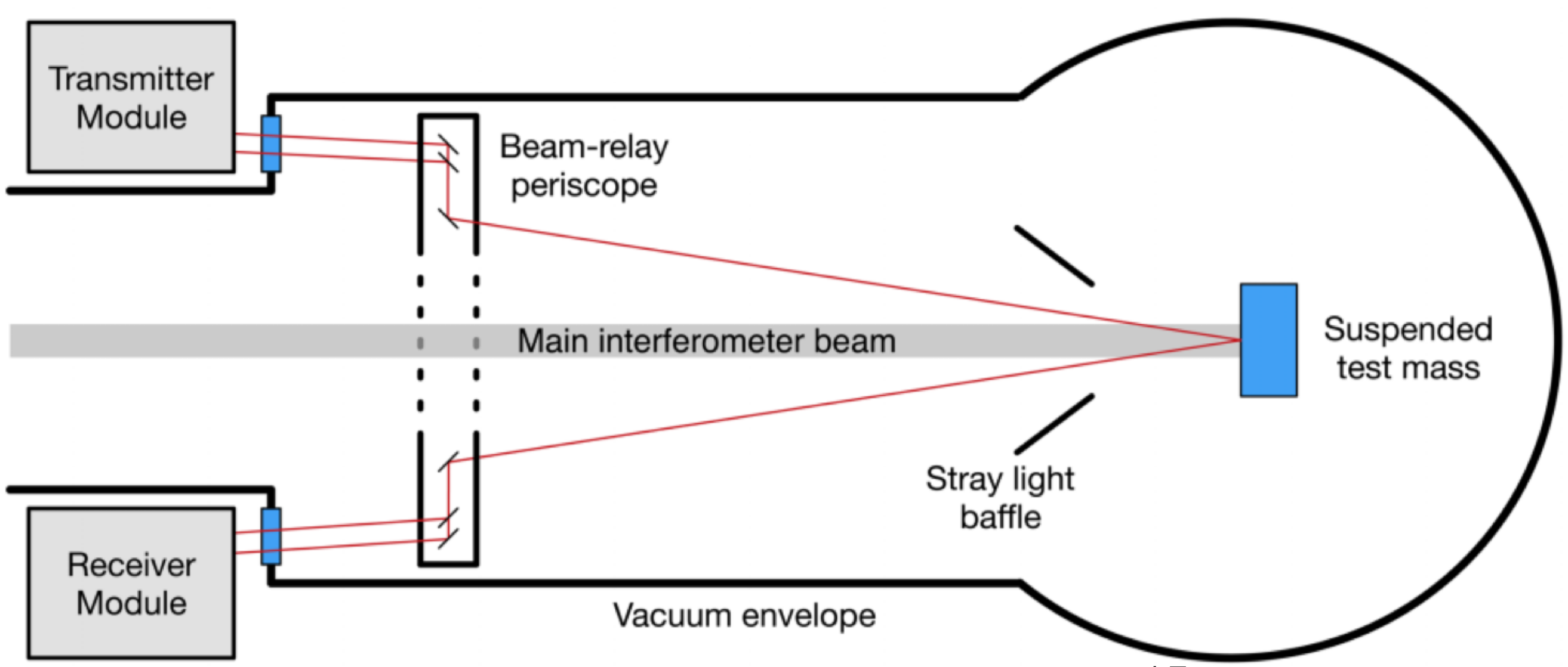
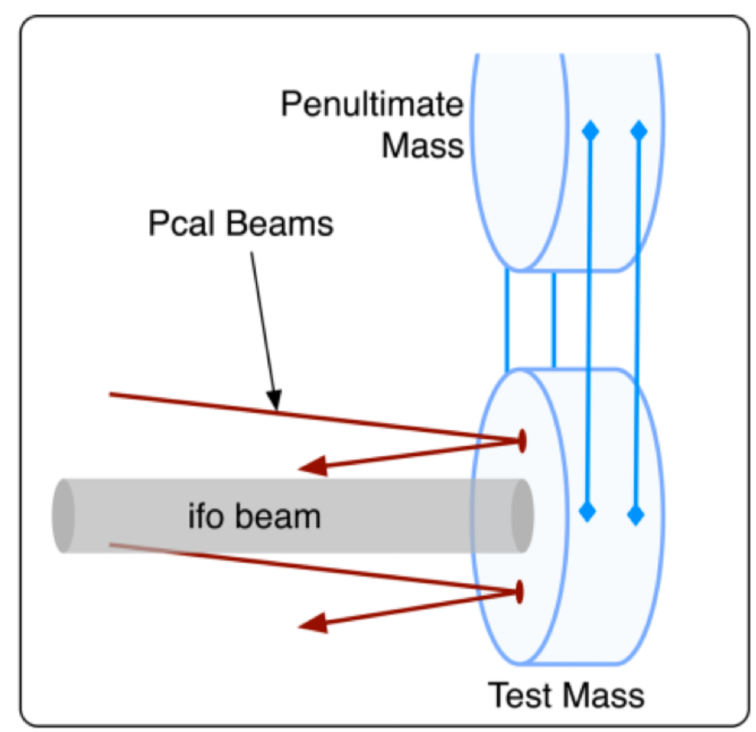


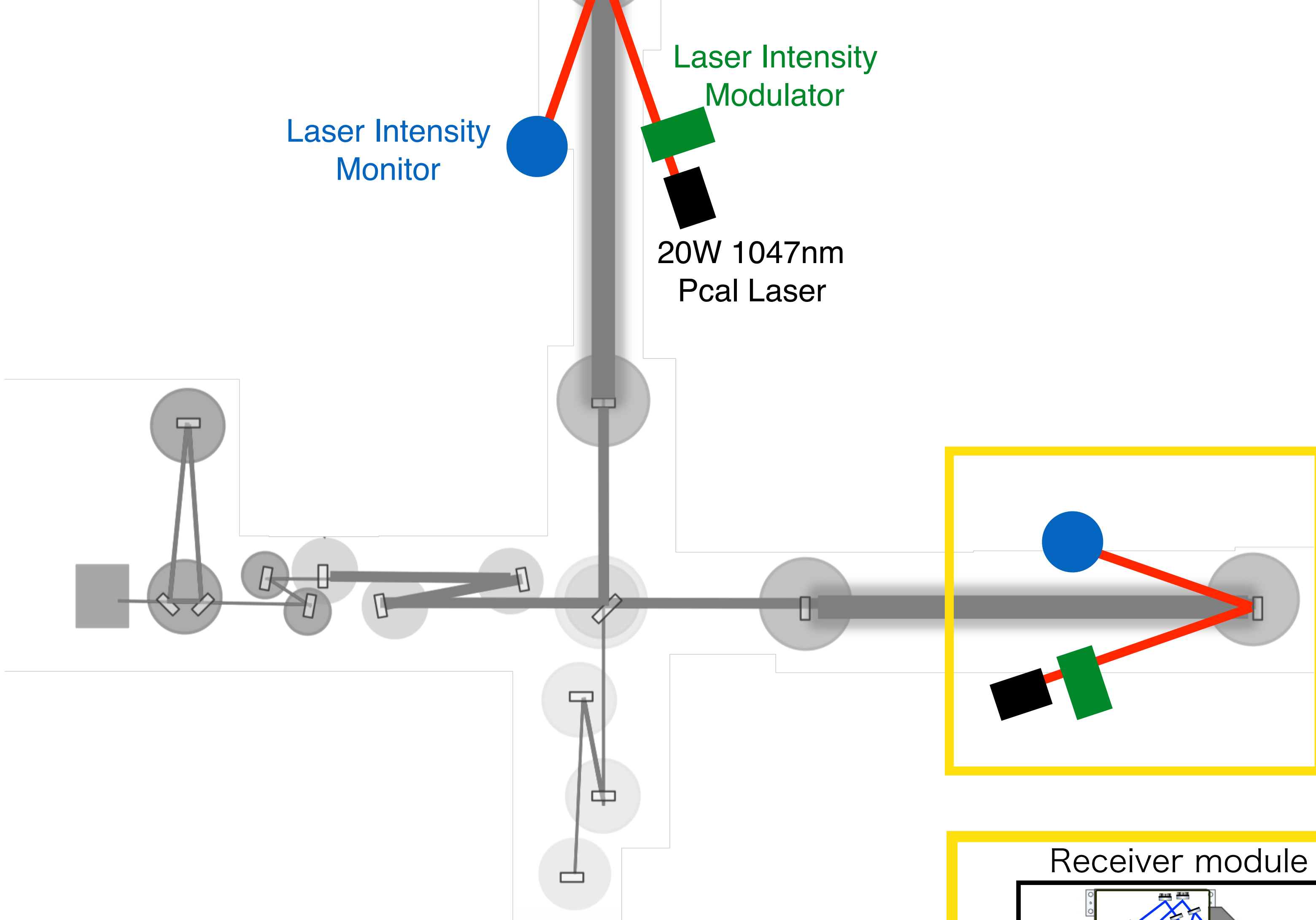
Figure 6| (Top) The HR (left) and AR (right) z-displacements for the photon actuation. The graphs show the 3D surface deformation as a percentage of the center of mass motion for 3 kHz and 6 kHz, respectively. (Bottom) The HR and AR surface Measured/Modelled Ratio profiles for the two photon calibrator forces, followed by four. The discrepancies experienced are about are about an order of magnitude less than the OSEM case for both configurations. This is because the optic flexes differently in perpendicular directions as they try to form the butterfly mode at 6823 Hz.

S. Karki, et al., “**The Advanced LIGO Photon Calibrators**”, Rev. Sci. Instrum. 87, 114503 (**2016**).

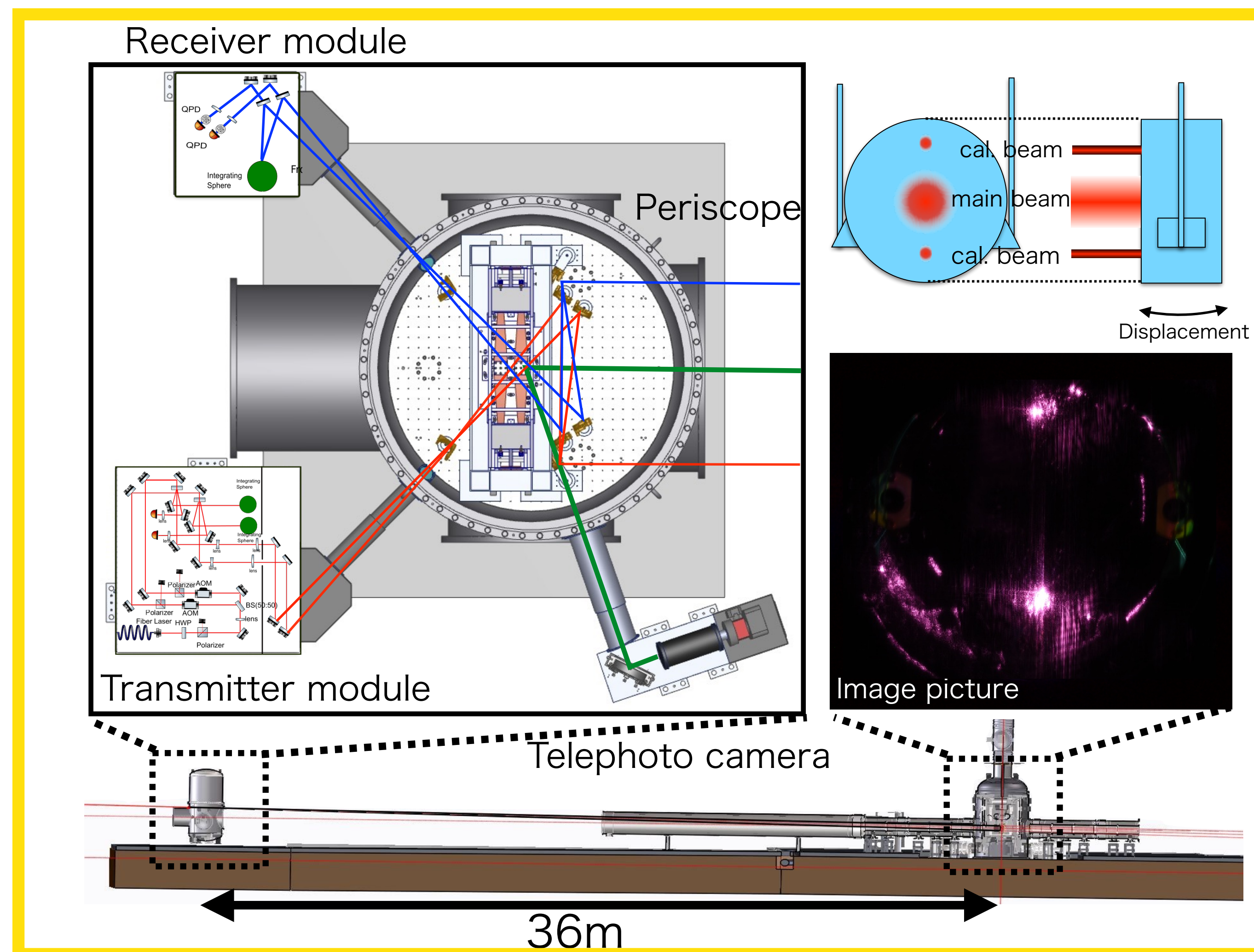




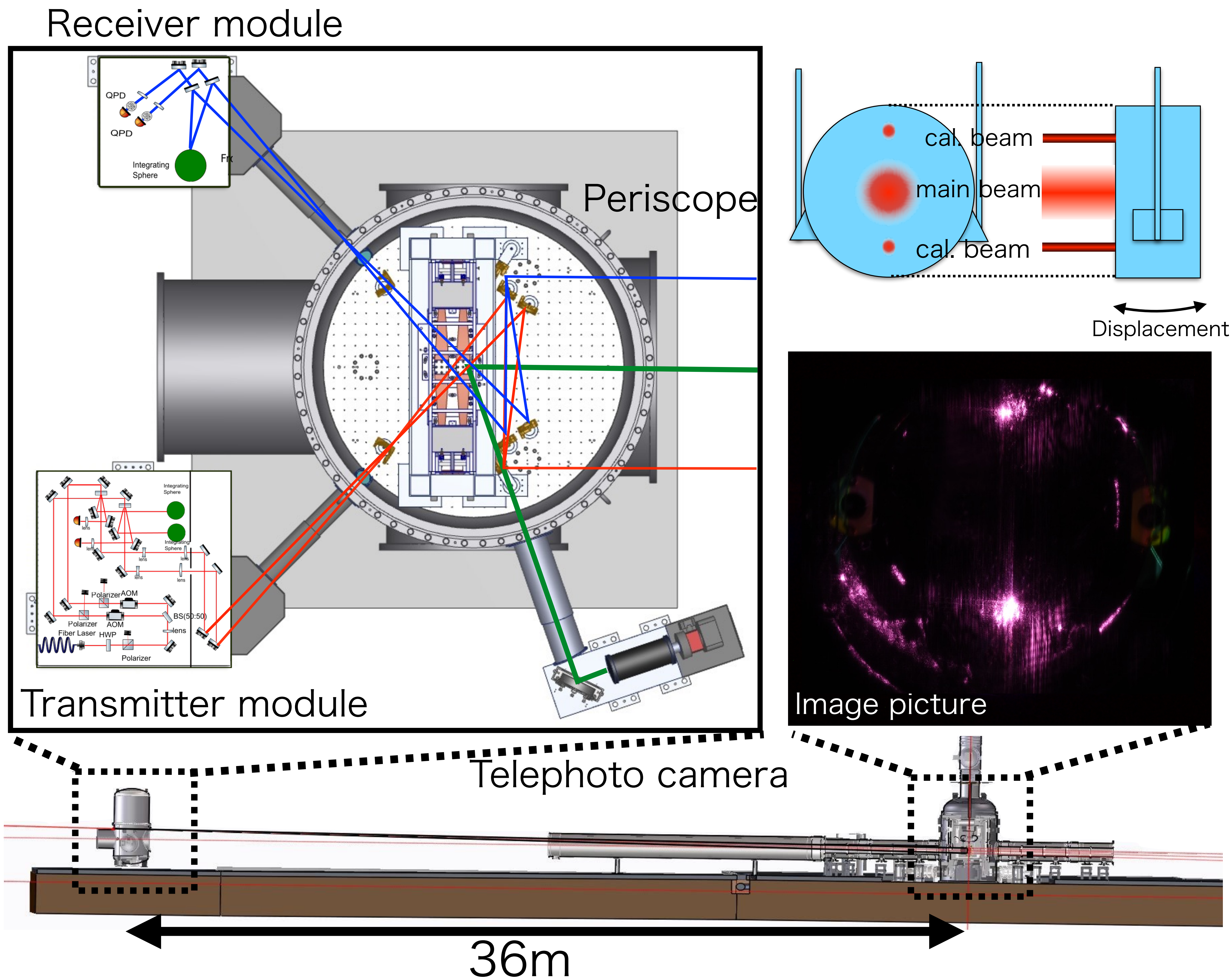
KAGRA Photon Calibrator



Laser Intensity
Modulator
Laser Intensity
Monitor
20W 1047nm
Pcal Laser



Receiver module
Periscope
cal. beam
main beam
cal. beam
Displacement
Image picture
Transmitter module
Telephoto camera
36m



From Yuki's slides


Receiver Module

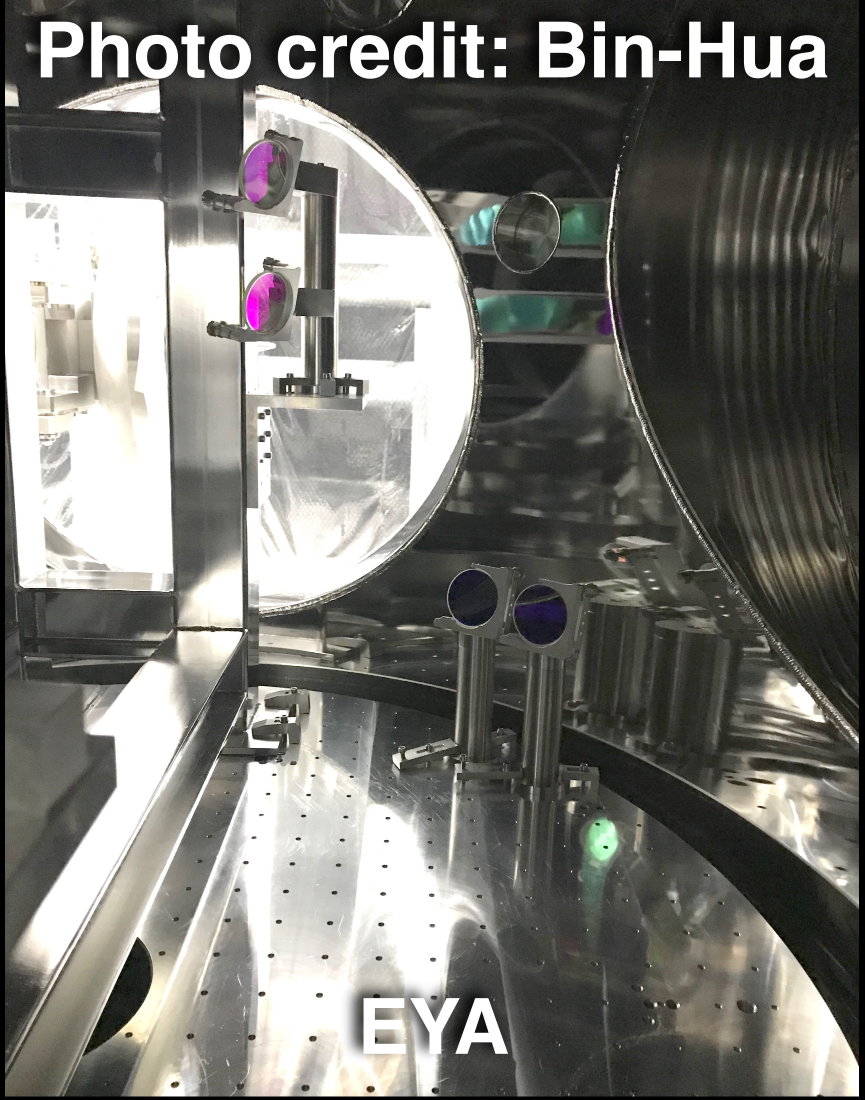
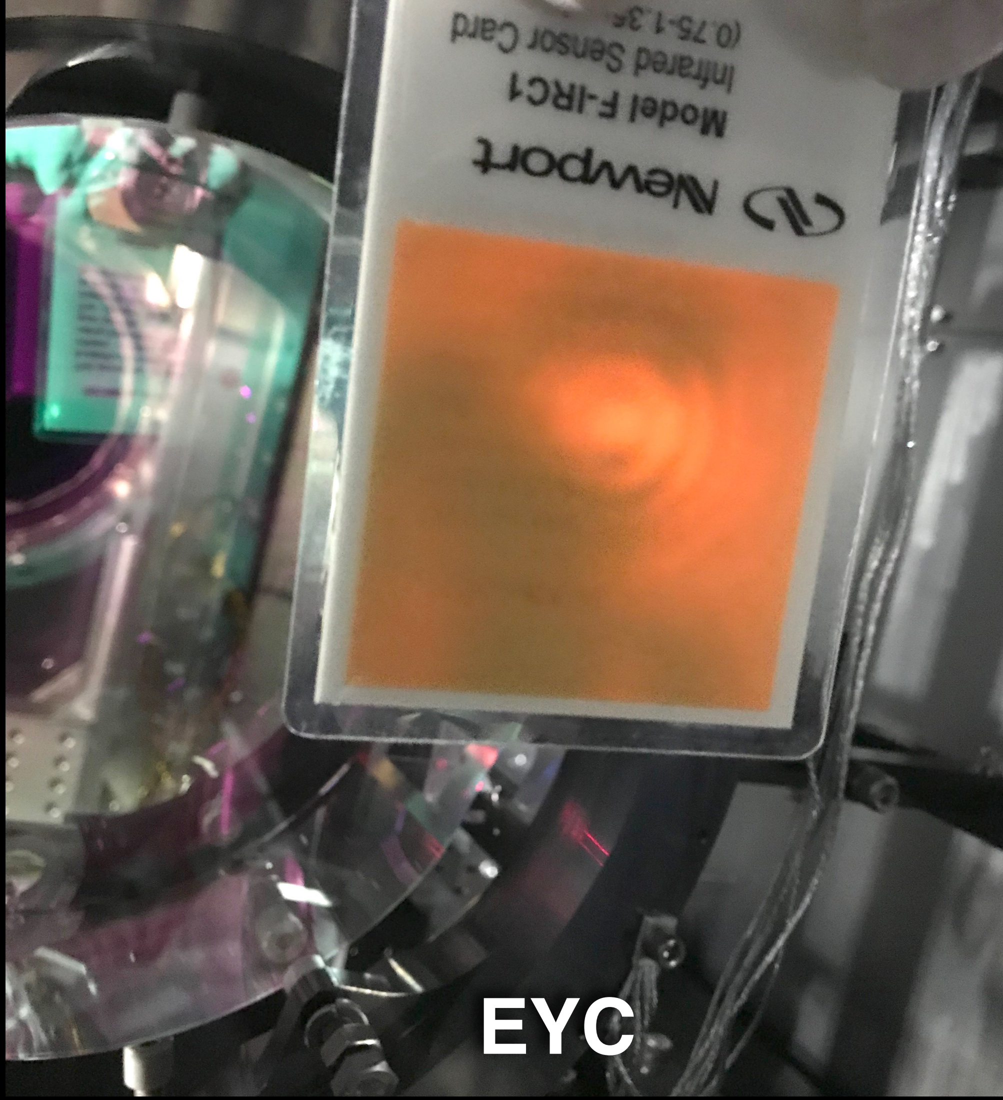
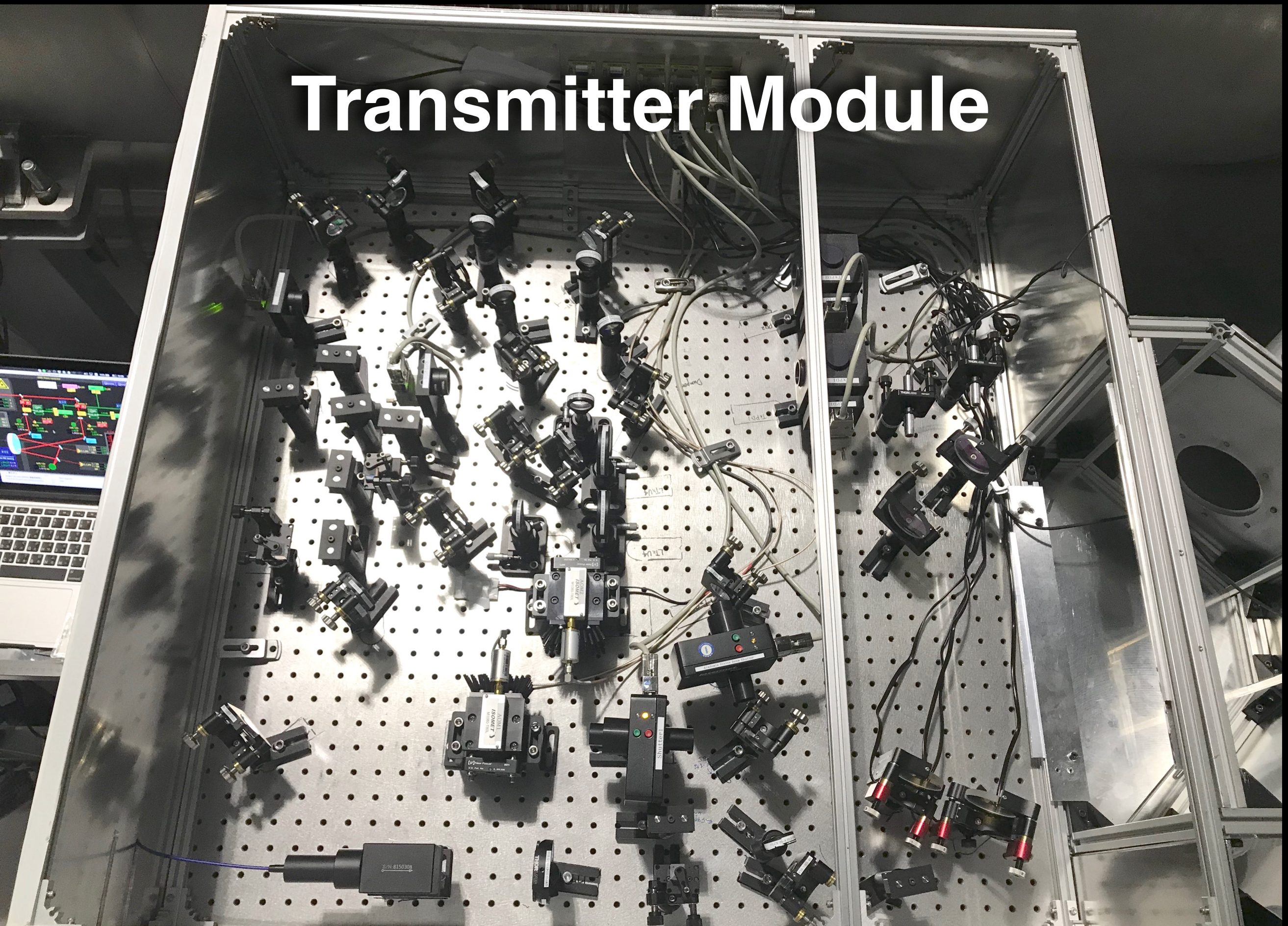


Photo credit: Bin-Hua
EYA


EYC


Transmitter Module


Transmitter Module

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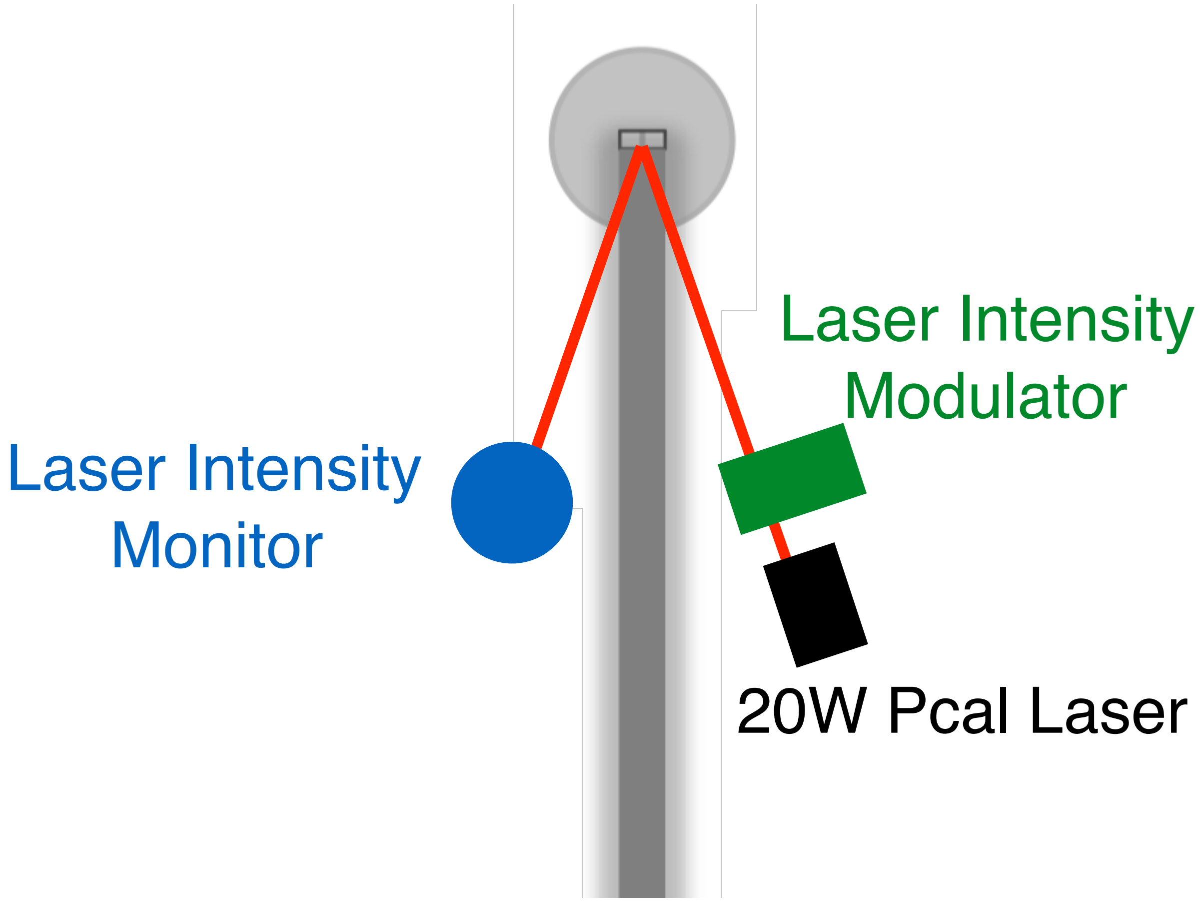
- Discussion and Future Works



$$\ddot{x}(t) + b\dot{x}(t) + \omega_0^2 x(t) = \frac{F(t)}{M}$$

$$x(\omega) = \frac{-1}{\omega^2 - \omega_0^2 - i\omega b}\frac{F(\omega)}{M}$$

$$\Delta L(f) = \underbrace{\frac{2\Delta P(f)\cos(\theta)}{c}}_{\text{Radiation Force exerted by Pcal}} \underbrace{\frac{\text{-}1}{M(2\pi f)^2}}_{\text{Force to length transfer function}}$$

$\Delta L(f)$: Interferometer Mirror displacement induced by Pcal Laser intensity modulation

Radiation Force exerted by Pcal

Force to length transfer function

Theoretical waveforms

$$\int_{-\infty}^{-\infty} x(\omega)e^{i\omega t}\ \mathrm{d}\omega = \frac{-2\cos(\theta)}{Mc}\int_{-\infty}^{-\infty}\frac{P(\omega)}{\omega^2}e^{i\omega t}\ \mathrm{d}\omega$$

$$\frac{Mc}{-2\cos(\theta)}\int_{-\infty}^{-\infty} x(\omega)\omega^2 e^{i\omega t}\ \mathrm{d}\omega = P(t)$$

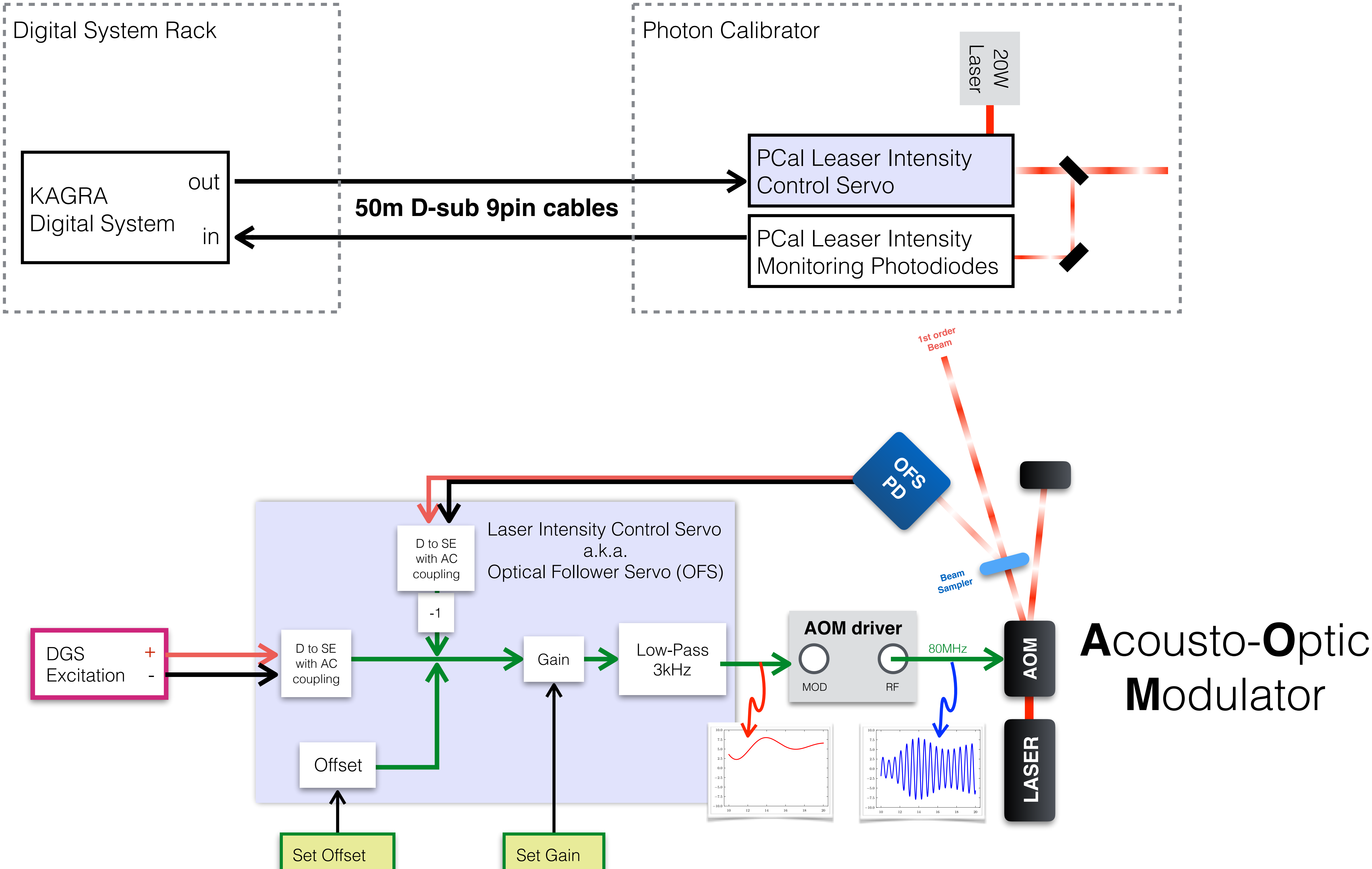
Required PCal laser intensity modulation

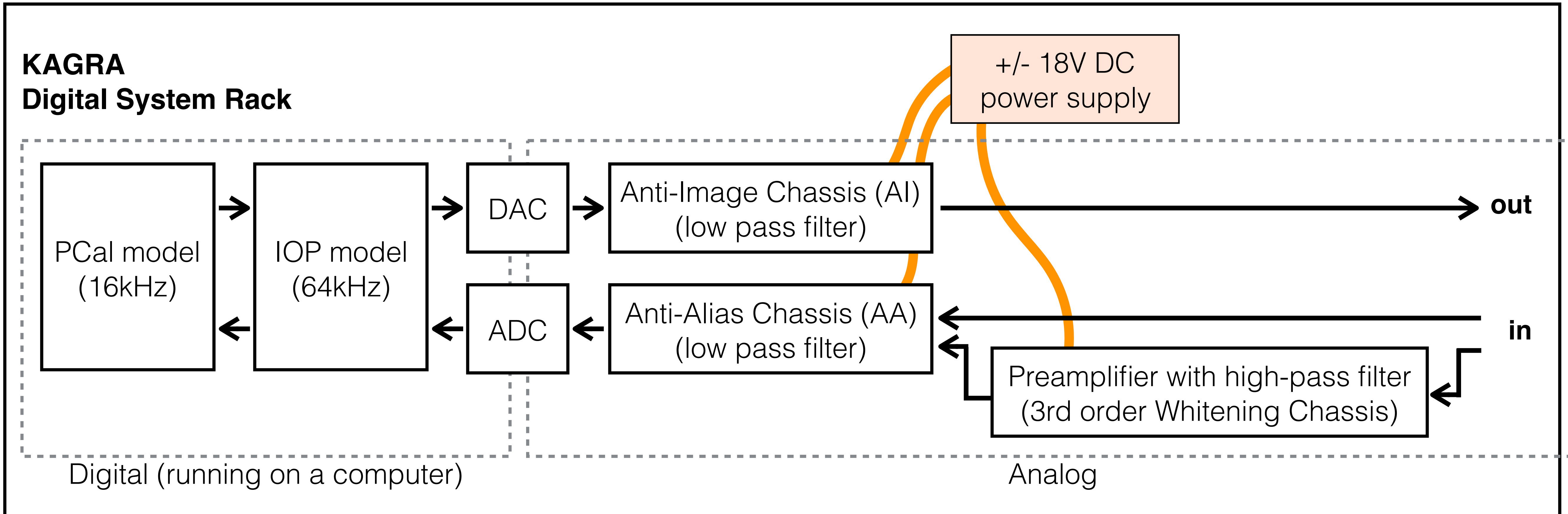
$$\Delta L(f) = \underbrace{\frac{2\Delta P(f)\cos(\theta)}{c}}_{\text{Radiation Force exerted by Pcal}}\ \underbrace{\frac{\text{-1}}{M(2\pi f)^2}}_{\text{Force to length transfer function}}$$

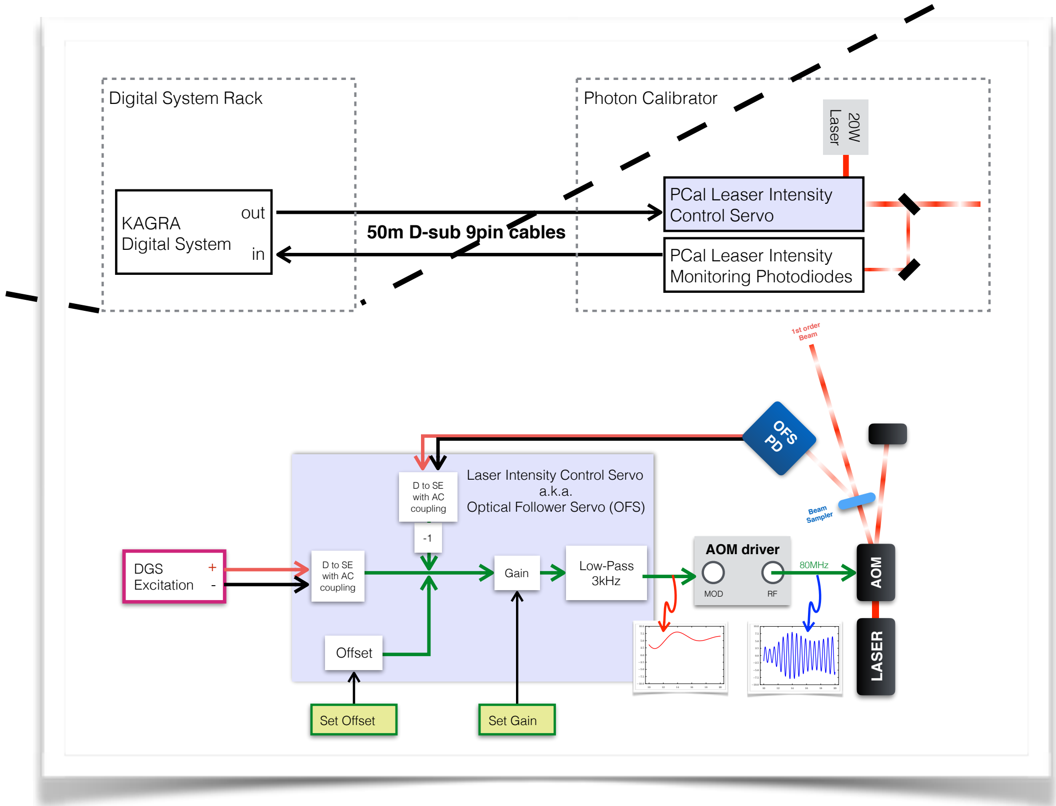
Interferometer Mirror displacement induced by Pcal Laser intensity modulation

Radiation Force exerted by Pcal

Force to length transfer function


Digital System Rack
KAGRA Digital System
out
in
50m D-sub 9pin cables
Photon Calibrator
20W Laser
PCal Leaser Intensity Control Servo
PCal Leaser Intensity Monitoring Photodiodes
1st order Beam
OFS PD
Beam Sampler
Laser Intensity Control Servo
a.k.a.
Optical Follower Servo (OFS)
D to SE with AC coupling
-1
DGS Excitation
+
-
D to SE with AC coupling
Gain
Low-Pass 3kHz
Offset
Set Offset
Set Gain
AOM driver
MOD
RF
80MHz
AOM
LASER
Acousto-Optic Modulator


KAGRA
Digital System Rack
+/- 18V DC
power supply
PCal model
(16kHz)
IOP model
(64kHz)
DAC
ADC
Anti-Image Chassis (AI)
(low pass filter)
Anti-Alias Chassis (AA)
(low pass filter)
out
in
Preamplifier with high-pass filter
(3rd order Whitening Chassis)
Digital (running on a computer)
Analog


Digital System Rack
Photon Calibrator
20W
Laser
KAGRA
Digital System
out
in
50m D-sub 9pin cables
PCal Leaser Intensity
Control Servo
PCal Leaser Intensity
Monitoring Photodiodes
Laser Intensity Control Servo
a.k.a.
Optical Follower Servo (OFS)
DGS
Excitation
Gain
Low-Pass
3kHz
AOM driver
Offset
Set Offset
Set Gain
OFS
PD
AOM
LASER

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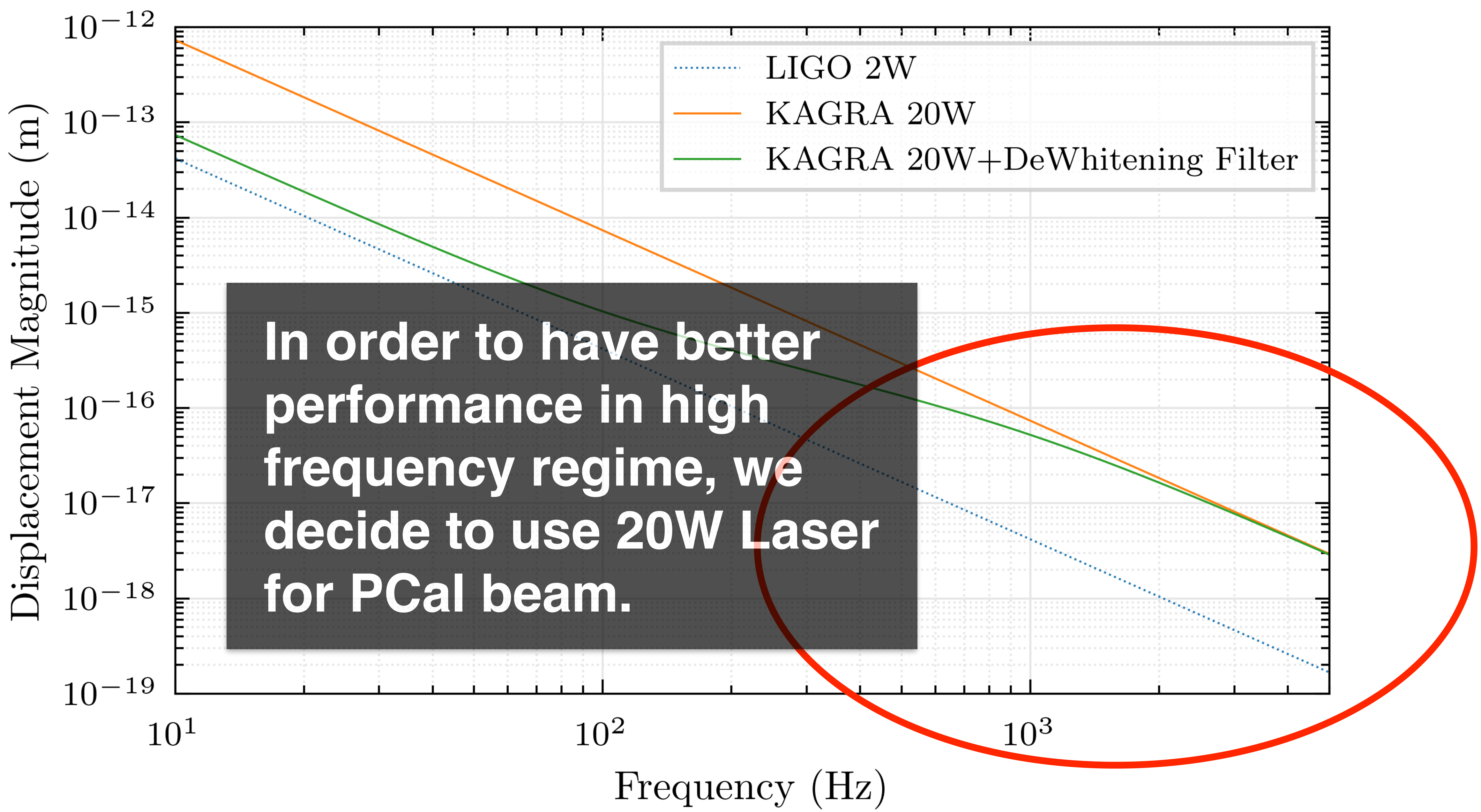
Excitation Signal Noise Problem



$$\Delta L(f) = \underbrace{\frac{2\Delta P(f)\cos(\theta)}{c}}_{\text{Radiation Force exerted by Pcal}} \underbrace{\frac{1}{M(2\pi f)^2}}_{\text{Force to length transfer function}}$$

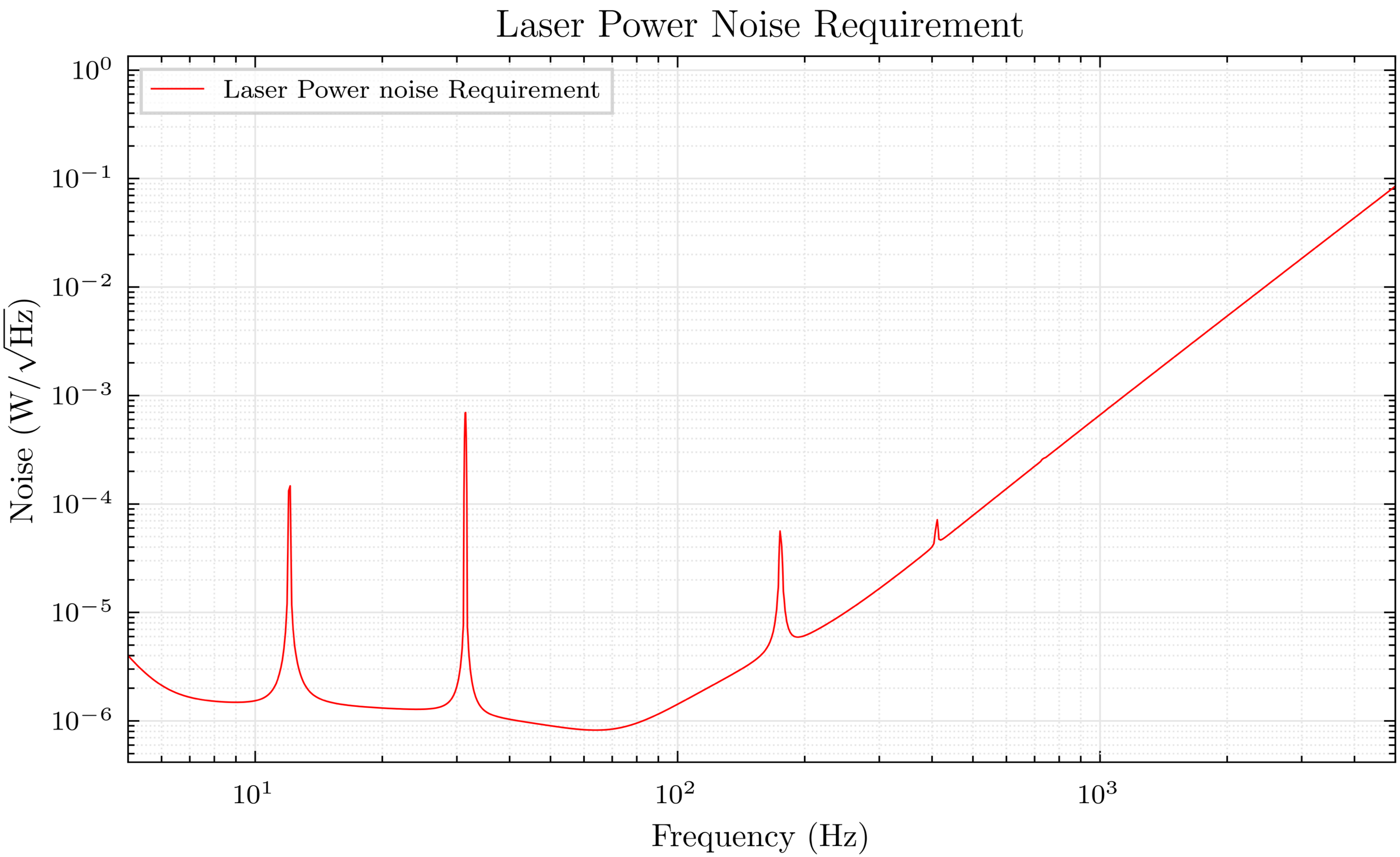
$\Delta L(f)$: Interferometer Mirror displacement induced by Pcal Laser intensity modulation

Radiation Force exerted by Pcal

Force to length transfer function

M = KAGRA 23kg
aLIGO 40kg

θ = KAGRA 0.72 deg
aLIGO 8.75 deg



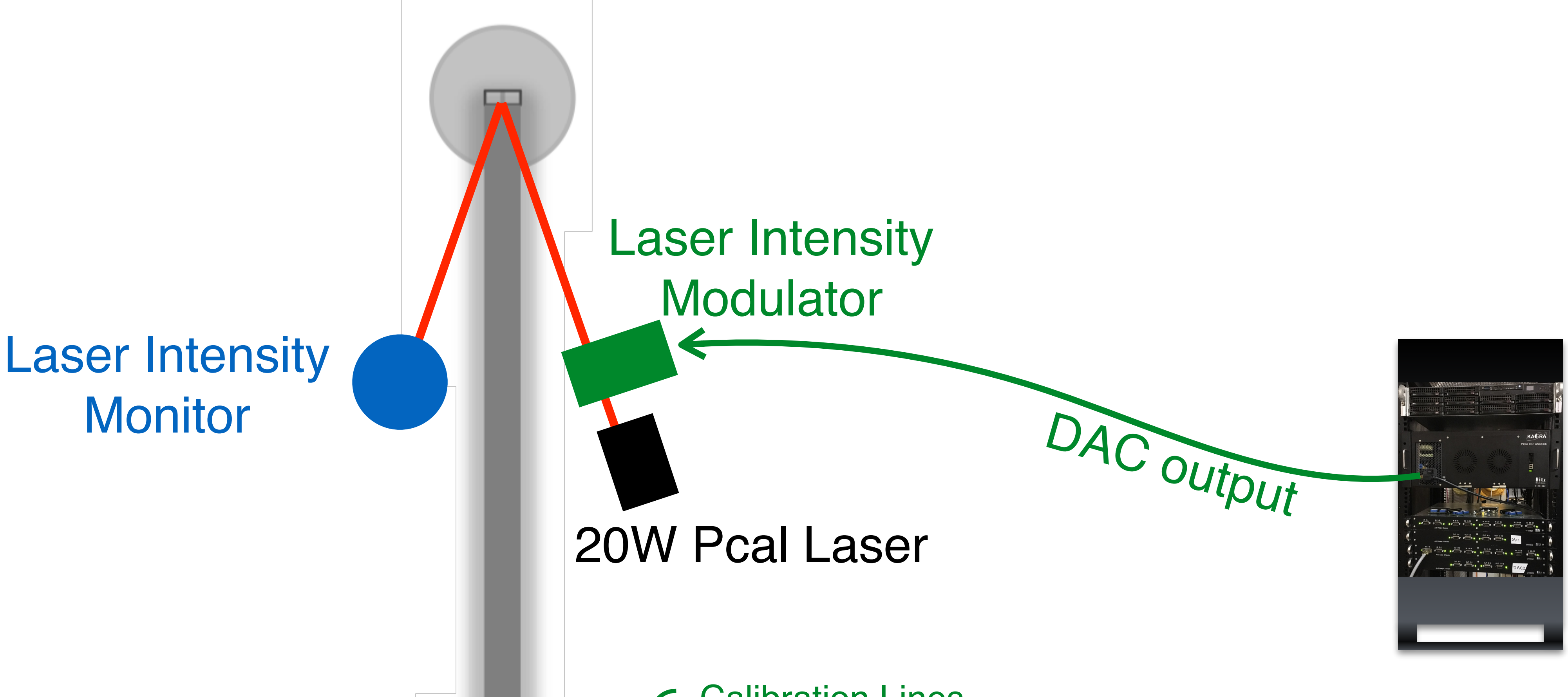
$$\Delta L(f) = \underbrace{\frac{2\Delta P(f)\cos(\theta)}{c}}\ \underbrace{\frac{1}{M(2\pi f)^2}} < \frac{1}{10}\Delta h(f) L$$

Interferometer Mirror displacement induced by Pcal Laser intensity modulation

Radiation Force exerted by Pcal

Force to length transfer function

strain sensitivity curve of KAGRA



Calibration Lines
single frequency sine wave as standard length

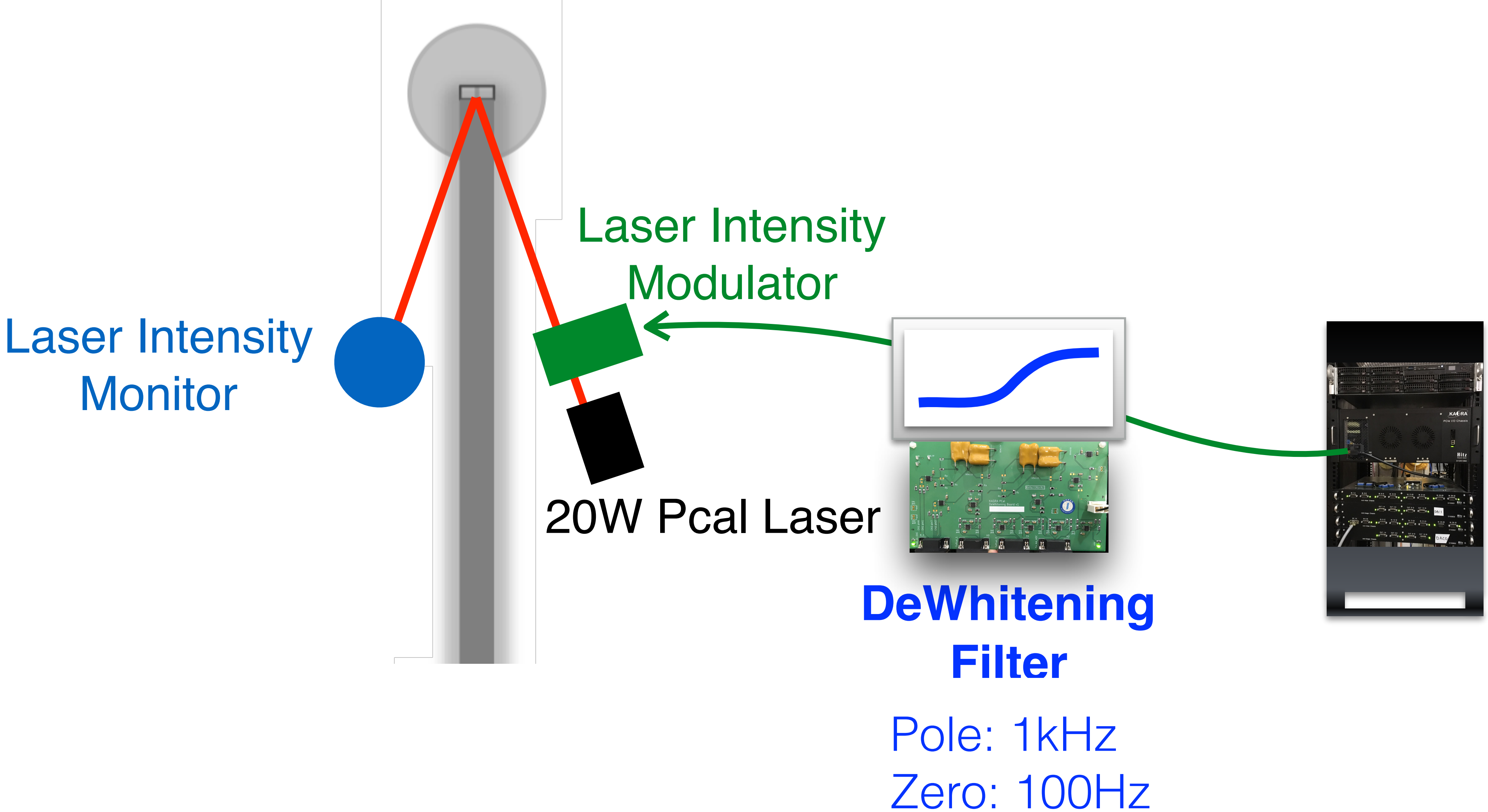
Theoretical GW waveform
Binary Neutron Stars, Binary Blackholes

Swept-Sine Excitation
Transfer Function Measurement

~~Noise~~
from Control System, DAC, Power supply……

$$\Delta L(f) = \frac{2\Delta P(f)\cos(\theta)}{c}\frac{1}{M(2\pi f)^2} < \frac{1}{10}\Delta h(f)L$$

- $\Delta L(f)$: Interferometer Mirror displacement induced by Pcal Laser intensity modulation
- $\frac{2\Delta P(f)\cos(\theta)}{c}$: Radiation Force exerted by Pcal
- $\frac{1}{M(2\pi f)^2}$: Force to length transfer function
- $\Delta h(f)$: strain sensitivity curve of KAGRA



$$\Delta L(f) = \underbrace{\frac{2\Delta P(f)\cos(\theta)}{c}}\underbrace{\frac{1}{M(2\pi f)^2}} < \frac{1}{10}\Delta h(f)L$$

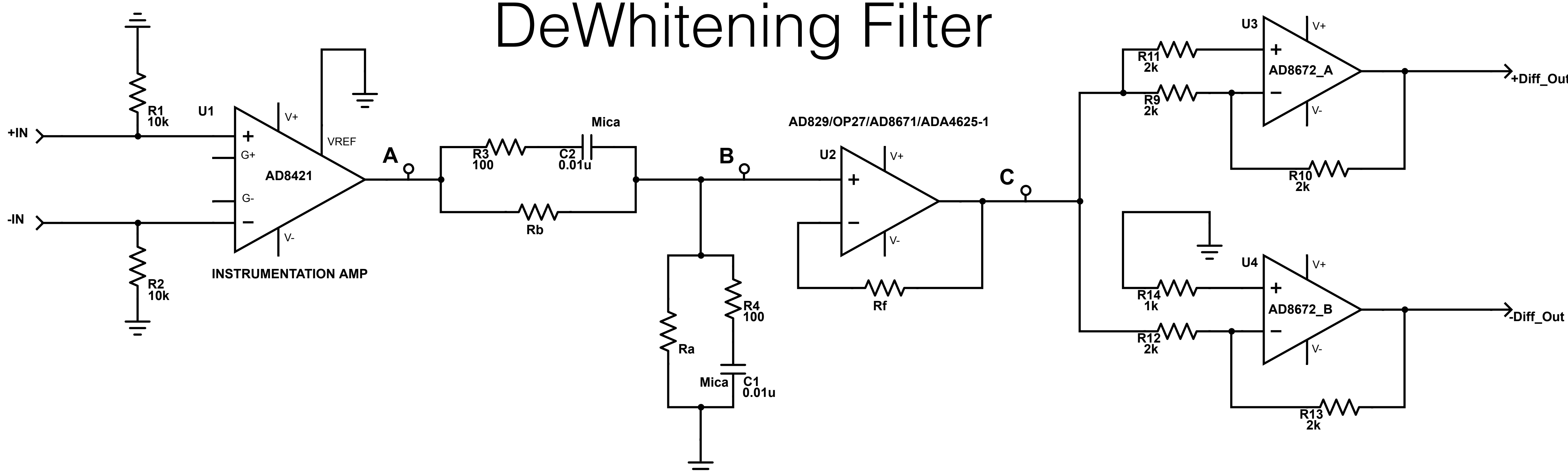
Interferometer Mirror displacement induced by Pcal Laser intensity modulation

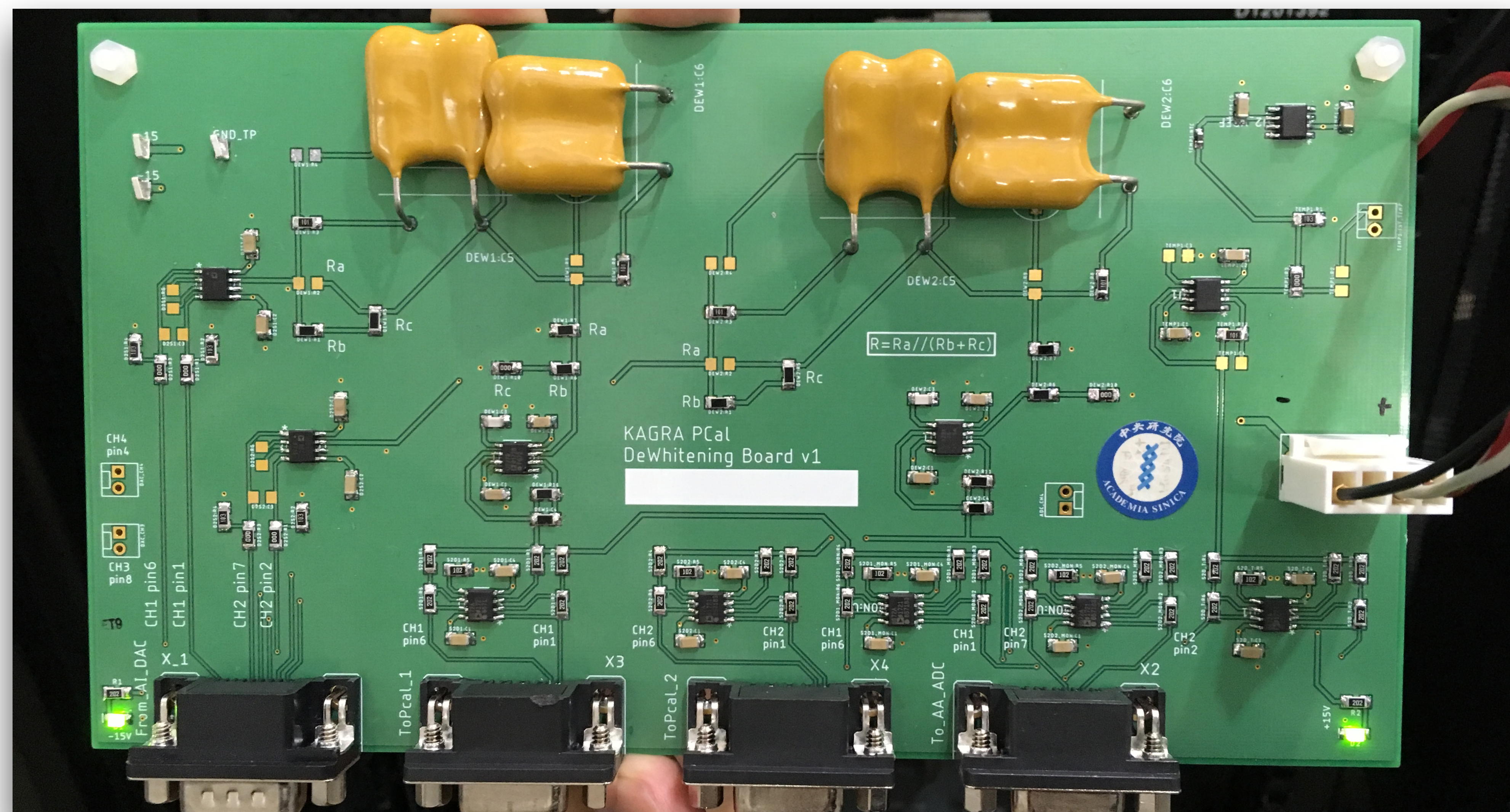
Radiation Force exerted by Pcal

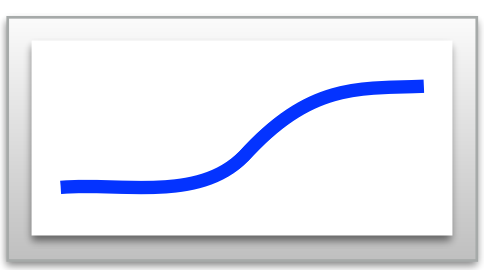
Force to length transfer function

strain sensitivity curve of KAGRA

DeWhitening Filter







Pole: 1kHz
Zero: 100Hz

Measurement of Noise Reduction Performance of De-Whitening Filter

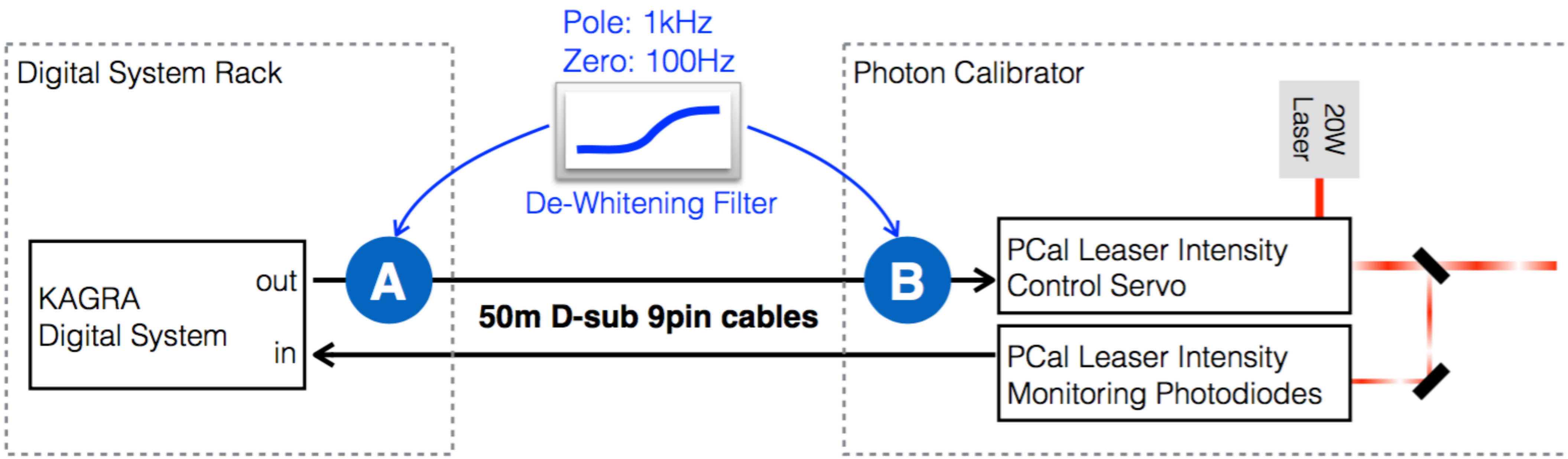


Figure 4.5: In order to reduce the noise coming from the digital system, the De-Whitening filter can be installed at either place A or B.

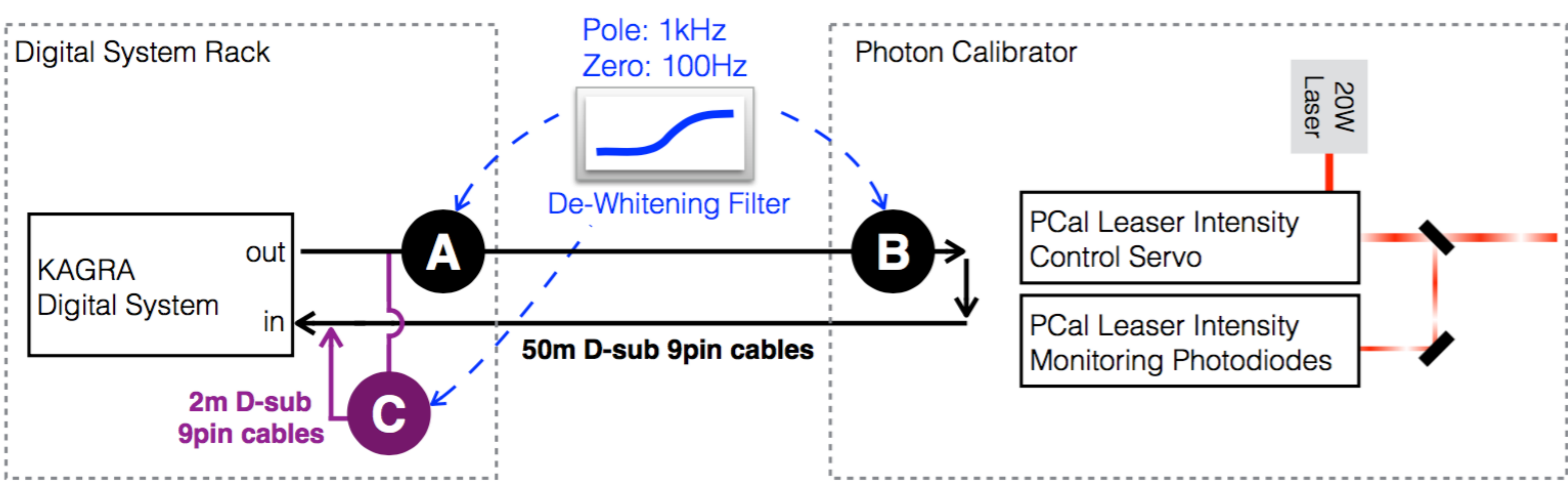


Figure 4.6: For our reference, we also measured the noise from the digital system without passing through the control loop of PCal. Place C means we connect De-Whitening filter in digital system rack with 2m cable only in order to investigate the influence from 50m cable.

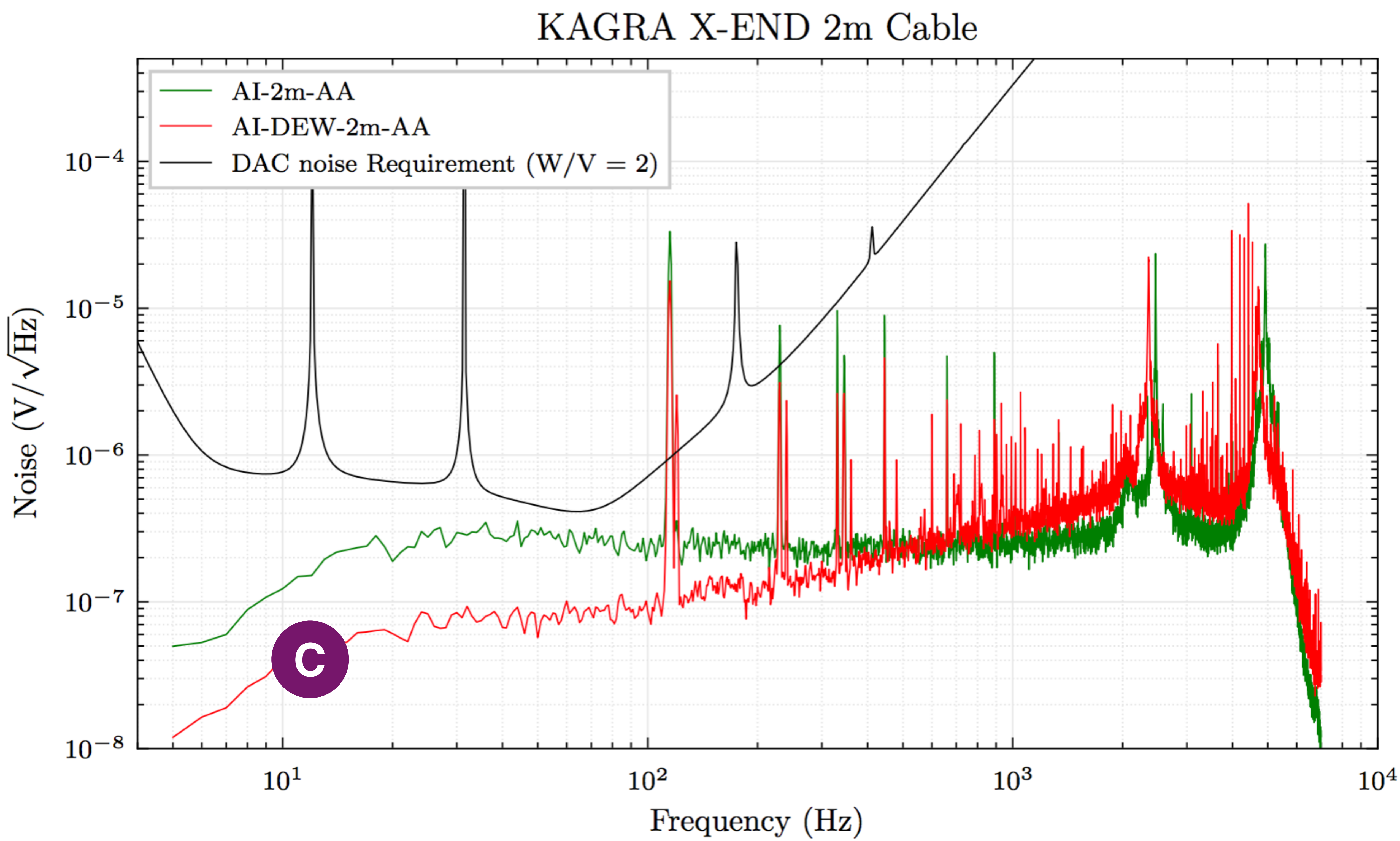


Figure 4.7: De-Whitening filter noise with short (2m) cable. The green line is the noise without De-Whitening filter, while the red one is the noise with De-Whitening filter.

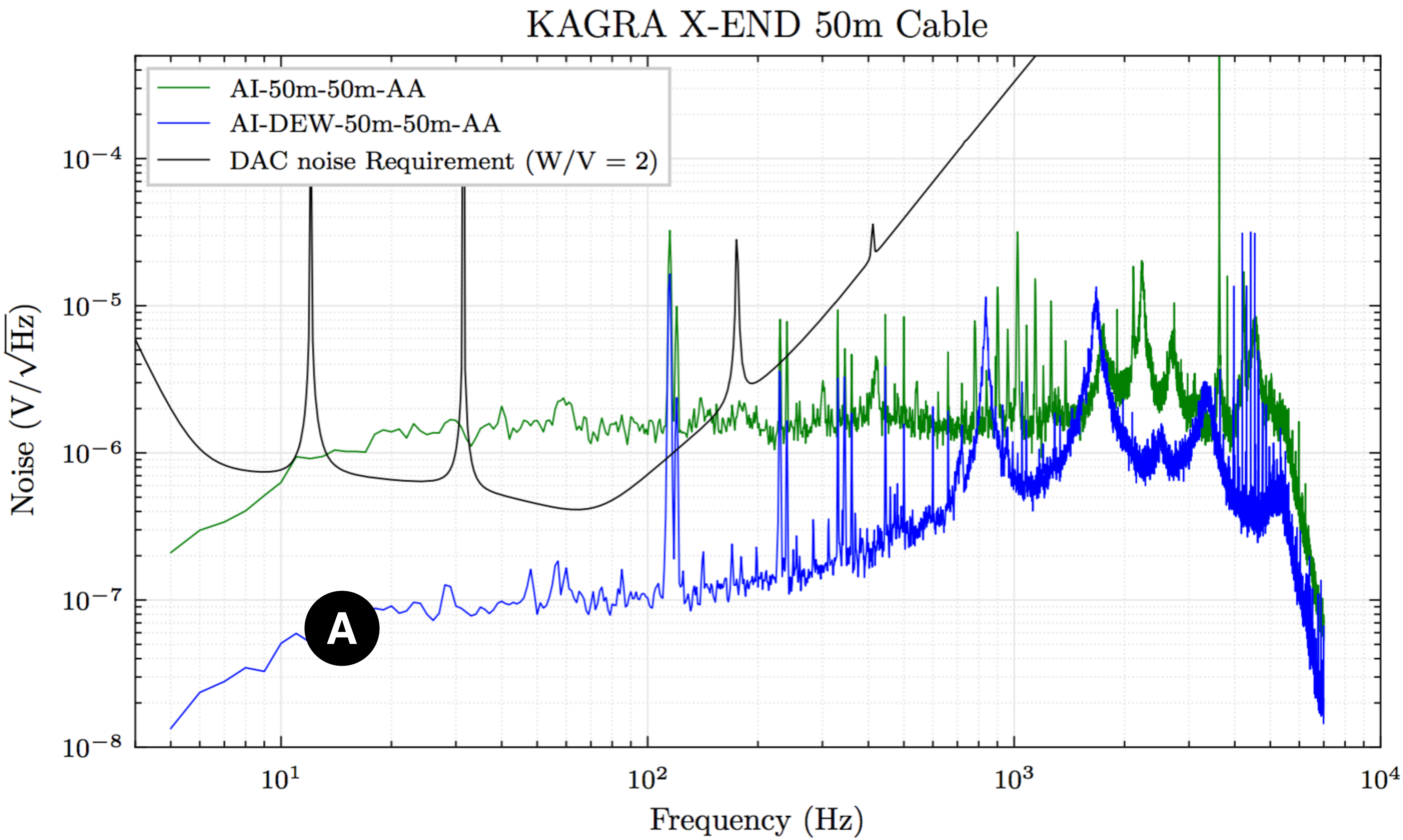


Figure 4.8: De-Whitening filter noise with long (50m) cable.

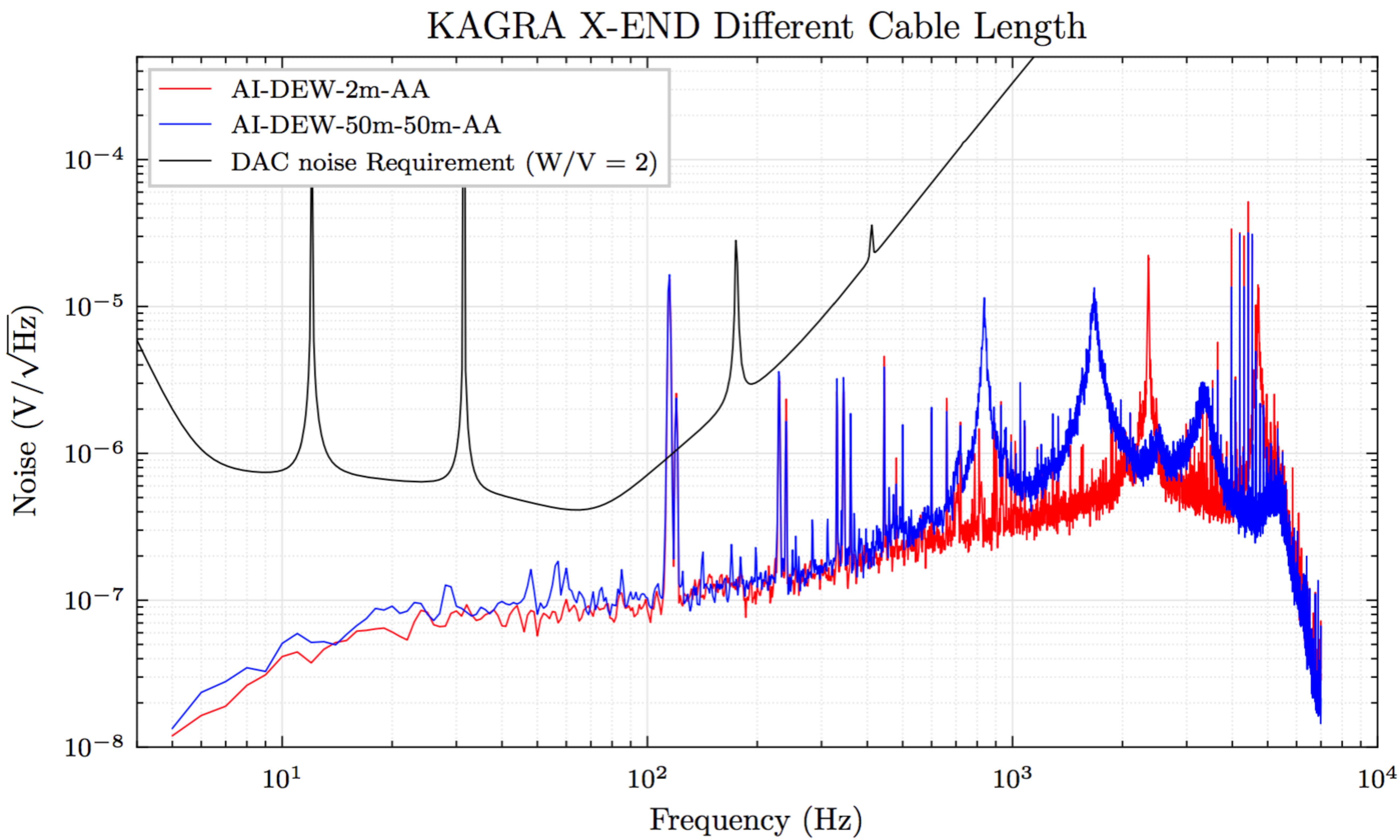


Figure 4.9: De-Whitening filter noise with different cable configuration.

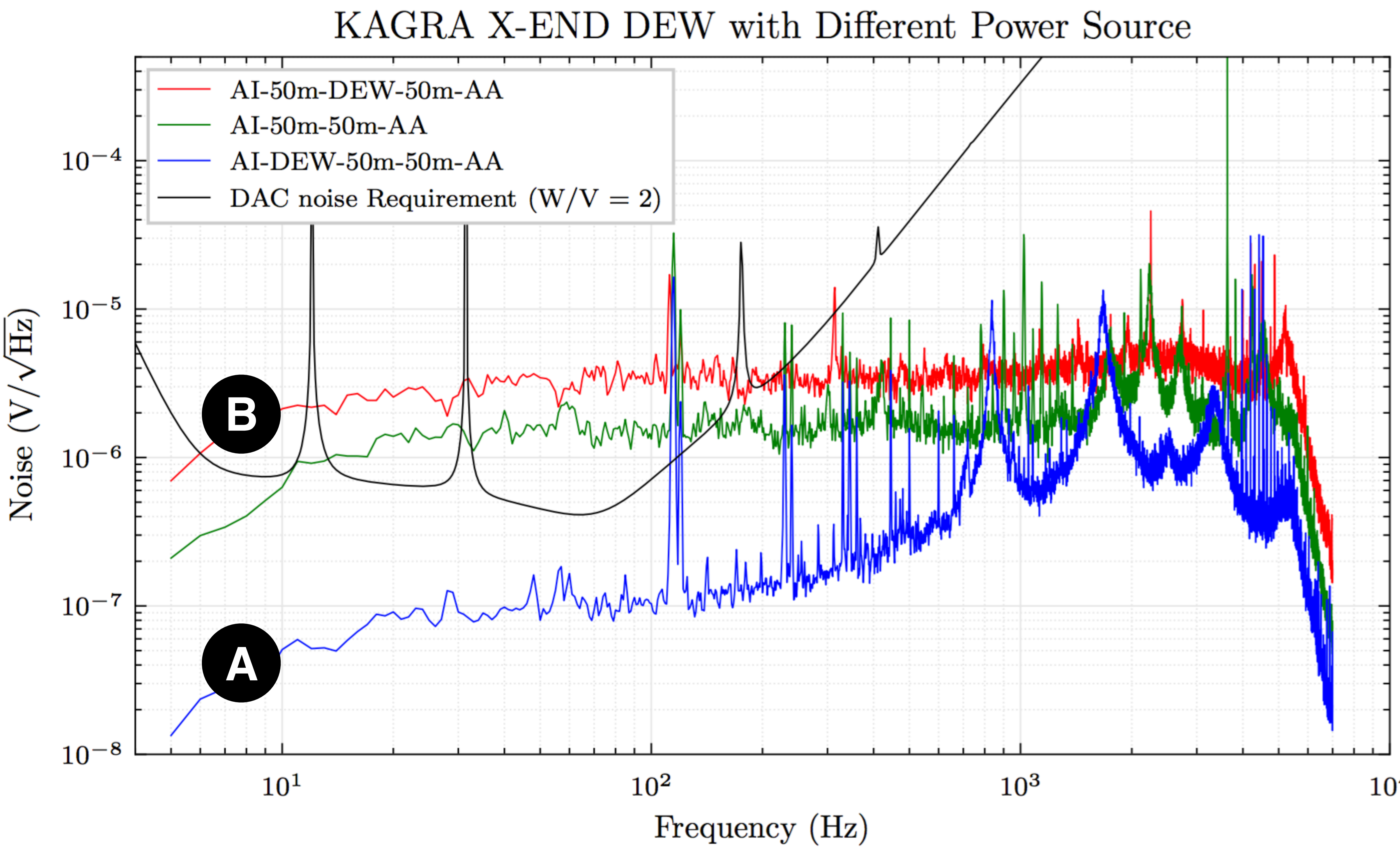


Figure 4.10: Noise measurement when the De-Whitening filter is installed at different location.

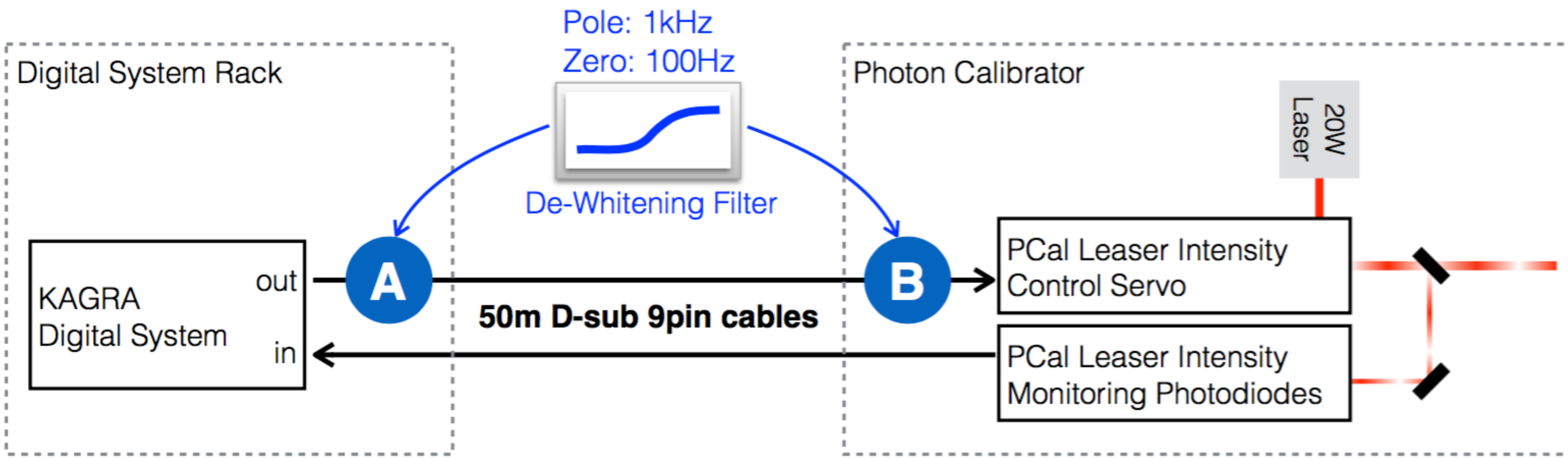


Figure 4.5: In order to reduce the noise coming from the digital system, the De-Whitening filter can be installed at either place A or B.

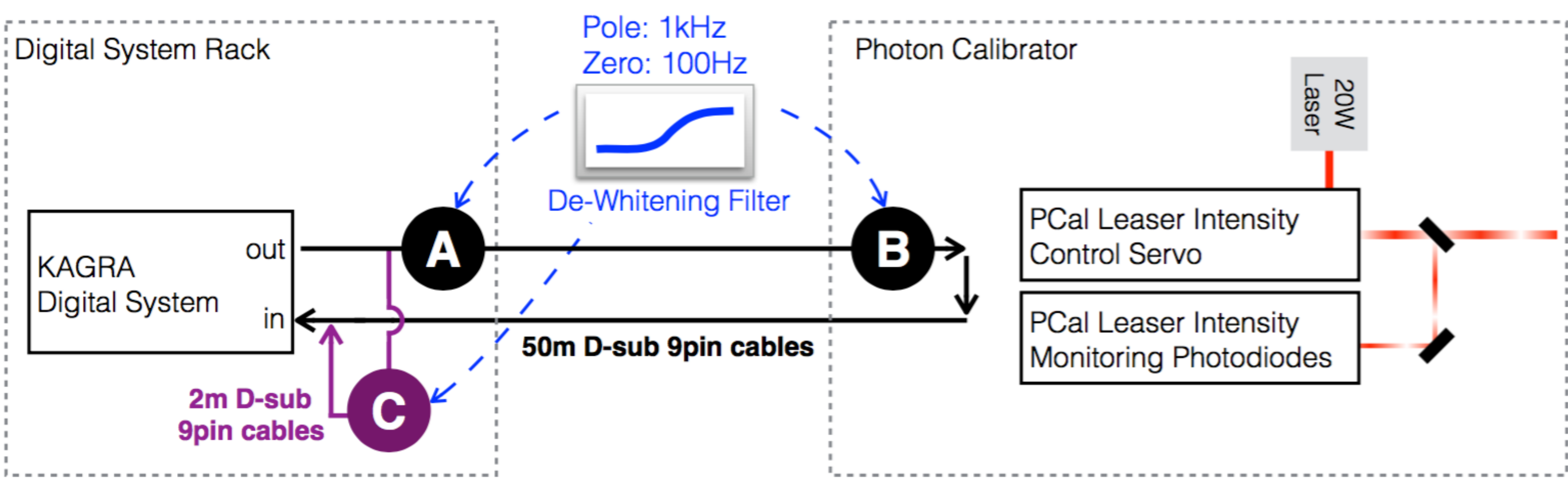


Figure 4.6: For our reference, we also measured the noise from the digital system without passing through the control loop of PCal. Place C means we connect De-Whitening filter in digital system rack with 2m cable only in order to investigate the influence from 50m cable.

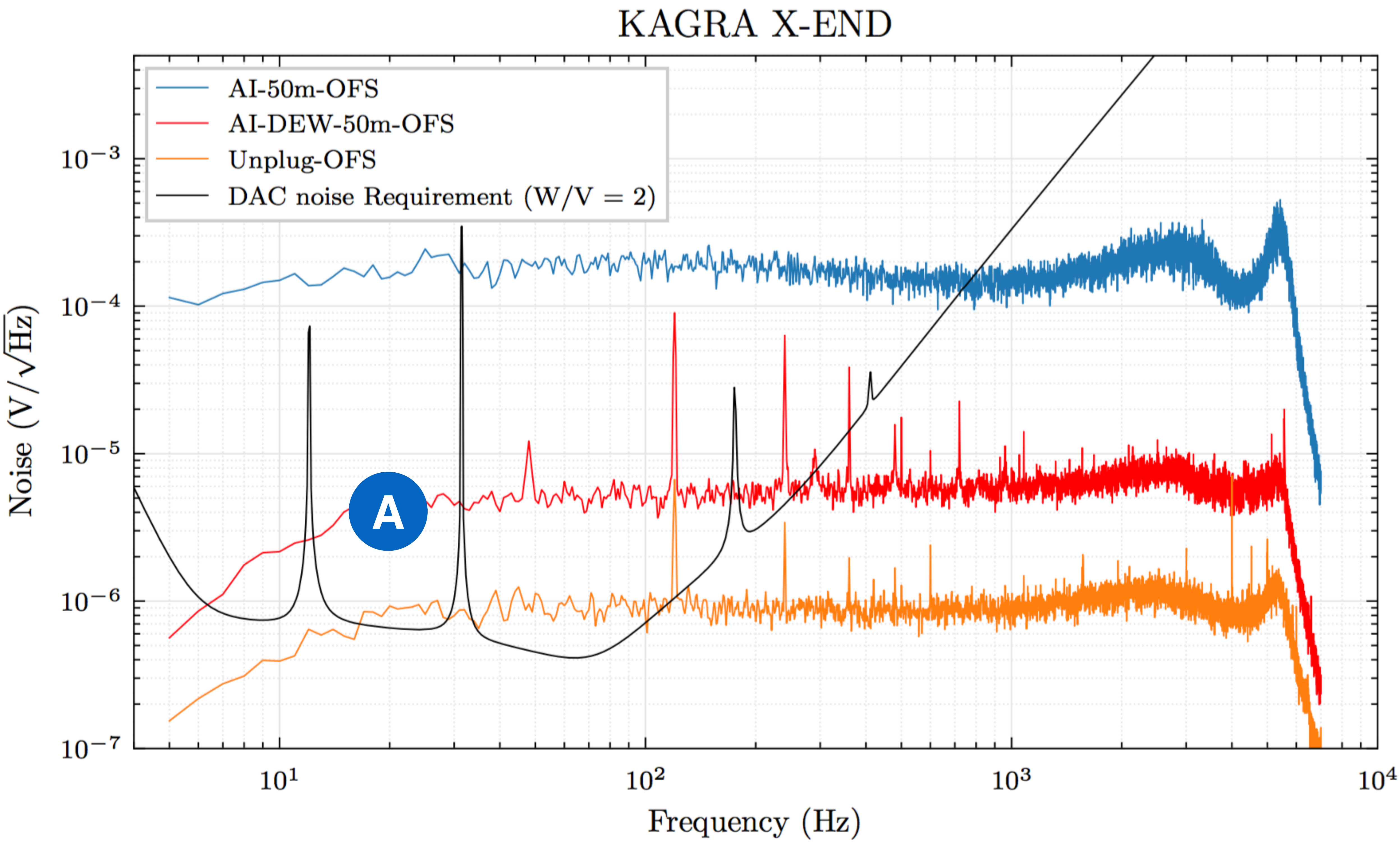


Figure 4.11: Noise measurement with PCal. These noises can be considered as laser intensity noises since we are measuring photodiode readout as depicted in Fig. 4.5. The blue line is the case without De-Whitening filer, while the red line is the case when De-Whitening filer has been installed at place A in Fig. 4.5. The orange line is measured when we disconnect our signal cable from the Laser Intensity Control Servo input port.

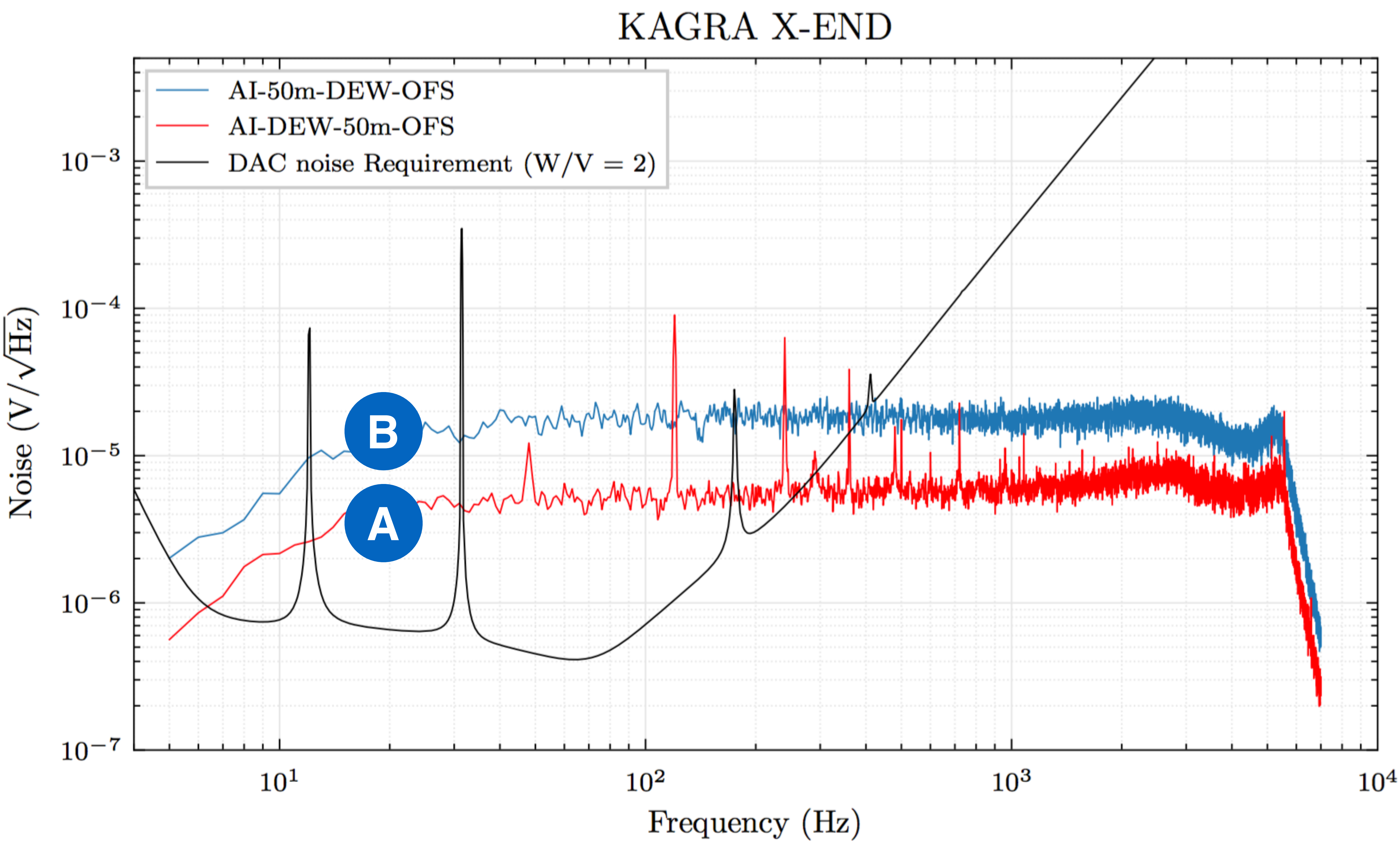


Figure 4.12: The red line and the blue line are measured when De-whitening is located at Place A and Place B in Fig. 4.5 respectively.

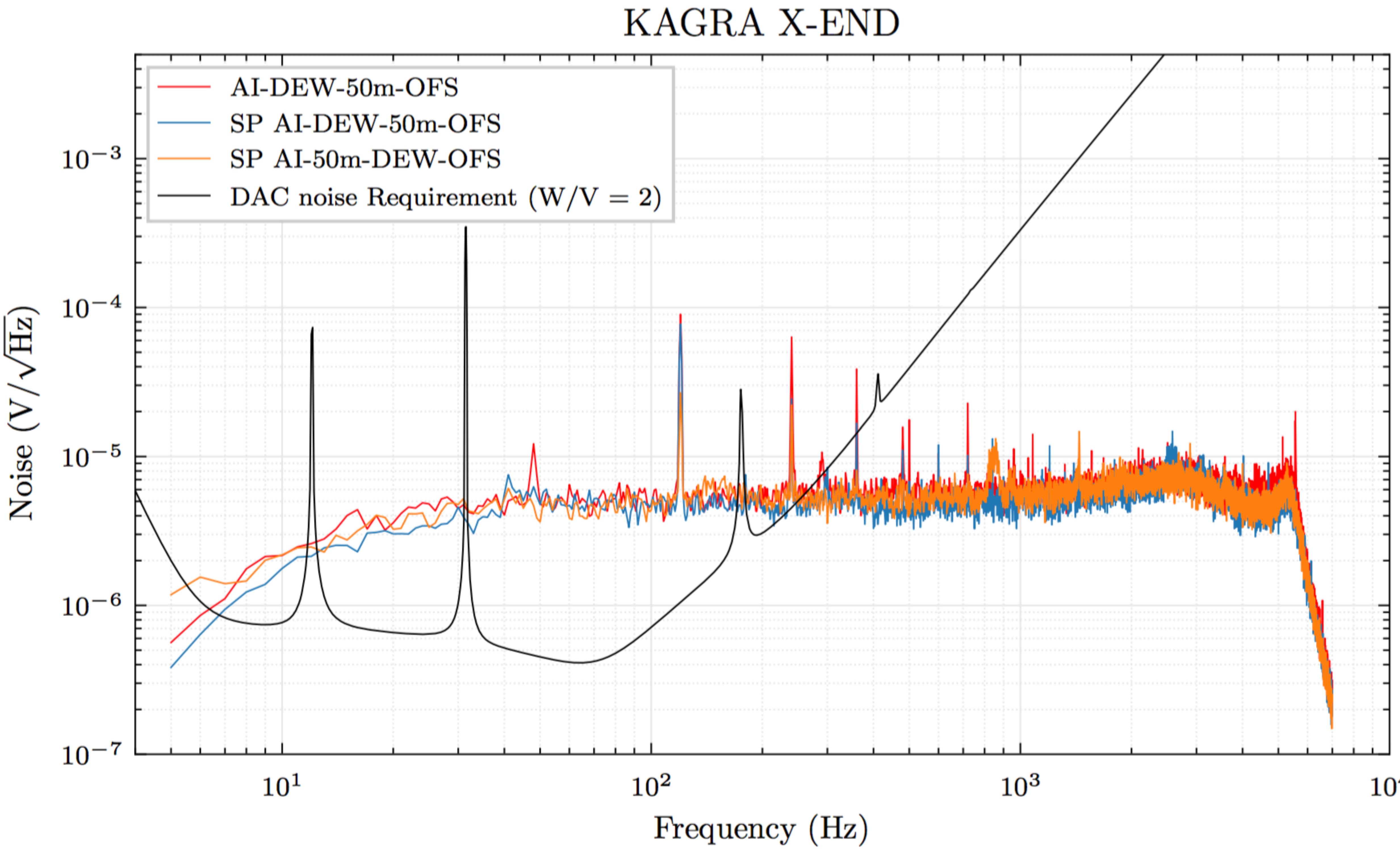


Figure 4.13: Lines labeled with "SP" were measured when we supplied digital system, De-Whitening filter and PCal with Same Power source located in digital system rack.

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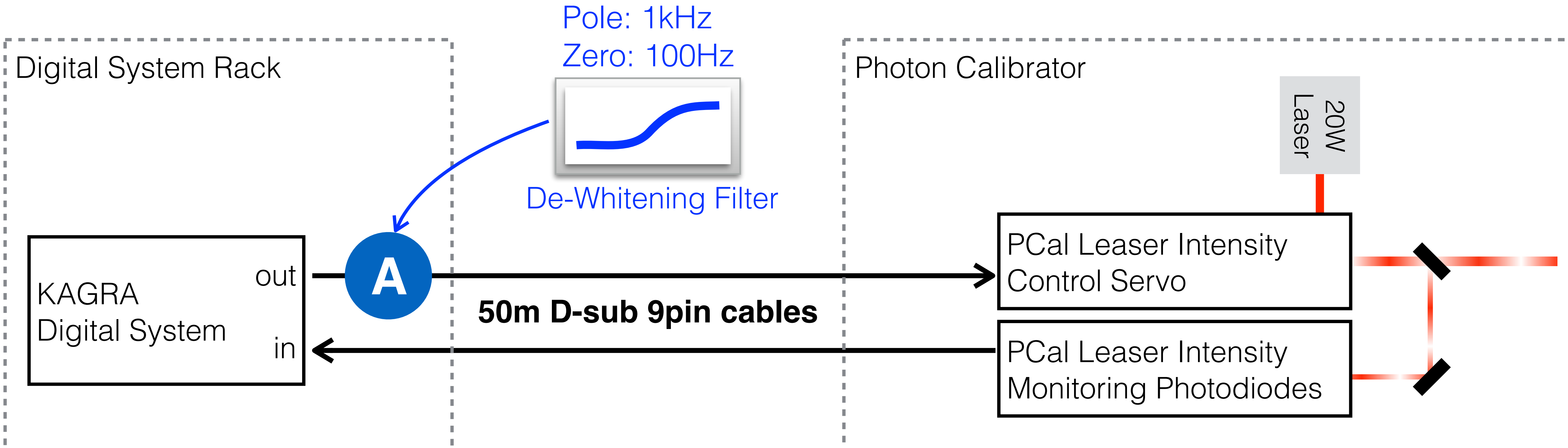
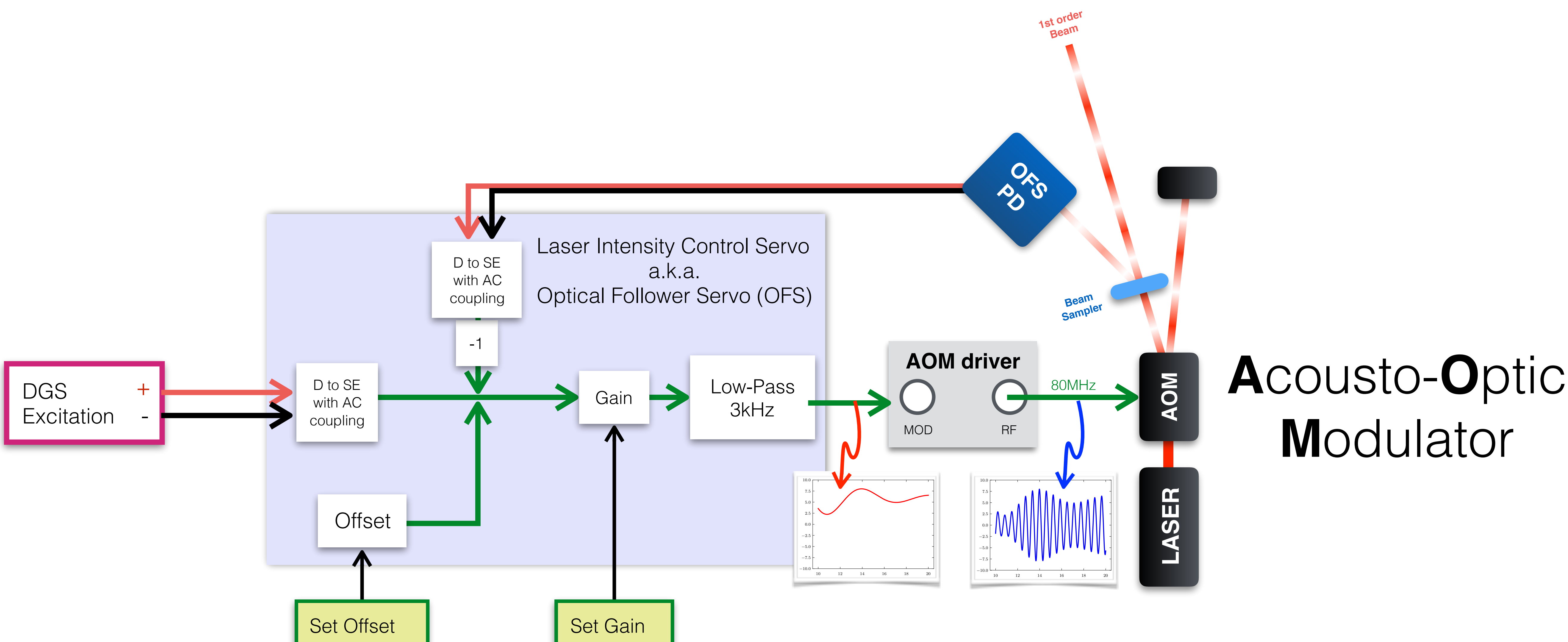
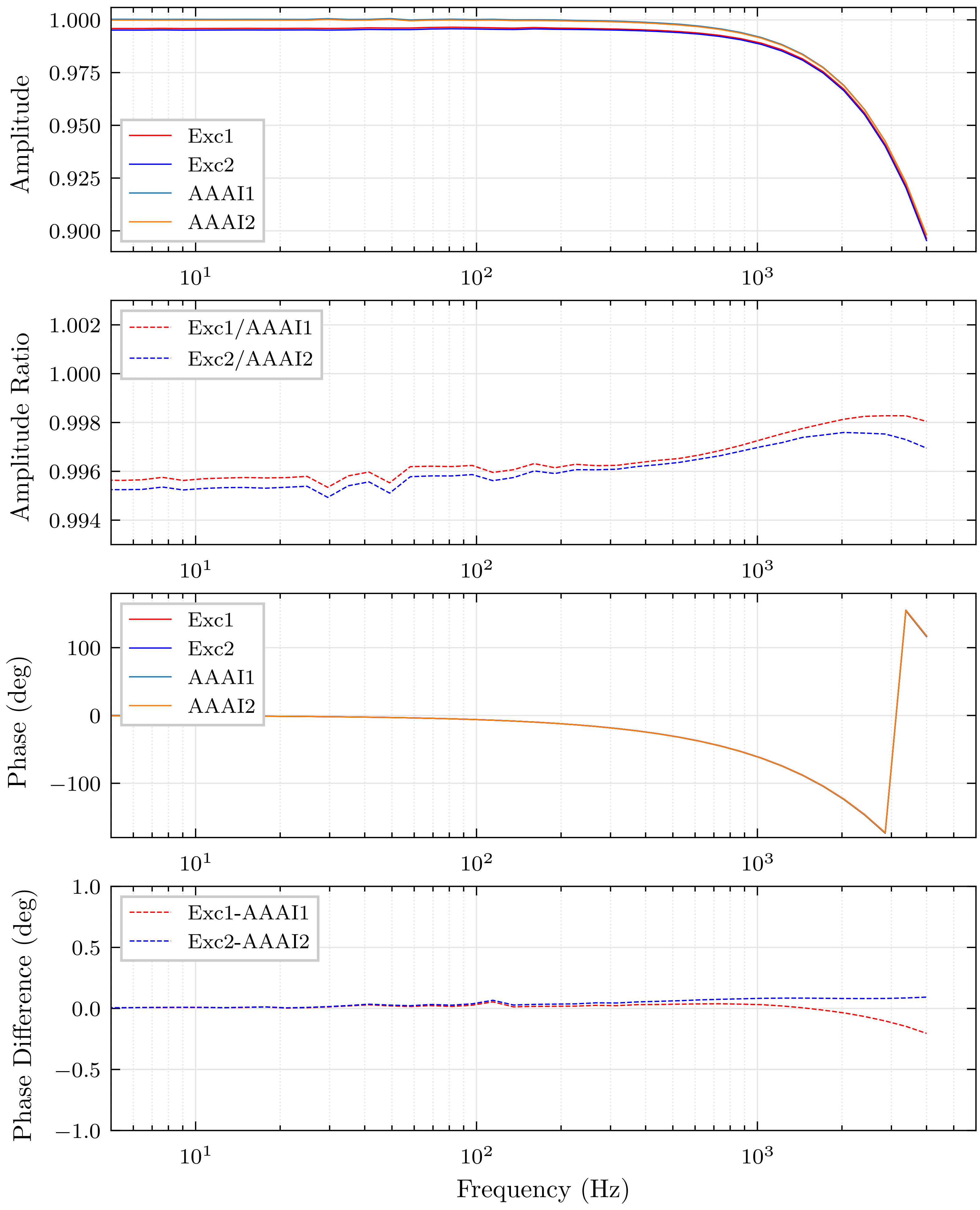
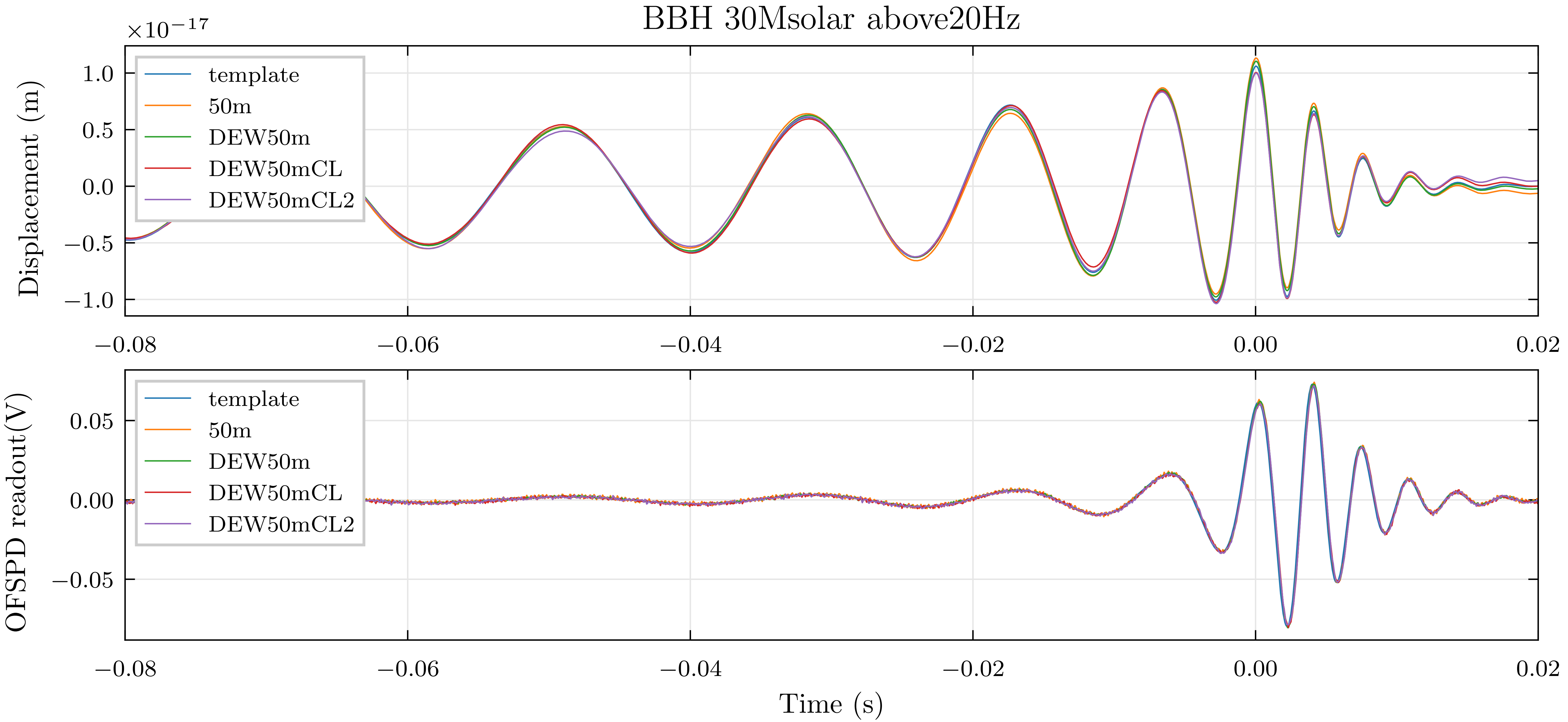
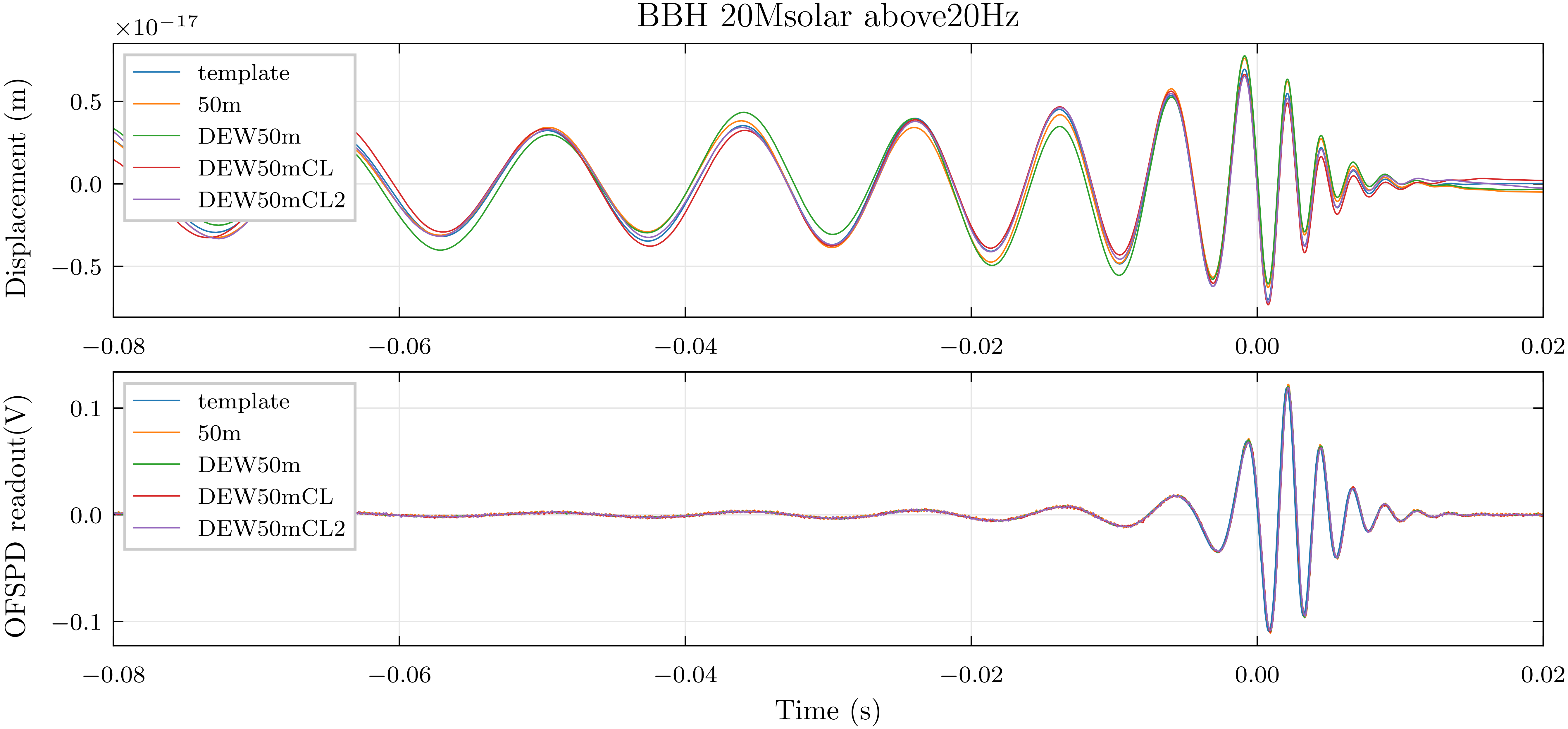

Pole: 1kHz
Zero: 100Hz
Digital System Rack
De-Whitening Filter
Photon Calibrator
20W Laser
KAGRA
Digital System
out
in
A
50m D-sub 9pin cables
PCal Leaser Intensity
Control Servo
PCal Leaser Intensity
Monitoring Photodiodes


1st order
Beam
OFS
PD
Laser Intensity Control Servo
a.k.a.
Optical Follower Servo (OFS)
D to SE
with AC
coupling
-1
Beam
Sampler
DGS
Excitation
+
-
D to SE
with AC
coupling
Gain
Low-Pass
3kHz
AOM driver
MOD
RF
80MHz
AOM
LASER
Acousto-Optic
Modulator
Offset
Set Offset
Set Gain

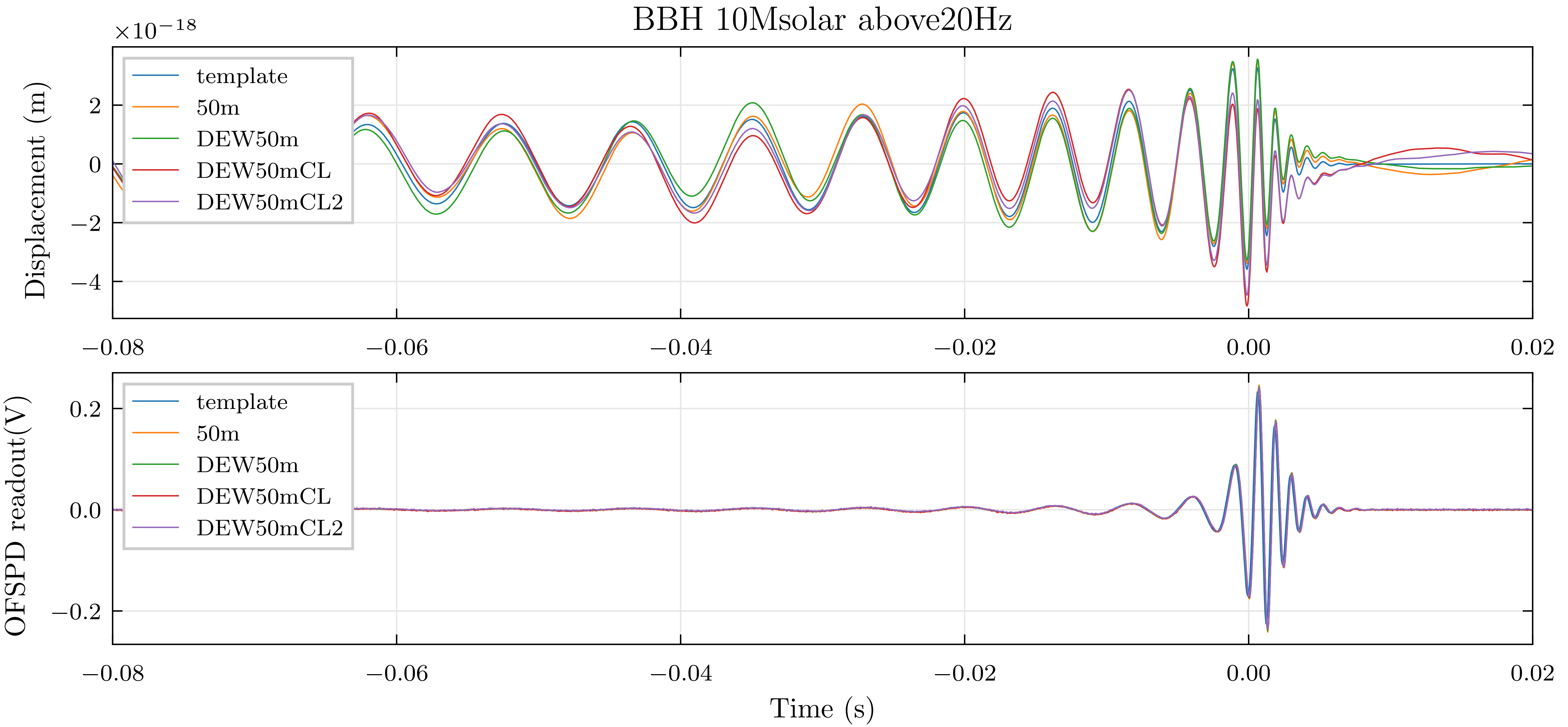


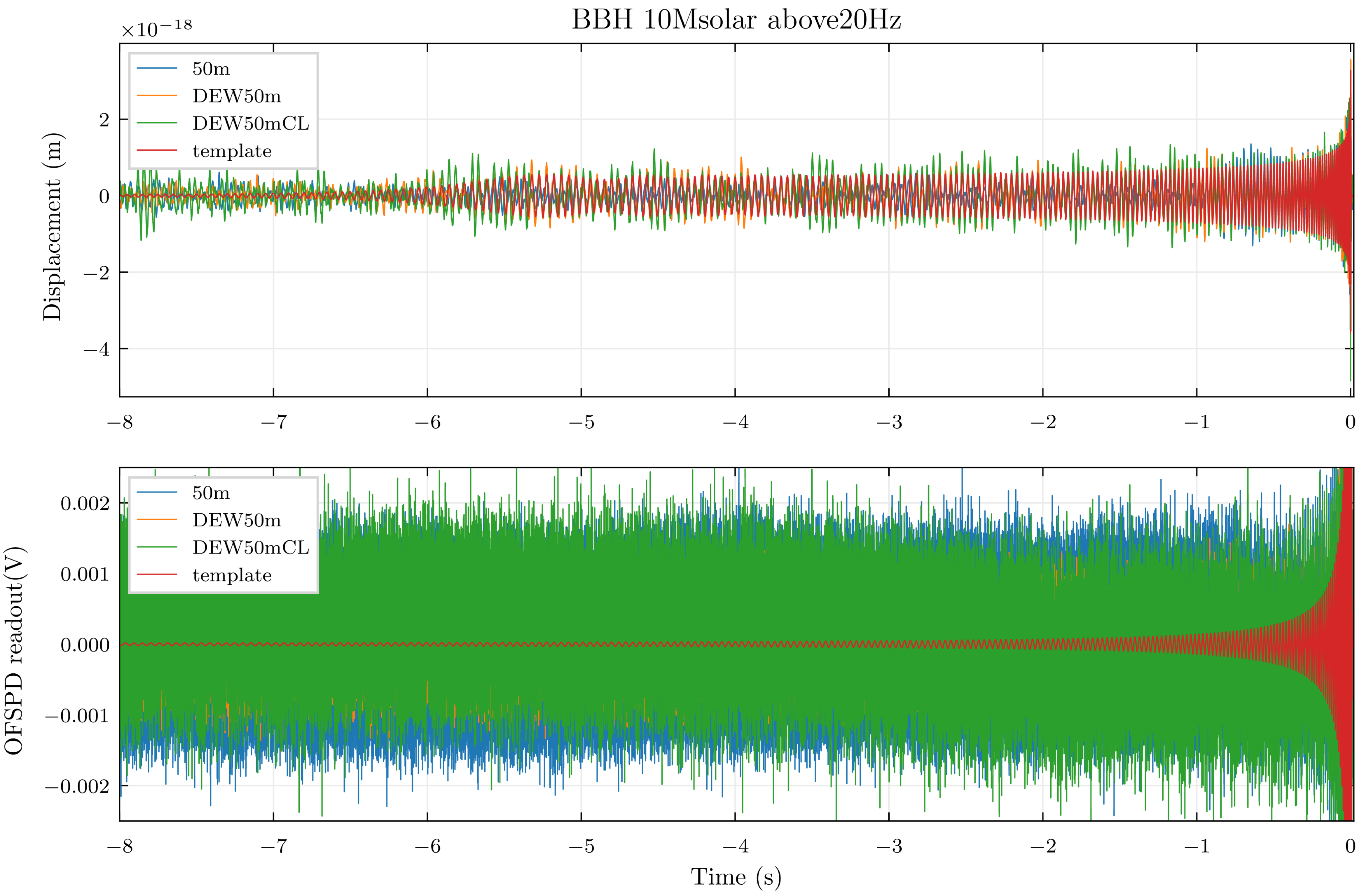
Amplitude
1.000
0.975
0.950
0.925
0.900
Exc1
Exc2
AAAI1
AAAI2
Amplitude Ratio
1.002
1.000
0.998
0.996
0.994
Exc1/AAAI1
Exc2/AAAI2
Phase (deg)
100
0
−100
Phase Difference (deg)
1.0
0.5
0.0
−0.5
−1.0
Exc1-AAAI1
Exc2-AAAI2
10^1
10^2
10^3
Frequency (Hz)


BBH 30Msolar above20Hz
×10^−17
Displacement (m)
1.0
0.5
0.0
−0.5
−1.0
template
50m
DEW50m
DEW50mCL
DEW50mCL2
−0.08
−0.06
−0.04
−0.02
0.00
0.02
OFSPD readout(V)
0.05
0.00
−0.05
template
50m
DEW50m
DEW50mCL
DEW50mCL2
−0.08
−0.06
−0.04
−0.02
0.00
0.02
Time (s)



BBH 20Msolar above20Hz
×10^−17
Displacement (m)
0.5
0.0
−0.5
template
50m
DEW50m
DEW50mCL
DEW50mCL2
−0.08
−0.06
−0.04
−0.02
0.00
0.02
OFSPD readout(V)
0.1
0.0
−0.1
template
50m
DEW50m
DEW50mCL
DEW50mCL2
−0.08
−0.06
−0.04
−0.02
0.00
0.02
Time (s)


BBH 10Msolar above20Hz
×10^−18
Displacement (m)
template
50m
DEW50m
DEW50mCL
DEW50mCL2
2
0
−2
−4
−0.08
−0.06
−0.04
−0.02
0.00
0.02
OFSPD readout(V)
0.2
0.0
−0.2
Time (s)


BBH 10Msolar above20Hz
×10^−18
50m
DEW50m
DEW50mCL
template
Displacement (m)
2
0
−2
−4
−8
−7
−6
−5
−4
−3
−2
−1
0
OFSPD readout(V)
0.002
0.001
0.000
−0.001
−0.002
Time (s)

outline

- Introduction
- Hardware Injection through Photon Calibrator
- Signal Generating System (Digital Control System)
- Noise reduction through De-Whitening Filter
- Validation of Injection Channel
- Discussion and Future Works

Future Works

- Performing Hardware Injection test using PCal with DeWhitening filter.

- Investigate analog excitation signal noise problem with long cable connection.

- Intrinsic limit of the De-Whitening Filter

- Noise shaping

END