Optimizing Active Vibration Isolation Systems in Ground-Based Interferometeric Gravitational-Wave Detectors

PhD thesis defense

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Thesis committee

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Outline

- What are gravitational waves and how do we detect them?
- What does vibration isolation have to do with gravitational waves?
- Optimizing active vibration isolation systems in gravitational-wave detectors.

Einstein’s Theory of general relativity

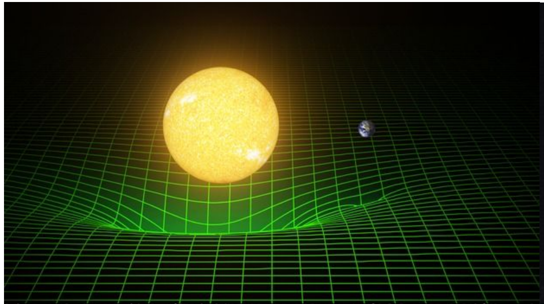
General relativity is a theory of gravity.

Describes gravity as curvature of spacetime.

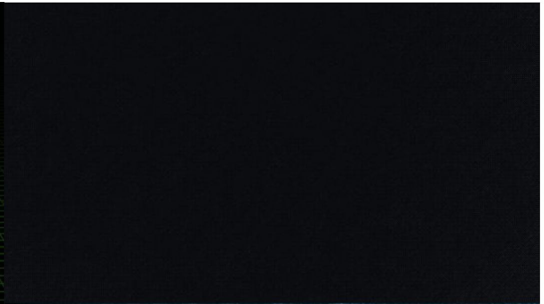
Several phenomena have been explained/predicted

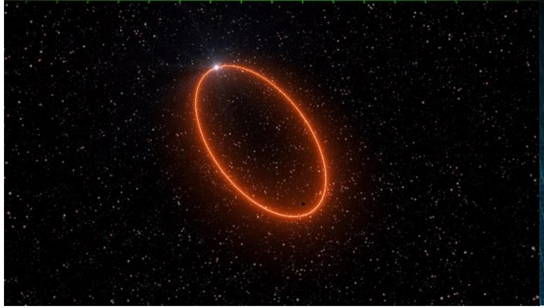
- Precession of perihelion of Mercury
- Bending of light by the Sun
- Gravitational waves

Curvature of spacetime

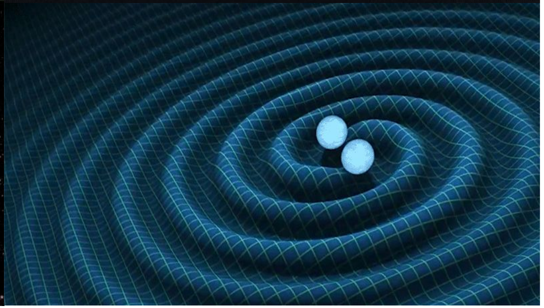


Bending of light





Precession of Mercury’s Orbit



Gravitational waves

Image Credits:
T. Pyle/Caltech/MIT/LIGO Lab
New York Times
NASA's Goddard Space Flight Center
R. Hurt - Caltech / JPL

Gravitational waves

Gravitational waves are ripples in spacetime

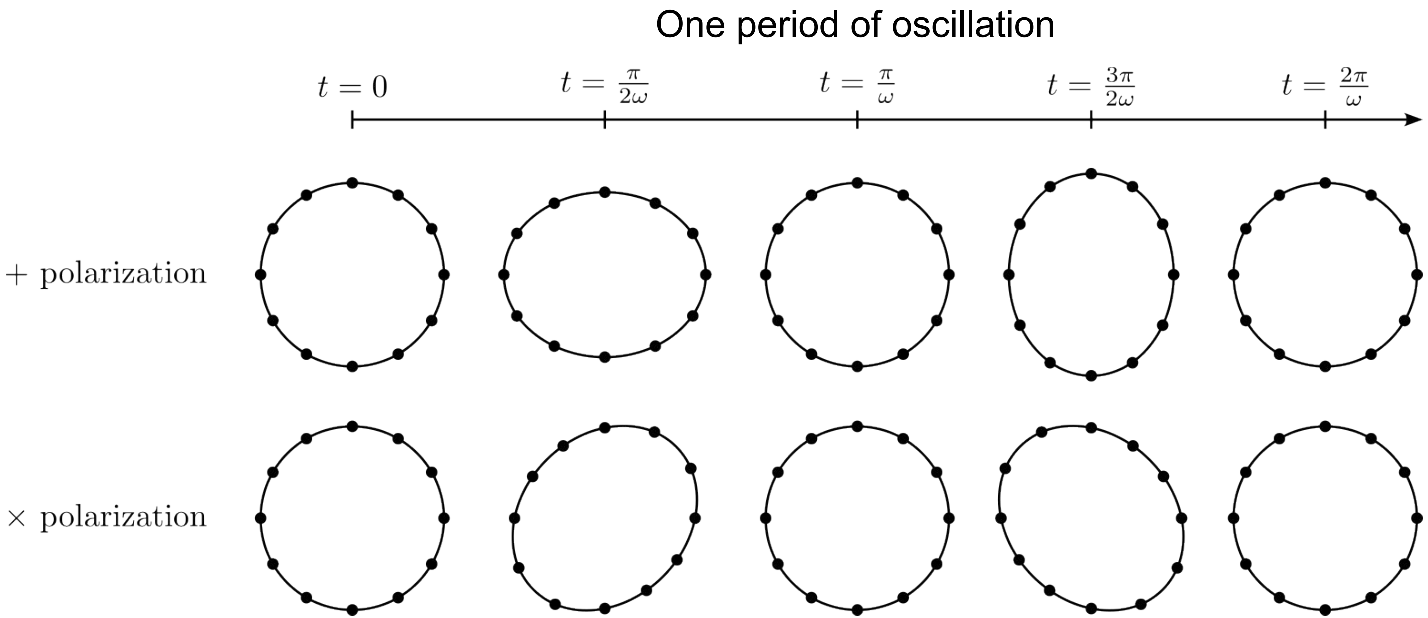
Generated by accelerated masses (time variation of quadrupole moment).

Stretches and squeezes space perpendicular to the propagation direction.

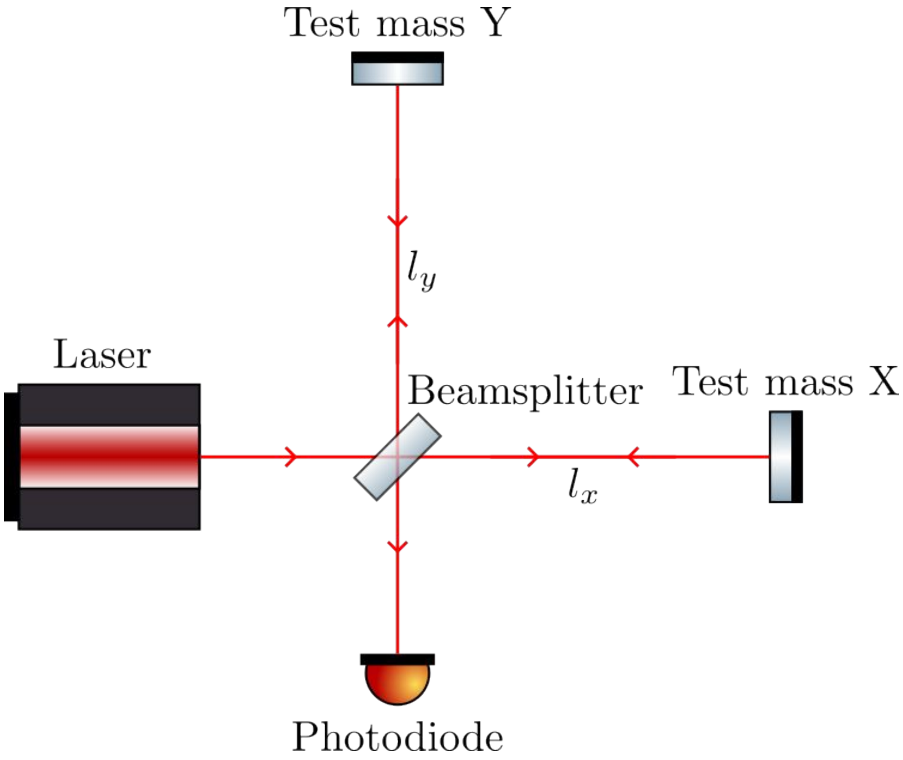
Image Credits:
Simulating eXtreme Spacetimes (SXS) project
LIGO/R. Hurt

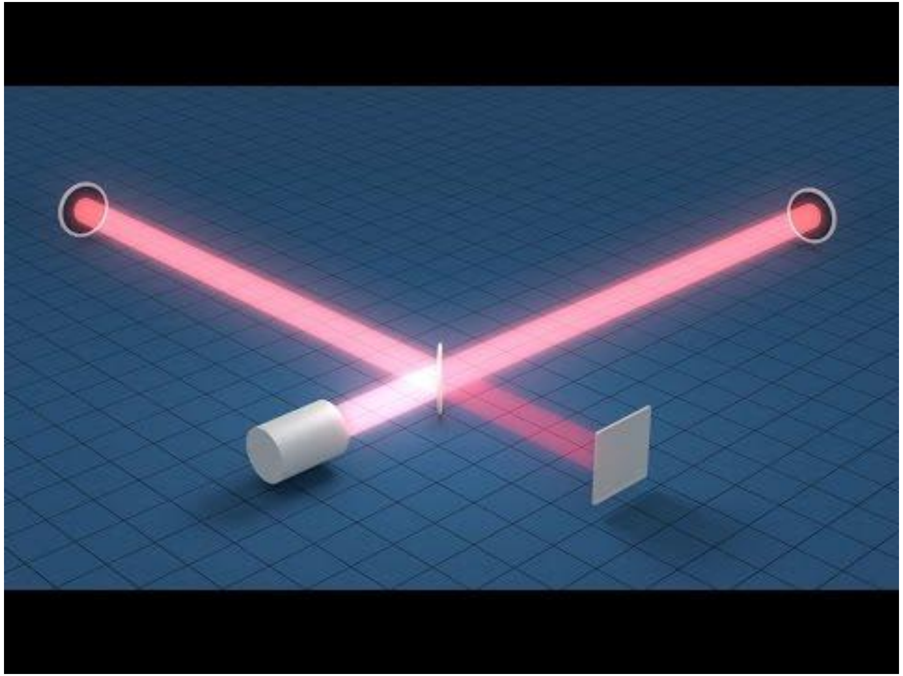
Ring of test masses

Gravitational wave propagating **into** the ring of test masses



Michelson Interferometer





Credit: LIGO/T. Pyle

Not just any Michelson interferometer

For starters:

Gravitational-wave detectors have really long interferometer arms

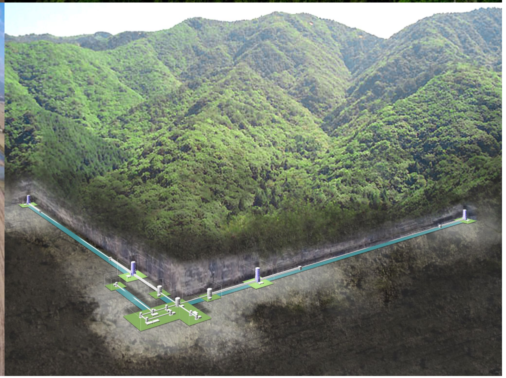
LIGO: 4 km arms

Virgo and KAGRA: 3 km arms

LIGO Hanford in the US

LIGO Livingston in the US

Virgo in Italy

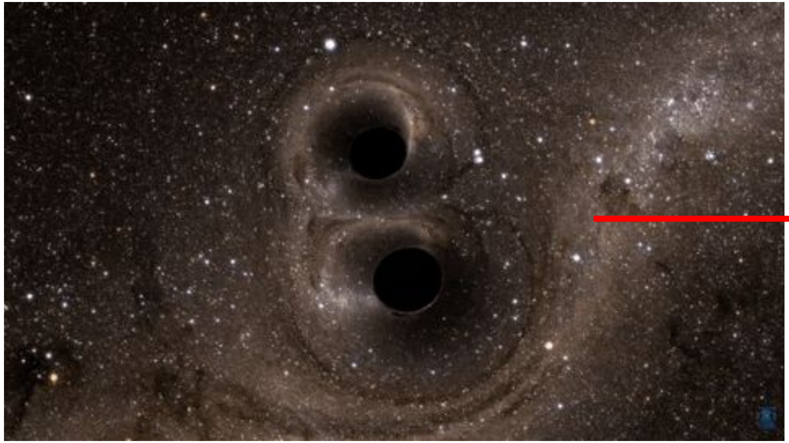


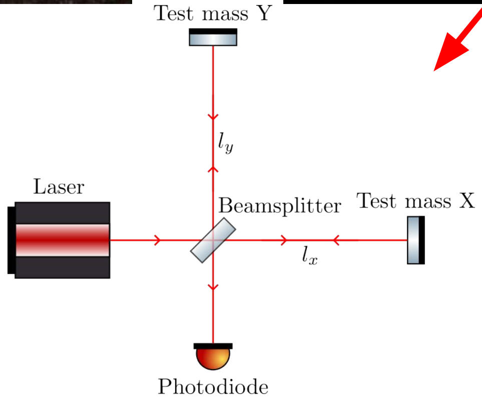
I worked here

KAGRA in Gifu, Japan (underground)

Image credits:
Caltech/MIT/LIGO Lab
ICRR, Univ. of Tokyo
The Virgo collaboration/CCO 1.0

Detecting gravitational waves?





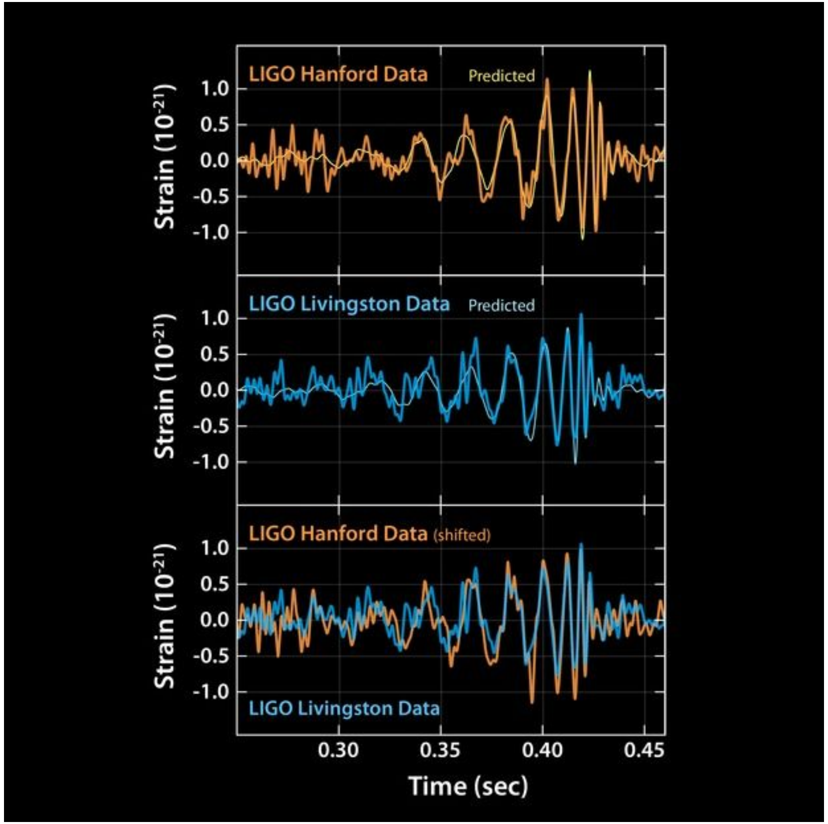
First detection GW150914

Detected by the two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO).

Coalescence of two black holes from 1.4 billion light years away.

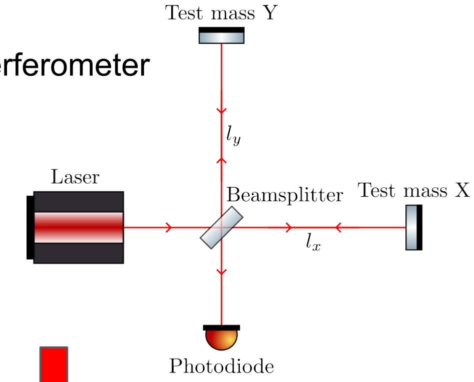
Increased from **~35-250 Hz**.

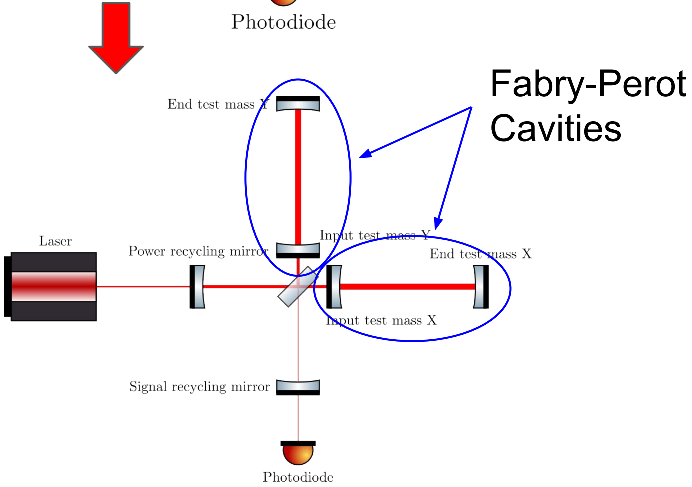
Peak strain of **~10^{-21}**.



Detecting gravitational waves is a daunting task (1)

Michelson Interferometer



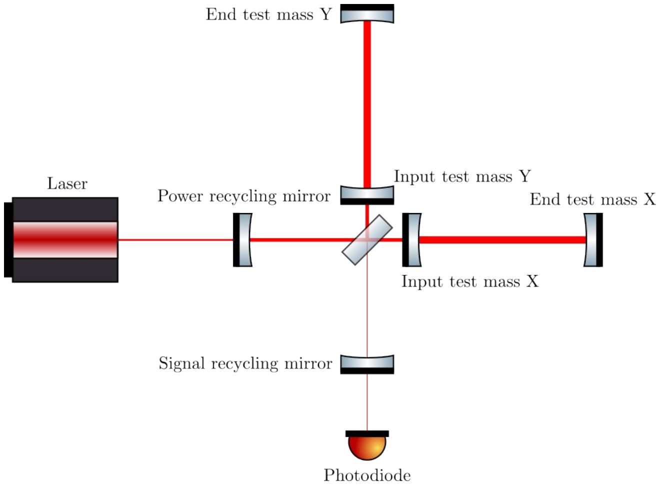


Michelson interferometer for GW signals at 100 Hz.

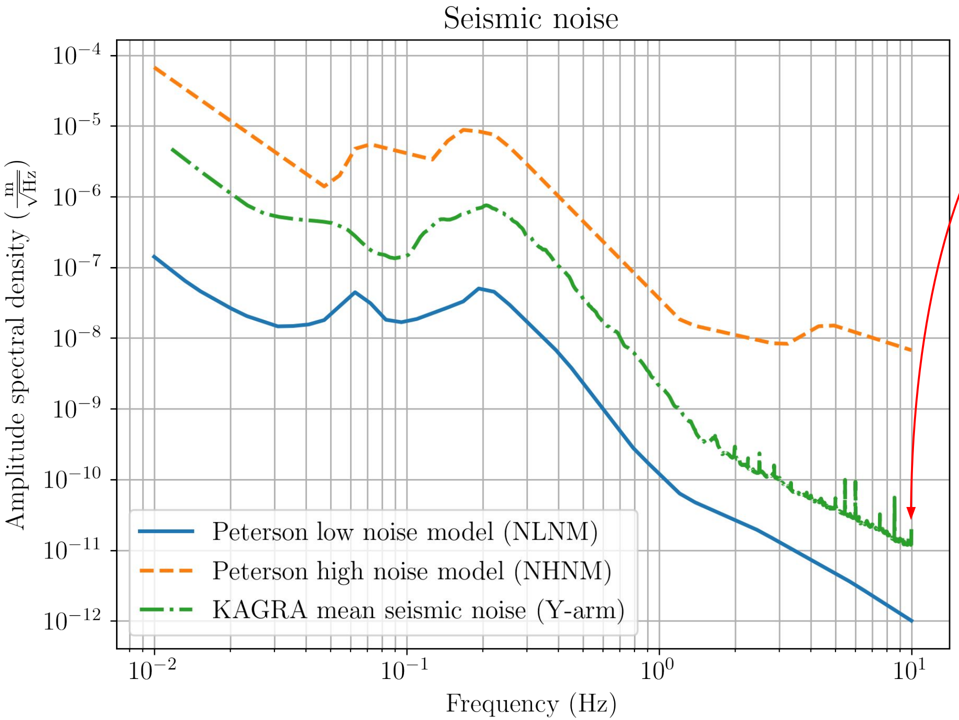
- Optimal arm length
  - The light needs to stay in the arm for half the period of the GW signal.
    $\longrightarrow \quad l = \frac{\lambda_{\mathrm{gw}}}{4}$
  - For gravitational waves at 100 Hz, the optimal length is **~750 km, ~1/9 Earth radius**.
- Use Fabry-Perot Cavity
  - Light travels back and forth in the cavity (effectively)
  - Effectively increased the arm length by the number of round trips.

Detecting gravitational waves is a daunting task (2)

- Gravitational waves are whispers in the universe.
  - GW150914: peak strain of $\mathbf{10^{-21}}$.
- Detector noises
  - **Quantum noise** (Shot noise and radiation pressure)
    - Increasing the laser power (Fabry-Perot cavity / Power recycling mirror)
    - Operating at dark port
  - **Thermal noise**
    - Low mechanical loss materials (Silica / sapphire)
    - Cryogenic (like KAGRA)
  - **Seismic noise**
    - Suspending the optics
  - And more…



Seismic noise (1)



Seismic noise at 10 Hz,
~10^{-11} m/√Hz

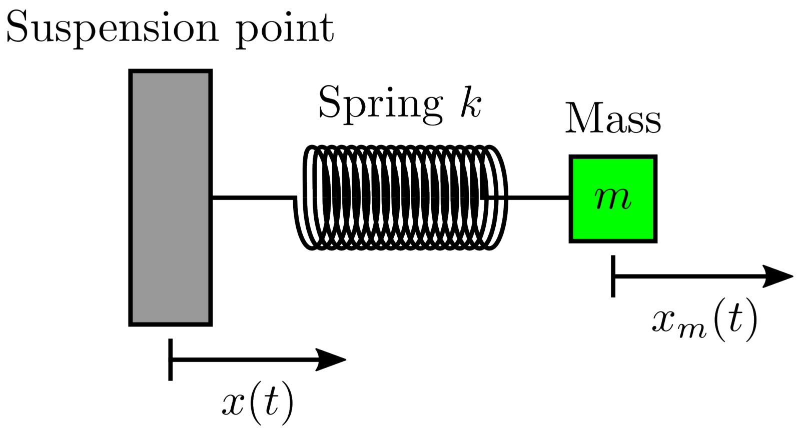
Interferometer baseline of ~10^{3} m
Equivalent strain noise is ~10^{-14} 1/√Hz

Gravitational waves at ~10^{-21} 1/√Hz*.
→Requires at least **10^{7} times reduction**.

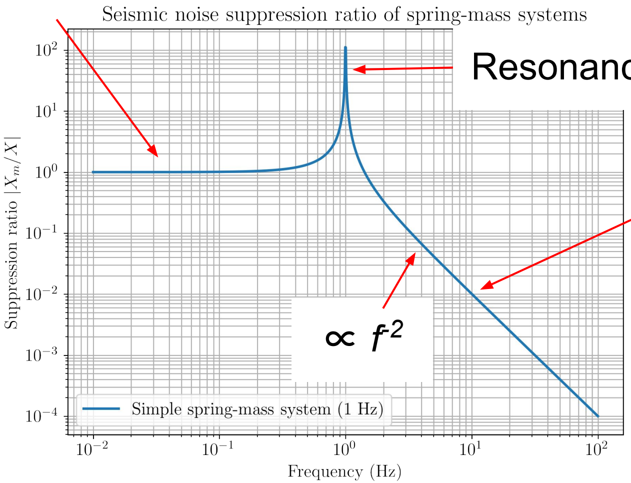
Thats **10 million** times of suppression.

*Not the same unit as pure strain but GW happens to have strain at around ~10^{-21} 1/√Hz.

Passive isolation (1) - simple spring-mass system



Moves with the ground



Resonance at 1 Hz

100 times reduction at 10 Hz

10^7 attenuation is possible with resonance at 0.00316 Hz

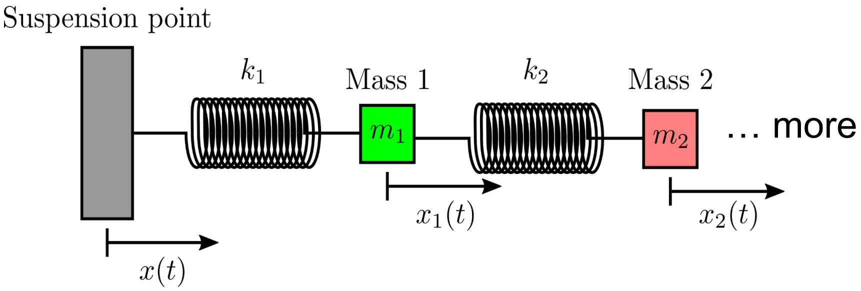
For spring constant = 10 N/m

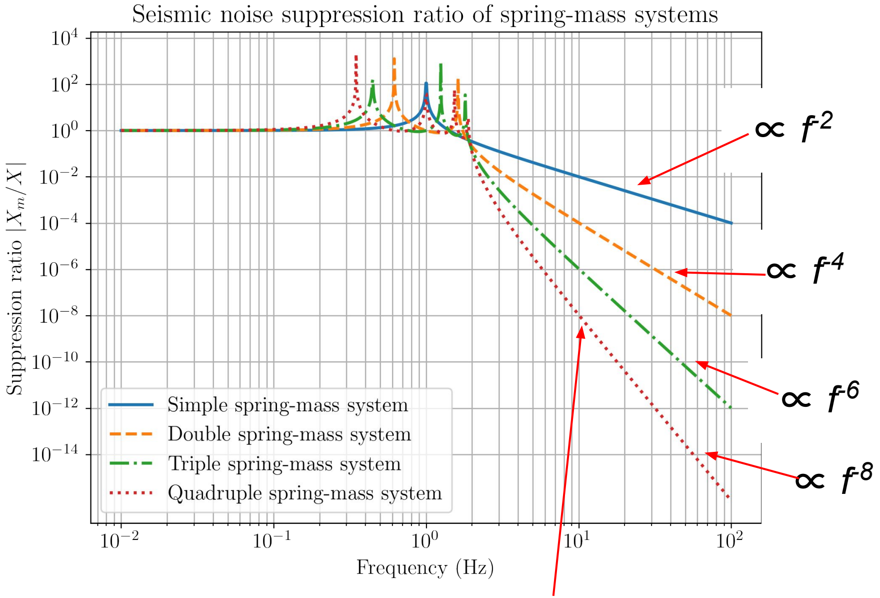
→mass = 25000 kg

Pendulum?

→length = 25000 meters (quite tall)

Passive isolation (2) - cascaded spring-mass systems





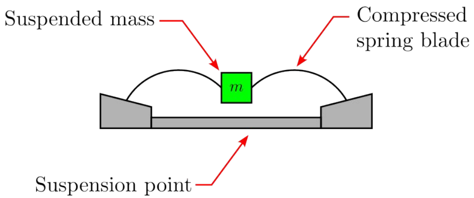
10^8 attenuation is easily achievable by a quadruple system

Passive isolation (3) - Anti-springs

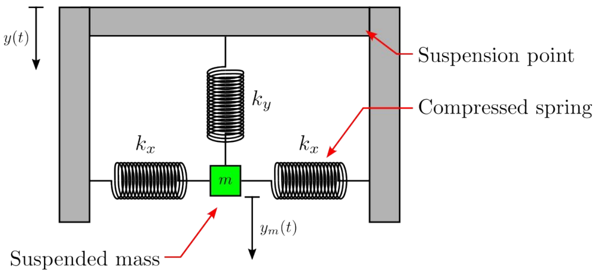
Lower resonance frequency?

- Geometric anti-spring (GAS)
  - Add negative stiffness by compressing the spring blades.

(a) Geometric anti-spring

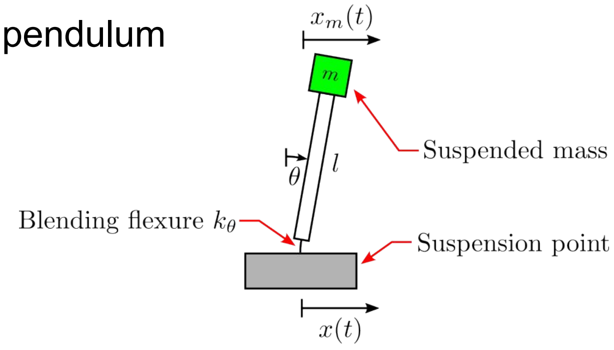


(b) Geometric anti-spring (equivalent model)

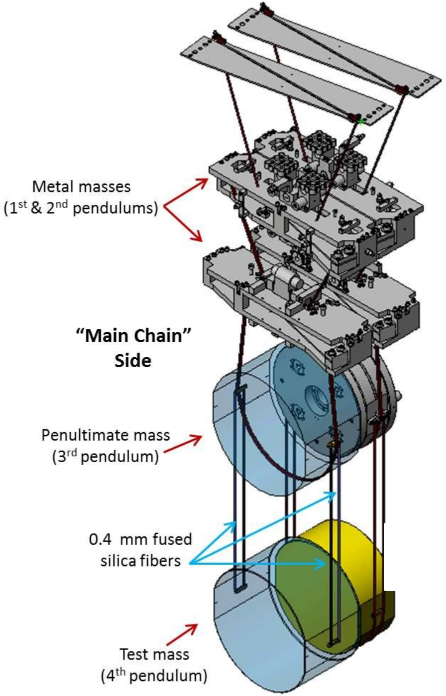


- Inverted pendulum
  - Add negative stiffness by increasing the mass.

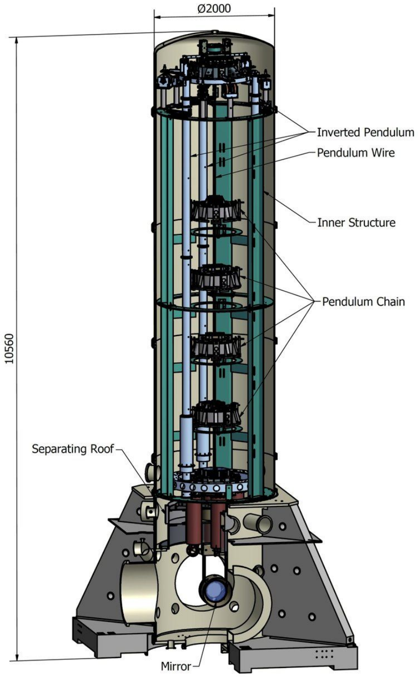
Inverted pendulum



Suspensions in gravitational-wave detectors



LIGO's quadruple pendulum

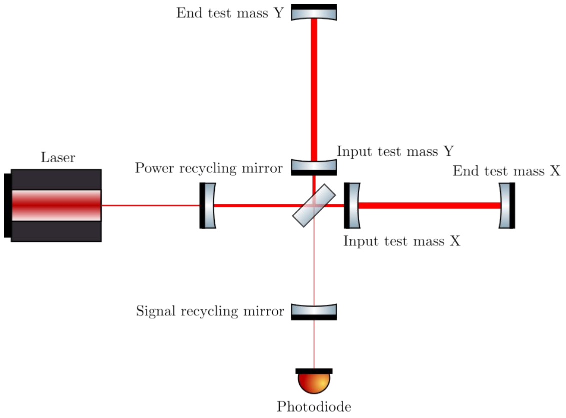


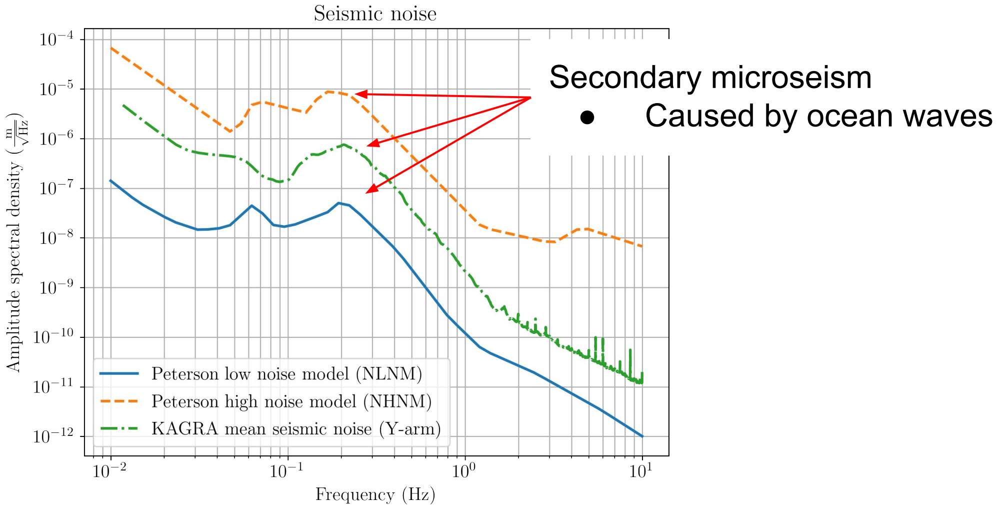
Virgo's Super Attenuator

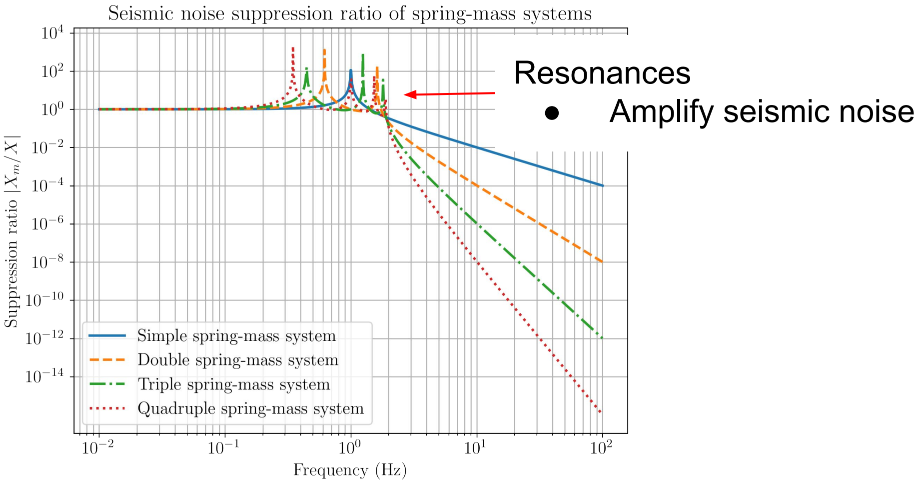
KAGRA's Type-B Suspension

Seismic noise (2)

- Seismic noise is large at low frequencies.
    - Microseism at 200 mHz.
- Seismic noise is enhanced by resonances of the suspensions.
- Fabry-Perot cavities need to stay “locked”
    - Displacements need to be small relative to the wavelength of the laser (1064 nm).
- During O3GK, KAGRA suffered lock-losses due to high microseismic activities.

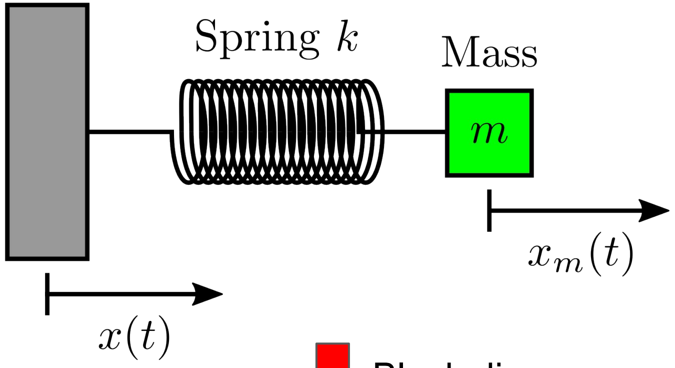






Interlude: Transfer functions and block diagrams

Suspension point



$$\mathcal{L}\left\{m\frac{d^2x_m(t)}{dt^2}+kx_m(t)\right\}=\mathcal{L}\{kx(t)\}$$

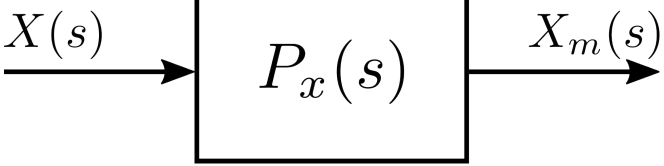
$$\left(ms^2+k\right)X_m(s)=kX(s)$$

$$\frac{X_m(s)}{X(s)}=\boxed{\frac{\omega_n^2}{s^2+\omega_n^2}}$$

Transfer function

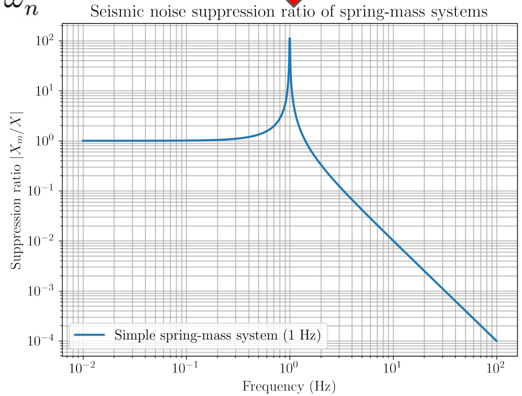
$$P_x(s)\equiv\frac{\omega_n^2}{s^2+\omega_n^2}$$

Block diagram



$$X_m(s)=P_x(s)X(s)$$

Evaluate along the positive imaginary axis *s=iω*

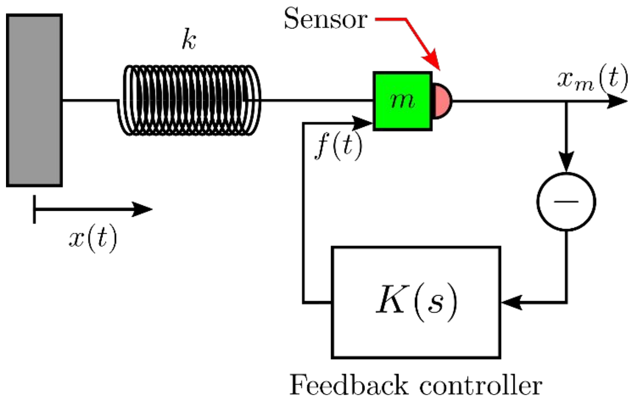


Frequency response

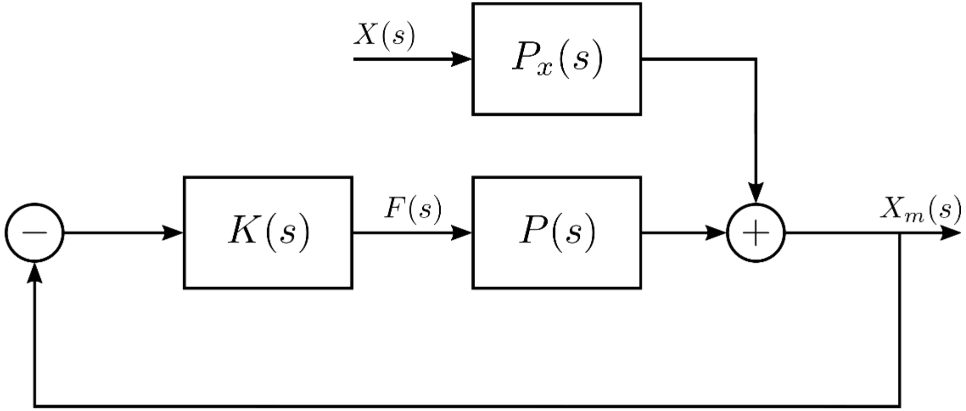
- Magnitude
- Phase

Active isolation: Feedback control (1)

(a) Feedback control of a spring-mass system



(b) Equivalent block diagram



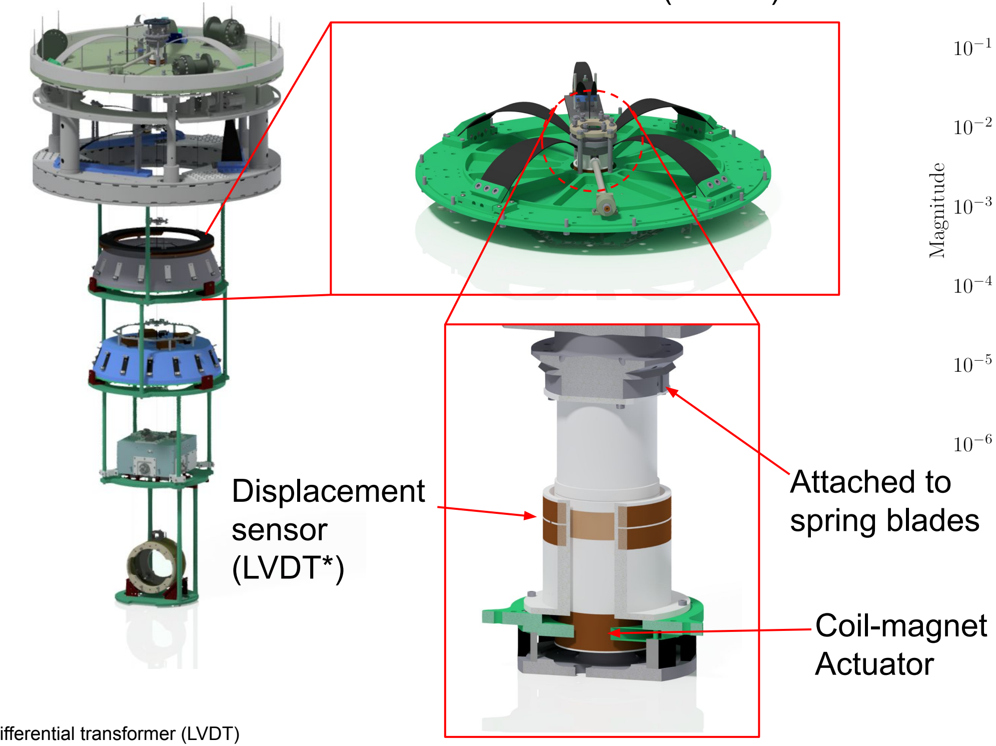
$$
\begin{aligned}
X_m(s) &= P_x(s)X(s) - [K(s)P(s)]\,X_m(s) \\
&= \frac{1}{1 + K(s)P(s)} P_x(s)X(s)\,.
\end{aligned}
$$

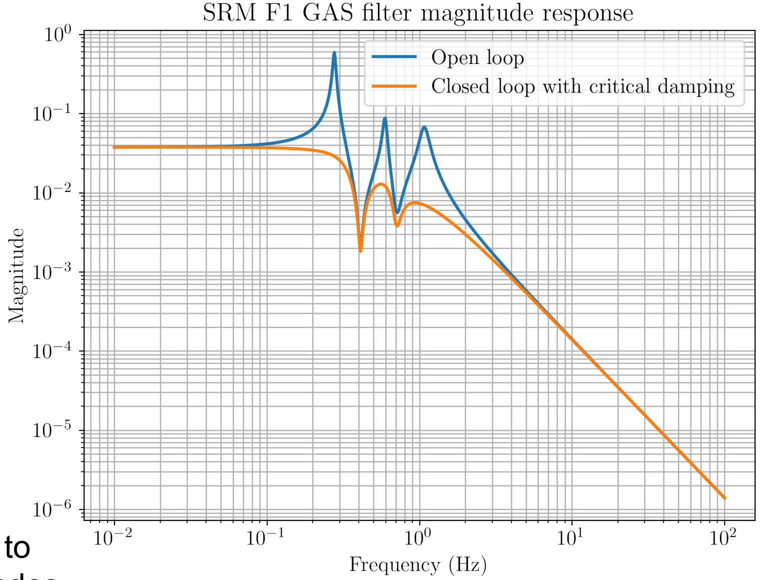
Goes to zero when *K(s)P(s)* is large

Active isolation: Feedback control example

KAGRA Type-B suspension

F1 GAS filter (interior)



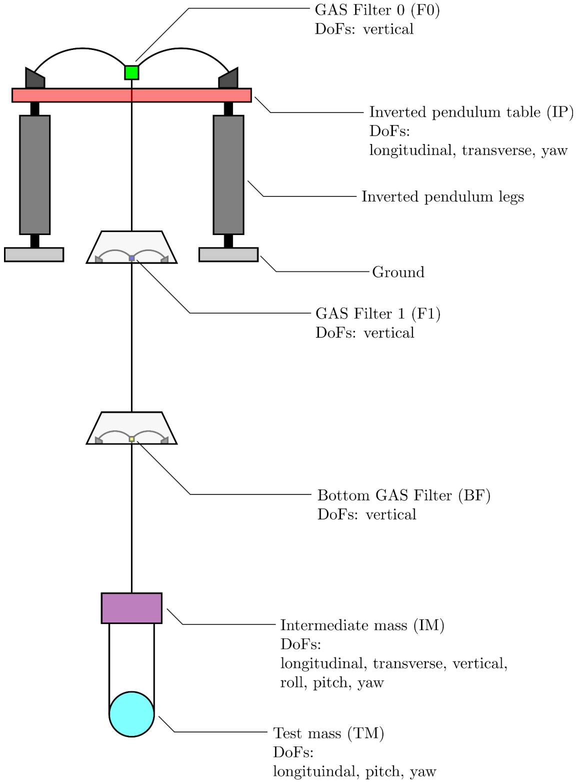


*Linear variable differential transformer (LVDT)

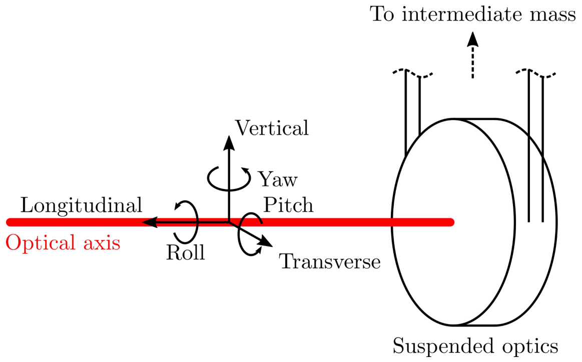
A lot of feedback control

KAGRA Type-B suspension

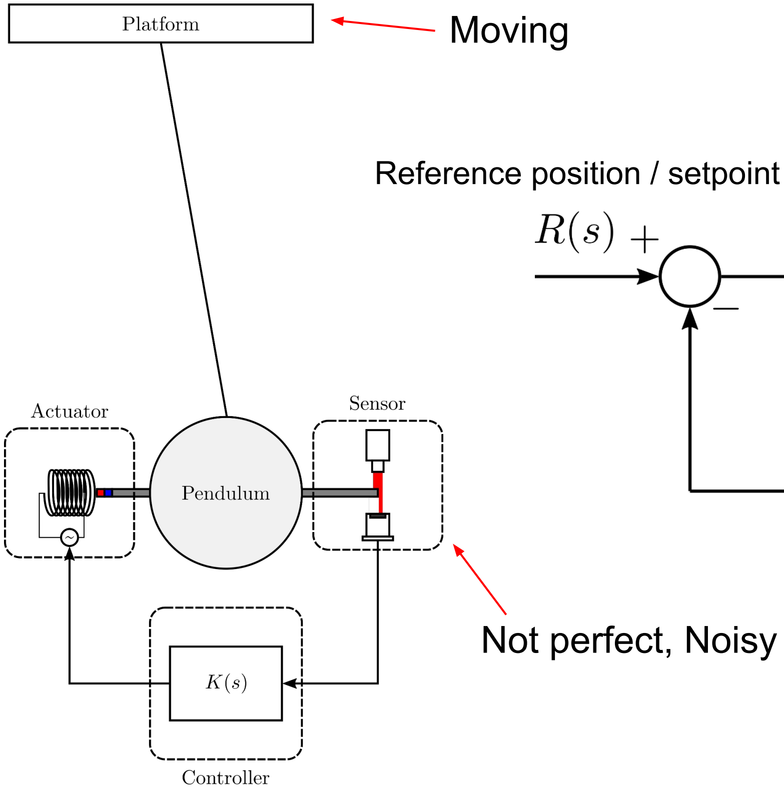
Simplified diagram

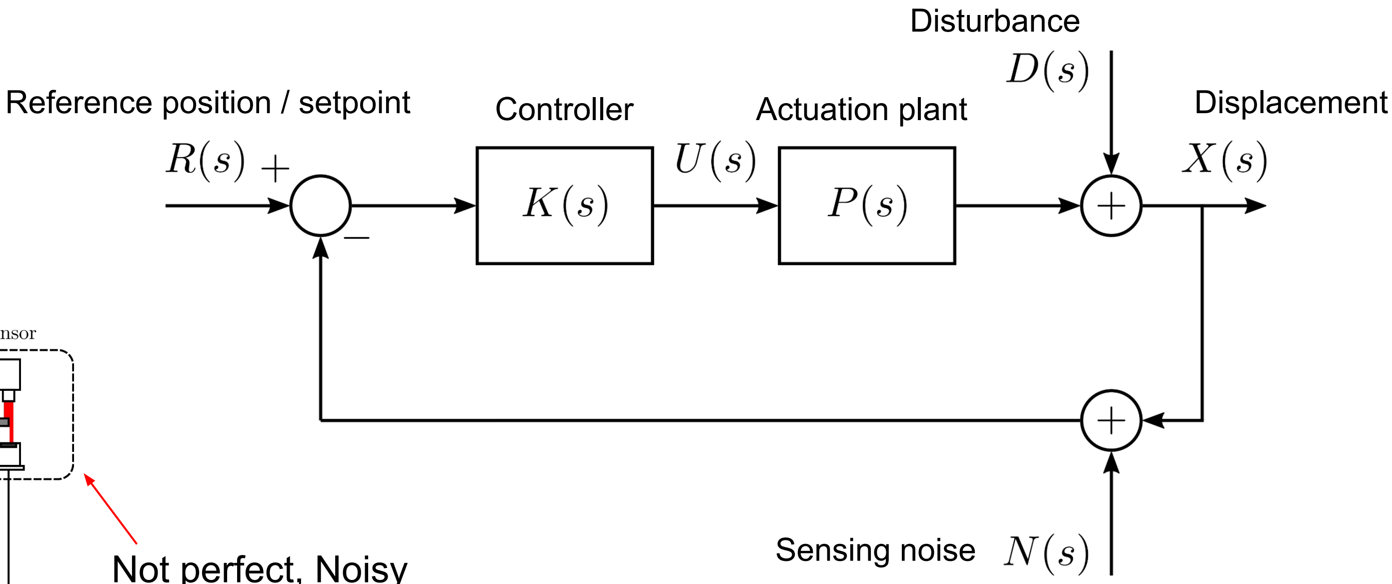


How directions are defined:

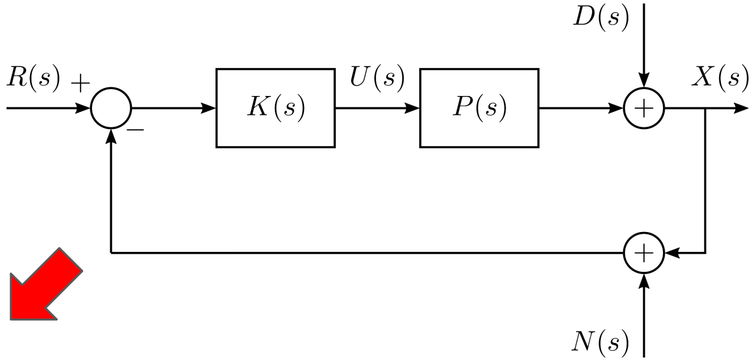


The general block diagram





The general problem



Displacement we want to minimize

$$X(s) = \boxed{\frac{1}{1+K(s)P(s)}} D(s) - \boxed{\frac{K(s)P(s)}{1+K(s)P(s)}} N(s)$$

Again, goes to zero as *K(s)P(s)* is large

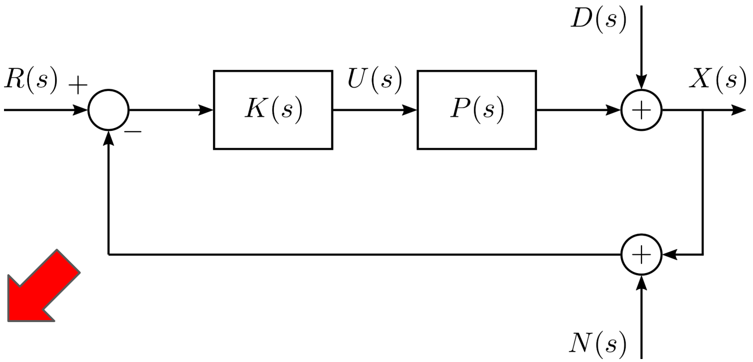
But, goes to 1 if *K(s)P(s)* is large

Coupling terms are complementary, i.e. summed to unity

- Disturbance and noise cannot be simultaneously minimized.
- Controller *K(s)* needs to be properly designed. But how?

$$K(s) = \frac{b_0 + b_1 s + b_2 s^2 \ldots}{a_0 + a_1 s + a_2 s^2 \ldots}$$

The general problem



Displacement we want to minimize

$$X(s) = \frac{1}{1+K(s)P(s)}D(s) - \frac{K(s)P(s)}{1+K(s)P(s)}N(s)$$

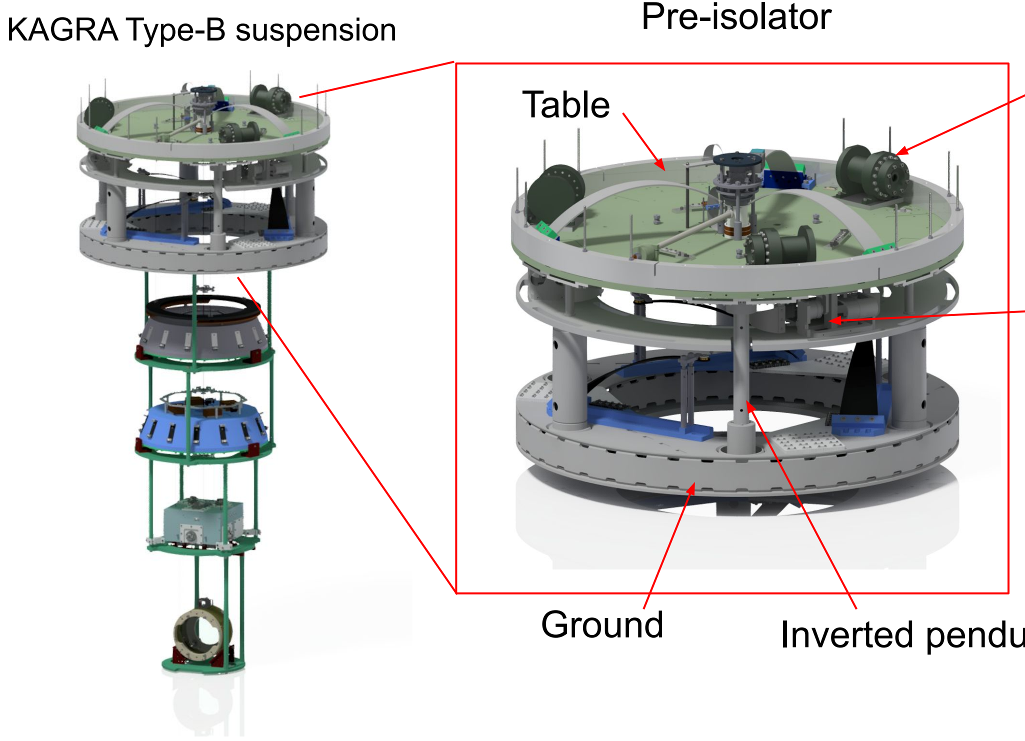
Alternatively, minimize the disturbance *D(s)*?

- Environmental disturbances, e.g. seismic noise, cannot be manipulated.
- Motion of an upper stage, better controls →problem recursive.

Minimize sensing noise *N(s)*? Yes.

- Make better sensors.
- Utilize multiple sensors:
  - **Sensor fusion**
  - **Sensor correction**

The inverted pendulum



Geophone

- Measures velocity of the table.

Linear variable differential transformer (LVDT)

- Measures relative displacement between the table and the ground.
- Coupled to seismic noise.

Sensor noises

LVDT:

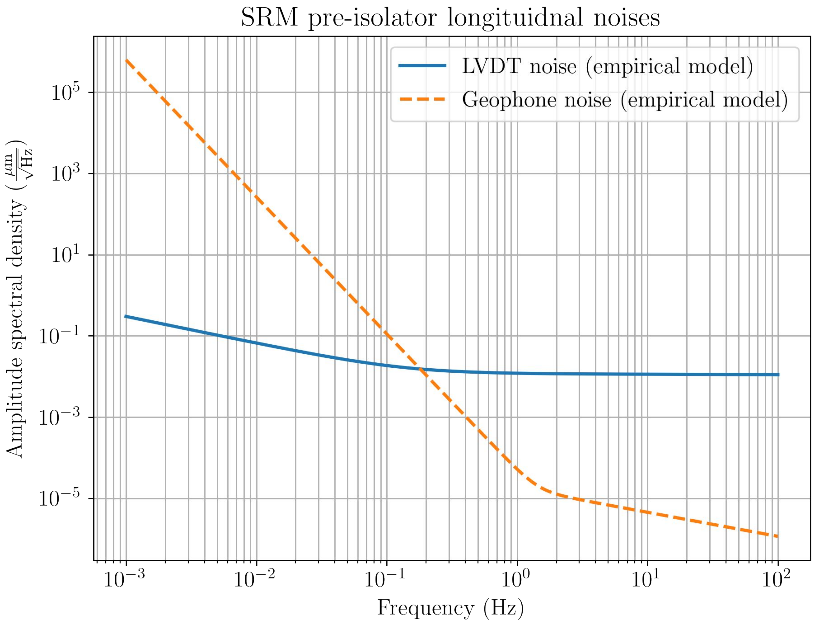
- Better at low frequency
- Coupled to seismic noise (but not shown)

Geophone:

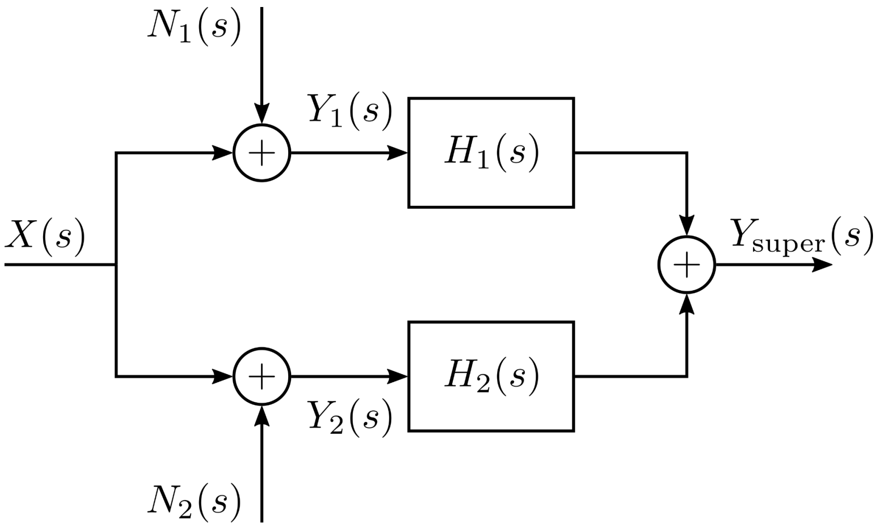
- Better at high frequency
- Really bad at low frequency

Wouldn't it be nice if we can use LVDT at low frequency and use geophone at high frequency?

→ Sensor fusion.
Combines the two sensors into a "super sensor".

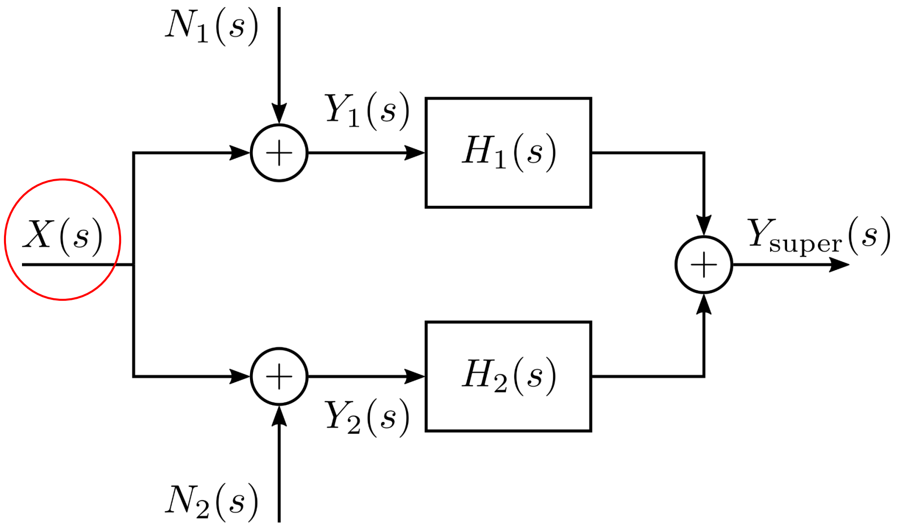


Sensor fusion using complementary filters

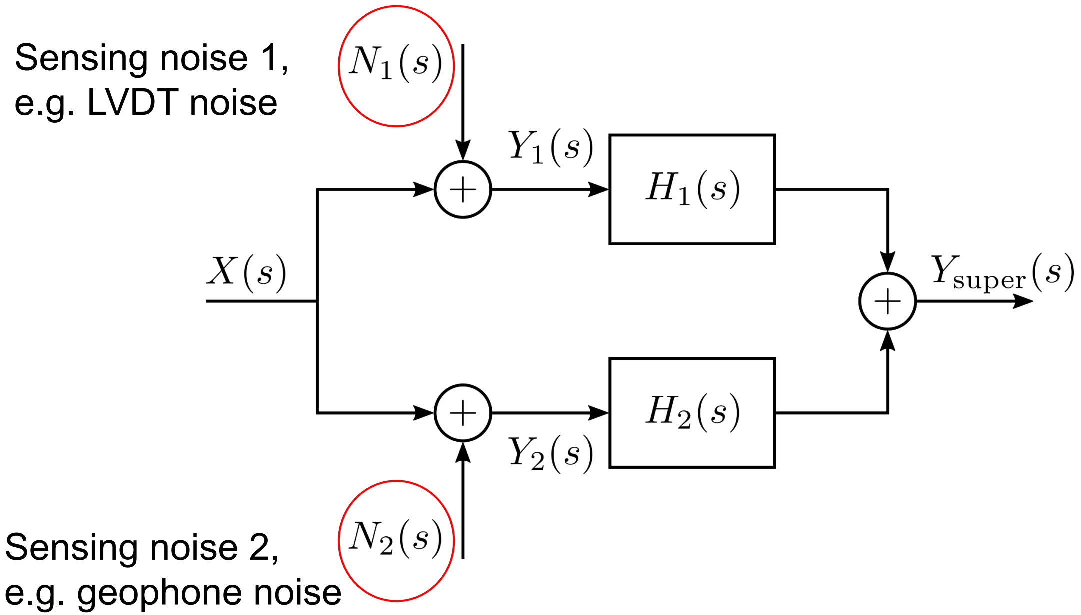


Sensor fusion using complementary filters

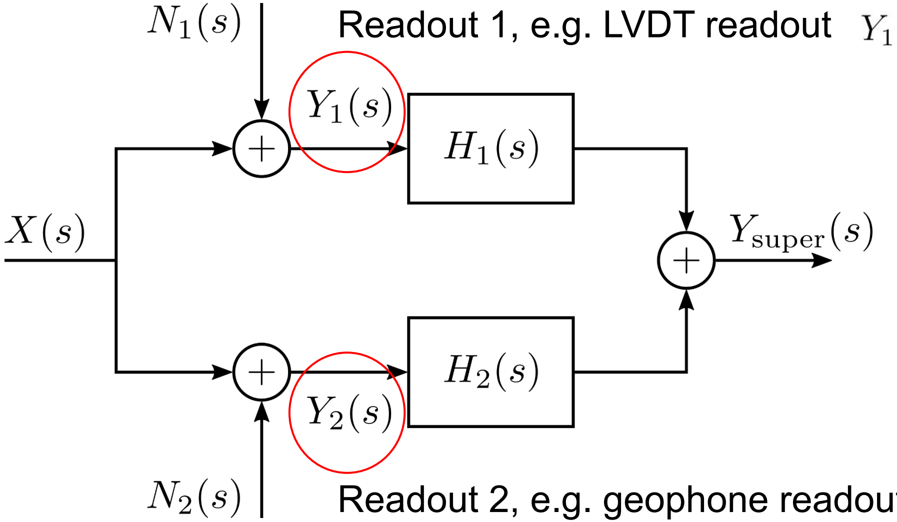
Displacement that we
want to measure.
Measured by two sensors.



Sensor fusion using complementary filters



Sensor fusion using complementary filters



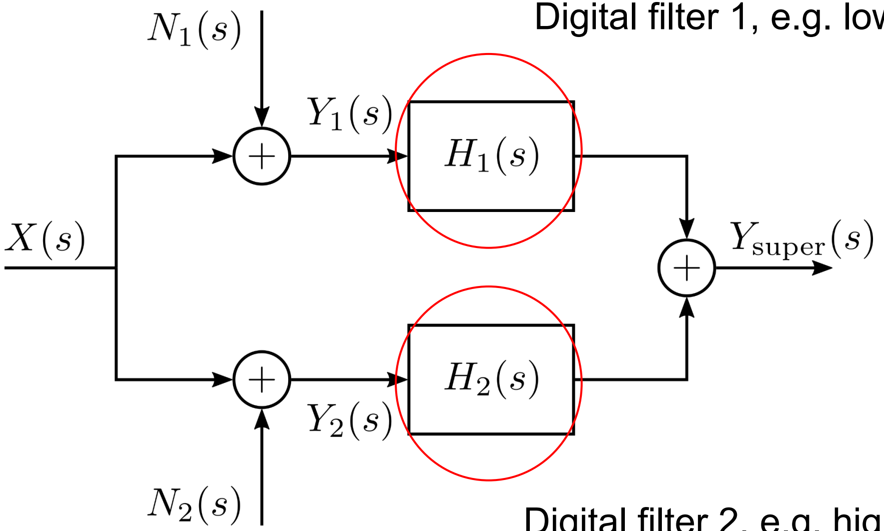
Readout 1, e.g. LVDT readout $Y_1(s) = X(s) + N_1(s)$

Readout 2, e.g. geophone readout

$$Y_2(s) = X(s) + N_2(s)$$

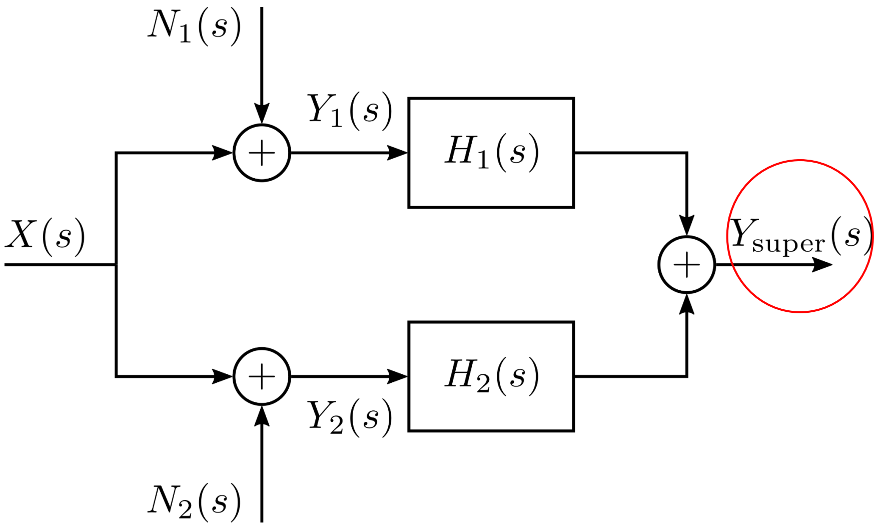
Sensor fusion using complementary filters

Digital filter 1, e.g. low-pass filter



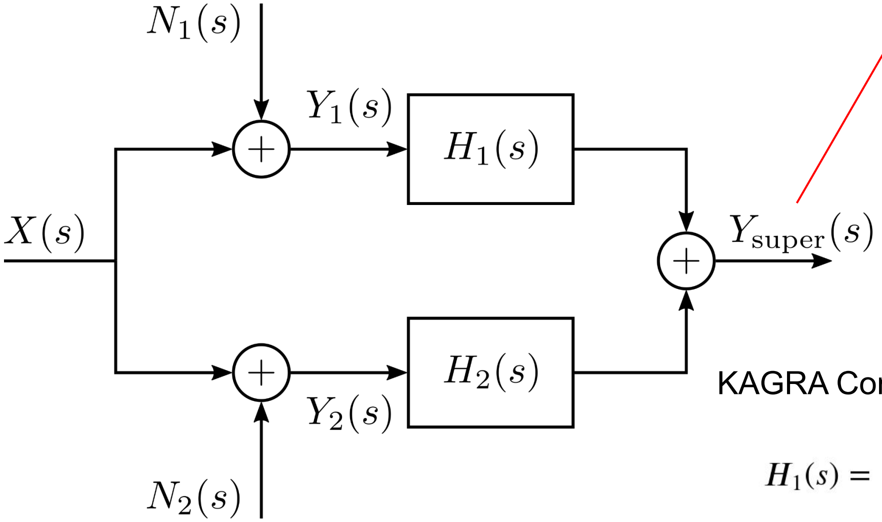
Digital filter 2, e.g. high-pass filter

Sensor fusion using complementary filters



The final readout or the readout of the “super sensor”.

Sensor fusion using complementary filters



$$Y_{\text{super}}(s) = H_1(s)Y_1(s) + H_2(s)Y_2(s)$$
$$= \boxed{[H_1(s) + H_2(s)]\, X(s)} + \boxed{[H_1(s)N_1(s) + H_2(s)N_2(s)]}$$

Signal

Noise

$$\boxed{H_1(s) + H_2(s) = 1}$$

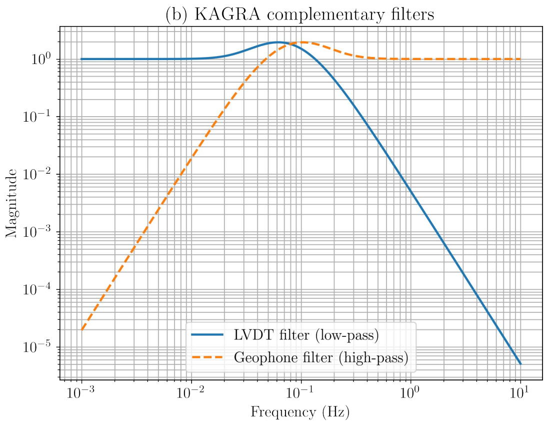
Complementary filters

KAGRA Complementary filters:

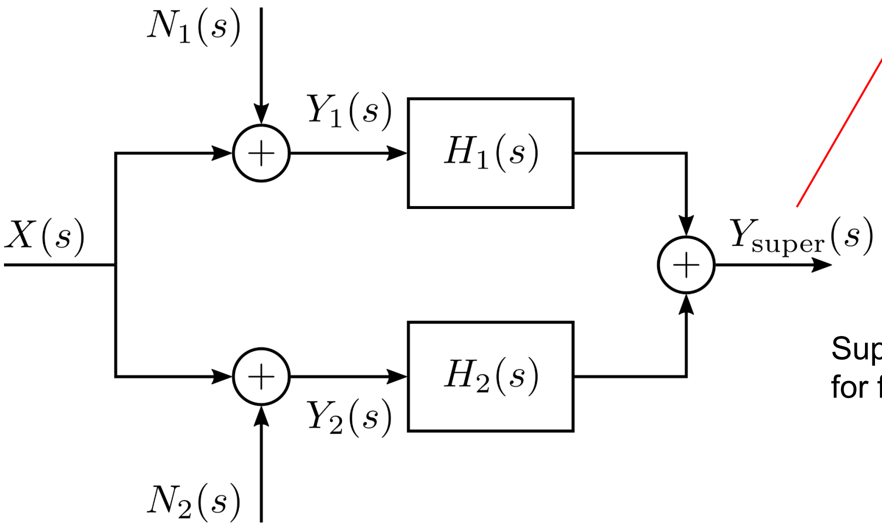
$$H_1(s) = \frac{10\omega_n^3 s^2 + 5\omega_n^4 s + \omega_n^5}{(s+\omega_n)^5}$$

$$H_2(s) = 1 - H_1(s) = \frac{s^5 + 5\omega_n s^4 + 10\omega_n^3 s^2}{(s+\omega_n)^5}$$

ω_n: Blending frequency



The complementary filter problem



$$\begin{aligned} Y_{\text{super}}(s) &= H_1(s)Y_1(s) + H_2(s)Y_2(s) \\ &= \boxed{[H_1(s) + H_2(s)]\, X(s)} + \boxed{[H_1(s)N_1(s) + H_2(s)N_2(s)]} \end{aligned}$$

Noise

$$\boxed{N_{\text{super}}(s) \equiv H_1(s)N_1(s) + H_2(s)N_2(s)}$$

$$Y_{\text{super}}(s) = X(s) + \boxed{N_{\text{super}}(s)}$$

Super sensor readout used for feedback control

Super sensor noise we want to minimize

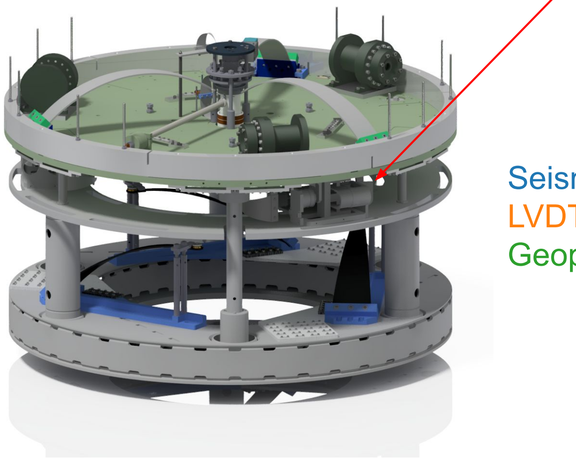
Design the complementary filters $H_1(s)$ and $H_2(s)$

Subject to $$H_1(s) + H_2(s) = 1$$

Sensor fusion will return in a moment

Sensor correction

Pre-isolator

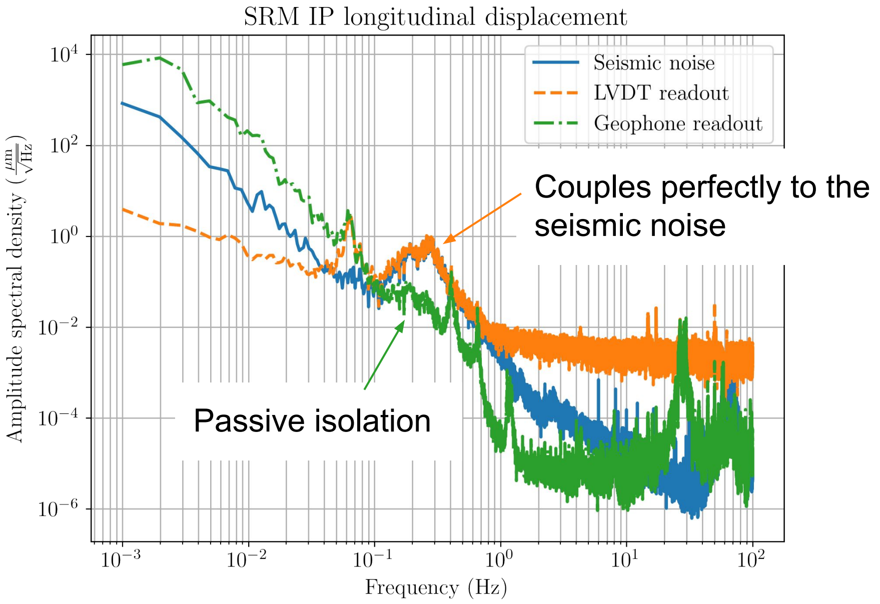


LVDTs are relative sensors.

- Measure **relative displacements** between the suspended table and the ground.

Seismic noise
LVDT readout
Geophone readout

Inverted pendulum table displacement readouts:



Feedback control with LVDT

- Ruins passive isolation performance
- (I think) Main reason why KAGRA was so susceptible to microseismic activity during O3GK.

Sensor correction

LVDT is coupled to seismic noise.

Seismometer measures seismic noise.

Can we subtract the seismic noise component in the LVDT readout using the seismometer readout?

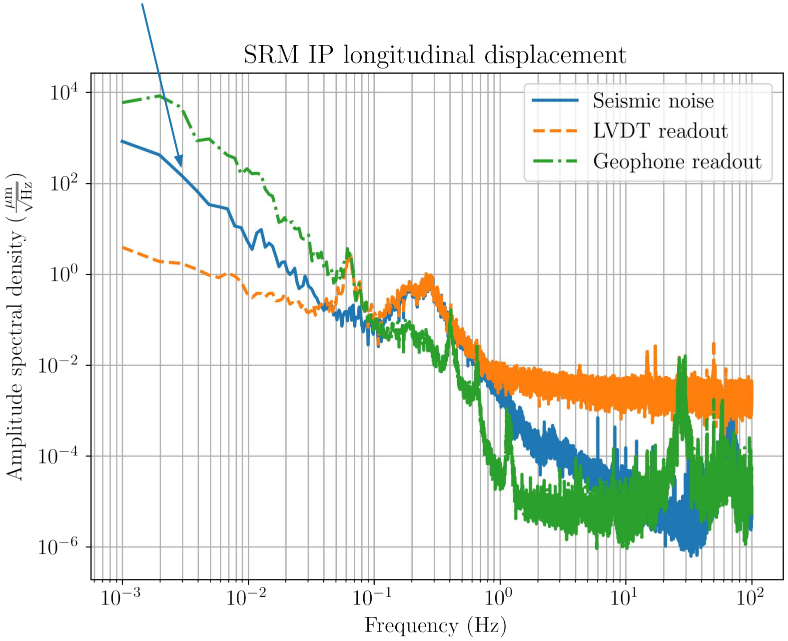
→Sensor correction

One problem

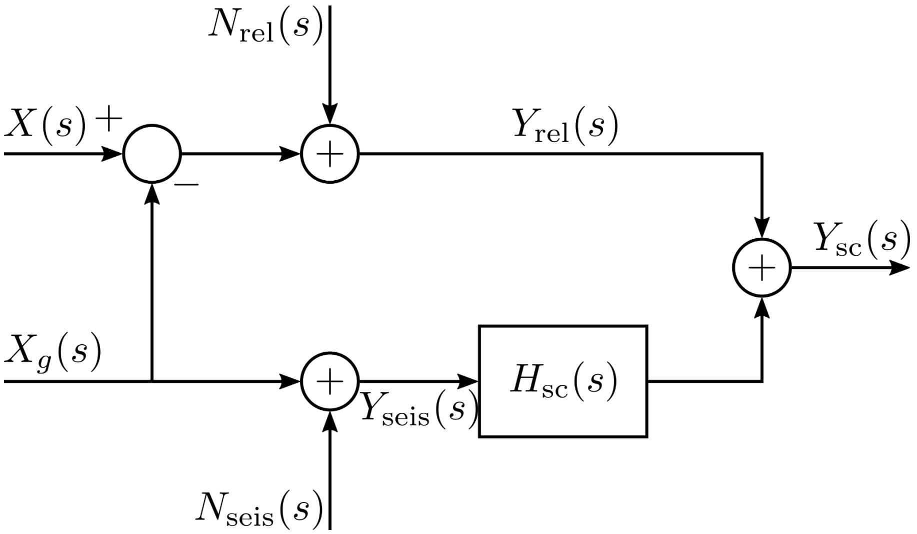
- Seismometer noise

Seismometer signal needs to be filtered before using it to “correct” the LVDT.

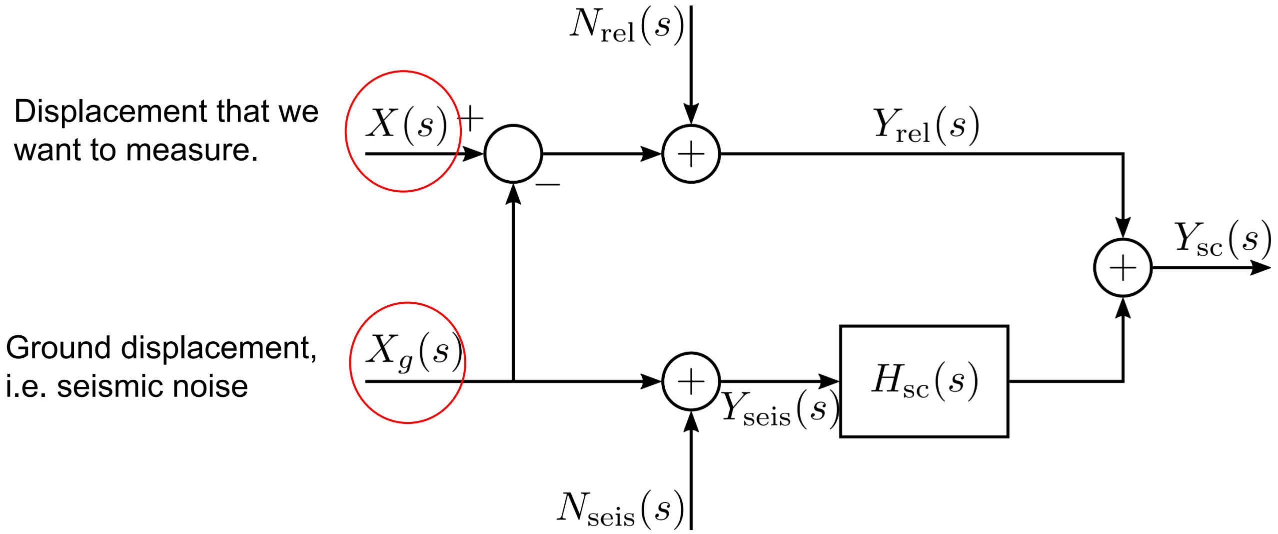
Seismometer noise



Sensor correction



Sensor correction

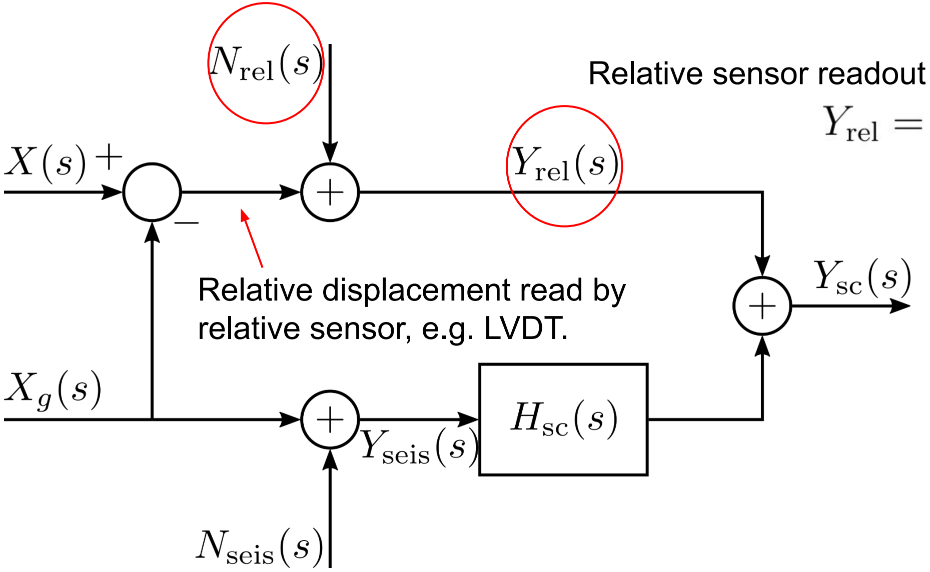


Sensor correction

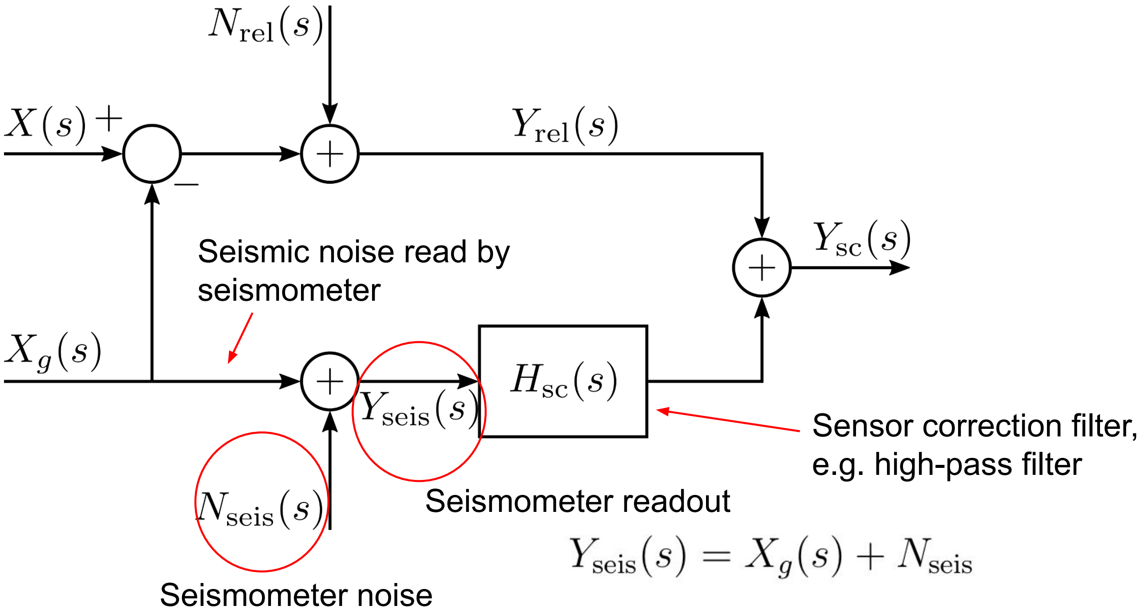
Sensor noise of relative sensor, e.g. LVDT noise

Relative sensor readout

$$Y_{\mathrm{rel}} = X(s) - X_g(s) + N_{\mathrm{rel}}(s)$$



Sensor correction



$$Y_{\mathrm{seis}}(s) = X_g(s) + N_{\mathrm{seis}}$$

Sensor correction

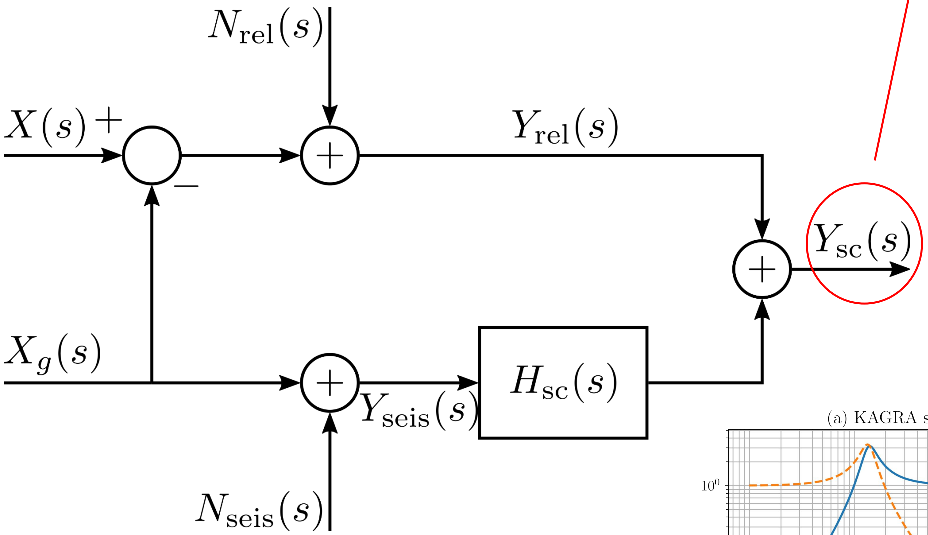
The final readout of the corrected sensor

$$
\begin{aligned}
Y_{\mathrm{sc}}(s) &= Y_{\mathrm{rel}}(s) + H_{\mathrm{sc}}(s)Y_{\mathrm{seis}}(s)\\
&= X(s) - X_g(s) + N_{\mathrm{rel}}(s) + H_{\mathrm{sc}}(s)\left[X_g(s) + N_{\mathrm{seis}}(s)\right]\\
&= \boxed{X(s)} + \boxed{N_{\mathrm{rel}}(s)} + \boxed{H_{\mathrm{sc}}(s)N_{\mathrm{seis}}(s) - \left[1 - H_{\mathrm{sc}}(s)\right]X_g(s)}
\end{aligned}
$$

Signal

Ambient noise

Sensor correction noise



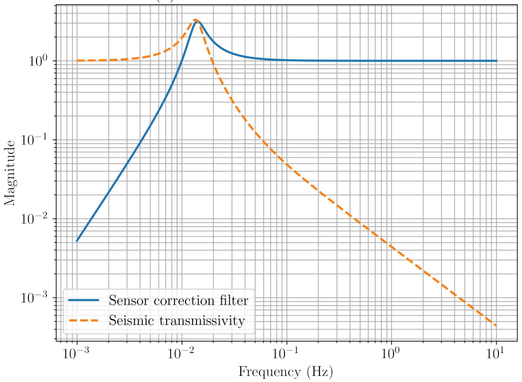
$$
\boxed{N_{\mathrm{sc}}(s) \equiv H_{\mathrm{sc}}N_{\mathrm{seis}}(s) - \left[1 - H_{\mathrm{sc}}(s)\right]X_g(s)}
$$

Sensor correction filter

Seismic transmissivity

Complementary

(a) KAGRA sensor correction filter



Sensor correction filter can be obtained by solving a complementary filter problem, but with a catch.

A short recap

We want to minimize the displacement *X(s)* of a feedback controlled pendulum.

1. Design feedback controller *K(s)*
2. Minimize sensing noise *N(s)*
    a. Sensor fusion by complementary filters $H_1(s)$ and $H_2(s)$.
    b. Correcting relative sensors by sensor correction filter $H_{sc}(s)$.

Feedback control

$$X(s) = \frac{1}{1+\boxed{K(s)}P(s)}D(s) - \frac{K(s)P(s)}{1+K(s)P(s)}N(s)$$

Sensor fusion

$$N_{\mathrm{super}}(s) \equiv \boxed{H_1(s)}N_1(s) + \boxed{H_2(s)}N_2(s)$$

Sensor correction

$$N_{\mathrm{sc}}(s) \equiv \boxed{H_{\mathrm{sc}}}N_{\mathrm{seis}}(s) - \left[1 - H_{\mathrm{sc}}(s)\right] X_g(s)$$

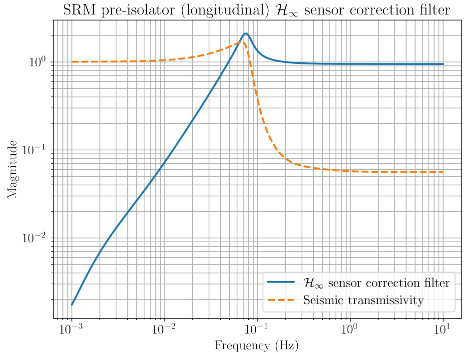
Three filter design problems are similar:

- Designing a control filter with conflicting objectives.
    - Feedback control (Disturbance vs noise)
    - Sensor fusion (Sensor noises)
    - Sensor correction (Seismic noise vs seismometer noise)

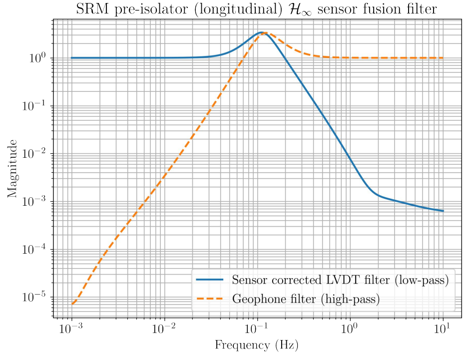
Sneak peek - where are we headed?

H-infinity method:

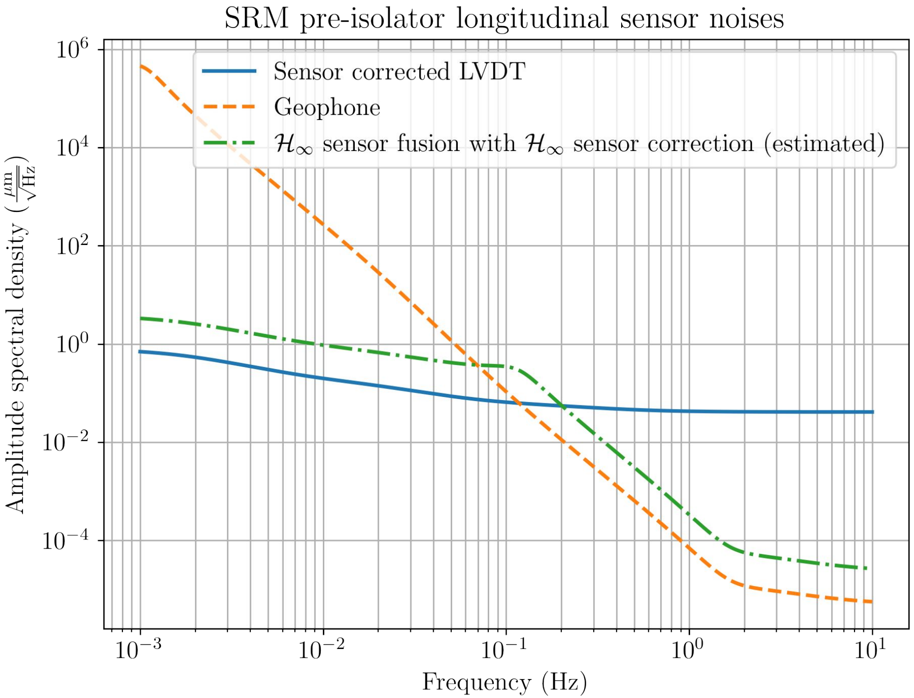
Sensor correction filter



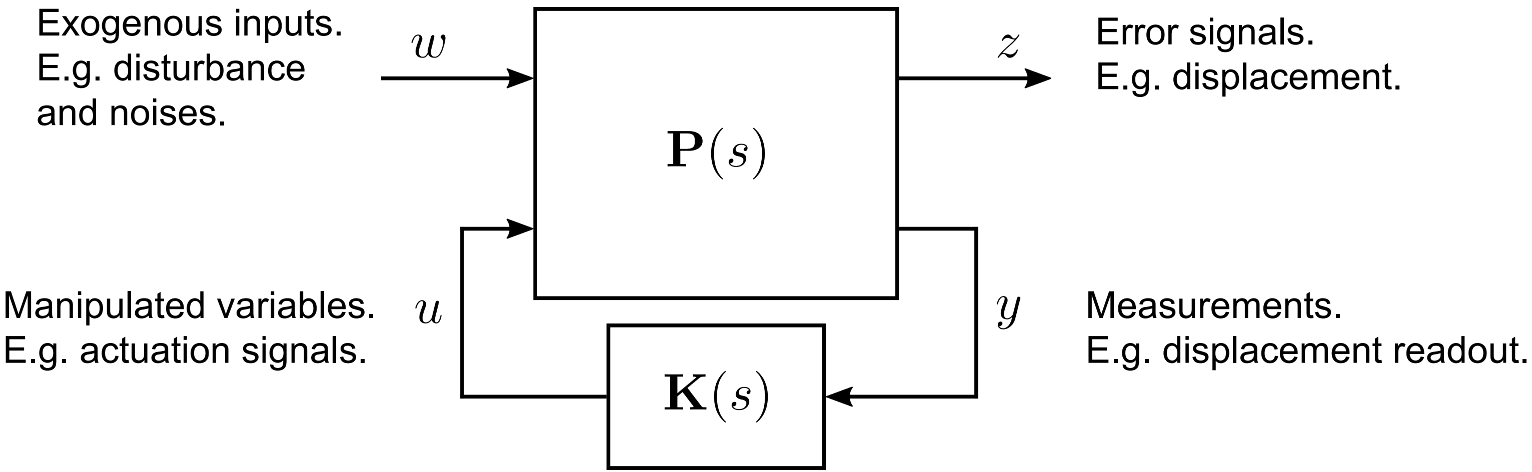
Complementary filters



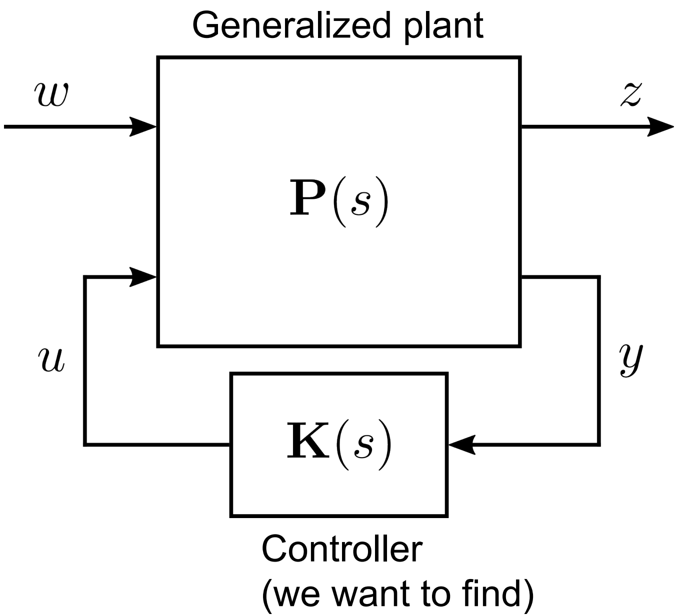
Sensor fusion of a sensor corrected LVDT and geophone



H-infinity method - generalized plant representation



H-infinity method - generalized plant representation



Open loop

$$\begin{bmatrix} z \\ y \end{bmatrix} = \mathbf{P}(s) \begin{bmatrix} w \\ u \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \begin{bmatrix} w \\ u \end{bmatrix}$$

Closed loop

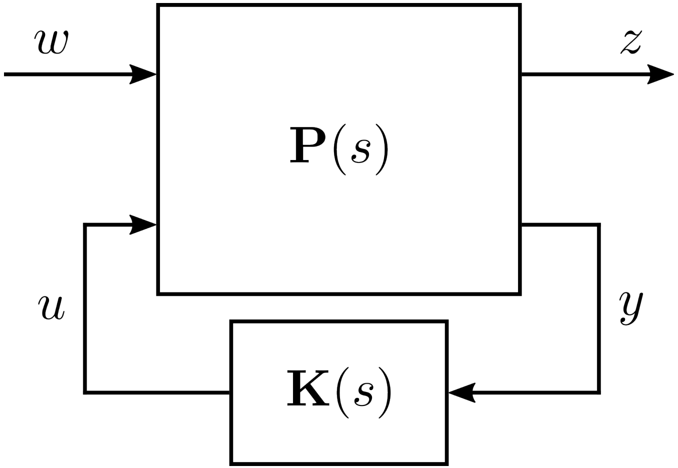
$$u = \mathbf{K}(s)y$$

$$z = \mathbf{G}(s)w$$

Closed-loop transfer function

$$\mathbf{G}(s) = P_{11}(s) + P_{12}(s)\mathbf{K}(s)\left[1 - P_{22}(s)\mathbf{K}(s)\right]^{-1} P_{21}(s)$$

H-infinity method - H-infinity norm



Closed loop

$$z = \mathbf{G}(s)w$$

H-infinity norm

$$\|\mathbf{G}(s)\|_\infty \equiv \max_\omega \bar{\sigma}(\mathbf{G}(j\omega)) \text{ *}$$

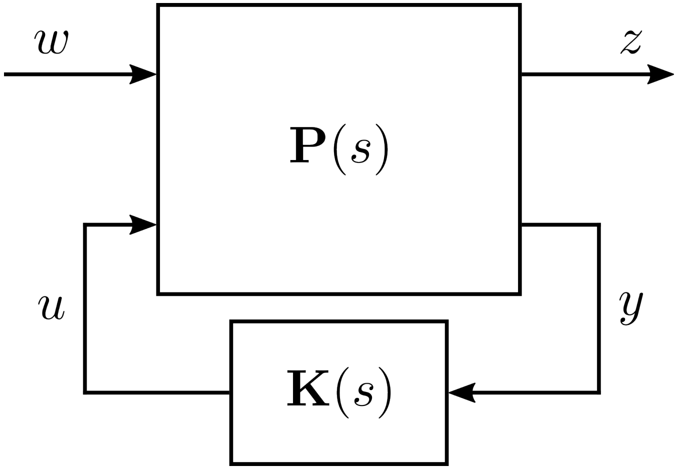
Maximum singular value

$$\bar{\sigma}(\mathbf{G}(j\omega)) = \max_i \sqrt{\lambda_i(\mathbf{G}(j\omega)^{\mathsf{H}}\mathbf{G}(j\omega))}$$

The interpretation of the H-infinity norm will be clear later.

* The supremum to be exact. But practically the same.

H-infinity method - H-infinity optimal controller

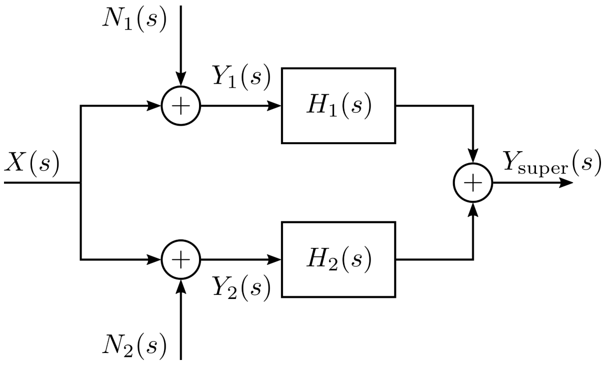


The H-infinity optimal controller

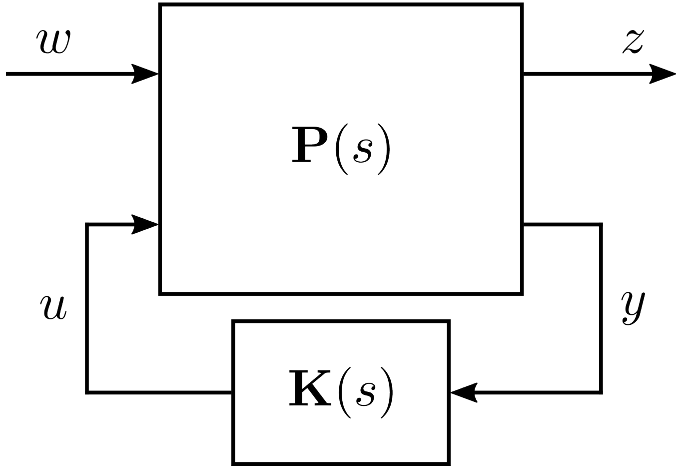
- Minimizes the H-infinity norm $\|\mathbf{G}(s)\|_\infty$
  - **P**(s) need not be representing a physical system, but a cost function instead.
- Obtained by H-infinity synthesis
  - Finds the optimal controller over all possible stabilizing controllers.
  - Available in Python and Matlab.

Complementary filter problem as an H-infinity problem

Sensor fusion



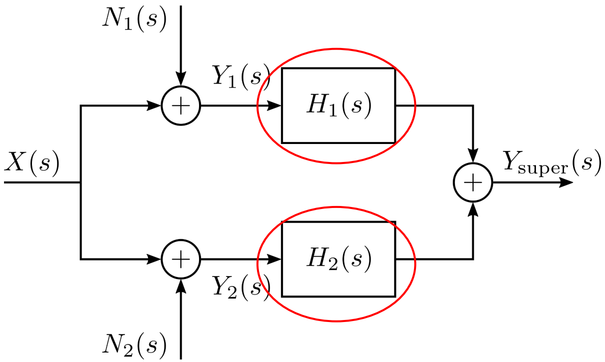
Generalized plant



H-infinity synthesis gives complementary filters that minimizes the super sensor noise.

Complementary filter problem as an H-infinity problem

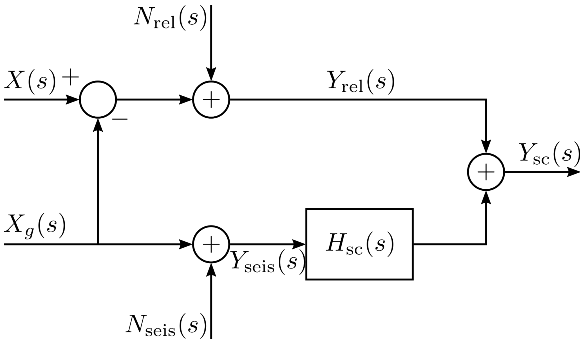
Sensor fusion



$$N_{\text{super}}(s) \equiv H_1(s)N_1(s) + H_2(s)N_2(s)$$

Complementary condition not implied

Borrow sensor correction

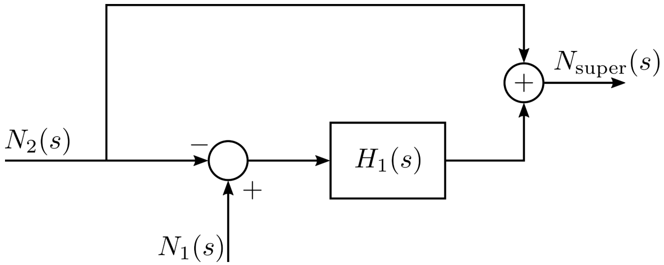


$$N_{\text{sc}}(s) \equiv H_{\text{sc}}N_{\text{seis}}(s) - [1 - H_{\text{sc}}(s)]\,X_g(s)$$

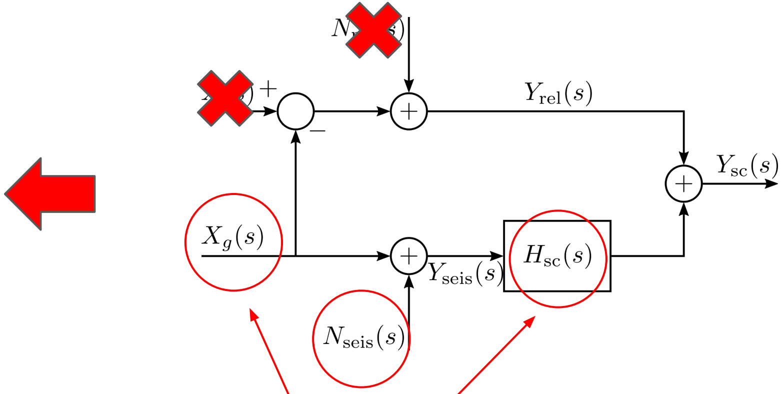
Complementary condition automatically satisfied

Complementary filter problem as an H-infinity problem

Sensor fusion (modified)



Borrow sensor correction



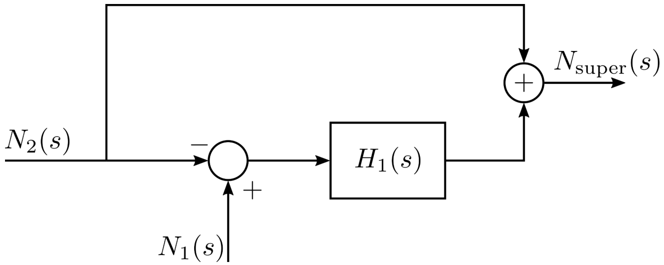
Modify these

$$N_{\text{super}}(s) = H_1(s)N_1(s) + \left[1 - H_1(s)\right] N_2(s)$$

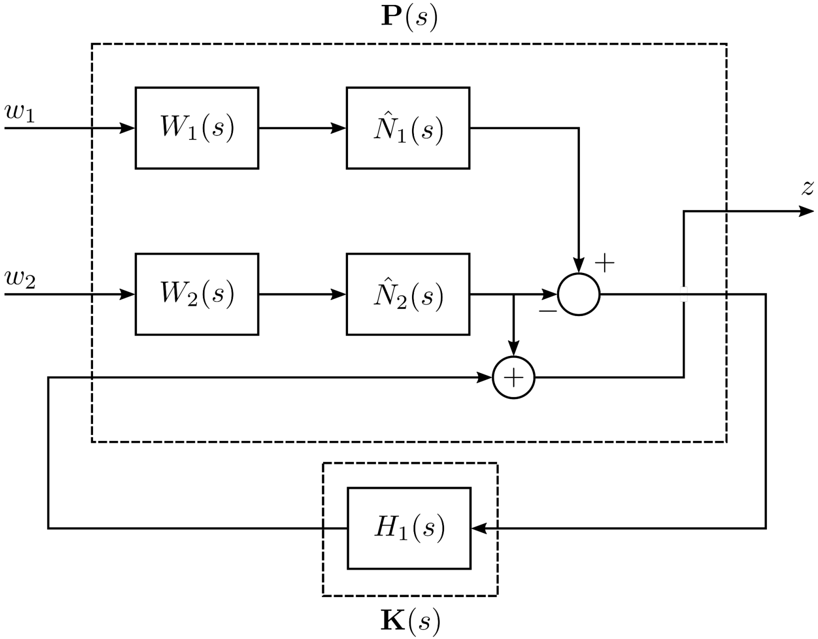
Complementary condition satisfied

Complementary filter problem as an H-infinity problem

Sensor fusion (modified)



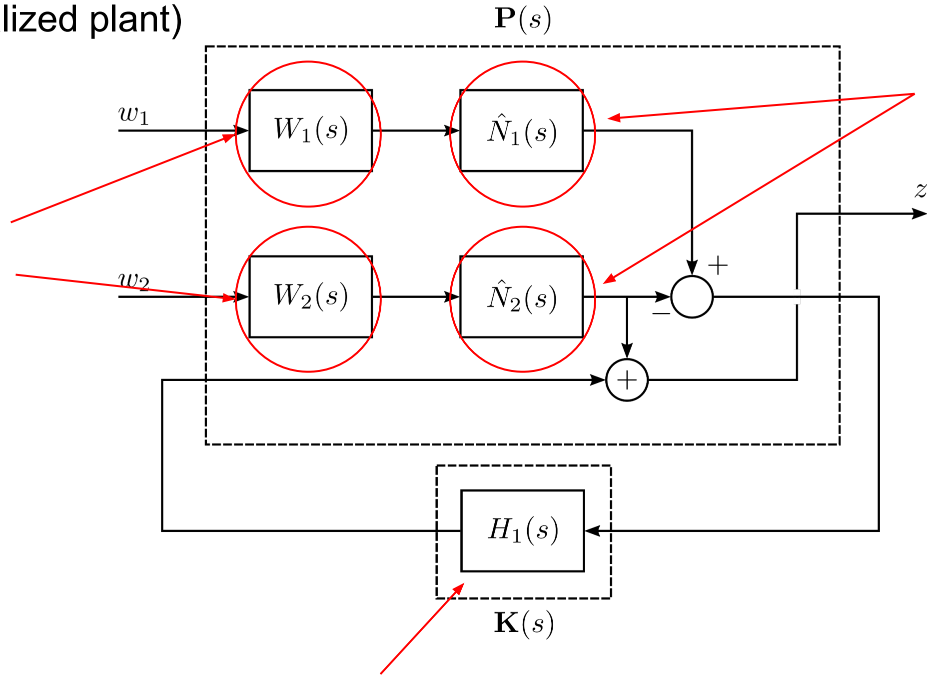
Sensor fusion (generalized plant)



Complementary filter problem as an H-infinity problem

Sensor fusion (generalized plant)

Weighting functions,
frequency dependent
specifications

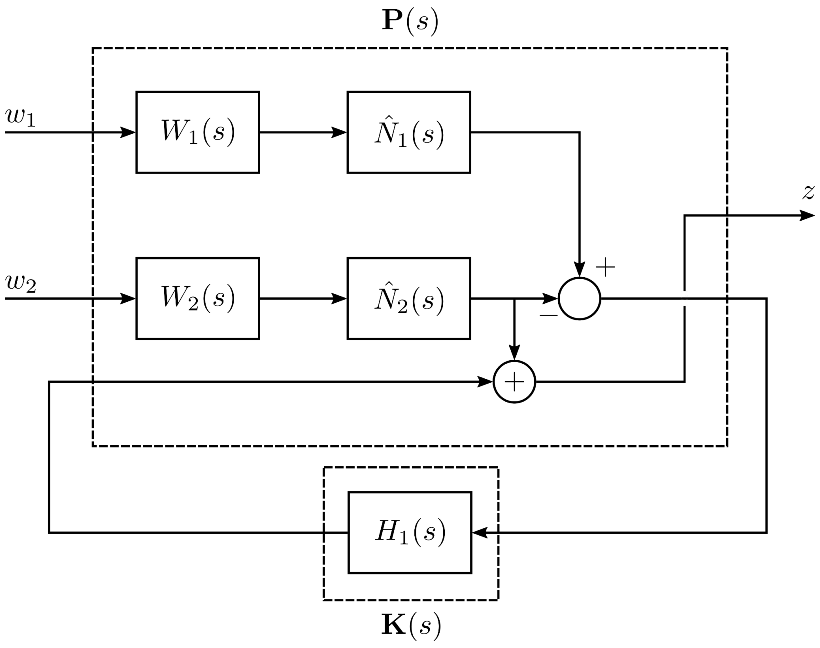


Noise models

H-infinity synthesis gives $H_1(s)$.

Get $H_2(s)$ from $H_2(s) = 1-H_1(s)$.

The H-infinity norm



The closed-loop transfer function

$$\mathbf{G}(s) = \left[H_1(s)W_1(s)\hat{N}_1(s) \quad [1 - H_1(s)]\, W_2(s)\hat{N}_2(s) \right]$$

H-infinity norm

$$\|\mathbf{G}(s)\|_\infty \equiv \max_\omega \bar{\sigma}(\mathbf{G}(j\omega))$$

$$= \max_\omega \sqrt{\left|H_1(j\omega)W_1(j\omega)\hat{N}_1(j\omega)\right|^2 + \left|[1 - H_1(j\omega)]\, W_2(j\omega)\hat{N}_2(j\omega)\right|^2}$$

A quadrature sum, dominated by the larger term.

Suppose H-infinity synthesis gives

$$\|\mathbf{G}(s)\|_\infty = \gamma$$

$$\boxed{\left|H_1(j\omega)\hat{N}_1(j\omega)\right| \le \gamma\, |W_1(j\omega)|^{-1}}$$

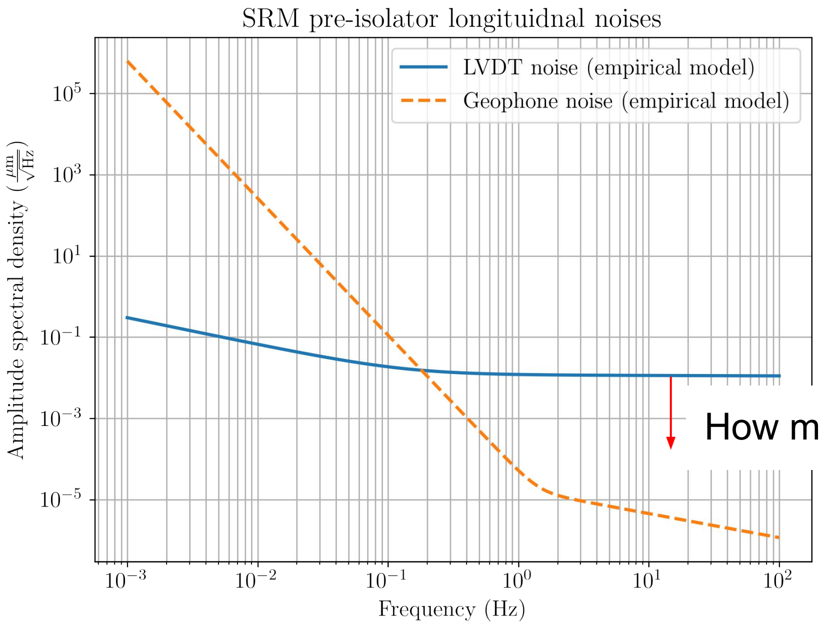
The weights

$$\left|H_1(j\omega)\hat{N}_1(j\omega)\right| \leq \gamma\left|W_1(j\omega)\right|^{-1}$$

Filtered noise

Upper bound
→Inverse of the weights are **frequency dependent specifications**, i.e. how much we want to suppress the sensor noises.

LVDT noise and geophone noise



How much?

$$\boxed{W_1(s) = \frac{1}{\hat{N}_2(s)} \qquad W_2(s) = \frac{1}{\hat{N}_1(s)}}$$

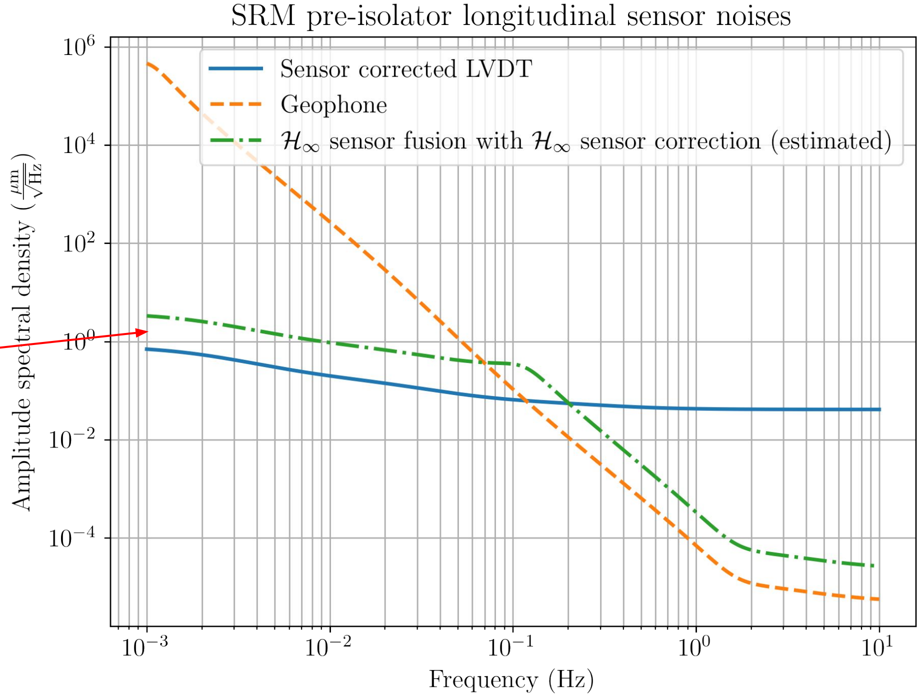
The generalized plant is self-defined by the sensor noises themselves.

The H-infinity norm - interpretation

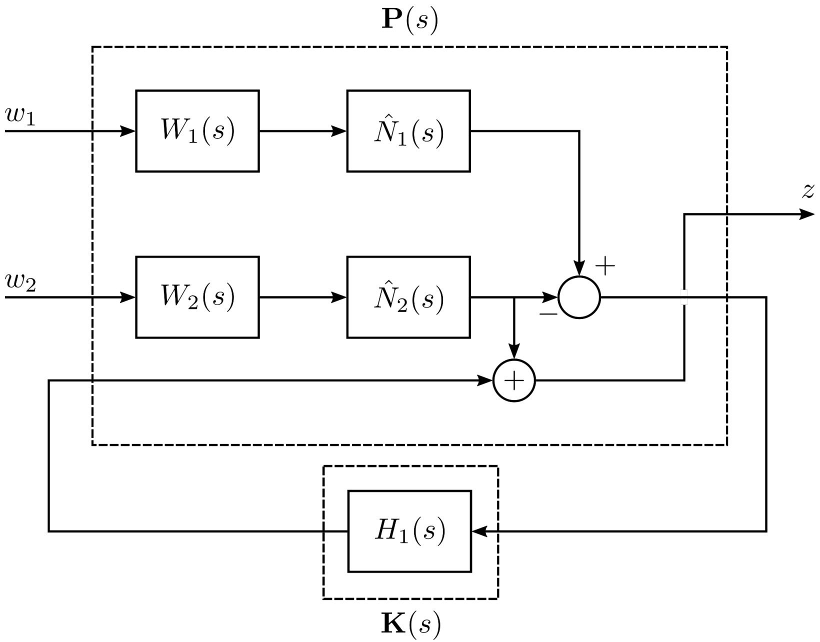
$$\left|H_1(j\omega)\hat{N}_1(j\omega)\right| \leq \gamma\,|W_1(j\omega)|^{-1}$$

Offset from the specification. This gap is what we minimize.

Sensor fusion of a sensor corrected LVDT and geophone

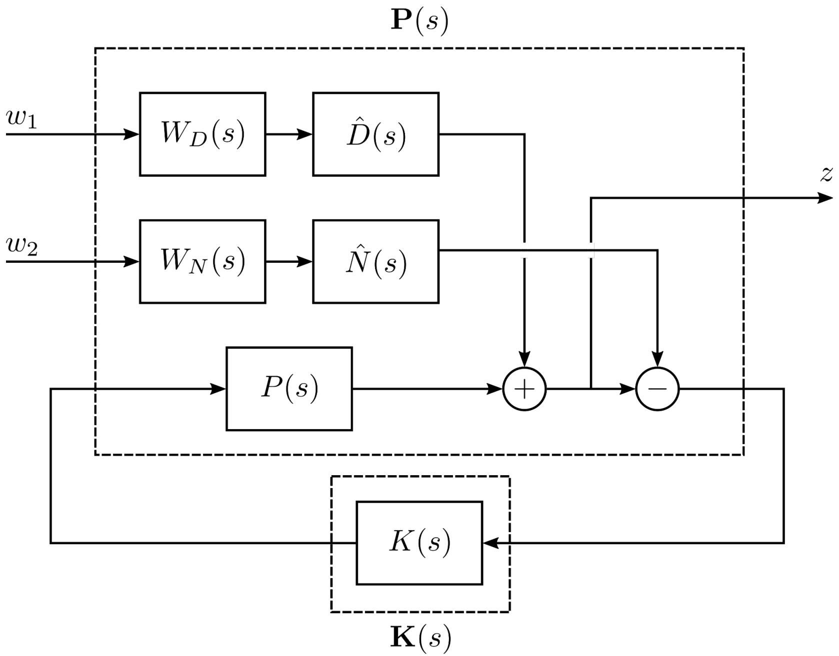


How about sensor correction and feedback control?



Works for

- sensor fusion,
- sensor correction (**Caveat**),
- and feedback control.



Alternative for feedback control

Results

Several configurations

- Sensor fusion of LVDT (seismic noise coupled) and geophone (Read thesis).
- Sensor correction of LVDT.
- Sensor fusion of corrected LVDT and geophone.
- Feedback control with sensor corrected LVDT.

H-infinity sensor correction and sensor fusion

Inverted pendulum freely swinging

LVDT

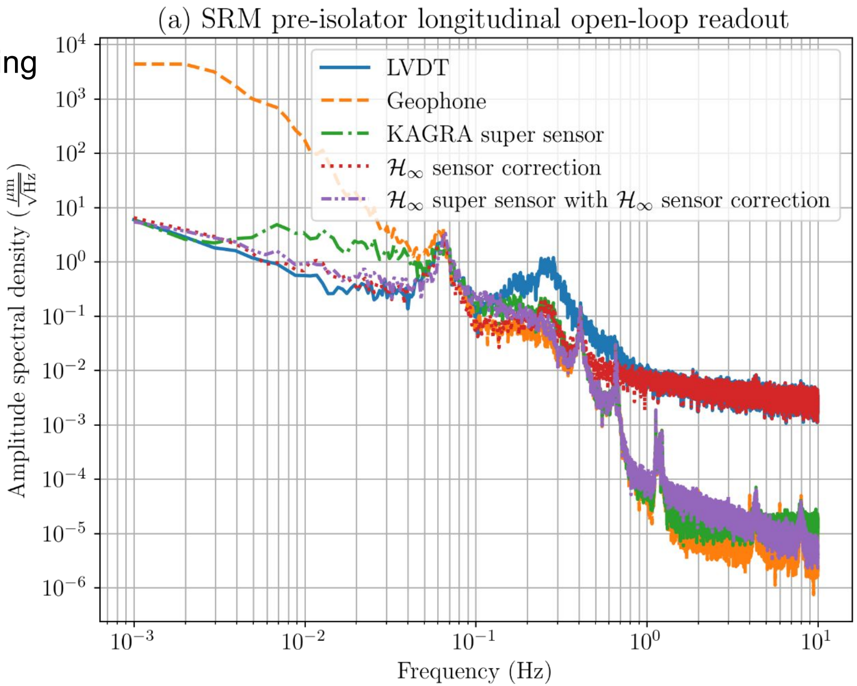
Geophone

KAGRA super sensor

H-infinity sensor correction

H-infinity super sensor

(with sensor correction)



H-infinity sensor correction and sensor fusion

Inverted pendulum freely swinging

LVDT

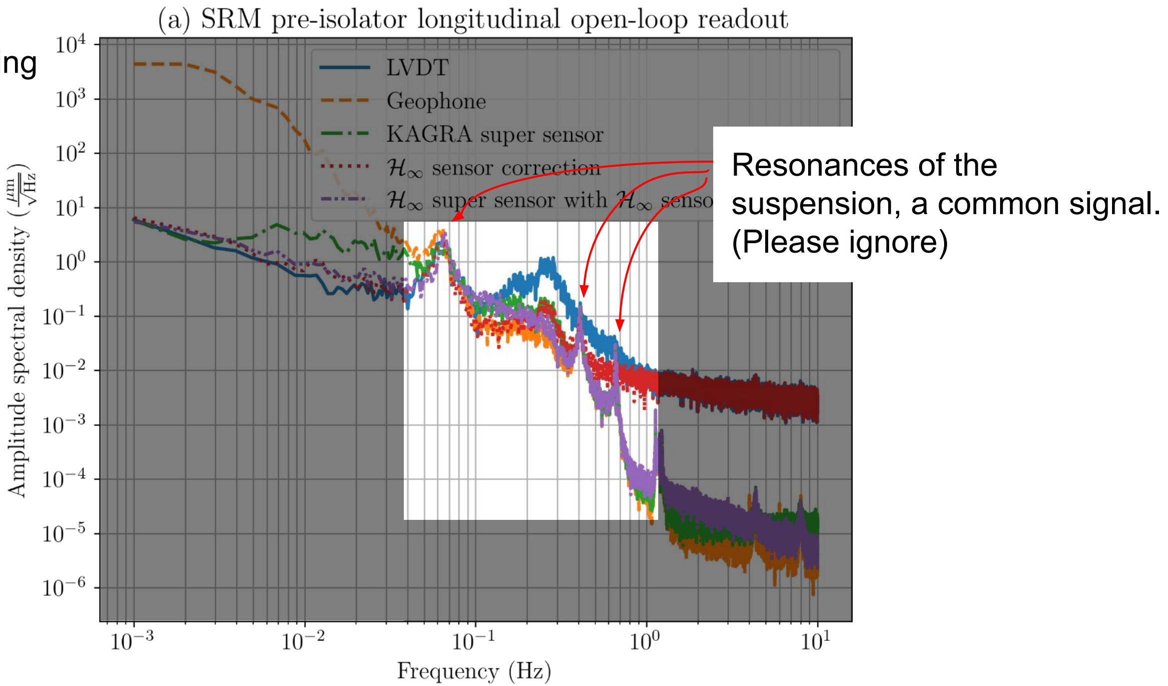
Geophone

KAGRA super sensor

H-infinity sensor correction

H-infinity super sensor

(with sensor correction)



H-infinity sensor correction and sensor fusion

Inverted pendulum freely swinging

LVDT

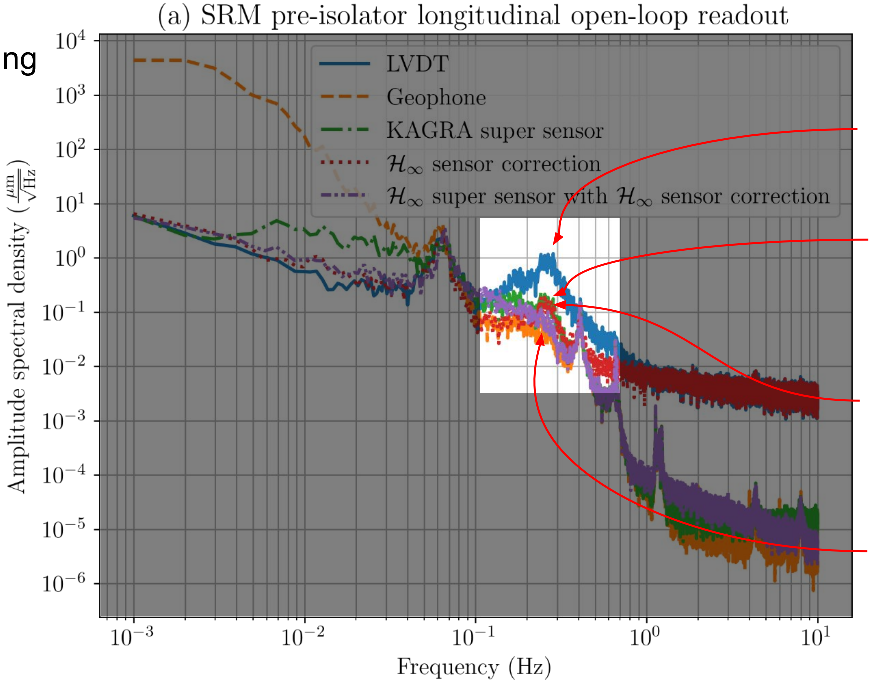
Geophone

KAGRA super sensor

H-infinity sensor correction

H-infinity super sensor

(with sensor correction)



LVDT
Coupled with seismic noise

KAGRA super sensor
~ 1 order of magnitude suppression

H-infinity sensor correction
~ 1 order of magnitude suppression

H-infinity super sensor with sensor correction
Even more suppression

H-infinity sensor correction and sensor fusion

Inverted pendulum freely swinging

LVDT

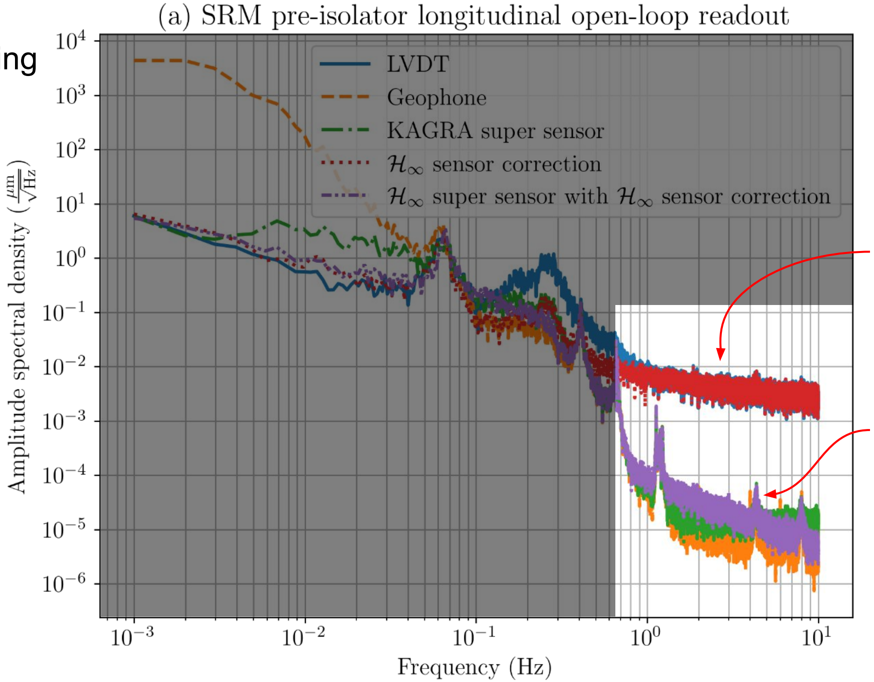
Geophone

KAGRA super sensor

H-infinity sensor correction

H-infinity super sensor

(with sensor correction)



LVDT
H-infinity sensor correction
Dominated by LVDT noise

KAGRA super sensor
H-infinity super sensor with sensor correction
Similar noise performance to the geophone.

H-infinity sensor correction and sensor fusion

Inverted pendulum freely swinging

LVDT

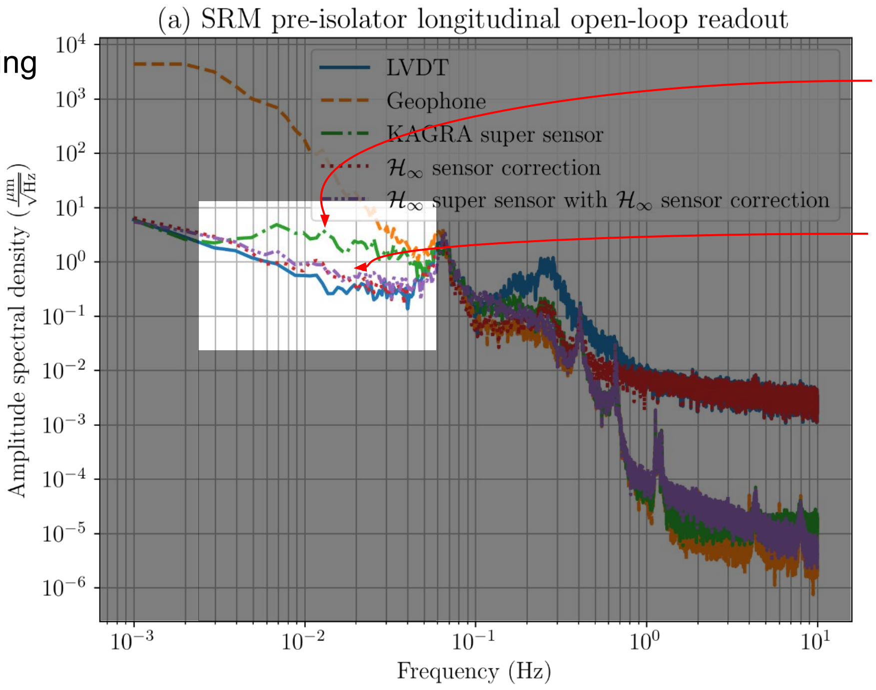
Geophone

KAGRA super sensor

H-infinity sensor correction

H-infinity super sensor

(with sensor correction)



KAGRA super sensor
Huge noise injection (huge cost)

H-infinity sensor correction
H-infinity super sensor with sensor correction
Little noise injection and still comparable to the LVDT noise.

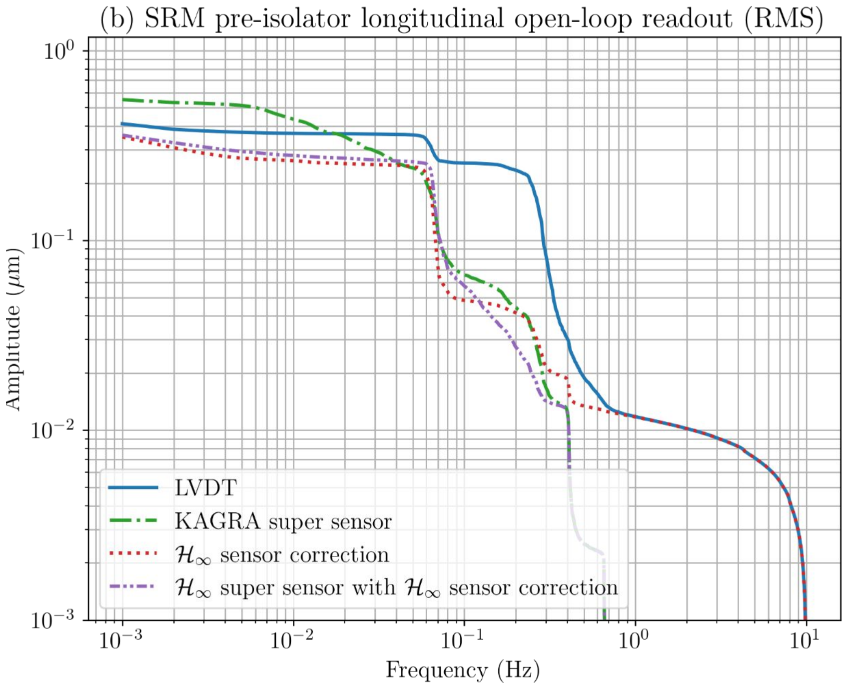
(Almost free seismic noise suppression)

H-infinity sensor correction and sensor fusion

Higher RMS value.
The optics will drift more.

Pre-isolator sensors	Sensor readout RMS (µm)
LVDT	0.412
KAGRA sensor correction	1.417
KAGRA super sensor	0.552
$\mathcal{H}_\infty$ sensor correction	0.351
$\mathcal{H}_\infty$ super sensor with sensor correction	0.359

Lower RMS values than
that of the LVDT

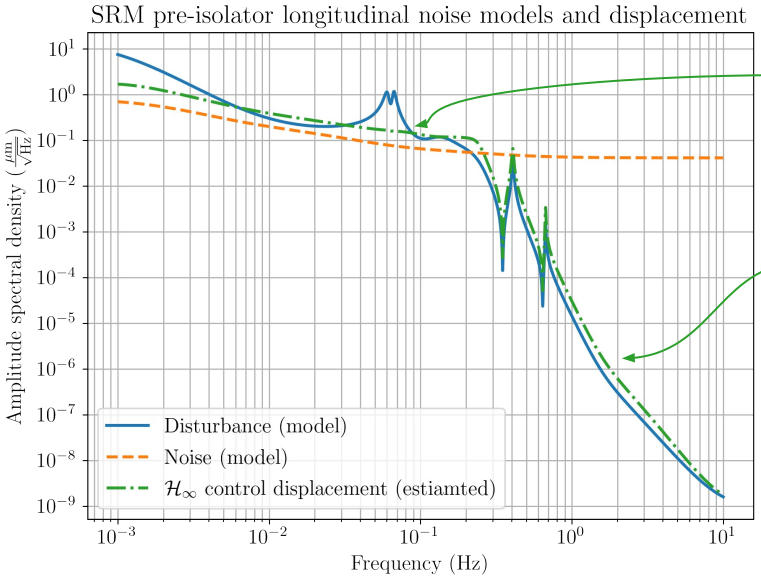


H-infinity control with corrected LVDT

Inverted pendulum displacement without control (passive isolation)

Sensor corrected LVDT noise

H-infinity control displacement (on paper)



Resonances suppressed to a level comparable to the sensing noise.

Without ruining the passive isolation performance.

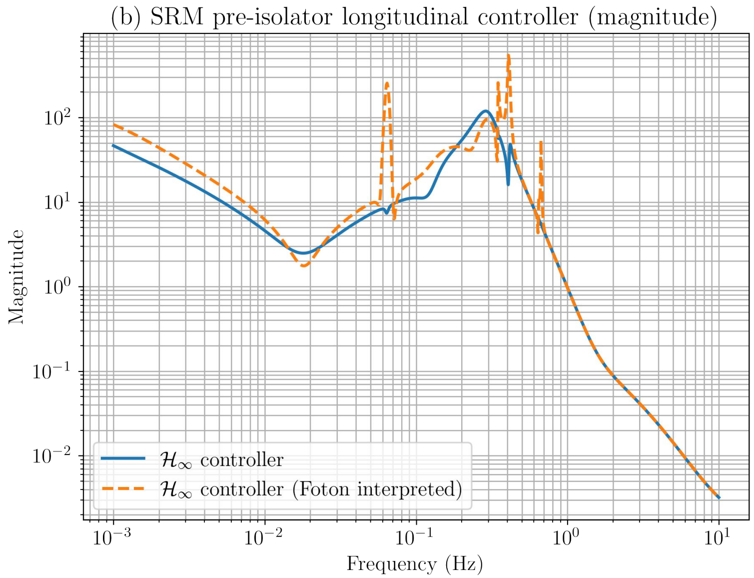
The H-infinity controller

H-infinity controller

Controller interpreted by the KAGRA (LIGO) control software (Foton).

46th-order controller too complicated?

Outlier coefficients causing numerical error?



Summary

- Gravitational waves are very hard to detect because of noises.
- Seismic noise needs to be suppressed in two ways
    - Passive isolation - filters high frequency seismic noise passively to reach required sensitivity. (Optics are hanged as multiple pendulum).
    - Active isolation - suppress the low frequency seismic noise and resonances so the interferometer can be aligned / locked.
- Two ways to improve active isolation performance
    - Reduce sensor noises
        - Sensor correction (removing seismic noise coupling)
        - Sensor fusion (combining different sensors)
    - Better feedback controller
- H-infinity method solves these control filter design problems.