Feed Forward Noise Reduction

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Outline

- A (very brief) history of feed forward in LIGO
- Why do we need feed forward noise reduction?
- How is feed forward different from feed back?
- Seismic feed forward in LIGO interferometers
- Other uses for feed forward in Advanced LIGO and beyond
- Adaptive feed forward (Online Adaptive Filtering)
- Plans for utilizing feed forward in Advanced LIGO and beyond

A Brief History of Feed Forward in LIGO

- Piezo fine actuators for Tidal feed forward
- Feed forward tidal signal to Reference Cavity (remove common mode noise)
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- Feed forward MICH, PRC, etc. out of DARM: Any non-Gravitational Wave control signals out of the Gravitational Wave channel

Feed Forward: Pros and Cons

Feedback can run into problems due to the speed of propagation back to the input

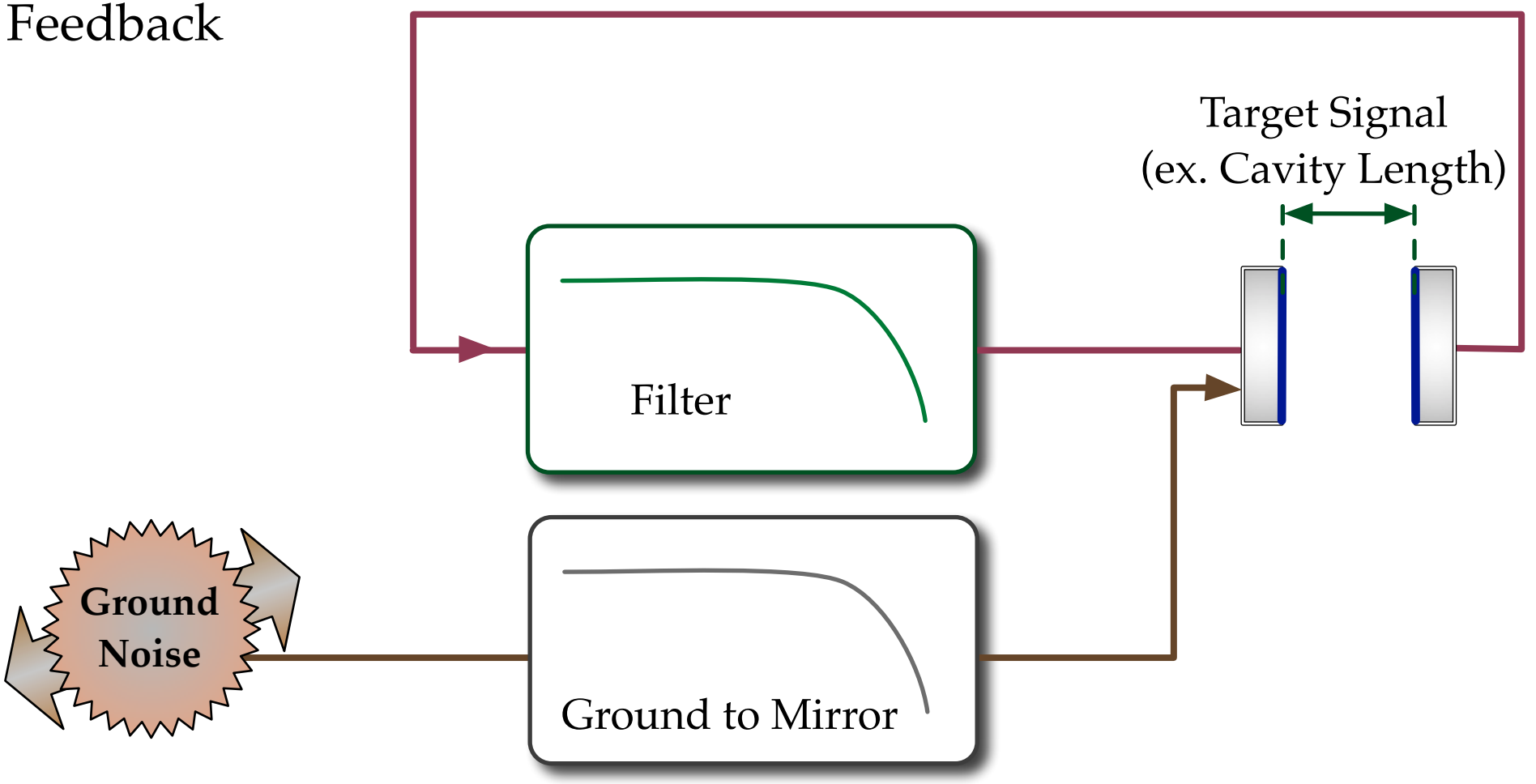
Feed forward is not limited by loop delay

Feed forward is useful for offloading feedback loops: lower loop bandwidths, reduce feedback forces

We pay a price for using feed forward: we have to know the transfer function a priori

Online Adaptive Filtering is a balance between feed forward and feedback, although it can be challenging to implement

Feed Forward vs. Feedback



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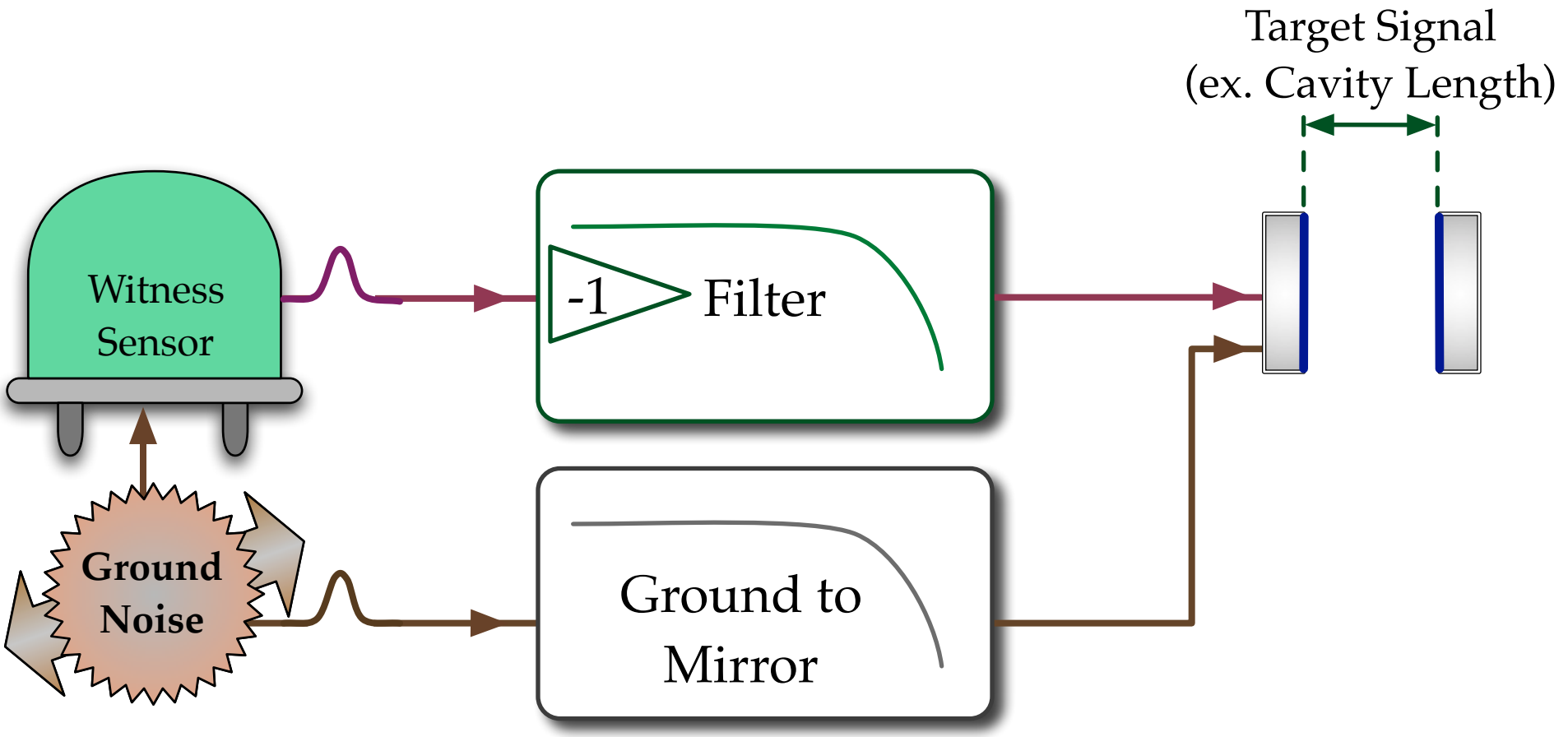

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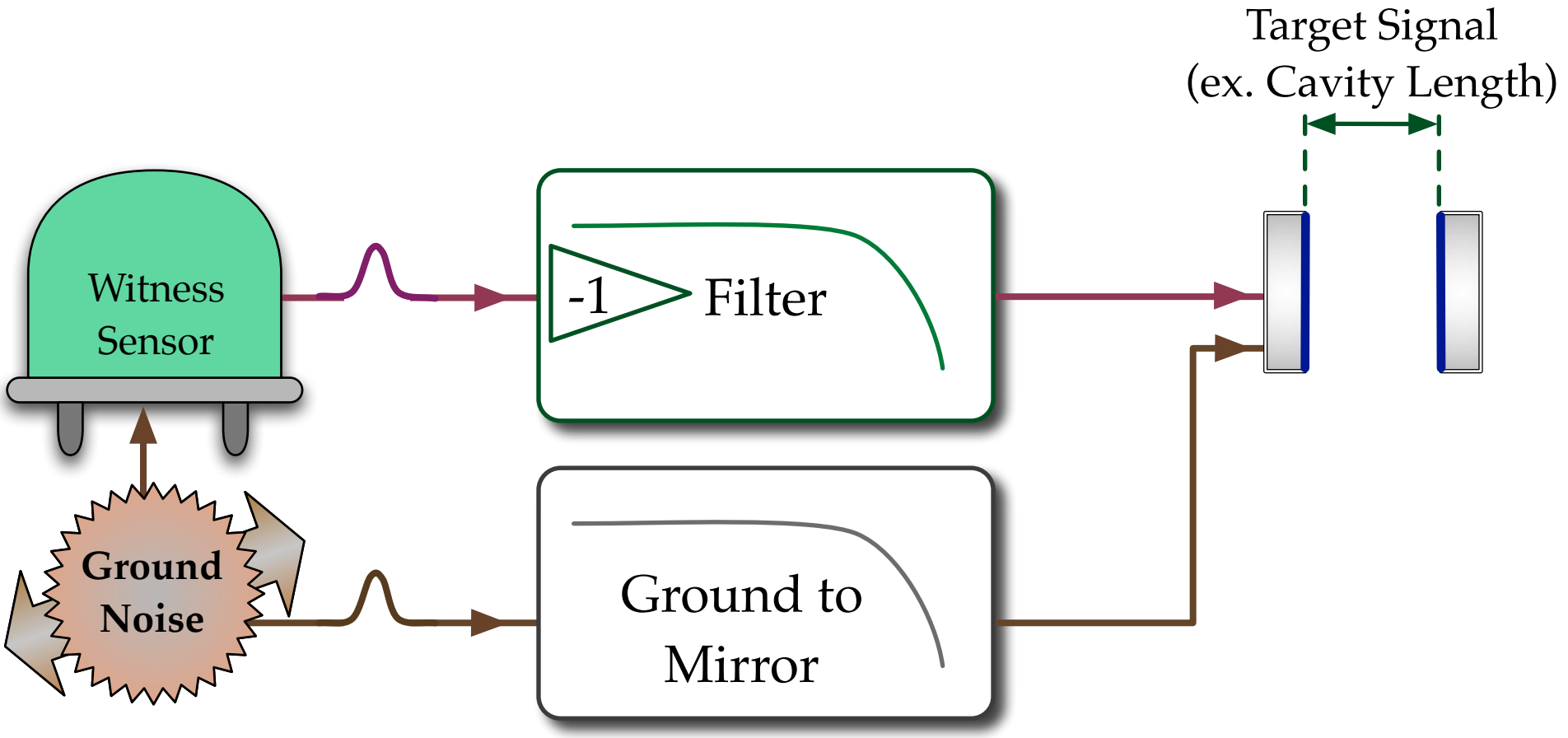

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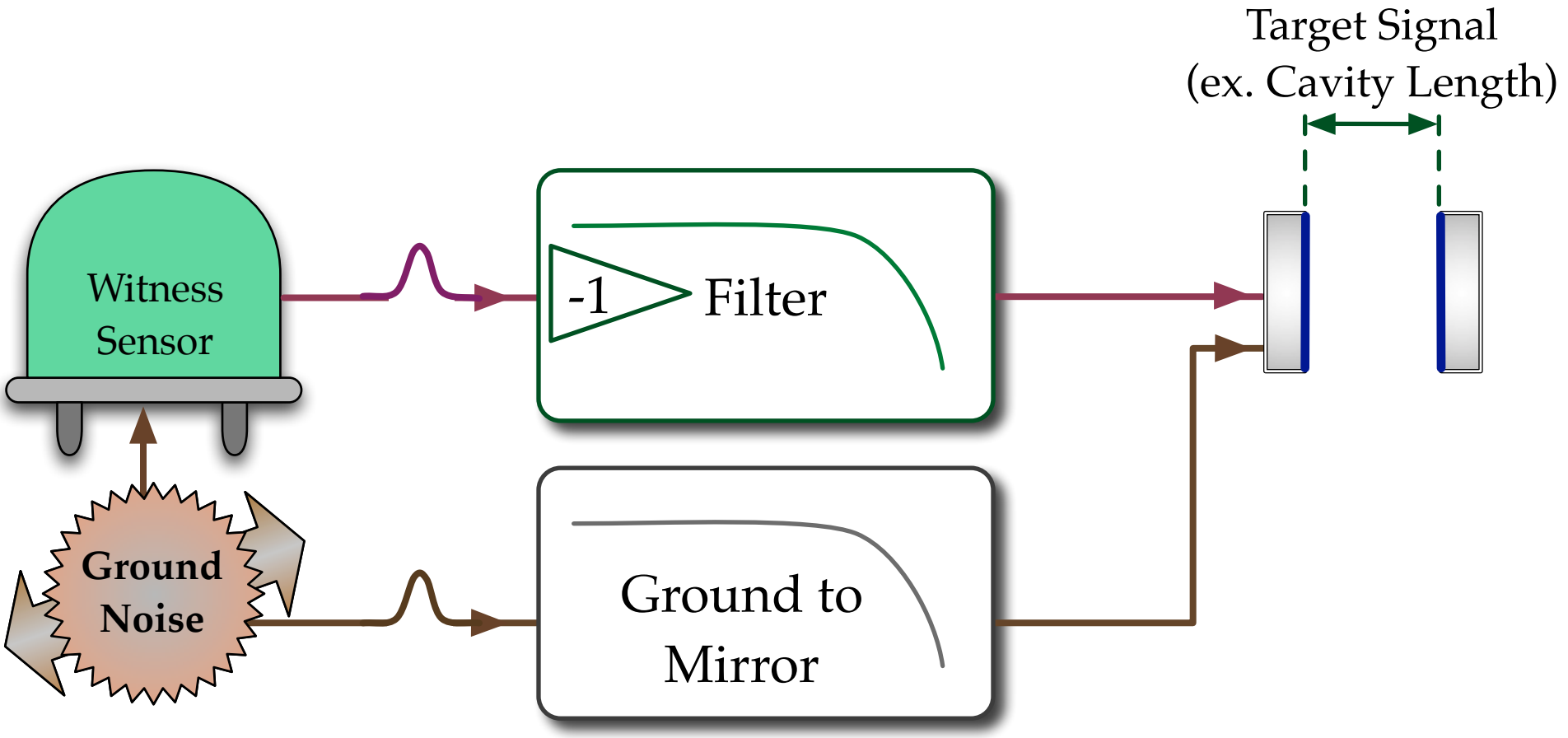

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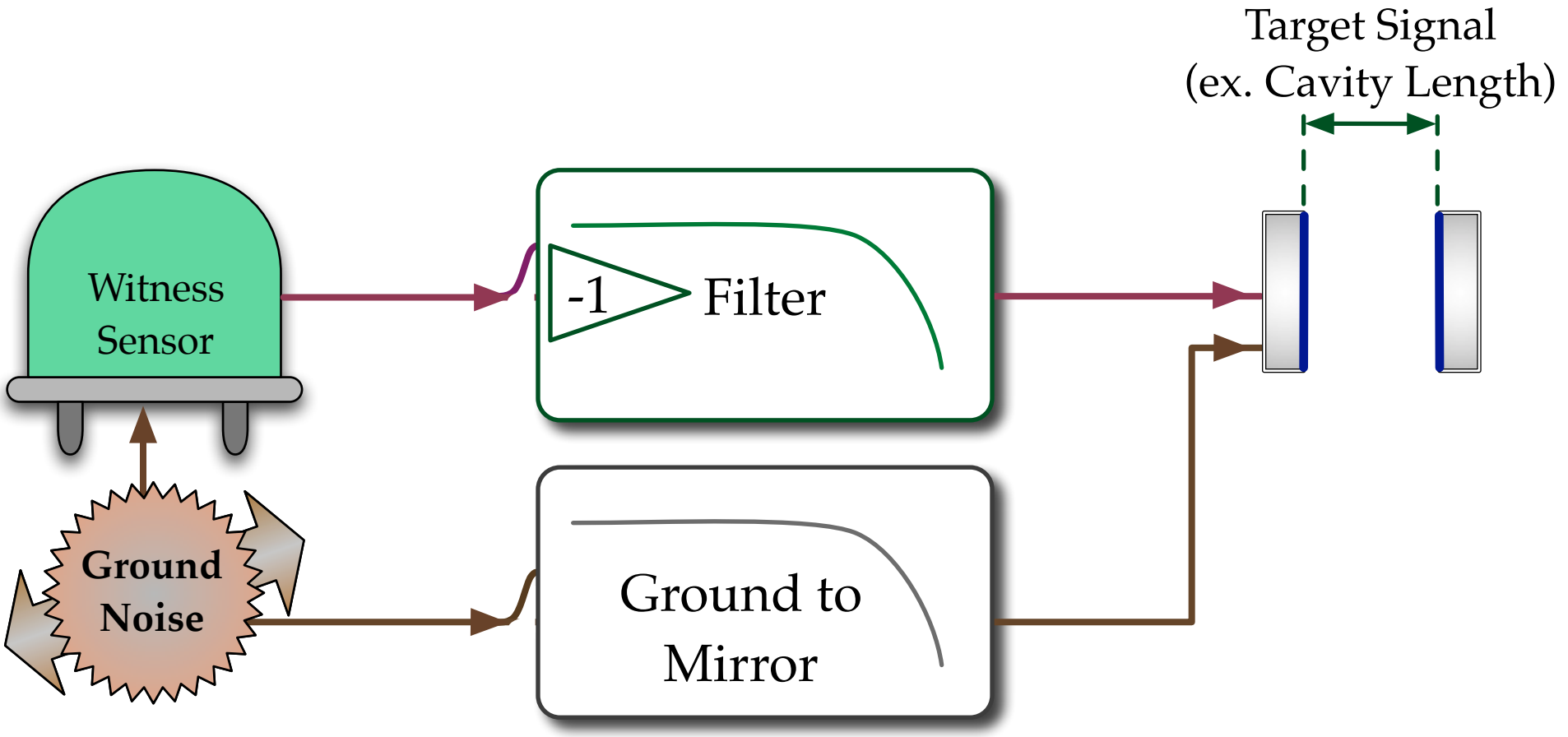

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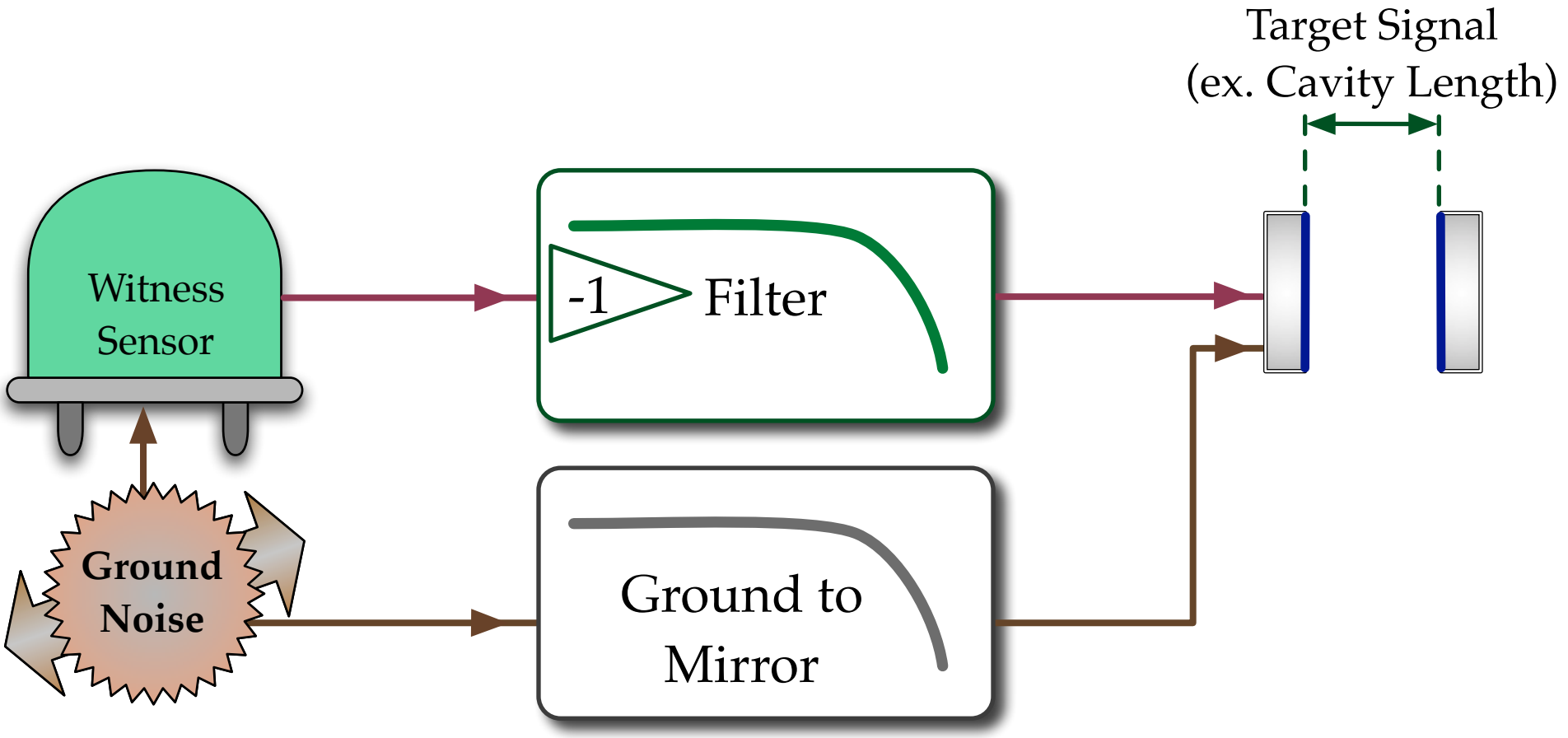

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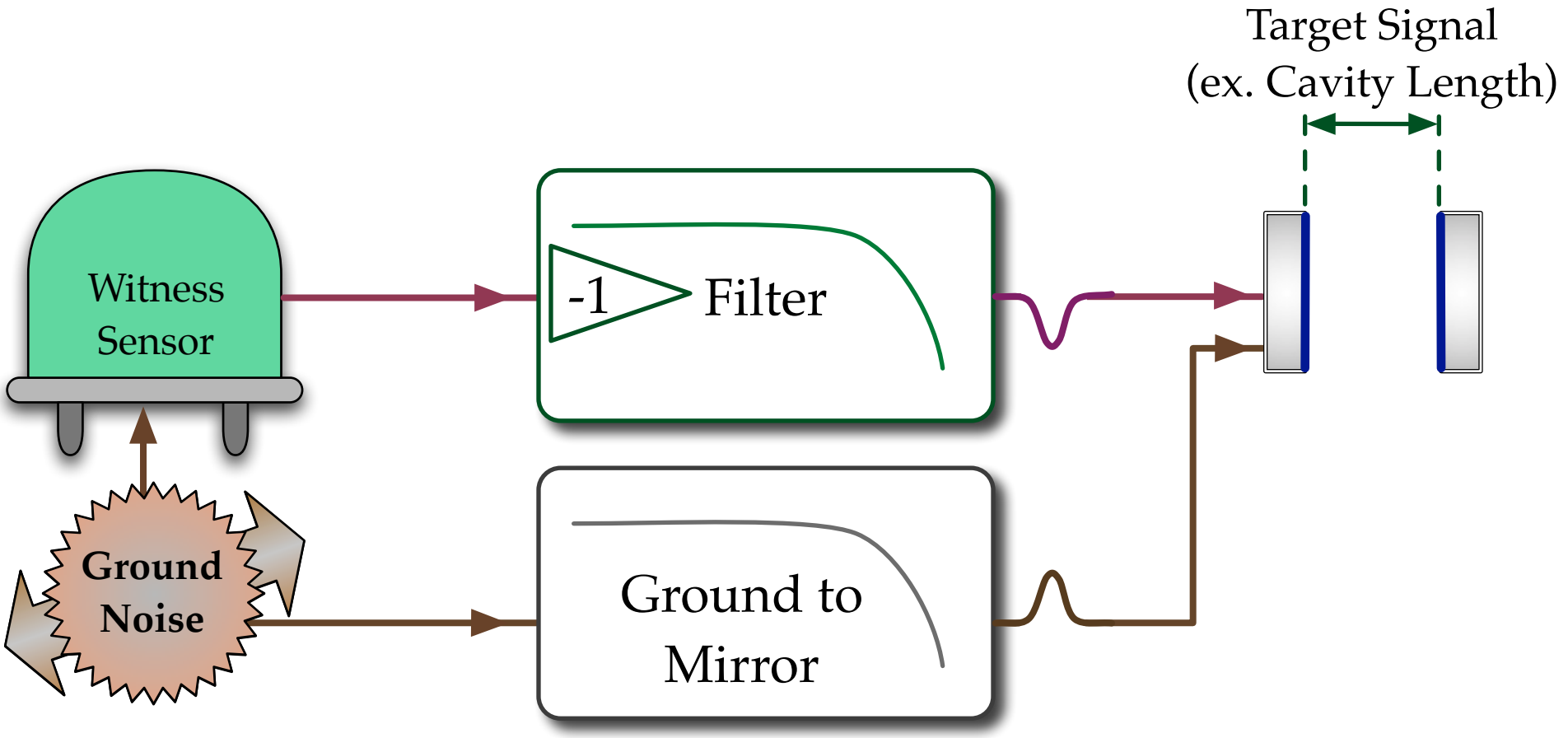

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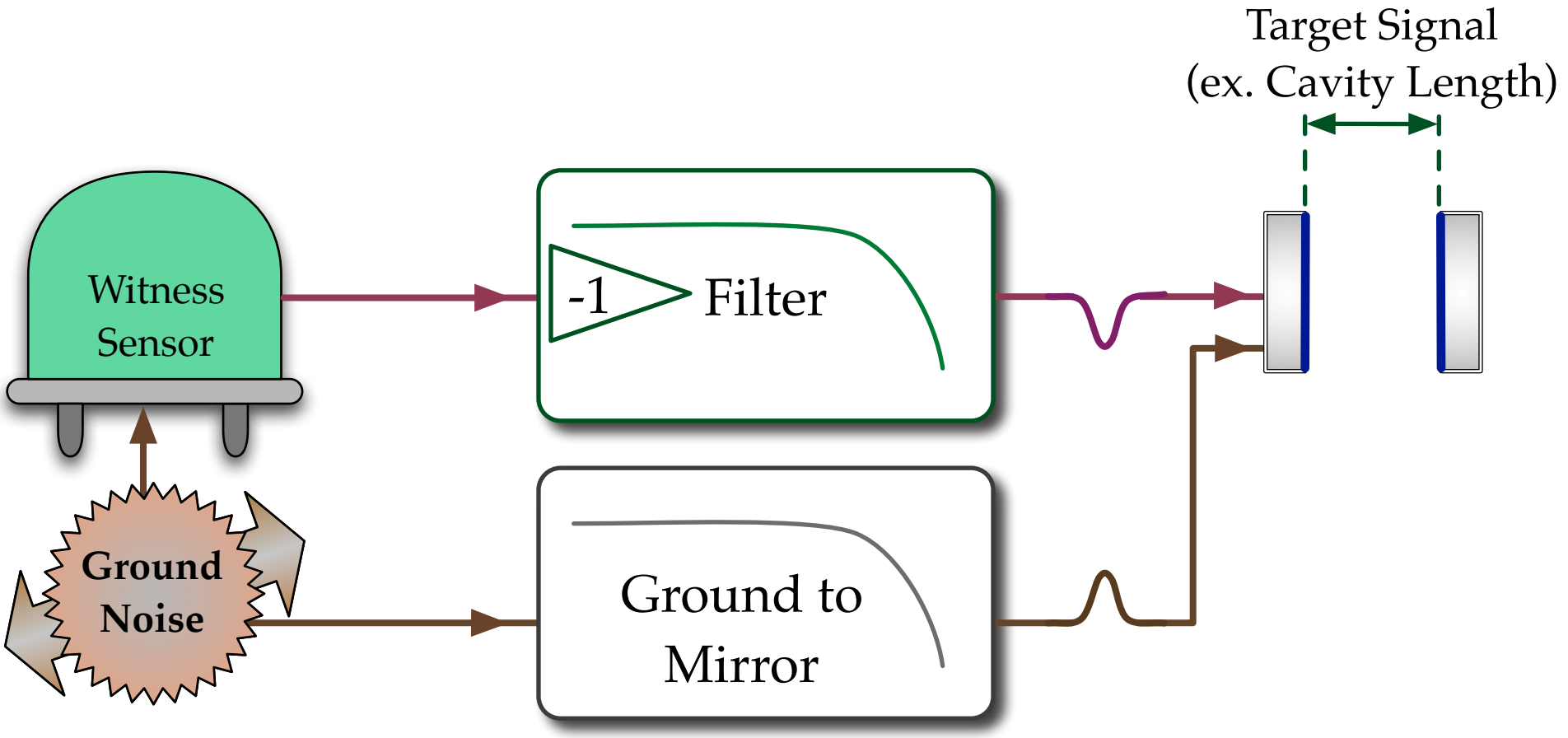

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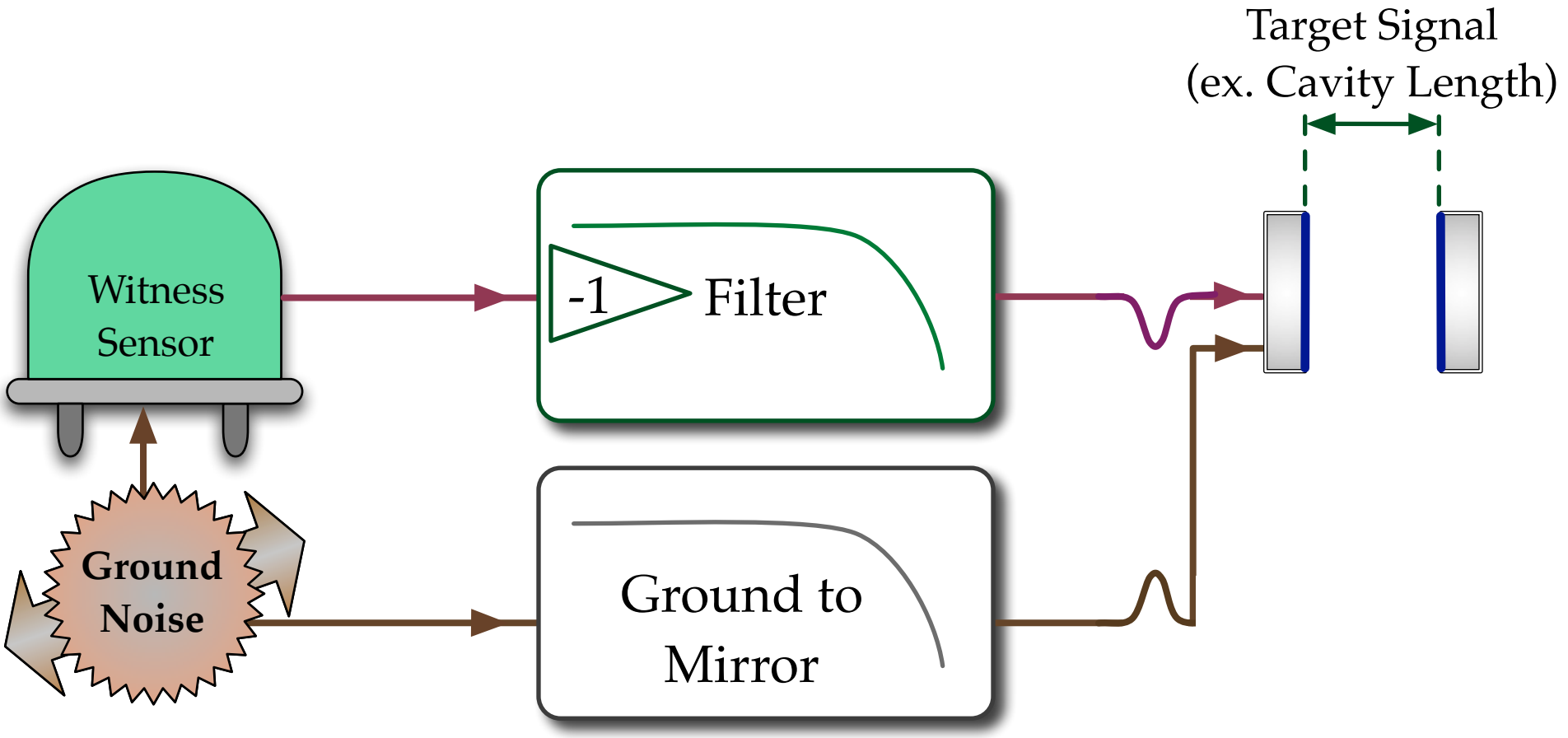

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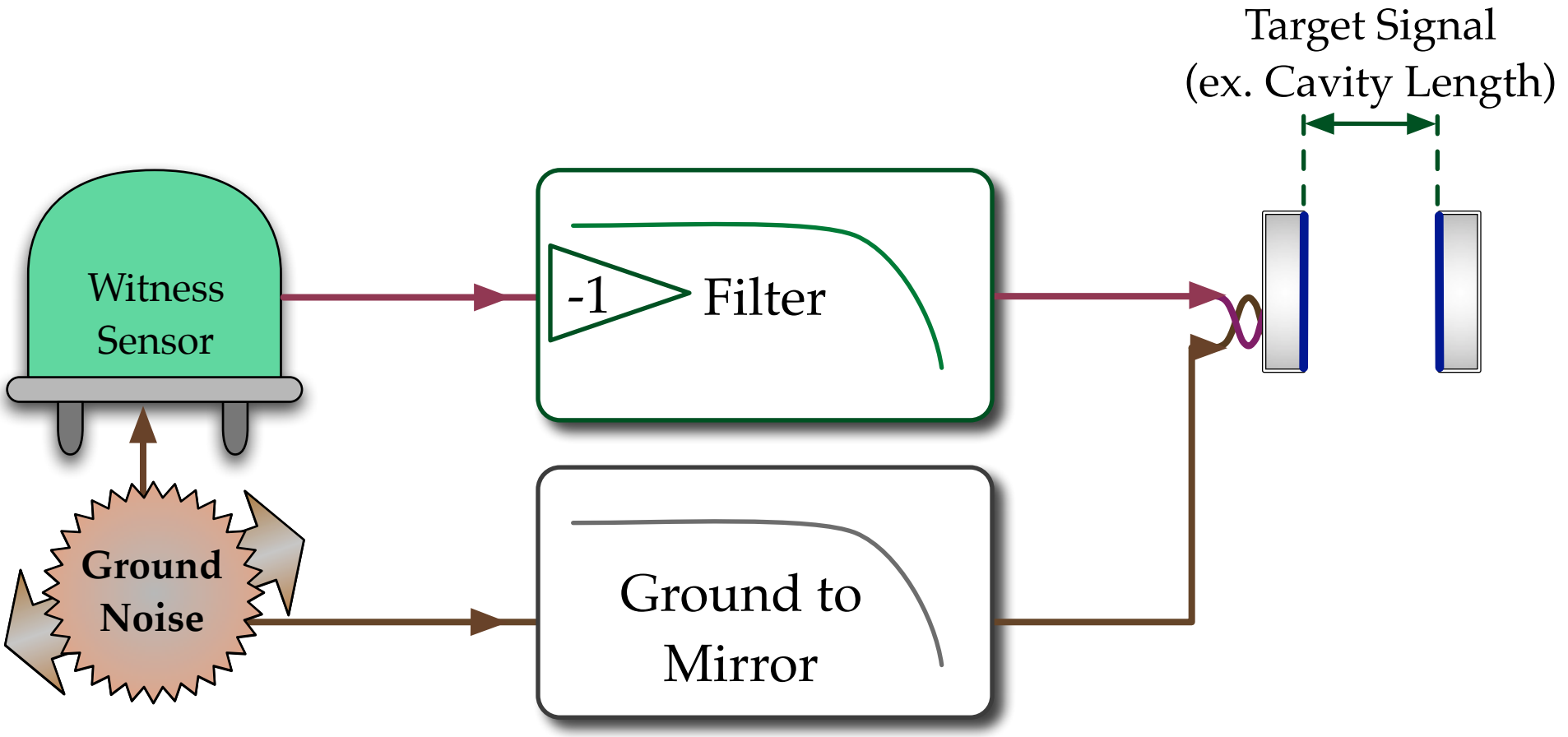
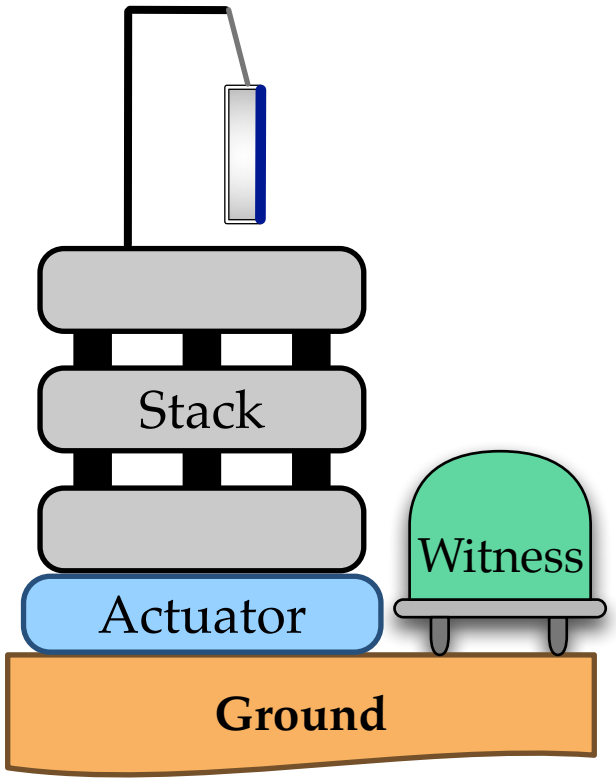


Local vs. Global Feed Forward

Local feed forward

Measure near a chamber, push on that chamber

Minimize test mass motion **relative to ground**

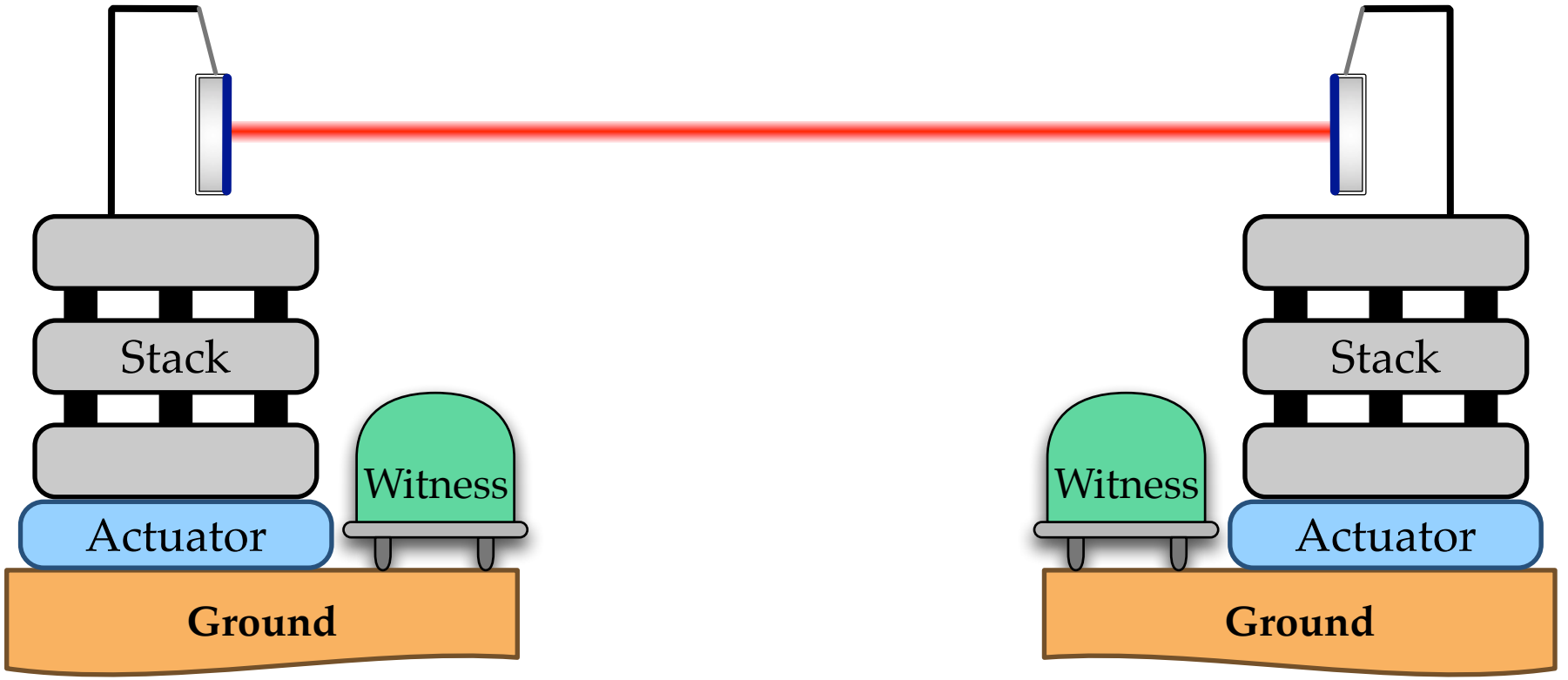


Local vs. Global Feed Forward

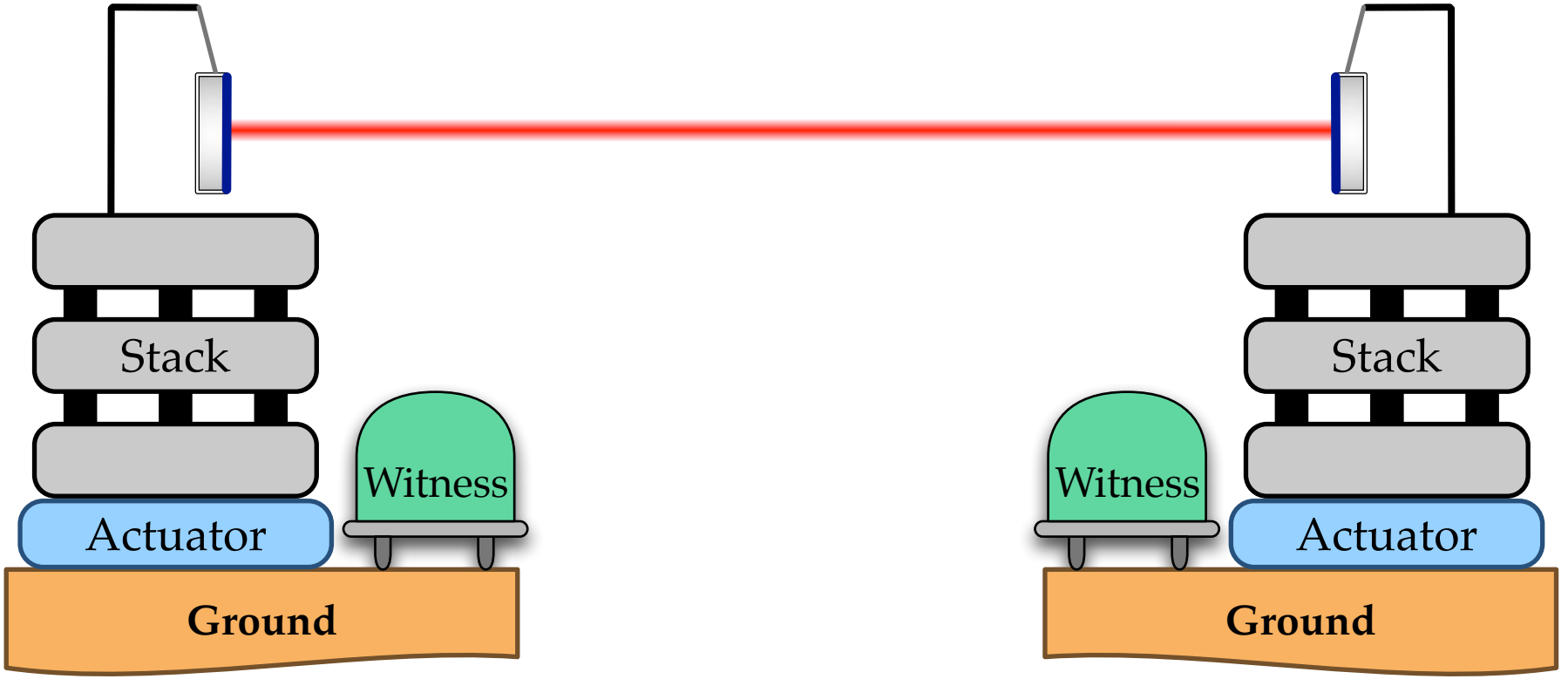
Global feed forward:

Measure near multiple chambers, push on multiple chambers

Minimize test mass motion relative to other mirrors



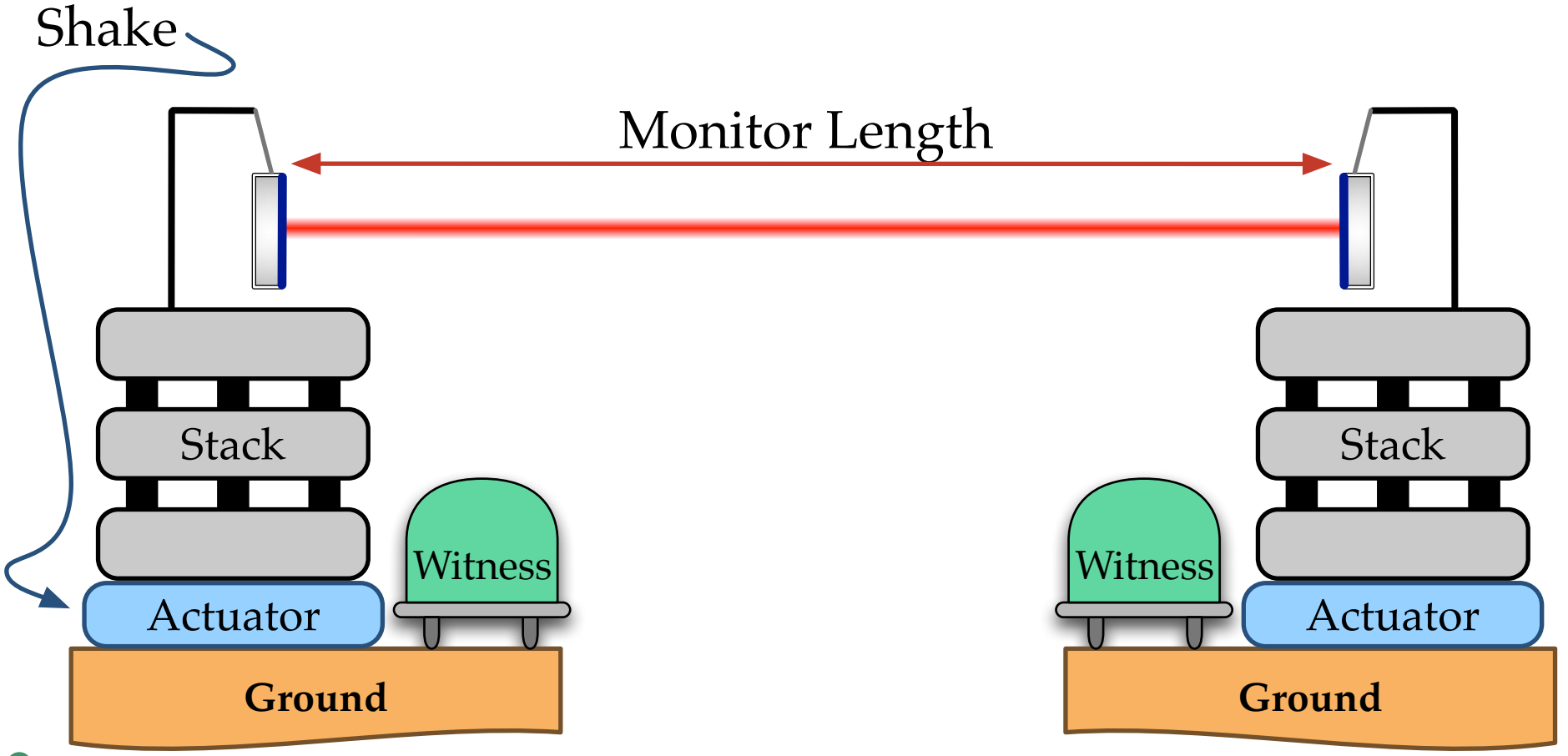
How To: Seismic Feed Forward



How To: Seismic Feed Forward

Measure transfer function by shaking actuator, watching cavity length

Require measurement coherence > 0.99

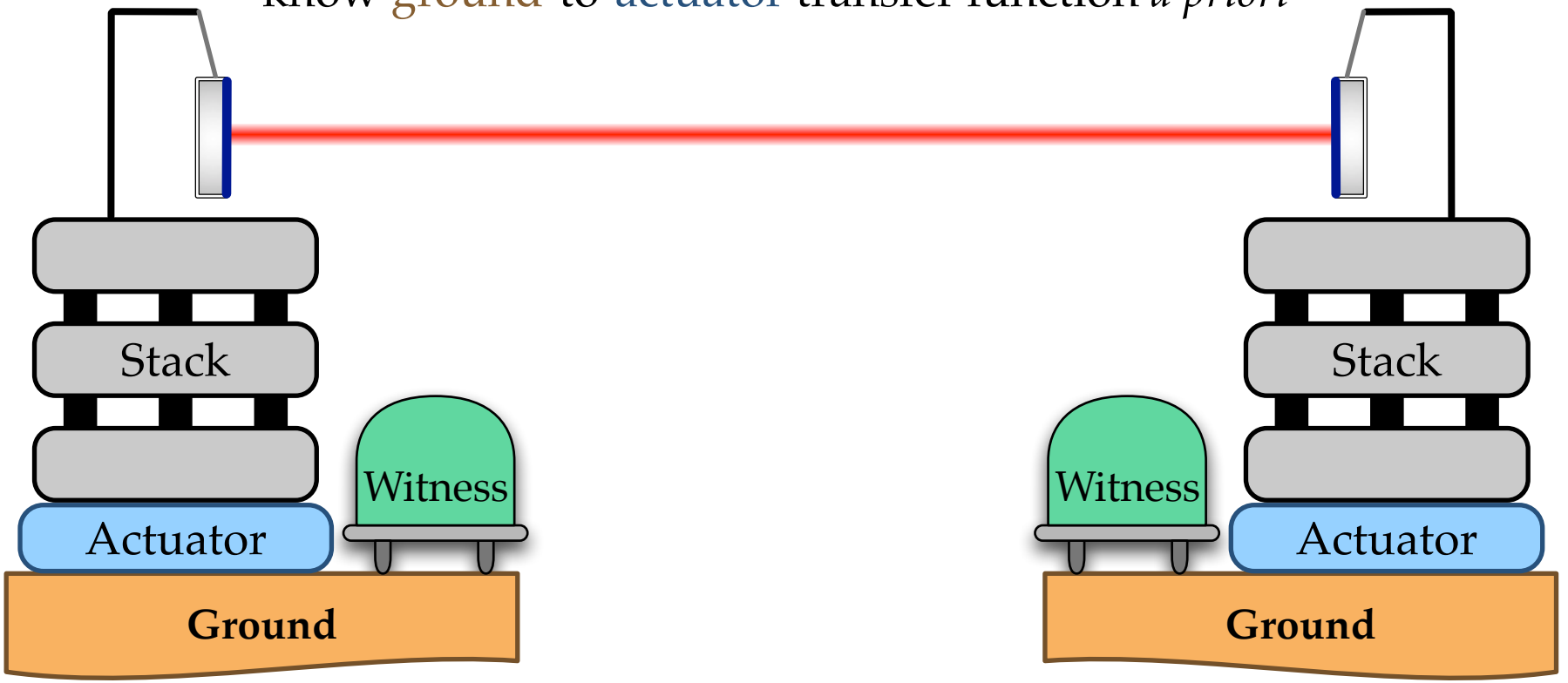


How To: Seismic Feed Forward

Calculate optimal filter between seismometer and cavity length

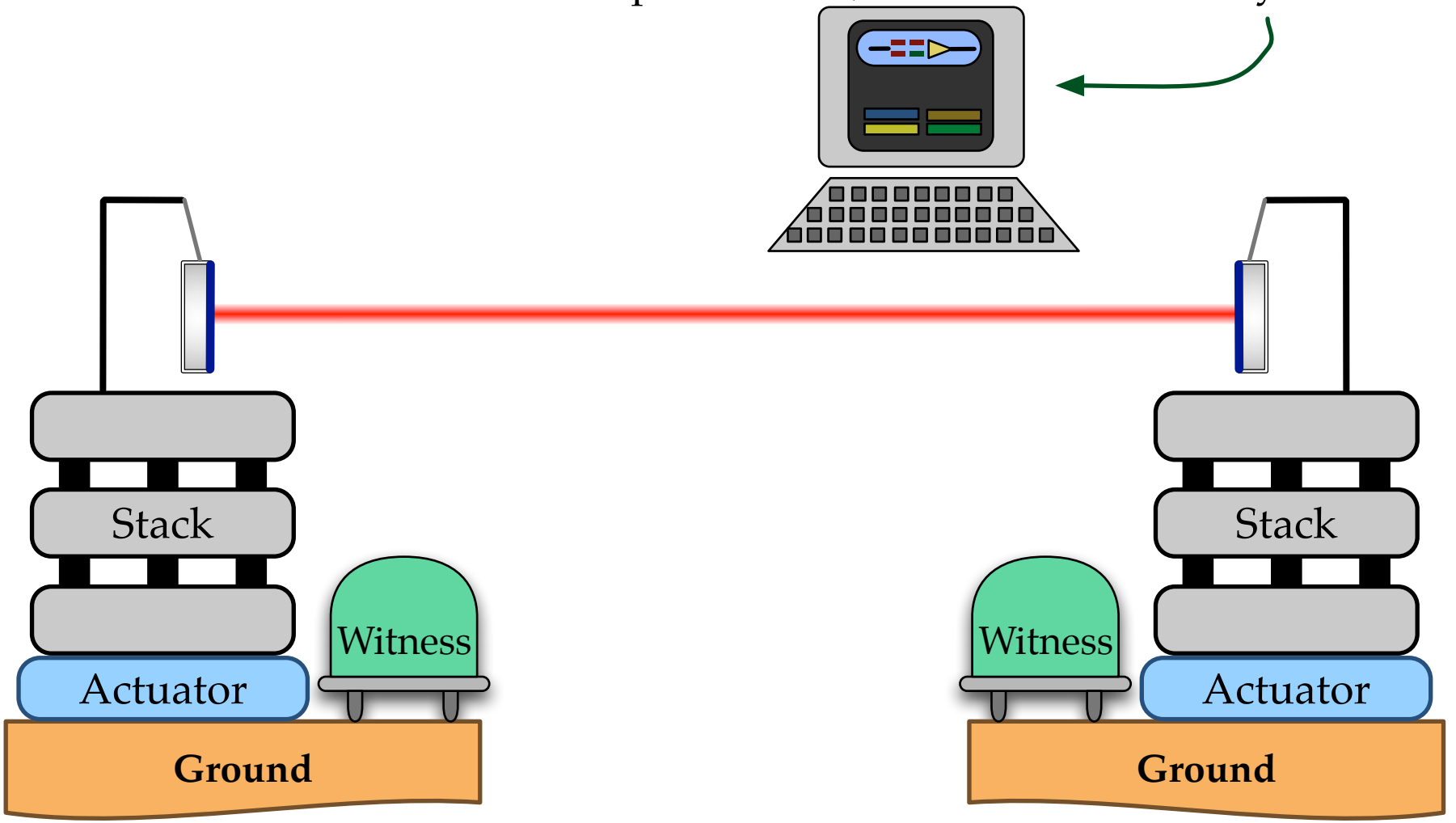
Since we know actuator-to-length, this gives us seismometer-to-actuator

By calculating the optimal Wiener filter, we don't have to know ground-to-actuator transfer function *a priori*



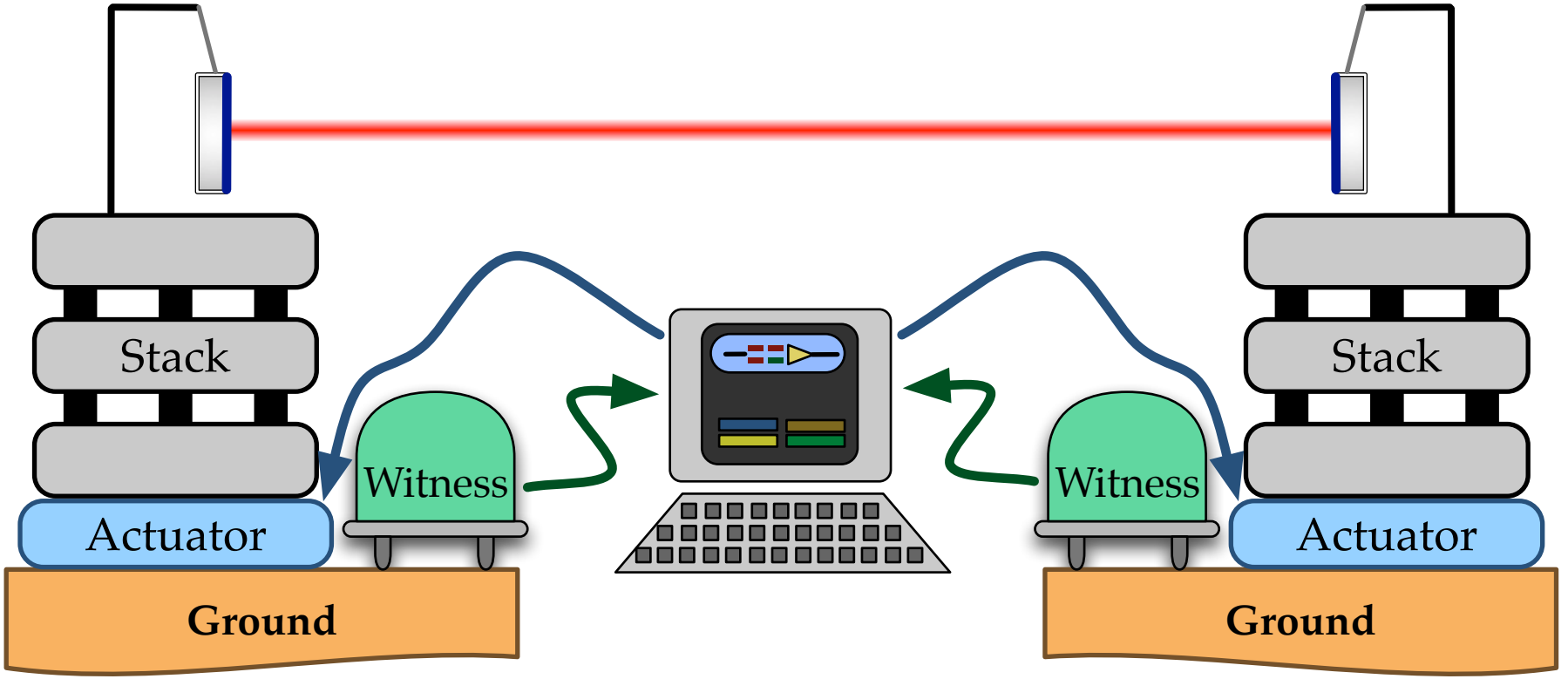
How To: Seismic Feed Forward

Fit second-order-sections to optimal filter, load into real-time system

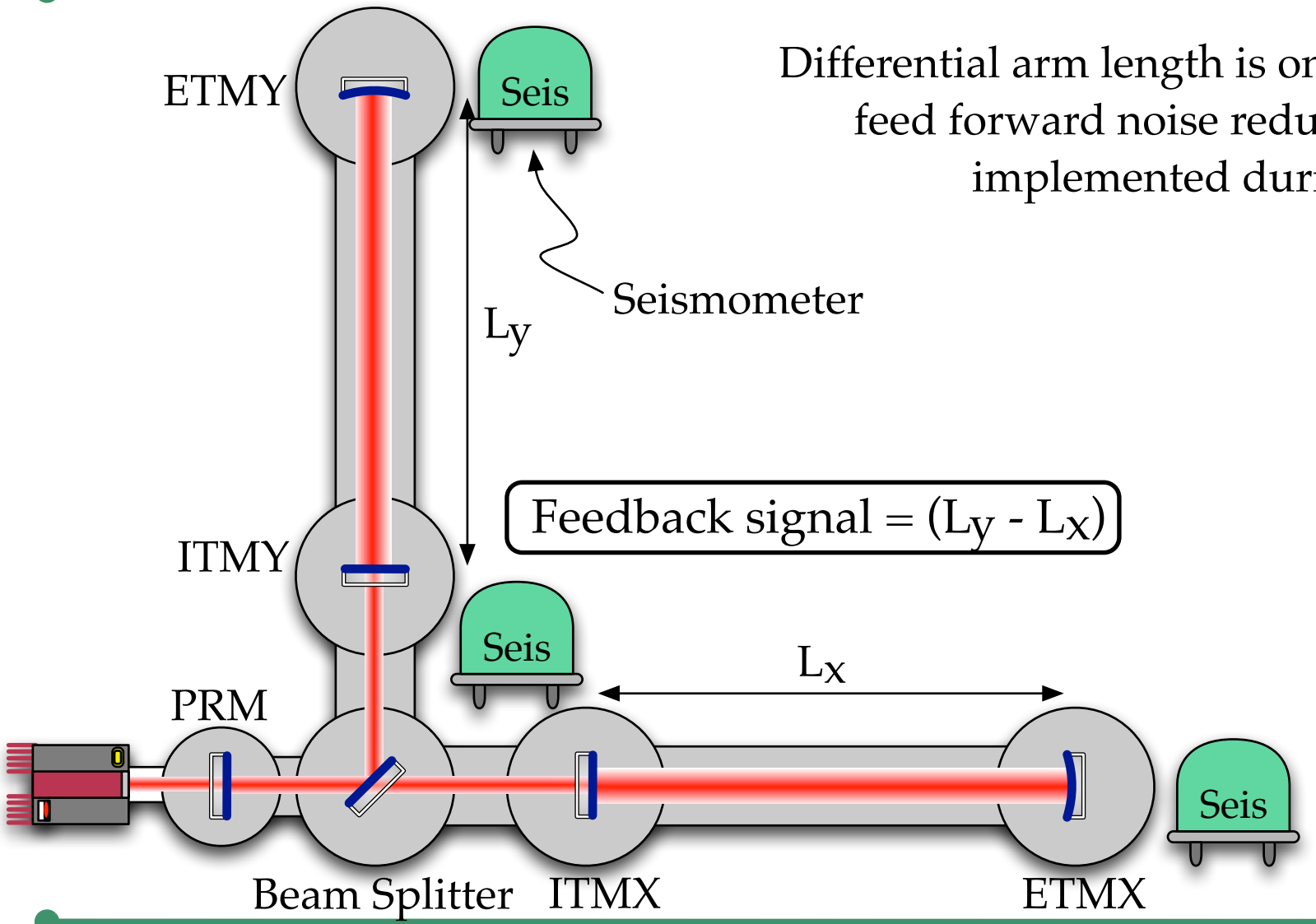


How To: Seismic Feed Forward

Try it out, see reduction in noise



Seismic Feed Forward During S6



Differential arm length is only **one of many** feed forward noise reduction points implemented during S6

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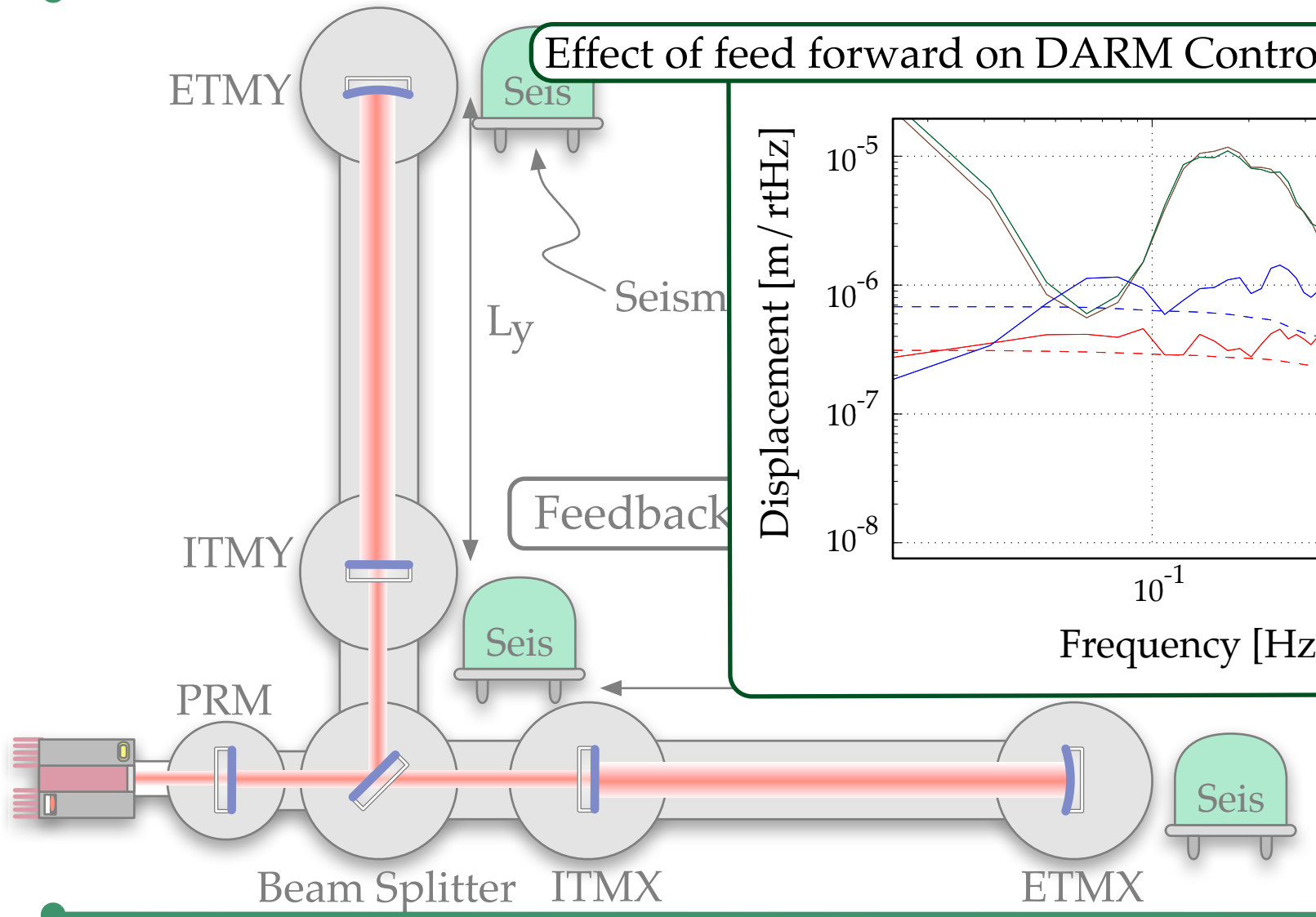
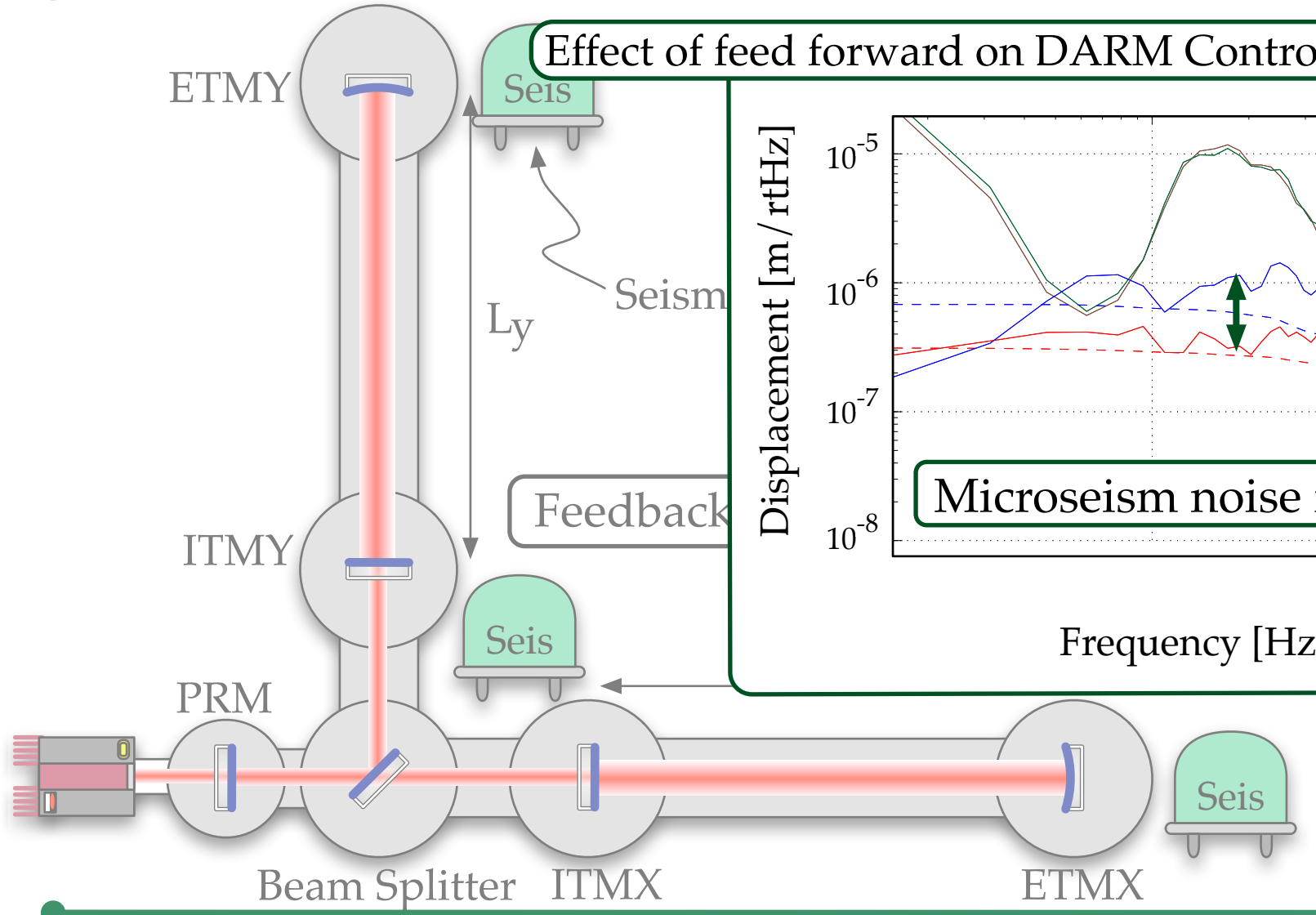


Effect of feed forward on DARM Control, February 2010

Seismic Feed Forward During S6



Effect of feed forward on DARM Control, February 2010

Benefits of Implementing Feed Forward

Improved duty cycle for the remainder of the Science Run

Reduced glitch rate

Made it easier to increase laser power up to 20W

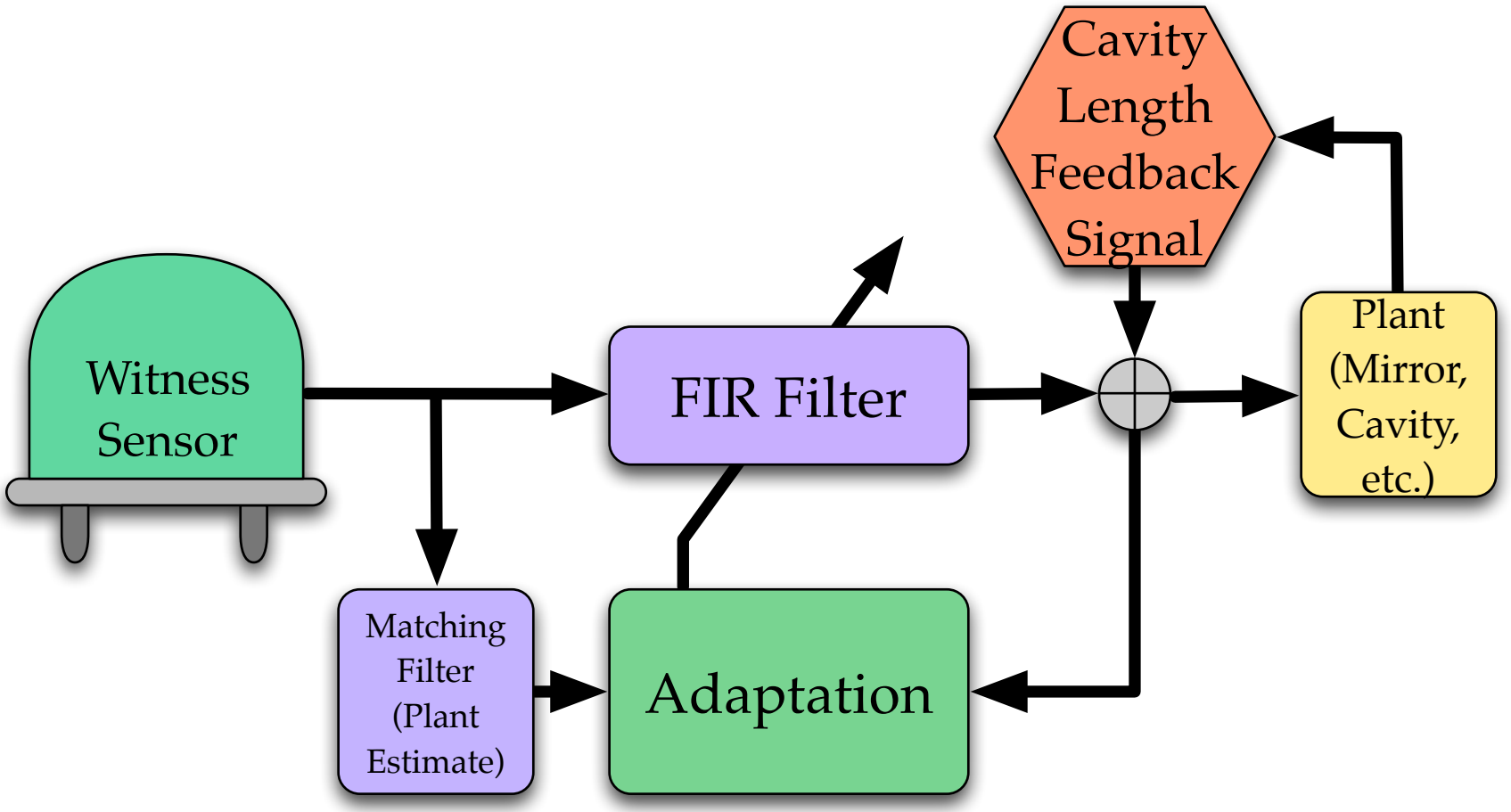
Difficulties Implementing Feed Forward

We achieve about a factor of 3 further reduction in seismic noise,
but hope for more

We are not currently limited by our ability to measure the ground motion

We need to figure out the feedthrough of noise from all possible sources
to figure out what is limiting the subtraction

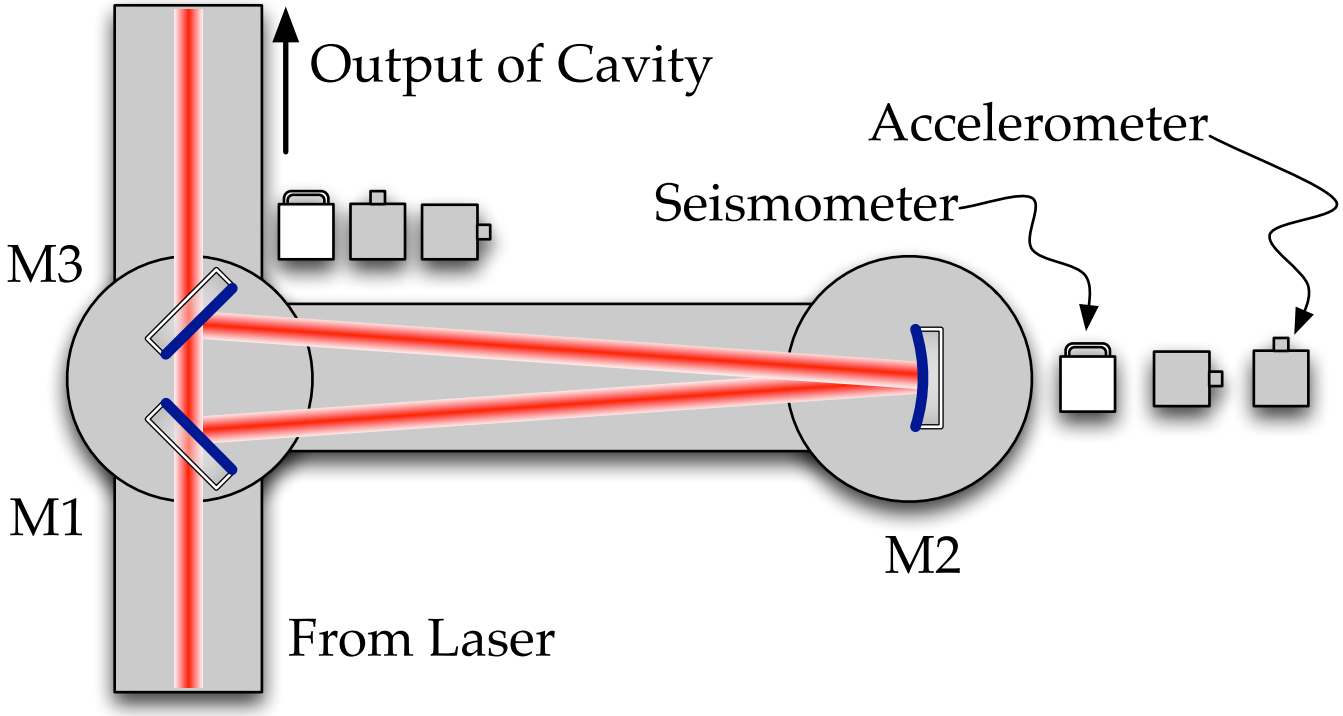
Online Adaptive Filtering



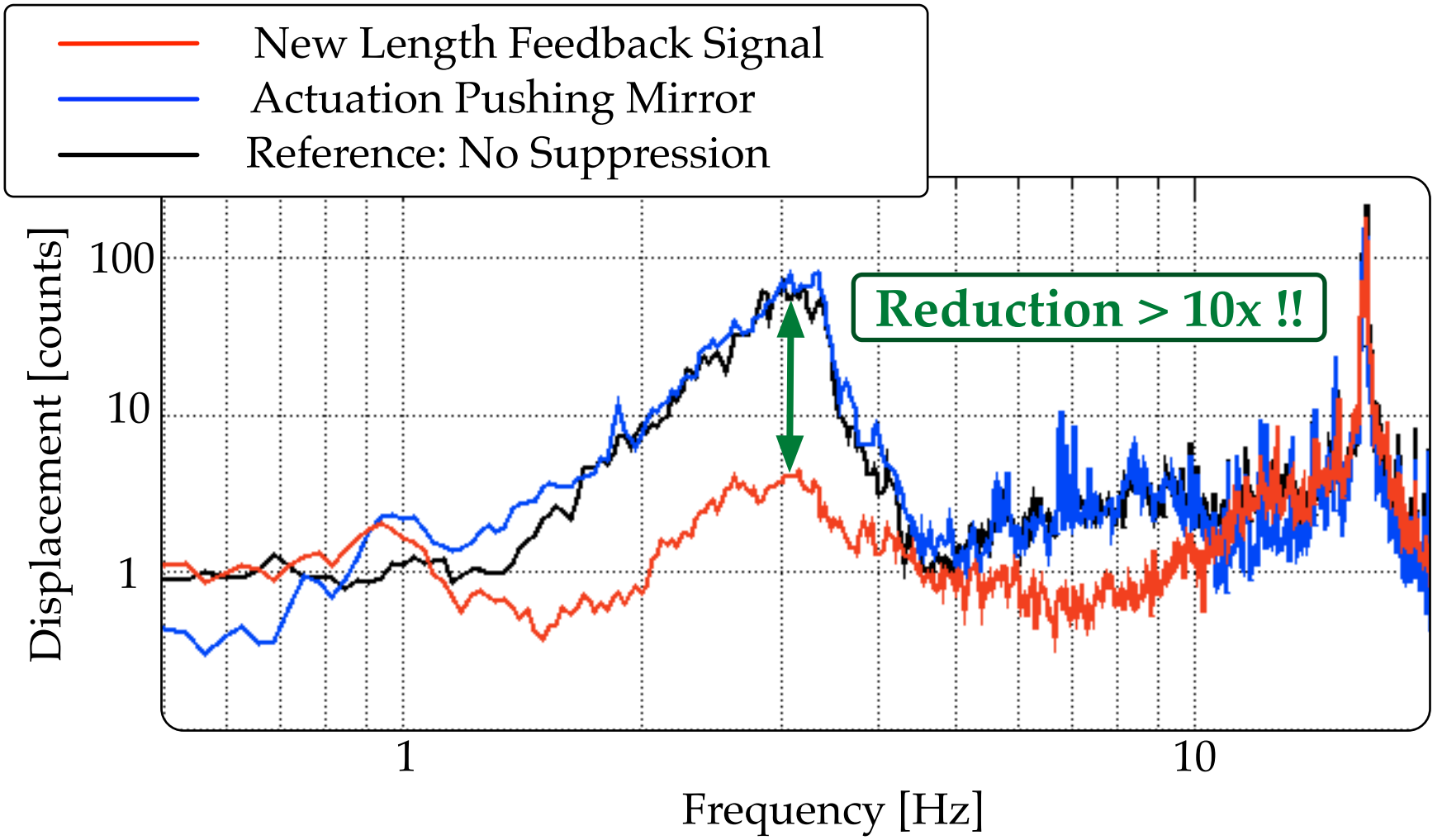
Online Adaptive Filtering

Proof of principle:

Online Adaptive Filtering works on 40m Mode Cleaner (13.5m ring cavity)



Online Adaptive Filtering: Result



Online Adaptive Filtering

Online adaptive filtering will be implemented on 40m DARM this summer

Plan: Calculate static feed forward filters,
let adaptive filter improve upon them

Online adaptive filtering requires careful tuning to avoid oscillations

We'll continue applying adaptive filtering to all control signals possible

More Uses for Feed Forward

Feed forward is also good for other noise sources -
magnetic (already implemented),
angular alignment (already implemented)
acoustic (to be tested at the 40m Prototype),
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Any noise source for which we have an independent witness sensor

Feed Forward in Advanced LIGO

- Local feed forward is part of the Advanced LIGO baseline design for HEPI and ISI
- We will utilize global feed forward and other techniques as necessary
  - Implement adaptive feed forward during Hanford 1-arm test
- Global feed forward may be most useful below ~0.3Hz where ISI etc isn't as good

Conclusions

Feed forward is a useful controls technique

We already achieve factors of ~3 in additional seismic reduction, and expect to be able to do more reduction once we determine limiting technical noise

Online Adaptive Filtering, in tandem with static feed forward, has great potential to reduce seismic noise in Advanced LIGO

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