Improving the Sensitivity of Gravitational Wave Interferometers

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IPAM GWAWS IV
Big Data in Multi-Messenger Astrophysics
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The gravitational wave data must come from somewhere

Lots of opportunity to apply Big Data techniques to improve the detectors
Many Varieties of Data
What Do We Control?

Distances between mirrors
Angles of mirrors
Laser frequency
Laser intensity

Several hundred simultaneous control loops
Bandwidths range from mHz to 750 kHz
Noise Limits Due To Controls

Control Noise Contributions

- Measured Total
- Design Total
- Seismic
- Newtonian Noise
- Thermal Total
- DAC
- Dark Sensing
- Angular Control
- Length Control
- Control Total

Displacement [m/√Hz]

Frequency [Hz]

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How should we push on a mirror, to maintain cavity resonance?
Length Displacement

LHO Calibrated SRCL

Measured displacement

Actuation

Inferred motion if no control

SRCL displacement $[m / \sqrt{Hz}]$

Frequency [Hz]
Criteria for Control System

Reduce motion, including root-mean-square of residual motion

Minimize control contribution to other loops’ residual motion

   Lower unity gain frequencies for auxiliary loops is generally preferred

Hold system in the linear regime

   Do not saturate actuators

Robust against changes in mechanical plant and changes in input disturbances

   Often cannot tolerate the solutions from “optimal controls” methods due to their limited stability margins

Must be causal, to implement in the realtime online system
Automating Loop Design

Hang Yu, PhD Thesis, MIT 2019
Information for “challenge problems” on github (provided by Prof. Rana Adhikari), for folks to get started trying new methods on LIGO-like problems

Interesting problem: combining the single-suspension damping loop design along with ‘global’ controls design, eg. how does single-suspension control affect control of cavity-axis motion?

https://github.com/rxa254/LIGO-Controls-Problems
Newtonian Gravitational Force

Along arm cavity axis:

\[ \delta \ddot{a}_{NN} = \frac{\delta \dot{F}}{m} = G \rho_0 \int dS \frac{\xi_{vert}}{r^2} \hat{r} \]

- **Mass is gone**
- **Reduced gravitational attraction**

Acceleration due to Newtonian Noise

**Gravitational Constant**

**Density of ground**

**Displacement of ground**

**Distance between ground and mirror**

Integrate over all ground near mirror

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Future generations of ground-based detectors depend on reduction of Newtonian gravitational noise

10x surface wave seismic
3x body wave seismic
Not yet requiring reduction of other sources of Newtonian noise

Difficult to ‘engineer away’, likely must subtract in post-processing
h(t) not sensitive enough (yet!) at low frequencies to directly measure Newtonian noise
Determining Seismic Speeds

Wavenumber maps can be generated for any given frequency at some time

Extract direction and speed of seismic waves travelling through the array

Understanding current sites helps indicate size and type of arrays needed for future detectors

Seismic speeds lie around 350m/s.
Subtraction Test

Use beam rotation sensor as proxy for Newtonian noise

Using Wiener filters, subtract seismometer data from tiltmeter to determine approximately how well we should be able to subtract Newtonian noise

Achieve factors of 10 subtraction

Still need to directly measure and show that we can subtract true Newtonian noise from a gravitational wave data stream

M. Coughlin, et al., CQG 33:24 (2016)
It takes a lot of data from a wide variety of sources to produce the single gravitational wave strain data stream.