Monitoring Spectral Lines to calibrate LIGO data

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Outline (0/5)

- Introduction to Gravitational Waves and LIGO
- Introduction to LIGO Differential Arm Length (DARM) Actuation
- DARM Control Loop
- Photon Calibrator
- Spectral Line Monitor upgrades
Outline (1/5)

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Newtonian Gravity
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Einsteinian Gravity
Gravity is the curvature/warping of space and time (collectively spacetime) due to the presence of matter and energy.
Static Spacetime

https://commons.wikimedia.org

Dynamic Spacetime

Credit: R. Hurt/Caltech/JPL
Static Spacetime

https://commons.wikimedia.org

This is what LIGO detects

Dynamic Spacetime

Credit: R. Hurt/Caltech/JPL
Signature of a Gravitational Wave on Earth
The LIGO Detectors

Hanford, WA

Livingston, LA

https://commons.wikimedia.org
LIGO uses differential arm motion to measure the displacement of spacetime

Displacements on the order of $10^{-18}$ meters!
The LIGO Test Masses (mirrors) are hung on a quad-suspension pendulum to reduce seismic noise.
Outline (2/5)

● Introduction to Gravitational Waves and LIGO
● **Introduction to LIGO Differential Arm Length (DARM) Actuation**
● DARM Control Loop
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● Spectral Line Monitor upgrades
Mirror displacements in LIGO’s quad-suspension pendulum are subdued by actuators
Mirror displacements in LIGO’s quad-suspension pendulum are suppressed by actuators

\[ \Delta L_{\text{ext}} = L_X - L_Y \]
for free test mass
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for free test mass

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for free test mass

\[ \Delta L_{\text{ctrl}} = \text{displacement from actuators suppressing free motion} \]

\[ \Delta L_{\text{res}} = \Delta L_{\text{ext}} - \Delta L_{\text{ctrl}} \]
Mirror displacements in LIGO’s quad-suspension pendulum are suppressed by actuators.

Note the quad-suspension pendulum with stages:
- Top mass
- Upper Intermediate Mass (U)
- Penultimate Mass (P)
- Test Mass (T)
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Schematic of differential arm length control loop

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\[ d_{\text{err}} \rightarrow \text{digital error signal} \]
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\[ \Delta L_{\text{ext}} = C^{-1} \cdot d_{\text{err}}(t) + A \cdot d_{\text{ctrl}}(t) \]

Sensing and actuation function models

The sensing function $C(f,t)$ is modeled as a single-pole low-pass filter due to the optical response of the signal recycled Fabry-Pérot cavities.

$$C(f, t) = \frac{\kappa_C(t)}{1 + if/f_C} C_R(f) \exp(-2\pi if\tau_C)$$
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The actuation function $A(f,t)$ is a function of the gain and normalized frequency dependance of the upper intermediate test mass (U), the penultimate mass (P), and the test mass (T)

$$A(f, t) = \kappa_{PU}(A_{P,0}(f) + A_{U,0}(f)) + \kappa_T A_{T,0}(f)$$
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The photon calibrator uses the response of the test mass to an input laser of known power and frequency to calibrate the interferometer.
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Calibration lines are also injected by the actuators (i.e., not Pcal) at ~35 Hz \( (x_{ctrl}) \) and ~37 Hz \( (x_{tst}) \).
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The Spectral Line Monitoring (SLM) tool functionality

- Tracks the amplitude, phase, and power spectral density of specified frequencies in the LIGO data channels
  - Designed to be a once-per-day diagnostic, not real time
- Creates independent plots of the time varying kappa factors from the sensing and actuation functions, as well as the cavity pole frequency as a function of time
- Calculates and plots ratios of GDS to Pcal and GDS to Front End (DARM_ERR, DARM_CTRL) calibration line amplitudes to discern potential discrepancies
- Plots ratios of transmitted and received Pcal light to discern potential clipping
- Plots other parameters and ratios relevant to Pcal
Example
Kappa Plot 1
Example Kappa Plot 2
Among other uses, SLM can be used to see light clipping with Pcal
This ratio should always be 1.

Conclusion: Not all of the light transmitted by Pcal was received. Some of the light must be clipping somewhere.
Comparison of current vs. updated SLM Functionality

Current Functionality

- SLM data only output to ascii text file
- EPICS channels needed to be manually updated
- Plotting tools all in MATLAB
  - Needs to recompile every time it is run
  - Proprietary...licence issues

New Functionality

- SLM data output to both ascii text files and gwf frame file (e.g., for discovery by NDS2)
  - Allows for easier integration with tools used by control room for plotting
- EPICS channels are updated automatically once per day
- Plotting tools now in Python
  - Does not need to recompile every time
  - Free, easier to maintain and integrate with other calibration code
Areas for improvement in SLM

- Hardcoded to do six specific frequencies. If you wanted to add more, then the SLM code would need to be changed.
- Automatically produce plots that compare the kappa values calculated by SLM to the kappa values recorded in online calibration pipeline.
Thank you!

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References

