Lessons from Commissioning
Advanced LIGO

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GWADW, Elba
23 May 2019
Status of LIGO

O3 a great success so far

Hanford: 185 kW circulating power, 2 dB squeezing

Livingston: 225 kW circulating power, 3 dB squeezing

Taking ~6 hours per week for sensitivity or other improvements
Hanford Noise Budget

Displacement Sensitivity [m/rtHz]

Frequency [Hz]

Measured DARM

Sum of known noises

Angular and length control noises
Low Frequency is Difficult

Empirically, it's easier to match noise budget expectations at high frequencies.

Control noise from loops matters at low frequency, less so at high frequencies.

Scattered light is tricky, and matters at low frequency.

Many noise sources are known, but others are still considered 'mystery noise'.

Every measurement takes time, which is in conflict with wanting to have high duty cycle observation time.
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We should still strive for low frequency detectors, but recognize that they will always be extremely challenging
High Power is Difficult

Non-uniform absorption matter more with more circulating power

Steer away from point absorbers

Other non-uniform absorption harder to avoid

Significantly affecting the recycling gains of RF sidebands, as well as carrier

Makes control more difficult

Thermalization takes time, and thermal tuning takes lots of time

Excited for future improvements in thermal compensation

Damping parametric instabilities has been very helpful
Facilities and Time

Balancing time of upgrades (and maintenance) against observing

Reducing pump down (and cool down) time will be very useful

Hosting many interferometers in a single facility will be challenging

Difficult to perform hardware upgrades on one interferometer while operating another

Many measurements take a long time

Low frequency measurements with high precision

Thermal state changes require thermalization

Must balance observation time against potential sensitivity improvements
Absorbers on Optics

Wavefront distortion of beam on mirrors

![Wavefront distortion diagram with absorber](image)

5 of 8 test masses replaced in LIGO

Still have non-uniform absorption

Limits recycling gain of carrier, sidebands

Circulating power

Control error signals

Coupling in laser jitter noise
Scattered Light

Hard to identify, and model

Nonlinear coupling to gravitational wave readout

LIGO end mirrors replaced to reduce light scattered from cavity

One of the biggest things we can do for future detectors: Install low frequency shakers on vacuum enclosure to help identify coupling sites for baffling
Scattered Light

Many baffles added before O3
Scattering seems better, but it's certainly not gone
Avoid reflective surfaces everywhere practicable

Camera looking at optics
Opto-Mechanical Instabilities

Acoustic modes of mirrors overlap with optical modes of cavity

Passively damp modes

Reaction plate moves, causes PZT to create voltage

Electrical energy converted by the plate is dissipated through a resistor

Negligible thermal noise increase

Successful; must be installed in any future high power detectors

Driggers, LIGO-G1900963

GWADW, 23 May 2019
Lowering Q of Suspension Modes

Bounce-Roll dampers installed for quad suspensions
Bounce-Roll dampers designed for other LIGO suspensions
Violin mode dampers under development

On the one hand, there are thermal noise consequences
On the other hand, with the modes causing high lines, we are already losing sensitivity due to upconversion
If the modes get rung up very high, we lose livetime to damping
Residual Gas Noise

Small gap between end mirrors and actuation reaction masses

Molecules bounce between mirror and reaction mass

LIGO has removed the material from the center of the reaction masses

Upgrades and maintenance on vacuum system to be at lower pressure

Overall reduction in damping forces by factor of 2.5
Charge and Electric Fields

Prevent ion vacuum pumps from directly "seeing" the optics at LIGO
Avoid optics hitting safety stops during earthquakes
Electric field meter for monitoring fields

Discharge optics via gentle flow of ions (positive and negative)
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This effect, as well as gas damping, argue strongly in favor of a photon actuator for the final mirror stages
Need to be mindful of electrical connections when constructing facility

Avoid ground loops, both in vacuum, at electronics racks, and at vacuum flanges

Plan for many, many magnetometers at electronics racks for identification of lines in DARM

Looking for cyclic currents that are coupling to DARM

Otherwise, monitor current in every wire - infeasible

Example: LEDs on electronics boxes flashed at the same time, created comb in DARM

Install large wall-mounted magnetic injection coils for feedforward cancellation, including Schumann resonances
Reducing motion of platforms is very important; but also ensure that every table has witness sensors.

See S. Cooper's talk Wed for exciting new sensor candidates.

See S. Biscan's talk Wed for seismic platform noise budgets.

Shorter term, consider replacing all coarse CPS (capacitive position sensors) with fine CPS on LIGO seismic platforms.
Concluding Thoughts

There have been many lessons learned - we need to compile them and incorporate them into the design of future facilities and interferometers

Some of my favorites:

Reducing the RMS motion of the optics will help address many issues

Avoid reflective surfaces everywhere practicable

Must be able to tune the thermal state of all mirrors in a non-axisymmetric way
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There have been many lessons learned - we need to compile them and incorporate them into the design of future facilities and interferometers.

Some of my favorites:

- Reducing the RMS motion of the optics will help address many issues.
- Avoid reflective surfaces everywhere practicable.
- Must be able to tune the thermal state of all mirrors in a non-axisymmetric way.

There will always be things that we cannot anticipate.

- Best thing we can do for these is to provide many witness sensors, and many diagnostic tools.