LIGO Laboratory / LIGO Scientific Collaboration

Advanced LIGO Operations Commissioning Plan

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1   Overview

This document contains the plan for commissioning the Advanced LIGO interferometers. It is based on Section 3.1 (*Advanced LIGO Commissioning and Sensitivity Optimization*) of the LIGO FY2014-2018 Operations Proposal, LIGO-M1200328.

2   Commissioning & sensitivity optimization scope

The end of the Advanced LIGO Project installation and integration phase is marked when each interferometer functions to the point where it *locks* (acquires and maintains interferometric resonance under automated control) for an extended time. Locking is of course a symbolic milestone, representing physical completion of the formal Project construction and installation scope. More importantly, locking is a functional prerequisite for noise characterization, diagnostics and plant tuning.

This milestone thus forms the gateway to all subsequent phases of what we call *commissioning*: the process of bringing each interferometer to its design sensitivity. Here we will describe the commissioning plan aimed at: a) bringing Advanced LIGO instruments from rudimentary function to sensitive detectors of gravitational wave strain, and b) improving the strain sensitivity whenever and however new technology and ideas permit.

Commissioning activities are carried out by the Commissioning Team, which establishes and commissions specific detector configuration, with the goal of improving performance of the instruments. This is distinct in function from the Detector Group, which focuses on maintaining and operating controlled detector configuration, with the goal of achieving high quality uptime.[1]

2.1.1   Planned Advanced LIGO Configuration Evolution

Among the lessons of iLIGO and eLIGO, one in particular stands out: achieving stable operation at full laser input power will likely take significant commissioning time. This will be managed in stages, by establishing intermediate levels of laser power as operating targets, as we learn to deal with thermal effects, opto-mechanical instabilities and other power handling issues. The eventual design maximum 125 W of input can be designated as the *high power* state; we designate 25 W of input (equivalent to the highest power used in eLIGO) as the initial *low power* state.

The aLIGO recycling cavities have been designed so that in the low power state, comparatively little or perhaps no compensation of thermal lensing in the input test masses is required to maintain good eigenmode matching between the recycling and arm cavities. Furthermore, this low power state imposes less stringent requirements on thermal compensation of higher order deformations.

Another somewhat flexible parameter is the transmission of the signal recycling mirror (SRM). The nominal design calls for a transmission of 20%, which in the high power state gives good sensitivity over a wide frequency band. At lower power, however, a larger SRM transmission can provide a deeper noise minimum, and thereby a larger detection range for binary inspiral signals, as illustrated by *Figure 1*. Importantly, this low-power optimization achieves a detection range deemed likely to yield events, given source population estimates. Even early runs at low power therefore have a strong chance at discovery. Directed by these results, we begin commissioning

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[1] See also LIGO-M1300188.

with a SRM transmission of 35%, using smaller 'surrogate' mirrors that are mounted in the SRM suspension using a composite mass.
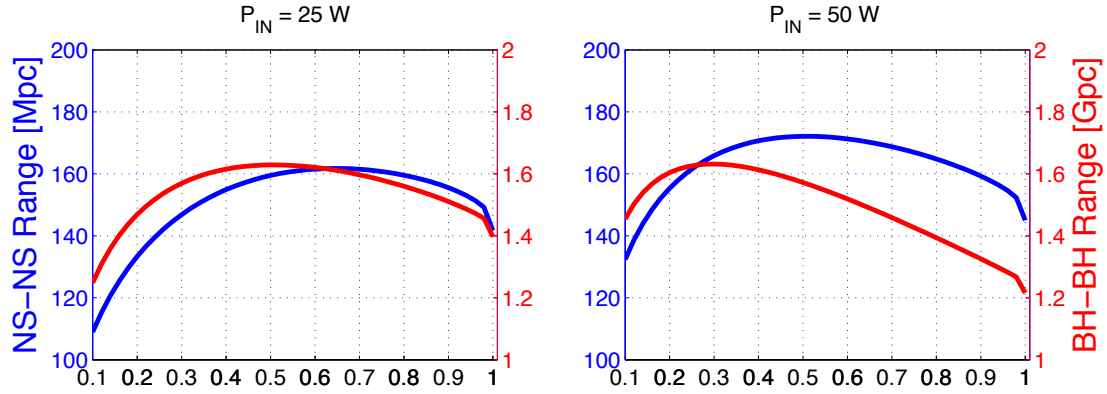

Figure 1: Binary neutron star (NS-NS, blue) and binary black hole (BH-BH, red) inspiral detection range as a function of SRM transmission, for two input laser power levels.

The strain noise spectrum achievable in this configuration is shown in **Figure 2**. Achieving the design sensitivity at low frequency is also expected to take significant commissioning effort, as there are many technical noise sources at low frequencies that must all be brought under control. Therefore, a realistic scenario for early operations is one where the low frequency noise is higher than the design curves; such an example is also shown in **Figure 2**, where excess $1/f^2$ noise that approximately doubles the budgeted strain noise at low frequencies has been artificially added.
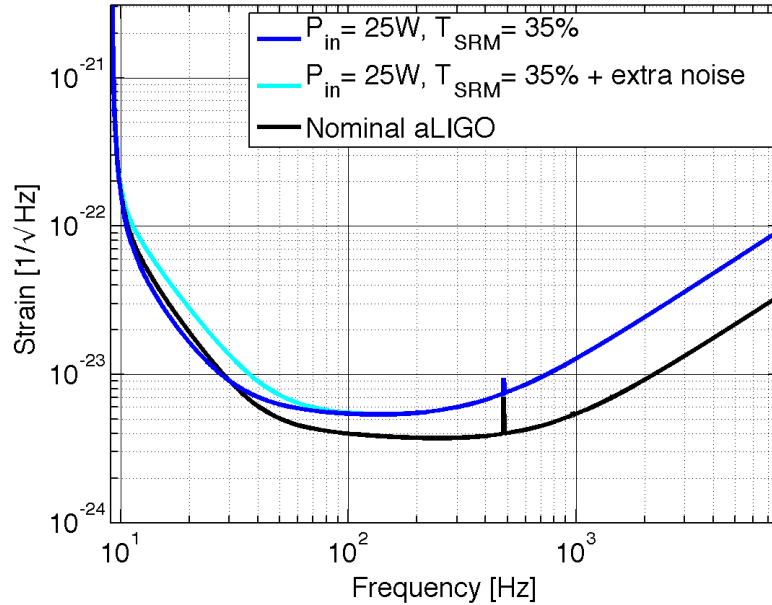
Figure 2: Strain noise spectral density models for three Advanced LIGO configurations. The black curve shows the nominal Advanced LIGO strain noise (SRM transmission of 20%), as limited by fundamental noise sources, at the full input laser power of 125 W. The blue and cyan curves correspond to an early configuration, where the laser power is 25 W and the SRM transmission is 35%: the blue curve contains fundamental noise sources only, while the cyan curve simulates the effects of added technical noise at low frequencies. The NS-NS inspiral detection ranges for these three configurations are 190 Mpc (black), 160 Mpc (blue), and 125 Mpc (cyan).

2.1.2 Low frequency technical noise

Another very challenging aspect of commissioning is controlling technical noises sources at the low frequency end of the band. A typical noise mechanism involves some relatively noisy channel or degree-of-freedom coupling into the gravitational wave readout channel; the coupling can normally be reduced with some form of digital filtering, though often with a trade-off in control band performance. The alignment controls are a prime example of this, where the design will involve a trade-off between feedback suppression of alignment fluctuations and low-pass filtering of the noisy alignment sensing channels.

Eventually all technical noise sources are to be reduced so that each one is no larger than 1/10th the interferometer strain noise target at all frequencies in the 10-10,000 Hz band. Since the low frequency end is expected to be more difficult to achieve, we set a higher target for the low frequency cutoff for early operations, guided by our strain sensitivity goals. Figure 3 shows the binary neutron star inspiral detection range as a function of the lower cutoff frequency, for the early interferometer parameters of 25 W input power, SRM transmission of 35%.
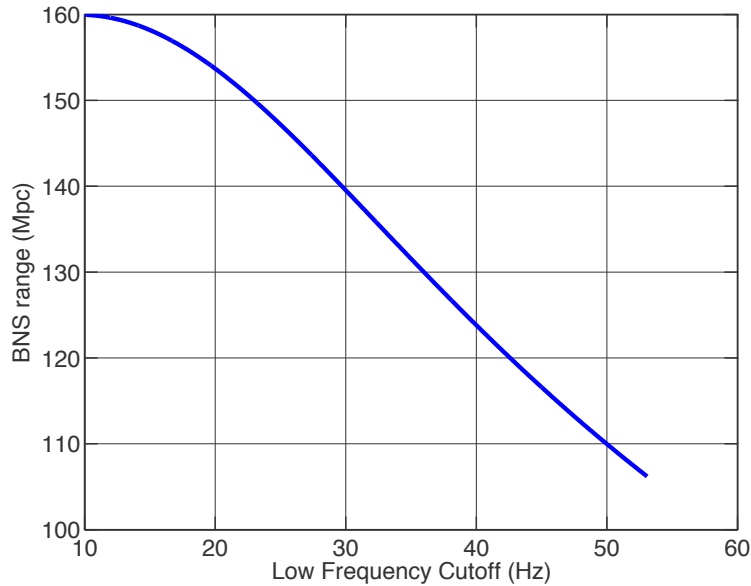
Figure 3. *Detection range for binary neutron star inspirals, as a function of the low frequency cutoff of the strain noise spectrum used in the integration. The strain noise spectrum used is the blue curve of Figure 2, with 25 W input power and SRM transmission of 35%.*

Based on Figure 3, we establish **20 Hz** as the initial low frequency target for technical noise sources (i.e., technical noises should be at least 10x below the strain noise at 20 Hz and above). This represents a 5% reduction in inspiral range from nominal.

Some of the noise sources that this relaxed target will affect are: suspension local damping sensor noise; alignment sensor noise; laser intensity noise; auxiliary length noise; test mass coil driver noise.

2.1.3 Sensitivity and robustness improvement

The core of commissioning is the work of improving the interferometer strain sensitivity—lowering the noise to the design level—and producing robust instruments that lock reliably and for extended duration. While there will be unanticipated noise sources and other challenges, many commissioning tasks are definable in advance and are discussed in the following.

2.1.3.1 Low-noise sensors for global control

Initial lock of the interferometer is achieved using error signals that are more robust, but of lower signal-to-noise ratio, than the error signals that are eventually used for low-noise operation. Once sufficiently tight control of the interferometer is achieved, the control authority can be handed off to low-noise error sensors. The different error signals are derived from different photodetectors: all low-noise signals come from detectors located in vacuum chambers, mounted on isolated platforms; error signals for locking typically come from in-air detectors operating at lower light power.

Length control detectors. Custom broadband detectors provide acquisition error signals for the corner-station degrees-of-freedom, using detection at triple the main modulation frequencies. These error signals are then transitioned to those derived from detectors that are tuned to the main modulations frequencies, providing significantly lower noise, though still operating in-air. Finally the transition is made to in-vacuum tuned detectors, operating at higher laser power for better signal-to-noise. The in-air tuned detectors used in the middle step allow greater flexibility than their in-vacuum counterparts for optimizing the detector parameters. Eventually, this middle step may be eliminated, and the transition made directly from the acquisition detectors to the in-vacuum low-noise detectors.

Alignment control detectors. As with the length detectors, the RF alignment detectors (or wavefront sensors) come in 'air' and 'vacuum' versions. Both versions are tuned to specific RF detection frequencies. The in-air versions are used initially, again because of their greater flexibility in tuning and optimizing detector parameters (including Gouy phases, in this case). Iterating on the alignment sensor parameters can be a complex task due to the large number of mixed degrees-of-freedom. Once such sensor parameters are defined, control can be switched over to the in-vacuum wavefront sensors.

2.1.3.2 Global length controls optimization

The process of optimizing the global length controls of the interferometer involves the following work on the various loops:

- *Differential arm length control.* Typically this loop is designed to have as wide a bandwidth as possible, limited by the digital I/O and delays in the system. Specific digital filters are implemented to both notch out resonant features above the unity gain frequency (suspension fiber modes, e.g.), and to provide more gain for spectral features within the control band.
- *Common mode & frequency control.* This analog loop is also designed to have as wide a bandwidth as possible, limited by the Input Mode Cleaner servo through which it acts. In-band, analog 'boost' filters may be designed to provide more gain at lower frequencies. The very low frequencies are handled digitally, and may control the common arm lengths or laser frequency, or both.
- *Auxiliary degrees-of-freedom (power- and signal-recycling cavities; Michelson).* The bandwidth of these feedback loops involves a trade-off: more gain/bandwidth provides more suppression of fluctuations and thereby reduces non-linear effects, but at the expense of injecting more sensor noise into the channels at higher frequencies. Since these degrees-of-freedom are all coupled to the gravitational wave (GW) readout to some degree, this sensor noise injection can ultimately degrade the GW sensitivity. This effect can be mitigated by digitally subtracting out the auxiliary channel noise from the GW readout channel— cancellation factors of one-to-several hundred can typically be achieved. Thus the design of these auxiliary feedback controls involves a combination of filters for suppressing displacement noise, filters for attenuating sensor noise, and correction filters for noise subtraction.

2.1.3.3 Alignment sensing and control

Commissioning the alignment controls is typically more challenging than the length controls because there are more degrees-of-freedom and they are more coupled on any given sensor. In

addition, radiation pressure can have a significant effect on the response to control torques. To deal with the complexity, we plan a two-step scheme for developing the alignment controls:

- *Acquisition mode,* in which the arm cavity alignment is controlled with high bandwidth loops ($\approx$ 1Hz) and high low-frequency gain, with a slow drift control ($\approx$ 100mHz) used for the vertex optics' alignment. This gain hierarchy produces an approximately diagonal sensing matrix, with the drawback of poor performance, due to the low-gain loops and the fact that the reconstruction of the alignment is not accurate. However this mode should be relatively simple to achieve, and allows accurate measurements of the sensing matrices to be made.
- *Science mode,* where the main non-diagonal sensing terms are included in the signal reconstruction, based on the measurements made in acquisition mode. The gain of the loops is increased to provide the final required alignment stability.

2.1.3.4 Seismic isolation controls optimization

The active seismic isolation controls allow a fair amount of flexibility in terms of trading off isolation performance at different frequencies, and trading off between isolation and robustness. Optimizing the performance of the isolation system will therefore be done in the context of the full interferometer operation, where the impact of the different performance trade-offs can be assessed. In particular, the following aspects will be studied:

- For each type of seismic isolation system (HEPI, HAM-ISI, BSC-ISI), we will produce noise budgets. They will be used for comparison and analysis of each individual module and to optimize the controls trade off at each stage of isolation.
- The impact of motion amplification at the control-band edges on interferometer performance will be studied and minimized through a combination of controls adjustments and compensation techniques (e.g., Wiener filtering between stages).
- Control configurations specific to several stages of operations will be defined, tested and optimized (e.g., General Commissioning Mode; Lock Acquisition Mode; Observation Mode).
- Backup-up control schemes that can be deployed in case of instrument failure will be designed, prepared and tested.
- Control configurations designed to improve the interferometer duty cycle will be studied and implemented (e.g., adaptive control that accounts for high input disturbance to maintain the interferometer lock).

2.1.3.5 Noise budget development

In initial LIGO, one of the key tools developed for commissioning was an on-line 'noise budget': a program that collects interferometer data, and calculates a calibrated power spectrum of the equivalent strain noise, and also a dozen or so known contributors to the strain noise (such as shot noise, or seismic noise). Some of the noise contributor estimates are derived from concurrent interferometer data (such as noise coupling from an auxiliary degree-of-freedom), and some are based on modeled sources (such as coating thermal noise). This noise budget will need to be developed iteratively for Advanced LIGO, where there are many more channels that can contribute to the interferometer noise.

The scope of the noise budget will also be expanded for Advance LIGO, beyond providing the on-line noise budget for the interferometer strain. It will be developed to create noise budgets for other elements and degrees-of-freedom of the interferometer (e.g., a noise budget for a given seismic isolation platform), and also a 'design-based' strain noise budget that can be used to compare the expected and actual noise performance.

2.1.3.6 Noise coupling investigations

Much of the work of hunting down and mitigating excess noise sources is done using noise coupling tests. This general technique involves artificially increasing the signal level in a "source" channel of interest and measuring the effect in a "receiving" channel, for example, the gravitational wave strain readout. The technique can be used to look for both coherent couplings (transfer functions) and incoherent or non-linear couplings. The coupling channels can be either internal degrees-of-freedom of the interferometer (laser frequency noise, e.g.), or external environmental inputs (acoustic noise, e.g.). Effective methods of applying this technique are well established from initial LIGO.

2.1.3.7 Glitch investigations

While the performance of an interferometer is usually characterized by its strain noise power spectrum, real detector noise naturally exhibits deviations from stationary, Gaussian noise—i.e., it contains glitches. Detector glitches can degrade the sensitivity of searches for transient GW sources, and therefore specific efforts to identify and eliminate sources of instrumental glitches must be a significant part of the commissioning plan.

Glitch investigations will be carried out in conjunction with the LSC Detector Characterization (DetChar) working group. While the primary goals of DetChar Glitch Group are the identification and characterization of transient instrumental artifacts, the LIGO Laboratory has the expertise and responsibility to act on this information and eliminate or reduce glitches at the source.

2.1.3.8 Duty cycle and lock duration

The operational goal for each interferometer is to achieve 90% duty cycle (percentage in science data-taking mode) with typical lock durations of tens of hours. Achieving these targets will take a dedicated effort of examining losses-of-lock over extended run times (engineering or science runs), and establishing causes and mitigations. Specific experiences with initial LIGO may not carry over to Advanced LIGO; lock losses in iLIGO often resulted from transient ground motion, due to iLIGO's poor seismic isolation below ~10 Hz. In aLIGO such events will be greatly suppressed by the active isolation system, and should not cause lock loss; longer term drifts may more relevant for maintaining lock in aLIGO.

Duty cycle can also be increased by improving the efficiency of lock acquisition and by accelerating the transition to a low-noise, data-collection state. This can be done by optimizing the acquisition algorithms and sequences and determining the best ways to anticipate and manage thermal time constants.

2.1.3.9 Regression & On-line adaptive filtering

Another approach to improving interferometer sensitivity that has been pioneered in the past few years is 'active noise cancellation', where noise sources that are measured by some sensor(s) can be subtracted from the strain readout channel, either offline from the recorded data stream or online via appropriate hardware channels. Such a technique may be applied to the reduction of fluctuating Newtonian gravitational forces, which are expected to limit Advanced LIGO sensitivity around 10 Hz. The technique could also be used to remove other environmental influences, such as acoustic or magnetic disturbances.

2.1.4   Laser power and thermal compensation

The increase in operating laser power presents its own set of challenges. Power increase will be a gradual process, with at least two intermediate levels of operation with some degree of optimization required before reaching full laser power. In particular, we are targeting 25 W as the power level for our first extended operations; this is approximately the maximum power level at which Enhanced LIGO was run.

2.1.4.1 Photodetector power handling

Global error signals are derived by detecting the beams at the five interferometer output ports. For all ports other than the anti-symmetric port, there is more light power available than needed for detection. However, to maximize the signal-to-noise ratio of these detectors, we want to detect as much light as possible. The limit to the detector power is typically not photodiode damage, but rather non-linear effects that depend in detail on the signal spectrum. Determination of the optimal detection power thus must be done in operation on the interferometer.

2.1.4.2 Absorption characterization

It will be important to measure the amount of absorption in each test mass and understand how spatially uniform it is. The total absorbed power can be inferred by measuring the frequency shift of test mass vibrational eigenmodes as they heat up. This technique was used fairly successfully in initial LIGO, but it needs further work to bring it to the level where it can be a reliable and more continuous monitor.

2.1.4.3 Hartmann wavefront sensing

The Hartmann wavefront sensor system is a new diagnostic for Advanced LIGO. It uses separate wavelength, low-power beams to probe the optical path distortions in the two arms of the Michelson, spatially resolving these distortions with Hartmann sensors. Similar probe beam-sensor pairs are implemented for the end test masses as well (probing from the back of each test mass). Since this type of system has not been used on a full-scale interferometer before, we expect that a significant task will be characterizing and understanding the data from these sensors, and figuring out how best to use the sensor information (see next paragraph).

2.1.4.4 Compensation optimization

Optimizing the thermal compensation is the most challenging task involved with increasing the laser power. The compensation is applied using two types of actuators: the ring heaters surrounding each test mass; and the CO_2 laser projector beams directed onto the compensation plates. The first line of compensation is provided by the ring heaters, which provide about a factor of 10 correction

of the thermal distortion. Greater levels of correction are attained by adding the CO_2 laser beams; these projector beams have an additional degree of freedom, which is their specific spatial profile. In principle it is possible to achieve large distortion correction factors with the right CO_2 projector beam profile. In practice, we will have to learn the best combination of ring heater power and projector beam power and shape. This will be guided by the Hartmann sensor information, as well as interferometer figures of merit such as contrast defect and optical gain. The spatial interferometer model mentioned in Section 2.1.2 (SIS) will also be a critical part of understanding the interferometer thermal behavior.

2.1.5 Supervisory control & automation

Progress on interferometer operations—such as implementing a new sequence of steps for increasing the laser power—is typically initially made by 'expert commissioners'. The new operations must then be incorporated into the Guardian-based automation system[2]. This process involves writing and debugging Guardian code, and defining nominal values and tolerances for channels. This will be a collaborative effort between the Commissioning Team and the LIGO Automation Scientist.

2.1.6 Calibration

Calibrating the gravitational wave (GW) readout channel in terms of GW strain is a significant task, with much of the effort going into verification and the determination of calibration uncertainties. This is the responsibility of the Calibration Team, distinct from the Commissioning Team, though it will involve significant input from and interaction with the latter.

2.1.7 Modeling and simulation

In parallel with the hands-on commissioning work, an active modeling and simulation effort is required to help interpret results of tests and measurements on the interferometer, and to provide guidance for the path forward. Modeling and simulation work is more distributed than hands-on commissioning, with contributions coming from non-observatory LIGO Lab people and several LSC institutions as well as the observatory commissioners. Several simulation codes will support commissioning:

E2E: End to End simulation

E2E is a time domain program that simulates opto-mechanical systems. The optical field representations are eigenmode-based, so some spatial variations (such as misalignments) can be simulated via modal expansion. E2E is used primarily for simulating the lock acquisition process.

SIS: Stationary Interferometer Simulation

SIS is an optical system simulation package that calculates static electric field spatial distributions, as well as the frequency response of those fields to test mass motions. The package provides many tools to help analyses, like modal expansion of the spatial fields, automatic inclusion of thermal

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[2] [LIGO-G1400016](#), *Advanced LIGO Guardian Overview*

deformations, and alignment control. SIS is used to simulate the effect of imperfect optics on the resonant fields in the interferometer and optical performance metrics such as recycling gain or contrast defect.

Optickle & Lentickle

Optickle is a Matlab package for doing time-dependent optical and mechanical interferometer simulation in the frequency domain. It includes quantum noise and radiation pressure, as well as mechanical transfer functions for suspensions. Lentickle adds feedback control loops to Optickle models. These have become the standard modeling tools for designing the length control and alignment control servos for Advanced LIGO.

MIST: Modal Interferometer Simulation Tool

MIST is Matlab package for optical system simulation in the paraxial approximation. It computes static fields in terms of Hermit-Gauss modes, using an algorithm that is particularly efficient when using a large number of higher order modes. This tool can be used when the full flexibility of the SIS is not required.

Finesse

Finesse is another frequency-domain simulation package that can also include higher-order (Hermite-Gauss) spatial modes. It has been used to simulate the IMC alignment controls and the power budget in the L1 power-recycled Michelson.

These codes will be exercised and augmented during commissioning for comparing test results with simulations, for exploring the effects of parameter variations, and for guidance in choosing courses of action.

2.1.8 Component and subsystem upgrades

Initial LIGO required that several components be redesigned or added after acceptance in order to achieve design sensitivity. Similar retrofits may be needed for Advanced LIGO as well. The Systems Engineering group has the responsibility for evaluating and approving any proposed retrofits or new components, with the Commissioning Team providing the key input on needs and priorities. The Engineering Change Request process defined in LIGO-M1200274 will be followed for such changes.

A list of potential upgrades can be found in LIGO-T1300176. This document will be updated as commissioning progresses so that it contains all the latest ideas.

2.1.9 Squeezed light injection

The addition of squeezed light injection to Advanced LIGO is a more significant upgrade (T1300176 covers upgrades of more minor scope). Our strategy is to prepare for the option of implementing squeezed light injection at the end of the projected second ('mid') science run in 2017. From the commissioning perspective, implementing squeezing could be seen as an

alternative to increasing the laser power by the final factor of 2-3 (to reach full power). The motivation and plans for squeezed light injection are more fully described in LIGO-T1400366, *Motivations and Outlook for Squeezing in Advanced LIGO*.

2.1.10 Commissioning staff

Commissioning teams typically comprise a mixture of local site-based personnel along with students, postdoctoral scholars, and scientists drawn from the MIT and Caltech campus groups. Each observatory has a Commissioning Leader for that site.

The Laboratory's investment of resources in commissioning and sensitivity optimization will vary with the phase of scientific observation, and with the degree and nature of problems encountered (and good ideas conceived). The baseline program discussed above, taken with planned allocation of science running time over the proposed period of performance, requires the Commissioning staff levels shown in Figure 4. Expected Commissioning staff declines from a peak of 26 FTE's in FY2015 to 19 FTE's in FY2018. This happens naturally as, with improving sensitivity, a greater fraction of interferometer time is invested in observing. In this scenario, liberated Commissioning staff are redeployed to Operations and Detector Improvement research activities.
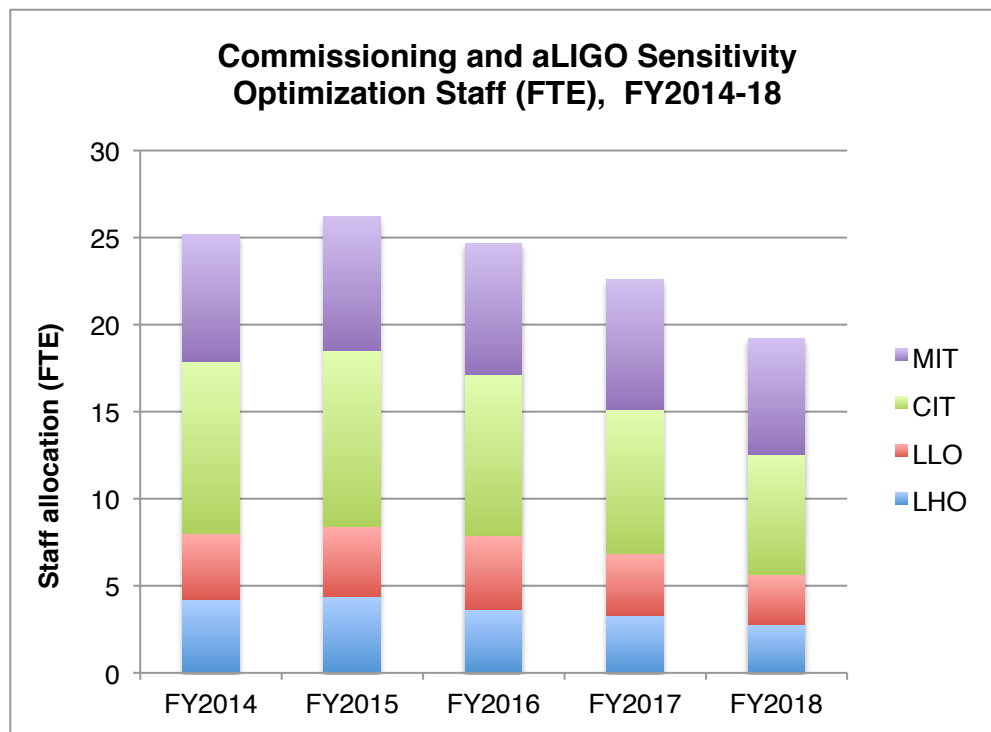

Figure 4: *Expected scientific staff, faculty, postdoctoral scholar and graduate student allocations from each Laboratory site to Advanced LIGO Commissioning and Sensitivity Optimization. Matrixed engineering, computing, and research facility operations efforts supporting this are not included in these numbers.*