

Advanced LIGO Optical Configuration and Prototyping Effort

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Abstract. The current plan for the Advanced LIGO dual-recycled optical configuration and control scheme is described, with emphasis on those elements which differ from Initial LIGO. Plans for prototyping this system are discussed, and the prototyping effort at the LIGO Caltech 40 Meter Interferometer Laboratory is described in some detail. Finally, some of the modeling efforts at Caltech are reviewed.

Introduction

From the beginning of the LIGO project, it has been planned that the initial LIGO interferometers would undergo upgrades to significantly improve their sensitivity to gravitational waves (GWs) and increase the sensitive bandwidth, some years after first turn-on. As the LIGO Laboratory and LIGO Scientific Collaboration (LSC) are commissioning Initial LIGO and preparing for scientific searches, they are concurrently pursuing intensive R&D in order to realize those upgrades by the end of the Initial LIGO science run. Now referred to as Advanced LIGO¹ (formerly LIGO II), these upgrades include (with “f” referring to the frequency band of LIGO sensitivity):

- Active seismic isolation systems to reduce low-f seismic / environmental noise;
- Multiple-pendulum suspensions and fused silica ribbons to reduce low-f, mid-f suspension noise;
- High-Q sapphire mirror material to reduce mid-f thermal noise;
- High mass (~40 kg) test-mass mirrors to reduce radiation pressure noise;
- High-power (~200 W) stabilized IR laser to reduce high-f shot noise;
- Dual-recycled optical configuration and readout scheme, to tune shot-noise response vs. frequency; and potentially beat the standard quantum limit (SQL).

Many of these R&D efforts are being discussed at this conference. This contribution focuses on the Advanced LIGO dual-recycled optical configuration and control scheme (shown schematically in Figure 1), and in particular, on the efforts to prototype and model this system at the LIGO Caltech 40 Meter interferometer laboratory (“40m”)².

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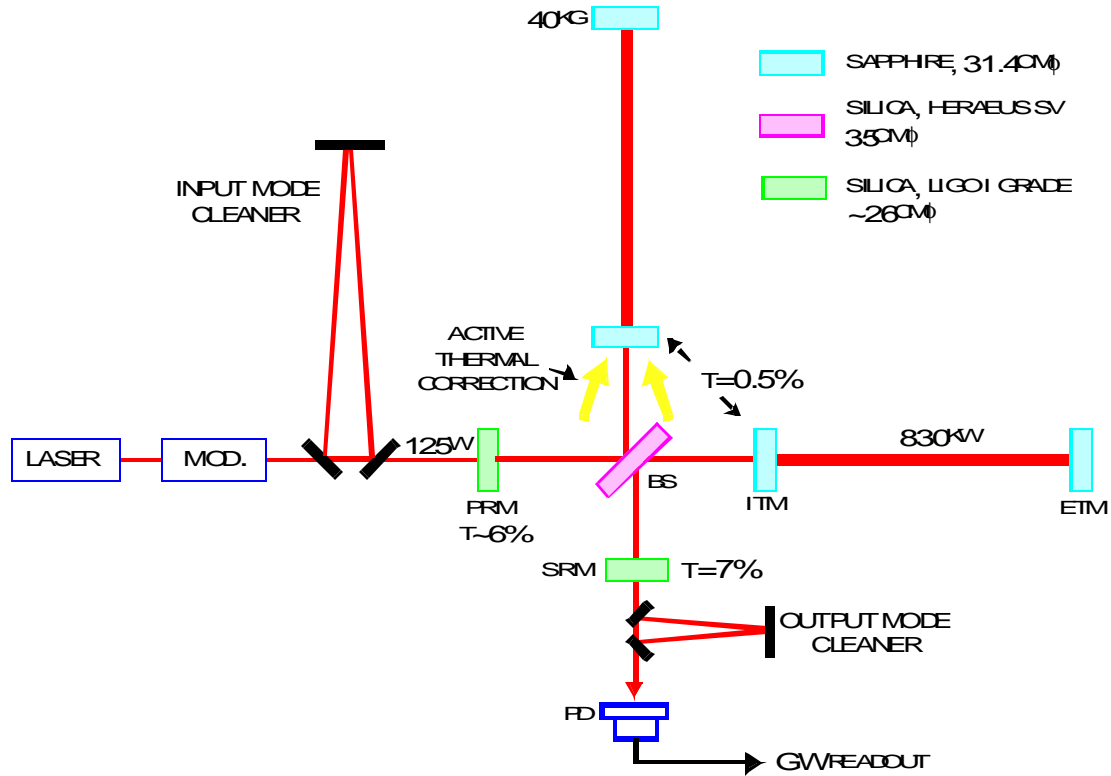


Figure 1: The Advanced LIGO optical configuration. The arm input and end test masses are made of sapphire, the beam splitter is made of Heraeus SV silica, and the two recycling mirrors are made of LIGO-I grade silica.

Advanced LIGO Dual-recycled optical configuration

Initial LIGO's core optical configuration is a power-recycled³ Michelson interferometer with Fabry-Perot arms. There are six suspended optics, and four lengths to be sensed and controlled. To this, Advanced LIGO adds a seventh suspended optic at the asymmetric port of the beam splitter, referred to here as the signal recycling mirror (SRM). This mirror, in combination with the rest of the interferometer, forms the signal recycling⁴ cavity (SRC). There is thus both power- and signal- recycling, and the resultant configuration is known as dual recycling⁴.

The functions of the SRM are to optimize the shot-noise limited response of the interferometer to gravitational waves, in the presence of other noise sources, and to permit the re-distribution of stored laser power to minimize undesired thermal effects. The various noise sources that are expected to contribute to the overall strain sensitivity for Advanced LIGO are shown in Figure 2.

The SRC serves to decouple the storage time of the carrier light in the long (4 km) arms from the storage time of the GW signal sidebands. Depending on the resonance conditions established in the SRC and the reflectivity of the SRM, the signal sidebands could be stored for longer times, thus narrowing the shot-noise limited bandwidth of the

detector (signal recycling); the signal can be resonantly extracted from the arms, thus broadening the bandwidth (resonant sideband extraction, RSE)⁵; or tuned to resonantly extract the signal at a chosen frequency over a relatively narrow bandwidth (tuned narrow-banding).

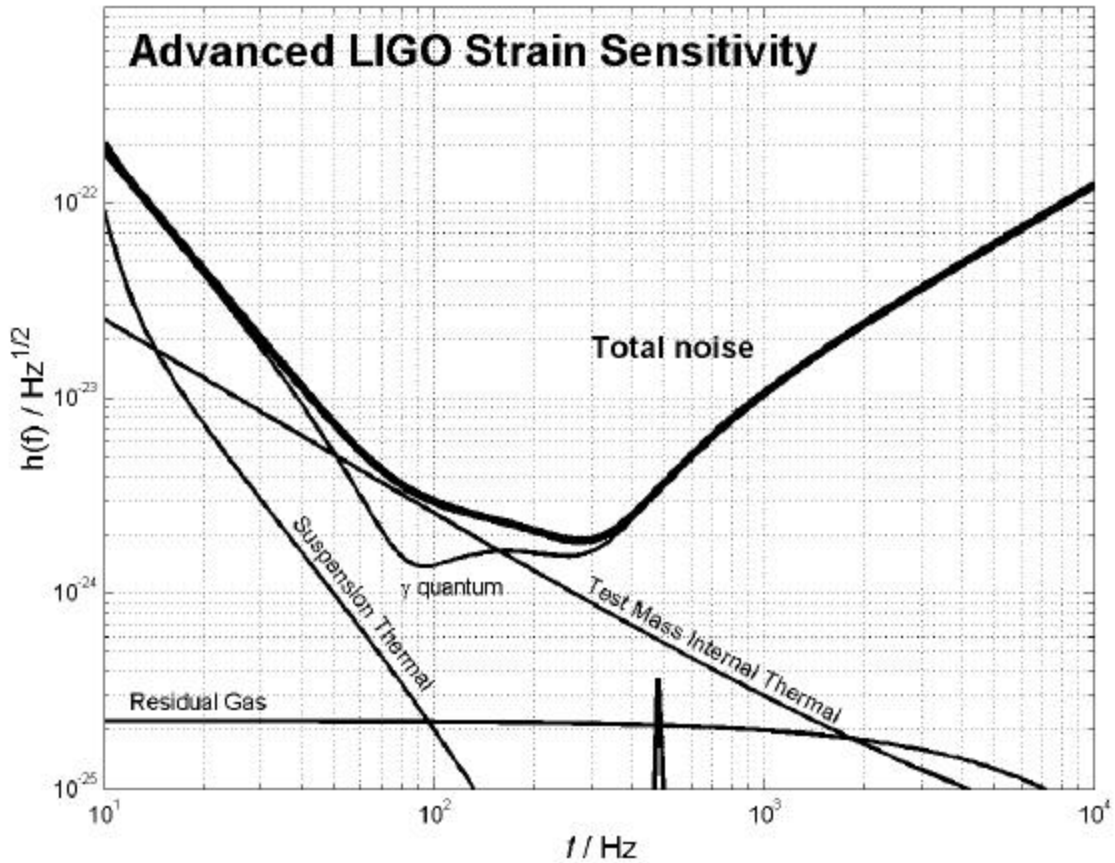


Figure 2: Predicted noise contributions to the strain sensitivity of Advanced LIGO.

Initial LIGO uses an arm input test mass (ITM) transmission of 3%. The Fabry-Perot arms thus have a finesse of approximately 205, a cavity pole frequency of 91 Hz, and a power gain of 131. This parameter yields a shot-noise-limited sensitivity that is optimized to provide the best signal-to-noise (S/N) for a compact binary inspiral, in the presence of expected noise levels from test mass motion due to seismic noise, internal thermal noise, and suspension noise. The plan for Advanced LIGO is to use an arm input test mass (ITM) transmission of 0.5%. This increases the arm power gain; the resulting increased loss of power in the arms means that the power recycling mirror (PRM) must have a larger transmissivity, and the power gain in the power recycling cavity (PRC) is correspondingly lower. This is desirable, because absorption in the transmissive optics of the PRC causes thermal lensing; minimizing the PRC power gain minimizes the thermal effects. In addition, the shot-noise-limited strain sensitivity is improved below the cavity pole frequency (where other noise sources dominate), but (in the power recycled

configuration) it is degraded at higher frequencies, where it is expected to dominate over other noise sources. This is *not* desirable.

The signal-recycling scheme allows one to increase the arm power gain and decrease the PRC gain, while independently manipulating the high-frequency shot-noise-limited strain sensitivity as desired. Advanced LIGO will operate in the RSE regime, resonantly extracting differential (gravitational wave, GW) signals from the arms. This can be used to restore the high-frequency shot-noise-limited strain sensitivity, compensating for the reduction in the bandwidth due to the higher finesse arms. The microscopic tune (the phase advance of the laser carrier light) of the SRC can be changed to further modify the shot-noise-limited strain sensitivity. One useful tuning of Advanced LIGO will be optimized to provide the best signal-to-noise (S/N) for a compact binary inspiral. These considerations are illustrated in Figure 3.

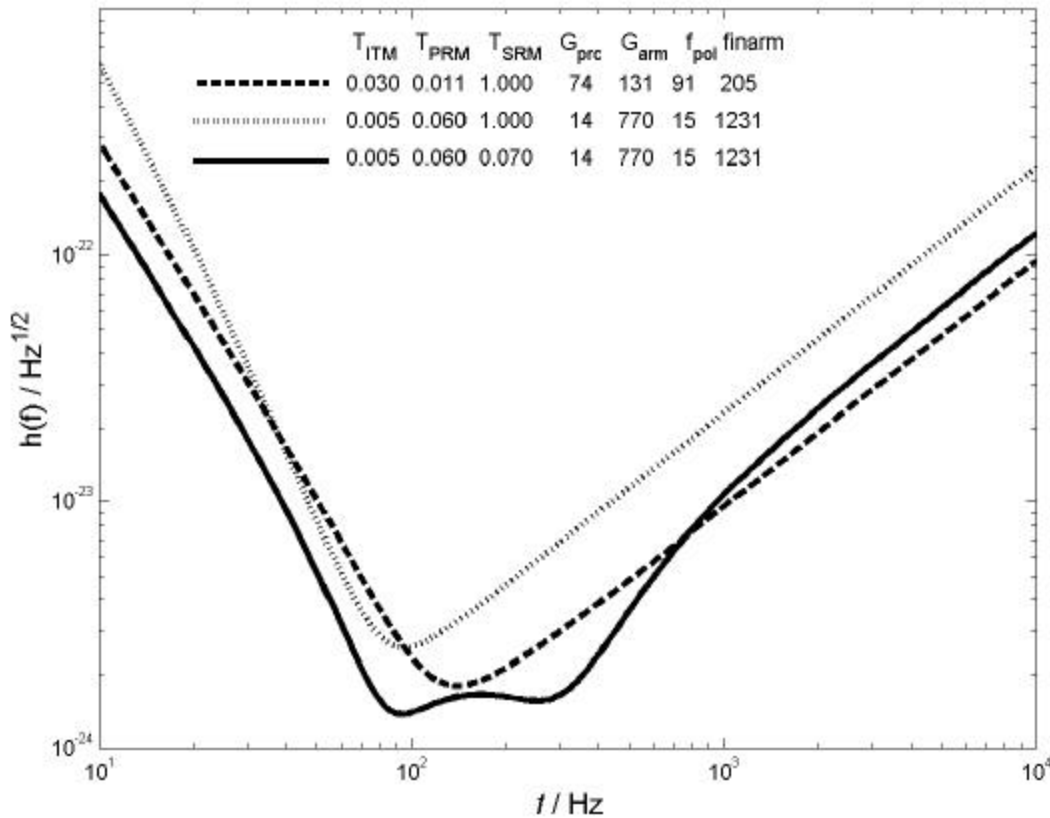


Figure 3: The predicted sensing noise (shot noise and radiation-pressure noise) for Advanced LIGO. The dashed curve (with the minimum between 100-200 Hz) would be the response with low-finesse arms as in Initial LIGO; the dotted curve (with the minimum around 80 Hz) is for higher-finesse arms as in Advanced LIGO, but no signal recycling. The solid curve (with two minima, at 80 and 300 Hz) is for higher-finesse arms and signal recycling (detuned). In the presence of other noise sources (dominating below 100 Hz), the solid curve provides the best sensitivity to compact binary inspirals.

The Advanced LIGO control scheme

The baseline scheme envisioned for sensing and controlling the suspended optics in Advanced LIGO draws upon the experience and best features of several “table-top” prototype interferometers. The challenge is to control seven suspended optics: two input test masses (ITMs); two end test masses (ETMs); the beam splitter (BS); the power recycling mirror (PRM); and the signal recycling mirror (SRM). These mirrors form four coupled optical cavities (the two arms, the PRC, and the SRC), with five length degrees of freedom to be controlled at the microscopic level (fraction of the Nd:YAG laser wavelength, $\lambda = 1064$ nm). The length degrees of freedom can be taken as L_{CM} (the common-mode or average arm length), L_{DM} (the differential mode or difference between the arm lengths, where the GW signal can be detected), L_{PRC} (the power recycling cavity length), L_{SRC} (the signal recycling cavity length), and L_M (the Michelson differential length, governing the darkness of the dark port). In addition, each mirror has angular degrees of freedom (pitch and yaw) which must be sensed and controlled (in practice, six of the seven suspended optic angular degrees of freedom are sensed and controlled; the seventh can be thought of as a fixed reference).

In Initial LIGO, all the length and angular degrees of freedom are sensed via variations on Pound-Drever⁶ or Schnupp⁷ sensing, in which RF sidebands are impressed upon the “carrier” laser light incident on the interferometer. These sidebands do not resonate in the arms. They thus can serve as reference oscillators, whose beats with the carrier light reflected from or transmitted through the interferometer permit the detection of tiny phase shifts due to mirror motions (heterodyne detection). The ~ 30 MHz RF sidebands are applied before the input mode cleaner (frontal modulation) using an electro-optic modulator. The resulting pair of sidebands is used in a balanced way; only differences in the two sidebands produce excess noise contributions. A “Schnupp” asymmetry is used to send the sidebands out the dark port, to act as a stable local oscillator for any carrier light exiting the dark port in response to a GW.

The need to control the SRC length is clearly one significant difference between Initial and Advanced LIGO. The SRC (nominally) does not see carrier light, so one cannot use carrier light to sense the position or angles of the SRM. The solution chosen for Advanced LIGO is to apply *two* pairs of RF sidebands; beats between these (and not the carrier) can be used to sense the SRC length. The sidebands are again applied via frontal modulation. They are chosen to be multiples of the free spectral range of the input mode cleaner, so that they can be transmitted through that optical cavity. One pair is made as small as possible (9 MHz) while the other is made as large as is practical (Advanced LIGO assumes that 180 MHz is a practical limit for the operation of electro-optic modulators and photodetectors, which must be able to handle high power with large aperture). Both pairs are resonant in the power-recycling cavity, and neither are resonant in the arm cavities. A small Schnupp asymmetry (± 20 cm) allows virtually all of the 180 MHz sidebands to exit the asymmetric port of the beam splitter, thus sensing the SRM position, while the 9 MHz sidebands are mainly reflected to the symmetric port, sensing the PRM position. Demodulation of the light exiting the interferometer, at 171 and 189 MHz, permits the sensing of the L_{PRC} , L_{SRC} , and L_M degrees of freedom, while being (to

lowest order) insensitive to the motion of the arm length degrees of freedom. In some cases, the signals obtained from demodulating at 171 and 189 MHz can be combined to enhance the discrimination between different degrees of freedom; this combining can be achieved using “double demodulation” at 9 and 180 MHz in series. This system, illustrated schematically in Figure 4, is in principle more robust and “diagonal” than the sensing scheme used in Initial LIGO.

The detuning of the SRC means that *if* carrier light were present in the SRC, it would not be resonant there. A GW impresses *signal* sidebands on the carrier light in the arms, at audio frequencies of hundreds or thousands of Hz. These signal sidebands exit through the asymmetric port of the beam splitter; they see the SRM, and the coupled cavity formed by the arm ITM and the SRC is detuned so that it resonates for these signal sidebands, but not for the carrier. This produces the dip at 300 Hz in the sensing-noise-limited strain sensitivity in Figure 3. The lower frequency dip is produced by a coupling between the photon pressure and the suspension gravitational restoring force, due to the recycling of the signal light by the SRM⁸. The position of the dips can be manipulated by changing the tune of the SRC, and their depths can be changed by changing the reflectivity of the SRM.

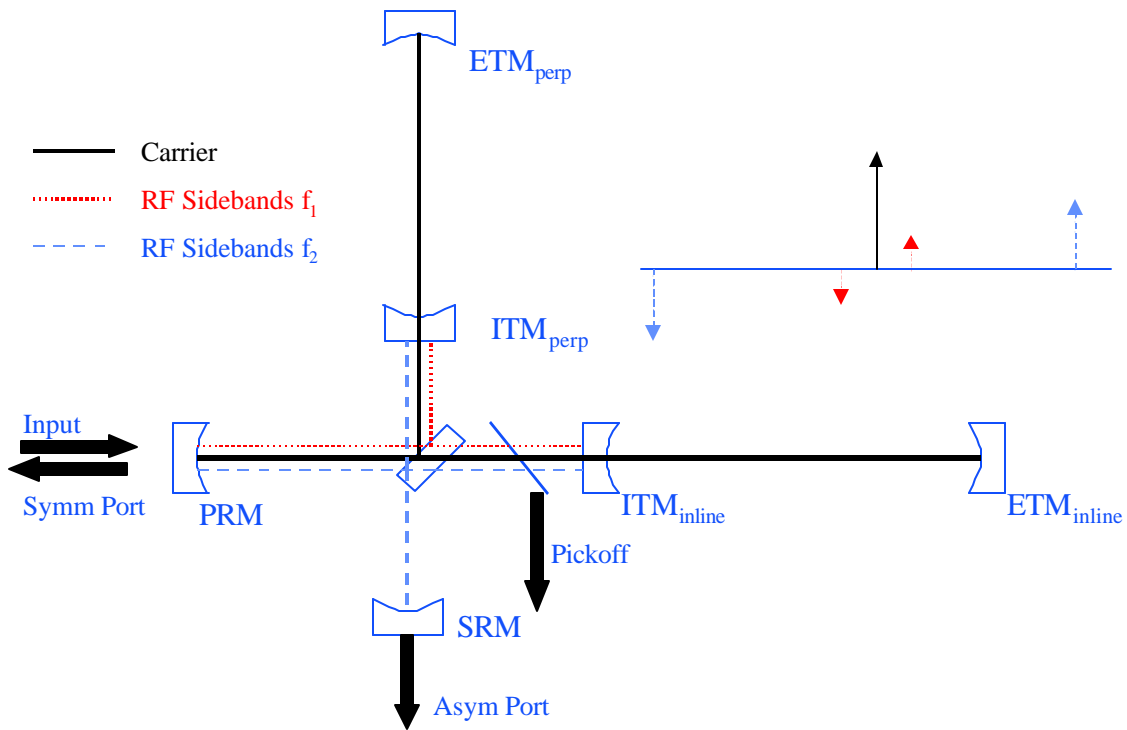


Figure 4: A schematic of the sensing light components resonant in the various optical cavities in Advanced LIGO.

In order for the 180 MHz sidebands to most effectively sense the SRC length, they must be resonant in that cavity; the length of the SRC is chosen appropriately. If, however, the SRC tune is changed (in order to change the frequency of the dip), the SRC length must be changed by a macroscopic amount (centimeters) in order to ensure that the 180 MHz sidebands remain resonant there. The resonance of the 180 MHz sidebands in the SRC enforce the microscopic detuning of the SRC for the carrier light (which, nominally, is not present in that cavity). The detuning also means that one of the pair of 180 MHz RF sidebands is actually resonant in the SRC, and also that only one of the pair of GW signal sidebands is resonantly extracted and sensed; the signal is reduced by a factor of $\sqrt{2}$ compared to the un-detuned RSE case, but this is compensated for by the greater improvement in sensitivity at 300 Hz due to the detuning.

Output mode cleaner and DC demodulation

An output mode cleaner serves to remove higher order spatial modes, which do not carry useful signal information but which do increase the shot noise at the asymmetric port (GW signal). This also includes carrier light leaking out due to imperfect Michelson contrast, and RF-modulated sideband light used for heterodyne GW detection (as described above). Given the much higher power levels in Advanced LIGO (see Figure 1), it is important to limit the power exiting at the asymmetric port to a level manageable by available photodiodes.

The output mode cleaner need not have the excellent noise performance required by the input mode cleaner; it may be a short, monolithic device, like the Initial LIGO pre-stabilized laser “pre-mode-cleaner”. In the current scheme, only carrier light and the GW signal sidebands would exit the output mode cleaner. One would then use DC (homodyne) demodulation to sense the GW signal beating against carrier light, used as a local oscillator.

Such DC demodulation is subject to many low-frequency noise sources. However, the carrier light local oscillator can be made very stable and pure Gaussian TEM₀₀, by using the light filtered by the high-finesse arms. One can offset-lock the arms (in opposite directions for the two arms) to allow a small, controlled amount of carrier light out the arms to exit at the asymmetric port and act as a local oscillator for DC GW detection. The output mode cleaner and the photodetector must be isolated from low frequency environmental noise.

DC readout seems favored in current modeling; further work is required to determine whether the traditional RF readout has better quantum-limited sensitivity. RF readout remains available as a fallback.

Prototyping the optical configuration and control scheme

The Advanced LIGO optical configuration and control scheme is extremely complex, with many innovations. A high-fidelity prototype of the system should make the transition from Initial to Advanced LIGO far less painful and time-consuming. The LIGO

observatories must remain undisturbed during initial science run, and the transition between Initial to Advanced LIGO must proceed as quickly and efficiently as possible, in order to minimize downtime between observations. A full engineering prototype is essential for minimizing such downtime.

Tabletop interferometers designed to operate and control signal recycling mirrors were developed at Caltech⁹, Florida¹⁰, Australia¹¹, and Japan¹². These efforts are all now complete, and they provided the experience and understanding needed to decide on an optical configuration and control scheme for Advanced LIGO, as described above. A new 10-meter interferometer is currently being developed at Glasgow¹³ to prototype dual recycling with multiple pendulum suspensions. This work is proceeding with an aggressive schedule, in order to provide input to the Advanced LIGO control system design by 2003. Then, a full LIGO engineering prototype of the optical configuration, sensing, and length and alignment control systems for Advanced LIGO will be tested at the LIGO Caltech 40 meter interferometer (40m), in 2003-2004.

The 40m prototype effort

The primary objective of the 40m is to make a full engineering prototype of the optics control scheme for a dual recycling suspended mass interferometer. Great care will be taken to ensure high fidelity between what will be tested at the 40m and what will be realized in Advanced LIGO. In particular, the design of the optical configurations and controls for Advanced LIGO and the 40m must proceed in parallel, using the same design tools and principles.

We will learn how to bring and keep the interferometer “in-lock” (controlling all seven suspended mirrors so that the carrier and RF sideband light are all resonant in the appropriate optical cavities). We will learn how to sense and control the mirror length angular degrees of freedom (the length sensing matrix goes from 4x4 in Initial LIGO to 5x5). We will learn how to generate 180 MHz sidebands on a high-powered input beam, and to detect and demodulate signals at that frequency. We will also be detecting signals demodulated at the difference and sum of the two RF frequencies, and will use “double demodulation” to produce error signals for one or more of the length degrees of freedom.

We will operate the SRC in a detuned RSE configuration. We will learn about sources of excess noise and unanticipated noise couplings, and have a first look at the dual-recycled shot noise response (at high frequencies), including the dip in the shot-noise-limited strain sensitivity due to the SRC detuning. We will learn to operate a short output mode cleaner to filter out all RF sidebands and higher-order transverse modes, use offset-locked arm cavities to allow a controlled amount of arm-filtered carrier light to exit the asymmetric port of the beam splitter, and evaluate the efficacy of DC readout of the GW signal. The expectations for the strain sensitivity of the 40m, with 0.1 watt of input power (much less than is available, in order to expose the shot-noise-limited part of the curve) is shown in Figure 5.

There will, of course, be significant differences between Advanced LIGO and the 40m prototype (aside from the much shorter arm cavities). Initially, LIGO-I single pendulum suspensions will be used. Full-scale Advanced LIGO multiple pendulums will not fit in the existing 40m vacuum chambers; these suspensions will be tested at the LASTI facility at MIT. Scaled-down versions of the multiple pendulums can fit, and it may be useful to develop these to test the controls hierarchy; this may be done in a second round of testing, in 2004 or 2005.

There is no room for anything like the full Advanced LIGO active seismic isolation system (which will be tested at LASTI). The 40m has Initial LIGO-like passive seismic isolation stacks. In addition, commercial active seismic isolation will be used.

The 40m will use an Initial LIGO 6-watt pre-stabilized laser (installed and commissioned in Summer 2001), so there will be negligible thermal effects. Other facilities will test high-power lasers and thermal effects, including LASTI and the Western Australian facility at GinGin. Active thermal compensation techniques will also tested elsewhere.

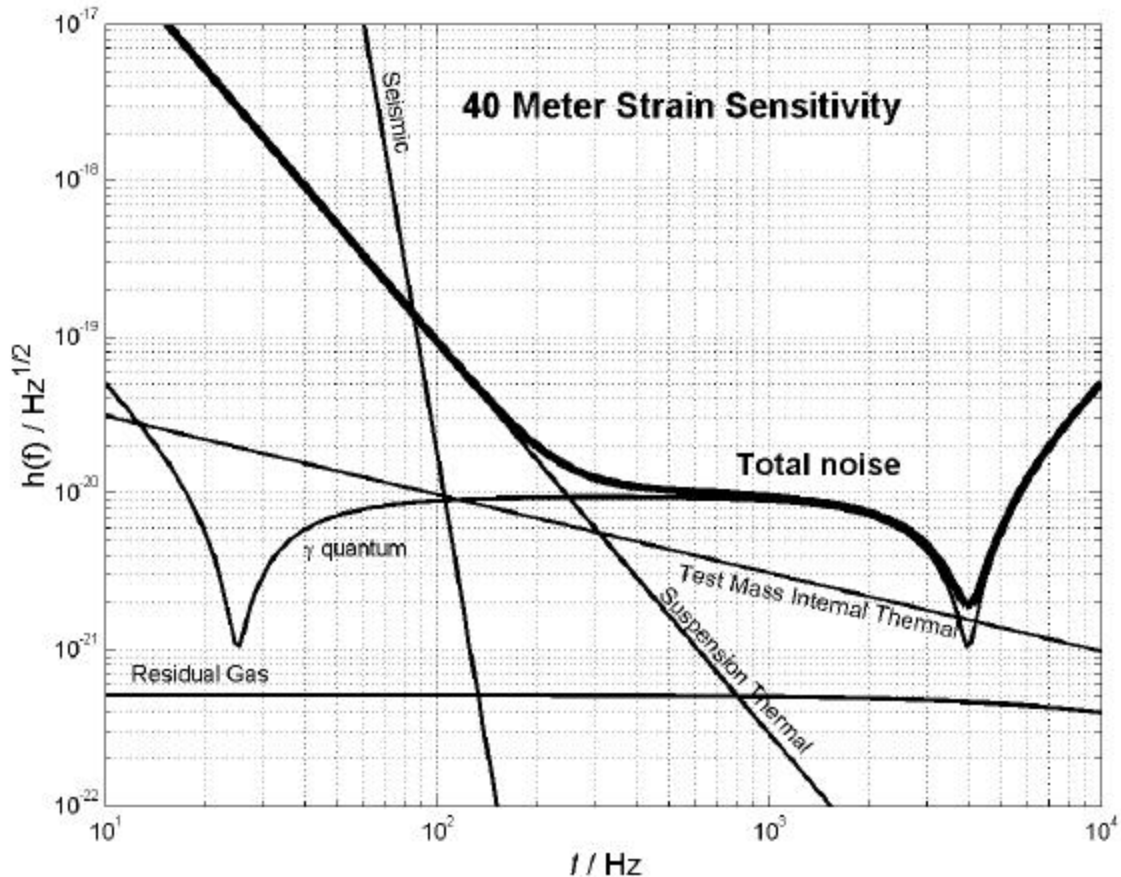


Figure 5: The expected strain sensitivity of the 40m dual-recycled prototype, operating with a detuned RSE signal cavity, and 0.1 watt of input laser power.

Because of the short cavity lengths at the 40m, the beam spots at the test masses will be relatively small (5 mm amplitude Gaussian sigma). The arm cavities are designed for

maximum stability, with g -factor of $1/3$, as in Initial LIGO. Advanced LIGO will have 6 cm beam spots, somewhat larger than at Initial LIGO, using less stable cavities (g factor closer to 1). The purpose of this is to reduce the thermoelastic noise¹⁴ of the sapphire test masses, which scales like the beam spot size to the $-3/2$ power. The 40m can move to less stable arm cavities if deemed useful.

The arm cavity finesse at 40m is chosen to be equal to that for Advanced LIGO (same ITM transmissivity). This means that the light storage time in the arms is 100 times shorter than in the 4 km LIGO arms. There will be significant differences in lock acquisition dynamics; however, these differences can be predicted and modeled.

Due to the limited vacuum envelope in the vertex area, the PRC will be shorter at the 40m than at Advanced LIGO; thus, the control RF sidebands will be 36/180 MHz instead of 9/180 MHz. This will produce less contrast between the sensing of the PRC and SRC lengths; the 40m length sensing matrix will be less diagonal than for Advanced LIGO, making it a conservative test bed for the control scheme.

The 40m will use fused silica for all suspended optics, like Initial LIGO. The baseline mirror material for Advanced LIGO is single-crystal sapphire. Thermal Brownian noise is expected to be small for such high-Q materials, but thermoelastic noise will be larger than for fused silica and will dominate the Advanced LIGO strain sensitivity in the 100 Hz region (see Figure 2). At the 40m, it should be possible to measure the thermal noise of the fused silica mirrors; if the interferometer is operated at full power (6 watts of input laser power), thermal Brownian motion is expected to dominate the strain sensitivity from 100-1000 Hz.

As mentioned above, options will exist for installing and testing multiple suspensions, and for using less stable arm cavities. In addition, the 40m laboratory will continue to be a useful facility for testing or staging of small LIGO innovations (such as improved earthquake mirror stops), and will provide hands-on training for new interferometer physicists. It is also available for public tours and student outreach programs.

A detailed work baseline schedule for the 40m prototype construction and experiment is in place. By third quarter 2001 the laboratory infrastructure will be complete (vacuum, seismic isolation, lab space, etc), the PSL commissioned, the DAQ commissioned, and environmental monitoring in place. In 2002, the optics will be delivered, and will be suspended in Initial-LIGO-like suspensions. Digital suspension controllers will be assembled and commissioned. By the end of 2002, the Glasgow 10m experiment will inform the 40m program, and the control system will be finalized. By the middle of 2003, all core subsystems are expected to be commissioned, and experiments will begin. These will include:

- Lock acquisition with all 5 length DOF's, 2x6 angular DOF's.
- Measurement of the transfer functions.
- Measurements of the noise contributions to the gravitational wave channel.
- DC readout of the gravitational wave channel.
- Inform controls electronics group of any required modifications.

- 4Q, 2004: Final report to LIGO Lab.

We expect that the optical configuration and control scheme for Advanced LIGO will evolve, and maybe depart from the scheme outlined above; we must remain flexible for as long as possible to ensure high fidelity between the 40m prototype and what will be realized in Advanced LIGO.

Summary of experimental tasks and challenges

Although the outlines of a design for the Advanced LIGO optical configuration and controls exist, much work is required to design and build a reliable, robust system. Much prototyping and modeling activity is in progress. The goal is to understand and test all the techniques and engineering required to build a dual-recycled suspended-mass IFO for Advanced LIGO, *before* construction begins, to minimize down-time between Initial LIGO and Advanced LIGO. At Caltech, the 40m prototype will be ready for detailed engineering tests of the Advanced LIGO optical configuration, control and readout schemes during 2003-2004 (after the Glasgow 10m tests).

Some of the most important experimental tasks and challenges to be faced at the 40m prototype in the next few years include:

- Develop and refine the length and alignment control schemes.
- Develop models of the interferometer response.
- Develop large-aperture, high power electro-optic devices operating at 180 MHz.
- Develop lock acquisition strategies and establish lock acquisition.
- Assemble and commission the dual-recycled IFO.
- Measure transfer functions for all degrees of freedom.
- Study noise in the L_{DM} and GW-DC signals.
- Characterize the 40m interferometer (lock acquisition, noise, etc).
- Make needed modifications to the control scheme.
- Develop and study the output mode cleaner design and DC readout scheme.
- Potentially, employ multiple pendulum suspensions.
- Prepare a final report with recommendations to the LIGO Laboratory directorate (sometime in 2004).
- Prepare one or more papers for publication.

We thank the many members of the LIGO Laboratory and the LIGO Scientific Collaboration who have contributed to this work.

The author wishes to thank the organizers of this conference for a thoroughly enjoyable experience in the beautiful city of Perth, Western Australia.

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