4 Sources of Noise

4.1 Seismic Noise

Because LIGO sits on the ground, it is susceptible to ground vibrations. Its sensitivity means that it can detect the passing of cars and trucks on highways, both near and far. It can detect ocean waves crashing on beaches many hundreds of miles away. It can detect pretty much every earthquake that happens in the world. All of these phenomena are not what LIGO is designed to measure, they are sources of noise that masks the signals form gravitational waves. So the first system we will look at is the one that isolates the interferometer from ground vibration.

The first layer of defense against unwanted ground motion is the structure of the building that houses the interferometer. The floor of the interferometer is 75 cm thick reinforced concrete that sits upon a concrete foundation and piers from which it is vibrationally isolated. The massive floor minimizes ground motions and helps stabilize the laser beam and test masses.

In addition to the building design, LIGO employs a passive/active system to hang the test masses by an assemblage of pendulums. Each pendulum has a different length, and so a different frequency of oscillation, and they are stacked, one below the other, into four stages. The test masses holding the interferometer mirrors are suspended on the lowest level. The setup keeps the test masses stable while allowing them to be in effective free-fall along the axes of the laser beams. The apparatus is shown schematically in Figure 4.1, and a photograph of one of the test mass assemblies is shown in Figure 4.2.

Above the two passive bottom elements, the top two pendulums have active feedback to stabilize them against low frequency motion. The net effect of this isolation strategy is to keep the test masses stable to better than 10^{-19} m, the threshold to detect displacements caused by expected gravitational wave strains.

A simple demonstration serves to illustrate how this technique works. If you make a simple pendulum out of a light thread and a heavy weight, like a large threaded nut or a fishing weight, then you can see the basic idea behind LIGO's seismic isolation strategy. Such a pendulum will have a natural frequency of oscillation given by the familiar relation below.

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{l}} \tag{4.1}$$

As usual, g is the local gravitational acceleration and l is the effective length of the pendulum. If you hold a pendulum as described and then move the pivot point (your hand) back and forth at a frequency much higher than the pendulum's natural frequency, the pendulum bob will barely move. For frequencies much lower than the natural frequency, the pendulum will follow the motion of your hand. You can give this a try if you like, but

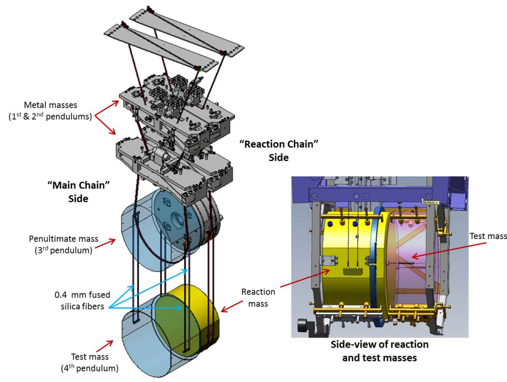

Figure 4.1: The LIGO test masses are suspended in a four-stage pendulum that uses active and passive elements to isolate the masses from ground vibration. The first three pendulums are suspended with metal chains. The last one uses fused silica fibers to help eliminate thermal noise. Image Credit: Caltech/MIT/LIGO Lab

take care to not move your hand up and down a lot. That increases the motion of the bob. You can also view the video we have made available on the website for the class.

The GW Optics site has created a very nice computer simulation of a pendulum. You can load that into your browser and then use the sliders to adjust the length of the pendulum and the frequency and amplitude of the forcing. Try small amplitudes with various frequencies and watch how the pendulum reacts. Is it what you expect? Try using large amplitudes with various frequencies. Are you surprised by the reaction of the pendulum under any of these conditions? Will your students find any of this surprising? The applet has a radio button that lets you simulate a compound pendulum with two elements. Try exciting that pendulum to see how the motion of the bob changes. Does the compound pendulum provide better isolation from motion than a single pendulum?

The latest incarnation of LIGO does not use a single pendulum, though earlier versions did. LIGO currently uses a stacked structure with four pendulums in succession. For large amplitudes, the motion of a multi-stage pendulum is quite complicated. But the amplitudes of the LIGO pendulums are minute. The point here, of course, is to have virtually no motion at all, and this method does an excellent job of isolating the test masses from any motion of their supports. If you like, you can make a compound pendulum with two or three or four stages and then see how it behaves as you move your hand back and forth. Or, as earlier, you can view the videos we have provided on the course website that show some of

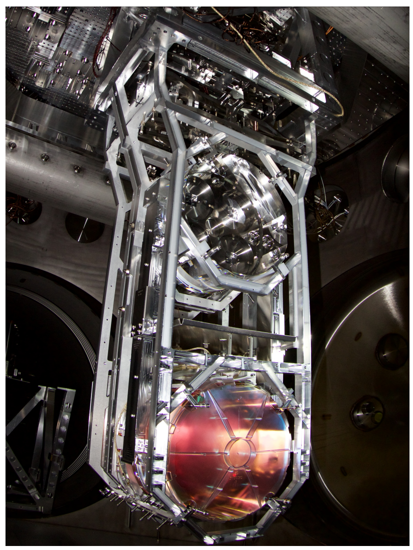

Figure 4.2: The suspension mechanism for the LIGO test masses. At the bottom is one of the test masses (the mirror). Above it can be seen the other elements of the four-stage pendulum that is used to isolate the test mass from ground vibration. Credit: Caltech/MIT/LIGO Lab

the motions of multistage pendulums.

4.2 Thermal Noise

Besides ground vibration, LIGO's high sensitivity makes it susceptible to disturbances that would not normally affect other experiments. These include sound vibrations in the air, which can affect both the motion of the test masses and refract the laser beam. Additionally, even the impact of air molecules on the test masses can cause detectable motion of the test masses. And dust that impacts and sticks to the mirror surfaces can scatter the laser light, causing a decrease in signal and coherence of the light. All of these sources of noise must be eliminated in the running experiment. Fortunately, they can all be addressed by a single strategy: evacuate the air in the laboratory and run the experiment in vacuum.

Figure 4.3: Looking down one of the long vacuum tubes that house the optical elements of LIGO during installation of the light baffles. Credit: Caltech/MIT/LIGO Lab

LIGO operates one of the largest vacuum environments ever created. The test masses and other optical components within each arm sit in a steel tube that is 4 km long and 1.2 m in diameter. These tubes are pumped down to 10^{-9} torr, a pressure equivalent to roughly a trillionth of an atmosphere. Figure 4.3 shows the inside of one of the tubes during maintenance.

Even in a vacuum environment, thermal physics dictates that there is a base level of noise that cannot be removed. For example, the strings holding the test masses have a tension and can vibrate like a stringed instrument. This means they will undergo thermal excitations of their various modes of vibration, and according to the Equipartition Theorem, they will contain kT worth of thermal energy in these vibrational modes at thermal equilibrium.

These types of modes, called “violin modes” are generally not important at all for the motion of a pendulum. However, in LIGO the usual oscillatory modes (swinging) are held to an absolute minimum, so even the motions of oscillation of the strings begin to have a noticeable affect. The same is true for stretching modes of the suspension strings (like a spring) and also the vibrational modes of the mirrors and their reflective coatings.

4.3 Quantum Noise

LIGO has gone to extraordinary lengths to minimize noise, even unavoidable noise such as the thermal noise described above. The strategies employed to reduce or mitigate the effect of noise in LIGO has been so successful that the experiment has reached the ultimate of noise limits: that imposed by quantum mechanics. This fundamental noise source is best understood in terms of the quantum mechanical Uncertainty Principle. Generally, we do not have to consider quantum phenomena with macroscopic systems, but because of LIGO’s extraordinary sensitivity, quantum physics comes into play in two respects.

The first has to do with the precise localization of the test masses. Recall that one formulation of the Uncertainty Principle relates the position and momentum of an object as follows.

$$\Delta x \Delta p \geq \frac{\hbar}{2} \tag{4.2}$$

In this formula, Δx is the uncertainty in the position of an object, Δp is the uncertainty in its momentum, and $\hbar = 1.054 \times 10^{-34}\,\mathrm{kg\,m^2\,s^{-1}}$ is Plank’s constant divided by 2π. The relation sets a minimum uncertainty in the momentum of the test masses because their position is constrained to such a high degree. This so-called quantum noise is a floor below which the precision of the experiment cannot be pushed.

Quantum uncertainty plays out in two respects with LIGO. First, consider the simple Poisson statistics associated with the laser. The amplitude of the laser light is related to the number of photons, and it is this amplitude that is the output signal of the interferometer. Now, it’s true that the interferometer is designed so that it creates nearly total destructive interference at the output port. Motion of the test masses, as in when a gravitational wave passes, disturbs the cancellation at the port, causing some light intensity to be measured. However, the laser light shows statistical fluctuations in the number of photons due to Poisson statistics, and ultimately to the interaction of the laser light with the vacuum fluctuations caused by the Uncertainty Principle. As a result of these fluctuations, the intensity of the light at the output port will not be constant, but will fluctuate due to the light statistics. Even if no motion occurs in the test masses, fluctuations in photon number, called *shot noise*, can give false signals of motion when there is none.

The standard way around Poisson limitations is to increase the strength of the signals, in this case the power of the laser. Doing so increases the number of photons in the laser in direct proportion to the power. And, per Poisson statistics, the noise increases only by the square root of the number of photons. Thus, as the power of the laser beam increases, the signal-to-noise ratio (SNR) also increases, as the square root of the power. In principle, any desired SNR could be achieved this way. But it is not quite that simple.

Each photon carries momentum. When it hits one of the test masses, the photon imparts some of its momentum to the mass, causing the mass to move. The motion of the test mass creates a change in phase of the laser light by changing the length of the resonant cavity in a manner not at all related to the passing of a gravitational wave. That in turn affects the interference at the output port of the interferometer, exactly the effect we are trying to avoid. What's worse, as the strength of the laser increases, perhaps in an attempt to decrease the shot noise, the momentum transfer also increases. The net effect is that by decreasing the shot noise we increase the uncertainty in the length of the arm, and that nullifies any improvement in signal related to decreased shot noise.

This is the classic Heisenberg uncertainty relation: decreasing the uncertainty in one measurement increases the uncertainty in a complementary one. And for a laser, the phase of the light is related to its position (x) and the intensity of the light is related to its momentum (p), so these complementary quantities are subject to the Uncertainty Principle as stated in Equation 4.2. This would seem to suggest that we cannot get around the coupled phase/intensity uncertainties imposed by quantum mechanics. But that is not quite true, either.

If we write the Uncertainty Principle in its "minimal"' form, then the equal sign applies.

$$\Delta p \Delta x = \frac{\hbar}{2} \tag{4.3}$$

According to this relation, we are free to decrease the uncertainty in p (the intensity of the laser, or shot noise) as long as we simultaneously and proportionately increase the uncertainty in x (the phase).

That is how LIGO will improve its noise below the shot noise limit: they will eventually inject states of light that have been prepared in such a way that they have decreased, or "squeezed," uncertainty in their intensity, lowering it below the standard Poisson shot noise. Simultaneously, this must increase the uncertainty in the phase of these states, of course. These *squeezed states* of light have already been produced in laboratory experiments and in the initial version of LIGO as a test. Additionally, squeezed light states are used regularly in an interferometer experiment in Germany called GEO600[10]. Squeezed states of light have not yet been implemented into the Advanced LIGO interferometers.

[10]GEO600 has 600 meter arms, not long enough to provide the sensitivity needed to detect gravitational

The squeezed light method works with experiments like LIGO because of the different sensitivity of the interferometers in different frequency regimes. At low frequencies the phase uncertainties of the light are more important. At high frequencies the shot noise uncertainty dominates. By adjusting exactly how the laser light is squeezed, either limiting the shot noise or the phase uncertainties, it is possible in principle to improve the output signal at both ends of the frequency band of the LIGO interferometers.

We just discussed how one source of noise affected by quantum effects is a coupling between the laser beam and the mirrors. Basically, radiation pressure on the mirrors can cause them to move, changing the length of the Fabry-Perot cavities. This effect is simulated in the Optical Spring applet on the GWO website. You can use the applet to explore how changing properties of the laser and the cavities changes the output intensity of the laser.

4.4 Additional Resources

Gravity Spy

LIGO scientists working with the Zooniverse project are developing a citizen science program called Gravity Spy. The object of Gravity Spy is to have the public help LIGO sort through some of the noise-caused artifacts in their data. The website trains participants to select obvious noise candidates and flag them for removal. This is a way to leverage the intelligence of interested members of the public in order to train the automated algorithms. If you are familiar with the Galaxy Zoo Project from the Sloan Digital Sky Survey, Gravity Spy will look remarkably similar. Even though the project has not yet gone live, you can still go to the site and inspect the activities. You can even give them feedback if you like. At this point, good feedback is appreciated.

Seismic Noise e-Lab

Seismic noise is one of the chief barriers to detecting gravitational waves with LIGO. Removing that noise has been one of the project's main challenges. The NSF/DOE e-Labs website (`https://www.i2u2.org/elab/`) has compiled seismic data from the LIGO antenna sites at both Hanford and Livingston, and they have created online activities that allow you to inspect that data. We have linked to their exercises on the site for this course, and you should go to Section Four of the Moodle and read about the activities and then check them out for yourself.

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waves, but still useful for developing the technology employed in larger interferometers. GEO600 has been a test platform to develop and optimize many of the systems used in Advanced LIGO.