Doing some stuff for LIGO

A Dissertation

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CURRENTLY STOLEN FROM MY GEN EXAM DOC!!! I assume in this section that the reader has a basic understanding of the LIGO detectors and the effect of gravitational waves on such a detector. This section will thus focus on a slightly more detailed description of instrument noise and data in order to provide context for the rest of this paper. We have already seen in **??** the importance of correctly characterizing an instruments noise and bandwidth.

2.2.1 DATA

The gravitational wave information is encoded in several channels which are sampled at 16384Hz with 16 bits of dynamic range. This makes the absolute bandwidth of LIGO instruments restricted to $(0, 8192]$ Hz (the Nyquist frequency).

Unfortunately LIGO GW data is not continous. Each detector has a limited duty cycle caused from commissioning downtime and lock loss from external disturbances. This means that the total amount of data in coincidence is reduced. Additionally many environmental monitors are used to establish the quality of data. For example, we will see in the next section how important seismic noise is for LIGO's operation. For that reason several seismometers and other instruments record ground motion, other environmental disturbances, and their effect near every test masse in order to establish times when data may be suspect. Depending on the specific search these times may also contribute to a loss in live time.

2.2.2 NOISE

Although LIGO is effectively a broadband detector frequency dependent noise greatly reduces its sensitivity at very low and very high frequencies. Thus it is useful to discuss, in the next few sections, briefly the noise sources in LIGO since it's effective bandwitdth is limited by these several sources and others. The arguments below come mostly from Saulson [?].

Before I discuss sources of noise it is useful to set a goal for the characteristic strain of binary inspirals [?],

$$h_c = 4.1 \times 10^{-22} \left(\frac{\mu}{M\odot}\right)^{1/2} \left(\frac{M}{M\odot}\right)^{1/3} \left(\frac{100Mpc}{r}\right) \left(\frac{100Hz}{f_c}\right)^{1/6} \tag{2.1}$$

where f_c is the characteristic frequency at which the detector has the lowest strain noise. For an optimally oriented neutron star inspiral at the Virgo cluster's distance (15 Mpc) one will have about 10^{-21} strain. However it is important to have a broad response around the characteristic frequency f_c since for matched filtering the SNR will grow with the time that a signal remains in band.

2.2.2.1 SEISMIC MOTION

Seismic noise is by far the largest overall contributor to LIGO noise. The fundamental coupling comes through the suspension of the test masses. Since we cannot have mirrors actually free falling (for long) we have to suspend them via wires, which of course act as a pendulum. The resonant frequency of the pendulum modes are all approximately $\leq 1Hz$. This guarantees large motion at low frequencies where seismic disturbances dominate thus giving very low sensitivity to GWs. If you just consider the ideal simple pendulum's response to seismic noise the gravitational wave strain sensitivity would be [?] (assuming ground motion with displacement noise $x(f) = 10^{-7}cm/\sqrt{Hz}(10Hz/f)^2$ above 10Hz.),

$$h(f) \sim 5 \times 10^{-11} \left(\frac{1Hz}{f}\right)^4 / \sqrt{Hz} \tag{2.2}$$

This requires a frequency of nearly $1kHz$ in order to reach the desired strain of $1\times10^{-21}/\sqrt{Hz}$[**?**]. This would exclude several high mass systems which merge before reaching that frequency. It also is not benificial for low mass systems since SNR will grow with the time that a signal spends in a low noise region. Clearly additional seismic isolation is necessary. This is done in two ways. One is passive isolation which empolyes the use of mass-spring pairs to add additional high frequency supression. The other is active isolation whereby the motion of the test mass housing is corrected by applying the appropriate counter motion [**?**]. Active seismic isolation was necessary at the LIGO Livingston Observatory due higher than usual low frequency noise as indicated in figure **??**.

Simple passive isolation alone adds more frequency poles to the strain noise each providing a similar supression as (2.2) (thus making the overal supression much steeper). Of course things are further complicated when considering the vibrational modes of the pendulum wires themselves which show up in the spectrum as higher frequency peaks. Nevertheless careful passive isolation reduces the low frequency noise floor to be able to reach the desired strain noise at $\sim 50Hz$ instead of $1KHz$.

2.2.2.2 SHOT NOISE

The discrete arrival of photons at the detector output provides a limit to LIGO's ability to measure phase changes. The simple expression for shot noise is [**?**]

$$h_{shot} = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P_{in}}} \tag{2.3}$$

Where P_{in} is the input laser power. Here the noise has no frequency dependence (it is white) with an amplitude that scales inversely as the square root of the laser power. The transfer function of the LIGO's Fabry-Perot cavity actually gives the shot noise a scaling that goes as $\propto f$. The next section describes why increasing the laser power to arbitrarily high values doesn't gaurantee lower noise.

2.2.2.3 RADIATION PRESSURE

Light does exert a force on whatever it interacts with. The notion of radiation pressure provides a fundamental reason why you cannot just crank up the laser power in hopes of reducing your shot noise. Although it is true that you will reduce shot noise, the noise created by pressure will soon dominate. This noise has (as you would expect) the opposite scaling with laser power [?] and for a simple Michelson is,

$$h_{rp} = \frac{1}{mf^2L}\sqrt{\frac{\hbar P_{in}}{2\pi c^3\lambda}} \tag{2.4}$$

2.2.2.4 THERMAL NOISE

The scaling of seismic noise $\propto f^{-n}$ and shot noise in a Fabry-Perot $\propto f^2$ give the limiting low and high frequency components respectively. The *in between* is dominated by thermal noise in the test masses and suspension wires. Derivation and accounting for this is probably beyond the scope of this document. I have provided a recent noise spectrum in figure **??**.

3. Signal Processing for Binary inspirals in LIGO data

4. S4 MACHO Search

4.1 TBD

4.1.1 TBD

5. Single IFO S4 Search

5.1 TBD

5.1.1 TBD

6. Future Work

6.1 TBD

6.1.1 TBD

7. Conclusionns

7.1 TBD

7.1.1 TBD