

Project: Adaptive Noise Filtering for the LIGO 40m Interferometer

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Abstract

Gravitational waves (GWs) are phenomena predicted by Einstein's theory of general relativity (GR): variations in the curvature of spacetime which propagate at the speed of light. Though GWs remained theoretical for many years following the conception of general relativity, their existence has been supported by the binary pulsar PSR 1913+16, whose orbital period decays at precisely the rate predicted by GR. The Laser Interferometer Gravitational-Wave Observatory (LIGO) is comprised of three Michelson interferometers at two locations whose purpose is to detect and study GWs of astrophysical origin. Currently, GWs have yet to be detected by LIGO, so there is considerable benefit to be gained by improving the sensitivity of the instruments. A significant source of noise, particularly at low frequencies, comes from seismic and acoustic vibrations, transmitted to components of the interferometer. Therefore, I propose to study these effects and utilize adaptive noise cancellation techniques to independently measure and subtract out noise from these sources.

Gravitational Waves

Einstein's theory of general relativity, formulated in 1916, replaced the Newtonian model of gravity, which depends solely on masses and distances, apparently resulting in instantaneous transfer of gravitational information. GR, on the other hand, describes the gravitational force as the curvature of spacetime; collapses, collisions, and rapid orbital motions of matter cause fluctuations in the spacetime curvature, and the propagation of those fluctuations are the gravitational waves.

Because the force of gravity is so dramatically weaker than the other fundamental forces (e.g. it is 31 orders of magnitude weaker than the electromagnetic force for a pair of protons), it would not be realistic to attempt to detect GWs created by any terrestrial or nearby sources, thus the search is taken to very massive astrophysical objects. Also, because the amplitude of the GW falls off as the inverse of

the distance travelled, the generating object must be reasonably close in order to allow for the possibility of detection – it is estimated that GWs produced by objects in our or nearby galaxies do not exceed strain levels of 10^{-21} on Earth. Fortunately, because the gravitational force is weak, GWs may propagate through space largely unperturbed.

Sources of Noise

The LIGO interferometers are designed to be able to detect gravitational waves (GWs) with strain amplitudes of 10^{-21} . However, several sources of noise present in the setup can greatly increase the uncertainty in the measurements – during the fifth science run (S5, run from November 2005 to September 2007), the root-mean-square noise reached 3×10^{-22} for the 100 Hz frequency band – so, it is desirable to find ways to reduce or subtract out the noise.

Displacement noise refers to the unwanted movements of the test masses, as opposed to sensing noise, which is the uncertainty in measuring those movements. A large contributor to displacement noise, particularly at the lower frequencies, is seismic and acoustic activity: vibrations from things like traffic or wind forces can be transmitted into the interferometer setup and cause unintended motion in the test masses. The interferometer incorporates a number of design elements which are intended to isolate the structure from seismic vibrations. The mirrors in the interferometer are hung as pendulums by thin, but strong steel wires, which are mounted on single-layer mass-spring isolation stacks (for Initial and Enhanced LIGO – Advanced LIGO will have quad isolation stacks).

Adaptive Filtering

Because the noise cannot be completely eliminated by physical isolation, we want to suppress the noise by an active noise cancellation technique. In short, the active-canceller receives two inputs: one is the desired signal blended with noise contamination, and the second is a “reference input,” which is an independent measurement of the noise, thus unrelated to the signal but correlated to the noise in the primary input. The reference input must then be filtered to approximate the noise in the primary, and then is subtracted to produce an uncontaminated signal. While there do exist methods to

replicate the “transfer function” between the independent noise measurement and the contaminated signal with a static filter – specifically, Wiener filtering – it is suspected that the noise transfer into the interferometer may vary with time, so it is important to have an adaptive system. The adaptive filter would automatically adjust itself via a recursive algorithm, which depends on an error signal from its own output. This filter would work under variable conditions to continuously optimize the signal.

Project Description

So, the purpose of this project will be to program the control system to independently measure and subtract out the remaining seismic and acoustic noise from the data, using an adaptive filtering algorithm. The work will be carried out at the 40m LIGO Prototype Lab in Pasadena, which is a small-scale version of the LIGO interferometers that is used to test new technologies for the project. That way, they can be tested and perfected before being sent off to the 2 and 4 km interferometers in Louisiana and Washington. The bulk of the project will involve coding in Matlab to create the active noise canceling program. However, there will also be some work with various sensors – seismometers, accelerometers, microphones, etc – which are used to measure the seismic and acoustic activity. The setup for taking acoustic measurements needs to be arranged in the experiment hall and connected to data collection systems so that the measurements can be used in the program. Understanding how the interferometer behaves and how the sensor data translates into signal noise are key to being able to write an effective noise cancellation program. The goal is to have the program complete and running by the end of summer.

References

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