LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Real-Time Temperature Monitoring of Coated Silicon Samples at 123K

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1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is the manifestation of over a hundred years of brilliant thinking, creativity, and desire to illuminate more of the Universe than ever before. The foundations for this joint Caltech and MIT project truly begins in 1915 with Albert Einstein's general theory of relativity, in which the proposed existence of gravitational waves is established. The possibilities that come from an instrument capable of directly measuring gravitational waves is vast and promising. Being able to capture and analyze these gravitational ripples means being able to get a close "listen" to some of the most exciting cosmic events, such as binary black hole or pulsar systems. Gravitational waves are able to reveal more about the early universe, far-away galaxies, supernovae, gamma-ray bursts, Einstein's theory of general relativity, and much more. Following a spark of development during the 1970's, the full-scale laser interferometers intended to detect gravitational waves are installed by the year 1999.

2 The Detectors

LIGO is currently composed of two detectors, the first is located in Washington state and the second in Louisiana. LIGO also collaborates with GEO, its European counterpart located in Germany; Virgo, located in Italy; and KAGRA, located in Japan. The detectors are essentially gigantic Michelson interferometers, with each arm being about 4 km in length. In addition to being larger, LIGO's detectors are also much more complex and detailed than a typical Michelson interferometer. Observable gravitational waves originate from energetic cosmic events occurring a billion light-years ago and the amplitude of these resulting waves are small, even more so by the time they reach Earth. LIGO is designed to be capable of detecting these signals. In fact, LIGO is currently sensitive enough to detect displacements below $10^{-23}\frac{1}{\sqrt{Hz}}$ between 70 and 1000 Hz. However, this means that LIGO is also very susceptible to local vibrations that contribute irrelevant data. LIGO tries to achieve this balance between being sensitive enough to detect gravitational waves and ruling out disruptive noise by introducing heavy modifications to the Michelson interferometer.

The Michelson interferometer, simply put, consists of passing a laser beam through a beam splitter that sends the two resulting beams down each arm of the interferometer. At the end of the arms, the laser beams are reflected off mirrors back to the beam splitter where they are to join into a single laser beam. The light waves from this interference are captured by a photodetector. LIGO's interferometers have incorporated, among other modifications, Fabry Perot cavities in each arm to increase sensitivity. Fabry Perot cavities use two test masses with which the laser beam is partially reflected continuously.

3 LIGO Voyager

Despite such efforts for accuracy, LIGO's current use of fused silica fixed by suspension still allows for a significant amount of noise production that needs to be accounted for. In hopes of reducing thermal noise in future versions of LIGO, notably LIGO Voyager, it is theorized that coated silicon test masses cooled to 123K can be utilized in place of the current fused silica test masses. The cryogenic test masses are expected to reduce disruptive noise from thermal fluctuations. This project aims to contribute some more information on the feasibility of a cryogenic LIGO, which if executed successfully will improve the detectors' accuracy. It is necessary to rigorously test how the material properties of coated silicon, cooled down to such an extreme temperature, will be affected. Efficient experimentation and data collection must be performed to determine the most suitable coating material for the silicon test masses.

4 Objective

To achieve the best testing conditions, there are a few possible complications that must be reviewed. The complication that this project will focus on addressing is the method of temperature monitoring while the silicon sample is being tested within the cryostat. Currently, resistance temperature detectors (RTDs) are being used to monitor the temperature of the environment in which the silicon disk is resting. However, there is a delay in the control loop. A successful result for this project will be to implement a method to provide real-time temperature readings to the control loop without disturbing the silicon disk being tested.

5 Approach

The set-up of this project involves a cryostat that encloses the following environment: the sample, a silicon disk, will rest upon a lens to minimize any possible restrictions imposed on the frequency response; an electrostatic drive will excite the silicon disk; a laser beam is produced directly onto the silicon disk; and a photodiode is used to measure the excitations. Additionally, several RTDs rest in the environment and provide temperature readouts. This project begins with a preparation period in which I will familiarize myself with the RTD readout circuitry, data acquisition process, and current control loop. In order to do so, I will be expected to build my own RTD circuit and perform readout testing in an isolated cryostat with a sample silicon disk. Once I have successfully built the RTD circuit, set up the cryostat for readout testing, and built a control loop comparable to the currently used one, we will move onto exciting the silicon disk in the main cryostat for data acquisition. After the necessary frequency shift measurements have been collected, we will work on incorporating this into the current control loop. The anticipated result will be real-time temperature monitoring for the silicon sample.

6 Project Schedule

Program Duration: June 19th, 2018 - August 24th, 2018 (10 weeks)

Week	Description
1	Prep week; learn about RTDs; learn data acquisition process and temperature control loop
2	Build RTD readout circuitry
3	Set up in isolated cryostat for testing
4	Build control loop; verify control loop, compare to current control loop
5	Use main cryostat; excite silicon disk for testing; compare frequency at room temperature vs. at 123 K
6	Measure frequency shift
7	Calibrate RTD
8	Incorporate frequency shift in control loop
9	Incorporate frequency shift in control loop
10	Project conclusion, final draft of presentation finished

7 Progress

7.1 Week 1

These initial three weeks have been centered around getting accustomed to the set up of our project. The first week mostly consisted of logistical tasks such as the SURF orientation, LIGO SURF orientation, safety training, getting forms signed, installing necessary software, and creating accounts for access to documents and data networks.

7.2 Week 2

The second week was spent going over the CryoQ lab procedures, the CryoQ experiment, the current temperature monitoring system, the data acquisition system and how to access it, and general control loop theory. There was a lot of studying to be done on topics such as the lock-in amplifier, resistance temperature detectors, calibration methods, and error propagation; more in-depth explanations have been included in the following sections. This, of course, was studied in addition to material on the current LIGO detectors and proposed changes to be implemented in LIGO Voyager; the resulting notes have been used to create a fuller description of the background for our project.

7.2.1 Lock-In Amplifier

Simply defined, the lock-in amplifier is an instrument capable of detecting and measuring extremely small AC signals. It is often used to recover signals buried in a significant amount of noise. Extremely sensitive, the lock-in amplifier can provide filter-sensitivity values ”Q” upwards of 100 000. For context,"a normal bandpass filter becomes difficult to use with Q's greater than 50" [8].

The lock-in amplifier utilizes phase-sensitive detection. Essentially, phase-sensitive detection is a method of highlighting the signal at a specific reference frequency and phase. The measurement signal is multiplied with a reference signal through the phase-sensitive detector, or multiplier. The phase-sensitive detector outputs the product of two sine waves [10].

Let V_{psd} be the voltage output of the phase-sensitive detector; let $V_{sig}sin(\omega_{sig}t + \theta_{sig})$ be the measurement signal; and let $V_{LO}sin(\omega_{ref}t + \theta_{ref})$ be the local oscillator (reference signal) where $omega_{ref}$ is the reference frequency and $theta_{ref}$ is the reference phase:

$V_{psd} = V_{sig}V_{LO}sin(\omega_{sig}t + \theta_{sig})sin(\omega_{ref}t + \theta_{ref})$

$= 1/2V_{sig}V_{LO}cos[(\omega_{sig}\omega_{ref})t + (\theta_{sig} - \theta_{ref})]$

$-1/2V_{sig}V_{LO}cos[(\omega_{sig} + \omega_{ref})t + (\theta_{sig} + \theta_{ref})]$

The output is interpreted as two AC signals, one at the difference frequency, $(\omega_{sig} - \omega_{ref})$, and the other at the sum frequency, $(\omega_{sig} + \omega_{ref})$. Using a low-pass filter and given that the measurement and reference frequencies are equal, the resulting output is the difference frequency component where the measured phase is $\theta = \theta_{sig} - \theta_{ref}$:

$V_{psd} = 1/2V_{sig}V_{LO}cos(\theta_{sig} - \theta_{ref})$

$V_{psd} \approx V_{sig}cos\theta$

This output is interpreted as a DC signal proportional to the amplitude of the measurement signal. In dual-phase lock-in amplifiers, this process is utilized twice. The second time, the reference signal is passed through a 90 degree phase-shifter before being multiplied with the measurement signal:

$V_{psd2} = 1/2V_{sig}V_{LO}sin\theta(\theta_{sig} - \theta_{ref})$

$V_{psd2} \approx V_{sig}sin\theta$

As a result, the lock-in amplifier outputs two values, which are labeled X and Y:

$X = V_{sig}cos\theta$

$Y = V_{sig}sin\theta$

The X output is known as the in-phase component and the Y output is known as the quadrature component. These two components collectively represent the measurement signal as a vector, relative to the reference signal [10]. The magnitude R and the phase shift θ can be calculated by converting from Cartesian to polar coordinates:

$R = (X^2 + Y^2)^{1/2}$

$\theta = tan^{-1}(Y/X)$

7.2.2 Resistance Temperature Detectors

A resistance temperature detector (RTD) is a reliable tool used for precision thermometry. Essentially, RTDs are temperature sensors preferable for their high accuracy, durability, and wide temperature range. There are many types of RTDs, however for our purposes, we will be focusing on the thin film platinum kind. Thin film refers to the style of the RTD element, or ”sensing part;” platinum refers to the material of of the RTD element [7].

RTDs function by relying on the positive, nearly linear relationship between electrical resistance and temperature that is characteristic of metals. Platinum is considered an efficient choice for its high resistivity and stability in extreme temperatures [6]. This relationship between electrical resistance and temperature is described by the Callendar-Van Dusen equation.

A small current is passed through the RTD sensor, an electrical component whose voltage is dependent on the resistance of the RTD. The RTD is expected to experience changes in resistance as the temperature varies. This change is reflected by measuring the voltage drop across the RTD. Once the voltage is obtained, temperature values can be found by applying a calibration equation specific to each sensor. CryoQ uses Thin Film Platinum RTDs purchased through Digi-Key [9].

7.2.3 Calibration Methods

Temperature calibration methods fall into two categories, fixed-point and comparative [2]. Fixed-point calibration is the more accurate of the two, although it is also more time-consuming and costly. This method works by testing at the fixed points of temperature at which a substance, such as nitrogen or gallium, experiences phase transitions. The intention is to choose points where the temperature readings can be consistently reproduced. The temperatures at these fixed points (triple, freezing, boiling) are defined by the International Temperature Scale of 1990 (ITS-90) [1]. The ITS is maintained by the National Institute of Standards and Technology (NIST). Calibration equipment include triple-point water cells ($900 to 2 000), calibration baths ($5 000 to 7 000), and dry-wells ($100 to 300). The NIST provides laboratory calibration services, but costs can easily exceed $10 000 [4]. The platinum RTDs calibrated to NIST standards have a maximum expanded uncertainty of 0.54 mK, for the temperature range of 13.8033 to 273.16K [3]. Coverage factor not given, but assumed to be k=2 [12].

Comparative calibration is the more commonly used method. These tests are performed by comparing readouts from the RTD to a standard, laboratory-calibrated reference thermometer placed in the same environments. The Standard Platinum Resistance Thermometers (SPRT), with which we compare our uncalibrated RTDs, cost at least $1 000 [4]. In accordance to comparison calibration tests performed by NIST, there exists an expanded uncertainty (given k=2) of 2.3 mK for liquid nitrogen baths or 2.4 mK for ice and boiling water baths [11]. When performing any of these calibration tests, consider the consistency of procedures between the different detectors, the placement depth, the distance between detectors in the bath, atmospheric pressure, etc. In order to be considered NIST traceable, the measurement equipment must eventually lead back to an NIST certificate; whether it be that the tool used, calibration equipment used, or lab that performed the calibration is

NIST certified [5].

7.3 Week 3

The third week was only four days long due to Independence Day. The four days were spent practicing how to solder, connecting the RTD setup, fixing any broken wires in the setup, plugging into the data acquisition system, and double-checking to ensure that the readout for the RTDs was functioning correctly. Following these tasks, some more studying was done on RTD calibration methods, and I have started to collect the necessary materials to begin creating calibration baths in week 4. I've also installed COMSOL, and have begun previewing some tutorials to prepare. Additionally, time was spent editing the project proposal and writing the first progress report.

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