DATA ANALYSIS TECHNIQUES FOR LIGO DETECTOR CHARACTERIZATION

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DEDICATION

To my wife, Lili.

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Gravitational-wave astronomy is a branch of astronomy which aims to use gravitational waves to collect observational data about astronomical objects and events such as black holes, neutron stars, supernovae, and processes including those of the early universe shortly after the Big Bang.

Einstein first predicted gravitational waves in the early century XX, but it was not until September 14, 2015, that the Laser Interferometer Gravitational-Wave Observatory (LIGO) directly observed the first gravitational waves in history.

LIGO consists of two twin detectors, one in Livingston, Louisiana and another in Hanford, Washington. Instrumental and sporadic noises limit the sensitivity of the detectors. Scientists conduct Data Quality studies to distinguish a gravitational-wave signal from the noise, and new techniques are continuously developed to identify, mitigate, and veto unwanted noise.

This work presents the application of data analysis techniques, such as Hilbert-Huang transform (HHT) and Kalman filtering (KF), in LIGO detector characterization. We investigated the application of HHT to characterize the gravitational-wave signal of the first detection, we also demonstrated the functionality of HHT identifying noise originated from light being scattered by perturbed surfaces, and we estimated thermo-optical aberration using KF.

We put particular attention to the scattering origin application, for which a tool was developed to identify disturbed surfaces originating scattering noise. The results reduced considerably the time to search for the scattering surface and helped LIGO commissioners to mitigate the noise.

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Chapter 1: INTRODUCTION

Gravitational-wave astronomy is an emerging branch of observational astronomy which aims to use gravitational waves to collect observational data about astronomical objects such as black holes and neutron stars, events such as supernovae, and processes including those of the early universe shortly after the Big Bang.

Einstein first predicted gravitational waves in the early XXth century; although a particular consequence of general relativity, they are a common feature of all theories of gravity that obey special relativity [1–3]. The first observational evidence for their existence first came in 1974 from measurements of the Hulse-Taylor binary pulsar, whose orbit evolves exactly as would be expected for gravitational wave emission [4].

On February 11, 2016, it was announced that the Laser Interferometer Gravitational-Wave Observatory, in its advanced configuration called aLIGO [5], had directly observed the first gravitational waves in September 2015 [6]. The second observation of gravitational waves was made on 26 December 2015 and announced on 15 June 2016 [7]. A third gravitational-wave signal was detected on January 4, 2017 [8].

aLIGO consists in two twin detectors, located more than 3000km apart. Each detector includes a laser interferometer and many auxiliary subsystems dedicated to provide good quality laser and isolate the interferometer from noise, such as a thermal compensation system and the suspensions system [9, 10].

In LIGO, achieving full isolation from instrumental and sporadic noise is particularly difficult, even with the help of the auxiliary systems. Combined with the fact that the detectors measure an extremely small change in distance proportional to the gravitational wave passing, data analysis is required to identify a gravitational-wave signal buried in undesired noise.

The Detector Characterization group largely performs the necessary task of characterizing the instrument and the noise limiting its sensitivity [11, 12]. The people working within this group conduct data quality studies [13–15] and constantly new techniques to identify, mitigate, and veto unwanted noise [16–19]; and distinguish them from a gravitational-wave signal. But, as problems are solved, new problems arise. Sometimes the mitigation of a constant noise yields the presence of a new one. Therefore, each correction or implementation of new auxiliary systems requires more characterization and new data analysis tools.

In this dissertation, motivated by the Detector Characterization group efforts and achievements, we present the application of data analysis techniques in LIGO detector characterization. The techniques shown here are relatively new. The Hilbert-Huang transform (HHT), a technique invented at NASA by Norden E. Huang in the late 90's that decomposes a signal into simpler signal and is designed to work well for data that is non-stationary and nonlinear [20]. And Kalman filtering (KF), an algorithm that uses the model of a system to correct its output measurements, containing statistical noise and other inaccuracies [21]. Named after one of its primary developers in the early 60's, Rudolf E. Kálmán, and utilized in navigation systems.

These two techniques have been employed in LIGO before. HHT was used to detect and characterize noisy simulated gravitational-wave signals [22], while KF found application in regressing resonance modes of the suspensions [23]. In this dissertation, we illustrate the use of HHT to characterize the gravitational-wave signal of the first detection. We demonstrate the functionality of HHT identifying noise originated from light being scattered in perturbed surfaces. We also show an application of KF to estimate thermo-optical aberration.

The results obtained confirm that HHT is capable of finding gravitational-wave signals in a real measurement. We also show the tool developed to identify which perturbed surface was originating the scattering noise, that reduced considerably the time to search for the culprit surface and helped LIGO commissioners to mitigate the noise. Lastly, our results show that the KF estimation of the aberration is clearly less noisy than the aberration measurements.

The dissertation contains two main parts: the introduction and the applications. Chapter 2 gives an introduction to gravitational waves, Chapter 3 provides an overview of Advanced LIGO and the auxiliary systems of interest, Chapter 4 reviews the important tasks of the Detector Characterization group and its achievements, and Chapter 5 explains the data analysis techniques employed.

On the other hand, Chapter 6 illustrate the application of HHT as event trigger generator, Chapter 8 demonstrate the application of HHT identifying scattering, and Chapter 8 shows the use of KF in thermo-optical aberration estimation.

Chapter 2: GRAVITATIONAL WAVES

2.1 Introduction

Einstein formulated the General Theory of Relativity at the beginning of the twentieth century, and he described gravity as the curvature of spacetime. General Relativity (GR) predicts that perturbations of the spacetime curvature satisfy a wave equation. These ripples in spacetime are called gravitational waves (GWs), and they propagate at the speed of light [1–3]. Similar to how the acceleration of charge produces electromagnetic (EM) waves are generated by the acceleration of charge, GWs are produced by the acceleration of matter; another similarity to EM waves is that GWs carry energy away from the source. However, unlike their EM counterparts, GWs interact very weakly with matter and combined with the decreasing amplitude as they travel away from the source, this makes the direct detection of GWs very challenging.

The relationship between matter and spacetime can be summarized in the Einstein field equation

$$G_{\mu\nu} = 8\pi T_{\mu\nu} \tag{2.1}$$

where $G_{\mu\nu}$ is the Einstein tensor, which describes the curvature of spacetime, and $T_{\mu\nu}$ is the stress-energy tensor, which describes the energy and momentum in spacetime; assuming geometrized units $G = c = 1$. The Einstein tensor is defined as

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \tag{2.2}$$

is described by the Ricci curvature tensor $R_{\mu\nu}$, the Ricci scalar R, and the spacetime metric $g_{\mu\nu}$.

Equations 2.1 and 2.2 may appear simple, but the Einstein field equations are ten coupled nonlinear differential equations, and exact solutions can only be found using some special assumptions. To demonstrate the prediction of gravitational radiation from the theory of GR, we only use the weak-field approximation. Far away from the source, in the weak-field limit, the stress-energy tensor $T_{\mu\nu}$ becomes zero.

In the weak-field limit, the spacetime metric can be approximated as

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \tag{2.3}$$

which states that the spacetime metric can be described as flat ($\eta_{\mu\nu}$, the Minkowski metric) with a small added perturbation ($h_{\mu\nu}$, the GW we are looking for).

One fundamental concept in Special Relativity is that the spacetime interval ds between any two neighboring points is given by

$$ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2 \tag{2.4}$$

or

$$ds^2 = \eta_{\mu\nu}dx^\mu dx^\nu \tag{2.5}$$

with the Minkowski metric $\eta_{\mu\nu}$ given, in Cartesian coordinates, by

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{2.6}$$

The same physical concept is carried over into GR. Then, the more general statement of the definition of the spacetime interval is

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu \tag{2.7}$$

To explore the effects of this perturbation, it is very useful to move into the *transverse-traceless* (TT) *gauge*, where coordinates are defined by the world lines of freely-falling test masses [24]. In