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Improving earthquake monitoring for gravitational-wave detectors with historical seismic data

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ABSTRACT

A remarkable level of isolation from the ground is required for Advanced gravitational-wave detectors such as the Laser Interferometer Gravitational-Wave Observatory LIGO) to function at peak performance. These ground based detectors are susceptible to high magnitude teleseismic events such as earthquakes, which can disrupt proper functioning, operation and significantly reduce their duty cycle. As a result, data is lost and it can take several hours for a detector to stabilize and return to the proper state for scientific observations. With advanced warning of impeding tremors, the impact can be suppressed in the isolation system and the down time can be reduced at the expense of increased instrumental noise. An earthquake early- warning system has been developed relying on near real-time earthquake alerts provided by the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA). The alerts can be used to estimate arrival times and ground velocities at the gravitational- wave detectors. By using machine learning algorithms, a prediction model and control strategy is developed to reduce LIGO downtime by 30%. This paper presents improvements under consideration to better develop that prediction model and decrease interruptions during LIGO operation.

INTRODUCTION

The two detectors that compose the Laser Interferometer Gravitational-Wave Observatory (LIGO) along with Virgo, and GEO600 detectors form a global network of gravitational wave interferometers. Keeping the detectors in operating mode requires an exceptional level of isolation from the ground so that the cavities can be held in optical resonance and be capable of observing displacements in space-time of less than one thousandth of the diameter of a proton. Environmental disturbances such as earthquakes can disrupt operating mode, destabilize detectors and cause the detectors to fall out of lock despite seismic isolation systems already in place to minimize interfering effects. When the detectors have fallen out of lock, where the control system cannot maintain optics at their stabilized positions, it can take many hours to return to the locked state and normal operation. During the observation run (referred as O1), from January 18, 2015 to January 12, 2016 operation was disrupted 62 times at LIGO Hanford and 83 times at LIGO Livingston due to earthquakes. Previous studies have shown that by using an early-warning earthquake system, relying on alerts provided by the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA), arrival times and ground velocities could be predicted which have a direct correlation with the operation status of the interferometers (Coughlin et al. 2017). The higher the incoming seismic velocities the more unstable the interferometer. A strategy intended to maintain lock and suppress these seismic disturbances early in the isolation system, at the expense of sensitivity and increased noise, would notably increase the interferometers' duty cycle (Biscans et al. 2018). Consequently, an earthquake early warning application named Seismon has been created to process real-time alerts from the USGS containing specific characteristic information about the earthquakes to provide estimated arrival times of the seismic phases and seismic amplitudes of the surface waves at the detector sites. By implementing detector control configurations, it is predicted that 40 to 100 earthquake operation interruptions could be prevented in a 6-month period.

OBJECTIVES

We aim to improve the algorithms of Seismon and as a result reduce LIGO downtime and increase the time the detectors are in observing mode. The alerts received from USGS contain information on time, location, depth, and magnitude of a specific earthquake which is then used to predict ground velocities, arrival time and amplitude of the various seismic phases at the detector sites. Seismon initially relies on earthquake notifications from a worldwide network of seismometers. P-waves (primary) traveling twice as fast as S-waves (secondary) reach the seismic stations first, thus providing the initial earthquake character estimations. As more and more data is acquired solutions to the hypocenter and magnitude of the earthquake are estimated and the solutions are sent to USGS's Product Distribution Layer (PDL). This ensures Seismon receives the most pertinent notifications. From there the notifications are processed to predict the seismic wave arrival time and the amplitude of the ground motion at the detectors. Past earthquake records and the seismic data at the detectors are also examined to predict how the ground motion will affect the observatories. The predicted amplitude and past earthquake data are compared, with the difference being minimized by adaptive simulated annealing algorithms to obtain solutions close to the global minima. Lastly, the predictions are used to create warnings to the detectors containing the amplitude prediction, lockloss probability and the anticipated earthquake arrival time at the observatories. Seismon performance can be evaluated by recording and analyzing the notification duration, accuracy of predicted ground-motion amplitude, time-of-arrival predictions and the detector lockloss predictions. Current evaluations with the LIGO Observing Run 1 from September 2015 to January 2016, show about 90% of seismic events are within a factor of 5 of the predicted ground velocity and within 3s of the final predicted arrival time (Coughlin et al. 2017). Examining the times lockloss occurred, it can be said that the detectors generally fall out of lock at ground velocities greater than 5 μm/s but at lower velocities the data is more complex. Therefore, incorporating more ways of determining better lockloss predictions are of interest and would demonstrate success in this project. We purpose to improve the Seismon algorithm by incorporating more machine learning methods, broadening ground motion parameters and collecting more accurate data to enrich the prediction models.

APPROACH

We intend on advancing the Seismon application by improving predictions and acquiring more data of various parameters of incoming teleseismic events. We will test if the arrival time predictions can be improved by machine learning algorithms. To enhance ground velocity predictions, we will explore broadening our data resources and determine if we can acquire more data from hundreds of other seismic stations around the U.S. and the world. In addition, we would like to discover if we can use moment tensor data to further improve velocity predictions.

PROJECT SCHEDULE

I propose the following analysis and timeline for improving the code base: **1.** (week 1-3) Running and understanding the existing infrastructure. **2.** (week 4-6) Applying existing methods to broader seismic datasets. **3.** (week 7-10) Employing machine learning algorithms to improve on the existing algorithms.

REFERENCES

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