LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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LIGO SCIENTIFIC COLLABORATION

Technical Note	**LIGO-T2200408–v1**	2023/07/19

Earthquake Picket Fence White Paper

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Distribution of this document:
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1 Summary

This document describes the need for the LIGO gravitational-wave detectors to receive ground motion data from a set of nearby seismic stations with less than 50 seconds of latency to prepare for seismic-wave arrival in the event of a teleseismic earthquake.

A new era in astronomy began when the LIGO instruments detected gravitational waves (GW) from a binary black hole merger. This required the ability to measure the change in length of the 4-km long LIGO interferometers to attometer precision. This is accomplished by operating the instruments as resonant optical cavities. Not surprisingly, these resonances are delicate and can be lost if elaborate isolation of external disturbances is not complete. The Rayleigh waves produced by earthquakes challenge this isolation. In the past five years, LIGO has implemented a control configuration called earthquake (EQ) mode to allow LIGO instruments to maintain resonant operation or "lock" during earthquake events whose strength would have previously caused lock loss. This is important because it usually takes hours to regain lock. Since LIGO's targets are astronomical systems, a GW event could occur at any time. LIGO is blind to GWs when out of lock. While EQ mode reduces sensitivity somewhat, detections may still be made during it and full sensitivity immediately regained after the EQ. Since some types of GW events are very rare (such as those with electromagnetic counterparts accessible to astronomers), maximizing on-air time is crucial to LIGO's scientific mission.

The goal of the Picket Fence is to increase the warning time for approaching seismic waves and thus the possibility to engage EQ mode by monitoring seismic signals from an array of five to six seismic stations hundreds of kilometers away from each site. The stations are streamed from the IRIS DMC using a SeedLink connection. Unfortunately, after setting up this system, we realized that the seismic data did not arrive in real time due to latencies in the data packets we receive from the different stations. This prevents effective warning time at the LIGO sites and thus negates the value of the Picket Fence.

To fully realize the potential of the picket fence as a warning system, we need stable low-latency connections to seismic stations near the LIGO observatories.

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2 Background

The LIGO detectors are a pair of gravitational-wave observatories in the U.S. that have been part of many scientific breakthroughs over the last decade [1–3]. In a very rough sense, each detector consists of a seismically-isolated, in-vacuum, 4-km long laser interferometer [4].

In order to meet the requirements for gravitational-wave observation, the detectors are designed to mitigate noise in the detection band of the observatories, including—but not limited to—seismic, thermal, and quantum noises.

The seismic isolation subsystem consists of multiple in-vacuum seismic isolation platforms (or ISIs). These combine passive suppression and active control to suppress the effect of the ground motion on LIGO optics suspended from the platforms.

To reduce the overall root-mean-squared (RMS) motion of the optics, the nominal control configuration of the seismic system is tuned to apply isolation in the microseism band (from 0.12 to 0.30 Hz), at the expense of amplifying the ground motion in the 50 to 80 mHz band (the earthquake band). Typically this is a good tradeoff, since much of the ground motion is concentrated around the microseismic band. However, in the event of an earthquake, the motion resulting from the Rayleigh waves is amplified by this configuration, leading to non-linear upconversion of motion, saturation of actuators and other negative effects. Ultimately, the amplified motion prevents the observatories from holding the optical resonance needed for low-noise operation, rendering them unable to detect gravitational waves.

For reference, during the second half of the third observing run (O3b), the total coincident low-noise time of the two LIGO observatories makes up for 66% of the run [5], with the Hanford, WA (LHO) and Livingston, LA (LLO) observatories running 78.3% and 78.1% of the time respectively. Therefore, despite the numerous observations and events of this run [6], a great deal of science was missed. Improving the duty cycle of the observatories is one of the main undertakings necessary to increase the scientific output of the observatories.

As shown in [7], earthquakes are the leading known cause for disruption of low-noise operation (or lockloss) in the interferometers. Much effort has been devoted to developing early alert systems such as SEISMON [8] and a special control strategy, the earthquake (EQ) mode [9], to help the observatories survive earthquakes while maintaining low-noise operation at the cost of some sensitivity. While these improvements have played an important role in increasing the robustness of the instruments, as shown in [9], there is still room to improve. For example, the SEISMON predictions are more than a factor of 5 away from the measured ground motion about 45% of the time. In order to use EQ mode effectively, we require an accurate forecast of the ground motion data at the observatories during an earthquake. The information must be precise and timely enough to allow the engineers to make control decisions before the Rayleigh waves arrive to the sites.

3 Picket Fence

3.1 Description

The earthquake picket fence is a complementary and parallel addition to SEISMON's machine-learning predictions. It attempts to *observe* earthquakes before they arrive at the observatories. This is achieved by monitoring a set of seismometers surrounding each of the LIGO observatories (like a fence). The seismometers are selected from a list of seismic stations—called picket stations—that can be streamed in near real time from the IRIS Data Management Center (DMC) and meet the criteria for data quality, data availability, and accuracy relative to the ground motion at their corresponding LIGO observatory. The data is streamed using the ObsPy python package [10–12], and used as a forewarning for earthquakes.

The first practical implementation of the picket fence for LIGO is documented in [13]. It has gone through multiple iterations, and here we compile a few details of the current implementation. Then we proceed to highlight performance metrics that will be relevant for evaluating its effectiveness as part of an early alert system for the observatories.

3.2 Picket Stations

Figure 1 shows the current seismic stations used for the LIGO Hanford Observatory (LHO) and LIGO Livingston Observatory (LLO) picket fences. The solid green line represents the effective perimeter of the picket fence, assuming a circular wavefront for the Rayleigh waves and a source located 3000 km away. All stations were selected to be about 400 km away from the LIGO sites with the intention that the seismic readings at the picket fence would be reflective of the ground motion at the observatories. The most notable exceptions to this rule are the TEIG (Tepich, Yucatan, Mexico) and DWPF (Disney Wilderness Preserve, Florida,

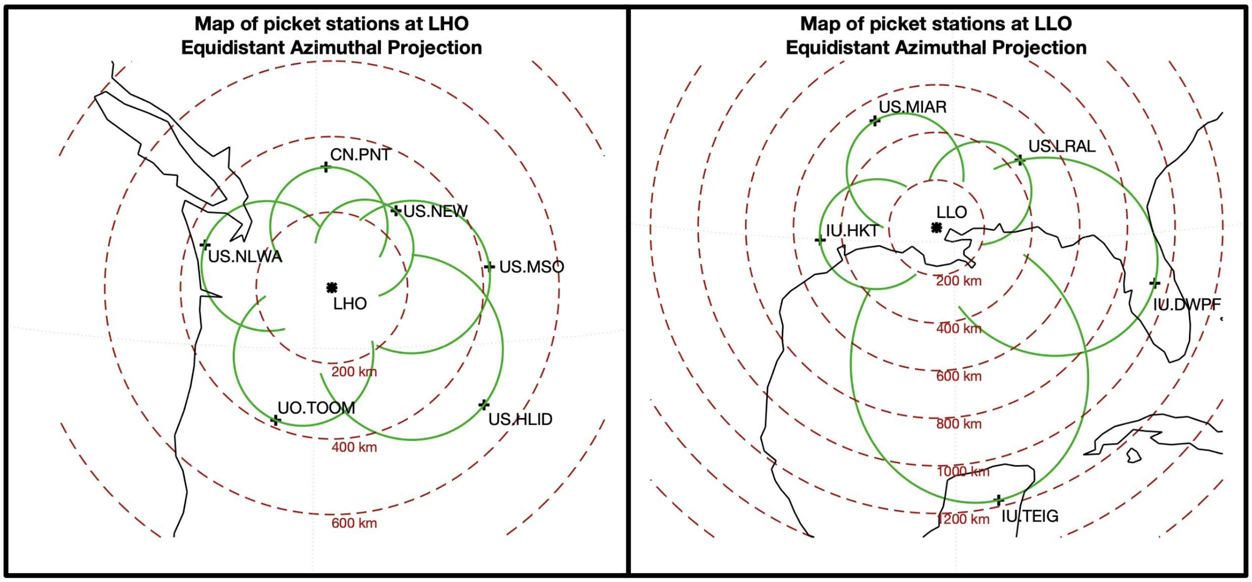

Figure 1: Picket stations around the Hanford, WA (LHO) and Livingston, LA (LLO) observatories. The solid green lines represent the zero-latency warning lines of the stations for incoming waves on a specific direction from the center of the map.

USA) stations to the south of LLO due to the Gulf of Mexico not having any seismometers we could access.

Ideally, the picket stations must be located as close to the observatories as possible so the streamed data is accurately predicts true motion at the LIGO sites. For early warning puropses, the picket fence must also provide 50 seconds of warning time before the Rayleigh waves of an earthquake arrive at the sites (20 seconds to capture one period of the Rayleigh waves to trigger EQ mode, plus 30 seconds to allow the controls transients to settle). Increasing the effective radius of the picket fence can allow for earlier, but less accurate earthquake warnings. This tradeoff determines the usefulness of the picket fence.

3.3 Latency

The travel time for Rayleigh waves between a picket station 400 km away and the LIGO observatories is around 100 seconds. To achieve the desired 50 second warning time we need the data travel time to be less than (100-50) = 50 seconds. This condition would guarantee the effectiveness of the picket fence as an early warning system for teleseismic events.

The tradeoff is further complicated when we consider the latency of the sensor data stream. The relevant figure of merit is the data travel time, defined as the time difference between data acquisition by a remote sensor and data delivery to the LIGO sites. Ideally, the data travel time is shorter than the time it takes for surface waves to travel between the boundary of the picket fence and the observatories. Figure 2 shows the distribution of time differences between data acquisition by a remote sensor and data delivery to the LIGO sites for the current picket stations. The typical 95th percentile data travel time for a station is around 75 seconds. We see that only 60% of datapoints arrive with a latency lower than the 50 second

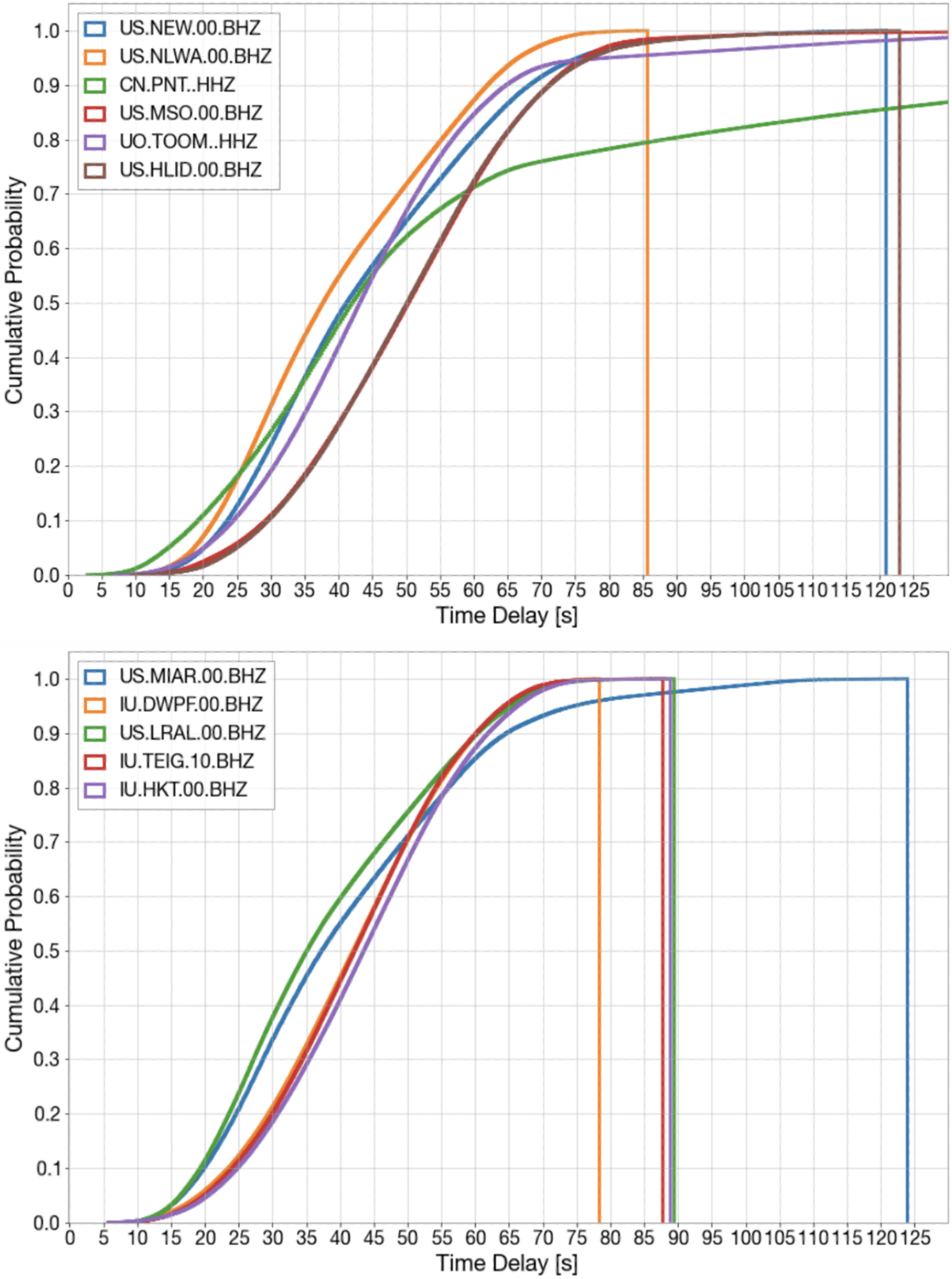

Figure 2: Comparison between the data travel times observed at selected picket stations and their two respective observatories. The latency test was performed over two segments of 4 hours on Jun 4th 2023.

threshold. This situation means that in practice the latency in data delivery prevents the picket fence from providing early warnings 40% of the time.

To remedy this situation, we could select picket stations farther away to satisfy the latency constraint, sacrificing accuracy. This requires a survey of potential stations to ensure they meet the rest of our criteria. Alternatively, we could reach out to seismology experts to scout for better connection to real-time seismic data or alerts. In this scenario, we would get better latency and accuracy for the whole picket fence.

3.4 Accuracy

Following [9], the EQ mode is most helpful in maintaining the low-noise conditions for earthquakes where the maximum ground amplitude at the observatory is between 1 µm/s and 3 µm/s. Accuracy for earthquakes with local motion in this range is central to the function of the picket fence. Our goal is to achieve for a factor of 2 between the expected and observed maximum amplitude of the filtered ground motion.

Figure 3 shows two examples of the comparison between the earthquake waveforms observed at the picket station and the LIGO sites. These figures demonstrate a larger trend where the picket fence is more accurate for teleseismic events (when the distance to the epicenter is much larger than the distance between the picket stations and the observatories). The disparity between the waveforms is caused by a combination between the geometric attenuation of the Rayleigh waves (proportional to $1/\sqrt{r}$), their dispersive nature, and wave interference effects. As such, we expect that no scale factor can relate the picket sensor's ground motion to the local sensors at the observatories without knowledge of the location and depth of the earthquake event.

Currently, we use a 1:1 scaling for the projected local ground motion from the picket fence. With this scaling, we expect the picket fence to provide accurate maximum ground motion amplitude predictions for teleseismic events and an oversized warning for nearby seismic activity. Since teleseismic events make up for most of the events relevant to the EQ mode activation, we believe this is a good starting point for the picket fence predictor. This is evidenced in Fig. 4, where we compare past picket station data with observatory ground motion in the EQ band and obtain predictions that are within a factor of two for about 80% of the events sampled, compared to SEISMON's 65% within a factor of 5. In the future, more accurate predictions will rely on our ability to obtain enough epicenter information to estimate the amplitude at the observatory before the arrival of Rayleigh waves. We suspect this information could be obtained from the IRIS DMC in a low-latency way, or inferred by using redundant picket stations.

3.5 Consistency

The last hurdle for automating the response of the sites to earthquakes is to ensure the availability of the picket fence data. Over the last year of running the picket fence, we have collected several examples delivering spurious data. An example is captured in Fig. 5, where the TEIG station (located in Tepich, Yucatan, Mexico) exhibited large amplitude oscillations at a period of 4 minutes.

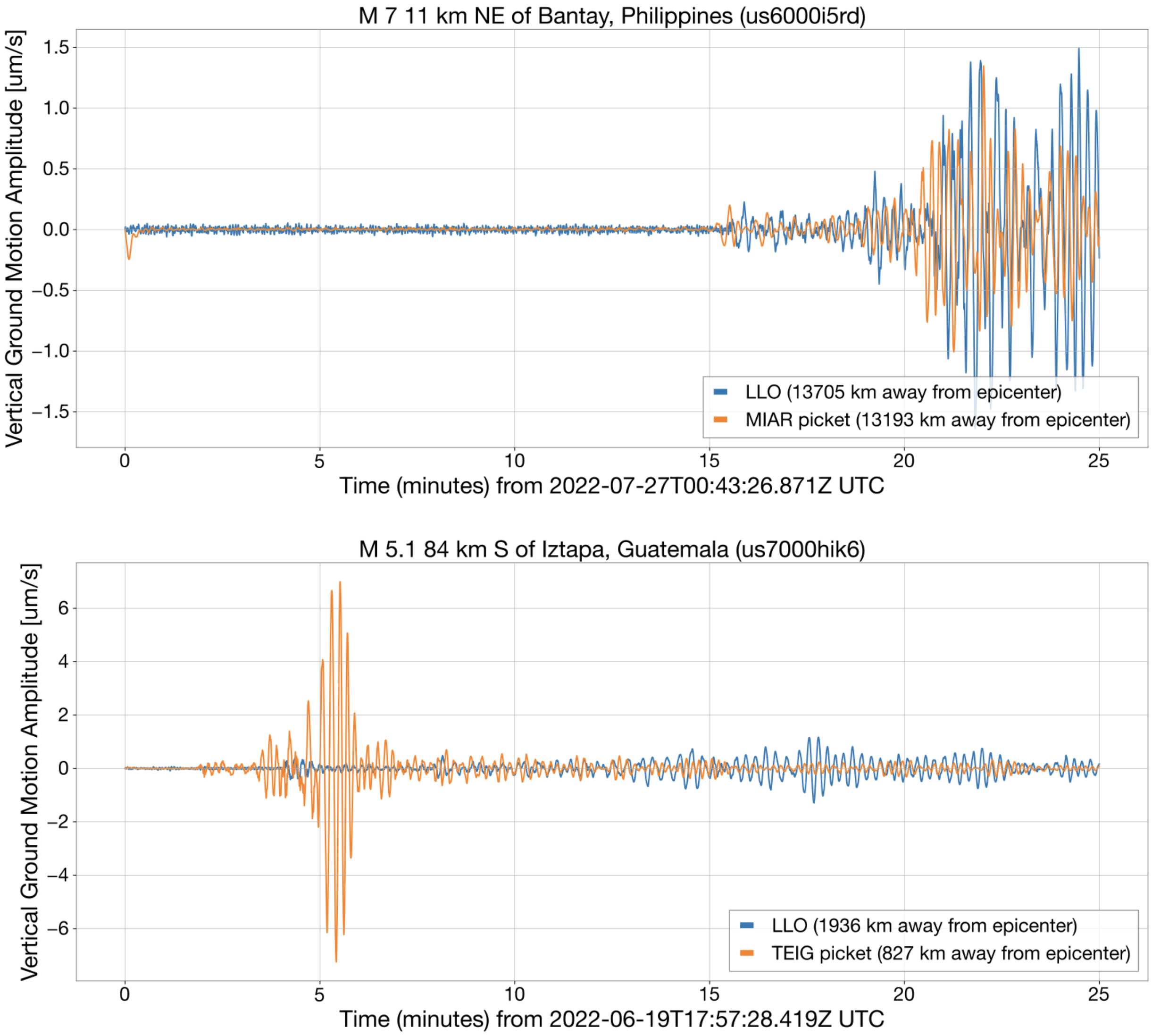

Figure 3: Comparison between the ground motion data observed at a picket station and LLO. The waveform amplitudes are better matched for distant events (top) than they are for nearby earthquakes (bottom).

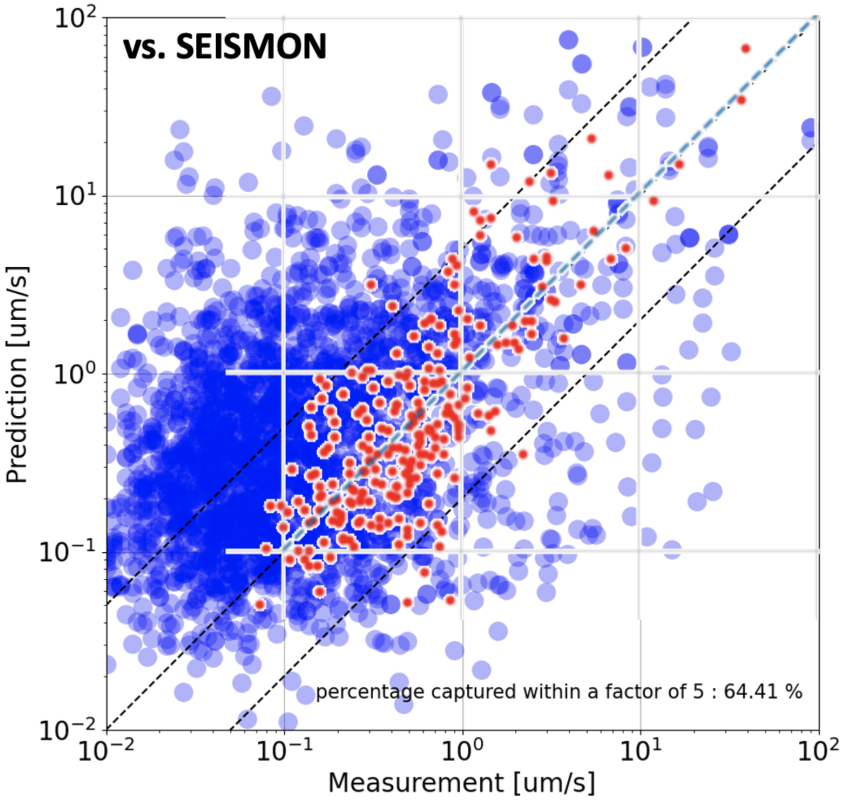

Figure 4: Comparison between the maximum earthquake amplitudes as predicted by SEISMON (blue dots) and the 1:1 picket fence (red dots). The black dashed lines encapsulate the region where the predicted and observed amplitudes are within a factor of five of each other.

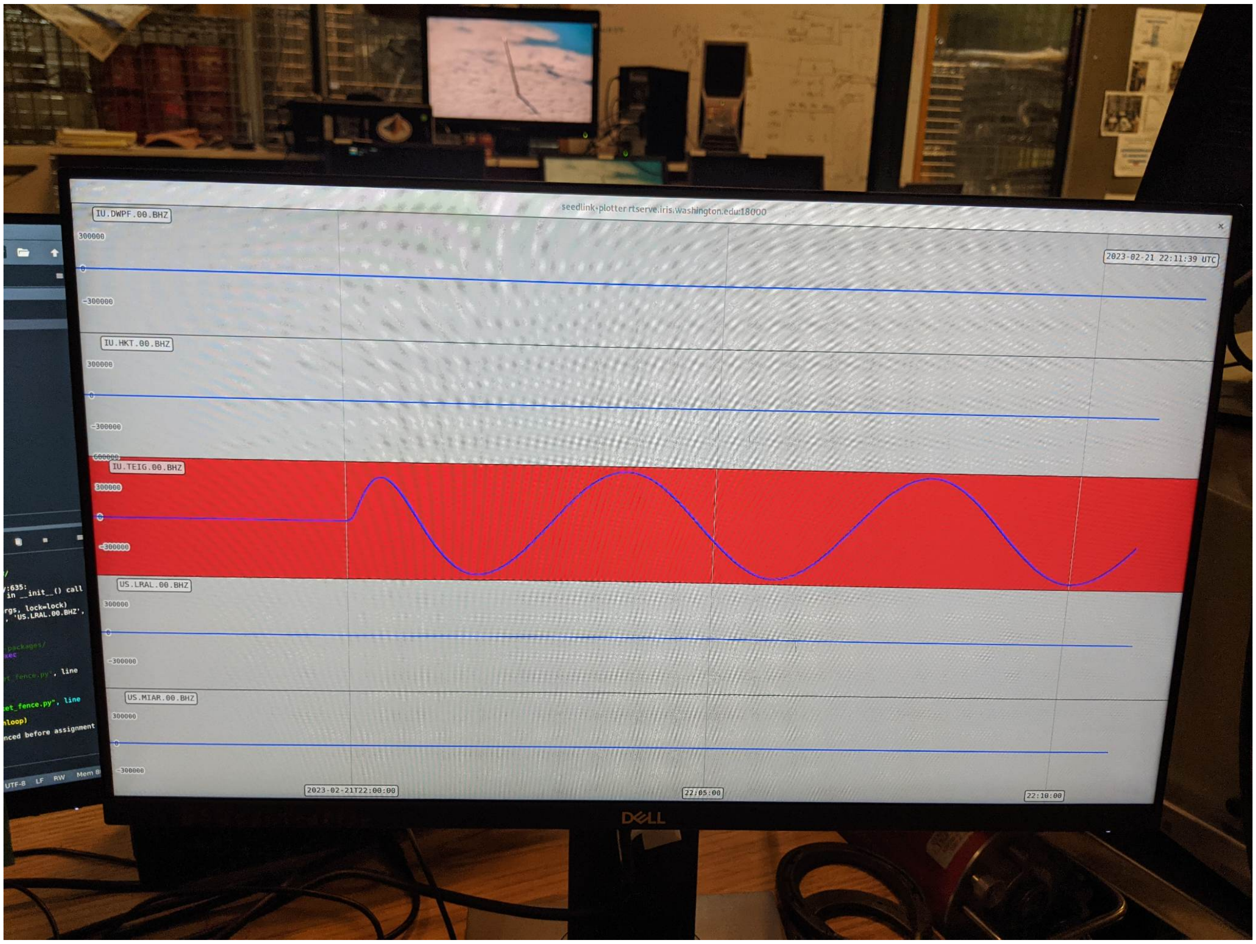

Figure 5: Anomalous behavior of the seismometer in the TEIG (Tepich, Yucatan, Mexico) station. Recorded February 21, 2023 at 22:00 UTC.

Another reliability issue are lag spikes. The extra data delay from the PNT station (located in Pentington, British Columbia, Canada) shown in Fig. 2 is caused by a segment of high time delay during our data collection test.

Both type of events are unpredictable with the information we possess, so we can only filter the data we receive until a better solution is achieved. To mitigate the effects of tests or glitches the code excludes picket stations with ground motion amplitude greater than 50 µm/s from data analysis for a short period of time. Since the EQ mode controls would not be effective for an real seismic event of that amplitude, losing the ability to predict a potential event is not a significant loss.

In the future, a better solution would involve redundancy on the picket fence coverage, so at least a pair of stations is covering every direction of the observatories at the desired latency. Additionally, we must aim to establish a channel of information on tests, maintenance or interruptions of the data stream from the picket stations by contacting the relevant experts.

4 Conclusion

We have shown the potential and limitations of the picket fence as an early warning system for the LIGO detectors. In principle, an early warning system would provide accurate and timely information to inform control decisions at the LIGO sites, improving the robustness of the detectors in the process. The tradeoff between accuracy and data latency constrains many of the choices we are able to make when selecting suitable seismic stations to monitor.

Using stations 400 km away from the LIGO observatories we are able to obtain remote data that is well correlated with the ground motion at the LIGO sites. However, in order for the picket fence to have a tangible impact on the scientific output of the LIGO detectors, we need to obtain a data latency of less than 50 seconds, a condition that is not consistently achieved by any of the streamed seismometers from the public database. Moreover, documented data anomalies have prevented the full adoption of the picket fence as part of our automated control flowchart.

In conclusion, in order for the picket fence to have a tangible impact on the scientific output of the LIGO detectors, we need to obtain access to high quality seismic data with a lower latency than we currently can. To that end, we need to partner with the people and institutions running the seismic networks and databases we wish to stream to the LIGO sites.

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