Earthquake Picket Fence Performance Analysis

Edgard Bonilla, Isaac Aguilar, Brian Lantz

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1 Background

During the periods where the interferometers are not locked, no astrophysical measurements can be made with them. During O3b, the total coincident time when the two LIGO observatories were in low-noise operation makes up for 66% of the run [1], with the Hanford (LHO) and Livingston (LLO) observatories running 78.3% and 78.1% of the time respectively. This means that the numerous observations and events of this run [2], there is still a lot of science we are missing out on. Consequently, 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 [3], seismic activity (namely, earthquakes) is the leading cause for lockloss in the interferometers. Much effort has been devoted to developing early alert systems [4] and a special control strategy, the EQ mode [5] to help the observatories survive earthquakes while in low-noise operation. These improvements have indeed played an important role in increasing the robustness of the observatories, as shown in [5]. However, there is still room to improve. The SEISMON predictions are more than a factor of 5 away from the measured ground motion about 45% of the time, which limits our ability to use the EQ mode effectively. Improvements in this predictive ability, as well as eventual tuning of the controls will likely have a significant impact in the robustness of the interferometers.

1.1 Picket Fence

The earthquake picket fence is one complementary and parallel addition to the SEISMON predictions. It attempts to *observe* rather than predict earthquakes before they arrive at the observatories. This is achieved by tapping into the data of multiple seismic surveys, which is available online through the ObsPy python package [6, 7, 8]. The idea is that by observing the measurements from sufficient seismometers in a “fence” around each observatory, we can accurately estimate the amplitude of the ground motion at the sites before the earthquake waves get to them. This increased accuracy can be used to better inform the control decisions at the observatories, ultimately leading to increased robustness of the interferometers.

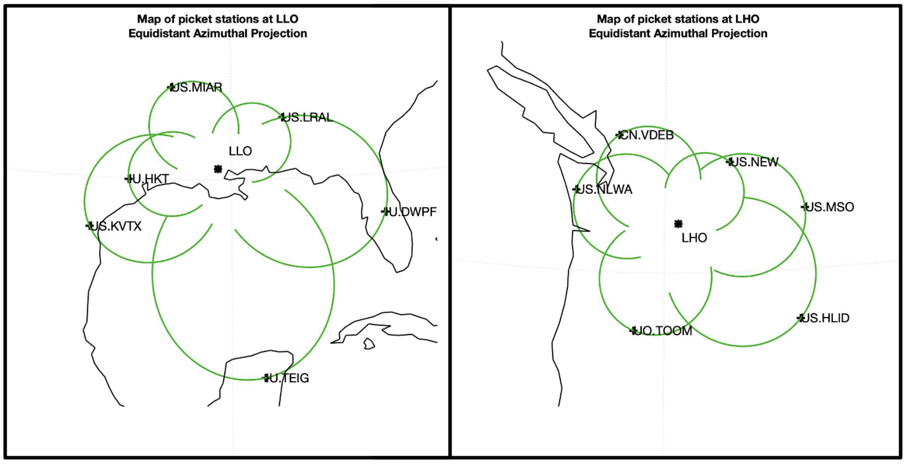

Figure 1: Picket stations around the Hanford (LHO) and Livingston (LLO) observatories. The green lines represent the equivalent virtual location where a particular station would be to get the same warning time for surface waves arriving from a different direction to the respective observatory in the center of the map.

The first practical implementation of the picket fence idea for the LIGO observatories is documented in [9], and it has gone through multiple iterations to the form we analyze in this document.

In what follows, we compile a few details of the current implementation of the picket fence. Then proceed to analyze a few performance metrics that will be relevant for evaluating its effectiveness as part of an early alert system for earthquakes at the observatories.

1.2 Picket fence stations

A map of the Hanford (LHO) and Livingston (LLO) observatories' picket fence stations is shown in Fig. 1. The image shows the stations in an equidistant aziumuthal projection relative to the observatory they encircle. This projection preserves the relative distance between all points in the map and the observatory in the center. The green solid lines going through each station represent the equivalent warning distance from the picket station to the corresponding observatory if the earthquake is coming from a different direction. As such, it represents the virtual zone of warning that the picket fence provides around the observatories.

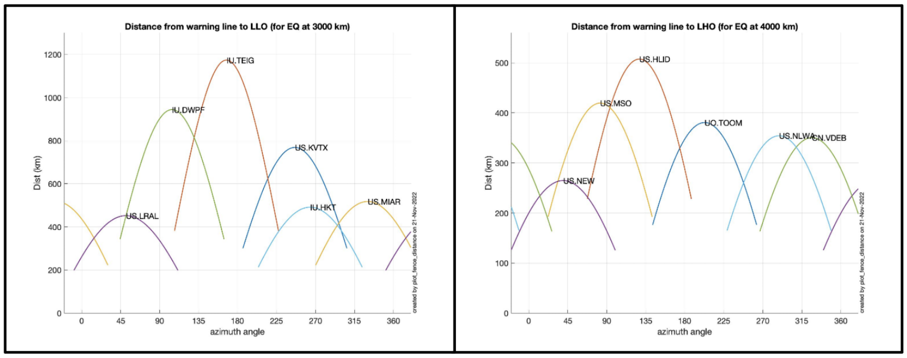

Figure 2: Unwrapped picket fence distances to the respective observatory. These diagrams are documented in [SEI log xxx], and [SEI log xxx].

1.3 Expected Warning times

Using the diagrams from Fig. 1 and an estimated Earthquake surface wave speed of about 4 km/s, we expect that the picket fence will be able to provide information about the surface waves between approximately 55 to 125 seconds at LHO and 85 to 290 seconds at LLO.

2 Analysis of prior earthquake data at the picket fence.

In this section, we analyze a shortlist of earthquakes as a first proof-of-concept test for the predictive power of the picket fence.

For each event in the shortlist, we associate a picket station per observatory (the closest one to the epicenter), and analyze the maximum amplitude, the warning time and other metrics of interest below.

2.1 Data availability

2.2 Maximum amplitude comparison

We can compare the maximum amplitude of the lowpassed earthquake waveforms between the observatories and the relevant picket station for each earthquake event. The direct comparison is shown in Fig. 3, where it can be appreciated that the amplitude of the ground motion is comparable at the sites with the picket fence, this could represent an opportunity to improve the recent results by SEISMON [10] also represented in Fig. 3. The amplitude of ground motion at the picket fence appears to be within a factor of two of what is seen at the observatories about 90% of the time for LHO and 70% for LLO (see Fig. 4, a significant improvement from the current accuracy of within a factor of five

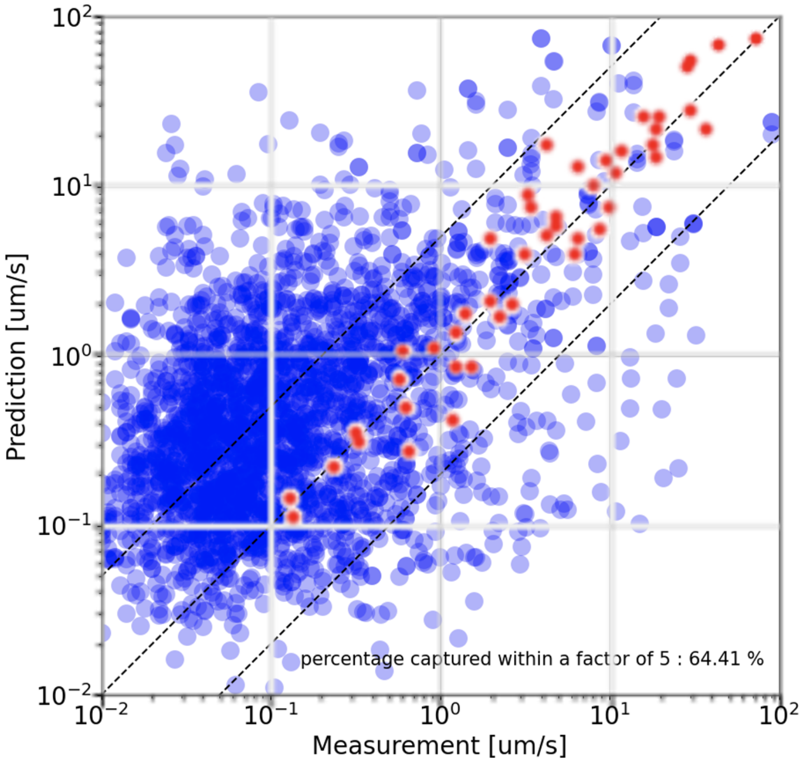

Figure 3: Comparison between the maximum earthquake amplitudes predicted by SEISMON (blue dots) [10], and the predictions of the picket fence if we assumed that the amplitude at the early warning picket station is equal to the one at the respective site. For the events considered the picket fence measurements are able to outperform the SEISMON predictions on average.

65% of the time from SEISMON. These results are preliminary, and likely will change as more earthquake data is included, but are nonetheless a promising indication of the potential of the picket fence.

2.3 Warning time comparison

2.4 First ground oscillations

As documented in [11], It has also been observed that the picket fence is very good at predicting the first few oscillations of the earthquake waveform. This has been shown to be related to direct observation of the P-waves of the seismic event [12], however more analysis needs to be carried to exploit the potential advantages of such detections. Two examples of this behavior are shown in Figures 5 and 6 for earthquake events originating in Alaska.

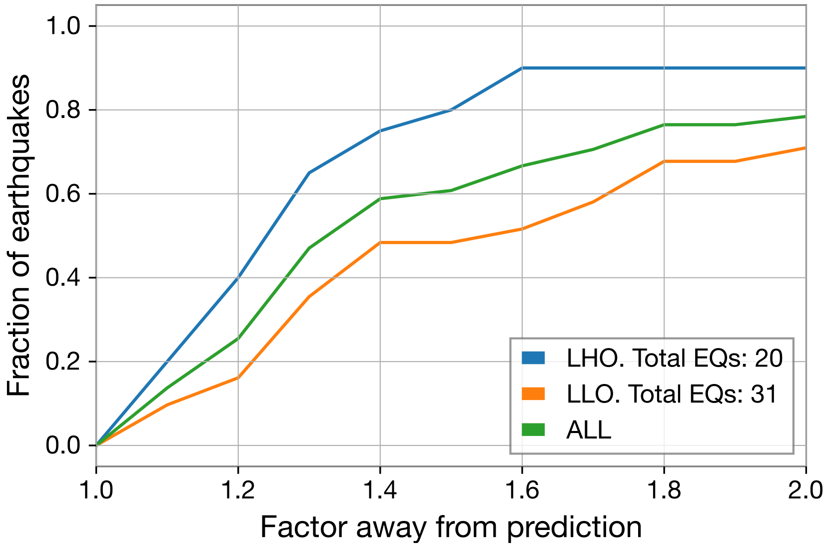

Figure 4: Coverage percentile versus factor of prediction for the earthquake picket fence. We can see that the picket fence observes a max amplitude of the earthquake that is within a factor of two of the one observed at the corresponding site in 80% of the analyzed data.

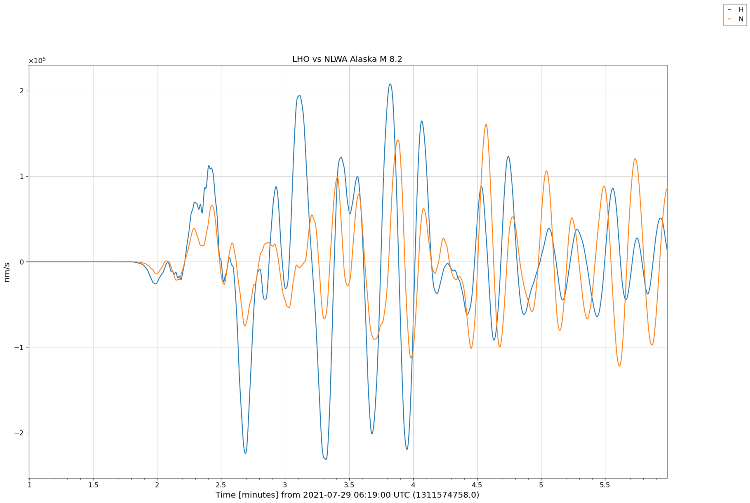

Figure 5: Comparison between first few oscillations of an earthquake as seen in LHO (blue trace), and the NLWA picket station (orange trace). The waveforms have been time shifted about 30 seconds to match the peaks [11].

2.5 P-wave prediction

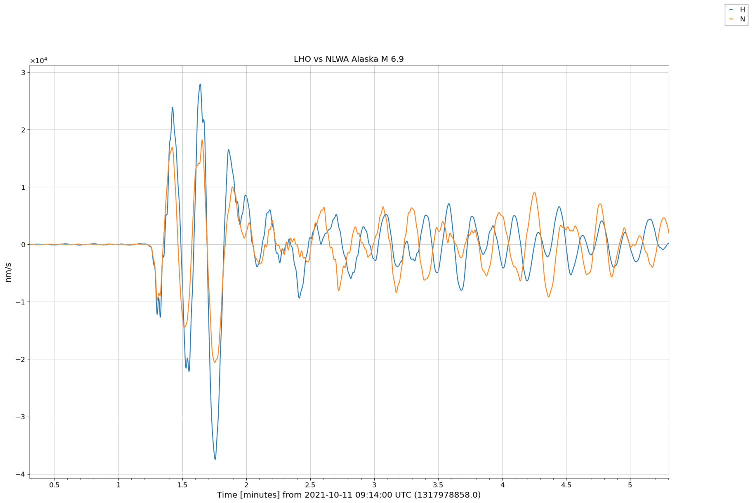

Figure 6: Comparison between first few oscillations of an earthquake as seen in LHO (blue trace), and the NLWA picket station (orange trace). The waveforms have been time shifted about 30 seconds to match the peaks [11].

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