Limiting the effects of earthquakes on gravitational-wave interferometers

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Introduction

- The detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) are susceptible to teleseismic events, which can significantly impact a detector's duty cycle.

- Here we describe an early-warning system for gravitational-wave observatories, which relies on near real-time earthquake alerts provided by the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA).

- Our initial results indicate that by using detector control configuration changes, we could regain duty cycle otherwise lost during 40–100 earthquake events in a 6-months time-period.

Notices
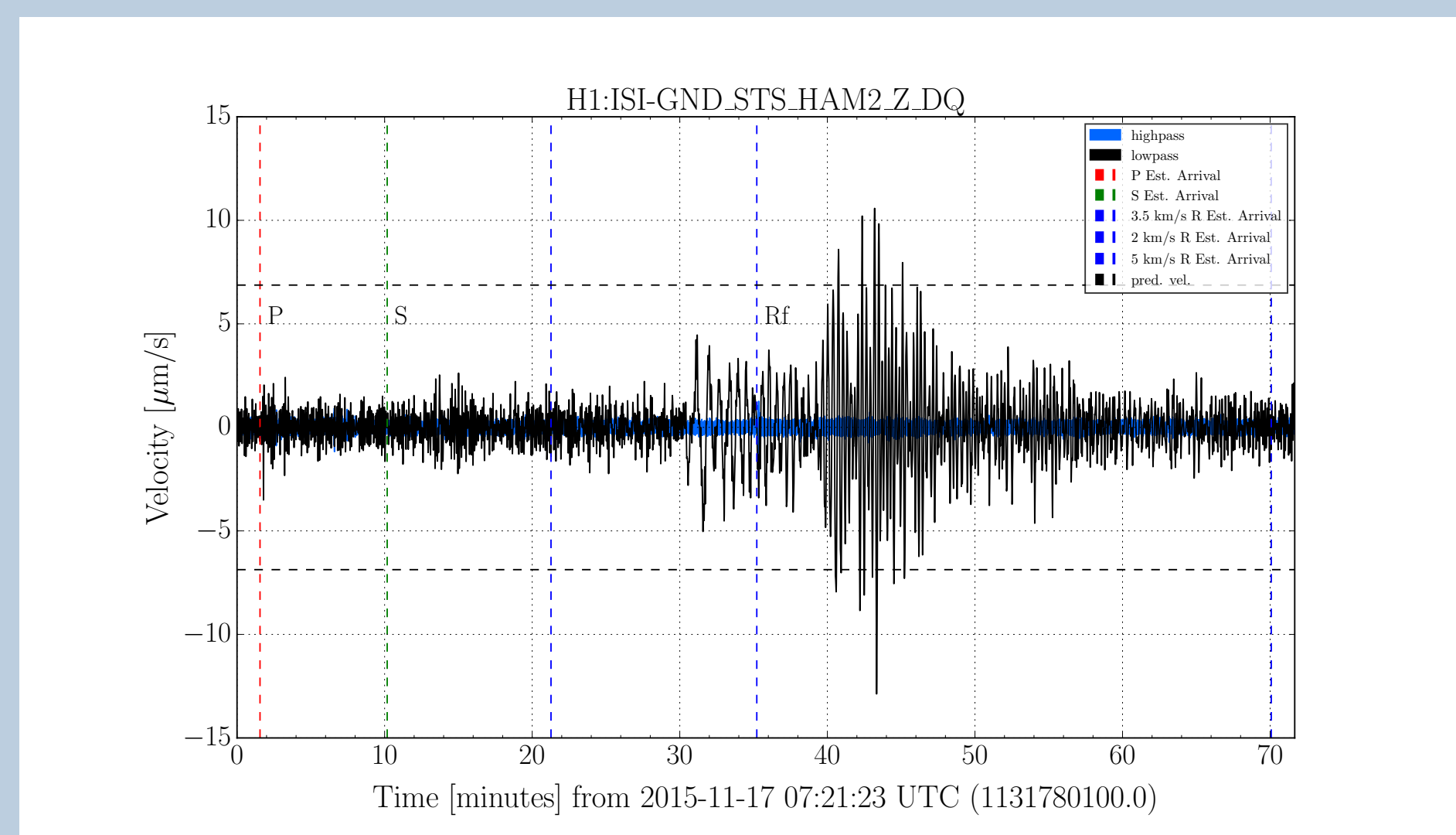
Ground motion from a seismometer at the LIGO Hanford site located in Washington, USA for the Nov 17, 2015 6.5 magnitude earthquake in Greece.

- Warning system relies on the most preliminary notices of earthquakes currently available generated by worldwide networks of seismometers.

- USGS provides preliminary estimates of the location providing latitude, longitude, and depth of each event.

- These solutions are distributed through USGS's Product Distribution Layer (PDL), which has been configured to receive all notifications of earthquakes worldwide.

Epics

- The final step of the process is to use the site amplitude and time-of-arrival predictions to create warnings (and possibly detector state changes) for the detectors.

- The algorithm analyzes the recent notifications and places a threshold on the predictions.

- We provide an epics variable that contains the following information: amplitude prediction, probability of lockloss, earthquake time-of-arrival

Acknowledgements

Ground Velocity Prediction
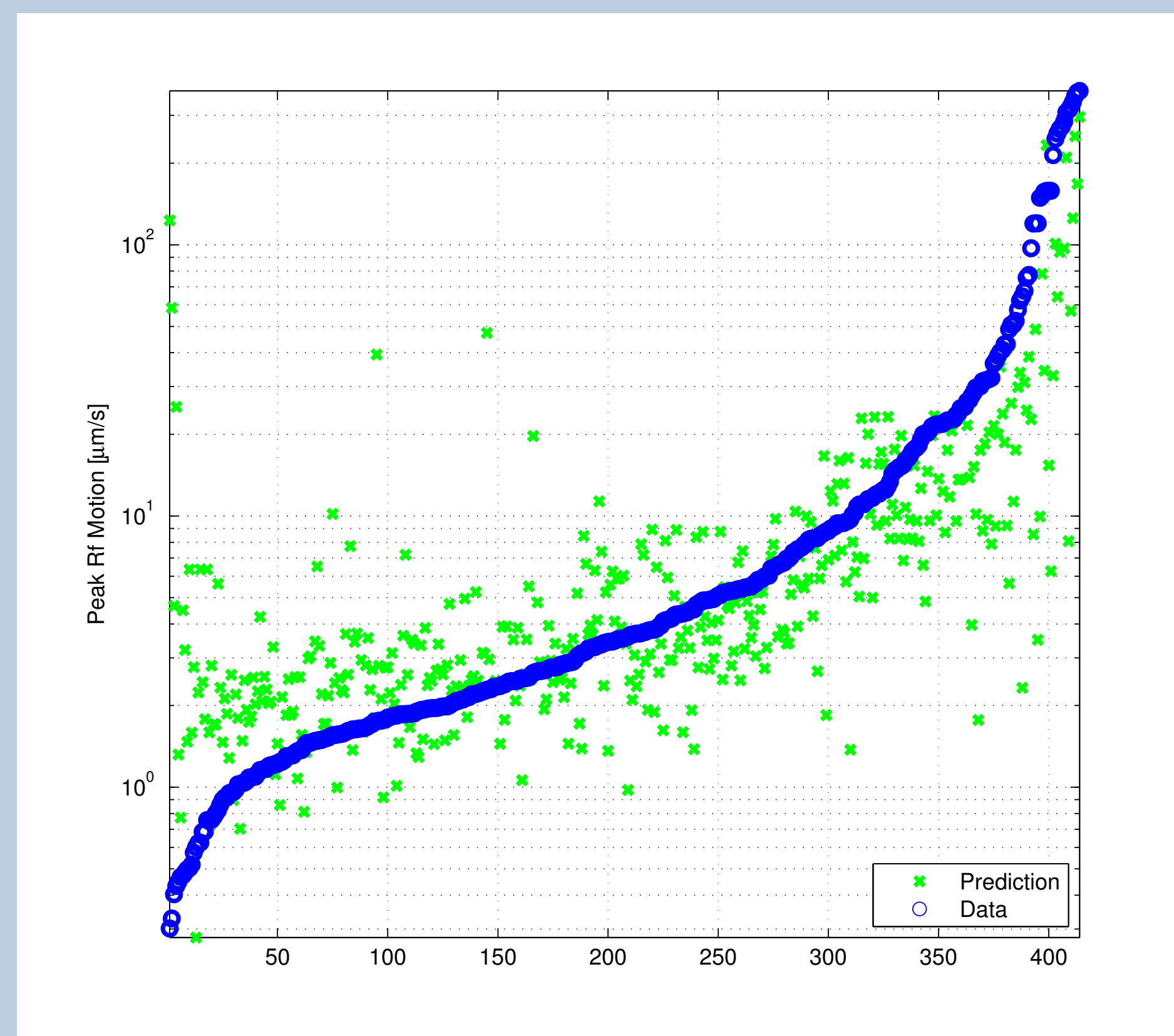
Fit of peak velocities seen during S5-S6 at the LIGO Hanford interferometer to equation 1.

We estimate the peak amplitude of the surface waves, $\mathrm{Rf_{amp}}$, at the sites using

$$\mathrm{Rf_{amp}} = Ae^{-2\pi h f_c/c_1}e^{-2\pi d f_c/c_2/Q}/r^{s_1} \quad (1)$$

where $f_c = 10^{2.3-M/2}$ is the corner frequency, $A = MA_0/f_c^{s_2}$, $Q = Q_0/f_c^{s_3}$, M is the magnitude of the earthquake, d is the distance, h is the depth of the earthquake. The free model parameters are A_0, Q_0, c_i, s_i whose values are derived from minimizing the difference between the amplitude seen at the interferometer and that predicted by the equation.
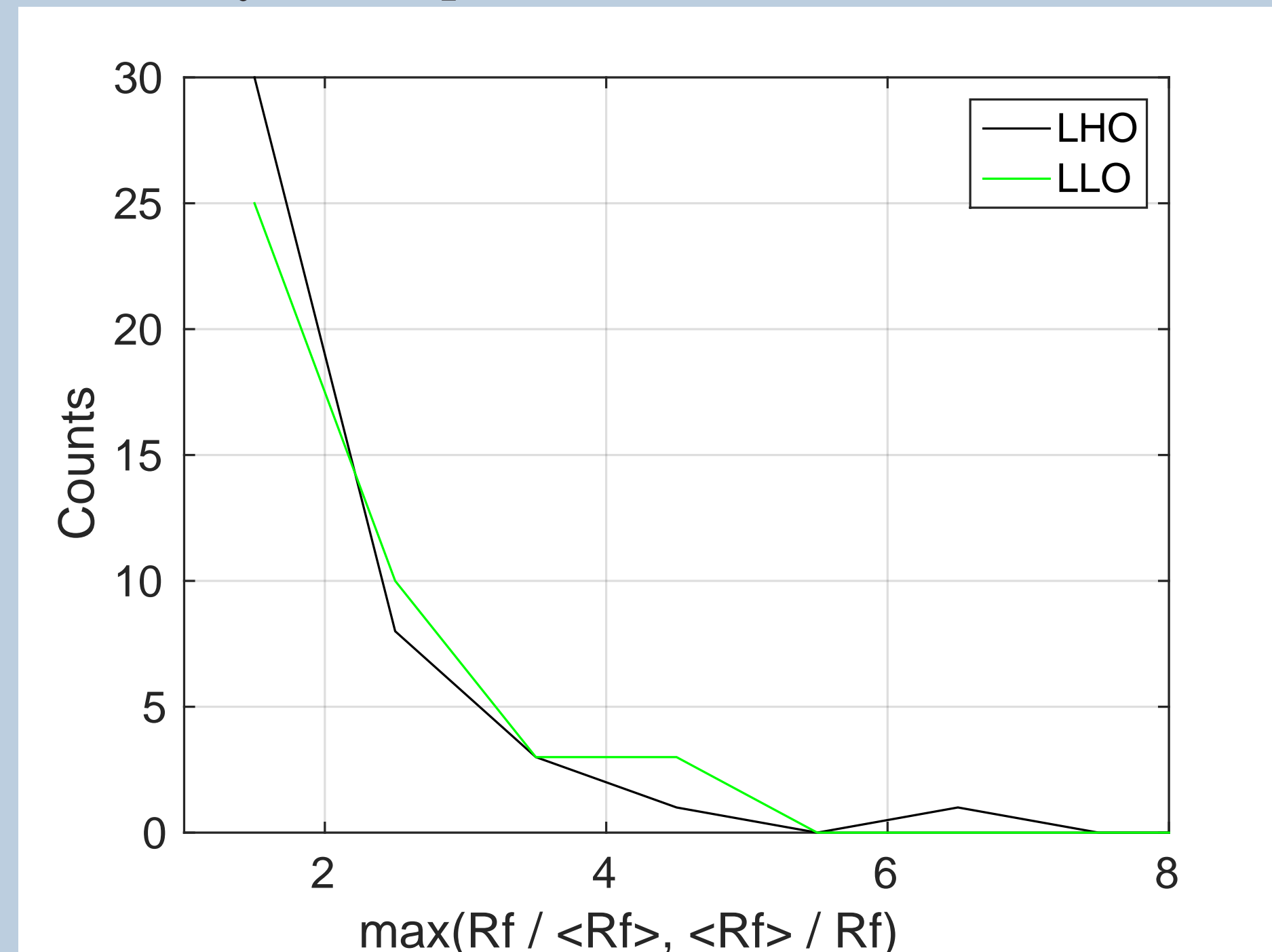

An important quality for an earthquake monitor is the accuracy of the ground-motion amplitude prediction and the time-of-arrival. We show the performance of prediction of peak ground motion seen at the interferometers (LHO and LLO) using fit parameters estimated from previous data. About 94% of events are within a factor of 5, while those that are not are almost exclusively events that are due to the overlap of many events.

Notification latency
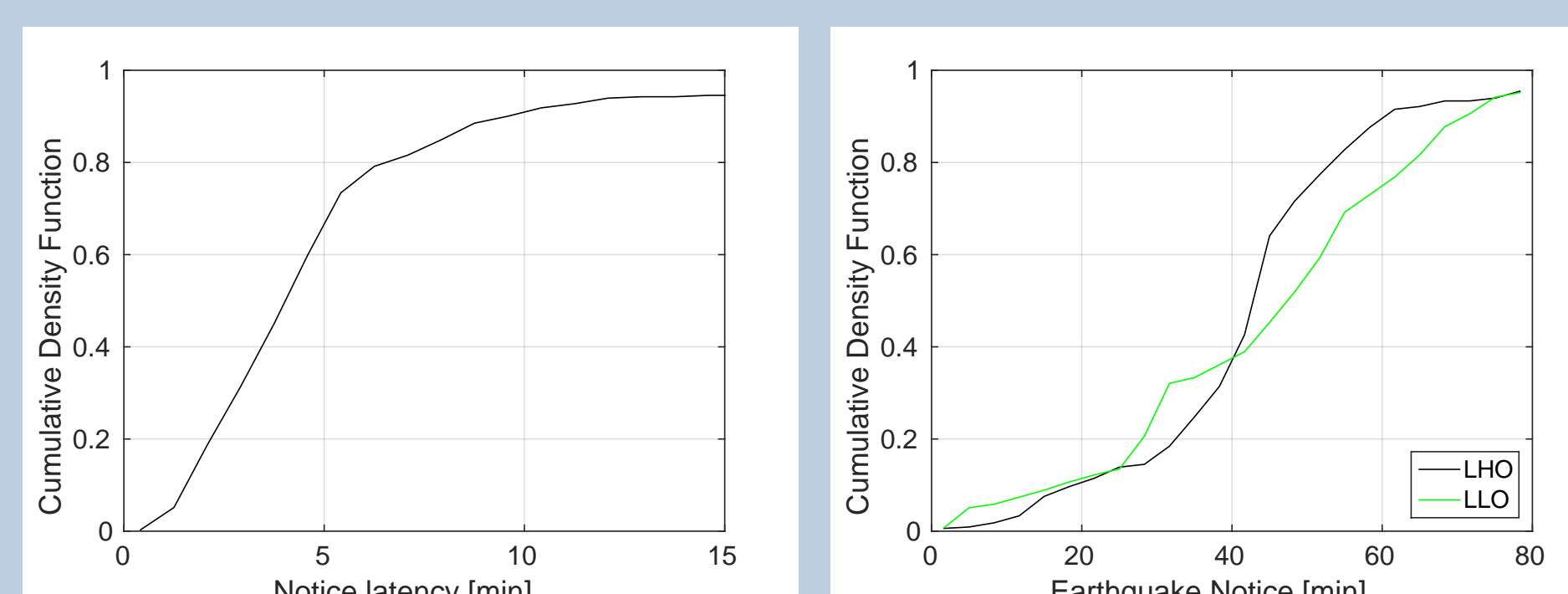
On the left is the time delay between the earthquake and PDL client notification. On the right, the cumulative probability distribution of time delays between the earthquake and approximate arrival of surface waves, assuming surface wave velocities of 3.5 km/s.

Effect of early notices
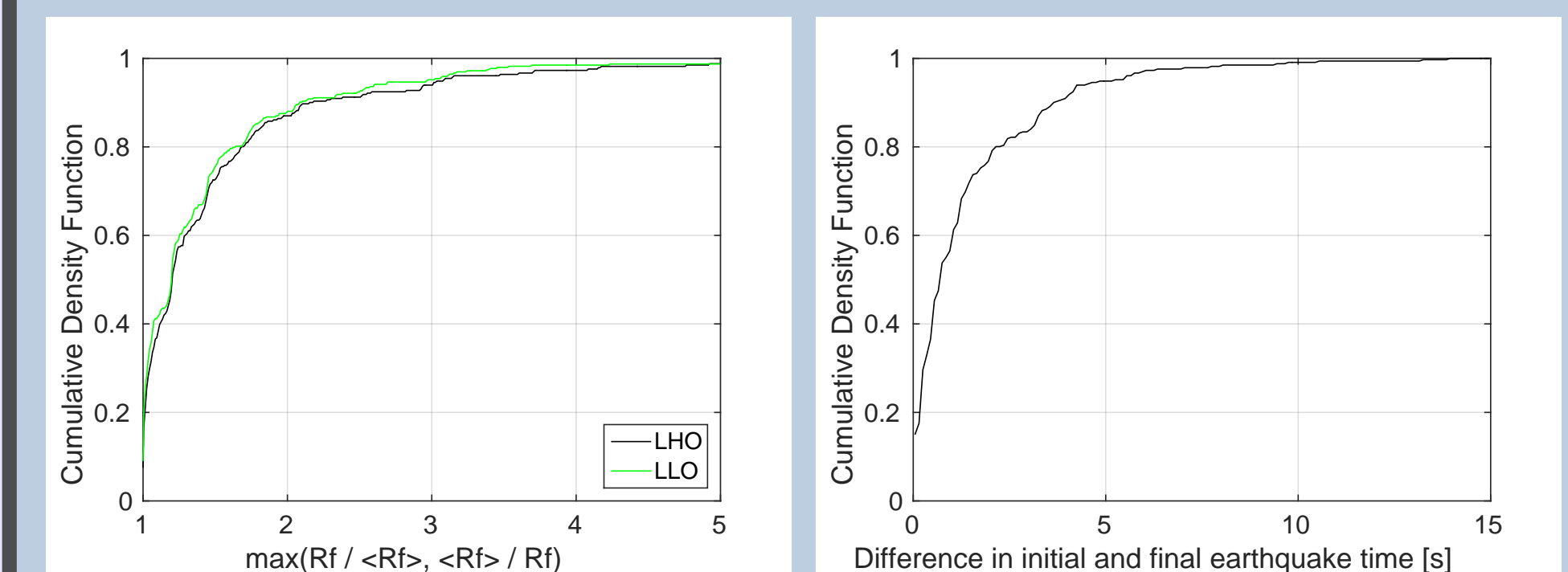
We use the earliest available notices for making time-of-arrival and amplitude predictions. Because the earliest notices may only rely on a few seismometers, as well as the fact that large earthquakes do not fault all at once, the estimates for both magnitude, depth, location, and time can be off. On the left is the difference of predicted peak amplitudes seen at the interferometers using the initial and final estimates. About 90% of events are within a factor of 2 of the final predicted value. On the right is the difference between the initial and final estimates of the earthquake time. About 90% of early estimates are within 4 s of the final time.

Detector Lockloss
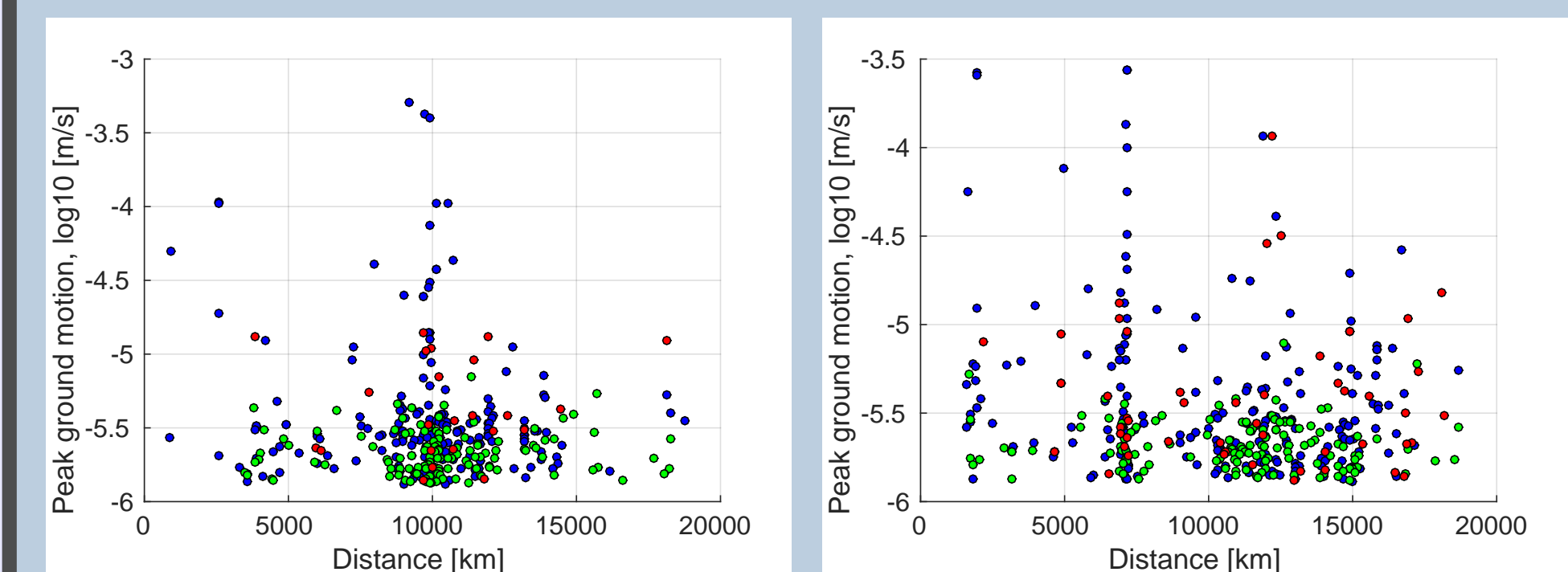
We now measure the amplitude of the seismic ground motion that causes the detector to lose lock. We show these times, both for those times when lock losses occurred (red), when they did not (green), and when the detector was not locked (blue). In general, the plot shows that while in general ground velocities greater than about 5 μm/s lead to lock loss, the situation is complicated at lower ground velocities.

Lockloss prediction performance
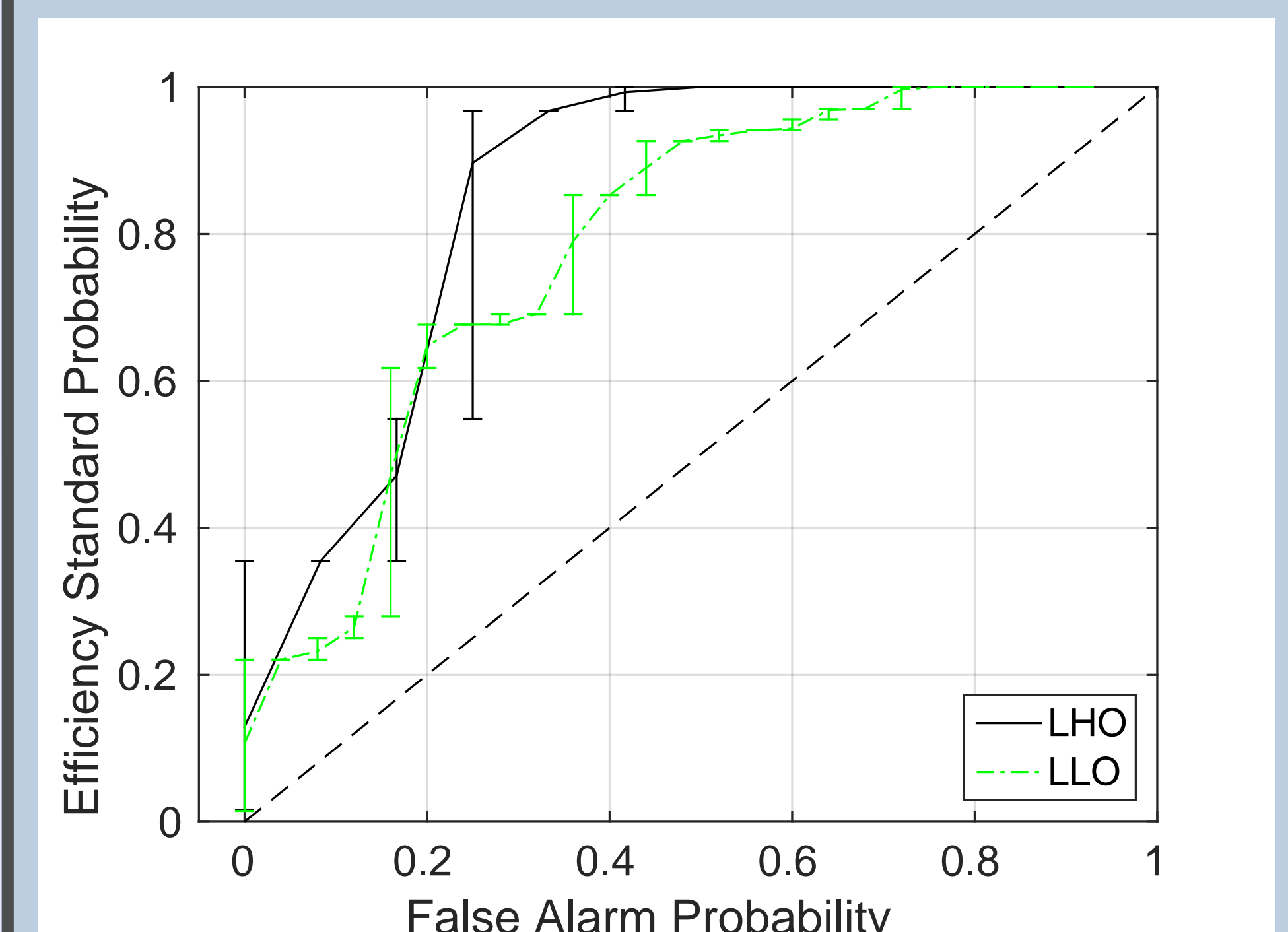
We use a Machine Learning Algorithm to develop a lockloss prediction model. Above, we show the efficiency curves using the earthquake parameters from the PDL client. The curves which include the observed ground velocity at the sites are similar. In general, there is a tradeoff between false alarm probability and efficiency standard probability. For example, if we adopt a false alarm probability threshold of 0.5, between 90-100% of earthquakes can be caught.