# QuakeCast: Distributed Seismic Early Warning

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***Abstract*—The "Did You Feel It?" program developed by the U.S. Geological Survey provides a relatively accurate online earthquake intensity map based on qualitative user reports. To further leverage the power of the community, this project uses inexpensive strong-motion sensors (three-axis accelerometers) connected to personal computers to pinpoint the location of an earthquake and provide early warning to first-responders and those farther away from the epicenter. These small sensors can be used to create a vast community seismic network, which can quickly report large quantities of data to central servers for analysis in the event of an earthquake. Through new robust algorithms resulting from this research, this fault-tolerant system can locate the earthquake epicenter and provide early-warning. With the online interface, users will be able to view this seismic data and analysis in real-time through cell phones or computers in order to better gauge the effect on their communities.**

## I. Introduction

SINCE the invention of the seismograph in the 1880's by John Milne, seismologists have sought to monitor, analyze, and predict destructive earthquakes[3]. Earthquakes pose a constant economic threat to the industrialized societies of the modern era, as seen by the carnage caused by the 2008 Sichuan earthquake.

With the dire consequences of powerful earthquakes, a dependable early warning system could minimize widespread suffering and economic losses. Just a few seconds of advance warning would allow activation of safeguards in critical operations, such as elevators, trains, industrial machinery, and the "active response systems" in skyscrapers[1].

Seismometers measure seismic ground motion and record the corresponding waveforms. By networking the seismometers to a central server, the data from these sensors can be used for estimating the source and magnitude of an earthquake. Recent advances in digital communication and computer processing speed have allowed early warning systems to be implemented in several locations, starting with the Japanese train system in the 1960s, leading to installations in Italy, Taiwan and Mexico[8].

Here, we introduce QuakeCast, a global distributed seismic network for early warning. QuakeCast leverages small, inexpensive strong-motion sensors connected to personal computers to create a dense seismic network capable of reporting real-time acceleration data to central servers for analysis. At the server-side, fault-tolerant algorithms pinpoint the source of an earthquake and send early warning alerts. Through an intuitive web interface utilizing Google Maps, users will be able to view real-time ShakeMaps[7] to better gauge the earthquake's effect on their communities.

Users can purchase inexpensive Phidgets[5] brand three-axis USB accelerometers for use with QuakeCast. Once the sensor is connected to a computer, users can install the QuakeCast client-side software to register on the seismic network. After a registration process, during which the user specifies the sensor location on an interactive map, the client is added to the server's catalog of active sensors.

Although the USB accelerometers are less sensitive than traditional seismic sensors, the client-side software employs filters to reduce ambient vibrations due to everyday activity. During an earthquake, primary waves (P-waves) have a significant lead time over damaging secondary waves (S-waves). Once a P-wave is detected, the client immediately triggers a "pick" event and sends a small waveform packet containing this pick data to the server for analysis. Because the client only sends data upon P-wave arrival, QuakeCast uses less bandwidth per sensor than traditional seismic networks.

As these pick messages arrive at the server, robust algorithms are able to correlate data from neighboring sensors to get a complete picture of the earthquake's wavefront. Erroneous data that was not confirmed by nearby sensors is discarded to limit false positives. The web interface is updated with a real-time ShakeMap and information about reporting sensors. After determining the locations that will experience shaking in the immediate future, the server sends early warning notifications to the public.

Early evaluation of the client-side and server-side algorithms shows reasonable performance and promising results. Overall, QuakeCast provides a crowd-sourcing framework for earthquake parameter estimation using a seismic array of personal low-cost accelerometers. The protocol is open and extensible, so client-side parameters can be tweaked in real-time. Future directions for this research include improving the accuracy of the server-side algorithms and expansion of the client-side software to other sensor models such as the built-in accelerometers in laptops and cell phones.

## II. Methods

### A. Client Operation

The client software is written in Java, using Phidget device drivers that are compatible with Windows, Linux, and Mac OS. During the client registration process, users can specify the sensor's location by entering an address, choosing a location on a map, or by allowing the bundled Skyhook[6] technology to automatically detect the location. After installation, the

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software runs as a background process, reading acceleration data into a ring buffer.

An interface allows users to view live tri-axial acceleration waveforms and confirm that the accelerometer is indeed working. We use the standard short-term average over long-term average (STA/LTA) method[4] to trigger pick events, i.e. when the STA/LTA ratio exceeds a certain tunable threshold, a "pick message" containing waveform data is sent to the server. These pick messages contain the contents of a window of data encompassing values before and after the trigger, and are transmitted via UDP to avoid the connection handshake delays of TCP.

Periodically, the client software sends a "heartbeat" message so that the central servers can maintain an accurate catalog of active sensors. The server responds with any software and algorithm parameter updates, as well as requests for raw data logged in a certain time interval. Log requests are used to collect data for thorough analysis some time after an earthquake occurs. All waveform data is encoded in the standard Seismic Analysis Code (SAC) format[2]. Seismic

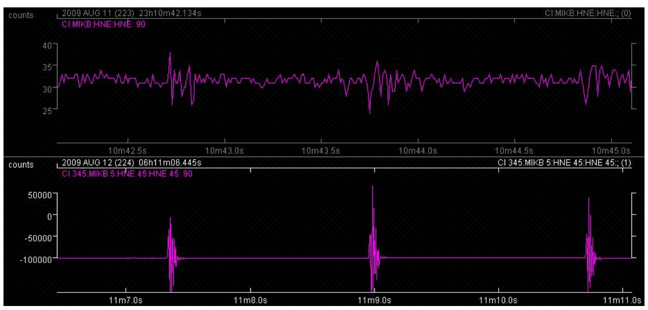


Fig. 1. The waveforms detected during the sledgehammer strike experiment. USB accelerometer response is plotted above that of SCSN sensor MIKB.

events can also be simulated on the QuakeCast network by automatic "playback" of acceleration data received from the server. To evaluate the network's operation during a synthetic or historical earthquake, the server can distribute playback data files to specific clients. During playback, clients read this pre-recorded data as if it were live, running the picking algorithm and sending pick messages as described above.

### B. Client Evaluation

To evaluate the sensitivity of our USB accelerometers, we conducted a direct comparison with a sensor in the Southern California Seismic Network (SCSN). The SCSN sensor was located in the basement of Millikan Library at Caltech (station name: MIKB). Striking the ground adjacent to the sensors with a sledgehammer yielded the results shown in Figure 1. As seen from the waveforms, the strike was detected by our sensor, albeit with much more background noise than the MIKB sensor. This is expected, and our algorithms are designed to filter these ambient vibrations.

### C. Server Operation

The QuakeCast server applications are written in Java, with data stored in a MySQL database. We use an open and flexible XML schema for communication between the client and server. To ensure the security of the network, these XML messages are signed and verified. Having accurate and consistent timestamps across the network is very important, so QuakeCast will allow clients to synchronize their clocks through a Network Time Protocol (NTP) server. An interface allows network administrators to schedule playback events and log requests for specific clients. During a seismic event, the

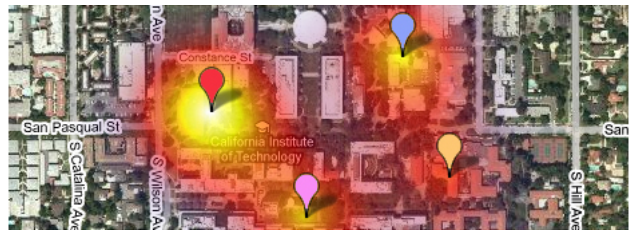


Fig. 2. Screenshot of the web interface showing simulated shaking detected by sensors around Caltech.

server creates a ShakeMap (Figure 2) based on data reported by the sensors in the network. This ShakeMap is available on the web interface, along with the locations of active sensors and a real-time view of pick messages as the server receives them. The interface was developed using Javascript and Google Maps, with PHP for the back-end work.

### D. Earthquake Parameter Estimation

$$P(I, L, T|D) = \frac{P(D|I, L, T)P(I, L, T)}{P(D)}$$

Fig. 3. Bayes' theorem as implemented in the simple aggregator, with I = earthquake intensity, L = location, T = earthquake start time, D = pick data

The simple aggregator developed by Caltech Professor Andreas Krause uses Bayesian inference (Figure 3) to locate the source of an earthquake. The prior distribution approximates the Gutenberg-Richter Law. The likelihood function is based on a normal distribution of pick arrival times.

The aggregator was evaluated using synthetic pick data, with performance shown in Figure 4.

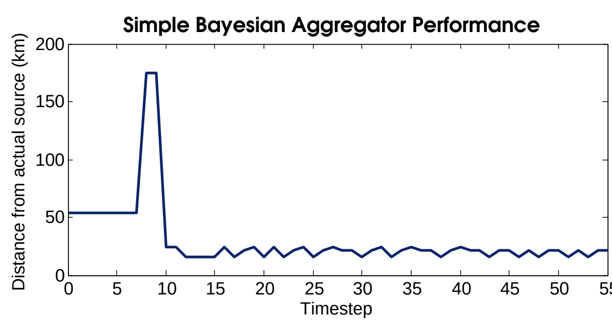


Fig. 4. Results obtained by running the simple Bayesian aggregator on synthetic pick data.

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