

# A Novel Strong-Motion Seismic Network for Community Participation in Earthquake Monitoring

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**S**eismic networks provide crucial data to scientists and the public about recent earthquakes, both large and small. These networks record waves that propagate away from the earthquake source and provide a host of information about the earthquake including magnitude, location, and how much slip occurs during an earthquake. Included in the details of each seismogram is information about the rocks and sediments which the seismic waves travel. By increasing the density of seismic stations, we can rapidly detect and locate earthquakes to provide an advance alert, improve our understanding of earthquake rupture and the associated seismic hazard, and generate in real-time, state-of-health information.

We have constructed a new inexpensive initiative to augment seismic networks quickly by using Micro-Electro-Mechanical Systems (MEMS) accelerometers and distributed computing techniques called the Quake-Catcher Network (QCN). Its use is expanding rapidly and increases the density of ground motion observations throughout the world [1]. In this paper, we describe our network including the people who volunteer to participate, the location of sensors in the system, detection and analysis of triggers from megadata, tagging with accurate time, and the MEMS accelerometer sensors that we use.

## Building the Network

Traditionally, seismic networks have been costly to install and maintain. A seismic station requires a sensor to record the ground motion, a computer to save the data, a GPS for accurate timing and location, telemetry or radio equipment to send the data back to a central clearinghouse and a power source to run the equipment. Each seismic station is a self-contained system that can take several hours to days to install. While these stations provide high-quality, reliable data, currently costs prohibit increasing the density of stations over a large region such as California. The Quake-Catcher Network (QCN) uses distributed computing and novel sensors to augment the current seismic networks, providing a higher density of observations of moderate to large earthquakes.

The QCN reduces the infrastructure costs of installing and maintaining a seismic network by using volunteers' computers located in the targeted areas that are installed with software and MEMS accelerometer sensors. Triaxial MEMS accelerometers sensitive enough to record moderate to large earthquakes have become widely available at relatively low cost in recent years. The MEMS sensors are installed external to desktop computers or internal to laptop computers and record ground accelerations. Volunteer participants' computers become seismic stations by providing the physical infrastructure, computer, internet, power, shelter, etc. The computers are then networked using distributed computing techniques that allow us to monitor the sensors and retrieve earthquake data automatically. QCN is made fully scalable (from 100s to 100,000s of participants) and platform independent by the open-source software package Berkeley Open Infrastructure for Networked Computing (BOINC) [2]. BOINC powers scientific distributed/volunteer computing projects such as SETI@home, Einstein@home, and *climateprediction.net*. QCN minimizes costs by monitoring low- or no-cost sensors operated and maintained by volunteer participants. Distributed computing projects are only successful if participants recognize the value of their contribution. Through QCN, participants are directly involved in collecting and distributing seismic data that is essential for seismic hazard assessment and detailed studies of earthquake rupture.

## Detecting and Analyzing Triggers

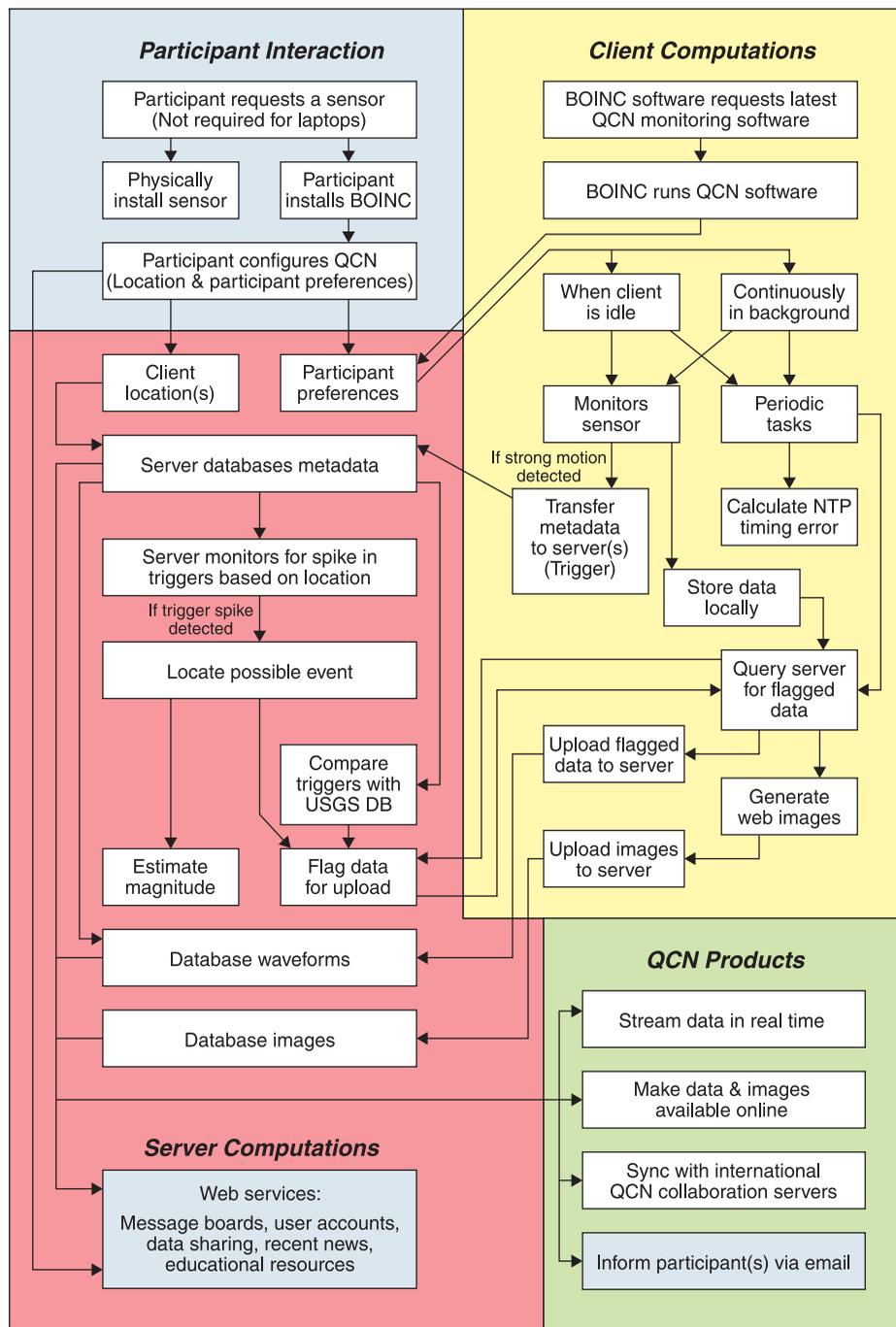
One of the challenges of QCN is to rapidly and reliably identify earthquakes in noisy data streams from thousands of sensors. In most seismic networks, complete time series of ground motions that are recorded by seismometers are transmitted in full to a central server for further processing. The transfer of continuous waveform data can result in 2 to 14 seconds of latency. QCN shifts the computationally heavy detection and analysis algorithms to the ample CPU power provided by the participant's computer. The client computers monitor the acceleration data for strong vibrations to determine if

a trigger has occurred and initially only the metadata for each trigger is sent to the server. The small packets of metadata transfer much faster to the server than the complete time series of acceleration data. The pertinent metadata useful for identifying large earthquakes in real-time include: the location of the sensor, the time at which the earthquake was measured, and the amplitude and period of the ground motion. QCN can minimize data transfer latency to less than 4 s for such parameters. For hazard assessment and emergency response, it is imperative to quickly and efficiently send data to a central server for further analysis. Figure 1 summarizes the participant interaction, data processing and products of the QCN.

Tuning the triggering algorithm is critical to ensure that real earthquakes are captured while also minimizing the number of false triggers. Earthquakes are usually identified using the ratio of the incoming signal to an average of previous signals referred to as the ratio of short-term average to long-term average (STA/LTA). QCN currently uses a similar method; more specifically, we determine if the current acceleration is more than 3 standard deviations larger than the previous minute of acceleration. We are currently testing several triggering algorithms to determine how to best identify earthquakes in often noisy time series data. Seismic waves from a nearby earthquake usually measured the frequency band between 2–20 Hz, similar to cultural noise such as passing cars, wind, etc. To better recognize earthquake-related vibrations, we are developing algorithms to quickly identify the two main seismic wave arrivals: primary (P) - and secondary (S)-waves. P-waves are compressional waves that arrive at a station first. S-waves are the more-damaging longitudinal or shear waves that travel at roughly half the speed of P-waves. By identifying the time

and amplitude of these wave arrivals we can more efficiently determine the location and magnitude of the earthquake.

Once a trigger occurs, the metadata is sent to a central server for further analysis to determine if there was an earthquake or if it was an isolated trigger. Because the sensors are located in houses, offices, and schools, a large number of triggers are due to local noise sources. We compare the trigger to the U.S. Geological Survey (USGS) catalog to establish if the trigger is spatially and temporally associated with a known earthquake. As the network increases in density, we will implement a clustering



**Fig. 1.** Flow chart outlining the interaction between participants, cyber infrastructure and products in the Quake-Catcher Network (QCN)

algorithm to identify large events, such as earthquakes, from random isolated triggers. There are several major challenges to real-time earthquake identification and characterization (such as earthquake location and magnitude estimation) using QCN data. First, the network configuration is ever changing as stations are added or removed, so QCN must develop efficient and flexible clustering algorithms for identifying patterns within the network. Flexible 'virtual' networks can be formed to spatially group sensors so incoming trigger data can be analyzed to determine if triggers cluster in space and time indicating an earthquake has occurred. Once a cluster of triggers is identified within a virtual network an 'event' can be declared. Once an earthquake is identified, the time and amplitude of the wave arrivals from at least three stations can be used to estimate the earthquake location and magnitude.

Currently, incoming trigger data from the entire network is sent to a single server. As the network continues to grow we will distribute the incoming triggers across multiple servers located throughout the world. However, the data handling must be flexible enough to correctly detect earthquakes at the edge of a designated server region. For example, if triggers from southern California are sent to a server at Riverside and triggers from northern California are sent to a server at Stanford, an earthquake occurring at a designated boundary may be poorly located or missed completely. In the QCN, triggers can be sent to multiple servers to both increase network robustness as well as improve identification of earthquakes that might fall between two regions.

### Sensor Specifications

Seismologists use two broad categories of sensors to record earthquakes: weak motion and strong motion sensors. Multiple sensor types are needed because currently no single sensor can capture the diverse amplitudes and frequencies of seismic waves that can vary over many orders of magnitude. Weak motion sensors can record low amplitude ground motion either from a small, local earthquake or a large earthquake located far from the station. Weak motion sensors have power spectral densities (PSD) around -120 to -160 dB between 0.01 to 10 Hz referenced to the squared acceleration amplitude of (1 m/s<sup>2</sup>). So, these sensors can resolve ground accelerations as small as 1 nm/s<sup>2</sup> at a very quiet site, but will go off-scale, or clip, at larger ground motions. Strong motion sensors can capture extreme ground motions from nearby moderate to large earthquakes that result in several g accelerations. The MEMS sensors currently used by QCN are equivalent to a



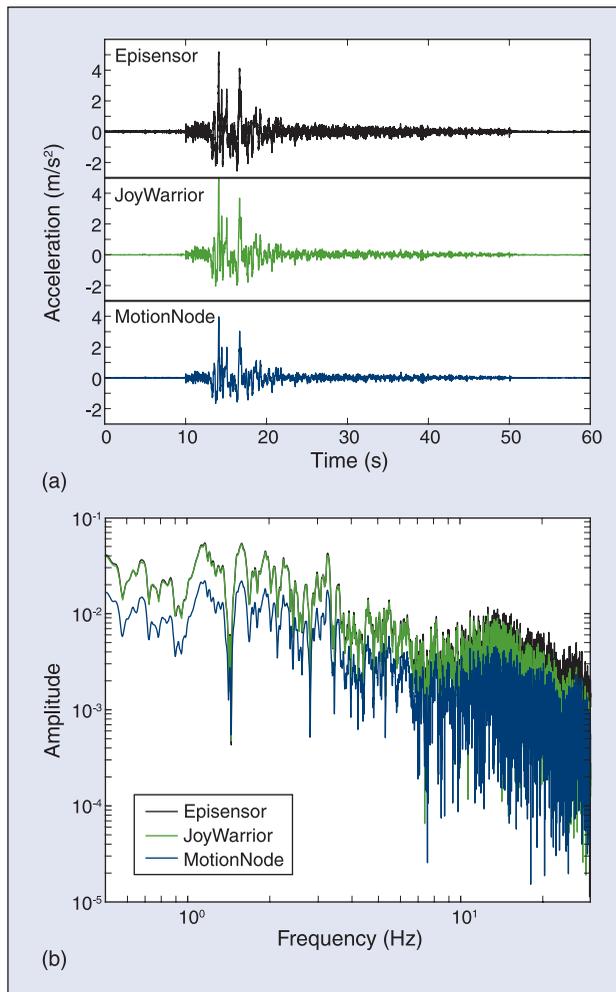
Fig. 2. MotionNode Accel (top) and JoyWarrior 24F8 (bottom): USB sensors currently used by QCN. Photo Credit: E. Cochran.

strong motion sensor and record local earthquakes (within a few tens of kilometers) with magnitudes greater than 3.0.

QCN has adopted two models of external MEMS sensors: the MotionNode Accel (MN), 0.001 g resolution for  $\pm 2$  g range, and the JoyWarrior 24F8 (JW), 0.004 g resolution for  $\pm 2$  g range (Figure 2). Both models connect via a USB cable to a desktop computer running any operating system (Windows, Mac, Linux). Sensors are mounted to the floor to provide good coupling to ground motion and have known orientations (with one horizontal component aligned to north and the other horizontal component aligned to east). QCN also currently supports two models of laptops (Apple and ThinkPad) that have internal MEMS sensors. We will not describe the internal sensors in detail here, as they are typically not well-coupled to the ground (e.g. passively sitting on a desk) and have unknown orientations. Table 1 lists the specifications of the external sensors used by QCN as well as next-generation sensors that may be integrated into the project in the future. We are continually exploring the most recent advances in MEMS technology and will implement higher resolution sensors as they become available at competitive costs.

Table 1—USB Sensors Comparison (\* indicates next generation sensors)

Model	Dynamic Range	Resolution	Cost	Frequency Range
MotionNode Accel	$\pm 2$ G	$\pm 1.0 \times 10^{-3}$ G	\$100-150	0.05-25Hz
JoyWarrior	$\pm 2$ G	$\pm 4.0 \times 10^{-3}$ G	\$30-50	0.05-25Hz
JoyWarrior 1 mG*	$\pm 2$ G	$\pm 1.0 \times 10^{-3}$ G	\$50-75*	0.05-25Hz
O-NAVI 60mG*	$\pm 2$ G	$\pm 6.0 \times 10^{-5}$ G	\$60-85*	0.05-25Hz
O-NAVI 24nG*	$\pm 2$ G	$\pm 2.4 \times 10^{-8}$ G	\$95-135*	0.05-25Hz



**Fig. 3.** Shake-table measurements for a simulation of the 1996 Northridge Earthquake recorded from a traditional sensor, Kinematics EpiSensor, and two USB sensors, JoyWarrior and MotionNode. (a) Accelerations recorded and (b) amplitude spectra of the accelerograms.

We conducted a series of shake-table tests to compare the response of the MN and JW MEMS accelerometers with a traditional strong motion sensor. The traditional strong-motion sensor used in the comparison test was the Kinematics EpiSensor ES-U2, a uniaxial force balance accelerometer. The test was conducted on a unidirectional shake table that allowed us to examine only one component of motion during a single test. Seismologists and engineers use both the uniaxial and triaxial, ES-U2 and ES-T Kinematics EpiSensors extensively for strong-motion applications. We used a variety of inputs during the shake table tests ranging from single frequency, single amplitude sine waves to actual ground motion recorded during past earthquakes. Figure 3 shows a comparison between the accelerations and frequency spectra from the three sensors (MN, JW, and ES-U2) for an input ground motion replicating the 1996 Northridge earthquake. The input signal was scaled to have a maximum displacement of 10 cm resulting in roughly 1 g accelerations. The accelerograms and the frequency spectra from the three sensors were nearly identical, indicating the sensors produced high-fidelity seismograms

that accurately captured the amplitude and frequency content of a typical earthquake. The main difference between the sensors was that the MEMS sensors used by QCN were lower resolution than the EpiSensor, and very small accelerations (less than 4 mg) cannot be resolved.

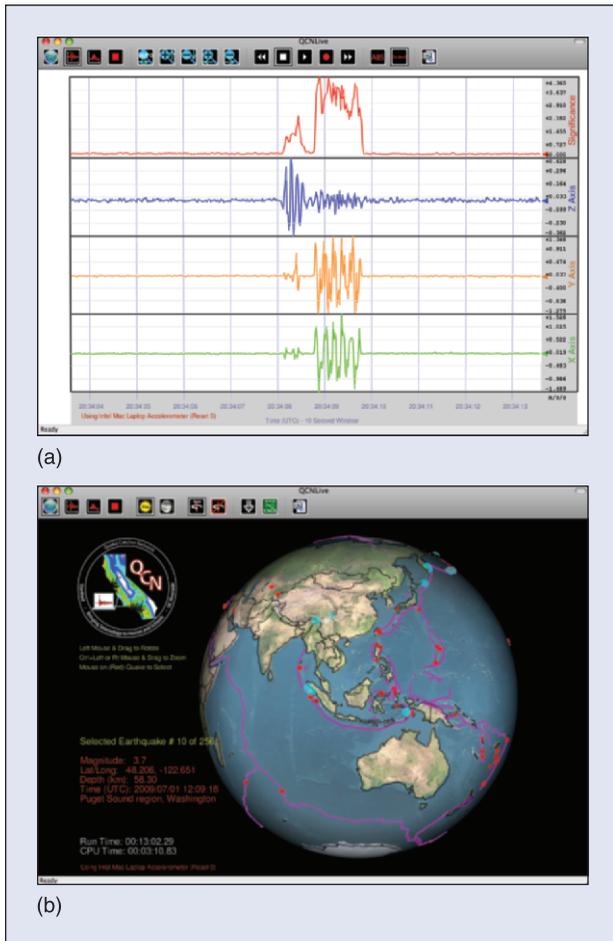
### Time and Location

The two most important considerations for any seismic station are time and location. Accurate sensor location and exact time are critical for locating earthquakes and estimating their magnitudes. Accurate locations are also important for high-resolution earthquake rupture models and seismic velocity models. GPS antennas provide the location and time information for a typical seismic station; however in the QCN we implement proven internet-based tools. Timing cannot come from the participant computer alone because the internal clocks on computers drift gradually over time. Instead, we utilize Network Time Protocol (NTP) to measure the clock drift every 15 minutes to determine the time offset between participants' computers and our server. Numerous tests have been run between QCN clients and our time server that show a maximum time synchronization error of 100 ms. This is consistent with a previous study that found, for most seismic applications, NTP time offsets are typically less than 20 ms [3].

Sensor location is estimated either automatically or, more commonly, through participant input. A rough location of each computer is estimated to within a few kilometers using Internet Protocol (IP) geotracking, which is based on the location of closest known router. This location is automatically determined and is the default location of a sensor when the software is first opened. However, for more accurate locations the participant may specify up to 5 locations using a Google Maps API and link those locations with the computer's IP address. Thus, each time the software opens it checks the current IP address against a list of the saved locations and uses the participant-specified location, if available. The location errors are typically a few kilometers or more if automatically determined but less than 10 m if specified by the participant.

### Participant Considerations

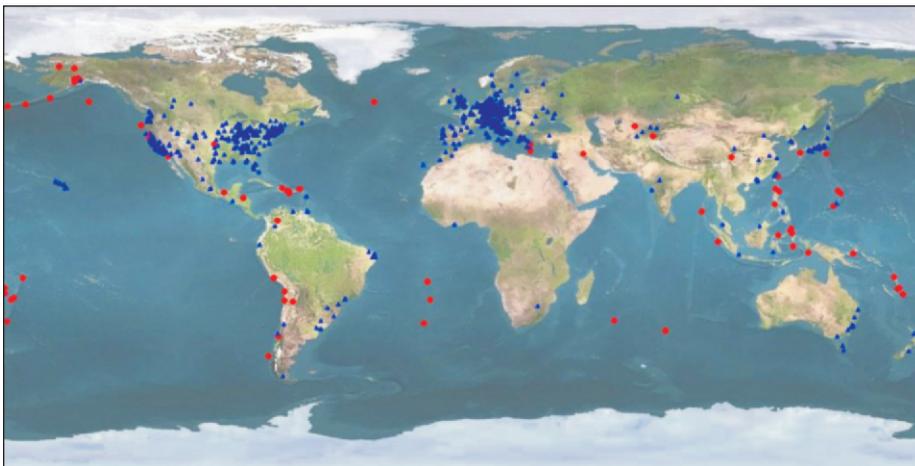
Building a distributed computing project that uses participant computers rather than dedicated machines has specific requirements. These requirements include minimizing computational resources, platform independence, and ease of installation. Unlike many other distributed computing projects that use up to 100% of a processor when a computer is in screen-save mode, we need software that uses as little computational power as possible so that it can run continuously in the background without being noticed by the user. This is especially important for computers equipped with the more sensitive external sensors. Thus, QCN software and any data processing algorithms implemented must be very efficient. In background mode, QCN core processes use less than 1-5% of the computing resources of an average computer.



**Fig. 4.** Screen-shots of the QCNLive interactive software. (a) Real-time display of accelerations measured by the sensors and (b) global view of current and historic earthquakes and plate boundaries.

In addition, BOINC allows users to modify their preferences and limit when the software runs, as well as processor and disk usage.

BOINC and QCN software is built to be platform independent to maximize the number of participants.



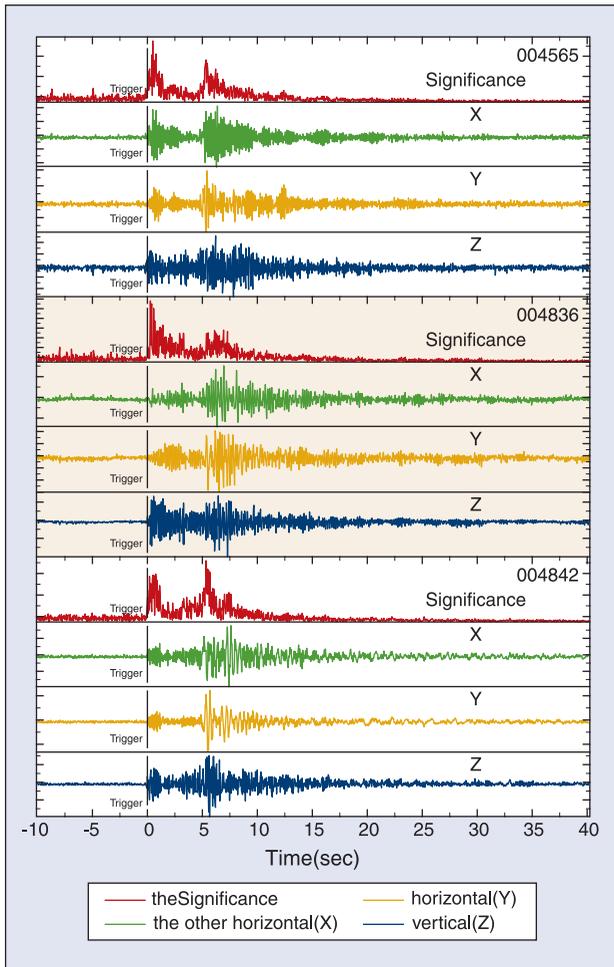
**Fig. 5.** Current global participants in the Quake-Catcher Network (blue triangles) and earthquake distribution from USGS (red circles).

Currently, QCN can monitor data between two external sensors, MotionNode Accel and the JoyWarrior 24F8, and two internal sensors in Apple and Thinkpad laptops. In addition, the software can run on Microsoft Windows, Mac OS X, and Linux operating systems. The software is fast and easy to install and run. QCN gives users access to sensor drivers as well as step-by-step instructions detailing how to install the software on the project website. The primary installation steps are to download BOINC software, connect to the QCN project, and modify user information and preferences. Participants can also learn about earthquakes through the interactive software (QCNLive) provided by the network (Figure 4). Teachers have incorporated the QCN sensors and software into hands-on activities that teach students about seismology and plate tectonics.

### QCN Earthquake Recording

Since its inception in early 2008, the Quake-Catcher Network has recorded dozens of earthquakes with magnitudes between  $3.1 \leq M \leq 5.4$  in multiple countries. As the number of sensors increases, the frequency of earthquake recordings has increased as well. Figure 5 shows the current sensor map for the Quake-Catcher Network. One of the earthquakes recorded by participants was the magnitude M5.4 Chino Hills earthquake recorded on July 29<sup>th</sup>, 2008 in Los Angeles. Figure 6 shows the recordings from this earthquake. The records provide accurate travel times and appropriate amplitudes for P- and S-waves. The sensors were all roughly the same distance from the earthquake, so the P- and S-waves recorded by each sensor arrived at nearly identical times. As designed, the triggering algorithm running on each participant computer detected the significant motions measured at the time of the P-wave arrivals, marked the arrival as a trigger and immediately sent the information back to the QCN server. These three computers triggered within half a second of each other. As expected, the S-waves are larger amplitude and are seen primarily on the horizontal components (X & Y) rather than the vertical components (Z). The graph labeled Significance shows the significance of the current signal relative to the past minute.

On January 9<sup>th</sup>, 2009 (a few months later) another earthquake of similar magnitude (M5.0) occurred in San Bernardino, CA (Figure 7). The earthquake recordings obtained through QCN also demonstrate typical P- and S-wave behavior. A quick analysis of the vertical and horizontal components allowed us to pick the P- and S-wave arrival times. The difference in time between the



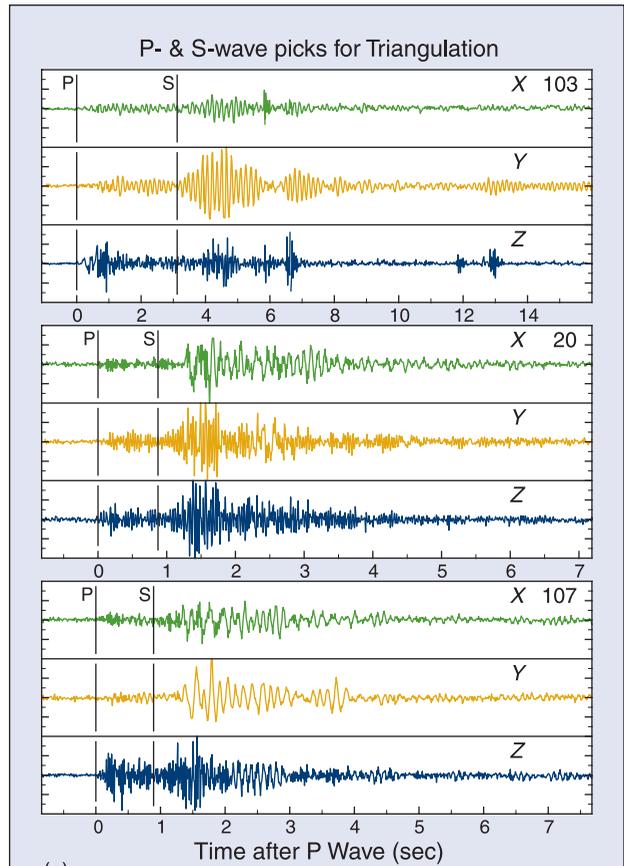
**Fig. 6.** Records from three QCSs of the M5.4 Chino Hills earthquake

P- and S-wave arrivals can be used to estimate the distance from the earthquake to the sensor (assuming the seismic velocities of P and S waves). Using the distances calculated from the P and S times, the location was triangulated to a location very close to the epicenter reported by the USGS. This demonstrates that the network is behaving appropriately, with sufficiently accurate timing and amplitude resolution. With additional QCN participants, the number of earthquakes recorded and located by QCN will increase. Our estimate of the earthquake location will also improve as our network density increases and more sensors record each earthquake.

## Goals of the Network

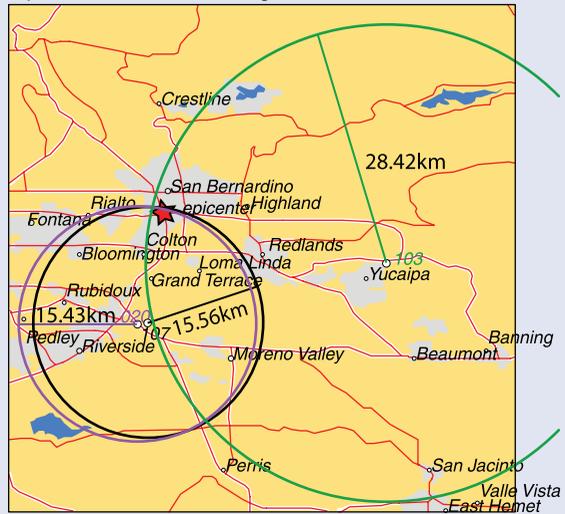
### Determine Earthquake Rupture Propagation

As the Quake-Catcher Network continues to grow, it will provide an unparalleled density of seismic observations that will allow us to address fundamental questions in seismology. Currently we are unable to exactly determine the rupture speed and slip distribution along a fault due to of the sparse distribution of strong-motion seismometers in current seismic networks in California. Rupture speed is how fast the rupture propagates along the fault plane; high rupture speeds are



(a)

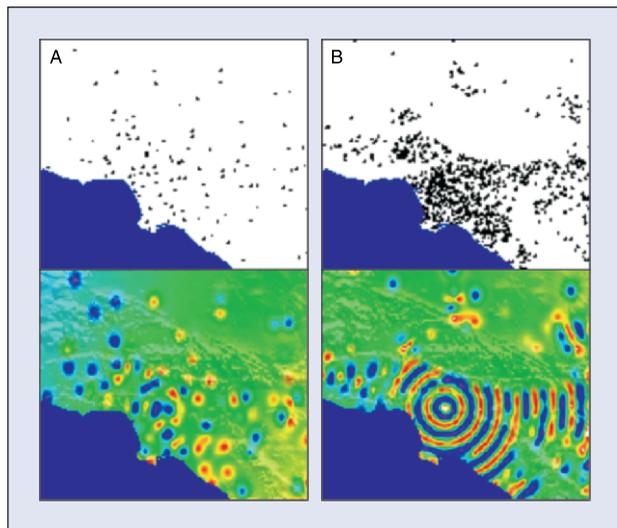
### Epicenter Location Using S-P wave Travel Times.



(b)

**Fig. 7.** QCN results computed from the M5.0 earthquake in San Bernardino. (a) The difference in P- and S- wave arrival times at the stations. (b) The intersection point of the 3 circles - the QCN earthquake location, the red star - the USGS location.

often associated with very planar fault segments and higher ground accelerations. Slip distribution is the amplitude of slip along various portions of the fault; the amount of slip can be highly variable across a fault plane with regions of higher



**Fig. 8.** A hypothetical wave field graphic for a seismic wave captured in (A) by the strong-motion network and in (B) by a combined network of the strong-motion network plus 2,700 hypothetical QCN USB sensors at actual K-12 schools in the Los Angeles basin.

slip experiencing larger ground motions. A dense network (seismometers every 100 km<sup>2</sup>) would be capable of capturing earthquakes with fine spatial resolution to produce unalised 4D images of wave propagation (Figure 8). Thousands of QCN sensors in earthquake-prone metropolitan areas will provide critical improvements in fault resolution for moderate to large earthquakes. The large quantity of proximal measurements will allow us to image moderate to large earthquake ruptures from initiation to termination. These images will constrain the time evolution, slip history, and directionality of fault ruptures as never seen before. Rapid and accurate assessment of source (rupture) characteristics of a moderate to large earthquake can be used for hazard assessment and to guide emergency services, which are critical for efficient rescue efforts to mitigate economic damages and/or loss of human lives. In addition, rapid earthquake characterization will provide valuable input for the scientific community regarding details of source propagation.

### Subsurface Properties and Amplification

Seismic waves provide information about the three-dimensional structure of the Earth's subsurface. Seismic waves bounce off interfaces at depth, travel faster in some regions than others, focus and defocus around subsurface structures, and dissipate over time and distance. With an increased density of observations, QCN will provide more details regarding the subsurface structure, yielding new insight into the dynamic evolution of the Earth and the current physical properties that affect heat flow, water cycles, and earthquakes. These resulting seismic images will assist seismic hazard assessment and mitigation by providing maps of anomalous structures that focus or dissipate seismic energy.

Data from QCN will help answer the question of how the near-surface environment affects seismic hazard. Currently

structural engineers must interpolate between widely spaced data to estimate the shaking hazard at each new location. QCN can greatly reduce the area over which data are interpolated and allow for improved estimates of site conditions for improved building safety. The data from QCN can be used in several ways to produce high-resolution (100 km<sup>2</sup> or better) images of site effects and amplification. Data from moderate earthquakes recorded on the dense QCN network can be used to explore variations in site amplification at much higher resolution than is possible with the current network. This data can be used to estimate the maximum amplitude of ground shaking expected for large magnitude earthquakes. Thus, seismic amplification maps will provide city planners and engineers more accurate information for each potential building site.

Current QCN sensors have the ability to record accelerations as high as  $\pm 2G$ , allowing us to measure extreme ground motions that have been poorly studied thus far but are an important consideration in seismic hazard analysis. During the recent 2008 M 6.9 Iwate-Miyagi earthquake, peak accelerations up to 3.9 G were observed [4] using newly installed accelerometers. These extreme accelerations are thought to be a near-surface, highly-localized site effect but may be used for seismic hazard assessment in unconsolidated soils. QCN can provide valuable information on the maximum accelerations at a level of detail previously not plausible [5].

### Large Building Responses

The technology developed by QCN has led to a promising new method to monitor the physical properties of large buildings. How a building shakes during an earthquake depends on the shape and weight of the building, construction material, and subsurface material. By monitoring buildings to determine their resonant frequency, we can estimate how they will behave in a large earthquake. Continuous monitoring over time also allows us to determine if a building develops any structural weakness or damage by looking for drift, or migration, of the resonant frequency of the building response. Techniques that use ambient noise (man made and natural signals such as wind) can predict how the ground will shake during an earthquake [6] and may allow us to determine the response of a building without needing a specific shaking event. This method provides the necessary information to predict how a building shakes given an input vibration at the lowermost floor. The method provides seismic velocity (elastic behavior), attenuation (energy dissipation), and resonance frequencies (modes) given only 14 days of recording from QCN's USB sensors. While the method does not predict how a building responds in non-linear stress-strain conditions (associated with the onset of building damage), the method could be used to predict if a building approaches sufficient interstory drift to possibly generate structural damage.

With the advent of QCN, it is now possible to deploy many sensors in a building for short durations at little cost. The sensors can be used on many buildings in the time it

would take to wait for a moderate earthquake to occur in a single traditionally-instrumented building. Campaign-style experiments will produce more structural response data for the broader comparative investigations of structural responses to earthquakes. By leaving a single sensor behind after a campaign-style experiment, it is possible to predict the interstory drift on each floor. Further analyses of campaign-style data measured in basements of adjacent buildings will provide site effects due to small-scale subsurface structure.

## Summary

The QCN is breaking new ground in seismology by combining new MEMS technology with volunteer seismic station distributed computing. Rather than distributing just computations, the Quake-Catcher network allows volunteers to participate in scientific data collection and computation. Using these innovative tools, QCN will increase the number of strong-motion observations for improved earthquake detection and analysis in California, and throughout the world. QCN's increased density of seismic measurements will revolutionize seismology. The QCN, in concert with current seismic networks, may soon provide advanced alerts when earthquakes occur, estimate the response of a building to earthquakes even before they happen, and generate a greater understanding of earthquakes for scientists and the general public alike.

You can help us improve strong-motion earthquake monitoring by participating in the Quake-Catcher Network. To join the network, please visit the project website at <http://qcn.stanford.edu> where you can request a sensor and download software to begin recording earthquakes. In addition, we have activities on our website that can be used in K-16 classrooms to teach students basic seismology and physics concepts.

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**Jesse Lawrence** received a PhD in Earth and Planetary Sciences from Washington University in Saint Louis in 2004. He is now an Assistant Professor of Seismology at Stanford University. His current research focuses on distributed computing seismic networks and seismic imaging of the subsurface.

**Carl Christensen** is the Chief Software Architect of the Quake-Catcher Network at Stanford University and is also a Senior Consultant (and formerly Chief Software Architect) to the climateprediction.net volunteer computing project at Oxford University. His research focus is on distributed, grid, and volunteer computing.

**Angela Chung** is a graduate student working with Jesse Lawrence at Stanford University. She has a broad range of interests including earthquake hazard analysis and earthquake rupture mechanics. Angela is currently working on the QCN project (both the earthquake detection and the building response aspects) as well as a seismic imaging project.