Mobile Phones as Seismologic Sensors: Automating Data Extraction for the iShake System

Jack Reilly, Shideh Dashti, Mari Ervasti, Jonathan D. Bray, Steven D. Glaser, and Alexandre M. Bayen

***Abstract*—There are a variety of approaches to seismic sensing, which range from collecting sparse measurements with high-fidelity seismic stations to non-quantitative, post-earthquake surveys. The sparse nature of the high-fidelity stations and the inaccuracy of the surveys create the need for a high-density, semi-quantitative approach to seismic sensing. To fill this void, the UC Berkeley *iShake* project designed a mobile client-backend server architecture that uses sensor-equipped mobile devices to measure earthquake ground shaking. *iShake* provides the general public with a service to more easily contribute more quantitatively significant data to earthquake research by automating the data collection and reporting mechanisms via the iShake mobile application. The devices act as distributed sensors that enable measurements to be taken and transmitted with a cellular network connection. Shaking table testing was used to assess the quality of the measurements obtained from the iPhones and iPods on a benchmark of 150 ground motions. Once triggered by a shaking event, the devices transmit sensor data to a backend server for further processing. After a seismic event is verified by high-fidelity stations, filtering algorithms are used to detect falling phones, as well as device-specific responses to the event. A method was developed to determine the absolute orientation of a device to estimate the direction of first motion of a seismic event. A "virtual earthquake" pilot test was conducted on the UC Berkeley campus to verify the operation of the *iShake* system. By designing and fully implementing a system architecture, developing signal processing techniques unique to mobile sensing, and conducting shaking table tests to confirm the validity of the sensing platform, the *iShake* project serves as foundational work for further studies in seismic sensing on mobile devices.**

***Note to Practitioners*—To try and recover ground motion measurements from the on- accelerometer in a smartphone, one should take into account the additional *variables* in the environment in which the measurement was taken. Such variables include that the device may be moved by the user rather than the ground, that the accelerometer may record internal phone vibrations rather than external effects, and that the absolute orientation of the device cannot be determined from the accelerometer readings alone. This report gives practical procedures and algorithms to address these newly introduced issues. We provide a three-step-loop procedure to only actively sense for significant ground motion when it is reasonably certain the phone is not in active use. We also give a number of filtering techniques to apply to the raw accelerometer signal, such as isolating frequencies relative to seismic ground motions, removing potential internal resonance of the device in the output signal, and detecting whether a device has undergone significant disruption from forces not pertaining to ground motion. Since the cardinal direction (north-south-east-west) and coordinate location are needed to determine fault movement properties, we give a procedure to recover absolute position and absolute orientation from a combination of accelerometer, compass, and GPS information. By comparing the performance of the devices' accelerometer readings against high-fidelity accelerometers on shaking tables, we demonstrate that the resolution of the devices' measurements show potential for ground motion estimation.**

***Index Terms*—Accelerometer, crowdsourcing, earthquake, mobile phones, participatory sensing, seismograph, signal processing.**

I. INTRODUCTION

EMERGENCY responders must assess the effects of an earthquake exhaustively and rapidly so that they can respond effectively to the damage it has produced. The *iShake* project created such a system by using a person's mobile device to measure ground motion, intensity parameters and process the data on a central server, rather than using a person as a measurement and reporting device. This research involves the use of the iPhone as a new ad-hoc sensor array based on participatory sensing, with mobile phones as the nodes of the sensing network.

Currently, much of post-earthquake damage assessment is made based on *Modified Mercalli Intensity* (MMI), a subjective measure of earthquake shaking evaluated by individuals volunteering information [4]. *iShake* provides a quantitative measure [12] of *Arias intensity* [20], which has been shown to be an excellent prediction of structural [28] and geotechnical [18] damage from shaking. One of the goals of this project is to feed this additional intensity information back to those in damage assessment rapidly after an earthquake event.

In particular, the iShake system was created to take advantage of the new source of seismic sensing capabilities offered by the GPS, accelerometer and magnetometer on the smartphones. A client application for the iPhone and iPod products was developed as the means of sensing ground motion activity. After a potential earthquake event is sensed, the data measured by the client application are streamed rapidly to the backend servers, where the raw data can be properly processed and aggregated with other client data. Then, summary data from the event, in the form of intensity maps [29], can be immediately provided

---

Manuscript received September 09, 2012; accepted January 02, 2013. Date of publication February 25, 2013; date of current version April 03, 2013. This paper was recommended for publication by Associate Editor R. Voyles and Editor S. Sarma upon evaluation of the reviewers' comments. This work was supported by the U.S. Geological Survey (USGS), Department of Interior, under Award G10AP00006.

J. Reilly, J. D. Bray, S. D. Glaser, and A. M. Bayen are with the Department of Civil Engineering, University of California at Berkeley, Berkeley, CA 94720 USA (e-mail: jackdreilly@berkeley.edu; bray@ce.berkeley.edu; glaser@berkeley.edu; bayen@berkeley.edu).

S. Dashti is with the Department of Civil, Environmental and Architectural Engineering, University of Colorado Boulder, Boulder, CO 80302 USA (e-mail: shideh.dashti@colorado.edu).

M. Ervasti is with the VTT Technical Research Center, 02044 Oulu, Finland (e-mail: Mari.Ervasti@vtt.fi).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASE.2013.2245121

to emergency workers (as well to the general public) to aid in rescue missions.

The envisioned use case for the *iShake* system is as follows. Most smartphone users have been accustomed to charging their phone nightly or while at their desk during a workday. During such times of inactivity, the mobile device will be leveraged as a sensing and data-transmission unit. The on-board array of sensors (accelerometer, GPS, magnetometer) will then be enabled to capture ground-motion events and properly determine its orientation from any potential position, be it lying face down on a desk, or upright in a charger. While an unoptimized implementation of the software may pose a problem to battery life, the ability of modern mobile operating systems to detect when a device is charging (such as Apple iOS and Android) circumvents such issues. Additionally, the stationary nature of charging phones also helps to target the ideal use case of sensing while the user is disengaged from the device. The aforementioned use case motivates the design decisions taken while developing the system architecture for *iShake*.

Contributions of this paper are enumerated as follows. The *iShake* system is one of the first, fully functional systems [17] to enable users to report ground motion measurements from a mobile device to a centralized data-collection system. This is also the first known participatory sensing system to report ground motion data within an orientation-aware context, giving both the magnitude and cardinal direction of shaking. Given the mobile nature of the computing platform, there are many uncertainties introduced into the sensing environment. *iShake* makes contributions to the mobile computing field by developing algorithms that account for such uncertainties inherent to the field, and implementing techniques that reduce the noise associated with uncertainty. In Section III, a mobile client application architecture is developed to determine when sensor-data transmission should and should not occur, basing the decision on the mobile device's current environment. Further, Section IV details several signal processing algorithms that filter out environment-specific noise, which is variable from device-to-device (such as smartphones falling off a table while sensing for ground motion, or device-related resonance unrelated to the ground motion) and unavoidable in mobile computing and participatory sensing applications. By implementing a circular buffer, the client software allows for very low-amplitude seismic waves to be captured and transmitted to the central server, even when the wave's first-arrival amplitude was not enough to set off the application's trigger. In Section V, we present results from testing which subjected seven iPhone and iPod Touch devices to a suite of over 150 shaking table tests [12]. This work is the first rigorous and quantitative testing of iPhone devices for the purpose of determining the suitability of on-board accelerometers for seismic sensing application. In Section VI, we detail an actual field test of the *iShake* system conducted on the UC Berkeley campus and surrounding areas, which demonstrated the feasibility of running this system in real time.

II. RELATED WORK

In the last decade, significant progress was made in rapid, post-earthquake analysis, and visual representation of seismic data [4], [11], [29]. The demand for immediate analysis of earthquakes comes not only from the scientific community, but also from public and private post-earthquake response groups as well as preparedness exercises and disaster planning groups [12], [23].

The USGS offers a service called *ShakeMaps* [29] that provides shaking intensity and ground motion maps of earthquakes minutes after an earthquake event happens. *ShakeMaps* leverages a network of regional seismic stations to create their ground motion estimates. Due the sparseness of the stations, *ShakeMaps* must interpolate over large areas to stabilize contouring. The interpolated values from these plots have no validation method due to the lack of seismic stations in a given area. Given the growing number of smartphone users, particularly in urban areas, a denser mesh of sensor nodes can be supplied by the *iShake* system to reduce the interpolation distances involved in creating spatial intensity maps.

The DYFI project is another program offered by the USGS, which uses human observations that are voluntarily submitted through the Internet, hours to days after an earthquake, to develop a Community Internet Intensity Map based largely on the MMI scale [20]. In addition to untrained humans being only a rough qualitative indicator of earthquake effects, the response times of such data sources would be expected to increase with the severity of the event. The *iShake* project aims to create more quantitative sensing data than the DYFI approach, while automating the response method via a mobile client application. Reducing response time becomes important as networks are known to experience downtime immediately following natural disasters from network overload and infrastructure damage [21], [25].

The idea for using mobile devices as an earthquake sensing platform was inspired by the rising field of participatory sensing, introduced by Burke *et al.* [10], in which the idea of the "shareability" of individual's sensor data is introduced. A general model of crowdsourced computation has been proposed in [30]. Participatory sensing has become influential in civil engineering by introducing modern sensing techniques to traditional civil engineering practices. In particular, Balakrishnan, Madden *et al.* have developed a mobile sensing platform attached to vehicles that enables monitoring of street surface conditions [14], [19], and new earthquake sensing techniques have emerged [11], [23], [26], which are detailed herein.

In a first for mobile participatory sensing in seismic applications, Estrin *et al.* successfully captured an earthquake event in the Los Angeles area using a *Nokia N95* mobile phone [16]. The acceleration signal showed a clear capturing of both the s-wave and the harder to detect p-wave of the earthquake event, giving promise to the field of seismic mobile sensing.

The *Quake-Catcher Network* (QCN) [11], a research project led by Stanford University and UC Riverside, seeks to utilize laptops and personal computers to record ground-motion data. When internal accelerometers are not available, inexpensive external accelerometers can be used as well. The QCN has had success in detecting and analyzing earthquakes with user devices, evidenced by accurately calculating the epicenter of an actual earthquake event.

A number of months after the *iShake* system went live and the mobile application was launched in the Apple App Store, the results of a mobile phone-based earthquake detection system

Fig. 1. Screen shots of the iShake client application. While the seismic sensing performs silently in the background, information is fed back to the user in the form of a status center and aggregate virtual shake location map.

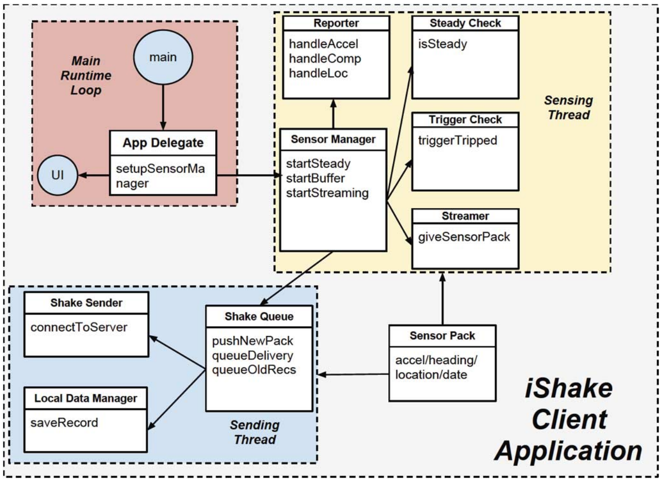

Fig. 2. An overview of the *iShake* client application's background processes.

were published by the *Community Seismic Network* (CSN) team [17]. The architecture of CSN and *iShake* indeed share similarities, and CSN also conducted numerous simulated shaking and actual shaking table testing with Android mobile devices to investigate the system's ability to detect earthquakes. The present paper differs from [17] by focusing on quantifying the ability of iPhones to accurately recover important earthquake-related parameters such as *Arias intensity* and spectral ordinate, useful in earthquake-engineering studies, rather than early-warning detection applications. Additionally, a focus is given to customized signal processing techniques that reduce the effect of environmental variabilities, while [17] present a more generic statistical approach based on Gaussian mixture models.

III. SYSTEM OVERVIEW

A client-server system architecture was designed to allow transmission of data from the mobile devices to a central location. When an earthquake occurs, the devices will be triggered to transmit their recordings to the server. The server will subsequently process the received signals by adjusting clock drift, determining the state/orientation of the signal, removing unrelated signals, and filtering out noise and the captured response of the device's housing. Fig. 4 shows an overview of the *iShake* system. While data from the devices may be transmitted at any time, only events registered by USGS (which publishes earthquake events as soon as a few minutes after the event) are considered actual earthquakes. All signals transmitted during the time and within a certain radius of a USGS earthquake event are pulled to get a spatial description of the event from the *iShake* measurements. Finally, the compiled data is then fed back to the devices for viewing. Fig. 1 shows an example of a shake map that can be generated from the user-generated data. The aggregation techniques for shake map generation is the subject of future work.

Due to the lack of orientation-aware sensors (such as a magnetometer) in PC's and USB-based accelerometers, existing seismic participatory sensing systems do not provide any information on the heading (the cardinal direction) of the signal [11], [17]. While this allows for computation of estimates for epicenter of earthquake and intensity values, there is no way for the measurements to capture direction of first arrival or determination of fault-plane [20]. The iPhone has the necessary sensors to satisfy the requirement that the client be able to broadcast enough information to determine its coordinate location (assisted GPS, "aGPS"), relative orientation (magnetometer, accelerometer), and surface shaking (accelerometer). aGPS allows for accurate locating capabilities when combining traditional GPS sensing with cellular triangulation and wireless-router location lookup-tables [3] in the absence of GPS availability.

Under ideal conditions, recovering orientation information from a combination of the magnetometer and the accelerometer is done by comparing each sensors' measurements to known reference vectors the earth's magnetic field and gravity respectively via the Triad Algorithm [8]. Unfortunately, magnetometer readings have been shown to be noisy, especially in variable environments where local magnetic effects can be present [6], [27]. Suggested approaches to overcoming this difficulty relevant to the iShake project include incorporating gyroscope data [6], and using the phone's camera to capture the panorama as a stable reference point [27] (both sensors available on recent iPhone models). Future work includes understanding how having many measurements for a single event can reduce the impact of individual heading measurement errors in the estimation of direction of first arrival.

A. Client Application

The *iShake* client application is, functionally, a background process that has two main components: sensing loop and sending loop. The purpose of the partition of sensing and sending tasks was to ensure no blocking of the sensing while the application attempts to make network connection for data transmission. This allows the app to be in a perpetual state of earthquake sensing.

An overview of the architecture of the client application can be seen in Fig. 2. While the sensing loop handles the interaction with the main application and the on-board sensors (and is discussed in depth in the proceeding sections), the sending loop handles local storage, transmission of recorded sensor events, and requeueing of events in the case of poor network connection. The sending loop was designed to queue recently recorded events immediately after recording to reduce the total latency of the *iShake* system. While a failed transmission of a recent event may not be useful for emergency response if not received after

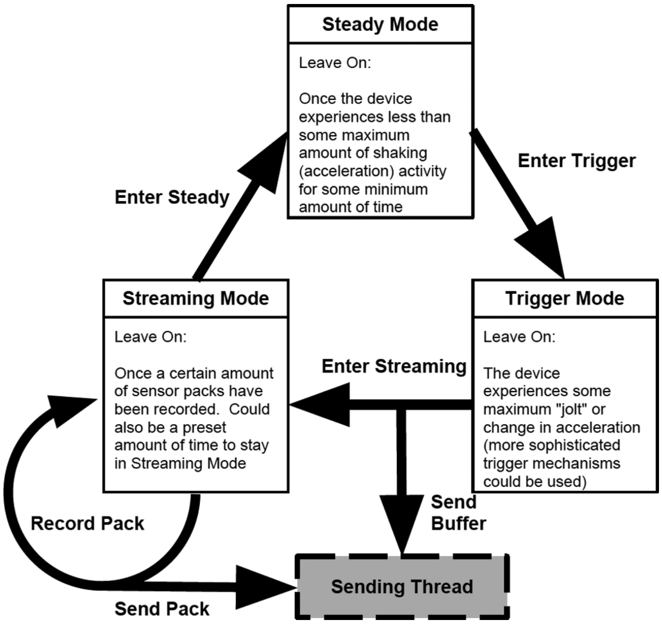

Fig. 3. Different modes of sensing by the client application. When the "Leave On" condition is satisfied, the application will transition to the proceeding mode. After the sensor is determined to be steady, the application will enter buffer mode. Once a trigger is set off, data will be streamed to the server, and the application cycle will repeat.

a day's time, there still exists scientific in post-event analysis of the event. Thus, failed events are always stored locally and indefinitely requeued until an eventual successful transmission.

For reasons such as data-usage rates and battery life, it is not practical for the mobile devices to be continuously streaming data to the servers. To handle this issue, a three-state model was created for the client application: Steady Mode, Trigger Mode, and Streaming Mode. This model permits minimal transmission of data to the server, while continuously recording and sensing for probable earthquake events locally on the device. Fig. 3 depicts the flow of the *iShake* client application.

1) Steady Mode: To begin determination of earthquake events, the mobile device must be stationary for a period of time prior to recording. The reasons for this are twofold. First, to determine orientation of the device, the gravity vector must be determined, and this can only be accomplished if the device is not experiencing other forces. Second, the *iShake* project is specifically analyzing recordings from stationary devices, thus devices carried on a moving person or experiencing a significant amount of movement unrelated to seismic events should not transmit their data to the server. Device movement is characterized by a change in the accelerometer reading. Using the previous accelerometer reading as the reference, the movement value of time step t, M_t is calculated by taking the L_2 norm of the difference acceleration vector

$$M_t = \left(a_t^x - a_{t-1}^x\right)^2 + \left(a_t^y - a_{t-1}^y\right)^2 + \left(a_t^z - a_{t-1}^z\right)^2 \quad (1)$$

where t is the current time step, and $a_t = (a_t^x, a_t^y, a_t^z)$ is the current acceleration vector. A moving average of the movement values are taken over a set period of time. A period of five seconds was chosen as a suitable interval. The sum represents the lack of stillness, or cumulative movement, of the device in the recent history. For the device to be verified as still, the cumulative movement value must be under a certain threshold. If the cumulative movement is under the threshold, then the device moves onto the next state. Otherwise, the device will continue to record indefinitely its cumulative movement, keeping only a history of 5 s of previous movements.

2) Trigger Mode: Earthquake waves are made up of several different modes of shaking, each of which travels with a characteristic velocity. The first wave energy to be felt is from the primary wave (*p-wave*), which has an amplitude significantly smaller than that of the secondary wave (*s-wave*) [24]. While the shaking caused by a *p-wave* is often not strong enough to be quickly and unambiguously discerned from unrelated background vibrations, capturing the *p-wave* is still of great interest to seismologists. The application is able to capture the *p-wave* by always keeping in a circular memory buffer a segment of the signal recorded before the threshold triggering of the system. The system is considered "triggered" when a shaking event above a predetermined threshold is recorded; this would most often be by the *s-wave*. Currently, the trigger is fired when an acceleration of 0.1 g is experienced by any of the three axes. A suitable buffer length was chosen to be 30 s, with a 15 s pretrigger.

3) Streaming Mode: Soon after an actual earthquake event, cellular coverage often becomes unreliable [21], [25]. Because of this, it is necessary to transmit data as soon as possible after a shaking event is determined by the application. The application records "packs" of sensor readings (acceleration, heading, location) at 3 s intervals and immediately transmits the data to the server. This is repeated for the 2 min following the shaking event in order to capture the entire event. In case the device does not have service during the shaking event, a local copy of the recordings are stored locally, and placed into a queue to be sent once service is available again.

B. Backend Hardware and Software

The *iShake* system has a unique load-handling specification, in that it must handle large and sudden spikes of requests and data uploading during earthquake events, yet use only the minimal amount of resources during the large periods of inactivity. The auto-scalability of the Google App Engine architecture fit the needs of this application, and was chosen as the backend. Since the App Engine's cloud-based architecture handles both hosting and software solutions, the backend was able to be implemented with minimal developer time and a very low recurring cost for maintenance. Fig. 4 summarizes the backend architecture implemented for the *iShake* system, while the following sections focus on some of the larger backend components.

1) Time Synchronization: Due to the high speed of seismic waves, time synchronization on the order of milliseconds is required for estimation of earthquake epicenter. From empirical testing, clock drift on the iPhone was determined to be on the order of seconds per day. iPhones correct their clock drift at a rate on the order of hours when connecting to cellular towers. The level of drift is unacceptable for calculation of an earthquake's epicenter, which requires millisecond accuracy and precise phasing information. To correct for clock drift,

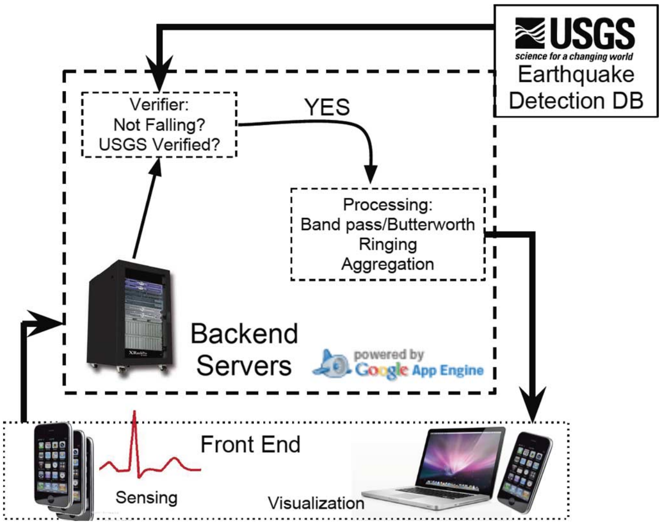

Fig. 4. Integration of backend architecture and frontend architecture: high-level overview of the subprocesses of the *iShake* backend. The components aim to reduce noise in raw transmitted signals, and verify to correlation of those signals with certified earthquake events.

iShake uses a system similar to QCN [11] that relies on *Network Time Protocol* (NTP) [2] communication to calculate the difference in time measurement between the client and server. This value is then stored on the server and used as a correction factor to the data sent by the client. Open source projects such as *ios-ntp Eadie* [13] serve as an implementation of NTP on iOS applications.

2) USGS Earthquake Verification: From high-fidelity seismic stations [1], the USGS is able to detect an earthquake event and publish sensor recordings only minutes after the event. Leveraging the high certainty of the USGS events, *iShake* is able to eliminate specific transmitted recordings as possible earthquake events. If a device's recording is not transmitted within a certain range of time and space of a USGS earthquake event, then it is categorized as unverified. Similarly, device recordings can then be grouped based on their relative proximity in time and space to a USGS earthquake event to begin the process of data analysis for a specific earthquake event. Currently, the earthquake verification process is automated on the *iShake* server for all submitted events in the California area. Although the scope is currently limited to this region, the process can easily be extended to other regions by adding more detected earthquake feeds to the *iShake* backend.

IV. EARTHQUAKE SIGNAL PROCESSING AND SENSOR STATE DETERMINATION

The ubiquity of mobile devices enables sensing to take place in a larger variety of places and situations. The sacrifice for increased coverage of sensing is an increase in the uncertainty of the environment of sensing. Using mobile devices as seismic sensors introduces previously unconsidered factors to the recordings of the ground motion. One such uncertainty already discussed is orientation determination of the mobile device. This section discusses methods to detect scenarios that would affect the signal produced by the mobile devices such as if the signal is recording the actual ground motion, or also capturing some of the response of the device housing, or if the device experienced moving unrelated to the earthquake such as falling off a desk.

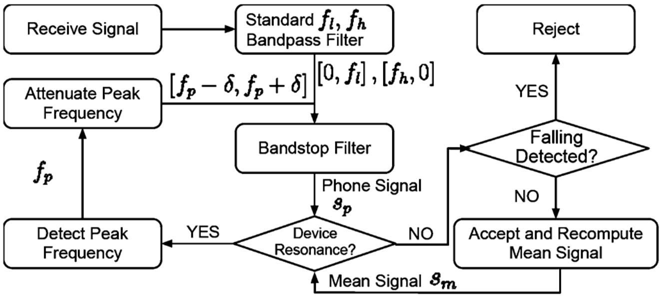

Fig. 5. Signal processing of received phone acceleration signals.

Fig. 5 shows a high-level flow diagram of algorithm to which incoming signals are subjected. Subprocesses of the processing algorithm are described in the following subsections.

A. Bandpass Filter Over Seismic Region of Interest

Ground motions from earthquakes will typically have spectral values in the range of 0.3–0 Hz. Due to effects such as ambient vibrations and sensor noise, the acceleration recording from a device will often contain frequencies outside of this range. The contributions to the signal of frequencies outside the range of interest are treated as noise. To diminish the contribution of ambient vibrations and device response, a butterworth bandpass filter is first applied to the acceleration signal [9]. The filter is applied both in the forward and reverse direction to correct for phase distortion. Phase conservation becomes important when comparing time-series of the same earthquake event from different mobile devices. This subprocess is depicted in Fig. 5 in the "Standard Bandpass Filter" subprocess with low and high frequencies of $f_l = 0.3$ and, $f_h = 30$ Hz, respectively.

B. Phase Alignment for Same-Event Time Series

Some ground motion parameters that describe the characteristics of a shaking event require time-domain analysis (e.g., *Arias Intensity* of the iPhone measurements compared to that of the reference accelerometer record [7]). To compare properly device signals in the time domain, the signals must be phase-aligned. While phase-alignment removes any information on earthquake travel-time, ground motion parameters such as *Arias Intensity* rely on the assumption of phase-alignment. For characteristics that account for signal propagation time, such as source localization, the phase-alignment procedure is not used. An algorithm based on cross-correlation was employed to properly align the phases of same-event signals. To find the phase misalignment between a discrete signal $f[t]$ and $g[t]$ with signal lengths of T time steps each, we seek a t^* time delay

$$\frac{t^*}{\tau} = \operatorname*{arg\,max}_{n \in \{-T, -T+1, \ldots, T\}} (f \star g)[n] \tag{2}$$

$$\frac{t^*}{\tau} = \operatorname*{arg\,max}_{n \in \{-T, -T+1, \ldots, T\}} \sum_{m=1}^{T} f[\tau m] g[\tau m + n] \tag{3}$$

where τ denotes the time step. Time-shifting f by t^* seconds will allow for more accurate time-series comparisons between signals.

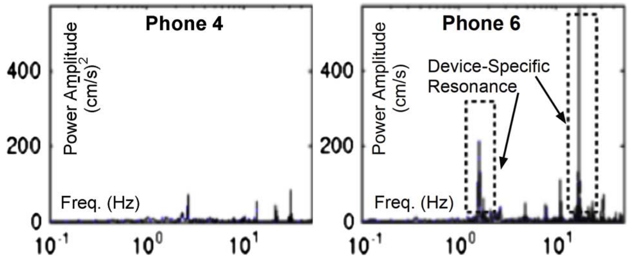

Fig. 6. Spectral response from 1978 Tabas, Iran Earthquake: Phone 6 shows unique peaks around 1 Hz and 15 Hz in the power spectrum of a simulated shaking event. This is indicative of device-specific "resonance" which amplifies specific frequencies unique to a device. These errors can be decreased by attenuating the frequencies amplified by "resonance."

C. Device "Resonance"

During shake-table testing, some devices experienced high levels of resonance around frequencies particular to the specific phone. Such resonance appeared after repeated shake testing and may be the result of a loose connection to the contact surface or internal resonance with the housing of the device. Fig. 6 shows an instance of resonance in the periodogram of Phone 6 for a trial at *ST-2*. While the reference and other devices do not have any dramatic spikes in the frequency spectrum (removing the possibility of the spikes appearing because of ambient vibrations), Phone 6 shows two pronounced spikes around 1 Hz and 15 Hz. By using a band-stop filter to attenuate the offending frequencies to an average level, the effect of resonance can be neutralized to a large degree.

To include collected signals that may or may not include the effects of resonance, an algorithm was developed for the backend server that detects the presence of resonance, and then applies the band-stop filter, effectively removing some device-specific corruption from the received signal.

The pseudocode and algorithmic details are given in Algorithms 1 and 2. For an earthquake event E, the inputs are the mean spectral acceleration s_m of the signals collected for the same shaking event E (as determined through spatial and temporal clustering of received signals) and a raw smartphone acceleration record $a_p \in A_E$ that we wish to check for the presence of resonance, where A_E are all raw smartphone records attributed to an event E.

```
Algorithm 1: FilterResonance

Input: mean spectrum signal $s_m$ for event $E$,
phone accel signal $a_p \in A_E$ to modify
Output: modified $s_p$ signal
do $s_p \leftarrow \mathrm{fft}(a_p)$
do $\delta_p \leftarrow |s_p - s_m|$
if ResonanceDetected($\delta_p$)
    then return FilterResonance($s_m$,
        BandStopFilter($s_p, \max(\delta_p)$))
else return $s_p$
```

The `ResonanceDetected` algorithm begins by selecting a candidate resonant frequency, $f_{\max}$ (the current implementation selects the frequency with the maximum spectral acceleration error value). From this peak value, the mean error value is calculated for the n_{avg} sample points to the left and right, then the ratios of these values are calculated with respect to the peak error, $\delta(f_{\max})$, where the ratios are δ_l and δ_r, respectively. If both ratios have a value lower than the "peak sharpness threshold," $\bar{\delta}$, then the frequency error peak at $f_{\max}$ is classified as sharp enough to be considered a resonance peak. The `FilterResonance` algorithm will subsequently reduce the effect of noise added by the resonance with the offending frequency by applying a standard `BandStop` filter.

```
Algorithm 2: ResonanceDetected

Input: spectral accel. error signal $\delta(f)$
Output: logical result of resonance test
do $n_{\mathrm{avg}} \leftarrow$ number of averaging points (user
provided)
do $\bar{\delta} \leftarrow$ peak sharpness threshold (user provided)
do $f_{\max} \leftarrow \arg\max_f(\delta(f))$
do $\delta_l \leftarrow (1/n_{\mathrm{avg}}\delta(f_{\max}))\sum_{i=0}^{n_{\mathrm{avg}}-1}\delta(f_{\max}-i)$
do $\delta_r \leftarrow (1/n_{\mathrm{avg}}\delta(f_{\max}))\sum_{i=0}^{n_{\mathrm{avg}}-1}\delta(f_{\max}+i)$
if $\delta_l, \delta_r \leq \bar{\delta}$
    then return True
else return False
```

In Fig. 5, the subprocess that detects and attenuates resonance effects is shown in the lower-left loop. Since the resonance subprocess is closed-loop, processing of resonance effects can successively applied until all effects are removed. We assume the left and right bounding steps are checked to be within the bounds of error signal.

D. Falling Phone Detection

Since the devices measuring ground motion will be in more volatile environments, they will be susceptible to outside forces affecting the signal. This includes devices falling, other objects falling on a device, or other similar events that would cause the device to measure non-earthquake-related effects. Signals produced by devices experiencing sudden and conspicuously unrelated forces will not accurately reflect the intensity of the underlying ground motion, thus making useful the detection of such events. We analyze the *Arias Intensity* [20] of the signal in our detection algorithm. The *Arias Intensity* measures the accumulation of energy of an earthquake event and is defined by

$$I_A = \frac{\pi}{2g}\int_0^{T_d} a(t)^2\, dt \tag{4}$$

where $a(t)$ is the acceleration record at time t, T_d is the duration period of the event, and g is the acceleration of gravity. The algorithm employed detects large rates of change of the *Arias Intensity* that are sufficiently dissimilar to a signal verified to have been produced by a given earthquake event. Phase-alignment is necessary to properly compare the *Arias Intensity* plots of the device and the reference signal. Fig. 7 shows an *Arias Intensity* plot of a phone experiencing falling compared with the reference recording of the shaking event. The two signals match

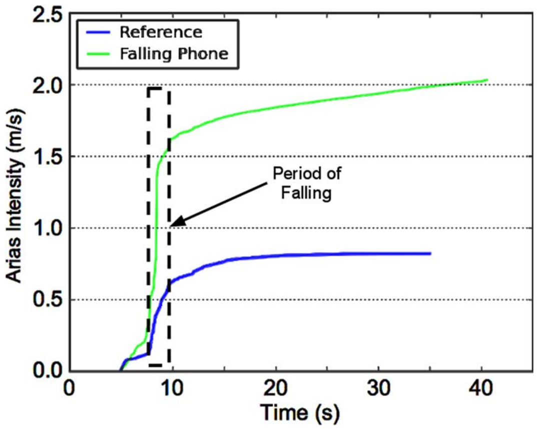

Fig. 7. *Arias Intensity* for falling phone: the instance the falling phone felt a severe jolt can be witnessed by the relative spike in *Arias intensity* in comparison to the reference acceleration.

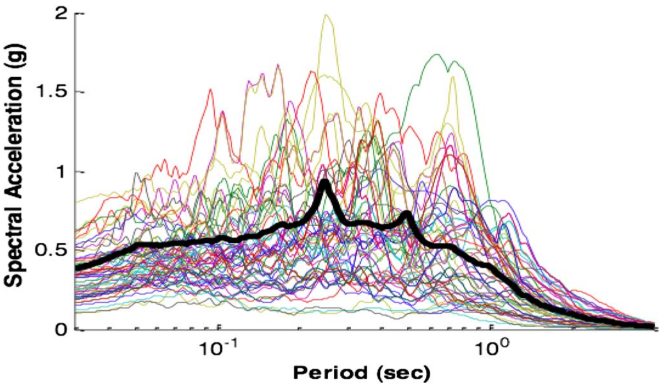

Fig. 8. Acceleration response spectra (5% damped) of the ground motions used at *ST-1*. The selected ground motions exhibit a wide range of spectral characteristics. This is intended to test the mobile device's versatility in seismic sensing. The *x-axis* is the natural period of the SDOF system, and the *y-axis* is the spectral response for the given period.

well until the shaking event, after which the falling phone has a large spike in intensity. When an unexplained spike in *Arias Intensity* is detected, the signal will be discarded from earthquake event analysis. Fig. 5 depicts this falling phone algorithm deciding whether or not a received signal should be accepted. The pseudocode for `FallDetected` is given in Algorithm 3, where I_s is the *Arias intensity*, and the definition is given in (4).

Algorithm 3: `FallDetected`

```
Input: acceleration signal $a$
Output: logical result of falling test
do $\bar{I} \leftarrow$ Arias Slope Threshold (user provided)
do $I_s \leftarrow \text{Arias}(a)$ (using 4)
do $\dot{I}_s \leftarrow (dI_s/dt)$
if $\max(\dot{I}_s) \geq \bar{I}$
    then return True
else return False
```

V. SHAKE TABLE TESTING RESULTS

A test procedure was devised to verify the quality of the accelerometer recordings in the context of earthquake sensing, of two types of mobile devices: four 3GS iPhones and three iPod Touches (third generation). The devices were secured to a custom-built base platform that was then secured to a shaking table. The base platform was designed to orient the devices at different directions in order to test for biases among axes of the accelerometers. Also, attached to the base platform were high-quality accelerometers that were used as a reference for the device measurements. Dashti *et al.* [12] gives a detailed analysis of the shaking table testing procedure, which is discussed at a higher level in this paper.

A suite of 150 historical ground motion replays with a wide range of amplitudes, durations, and frequency contents, as well as sinusoidal motions were applied to the base of the shake table to test the measured acceleration response of the devices. The devices and reference accelerometers captured the shaking events in a series of trials. While testing site 1 (UC San Diego, *ST-1*) only had a uniaxial (1-D) shaker, testing site 2 (Richmond Field Station, *ST-2*) had three-dimensional (3-D) shaking capabilities, and the reference accelerometers were oriented to capture all axes of motion. Relatively high-quality reference accelerometers commonly used in earthquake engineering research were mounted to serve as a comparative or "ground truth" record of the shaking events with which to compare the lower-quality mobile phone sensors. Comparisons between the mobile devices and the reference accelerometers were made for each trial to validate the devices' ground-motion capturing ability.

Fig. 8 shows the acceleration response spectra of the input ground motions in tests *ST-1* and *ST-2*. The acceleration response spectra is commonly used in earthquake engineering to define the peak acceleration experienced by single-degree-of-freedom (SDOF) structures—with the same damping ratio (e.g., 5%) but different natural frequencies—to the base acceleration time-history [22]. To subject the devices to shaking with a wide range of amplitudes, the same earthquake event pattern was sometimes applied multiple times at varying amplitudes. The varying amplitudes served to test the hypothesis that the iPhone's recording accuracy would increase with higher amplitude shaking, as the signal-to-noise ratio decreased with higher amplitudes [12].

The rest of this section presents a summary of the main results of shake table testing, while further conclusions are discussed in greater detail in [12], such as the increase in accuracy of measurements from the iPhones with respect to the increase in ground motion intensity.

A. Stationary Device Comparison

The accelerometer data was used to calculate common ground motion intensity parameters including *peak ground acceleration* (PGA), *peak ground velocity* (PGV), and *peak ground displacement* (PGD) [20], *Arias Intensity* (I_A), (defined in (4)), and *response spectra* [22]. If accelerometers in mobile phones can accurately capture the acceleration response spectra of most earthquake motions, then there is a compelling case not only for earthquake researchers to benefit from this data, but practitioners as well. For example, when designing

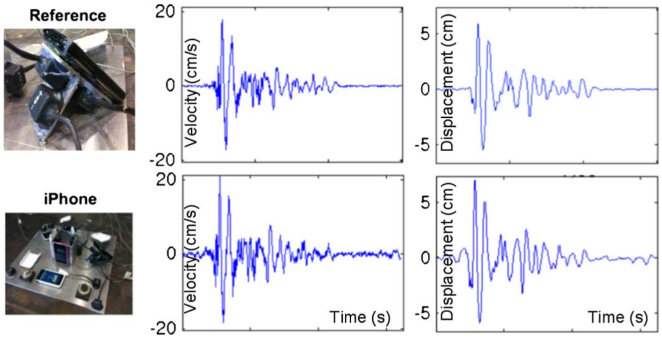

Fig. 9. Stationary phones: the accelerometer records of the stationary phone compare well to the reference accelerometers, even under integration to produce velocity and displacement records.

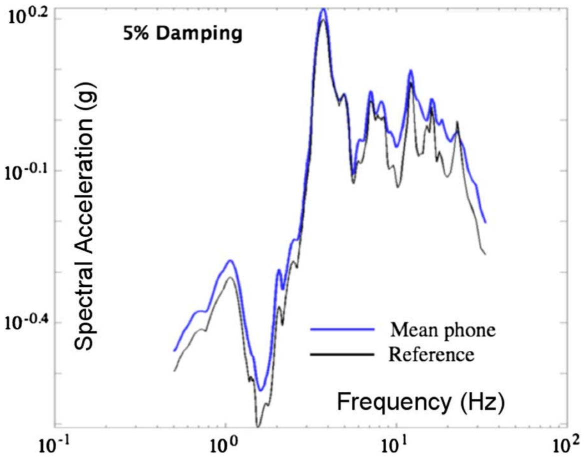

Fig. 10. Response spectrum with 5% damping: mean response of the devices compared with the reference. The main trends from the reference signal are captured well by the mean response.

structures for earthquake loads, structural engineers must design the natural frequency of the structure to minimize the effects of earthquakes on the structure [22]. If mobile phones could accurately reproduce the response spectra of a recorded earthquake, then a more localized description of the expected seismic response of the structure may be obtained.

The devices were shown to be capable of accurately capturing the primary ground motion intensity parameters used by earthquake engineers in design, such as PGA, PGV, and PGD. Fig. 9 shows the velocity and displacement time-series recorded by the high-fidelity reference accelerometers, as well as the time-series recorded by an iPhone device for the 1979 Imperial Valley earthquake (6.4 M), recorded 40 miles from the epicenter. The records were calculated by successive integration of the original accelerometer signal after proper baseline correction and filtering [9].

The testing analysis done in this section focuses on the performance of the mobile phone sensors when the device is rigidly attached to the device board. This serves as a specific "best case" scenario for the application of smartphones as seismic sensors, as it requires the most constrained environment for sensing.

It can be seen from Fig. 9 that the peaks from the two sources are similar and occur at the same time. The PGA, PGV, and PGD values help in determining where the most severe shaking occurred during an earthquake. A dense distribution of mobile phones running the *iShake* software would aid in the immediate rescue effort [23]. By providing emergency responders with information on the hardest-hit areas after an earthquake, rescue efforts would be more focused and potentially more effective.

Fig. 10 presents a comparison of the response spectra of the reference and mobile devices. The mean responses of the mobile devices show promising results in frequency-domain analysis. They were able to capture the key periodic components that the reference signal indicates. The results show the devices can be used to aid engineers in the design of buildings and structures. With a more accurate characterization of local earthquakes, engineers will have better information when designing for earthquake loads.

B. Device Bias

While a standalone accelerometer, such as one used by QCN, is designed as not to be biased by the housing of the sensor, there is no such guarantee in the accelerometers provided by the smartphones. The mounting of the accelerometer may have its own resonance that would in turn affect the recordings of the accelerometer. To investigate the consequences of resonance, the bias of the devices was calculated in the frequency domain.

The bias value considered in this section is the tendency for a particular device to overestimate or underestimate the spectral response of a certain frequency (as compared to the reference accelerometer's response), for all frequencies in the domain of importance (0.3–30 Hz). Bias was calculated using the methods of Augello *et al.* [5]. First, a residual error, r_i, in the acceleration frequency domain was calculated for each frequency and each ground motion

$$r_i(f_k) = \log\left(S^r_{A_i}(f_k)\right) - \log\left(S^d_{A_i}(f_k)\right) \tag{5}$$

where $S^r_{A_i}$ is the spectral ordinate of the reference signal as a function of frequency, f_k; $S^d_{A_i}$ is the spectral ordinate of the device signal; and i is the ground motion index. For *ST-2*, this process was repeated for each axis of motion, m.

The bias was obtained by calculating the mean residual error for each frequency f_k

$$\text{bias}\ (f_k) = \frac{\sum_{i=1}^{N_i}\sum_{m=1}^{N_m} r_{im}(f_k)}{N_i \cdot N_m} \tag{6}$$

where r_{im} is the residual error for trial i measured on axis m, and N_i and N_m are the number of ground motion trials and axes of motion, respectively.

Fig. 11 shows the results of the bias calculations, after offsetting of individual phones' mean bias. The offset was added in order to gain insight into systematic bias across all devices. After applying such offsets, the results reveal an apparent bias to overestimate the spectral response of midrange frequencies (1–10 Hz), and to underestimate higher frequencies (>10 Hz). From observation of Fig. 11, one notices that the error bars are smallest (i.e. the variance is smallest) in the midrange frequencies. With the smaller variance there is more confidence that attenuating the midrange frequencies, by the amount estimated

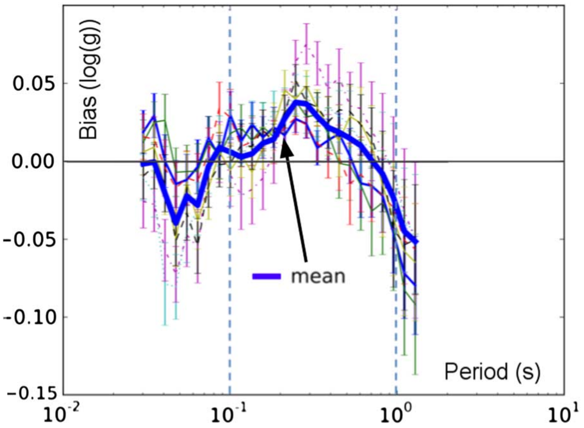

Fig. 11. Bias of the devices for ST-1 testing. Across all phones, there is systematic overestimation of midrange frequencies (1–10 Hz), and underestimation of higher frequencies (>10 Hz).

by the bias parameters, will more faithfully estimate the true ground motions sensed by the devices.

VI. Virtual Earthquake Field Test

During the month of January 2011, a field test was conducted to evaluate the performance of the *iShake* system as well as providing valuable feedback for a user study on participatory sensing applications on mobile devices [15]. Dozens of *iShake* application users downloaded the free *iShake* application from the Apple App Store to participate in the field tests. The majority of these users were from the Berkeley area.

The field test consisted of two types of trials. The first type alerted application users that a imaginary earthquake had occurred (via the Apple Push Notification Service), and then asked for the users to give input on the emotional response of such information being delivered through a mobile application.

The second trial type, which is more related to the *iShake* system and application target use case, asked for users to simulate a "virtual earthquake" at a predetermined time (coordinated through the same push notification process as the imaginary earthquake). The virtual earthquake was simulated by having all the participants activate the application, let the phone transition into pretrigger mode, and then manually shake the phone to set off the trigger and begin streaming individual shaking data back to the server at the same time. Since the backend for application was intentionally chosen to be massively scalable (by using the Google App Engine infrastructure), the relatively modest participant pool size was easily handled. While the successful handling of the modest number of concurrent requests was expected, the virtual field test was useful as a proper verification of the functionality of the state machine architecture of the client application, and enabled the creation of summary visualizations. The summary visualizations were fed back to the participants after most participants were able to transmit their recordings to the server. Screen shots of the application and visualizations used by the participants of the virtual earthquake (currently retired from the Apple App Store) can be seen in Fig. 1.

VII. Conclusion

iShake is a system that allows anyone with an iPhone or iPod Touch device to participate in seismic sensing. This provides the scientific community and emergency responders with a dense array of ground motion data rapidly after an event, with assurance of quantitative accuracy previously unattainable from crowdsourced earthquake data. Through shake table tests, we have validated the accuracy of the device's internal sensors for seismic sensing application. To account for environmental uncertainties inherent to a mobile computing platform, novel signal processing methods were developed to reduce the noise introduced from the variabilities. As evidenced by the large pool of "virtual earthquake" participants in our field study, and the over 2600 users who have downloaded the *iShake* client application (as of December 2012), people are intrigued by earthquakes and earthquake research. Ultimately, the *iShake* project is a system that turns this intrigue into positive societal impact.

Future directions of the project include investigation of latencies involved in seismic sensing of earthquakes and possible applications to earthquake early-warning systems, and battery-life optimization techniques for scientific sensing on mobile phones to increase the participation rate of crowdsourced sensing.

Acknowledgment

The authors thank Prof. T. Hutchinson and the staff at the UCSD South Powell Laboratory for their assistance and free use of their facilities. They are thankful for Deutsche Telekom and their interest in the project and ongoing support and for Prof. S. Mahin at UC Berkeley and PEER, who generously allowed us to mount the phones onto the multidirectional shaking table during PEER structural engineering shaking campaigns. They gratefully acknowledge Dr. D. Wald of USGS for his valuable recommendations and advise throughout the project and would also like to acknowledge that the original concept of using smartphones as accelerometers came from Dr. R. Bonaparte, CEO of Geosyntec Consultants, Inc. Finally, we are indebted to D. Estrin for her pioneering work in this field and vision of participatory sensing.

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

References

[1] National Geophysical Data Center. [Online]. Available: http://www.ngdc.noaa.gov

[2] Network Time Protocol Website. [Online]. Available: http://www.ntp.org

[3] Skyhook. [Online]. Available: http://skyhookwireless.com

[4] G. M. Atkinson and D. J. Wald, "'Did you feel it?' Intensity data: A surprisingly good measure of earthquake ground motion," *Seismological Res. Lett.*, vol. 78, no. 3, p. 362, 2007, 08950695.

[5] A. J. Augello, J. D. Bray, R. B. Seed, and N. A. Abrahamson, "Dynamic properties of solid waste based on backanalysis of OII landfill," *J. Geotech. Geoenviron. Eng.*, vol. 124, no. 3, pp. 211–222, 1998.

[6] R. Azuma, B. Hoff, H. Neely, III, and R. Sarfaty, "A motion-stabilized outdoor augmented reality system," *IEEE Virtual Reality*, vol. 99, pp. 252–259, 1999.

[7] L. G. Baise and S. D. Glaser, "Consistency of ground-motion estimates made using system identification," *Bull. Seismological Soc. Amer.*, vol. 90, no. 4, p. 993, 2000.

[8] H. D. Black, A passive system for determining the attitude of a satellite Johns Hopkins Univ., Applied Physics Lab., Silver Spring, MD, USA, No. TG-517, 1963.

[9] D. M. Boore and J. J. Bommer, "Processing of strong-motion accelerograms: Needs, options and consequences," *Soil Dynamics and Earthquake Engineering*, vol. 25, no. 2, pp. 93–115, 2005.

[10] J. Burke, D. Estrin, M. Hansen, A. Parker, N. Ramanathan, S. Reddy, and M. B. Srivastava, "Participatory sensing," in *World Sensor Web Workshop*, 2006, pp. 1–5, Citeseer.

[11] E. Cochran, J. Lawrence, C. Christensen, and A. Chung, "A novel strong-motion seismic network for community participation in earthquake monitoring," *IEEE Instrum. Meas. Mag.*, vol. 12, no. 6, pp. 8–15, 2009.

[12] S. Dashti, J. D. Bray, J. Reilly, S. Glaser, and A. Bayen, "iShake: Evaluating the reliability of mobile phones as seismic monitoring instruments (under review)," *Earthquake Spectra J.*, pp. 1–11, 2011.

[13] G. Eadie, ios-ntp.

[14] J. Eriksson, L. Girod, B. Hull, R. Newton, S. Madden, and H. Balakrishnan, "The pothole patrol: Using a mobile sensor network for road surface monitoring," in *ACM MobiSys*, 2008.

[15] M. Ervasti, S. Dashti, J. Reilly, J. D. Bray, A. Bayen, and S. Glaser, "iShake: Mobile phones as seismic sensors-user study findings," in *Proc. 10th Int. Conf. Mobile and Ubiquitous Multimedia*, 2011, vol. 28, pp. 43–52. [Online]. Available: http://dl.acm.org/citation.cfm?id=2107601

[16] D. Estrin, Mobile Sensing Systems: From Ecosystems to Human Systems, 2009.

[17] M. Faulkner, M. Olson, R. Chandy, J. Krause, K. M. Chandy, and A. Krause, "The next big one: Detecting earthquakes and other rare events from community-based sensors," in *Proc. 10th ACM IEEE Int. Conf. Inf. Process. Sens. Networks*, 2011, pp. 13–24, 9781450305129.

[18] R. Foulser-piggott and P. J. Stafford, "Incorporation of the spatial correlation of arias intensity within earthquake loss estimation," *Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, no. 4, pp. 1–12, 2010.

[19] B. Hull, V. Bychkovsky, Y. Zhang, K. Chen, M. Goraczko, A. Miu, E. Shih, H. Balakrishnan, and S. Madden, "CarTel: A distributed mobile sensor computing system," in *Proc. 4th Int. Conf. Embedded Networked Sens. Syst.*, 2006, pp. 125–138.

[20] T. Lay and T. C. Wallace*, Modern Global Seismology*. New York, NY, USA: Academic, 1995, vol. 58.

[21] Y. N. Lien, H. C. Jang, and T. C. Tsai, "A MANET based emergency communication and information system for catastrophic natural disasters," in *Proc. IEEE 29th Int. Conf. Distrib. Comput. Syst. Workshops*, 2009, pp. 412–417.

[22] N. M. Newmark and W. J. Hall, "Earthquake spectra and design," Earth System Dynamics vol. 1, monograph, pp. 1–99, 1982.

[23] D. Obenshain, K. M. Chandy, R. Chandy, R. Clayton, A. Krause, M. Olson, D. Rosenberg, and A. Tang, Community Seismic Network.

[24] G. R. Pickett, "Acoustic character logs and their applications in formation evaluation," *J. Petroleum Technol.*, vol. 15, no. 6, pp. 659–667, 1963.

[25] D. J. Pines and P. A. Lovell, "Conceptual framework of a remote wireless health monitoring system for large civil structures," *Smart Mater. Structures*, vol. 7, p. 627, 1998.

[26] T. Sakaki, M. Okazaki, and Y. Matsuo, "Earthquake shakes Twitter users: Real-time event detection by social sensors," in *Proc. 19th Int. Conf. World Wide Web*, 2010, pp. 851–860.

[27] G. Schall, A. Mulloni, and G. Reitmayr, "North-centred orientation tracking on mobile phones," in *IEEE Int. Symp. Mixed Augmented Reality*, Oct. 2010, vol. 3, pp. 267–268, 10.1109/ISMAR.2010.5643600.

[28] T. Travasarou, J. D. Bray, and N. A. Abrahamson, "Empirical attenuation relationship for Arias Intensity," *Earthquake Eng. Structural Dynamics* vol. 32, no. 7, pp. 1133–1155, 2003., DOI: 10.1002/eqe.270. [Online]. Available: http://doi.wiley.com/10.1002/eqe.270, 00988847

[29] D. J. Wald, V. Quitoriano, T. H. Heaton, H. Kanamori, C. W. Scrivner, and C. B. Worden, "'TriNet ShakeMaps': Rapid generation of peak ground motion and intensity maps for earthquakes in Southern California," *Earthquake Spectra*, vol. 15, no. 3, p. 537, 1999, DOI: 10.1193/1.1586057, 87552930.

[30] H. Zhang, E. Horvitz, R. C. Miller, and D. C. Parkes, "Crowdsourcing general computation," in *ACM CHI 2011 Workshop on Crowd Sourcing and Human Computation*, 2011, pp. 1–5.

Jack Reilly, photograph and biography not available at the time of publication.

Shideh Dashti, photograph and biography not available at the time of publication.

Mari Ervasti, photograph and biography not available at the time of publication.

Jonathan D. Bray, photograph and biography not available at the time of publication.

Steven D. Glaser, photograph and biography not available at the time of publication.

Alexandre M. Bayen, photograph and biography not available at the time of publication.