Evaluating the Reliability of Phones as Seismic Monitoring Instruments

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Emergency responders must "see" the effects of an earthquake clearly and rapidly for effective response. This paper presents a novel use of cell phone and information technology to measure ground motion intensity parameters. The phone sensor is an imperfect device and has a limited operational range. Thus, shake table tests were performed to evaluate their reliability as seismic monitoring instruments. Representative handheld devices, either rigidly connected to the table or free to move, measured shaking intensity parameters well. Bias in 5%-damped spectral accelerations measured by phones was less than 0.05 and 0.2 [log(g)] during one-dimensional (1-D) and three-dimensional (3-D) shaking in frequencies ranging from 1 Hz to 10 Hz. They did tend to overestimate the Arias Intensity, but this error declined for stronger motions with larger signal-to-noise ratios. With these ubiquitous measurement devices, a more accurate and rapid portrayal of the damage distribution during an earthquake can be provided. [DOI: 10.1193/091711EQS229M]

INTRODUCTION

Effective post-event emergency planning and response can reduce the loss and damage caused by an earthquake. Hence, the U.S. Geological Survey (USGS) is committed to the rapid delivery of critical post-earthquake information to emergency responders and the public (e.g., Wald et al. 1999). "ShakeMap" and "Did You Feel It?" (DYFI) are two existing, successful USGS products developed for this purpose. ShakeMap (Wald et al. 2008) uses the high-quality recordings from the existing strong motion stations to provide a rapid and quantitative assessment of the level of shaking produced by earthquakes. While it contains algorithms that estimate the intensity of shaking in areas with sparse strong motion stations through interpolation and use of rapid finite-fault analyses (including generalized site amplification), its resolution is hindered directly by the limited number of high-quality instruments available. DYFI (Atkinson and Wald 2007, Wald et al. 2011) uses human observations voluntarily submitted through the Internet after an earthquake to estimate the intensity of

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shaking in different areas. DYFI-based maps, using the concept of citizen scientists, are of significant value as they directly report the macroseismic intensities (Wald et al. 2011). These maps are intended to be used in conjunction with ShakeMap, to improve its accuracy when strong motion stations are scarce. The highest contribution of DYFI has been from events with the following characteristics: (1) dense population; (2) abundant Internet access; and (3) lack of major damage (Wald et al. 2011). The reliability of DYFI becomes questionable for destructive earthquakes. Further, the effectiveness of DYFI-based maps may be greatly hampered by the speed at which people report critical information during crises. Limited public access to a fast and reliable Internet connection after a destructive earthquake is a concern. ShakeMap, on the other hand, does not depend on the availability of Internet users, but it relies on high-quality instrumentation that may not be available in many parts of the world. Thus, an inadequate number of strong motion stations and limited or delayed feedback from the people in a given area after a strong earthquake could lead to large uncertainties in the distribution of shaking intensity and damage. There is need for additional capability to accommodate reliable alternative measurements, particularly during more destructive earthquakes (Wald et al. 2011).

In an attempt to improve the quality and quantity of data supplied by the public particularly during more significant earthquake events, this research uses their cell phones to measure ground motion intensity parameters and to automatically deliver the results to a central server for processing and dissemination. The goal of this research is to eventually employ phones in conjunction with ShakeMap and DYFI to improve the resolution and accuracy of shaking intensity maps following an earthquake. Smartphones are equipped with a variety of sensors, including accelerometers, magnetometers, and a Geographical Positioning System (GPS) and are connected to an Internet connection often. Therefore, smartphones that are in a stable, charging position prior to an earthquake event may be used as a large network of lower-quality seismographs for hazard assessment. The recorded accelerations may be sent to a central server immediately following an earthquake in patches, before the networks are overwhelmed and saturated. If no Internet connection is available (possibly due to damage to cell towers or network saturation), the phone can save the data indefinitely until it reconnects to a network.

Admittedly, the distribution of smartphones is not uniform and is biased toward dense urban centers. This is not ideal, but the recorded data will still be valuable for hazard evaluation. Additionally, many of these phones will not be in a still position during an earthquake event (e.g., phones in a person's pocket or bag while moving), making their measurements unreliable. These factors, in addition to the possible oversaturation of cellular networks following a major earthquake, present challenges to this endeavor. But given the limitations of using humans to provide objective observations immediately after destructive earthquakes in DYFI and the limited number of high-quality strong motion instruments available for ShakeMap, the application of smartphones is worthwhile. Additionally, smartphones are increasingly growing in number and improving in capabilities, and their use as seismic monitoring instruments is thus promising for hazard assessment. Similar efforts are underway by other researchers who aim to use cellphones for earthquake early warning and detection with a different set of challenges (e.g., Faulkner et al. 2011, Olson et al. 2011, and Faulkner and Olson 2011). For example, characterizing rare earthquake events to maximize detection performance in addition to the heterogeneity of smartphones in quality and communication constraints present critical challenges in reliably detecting earthquake events. In the participatory sensing paradigm offered in this paper, semi-quantitative shaking data from numerous cellular phones that are able to capture reasonable data may enable the USGS to produce shaking intensity maps more accurately than presently possible.

The phone sensor, however, is an imperfect device, with a limited operational range and with performance variations among phones of a given model as well as between models. The entire phone is the inertial sensor, not just the micro-machined transducer inside. Thus, a series of one-dimensional (1-D) and three-dimensional (3-D) shake table tests were performed to evaluate the performance and reliability of a class of cell phones as seismic instruments. Handheld devices that were mounted on the tables at different orientations in space were subjected to over 100 ground motions. In this paper, we characterize the operational range of phone accelerometers and discuss the results of shake table experiments to evaluate their reliability individually and as a cluster. Clustering or grouping a number of low-quality acceleration records obtained from phones based on their physical distance (e.g., grouping the phone records within one block, for instance) may improve the quality of the collected data. We compare the error in a few ground motion intensity measures obtained from individual phone records to a cluster of seven phones. The experiments summarized here also provide insight into the performance and response of unsecured and falling handheld devices. Testing the performance of phones as a network to improve the existing earthquake monitoring and reporting systems is not within the scope of this paper.

SHAKE TABLE TESTING

OBJECTIVES

Representative phone devices were used in a series of shake table tests to measure the consistency of the acceleration response across multiple sensors and for each phone through multiple identical shakings. The uniaxial shake table at the UC San Diego South Powell Lab was used to simulate 1-D ground motions of a variety of earthquakes (the first series of shake table tests, referred to as ST-1). Subsequently, the phone sensors were mounted on the large, multidirectional shake table at the UC Berkeley Richmond Field Station during three weeks of testing (the second series of shake table tests, ST-2). Through these experiments, the phone response was studied under more realistic, 3-D earthquake motions at various intensities. The primary objective of these tests was to assess the reliability of one class of smartphones as seismic monitoring instruments. Additional goals were to explore techniques to distill the needed information from a large number of imperfect signals obtained from mobile phones with variable connectivity conditions and to detect the fall of an instrument.

SYSTEM DESCRIPTION AND TESTING PLAN

The iPhone models after 3GS, which were used in this study, have an STMicroelectronics, LIS331DL (STMicro 2008), triaxial MEMS accelerometer that can measure the acceleration time histories experienced by the phone in three orthogonal directions. The accelerometers inside these handheld devices have a maximum sampling rate of 100 samples per second (sps), corresponding to a Nyquist frequency of 50 Hz, a resolution of approximately 0.018 g, and a dynamic range of ± 2 g. Although the sensor resolution is low, its sampling rate is sufficient for most earthquake engineering applications. The available capacity of these phones is 8GB at a minimum. In addition to the accelerometer, the iPhone has a GPS unit for geo-location and navigation and a three-axis magnetometer that determines and records the orientation of the phone as a function of time. The expected error in the phone's location is approximately 10 m, which was observed to increase to 30 m when inside a building. The phone magnetometer has a maximum sampling rate of 33 sps. The accuracy of the phone time stamp is on the order of 1/10,000 s. The clock drift was observed to be approximately 1 s per day. The long-term drift depended on the phone's ability to update its readings with access to cellular towers. The clock drift on the phone makes it difficult to use these devices in locating the epicenter of the earthquake (which was not the objective of this study). However, if desired, the Network Time Protocol (NTP) may be used to assess and record the time drift in individual phones and offset these errors when processing the data on the server (e.g., Cochran et al. 2009). The NTP was not implemented in this study.

The iShake system, which includes a client application and a backend server, was developed to record, verify, analyze, and visualize the ground motion data collected by phones during actual earthquakes. The system is discussed in more detail by Dashti et al. (2011) and Reilly et al. (2012). Additionally, an independent, preliminary, pilot iPhone application was specifically developed to record accelerations during shake table experiments. Prior to any activity, the server initially confirmed the phone's connectivity to a wireless network. The client application then underwent a period of stillness prior to recording a ground motion. A "shake meter" was displayed on the phone screen to visualize the status of different phones as stable or unstable prior to shaking. The client also allowed visualization of the recorded three-component acceleration time histories on the server and the phones. The three orthogonal acceleration time histories obtained from each phone were successfully stored and transmitted to the database on the server, quickly visualized, and saved on the server during the shake table tests.

Figure 1 shows the testing configuration on the shake table. In each test, seven representative handheld devices were mounted on holders at different angles in 3-D. The holders were welded to a 46 cm × 46 cm square aluminum plate that was rigidly bolted to the shake table. Small, relatively high-quality accelerometers (High Output Accelerometer Model 141, manufactured by Setra, available at the shake table facility) were mounted next to each phone device, as well as on the base platform to provide reference measurements in three orthogonal

Figure 1. Phone and instrumentation set up during the shake table tests.

directions. These accelerometers (referred to as "reference" sensors in this paper) had a nominal range of ±2 g and a natural frequency of 300 Hz, as reported by the manufacturer. They were judged adequate for capturing the shake table motion over the frequency range of interest to earthquake engineers (i.e., approximately 0.2 Hz to 25 Hz).

Operational Range of Phone and Reference Accelerometers

The acceleration records of interest (i.e., earthquake motions) are transient and band-limited, while the noise floor of a particular sensor is approximately stationary. But the operational range of the instrument (e.g., phone or reference accelerometer in this case) may be determined to reflect the common signal and background noise sources encountered when recording earthquake motions that fall between the sensor's self-noise and clipping levels (Evans et al. 2010).

The noise floor and operational range of a high-quality instrument used by the seismic monitoring community must be characterized in a low-ambient, steady environment, which is also their expected background condition. However, the lower-quality sensors presented in this paper are expected to experience different environmental conditions during an earthquake event (e.g., phones are typically resting on a table or are in a purse or pocket). Even if the phone is attached to a table, it will typically experience higher ambient noise compared to a standard seismic instrument. Therefore, the phone's dynamic range may better be characterized in the context of its expected background environment and activity. In this research, the noise floor of the reference and phone accelerometers was measured prior to shaking when rigidly mounted on the shake table, instead of in a low-ambient environment, in order to roughly characterize their operational range in a more probable background condition.

The noise floor of the accelerometer was characterized in terms of: (a) the mean value over time (representing the sensor's offset or bias); and (b) root mean square (RMS). The total RMS of instrument noise is one common way to describe the resolution of the signal. The mean value of noise ranged from −0.0033 g to 0.0019 g, and the RMS ranged from 0.0095 g to 0.019 g for different phones and their different axes. In general, no systematic difference was observed in the noise floor of different accelerometer components. The noise floor of reference accelerometers had a mean ranging from −0.0021 g to 0.0025 g and an RMS ranging from 0.019 g to 0.04 g, which showed a significant improvement compared to the phones.

The frequency dependency of the instruments' self-noise and their operational range were explored by comparing the self-noise acceleration RMS spectral densities of the phones and reference accelerometers with their corresponding total RMS and clipping RMS, as recommended by Evans et al. (2010), shown in Figure 2. As expected, the phone and reference accelerometers both had a higher noise level relative to broad-band, high-quality, strong motion sensors that are often employed by seismologists (e.g., presented by Evans et al. 2010). But the operational ranges of these instruments were adequate to cover the range of acceleration amplitudes that are of particular interest in this application (moderate to strong earthquake events). The comparison of phone measurements with a relatively high-quality sensor available for earthquake engineering laboratory testing was judged appropriate as a first step in identifying potential seismological applications. Several handheld devices are to

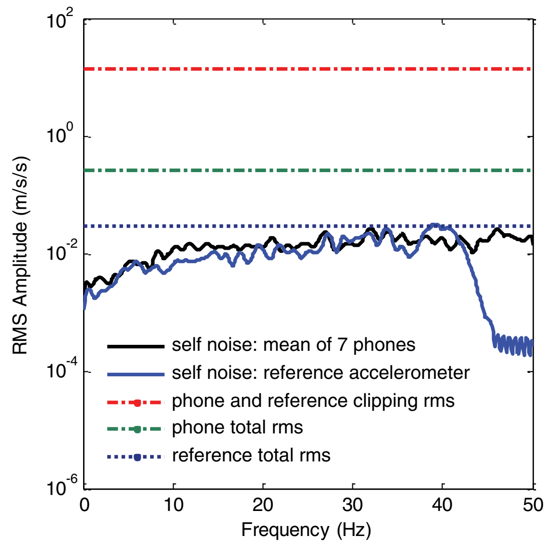

Figure 2. Amplitude operational range diagram in acceleration units for the phones and reference accelerometer: acceleration RMS spectral density of phone and reference accelerometer self-noise in comparison with the total RMS of their noise floor and clipping RMS.

be installed at strong motion stations and seismological laboratories with low environmental noise conditions for future comparisons during real earthquakes.

INPUT MOTIONS

A suite of 38 earthquake ground motions with varying characteristics (i.e., intensity, frequency content, duration, and energy rate) in addition to a synthetic record and 15 sinusoidal motions were applied in one direction to the base platform during ST-1. A few of the 1-D ground motions in ST-1 were subsequently repeated at different intensity levels, so that a total of 79 input motions were run through the UC San Diego 1-D shake table. The suite of input earthquake motions in ST-1 was selected primarily based on a probabilistic seismic hazard analysis of the UC Berkeley campus (Wong et al. 2008). These ground motions covered a range of representative motions in California (shallow crustal tectonic environment), where the iShake methodologies were initially developed and tested. The seismic hazard at the selected site was mostly dominated by near fault events that included the forward directivity effect (e.g., Bray et al. 2009). However, several less intense, far-field, strike-slip ground motions were added to the suite of selected motions to study the mobile sensors' response to a wide range of motions with different characteristics. These records conformed to the following criteria: (1) frequencies outside of the range 0.2 Hz to 25 Hz were filtered; and (2) they were recorded at Simplified Geotechnical Sites C and D – soft rock/shallow stiff soil or deep stiff soil, respectively (Rodriguez-Marek et al. 2001). The selected ground motions were then modified to reduce displacements to the allowed stroke of the shake table at the UC San Diego facility (i.e., ±150 mm) during ST-1. Figures 3a and 4a present the 5%-damped acceleration response spectra and Arias Intensity time histories of the input motions in ST-1

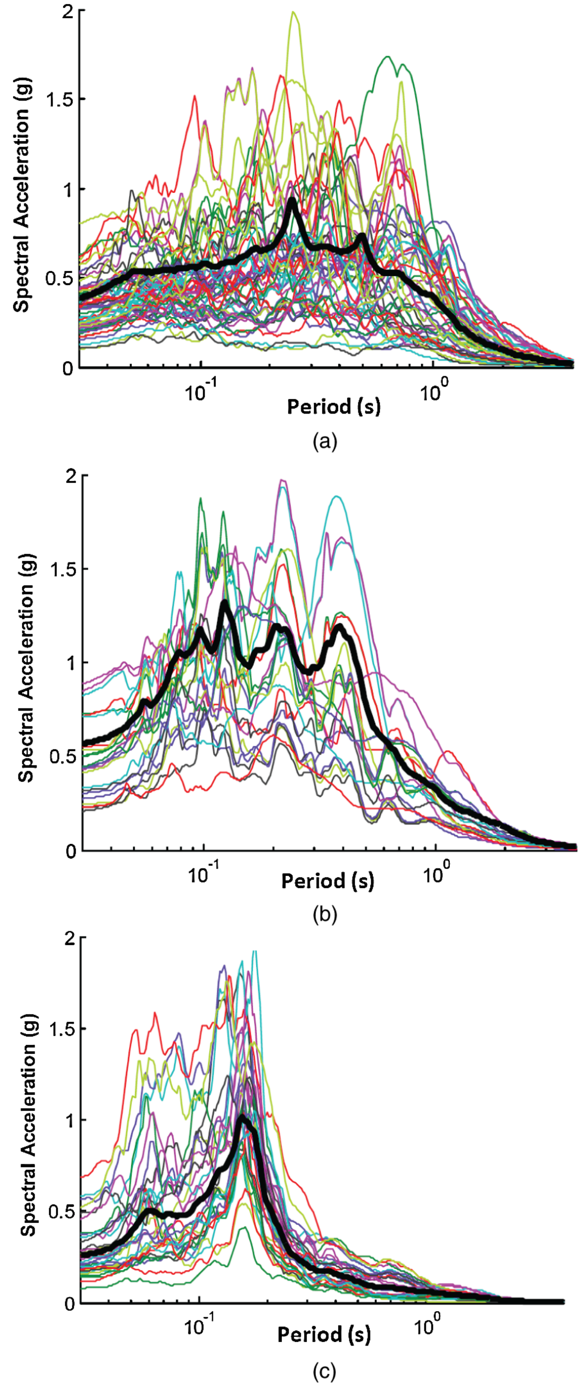

Figure 3. Acceleration response spectra (5% damped) of the: (a) 1-D shake table motions in ST-1; (b) two components of horizontal shake table motions during ST-2; and (c) vertical motions during ST-2. Thinner lines show the spectral accelerations of individual motions for each shake table component. The thick line presents the mean spectral acceleration of all records in the corresponding direction.

(excluding the sinusoidal waves). Arias Intensity (I_a) is an index roughly representing the energy of the ground motion in units of L/T (Arias 1970) and defined as:

$$I_a(T) = \frac{\pi}{2 \cdot g} \int_0^T a^2(t) \cdot dt \tag{1}$$

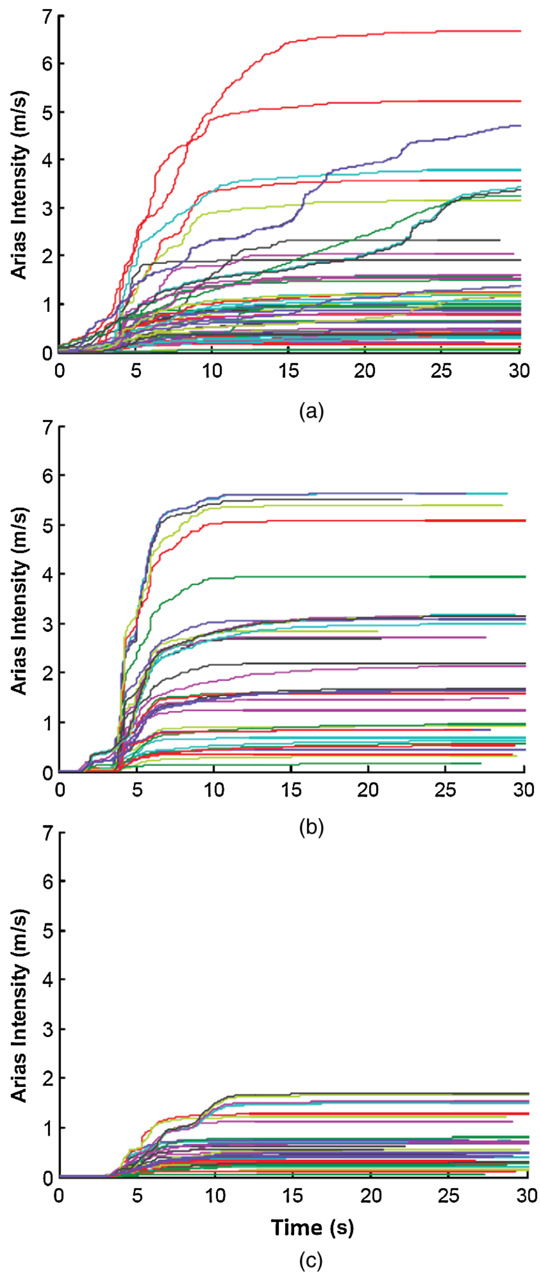

Figure 4. Arias Intensity time histories of the individual: (a) 1-D shake table motions during ST-1; (b) two components of horizontal shake table motions during ST-2; and (c) vertical motions during ST-2.

Arias Intensity is a parameter that brings into effect all three characteristics of the ground motion (i.e., intensity, frequency content, and duration). Hence, it provides additional information compared to simplistic intensity measures, such as *PGA* or *PGV*, and is of particular interest to earthquake engineers.

Intensity-scaled versions of five baseline earthquake ground motions (i.e., records from the 1978 Tabas, Iran, earthquake, 1995 Kobe, Japan, earthquake, 1994 Northridge earthquake, and the 1985 and 2010 Chile earthquakes) were applied to the iShake device platform in three orthogonal directions in addition to sinusoidal waves during ST-2. A total of 41 three-component ground motion records were applied in ST-2. Figures 3b, 3c and 4b, 4c present the 5%-damped acceleration response spectra and Arias Intensity time histories of the input motions in the two horizontal and one vertical directions during ST-2. Detailed characteristics of all the ground motions in ST-1 and ST-2 were provided by Dashti et al. (2011).

Phones were rigidly connected to the shake table, with a few exceptions. During ST-1, one phone with no cover (Phone-6) was allowed to move freely on the shake table during five of the ground motions. Three of these motions were sinusoidal waves and two were realistic motions: the 1989 Loma Prieta earthquake recorded at the Treasure Island station and the 1999 Chi-Chi, Taiwan, earthquake recorded at the TCU078 station. Subsequently, during ST-2, two phones (Phones 3 and 7) with different types of covers were allowed to move freely on the shake table during four of the input ground motions. All four motions were intensity-scaled variations of the 1978 Tabas, Iran, earthquake record. Furthermore, Phone-3 was allowed to fall in one event to evaluate the response of a falling instrument. In the following sections, we discuss observations of the response of stationary and unanchored phones during these experiments.

DATA RESULTS AND ANALYSIS

SAMPLING PROTOCALS

Data collected during the shake table tests were analyzed to evaluate the response of handheld devices as seismic instruments. The earthquake motions recorded by seven phones were compared with those recorded by the reference sensors in terms of acceleration, velocity, and displacement time histories, Fourier amplitude and power spectra of acceleration and velocity, Arias Intensity time histories, and 5%-damped acceleration response spectra to investigate their performance as seismic monitoring instruments in terms of motion characteristics that correlate well with different types of damage to engineered facilities (Dashti et al. 2011).

A sampling rate of 100 sps was adopted for the phones throughout these tests, while the reference accelerometers recorded data at 200 sps. Signals from the higher-quality accelerometers that were rigidly connected to the base were averaged in each direction to obtain the reference signal. For a consistent comparison, the sampling rate of the reference signal was reduced from 200 Hz to 100 Hz (using the *decimate* function in MATLAB with proper filtering).

A high-quality instrument is expected to record samples at consistent time intervals. The sample time intervals, however, were not uniform in the phone records and appeared to fluctuate in time slightly. The mean and standard deviation of phone sample intervals were measured to be approximately 1e-2 s and 9e-4 s, over a long period. This jitter in the sample interval appeared to be related to increased processing on the phone. The mean time-step throughout the record (i.e., approximately 1e-2 s) was used as a constant interval for further data processing and spectral analyses. Although the existing sampling-rate jitter may have introduced another source for noise, using a uniform sample interval in the analyses was assumed to have a negligible effect on the spectral properties of the signals because of the relatively small jitter. However, the implications of sampling rate error are admittedly complex and need to be studied further in the future.

Uneven time sampling may cause signal aliasing at times, which should be checked for any sensor. Frequencies of interest for earthquake engineering applications typically range from approximately 0.2 Hz to 25 Hz. To provide a Nyquist frequency that is greater than about 25 Hz and avoid signal aliasing, a minimum sampling rate of 50 Hz is required. A phone sampling rate of 100 Hz was used (i.e., mean sample interval of 1e-2 s), which is approximately twice the minimum required sampling rate. The variation in the phone's sample interval measured over a period of a few weeks (i.e., standard deviation of sample interval = 9e-4 s; peak value = 1.7e-2 s) did not reduce the sampling rate from 100 Hz to 50 Hz at any time (i.e., the Nyquest frequency of the sensor was greater than 25 Hz at all times). Therefore, aliasing was judged not to be an issue. The phone and reference signals were subsequently baseline corrected, zero-padded, and band-pass filtered at corner frequencies of 0.2 Hz and 25 Hz with a third-order acausal filter.

STATIONARY PHONES

All phones were rigidly mounted to their holders during the majority of shakes in both experiments. Independent phone movements were negligible in these shakes. Figures 5 and 6 compare the response of one representative handheld device with that of the reference accelerometer in terms of acceleration, velocity, and displacement time histories, and Fourier Amplitude Spectra of acceleration in ST-1 and ST-2. The smartphones performed well

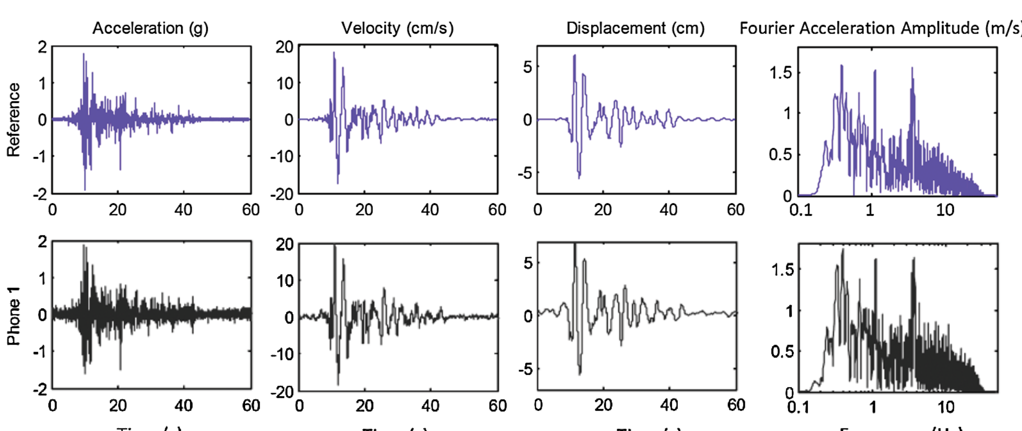

Figure 5. The response of a representative handheld device compared to the reference accelerometer during ST-1. Input ground motion: 1979 Imperial Valley Brawley Airport 225.

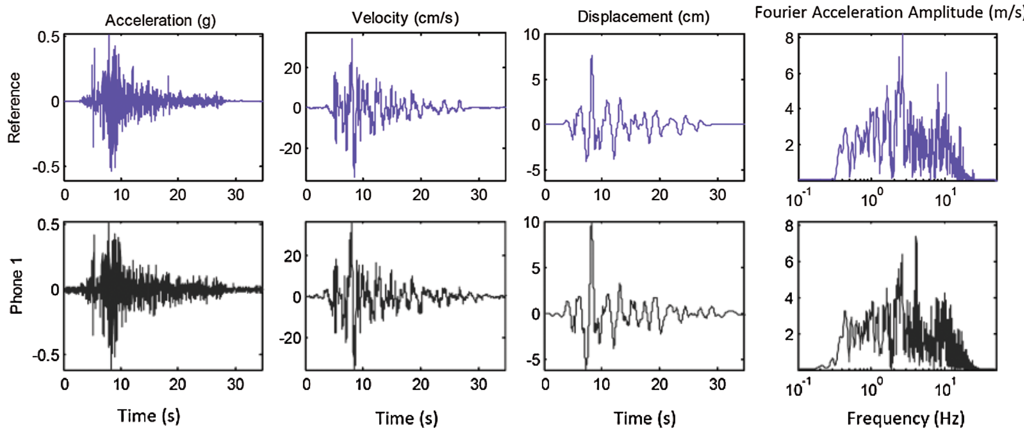

Figure 6. The response of a representative handheld device compared to the reference accelerometer during ST-2. Input ground motion: 1978 Tabas, Iran, earthquake.

when attached to the table for measuring the peak ground acceleration (*PGA*), peak ground velocity (*PGV*), and peak ground displacement (*PGD*), which are important indicators of damage. Acceleration response spectra (5%-damped) also compared reasonably well with the reference (Figures 7 and 8). In some cases, the measurement by one of the seven phones was poorer. However, the mean of the spectra from the seven phones compared remarkably well with that of the reference accelerometer. These observations are helpful in evaluating the response of a local array of phones used as a combined seismic sensor.

In general, the tested phone sensors had a tendency to overestimate the ground motion energy in both experiments and thus also overestimated Arias Intensity (I_a), as shown in

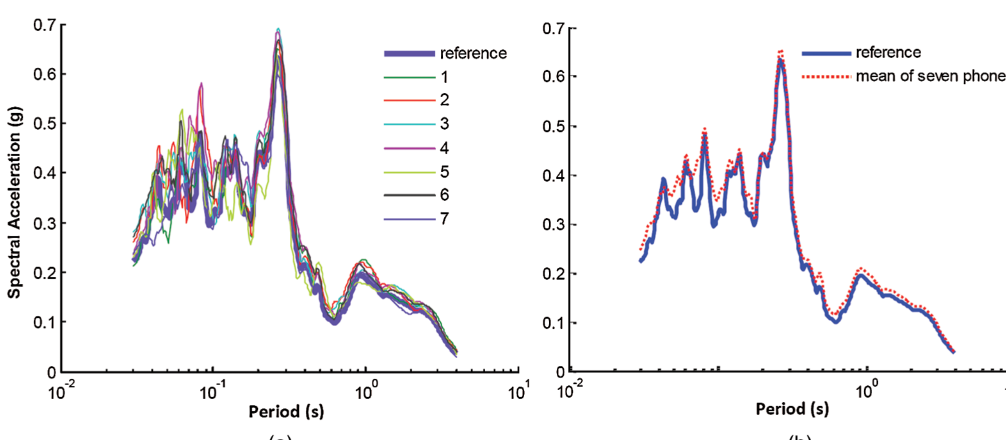

Figure 7. 5%-damped acceleration response spectra recorded by the reference accelerometer in ST-1 compared to: (a) seven individual phone records; (b) the mean of a cluster of seven phone records. Earthquake record (horizontal component only): 1979 Imperial Valley Brawley Airport 225.

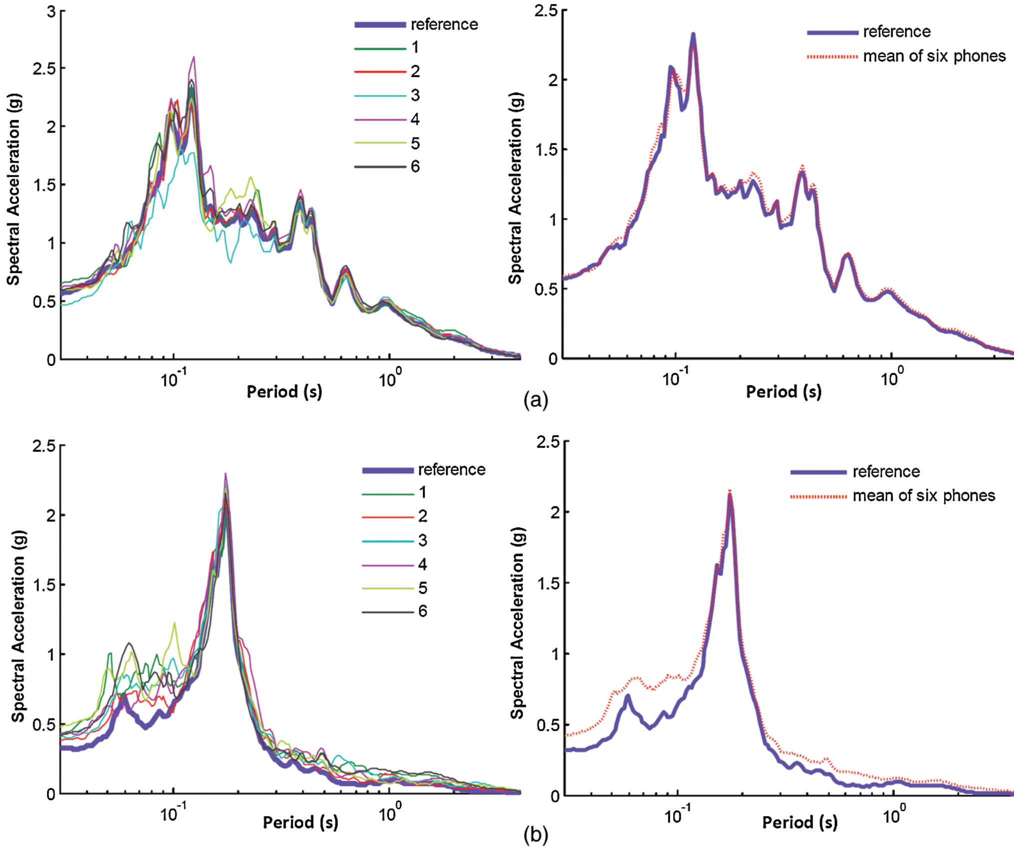

Figure 8. 5%-damped acceleration response spectra recorded by the reference accelerometer compared to individual phones and mean of a cluster of seven phone records in ST-2: (a) geometric mean of two horizontal components of the shake table motion; (b) vertical component of motion. Earthquake record: 1978 Tabas, Iran, earthquake.

Figure 9. Based on previous studies (e.g., Joyner and Boore 1988), response spectral values and other earthquake intensity parameters, such as I_a, are approximately log-normally distributed. Thus, the error in a given intensity measure compiled from the phones was computed in log space. The error in the log of Arias Intensity (I_a) as a function of *PGA* is shown in Figure 10. The absolute value of these errors did not exceed 1.4 and 4 [log(m/s)] during ST-1 and ST-2. The error in I_a declined for stronger ground motions, becoming negligible for *PGA*s exceeding about 0.4 g to 0.5 g. Similar trends were observed in other intensity measures, likely due to a higher signal-to-noise ratio. A parametric study of these errors could lead to better estimates of key ground motion parameters from a cluster of low-quality phone records. Comparisons between the records obtained from the phones and the reference accelerometer worsened slightly during ST-2 (e.g., Figure 10a versus 10b). The response of the entire phone as an inertial instrument is more complex during a 3-D motion, which influences the accuracy of its recorded signals in each direction.

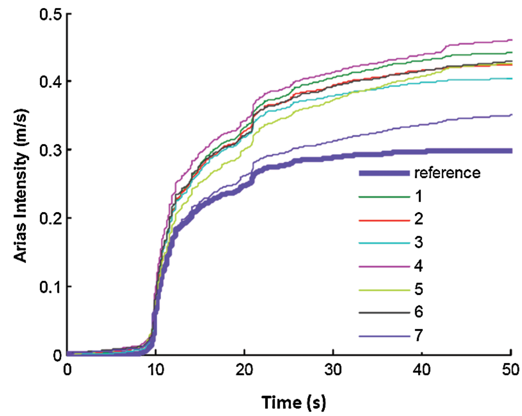

Figure 9. Arias Intensity time histories recorded by seven individual phones compared to that of the reference accelerometer during ST-1. Earthquake motion: horizontal component of the 1979 Imperial Valley Brawley Airport 225.

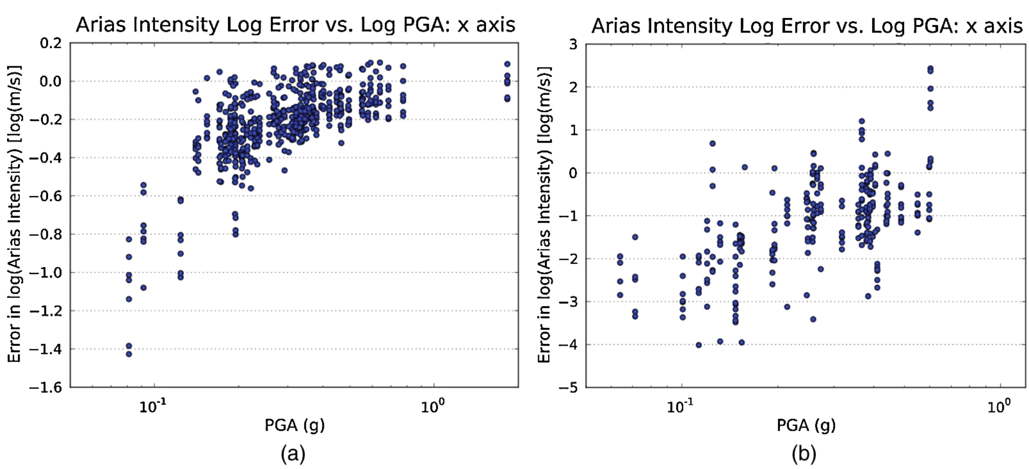

Figure 10. Error in log of the Arias Intensity of individual phone records with respect to the reference versus the *PGA* of shake table motion during: (a) ST-1 (1-D horizontal); (b) ST-2 (two horizontal components shown).

Errors in Acceleration Time Histories

In addition to individual ground motion intensity parameters from phones, the accuracy and consistency of the entire acceleration time history were quantified by the mean value of the squared error term (*MSE*). The *MSE* of a phone record during a given earthquake trial may be computed as:

$$MSE(acceleration_{phone}) = \frac{\sum_{i=1}^{N}[a_{phone}(t_i) - a_{reference}(t_i)]^2}{N} \quad (2)$$

where a_{phone} and $a_{reference}$ are the acceleration time histories recorded by a phone and the reference instrument, and N is the number of samples in a given record. The *MSE* is an overall measure of the error in phone acceleration measurements. By computing the *MSE* of each phone (as opposed to the average of a cluster of seven phones), one can also measure the scatter of phone measurements due to sensor variability. Because earthquake acceleration time histories are non-stationary (deterministic), the *MSE* is likely non-stationary as well (Baise and Glaser 2000). Therefore, it is necessary to specify the portion of the earthquake motion that is to be analyzed for computing the error with the assumption of a constant mean. The time window of the ground accelerations with peaks that exceeded $0.2 \times PGA$ was used to calculate *MSE*. The normalized prediction error (*NPE*) was then computed through normalizing *MSE* by PGA^2 of the corresponding ground motion (Baise and Glaser 2000). Figures 11 and 12 present the *MSE* and *NPE* values for each phone during different trials as a function of the *PGA* of the input motion in ST-1. The *MSE* of the phone records did not exceed about 0.012 g^2 during ST-1, which is large compared to a high-quality sensor.

The reliability of the phone measurements during a particular test is a function of the scattering of the results and the number of phones. To quantify the reliability of these phone measurements at a given time instant t_i, the half-width b of the confidence interval was used, which is centered at the reference acceleration value ($a_{reference}$) and contains the estimated true mean value of phone measurements (m_{phone}) with the probability β (Popescu and Prevost 1995). The acceleration measurements from each phone ($a_{phone-k}$) at each time instant t_i are random variables with an expected value $E(a_{phone-k})$ and a standard deviation $\sigma_{phone-k}$, for $k = 1, 2, \ldots, 7$ (i.e., seven phones in this case). As shown schematically in Figure 13, β is the likelihood that m_{phone} would be within the confidence interval of length $2b$ and centered at the reference value $a_{reference}$ at time t_i:

$$\beta = P[a_{reference} - b \le m_{phone} \le a_{reference} + b], \quad (3)$$

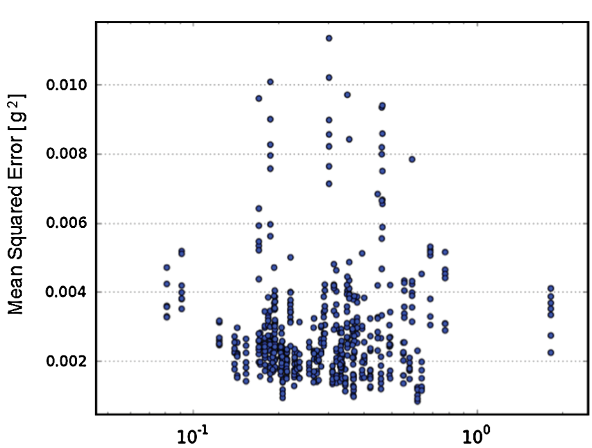

Figure 11. Mean squared error (*MSE*) of individual phone records versus *PGA* of the shake table motion during ST-1.

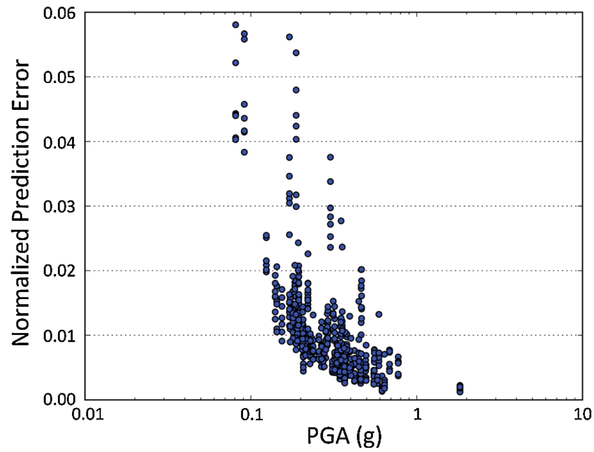

Figure 12. Normalized prediction error (*NPE*) of individual phone records versus *PGA* of the shake table motion during ST-1.

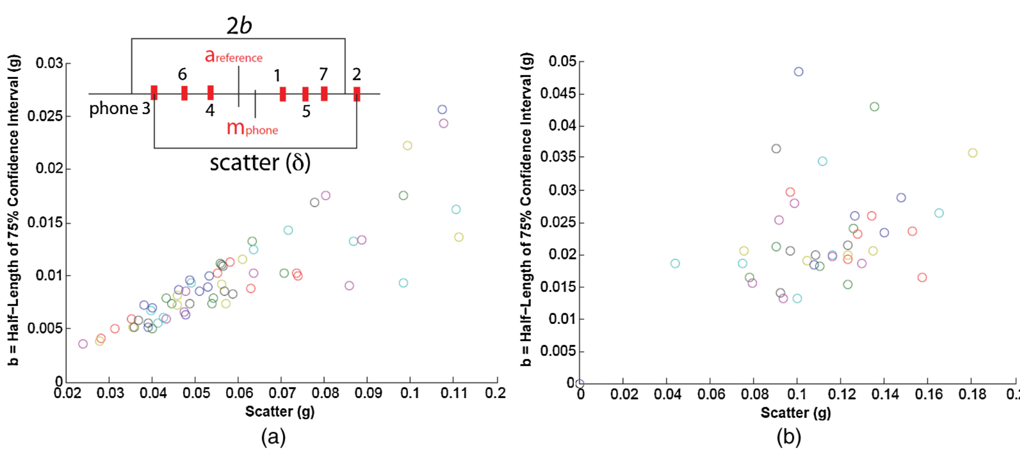

Figure 13. Half-width (b) of 75% confidence interval versus the scatter (δ) in phone measurements (averaged over the analysis time) during: (a) 1-D shake table tests in ST-1; (b) 3-D shake table tests in ST-2 (two horizontal components shown only).

The underlying assumptions are as follows (Popescu and Prevost 1995):

- Phone measurements are obtained under identical conditions.
- Measurements are mutually independent (bias can be neglected).
- Measurements at time t_i are normally distributed.

The first assumption implies that the phone measurements ($a_{phone-k}$) are uniformly distributed random variables: $E(a_{phone-k}) = E(a_{phone})$ and $\sigma_{phone-k} = \sigma_{phone}$ for $k = 1, 2, \ldots, 7$; the second assumption implies that $E(a_{phone}) = m_{phone}$; and the third assumption implies that the average phone measurement ($\overline{a_{phone}} = (1/n)\sum_{k=1}^{n} a_{phone-k}$; with $n = 7$ here) at each instant of time is a normally distributed random variable. The new random variable, which follows a student's t distribution with $(n-1)$ degrees of freedom (Benjamin and Cornell 1970, Popescu and Prevost 1995), is defined as:

$$T = \frac{(\overline{a_{phone}} - m_{phone})\sqrt{n}}{a_{phone}}, \tag{4}$$

If T_{N-1} represents the respective cumulative distribution and m_{phone} in Equation 3 is replaced using Equation 4:

$$\beta = P[x_1 \leq T \leq x_2] = T_{N-1}(x_2) - T_{N-1}(x_1), \tag{5}$$

$$x_j = \frac{\overline{a_{phone}} - a_{reference} + (-1)^j b)\sqrt{n}}{\sigma_{phone}} \tag{6}$$

After each earthquake trial, the phone measurements ($a_{phone-k}$) are known from seven phones at any time instant t_i. Therefore, $\overline{a_{phone}}$ may be computed at time t_i, and for a given value of β, Equation 5 may be numerically solved for b. For a given reference acceleration value ($a_{reference}$) at time t_i, the β confidence interval has a length $2b$. To quantify the amount of scatter in phone measurements at t_i, δ was defined as the maximum difference between the phone acceleration measurements at the corresponding time (schematically shown in Figure 13).

An overall measure of how close the acceleration time histories of each phone are to that of the reference were obtained by averaging the b value computed at every time over the analysis time interval (similar to Equation 2):

$$b^{ave} = \frac{\sum_{i=1}^{N}(b)}{N} \tag{7}$$

Similarly, the scatter between phone measurements computed at every time (δ) was averaged over the entire time history to obtain an overall measure of scatter (δ^{ave}) during a given earthquake record. Figure 13 presents the calculated b^{ave} versus δ^{ave} during each earthquake scenario in ST-1 and ST-2. As expected, the half-width, b^{ave}, of 75% confidence interval increased as the scatter in phone measurements increased and was less than approximately 0.025 g and 0.05 g during ST-1 and ST-2. The scatter (δ^{ave}) in horizontal accelerations measured by phones was larger during ST-2 compared to ST-1, but still reasonable (i.e., less than approximately 0.18 g).

Error in Response Spectral Accelerations

The "goodness-of-fit" between the 5%-damped acceleration response spectra obtained from the phones and the reference accelerometer was also quantified using the statistical evaluation procedure developed by Abrahamson et al. (1990) in terms of phone's bias and uncertainty. For a given model, the residual, r, was calculated as:

$$r_{im}(f_k) = \log S_{Aim}^{ref}(f_k) - \log S_{Aim}^{phone}(f_k), \tag{8}$$

where $S_{Aim}^{ref}(f_k)$ and $S_{Aim}^{phone}(f_k)$ are the spectral ordinates of the reference and phone recorded motion as a function of frequency, f_k; i is the earthquake index; k is the frequency index; and

m is the component of motion considered. The bias (or mean of the residuals) was calculated at each frequency, f_k, as:

$$bias(f_k) = \frac{\sum_{i=1}^{N_i}\sum_{m=1}^{N_m} r_{im}(f_k)}{N_i \cdot N_m}, \tag{9}$$

where N_i is the number of earthquake events; and N_m is the number of components of motion considered. The variance in the error term (phone variance) and the standard error of the bias were then calculated as:

$$\sigma^2_{phone}(f_k) = \frac{\sum_{i=1}^{N_i}\sum_{m=1}^{N_m}[r_{im}(f_k) - bias(f_k)]^2}{(N_i \cdot N_m) - 1}, \tag{10}$$

$$\sigma_{bias}(f_k) = \frac{\sqrt{\sigma^2_{phone}(f_k)}}{\sqrt{N_i \cdot N_m}}, \tag{11}$$

The bias in the acceleration response spectra obtained from stationary phones during ST-1 and ST-2 are plotted in Figure 14. As shown in Equation 8, these plots combine the bias of each individual phone during all the input ground motions in a given experiment as a function of frequency or period. Bias in the spectral accelerations obtained from phones was less than 0.05 and 0.2 [log(g)] in frequencies ranging from 1 Hz to 10 Hz during ST-1 and ST-2, respectively.

UNANCHORED PHONES

One phone with no cover (Phone-6) was allowed to move freely on the shake table during five earthquake records in ST-1. The input motions were one-dimensional. However, since the phone was allowed to move and rotate freely on the table, the vector sum of the two

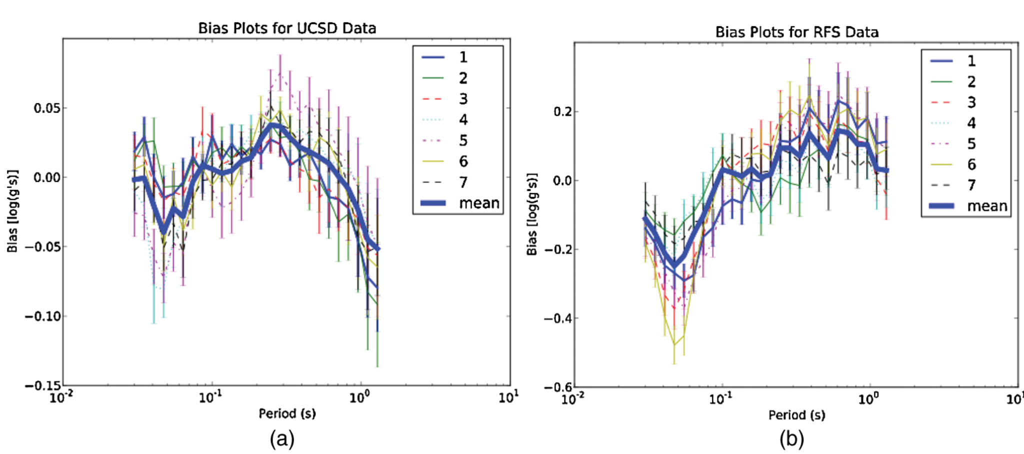

Figure 14. Bias in 5%-damped acceleration response spectra recorded by seven phones during: (a) 1-D shaking in ST-1; (b) 3-D shaking in ST-2 (showing bias in the horizontal direction only).

horizontal phone accelerometers appeared to yield the best comparison with the reference record. As shown in Figure 15, the phone records highly underestimated the amplitude of sinusoidal input accelerations due to phone sliding, although their frequencies were roughly captured. The comparisons between the non-stationary Phone-6 and the reference accelerations were, however, reasonable during realistic earthquake motions with a wide range of frequencies. Figure 16 compares the acceleration time history and Fourier amplitude spectrum obtained from Phone-6 with the reference accelerometer during the 1989 Loma Prieta earthquake motion in ST-1. These plots show promise in obtaining useful estimates

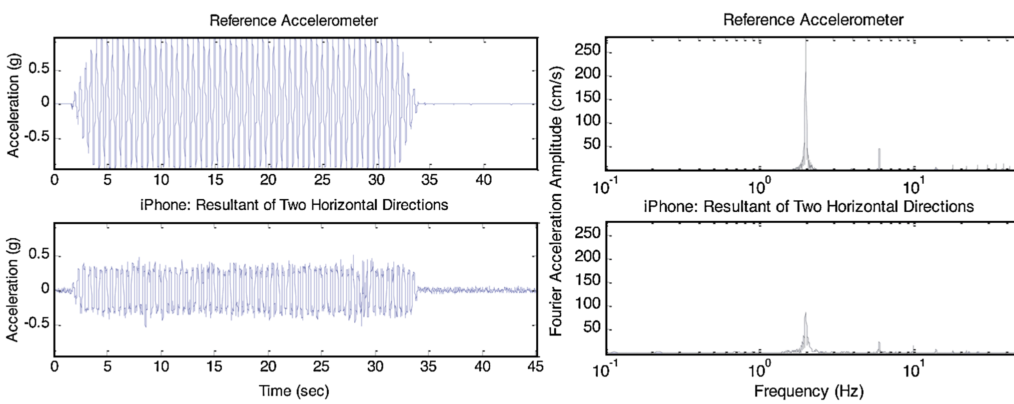

Figure 15. Comparison of the reference accelerometer and Phone-6 (free to move on the shake table) during a representative 1-D sinusoidal shake table motion in ST-1 (in both time and frequency domains).

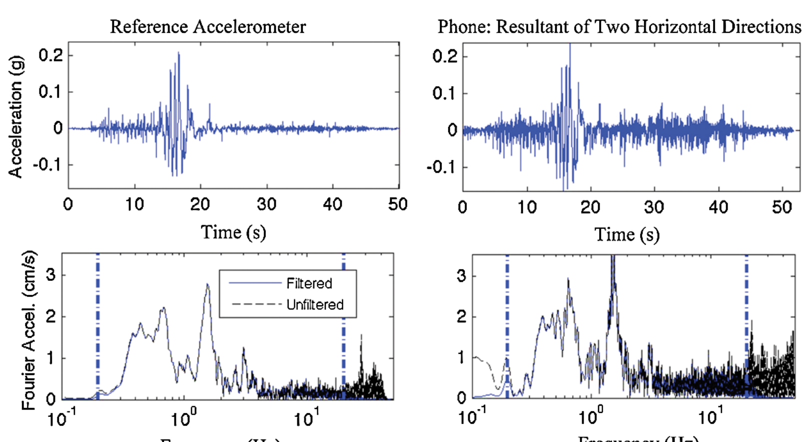

Figure 16. Comparison of the reference accelerometer and Phone-6 (free to move on the shake table) in time and frequency domains during the 1989 Loma Prieta earthquake motion (1-D horizontal component) in ST-1.

of ground motion intensity from loose phones during earthquakes, even when the phone has no cover.

During ST-2, two phones (Phones-3 and 7) with different types of covers were allowed to move freely on the shake table during four 3-D records. Figure 17 compares the acceleration time histories and the 5%-damped acceleration response spectra recorded by Phones-3 and 7 with that of the fixed reference accelerometer during the 1978 Tabas, Iran, earthquake motion in ST-2. As expected, the comparisons were significantly improved for phones with frictional covers compared to those without any cover (e.g., Figure 17 compared to Figure 16). Phone-3

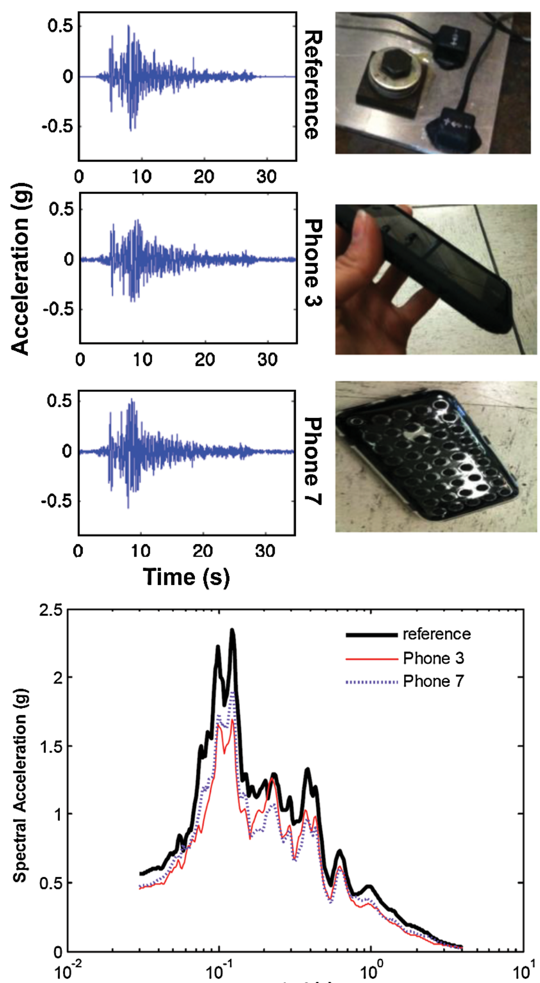

Figure 17. Acceleration time histories and 5%-damped acceleration response spectra obtained from phones with frictional covers allowed to move freely on the shake table compared to the reference during the 1978 Tabas, Iran, earthquake motion in ST-2 (only showing the horizontal component of the motion).

and Phone-7, which had covers, did not show noticeable independent sliding on the table even during intense 3-D shaking with a *PGA* of approximately 0.5 g. The acceleration amplitudes recorded by Phone-3 were slightly underestimated due to its minor tendency to slide. The use of a high-friction cover on Phone-7 was particularly successful in minimizing the amount of sliding and, therefore, maintaining the accuracy of the smartphone measurements.

Phone-3, which was allowed to fall during one shake (i.e., the 1978 Tabas, Iran ground motion), showed a spike in frequencies ranging from about 0.2 to 0.5 Hz. This acceleration spike was also evident as a sudden increase in the corresponding Arias Intensity time histories at the time of the fall. The comparisons of the recorded time histories were largely unacceptable. However, the intense acceleration spike and the sudden increase in the value of Arias Intensity may be used as a way to detect a fall and remove the signal from the cluster of phone recordings.

CONCLUSIONS

Emergency responders must see the effects of an earthquake clearly and rapidly to respond effectively to the resulting damage. This research uses cellular phones and information technology to bridge the gap between high-quality, but sparse, ground motion instrument data used to develop ShakeMap and the lower quality, but abundant human observational data used to construct DYFI maps. A software client and a backend server (e.g., Reilly et al. 2012) were developed to measure, collect, validate, analyze, and visualize the ground shaking data for general use. A series of 1-D and 3-D shake table tests were performed to evaluate the reliability of cell phones as seismic instruments. The testing also provided insight into the seismic response of unsecured instruments. A modified client application and server were developed particularly for the purpose of shake table testing. Testing the performance of phones as a network to improve the existing earthquake monitoring and reporting systems is planned for future.

The handheld devices tested were shown to measure well such shaking intensity parameters as *PGA*, *PGV*, *PGD*, and 5%-damped spectral acceleration values. The mean spectral acceleration of seven phones compared well with that of the reference accelerometer in the frequency range of interest for most earthquake engineering applications (about 0.2 to 25 Hz). Bias in the horizontal spectral accelerations obtained from phones was less than 0.05 and 0.2 [log(g)] in frequencies ranging from 1 Hz to 10 Hz during 1-D and 3-D shake table tests. The average half-width of 75% confidence interval (b) and scatter (δ) of phone measurements during these experiments were less than approximately 0.05 g and 0.18 g in the two sets of tests. In general, these phones slightly overestimated the accumulation of earthquake energy, as quantified by the Arias Intensity (I_a). The errors, however, declined for moderate and intense motions with larger signal-to-noise ratios. Therefore, at this time, smartphones are recommended to compliment ShakeMap and DYFI for hazard assessment only during moderate to intense earthquake events.

Even smartphones that were not rigidly connected to the table typically captured the key characteristics of realistic earthquake motions despite their tendency to slide somewhat when undergoing intense shaking. The accuracy of the smartphone measurements improved when a high-friction phone cover was employed. An unusually large acceleration spike or the sudden increase in the phone's Arias Intensity time history may be used to detect and remove the signals obtained from falling phones. The insights gained from these experiments are useful for distilling information from a large number of imperfect signals measured by smartphones that may not be rigidly connected to the ground. With these ubiquitous measurement devices, a more accurate, rapid, and detailed portrayal of the damage distribution from an earthquake could eventually be provided to emergency responders and the public.

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