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COMMUNITY SEISMIC NETWORK AND LOCALIZED EARTHQUAKE SITUATIONAL AWARENESS

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ABSTRACT

Community-hosted seismic networks are a solution to the need for large numbers of sensors to operate over a seismically active region in order to accurately measure the size and location of an earthquake, assess resulting damage, and provide alerts. The Community Seismic Network is one such strong-motion network, currently comprising hundreds of elements located in California. It consists of low-cost, three-component, MEMS accelerometers capable of recording accelerations up to twice the level of gravity. The primary product of the network is to produce measurements of shaking of the ground and multiple locations of every upper floor in buildings, in the seconds during and following a major earthquake. Each sensor uses a small, dedicated ARM processor computer running Linux, and analyzes time series data in real time at hundreds of samples per

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second. The network reports on shaking parameters that indicate intensity of the structural response levels such as maximum floor acceleration and velocity, displacement of a floor in a building, as well as data products that depend on the response time histories. To do this, Cloud computing has been expanded through the use of statically defined subsets of sensors called cloudlets. These are smaller subsets of similar sensors that carry out customized calculations for those locations. The measurements are reported as rapidly as possible following an earthquake so that they may be incorporated into structural diagnosis and prognosis applications that can be used by first responders to prioritize their initial disaster management efforts. The cloudlet displays are customized for specific buildings and they show in real time: instantaneous displacement, inter-story drift, and resonant frequency and mode shapes using system identification software tools. The real-time display products are useful for decision-making about whether the potential for damage exists, what level of damage may have occurred and where, and whether total business disruption is necessary. City-wide dense monitoring makes it possible for emergency response managers to prioritize the target locations requiring first response on a block-by-block scale based on reports of shaking intensity.

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Introduction

The U.S. Geological Survey has developed and maintains a suite of situational awareness software applications to provide assessments of intensity and structural damage potential due to earthquake strong-ground shaking. This suite consists of the ShakeMap application [1-4], and the ShakeCast tool [5-7]. The applications together provide a bridge between science-focused measurements, engineering knowledge of human-built structures, and operational safety concerns.

ShakeMap [1-4] analyzes the data produced by regional network seismometers in the field, incorporates geophysical surface and subsurface models, and interpolates between the sparsely located exact measurements to provide estimates of ground motion across a region. The accuracy (and thus effectiveness) of ShakeMap is heavily dependent on the density of the measurements and the accuracy of the models used to infer ground motion behavior at non-instrumented locations of interest.

The inferred ground motion from ShakeMap is then fed into ShakeCast [5-7], which combines engineering models of specific structure types and vintages, with the estimated ground motion from ShakeMap at the structures' interface with the soil, to produce estimates of stress upon the structures. The key tool used here is a fragility curve, derived from the Hazus structure classification scheme [8]. ShakeMap operates on near-real-time, peak acceleration pick information from approved stations within selected regional seismic networks. The canonical U.S. Geological Survey (USGS) ShakeMap engine in Pasadena is limited to accepting data from specific networks, in particular the Southern California Seismic Network. These stations are vetted for stability, reliability, trustworthiness, and signal-to-noise ratios. In some cases, site correction factors empirically based on soil response are applied to the data. National and regional seismic networks are constrained by limited funding and the relatively high cost of installing and maintaining instrumentation and telemetry. The result is sparse deployments in locations selected to yield maximal scientific value, which is often at odds with practical application of ground motion measurements.

The comparative low cost of USGS-designated Class C sensors such as those used in the Community Seismic Network (CSN) [9-12], inexpensive for both instrumentation and telemetry, encourages their placement at specific locations of interest, such as building foundations. This allows for exact measurements to be fed into ShakeCast, eliminating the reliance on typically low-resolution and numerically smoothed input provided by ShakeMap. CSN operates an experimental ShakeMap engine solely for the purpose of incorporating data from CSN stations that may or may not be of the same level of quality, sensitivity, or reliability as the regional seismic networks. Customized configurations of Shakecast for CSN volunteer host locations use ShakeMap data as their ground motion input parameters for the degree of shaking to input into fragility curve models for each building making up the host institutions, classified by type and vintage. If a user has measurements from the actual civil structure of interest, the ShakeMap modeling step could be bypassed altogether. Currently, CSN's software client computes peak values from broadband temporal and spectral accelerations at 0.3, 1 and 3 s, which are reported to ShakeMap.

This new approach of providing high-resolution CSN measurements to experimental ShakeMap-Shakecast installations is being used in two real-world test applications. The first is the example mini-city at the NASA-JPL campus where one or multiple CSN accelerometers are installed at 90 buildings on the JPL campus (Figure 1). Of the total 220 stations deployed at JPL, only the 100 ground-level stations are contributing maximum shaking peak acceleration pick data to the experimental ShakeMap. JPL building types include wood frame, reinforced concrete, steel-moment frame, steel sheds and modular trailers. Each of these structures has a canonical fragility curve associated with it based on a building classification supplied by Hazus [8]. The ShakeCast configurations for every JPL site are set up so that they can ingest the experimental CSN ShakeMap as input for localized and customized building performance assessment by JPL emergency managers. For example, Figure 2 shows assessed fragilities due to a scenario M6.9

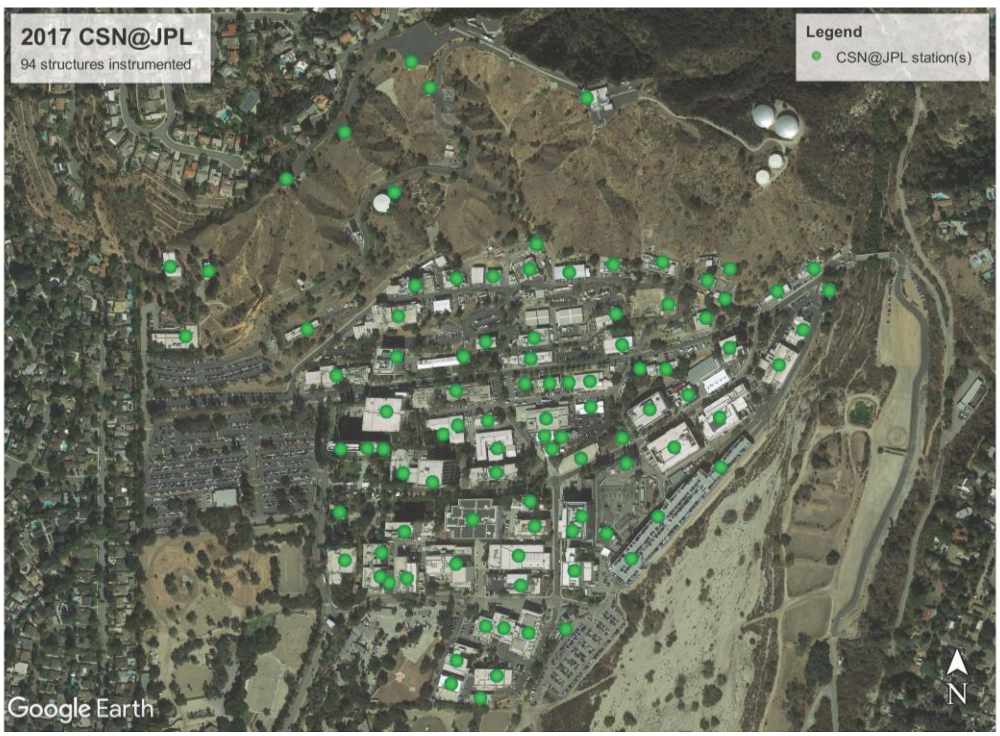
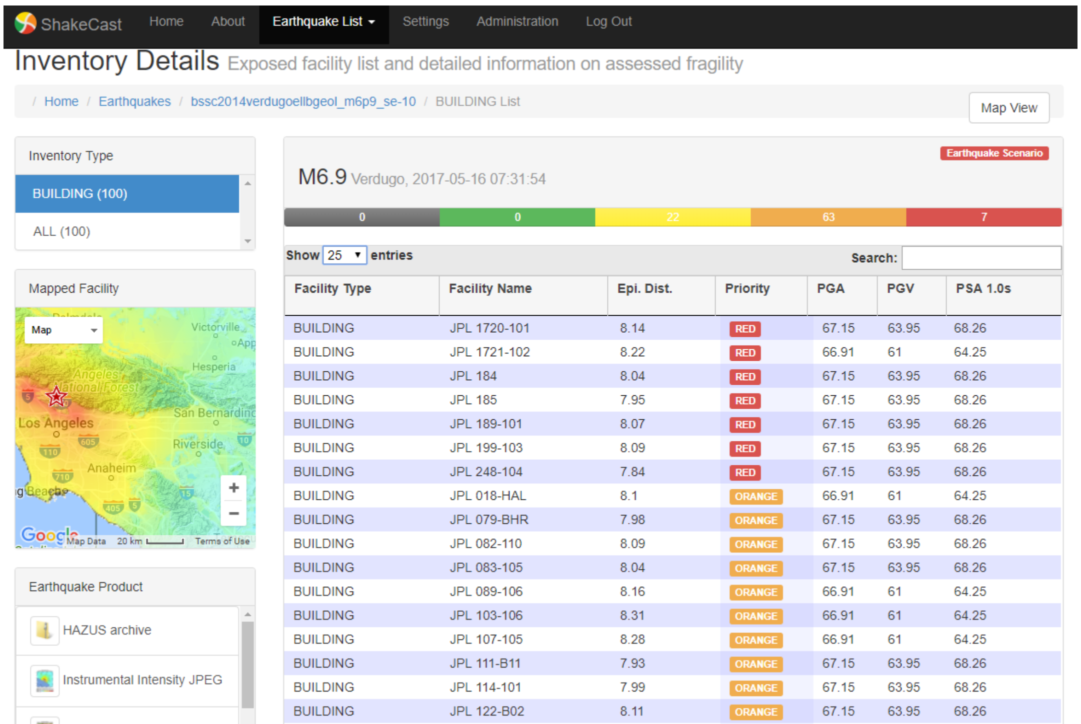


Figure 1. Map of NASA-JPL campus in Pasadena, CA showing locations of CSN accelerometer deployments. Horizontal dimensions are approximately 1 km by 1 km.

Verdugo fault earthquake near the JPL campus. Several buildings have either two or three sensors located on the ground level floors because the structures are long or they contain a significant element joint halfway down the longitudinal axis of the building. In these cases, both or all three measurements are used as input into ShakeMap.



Facility Type	Facility Name	Epi. Dist.	Priority	PGA	PGV	PSA 1.0s
BUILDING	JPL 1720-101	8.14	RED	67.15	63.95	68.26
BUILDING	JPL 1721-102	8.22	RED	66.91	61	64.25
BUILDING	JPL 184	8.04	RED	67.15	63.95	68.26
BUILDING	JPL 185	7.95	RED	67.15	63.95	68.26
BUILDING	JPL 189-101	8.07	RED	67.15	63.95	68.26
BUILDING	JPL 199-103	8.09	RED	67.15	63.95	68.26
BUILDING	JPL 248-104	7.84	RED	67.15	63.95	68.26
BUILDING	JPL 018-HAL	8.1	ORANGE	66.91	61	64.25
BUILDING	JPL 079-BHR	7.98	ORANGE	67.15	63.95	68.26
BUILDING	JPL 082-110	8.09	ORANGE	67.15	63.95	68.26
BUILDING	JPL 083-105	8.04	ORANGE	67.15	63.95	68.26
BUILDING	JPL 089-106	8.16	ORANGE	66.91	61	64.25
BUILDING	JPL 103-106	8.31	ORANGE	66.91	61	64.25
BUILDING	JPL 107-105	8.28	ORANGE	66.91	61	64.25
BUILDING	JPL 111-B11	7.93	ORANGE	67.15	63.95	68.26
BUILDING	JPL 114-101	7.99	ORANGE	67.15	63.95	68.26
BUILDING	JPL 122-B02	8.11	ORANGE	67.15	63.95	68.26

Figure 2. NASA-JPL ShakeCast [5-7] instance showing assessed fragilities in select buildings due to a scenario M6.9 Verdugo fault earthquake near the JPL campus.

The second experimental ShakeMap-ShakeCast setup is at 102 Los Angeles Unified School District (LAUSD) campuses, located near the center of the city of Los Angeles. CSN has deployed a sensor at each of the campuses. The LAUSD campuses used in this installation consist of only low-rise structures across a lateral dimension spanning about 20 km. About 90 of the total sensors are located on the ground levels and are the ones used in the experimental LAUSD ShakeMap. All sensors are located in communication or utility closets; none are in classrooms. The ShakeCast application is installed in the central LAUSD office in downtown Los Angles and communication is modeled on a centralized decision engine setup in which information is subsequently sent via formal channels to local principals and campuses.

CSN’s current software client computes broadband peak accelerations which are reported to ShakeMap if values are > 0.5% g, obtained from the time series’ deviations from the long-term mean, on any axis. Many CSN stations are in locations with frequent human activity that influences noise levels. For example, many LAUSD stations exhibit noticeably higher noise levels during school hours. In future work, station-specific noise models taking into account time of day and day of the week will be trained. This will allow for more reliable picking and signal-to-noise estimation at stations with predictable human-generated noise.

In both the JPL and LAUSD settings, the immediate Shakecast product permits remote and/or centralized management to obtain a quick snapshot of the overall situation, highlighting specific structures of exceptional concern. ShakeCast uses a notification scheme with red, orange, yellow, or green flags to qualitatively report on the potential level of building damage (Figure 2).

Real-time CSN displays

Each CSN sensor uses a small, dedicated ARM processor computer running Linux, and analyzes time series data in real time at hundreds of samples per second. The network reports on shaking parameters that indicate intensities of the structural response levels such as maximum floor acceleration and velocity, displacements of a floor in a building, as well as data products that depend on the response-time histories.

To carry out localized computations such as inter-story drift, Cloud computing has been expanded through the use of statically defined subsets of sensors called cloudlets. These are smaller subsets of similar sensors that carry out customized calculations for those locations [13]. The measurements are reported as rapidly as possible following an earthquake so that they may be incorporated into situational awareness and structural diagnosis and prognosis applications that can be used by first responders to prioritize their initial disaster management efforts. The cloudlet displays are customized for specific buildings and they show in real time: instantaneous displacement, inter-story drift, and resonant frequency and mode shapes using system identification software tools [13].

As part of the real-time cloudlet display, the natural excitation technique (NExT) [14] is being incorporated using input data from the CSN sensors. NExT is a method to identify the natural frequencies and mode shapes of a linear dynamic system, using the measured output response of the system to a broadband (i.e., white noise) input excitation [14]. This method is based on the assumption that the cross-correlations of the measured vibration responses of a linear system subjected to a broadband excitation have the same analytical form as the free vibration responses of the structure [14]. The cross-correlation functions are then used in the ERA method [15], which estimates the mode shapes by identifying an equivalent state-space model. The cross-correlation functions are computed using the inverse Fourier transform of the corresponding cross-power spectral density functions, estimated using Welch's method [16] with a Hanning window. NExT results are computed in real-time and can be used to indicate where changes in mode shapes and natural frequencies can be used as indicators of damage due to earthquake strong shaking.

The real-time display products are useful for decision-making about whether the potential for damage exists, what level of damage may have occurred and where, and whether total business disruption is necessary. Citywide dense monitoring makes it possible for emergency response managers to prioritize the target locations requiring first response on a block-by-block scale based on reports of shaking intensity.

Conclusions

Community-hosted acceleration time histories are reported continuously in real time at up to 250 sps for use in situational awareness products, as well as real-time displays for structural health monitoring applications. The situational awareness products are an experimental ShakeMap which indicates the horizontal geographical distribution of ground shaking intensities, and ShakeCast which uses ShakeMap as input to compute building-specific fragility assessment based on Hazus classification. Traditionally these products both use regional seismic network shaking intensities, but the spatial resolution of these is limited to the density of the seismic stations. Use of community-hosted CSN sensor observations increases the resolution of the shaking intensity such that a much more localized, site-specific assessment can be carried out.

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References

1. Wald DJ, Worden BC, Quitoriano V, Pankow KL. ShakeMap Manual: Users Guide, Technical Manual, and Software Guide, *U.S. Geological Survey Open File Report*, 131 pp, 2005.
2. Wald D, Worden B, Quitoriano V, Pankow K. ShakeMap Manual, Technical Manual, Users Guide, and Software Guide. *Advanced National Seismic System*, Version 1.0, 2006.
3. Worden CB, Wald DJ. ShakeMap Manual Online: Technical Manual, User's Guide, and Software Guide, *U. S. Geological Survey*. usgs.github.io/shakemap. doi: 10.5066/F7D21VPQ, 2016.
4. Worden CB, Thompson EM, Hearne M, Wald DJ. ShakeMap V4 Manual: Technical Manual, User's Guide, and Software Guide, *U. S. Geological Survey*. usgs.github.io/shakemap, 2017.
5. Wald DJ, Lin K-W, Worden B, Turner L. ShakeCast: facilitating the use of ShakeMap for post-earthquake decision-making and response within Caltrans and other Critical Lifeline Communities, *Proceedings of the Fifth National Seismic Conference on Bridges & Highways*, San Francisco, September 2006.
6. Lin K-W, Wald DJ. ShakeCast manual: *U.S. Geological Survey Open-File Report*, **2008-1158**, 90 pp., 2008.
7. Wald DJ, Lin K-W, Porter K, Turner L. ShakeCast: automating and improving the use of ShakeMap for post-earthquake decision-making and response, *Earthquake Spectra*, **24** (2), 533-553, 2008.
8. HAZUS: Multi-Hazard Loss Estimation Methodology Earthquake Model, Hazus-MH2.1 Technical Manual, Department of Homeland Security and Federal Emergency Management Agency (FEMA), Mitigation Division, Washington DC., 2011.
9. Clayton R, Heaton T, Chandy M, Krause A, Kohler M, Bunn J, Olsen M, Faulkner M, Cheng M, Strand L, Chandy R, Obenshain D, Liu A, Aivazis M. Community Seismic Network. *Annals of Geophysics*, **54** (6), 738-747, 2011.
10. Kohler M, Heaton T, Cheng M. The Community Seismic Network and Quake-Catcher Network: enabling structural health monitoring through instrumentation by community participants. *Proceedings of the SPIE Smart Structures/Non-destructive Evaluation Conference*, San Diego, CA, 2013.
11. Kohler M, Heaton T, Cheng M, Singh P. Structural health monitoring through dense instrumentation by

community participants: the Community Seismic Network and Quake-Catcher Network. *10th U.S. National Conference on Earthquake Engineering (NC10EE)*, Anchorage, Alaska, 2014.

12. Clayton R, Heaton T, Kohler M, Chandy M, Guy R, Bunn J. Community Seismic Network: a dense array to sense earthquake strong motions. *Seis. Res. Lett*., **86**, 1354-1363, doi: 10.1785/0220150094, 2015.
13. Kong Q, Allen RM, Kohler MD, Heaton TH, Bunn J. Structural Health monitoring of buildings using smartphone sensors. *Seis. Res. Lett*. (see Supplemental Section). **89** (2A), 594–602, doi: https://doi.org/10.1785/0220170111, 2018.
14. James GH, Carne TG, Lauffer JP. The natural excitation technique (NExT) for modal parameter extraction from operating wind turbines. *Technical Report SAND92-1666*, *UC-261*, Sandia National Laboratories, Sandia, NM, 1993.
15. Juang JN, Pappa RS. An eigensystem realization algorithm for modal parameter identification and model reduction. *Journal of Guidance, Control, and Dynamics*; **8** (5), 620–627, 1985.
16. Welch, PD, The use of Fast Fourier Transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms, *IEEE Trans. On Audio and Electroacoustics*, **AU-15**, 2, 70-73, doi:10.1109/TAU.1967.1161901, 1967.