Supplementary Material

Title: Earthquake Early Warning ShakeAlert 2.0: Public Rollout

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This is the supplementary material for *Earthquake Early Warning ShakeAlert 2.0: Public Rollout*. The supplement includes: 1) two additional figures that are referenced in the main manuscript (Figures S1 and S2); and 2) a detailed description of ground motion assessment tests with two figures that are referenced in this supplementary text (Figures S3 and S4).

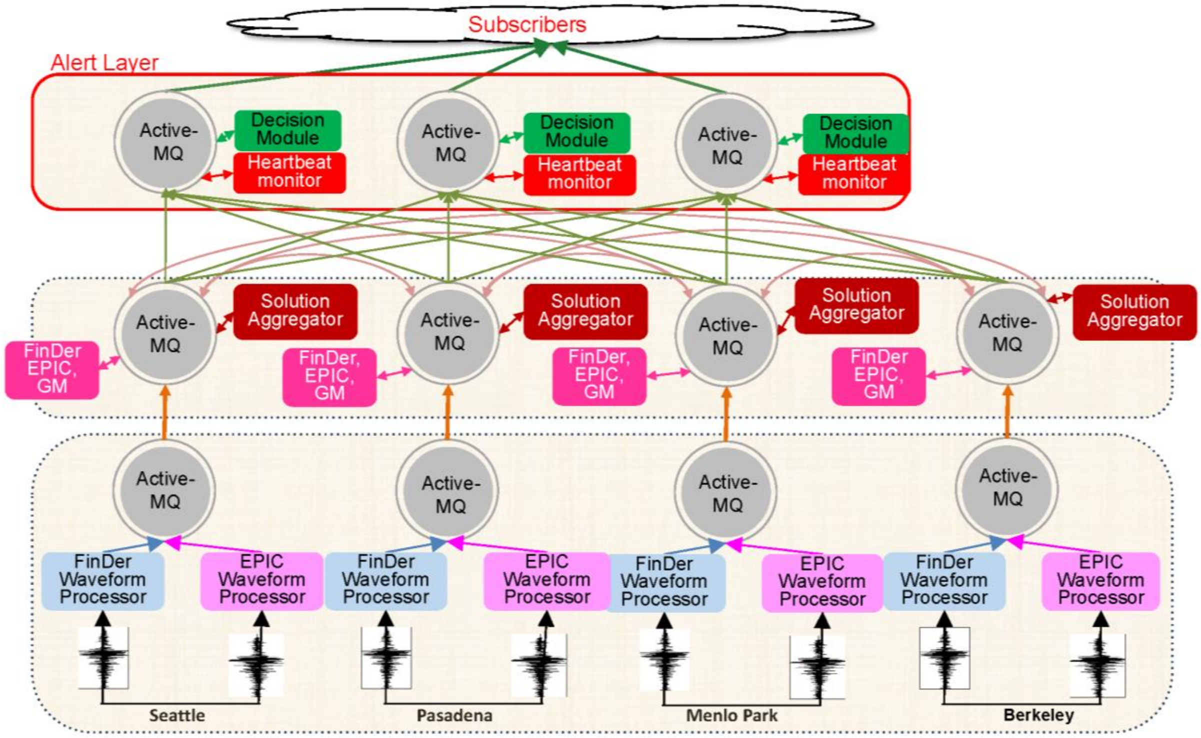

Figure S1. Schematic showing ShakeAlert 2.0 algorithms EPIC and Finder, and the messaging architecture illustrating similarities, differences, and message-sharing among the four contributing regional networks based in Seattle, Pasadena, Menlo Park, and Berkeley. Schematic shows data flow pathways starting from incoming seismograms (bottom), to alerts sent to subscribers (top). Different color polygons represent different purposes of each algorithm and where they occur on the data flow pathway for each regional network. Light blue boxes: waveform processors which process incoming raw waveforms, symbolized by seismogram image, from the seismic stations for FinDer. Violet boxes: waveform processors which process incoming raw waveforms for EPIC. Gray circles: ActiveMQ message-passing software instances. Magenta boxes: FinDer, EPIC, and eqInfo2GM ("GM") algorithms. Dark red boxes: Solution Aggregator algorithm. Green boxes: Decision Module algorithm. Red boxes: Heartbeat monitor. See main text for algorithm details. Large tan boxes indicate different groupings of tasks where the top-most layer is referred to as the 'Alert Layer.' Line segments indicate data flow where arrowhead indicates that in some cases direction is one-way, and in others two-way. 'Subscribers' are the general public receiving the alerts. Note that alerts are sent from three out of the four regional network locations.

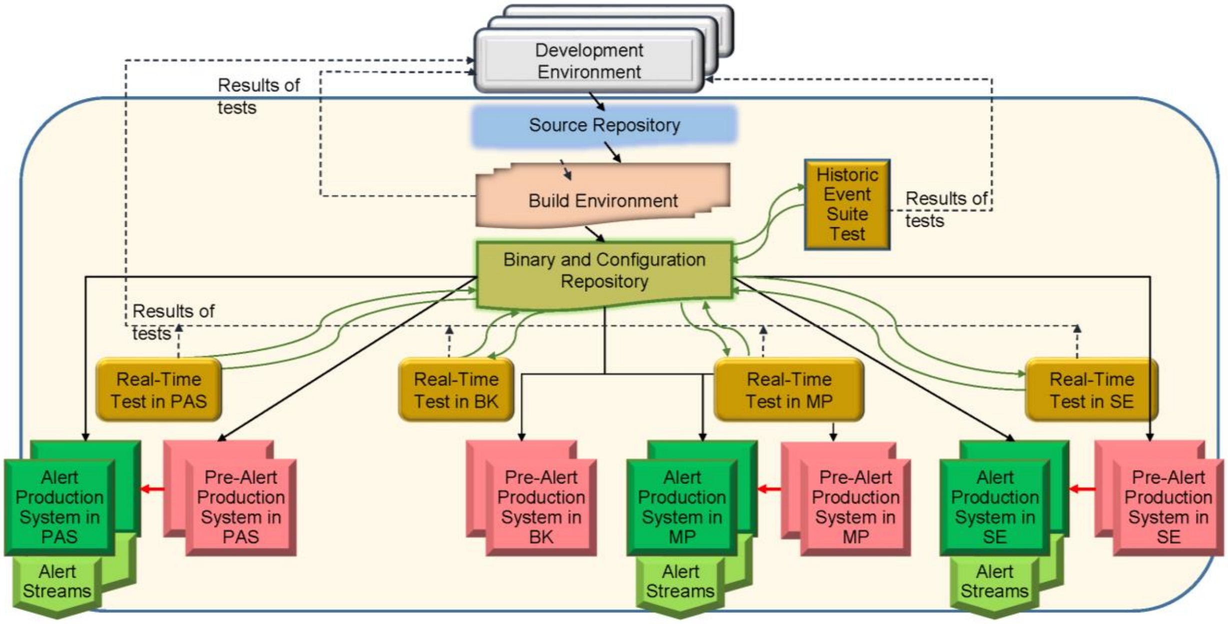

Figure S2. ShakeAlert 2.0 development, testing, and production environments and workflows. Different color boxes represent the different purposes of each processor. From top to bottom, Gray: processors where algorithms are developed or modified. Light blue: source code repository. Tan: environment where code is built, compiled where relevant, and linked to libraries. Olive green: repository containing binary and configuration files associated with code. Brown: processors that are part of the testing environment in-situ at the four contributing regional network operations locations in Pasadena (PAS), Berkeley (BK), Menlo Park (MP), and Seattle (SE). Dark green squares: pairs of Alert Production processors in-situ at three out of the four contributing regional network locations. Salmon squares: Pairs of Pre-alert Production processors in-situ at each network location. Light green pentagons: Pairs of processors in-situ at three out of the four network locations responsible for disseminating alerts to general public. Curved lines: feedback loop between code and code test results. Solid lines: one-way data-passing between processors. Dashed lines: communication feedback loop between code developers and results of tests performed on code. Tan oval defines processors and tasks that are formal components of ShakeAlert; the Development Environment is, by contrast, under the control of the developers.

Description of additional ground motion validation tests

Validation of GMPE/GMICE implementation in eqInfo2GM

The validation of GMPE/GMICE implementation is tested by assessing their use by the algorithm eqInfo2GM (Thakoor *et al*., 2019). Eqinfo2GM is used to translate earthquake source parameters to ground motion estimates and contains some critical differences with respect to the ShakeMap software. This analysis is carried out to validate the GMPE and GMICE implementations in eqInfoGM, and to understand the effect of deviations from ShakeMap methodology; these include different treatment of source-site differences, and the effect of voiding source terms that cannot be determined (see Thakoor *et al*. [2019] for further details).

The eqInfo2GM messages are generated for the source parameters from the ShakeAlert 2.0 DM alerts. This includes both contour messages and gridded map messages. ShakeMaps are then also generated using similar latitude/longitude ranges and GMPE/GMICE settings, but no observed station data are used. Next, a point-by-point comparison is generated for the historic events, comparing the ShakeMaps to eqInfo2GM maps at the lower resolution of the latter. Plots are generated to compare SI (Shaking Intensity), PGA, and PGV for different regions, including southern California, northern California, Pacific Northwest, and “Unknown” which corresponds to different GMPE/GMICE selections. The comparisons between ShakeMaps and eqInfo2GM are assessed from the union of the two grids, looking at all earthquakes in the test suite, for grid points with MMI II or greater. The average SI MMI difference between all points on the two grids corresponding to eqInfo2GM and ShakeMap ranges from -0.32 to 0.68, with a peak near 0.05. Fig. S3a shows the average SI MMI differences for each earthquake in the test suite. Each point in the histogram is an average over all points for every pair of eqInfo2GM-ShakeMap grids produced for that earthquake’s first alert and its updates. The Variance Reduction (VR) for the SI differences ranges from 91% to 99.7%, where 100% is a perfect fit (Fig. S3b). Note that VR is defined from Thakoor *et al.* (2019) as

$$VR = \left[1 - \frac{\sum misfit^2}{\sum observation^2}\right] * 100 \tag{1}$$

originally based on Dreger and Woods (2002).

The eqInfo2GM algorithm performs similarly to ShakeMap in southern California and northern California, and good matches are observed between eqInfo2GM and ShakeMap for the historic test suite comparison. Looking at the comparison between ShakeAlert 2.0 and ShakeAlert 1.0 (our baseline), approximately 64% of the comparisons have an SI VR of 99% or better, and 83% of the comparisons have an SI VR of 98% or better. With eqInfo2GM there are larger variations for Pacific Northwest events in the historic test suite comparison. This is more noticeable for the PGA and PGV VR statistics than SI VR statistics because SI is based on the logarithm of PGA and PGV values. Slight differences in the way in which vs30 data are used by eqInfo2GM and ShakeMap calculations explain most of the discrepancies; the extent of the vs30 map used by eqInfo2GM is smaller and has to be extrapolated into uncovered areas such as Canada. Examining the average SI difference for all regions, this test result comparison suggests average SI errors of up to ~0.5 MMI units. The maximum SI difference, which looks at the differences point by point (and includes small length-scale variability), is on average 1.0 MMI unit (where the average is computed over all the point-by-point differences, individually for each earthquake’s first alert and its updates), and as large as 2.5 MMI units (Fig. S3c). Larger maximum differences tend to occur for larger magnitudes, which may be due to how the source-receiver distance is computed, first noted by Thakoor *et al.* (2019). For M>5, Shakemap computes a

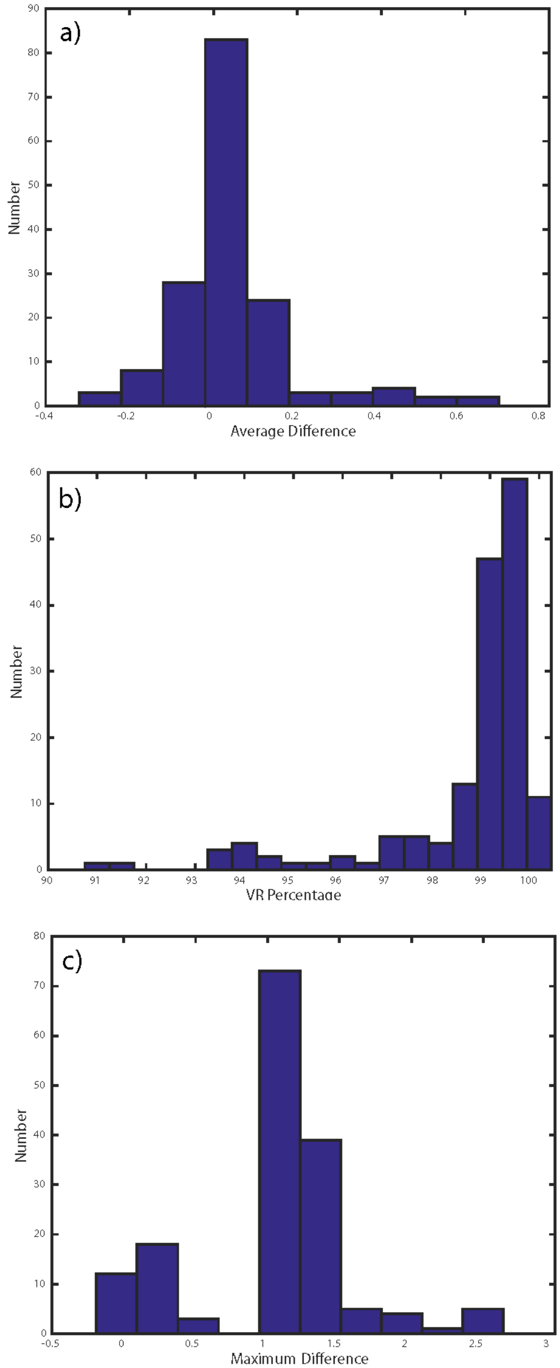

Figure S3. Histograms showing: (a) the average shaking intensity (SI) MMI differences between eqInfo2GM and ShakeMaps, (b) the range of variance reductions for the different SIs, and (c) the range of maximum SI MMI differences between eqInfo2GM and ShakeMaps. The values in (a), (b), and (c) are computed for each earthquake's first alert and its updates.

‘median distance’ (the distance that produces the median ground motions of all the possible fault orientations that pass through the hypocenter; Worden and Wald, 2016) that addresses the deficiency of using an epicentral distance for an extended rupture. In contrast, eqInfo2GM always uses epicentral distance unless a FinDer fault is available, which is rare in the test examples as early alerts usually do not incorporate the FinDer fault when the point-source estimate of magnitude is below 6.0. Where a line source is available, eqInfo2GM uses the Joyner-Boore distance where relevant for the GMPE.

The ShakeMaps produced for the historic test suite only use the point-source information, regardless of magnitude. Since eqInfo2GM uses the finite-fault source for **M** 6+ earthquakes, some differences can arise between the ShakeMap and the eqInfo2GM map message output for the larger events in the historic test suite. In contrast, for the large finite-fault scenario earthquakes discussed next, the ShakeMaps are calculated using finite-fault information; hence, these are a better test of the finite-fault capabilities of eqInfo2GM. In general, eqInfo2GM matches better in southern and northern California. There is greater variation in the near-source regions for the Pacific Northwest (note 0.2° resolution for eqInfo2GM and a finer 0.05° resolution for the ShakeMaps, the latter are downsampled during comparison).

We also tested eqInfo2GM against ShakeMaps for three large-magnitude finite-fault scenario events: an **M** 7.3 Hayward fault scenario, an **M** 7.9 Southern San Andreas fault scenario, and an **M** 9.34 Cascadia scenario (Fig. S4) (see Data and Resources for details on scenario data sources). Note that these comparisons show how well eqInfo2GM can generate a ShakeMap-like product from source parameters, but not how well the ShakeAlert system will predict the source parameters for this type of event or the timeliness of the alerts. For this test, we first regenerated the scenario event ShakeMaps with expanded boundaries to better compare with eqInfo2GM output. We then translated finite-fault information (already produced by the scenario datasets) to FinDer-style XML messages by reducing fault plane descriptions from the scenario to line-source descriptions by taking the upper or lower edge, as this is the limit of the capability of eqInfo2GM input. Next, we generated eqInfo2GM map messages using the FinDer-style XML messages as input, to generate map output. Last we compared the (independently produced) ShakeMap and eqInfo2GM ground motion estimates. Figs. S4a,d,g show the differences in shaking intensity (in MMI units) between the ShakeMap ground intensity estimates (Figs. S4b,e,h), and the eqInfo2GM ground intensity estimates (Figs. S4c,f,i) for the three scenario earthquakes. The Hayward fault **M** 7.3 scenario earthquake has a good SI VR of 99.6%, and the Southern San Andreas **M** 7.9 scenario earthquake also has a good SI VR of 99.2%. To model the **M** 9.34 Cascadia scenario, we used two different FinDer line sources, one with shallow slip (5 km) and one with deep slip (26 to 35 km). The shallow slip scenario generated an SI VR of 94.8% and the deep slip scenario generated an SI VR of 96.3%.

Validation of ShakeAlert ground motion map accuracy

The assessment of full ShakeAlert ground motion accuracy involves comparisons of eqInfo2GM map predictions with USGS-NEIC Shakemaps which include station observations. This comparison is a better measure of how ShakeAlert 2.0 will perform compared to observed ground motions, whereas the previous comparison tested how well eqInfo2GM replicates Shakemap’s ground motion prediction equations (i.e. source information without station data). This work is discussed in Thakoor *et al.* (2019) and is summarized here, but these types of tests are an ongoing part of ShakeAlert. Thakoor *et al.* (2019) implemented the comparison of eqInfo2GM output to NEIC Shakemaps for regions with MMI ≥ II. In their study, they found that

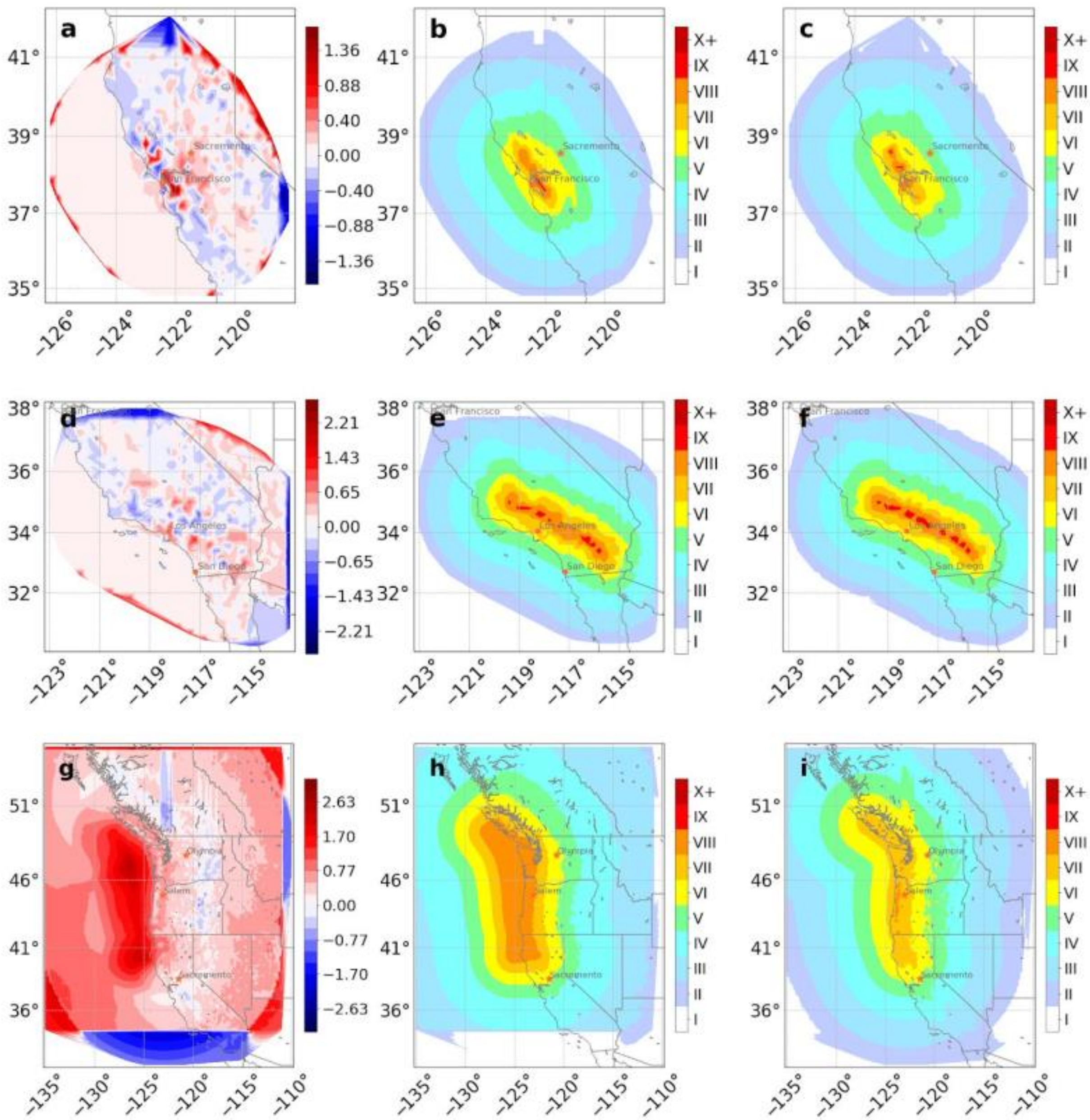

Figure S4. Ground motion test assessment for three scenario earthquakes, and comparison between ShakeMap and eqInfo2GM output. (a) Hayward fault scenario comparison between ShakeMap and eqInfo2GM showing difference in shaking intensity in MMI units. (b) Hayward fault scenario ShakeMap. (c) Hayward fault scenario eqInfo2GM output. (d) San Andreas fault scenario comparison between ShakeMap and eqInfo2GM showing difference in shaking intensity in MMI units. (e) San Andreas fault scenario ShakeMap. (f) San Andreas fault scenario eqInfo2GM output. (g) Cascadia scenario comparison between ShakeMap and eqInfo2GM showing difference in shaking intensity in MMI units. (h) Cascadia scenario ShakeMap. (i) Cascadia scenario eqInfo2GM output. In all three cases, the differences between ShakeMap and eqInfo2GM output are very small, illustrating the effectiveness of eqInfo2GM estimates.

97% of the maps had an SI VR > 50%, 76% of the maps had an SI VR > 80%, and 46% of the maps had an SI VR > 90%. In terms of SI difference, 14% of the maps had a mean SI difference within 0.25 MMI units and 62% of the maps have a mean SI difference within 1.00 MMI units. For the August 24, 2014 **M** 6.0 South Napa earthquake, they had a VR of 99.5% when comparing output to Shakemaps (with same source and no station observations) vs. a VR of 62% when comparing output to ShakeMaps (with earthquake catalog source parameters and with station observations).

References

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