ELECTRONIC SEISMOLOGIST

An Open-Source Earthquake Early Warning Display

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ABSTRACT

We present the earthquake early warning display (EEWD), an effort to build a free and open-source software to display earthquake early warning (EEW) information. The EEWD design and development builds on the experience of the Swiss Seismological Service at ETH Zürich in running the ShakeAlert UserDisplay developed by Caltech in California. The EEWD is a client-side end-user software capable of (1) supporting alerts generated by the main EEW algorithms used in Europe, starting with the Virtual Seismologist and the PRobabilistic and Evolutionary early warning SysTem (PRESTo); (2) allowing configuration for regionalization of shaking parameter predictions, such as local ground-motion prediction equations (GMPEs), ground-motion intensity conversion equations (GMICEs), and amplification due to local site effects; and (3) supporting future developments for configuration according to particular end-user requirements. In addition to real-time operations, the EEWD can replay recorded real-time earthquake alerts and play scenarios. The EEWD, including its source code, is freely distributed to the community of interested users, who are also welcome to contribute to further developments, in particular to the inclusion of custom GMPEs, GMICEs, and intensity prediction equations.

INTRODUCTION

Recent earthquake early warning (EEW) research initiatives worldwide (see Data and Resources) have shown the importance of communicating rapid earthquake information to potential end users and stakeholders in a user-friendly, end-user-oriented, and customizable way. Although EEW is optimally coupled with automatic implementation of earthquake risk mitigation actions, many critical industrial and public applications rely on human-made decisions in case of heightened hazard. This is the case, for example, in the nuclear industry in regions of moderate seismicity, where automatic shutdown of plant components is typically not foreseen (Cauzzi *et al.*, 2016), and in railway operations, where drivers may need to decelerate and eventually stop in response to an EEW message. A graphical user interface (GUI) displaying EEW alerts in real time is also an indispensable tool for building the trust of end users in the EEW system and, therefore, is an important part of public outreach and education.

With this background, we present the first public release of the earthquake early warning display (EEWD). This is a European effort to build a free and open-source software to display EEW information. The EEWD design and development builds on the experience of the Swiss Seismological Service (SED) at ETH Zürich in running the ShakeAlert UserDisplay (Böse *et al.*, 2014; see Data and Resources), developed by Caltech in California. The EEWD is a client-side end-user software capable of (1) supporting all alerts generated by the main EEW algorithms used in Europe, starting with Virtual Seismologist (VS) (Cua, 2005; Cua and Heaton, 2007; Behr *et al.*, 2015, 2016; see Data and Resources) and PRobabilistic and Evolutionary early warning SysTem (PRESTo; Satriano *et al.*, 2011; see Data and Resources); (2) allowing configuration for regionalization of shaking parameter predictions such as local ground-motion prediction equations (GMPEs), ground-motion-to-intensity conversion equations (GMICEs), and amplification due to local site effects; and (3) supporting future developments for configuration according to particular end-user requirements. Other EEW algorithms (Gasparini *et al.*, 2007; Allen *et al.*, 2009) can, of course, use the current software, provided they conform to message nomenclature and communication protocols. In addition to real-time operations, the EEWD can play back real-time earthquake alerts and play scenarios. The EEWD, including its source code, is freely distributed to the community of interested users, who are also welcome to contribute to further developments, in particular to the inclusion of custom GMPEs, GMICEs, and intensity prediction equations (IPEs).

The EEWD is a stand-alone Java client application ensuring platform independence. The choice of Java provides an inexpensive implementation path toward Android-based devices.

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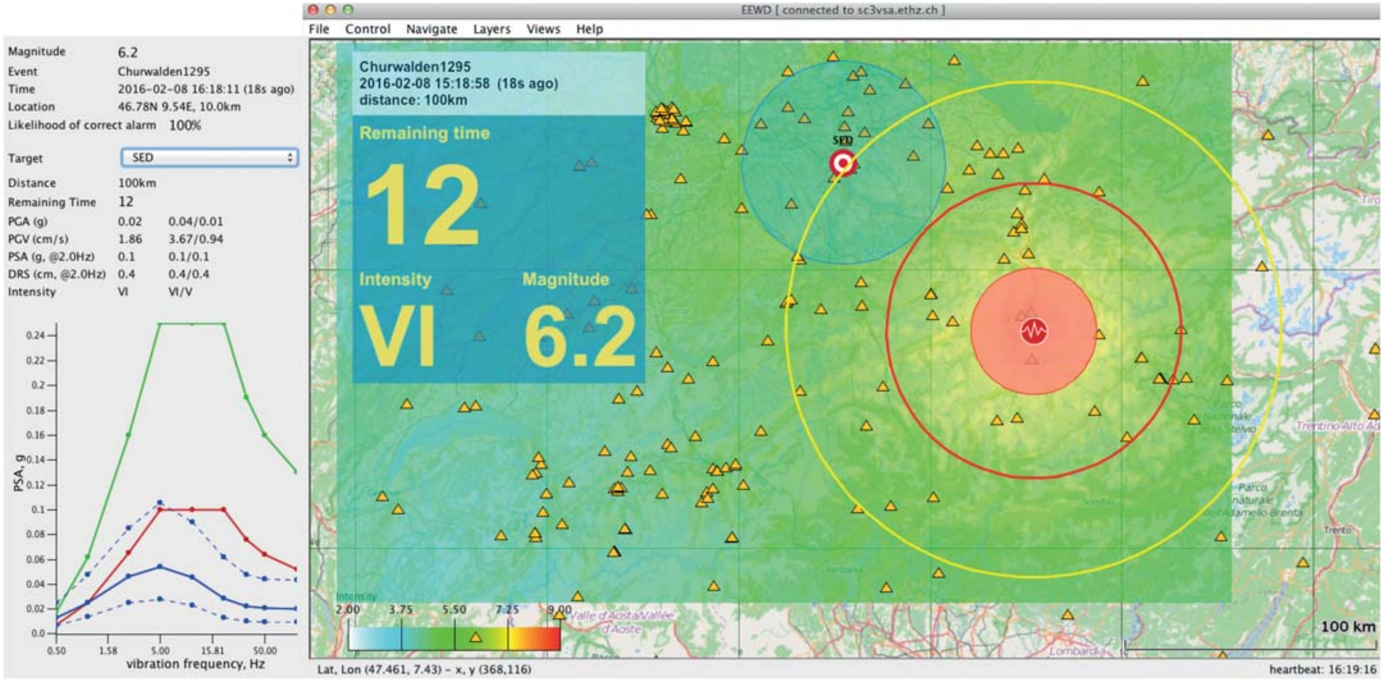

▲ **Figure 1.** Basic elements of the earthquake early warning display (EEWD) graphical user interface (GUI). The two main parts are (right side) a map panel displaying predicted shaking information, as well as identifying the location of the event and target sites and (left side) a summary information panel describing the event and predicted shaking for a selected location. The information panel can be optionally turned off. The map panel shows (a) a background geographic map; (b) a predictive shaking scenario (macroseismic intensity in this case); (c) the available seismic network stations (orange triangles); (d) the earthquake point source location and associated uncertainty; (e) the target site (Swiss Seismological Service [SED] in this case) with a shaded region corresponding to an estimate of the region where earthquake early warning (EEW) cannot be expected to provide advanced warning of strong ground shaking; (f) the predicted *P* and *S* wavefronts (yellow and red circles) emanating from the epicenter; and (g) a summary of the earthquake magnitude and distance from the target site, along with the expected severity of shaking and the time prior to strong shaking at the target. The summary information panel shows the earthquake parameters, the likelihood of the EEW message, and 16th, 50th, and 84th percentile levels of the predicted peak ground acceleration (PGA), peak ground velocity (PGV), intensity, and spectral ordinates at the chosen target. The user can compare response spectral predictions (blue solid curves, 50th percentile; blue dashed-dotted curves, 16th and 84th percentiles) with reference spectra at the target (red and green curves; the reference spectral amplitudes were arbitrarily chosen and do not represent any design criteria for the SED headquarters). The information panel on the left side of the EEWD will also show uncertainties, if available, for magnitude, distance, and shaking parameters. The screenshot shows a playback for the 1295 Churwalden (Switzerland) M_w 6.2 earthquake. The screenshot is taken when the predicted *P* wavefront hits the target site at the SED in Zürich, 12 s prior to the arrival of strong *S*-wave shaking. The seismic stations in the pictures represent a subset of the current real-time network configuration in Switzerland (see Data and Resources).

The key features of the EEWD GUI are shown in Figure 1 and described in detail in the following sections.

BACKGROUND GEOGRAPHIC LAYER

The background of the EEWD GUI is a geographic layer. The mapping style and the geographic extent can be defined by the user in a configuration file. The user can zoom in and out, subselect a rectangular region, and move the map to better focus on the region of interest. If an earthquake occurs outside the region initially specified by the user, the EEWD automatically modifies the geographic extent to include the epicenter. The geographic layer uses the free and open-source mapping technology, OpenMap (see Data and Resources). It is important that the EEWD relies on as few external resources as possible (e.g., from the Internet) during operation, because they may be subject to outages and application programming interface changes. So, for a task such as the map display, a wholly local and autonomous implementation was preferred.

TARGET SITES

Target sites are points shown with target symbols in the GUI. As a minimum, the user specifies one target site in a configuration file. A target site is identified by its name, latitude, longitude, elevation, and the values of an amplification proxy (e.g., V_{S30}) at the site. The amplification proxy specified for the target is consistently used by the ground-shaking prediction modules described in the Shaking Prediction at the Target(s) section.

A gray shaded area around the target(s) represents the region where the lead time is expected to be smaller than or equal to zero, that is, where no warning is possible before potentially damaging *S* waves hit the target. This region is centered on the target site. It is a (configurable) prediction that provides a graphical indication of the epicentral area too close to the target site for the EEW system to provide a pre-alert to the target. The radius of the zone is specified by the user in a configuration file. This radius should depend on the network geometry, the average processing time of the EEW system, and the normal depth of seismicity (e.g., Behr *et al.*, 2015).

SEISMIC STATIONS

The seismic stations are point elements shown as triangles on the GUI. Using a configuration file, the user has the option to display the network stations and their names. A station is identified by its name (or international code), latitude, longitude, and amplification proxy value at the recording site. The amplification proxy specified for the target is consistently used by the ground-shaking prediction modules described later in the article. The stations contributing to a given real-time alert can be set to blink if this information is passed to the EEWD by the EEW algorithm. The set of stations used at each stage of an EEW alert is passed to the EEWD as described in the Event Information section.

EVENT INFORMATION

The EEWD receives and displays earthquake information as soon as it is provided by the EEW software, subsequently updated as often as an update is available. The message format follows the QuakeML international standard (see Data and Resources). Apart from the existing validation tools and the large number of optional elements, the major advantage of using QuakeML is the system of public identifiers (public IDs) that are assigned to every major element (such as origin, event, magnitude, amplitude, pick, arrival, etc.). This makes it very flexible, supporting for example, (1) limiting message content to only those elements updated since a previous message while keeping older elements in a local buffer at the receiving end and (2) allowing intermediate merging of messages where alerts from different algorithms are combined into a single best alert, as done by the Decision Module (Böse *et al.*, 2011, 2014; Henson *et al.*, 2012) within the California ShakeAlert project. More generically, QuakeML also supports sending notification of an event without an origin, an option that could prove valuable for on-site-type algorithms (e.g., Böse, Hauksson, Solanki, Kanamori, and Heaton, 2009; Böse, Hauksson, Solanki, Kanamori, Wu, *et al.*, 2009) that trigger on the exceedance of a threshold but do not provide information on source parameters. If some EEW-specific information is not covered by QuakeML standard elements, extensions can be easily defined.

The communication between the EEWD and the EEW software in use is managed by an ActiveMQ broker (see Data and Resources). The configuration of the broker system is the responsibility of the provider of the EEW messages (i.e., the server side). The user only needs to be aware of the basic settings (provided by the EEW provider) included in a configuration file, such as the address of the connection host, the port, topic, user name, and password. ActiveMQ is also used by the ShakeAlert UserDisplay operated in California. This broker uses message acknowledgments to guarantee message delivery. The latency associated with this procedure is negligible for EEW display applications, where the number of messages delivered is of the order of a few per second at most (see the Update of the Display and Logging section). The size of XML messages delivered by VS to the EEWD in Switzerland typically ranges between 10 and 50 KB.

The current EEWD requires an (evolving) earthquake location that is a geographic point element on the map. The symbol can be specified in the EEWD configuration file. If the EEW algorithm provides information about the location uncertainty (currently expected as major and minor ellipse axes, in kilometers), then this is also displayed as a semitransparent ellipse below the epicenter.

The EEWD also displays the estimated likelihood of the earthquake, if provided by the EEW software. In the case of VS, the likelihood estimate is a function of the number and distribution of stations and the variance of magnitudes contributing to the alert (see Data and Resources). The VS likelihood provides end users with a real-time estimate of the reliability of a given EEW alert. In other words, the likelihood parameter expresses the degree of belief that the incoming data come from a real earthquake, as opposed to non-earthquake-related signals. Earliest alerts using the fewest stations for both location and magnitude tend to have lower likelihoods. To balance the user tolerance of false alarms, missed events, and speed of the first alerts, the user can filter the incoming messages based on magnitude and likelihood.

P AND *S* WAVEFRONTS

The predicted *P* and *S* wavefronts are circles colored in yellow and red in the EEWD, respectively. They are centered on the epicenter with radii expanding over time. The user specifies average regional values of *P* and *S*-wave velocity (V_P, V_S) in km/s in a configuration file. The time-dependent radii of the *P*- and *S*-wavefronts (R_P, R_S) are computed by the EEWD as

$$\begin{cases} R_P = V_P(t_C - \mathrm{OT}) \\ R_S = V_S(t_C - \mathrm{OT}) \end{cases}, \quad (1)$$

in which t_C and OT are the current time and the earthquake origin time, respectively. R_P and R_S are hypocentral radii, that is they are centered on the earthquake focus at depth. The software also computes the (point-to-point) distance between the earthquake location and the target (R_T) and uses it to compute the available time in seconds before strong shaking arrives (i.e., the time prior to *S*-wave shaking at the target T_S):

$$T_S = (R_T - R_S)/V_S. \quad (2)$$

SHAKING PREDICTION AT THE TARGET(S)

The EEWD can display site-specific predictions of peak-motion parameters (e.g., peak ground acceleration [PGA] in *g*, peak ground velocity [PGV] in cm/s), response spectra (e.g., elastic acceleration in *g* or displacement in cm), and macroseimic intensity, including local site amplification, given the location and magnitude of the ongoing earthquake alert. This targets end users who wish to make decisions based on predicted exceedance of engineering parameters, such as design response spectra (see Convertito *et al.*, 2008). The user specifies at least one vibration period of interest through a configuration file. The user can additionally configure reference values for the response spectra, with the meaning, for example, of a serviceability spectrum and a collapse spectrum that would be displayed by the EEWD along with the predicted response spectrum.

The user provides a prediction method for these shaking parameters. Two main prediction methods are supported, using either equations or tables. That is, the user can either provide precomputed magnitude- and distance-dependent shaking estimates (16th, 50th, and 84th percentile levels) in tabular form or write Java classes for each shaking parameter. We recommend using predictive equations implemented as Java classes. The EEWD interface provides the following examples: the GMPEs of Akkar and Bommer (2007), Emolo *et al.* (2011), Bindi *et al.* (2014), Cauzzi, Edwards, *et al.* (2015), and Cauzzi, Faccioli, *et al.* (2015); the IPEs of Faccioli and Cauzzi (2006) and Allen *et al.* (2012); and the GMICE of Faenza and Michelini (2010). These models were included in the first public release of the EEWD because they are largely used by the main developers and testers of the EEWD in Switzerland and Italy. Users are recommended to check the source code to be aware of the assumptions made during the implementation of the models above. Users interested in running the EEWD are encouraged to supplement the distribution by adding predictive models suitable for their region of interest, thus supporting community development of the EEWD.

The EEWD GUI also can display shaking predictions at the regional level, based on these same models—in effect displaying purely predictive (i.e., not corrected by station recordings) shaking scenarios in real time. This is critical for users interested in multiple target sites and for operators of spatially distributed infrastructures (e.g., lifelines). These estimates are displayed as a raster 50% transparent grid on the EEWD. Maps of expected ground shaking can take into account site amplification, if a file with a grid of the amplification proxy used by the implementation of the predictive equations is provided. Our future strategy for inclusion of station recordings in the shaking scenarios will follow the logic of U.S. Geological Survey ShakeMap (Wald *et al.*, 1999; Worden *et al.*, 2010), in which each station has a radius of influence in the map.

The estimation of the predicted shaking at site and regional levels is computed by the EEWD software, given the earthquake location and magnitude. At this stage, there is no capability to take finite-fault rupture into account for the shaking estimates.

Overall, the operations made by the current version of the EEWD are computationally inexpensive. On a standard laptop with a 2.9 GHz processor and 16 GB 1600 mHz DDR3 RAM, the computation of the predicted parameters at the target site and of the regional shaking scenario takes typically less than 30 ms. This value refers to the case in which the shaking scenario is computed on a regular grid of $\sim$15, 230 points covering the Swiss region.

UPDATE OF THE DISPLAY AND LOGGING

The EEWD dynamic content is updated every 0.25 s, starting from the first message received until a timeout set by the user. Earthquake information is shown even if the event occurs inside the zone, where there is no positive alert warning time (i.e., the alert is too late; arriving after any predicted strong shaking has begun). The EEWD starts a countdown (if enabled by the user) 10 s prior to shaking for all earthquakes.

The EEWD logs the magnitude and location evolution of the event as a function of time in plain-text format. Logging can be viewed from inside the client. The EEWD also tracks event deletion if provided by the EEW algorithm. This is done if the EEW algorithm provides an updated message that sets the event type to “not existing.” Filtered messages are not logged. The EEWD currently does not notify the user if an event is cancelled.

PLAYBACKS AND SCENARIOS

The EEWD allows replay of any alert based on the log files generated. Scenario events can be created by manually creating these log files; an example is shown in Figure 1. Replays can be easily selected through the client interface. The EEWD distribution contains several scenarios for relevant events that occurred in Switzerland (see Data and Resources) and in Italy. The user can modify these examples to create new scenarios.

TIME SYNCHRONIZATION, CONNECTION TO THE EARLY WARNING SERVER, AND EEW ALGORITHM HEARTBEAT

To ensure the EEWD is live, an EEW algorithm sending messages to the EEWD should be capable of sending heartbeat (HB) messages to the display. The time of the last HB received is displayed in the right corner of the status bar at the bottom (see Fig. 1). The status of the connection to the server is displayed in the title bar. Note that the application presently does not check time synchronization against any Network Time Protocol (NTP) server, but uses the time of the computer it is installed on. The user should ensure that the computer running the EEWD is well synchronized in time.

CONCLUSIONS

The first public release of the open-source EEWD is made available to interested users through the website of project REAKT (see Data and Resources). Future versions and releases will be based on collaborative code development through GitHub (see Data and Resources). The key innovations of the EEWD are (1) the possibility of using custom GMPEs, GMICEs, and IPEs; (2) the adoption of a standard, extensible messaging interface based on QuakeML; (3) the open-source strategy; and (4) the possible application as a rapid information system not strictly tailored to EEW information only.

The EEWD is already operated by selected academic and/or research institutions and private and public stakeholders in the Euro-Mediterranean region (Cauzzi and the WP7 Participants, 2015). We hope for a continued community effort, centered on this group, to maintain and improve the EEWD. Among the most important future developments are (a) the inclusion of station peak motion recordings or predictions in the shaking scenarios; (b) the implementation of an alert filter based on shaking thresholds at the target; (c) the possibility of simultaneously communicating with different EEW algorithms running on the same network, similar to the ShakeAlert UserDisplay; (d) including likelihoods of secondary hazards like landslides and liquefaction; (e) including shaking probabilities as provided by earthquake forecasting methods; and (f) allowing the use of finite-fault information. We are also considering the possibility of importing the GMPEs and IPEs implemented in OpenQuake (Pagani *et al.*, 2014) into the EEWD. The EEWD can be viewed as a tool to broadcast real-time or near-real-time information to end users, including, but not restricted to, EEW alerts. The EEWD is a key element within the framework of the European project European Plate Observing System (EPOS) (see Data and Resources), presently being implemented.

DATA AND RESOURCES

The earthquake catalog of Switzerland is available at http://hitseddb.ethz.ch:8080/ecos09/index.html?&locale=en (last accessed February 2016). The Swiss national seismic networks are described at http://www.seismo.ethz.ch/monitor/index_EN (last accessed February 2016). Information about recent earthquake early warning research initiatives worldwide is available at http://www.shakealert.org/; http://www.reaktproject.eu/; the ShakeAlert UserDisplay is described at http://www.eew.caltech.edu/research/userdisplay.html; the Virtual Seismologist (VS) software is available at http://www.seiscomp3.org/doc/seattle/2013.200/apps/vs.html and http://www.seiscomp3.org/doc/jakarta/current/apps/scvsmag.html; PRESTo is available at http://www.prestoews.org/; OpenMap is available at https://code.google.com/p/openmap/; QuakeML is described at http://www.quakeml.org; ActiveMQ can be found at http://activemq.apache.org/run-broker.html; the EEWD is available on the REAKT project website at http://www.reaktproject.eu/index.php?option=com_content&view=article&id=496&Itemid=58; the EEWD is available on GitHub at https://github.com/SED-EEW/EEWD; and the European project EPOS is described at http://www.epos-eu.org/. All the above websites were last accessed in February 2016.

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