3rd International Conference on Earthquake Early Warning:

Implementing Earthquake Alerts

September 3-5, 2014
UC Berkeley, California
Agenda

Wednesday September 3rd Policy Forum: US EEW Implementation

1:30-2:30	California State Senator Alex Padilla: Opening remarks on Bringing EEW to the US
	California State Senator Jerry Hill: Moving forward in California
	California Lieutenant Governor Gavin Newsom: Gov. calls on Cal OES
	San Francisco Mayor Ed Lee: EEW importance for cities
	Director Mark Ghilarducci CalOES: California Plan and Status
	Acting Director Suzette Kimball, USGS: Beyond California—EEW for the US
2:30-3:00	Coffee Break
3:00-4:00	*State panel on implementation strategy and policy*
	Michelle Moskowitz, UC Berkeley—moderator
	California State Senator Jerry Hill
	Angela Manetti, Office of Senator Padilla
	Deputy Director Christina Curry, CalOES
4:00-5:00	*National Panel on implementation strategy and policy*
	Hall Daily, California Institute of Technology—moderator
	Courtney Fogwell, Legislative Assistant Office of Congressman Schiff
	Douglas Given, USGS Earthquake Early Warning Coordinator
	Nancy Koch, Gordon and Betty Moore Foundation
5:15-7pm	Reception at the University Club, Memorial Stadium

Thursday September 4th Session I: Global Implementation Status
Chair: Tomas Heaton (Caltech)

9:00-10:30	*Nakamura, Kotera, Tamaribuchi, Yamada, Adachi, Morimoto, Hoshiba*
	The Earthquake Early Warning of Japan Meteorological Agency
	Clinton, Zollo
	An Overview of Earthquake Early Warning Efforts in Europe through the prism of REAKT
	Espinosa, Petel
	Earthquake Alerts - From Black Magic to Science and Engineering
	Given, Allen, Heaton, Vidale
	ShakeAlert: Public Earthquake Early Warning for the United States
10:30-11:00	Coffee Break

Session II: Big Earthquakes   Chair: John Vidale (Univ. of Washington)

11:00-1:00   *Boese, Felizardo, Heaton, Hauksson*
Real-time performance of FinDer during the 2014 M5.1 La Habra earthquake, Los Angeles and M6.0 American Canyon/Napa EQs
Grapenthin, Johanson, Allen
Operational Real-time GPS enhanced Earthquake Early Warning
Melbourne, Szeliga, Santillan, Scrivner, Webb
Real-time GPS monitoring of the Cascadia megathrust
Kawazoe, Nakamura, Aizawa, Aoki, Sakihara, Kubo, Uratani, Hoshiba
Information on long-period ground motion of the Japan Meteorological Agency
Minson, Murray, Langbein, Gomberg
Real-time inversion for finite fault slip models and rupture geometry based on high-rate GPS data
Meng, Allen, Ampuero
Application of Seismic Array Processing to Earthquake Early Warning

1:00-1:30   Lunch

1:30-3:00   Poster Session

Session III: New Concepts in EEW   Chair: Doug Given (USGS)

3:00-5:00   *Hoshiba, Aoki*
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Karakus, Heaton
A Waveform Envelope-Based Reality Check Algorithm in Early Warning
Colombelli, Zollo, Festa, Picozzi
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Zollo, Caruso, Colombelli, Festa, Kanamori
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Men-Andrin, Clinton, Heaton
A Filter Bank Approach to Earthquake Early Warning

Friday September 5th   Applications of EEW

9:00-10:30   Public use of EEW panel: Kate Long, CalOES —moderator

Gordon Woo, RMS	*Beth Pratt-Sitaula, CWash Univ/UNAVCO*
Ann Bostrom, University of Washington	*Mark Lucero, FEMA*

10:30-11:00   Coffee Break

11:00-12:00   Industry use of EEW panel: Jennifer Strauss, Berkeley Seismo Lab—moderator

Shunta Noda, Railway Tech Research Inst	*Josh Bashioum, Early Warning Labs, LLC*
John McPartland, Director, BART	*Aviv Siegel, AtHoc*

12:00   Adjourn

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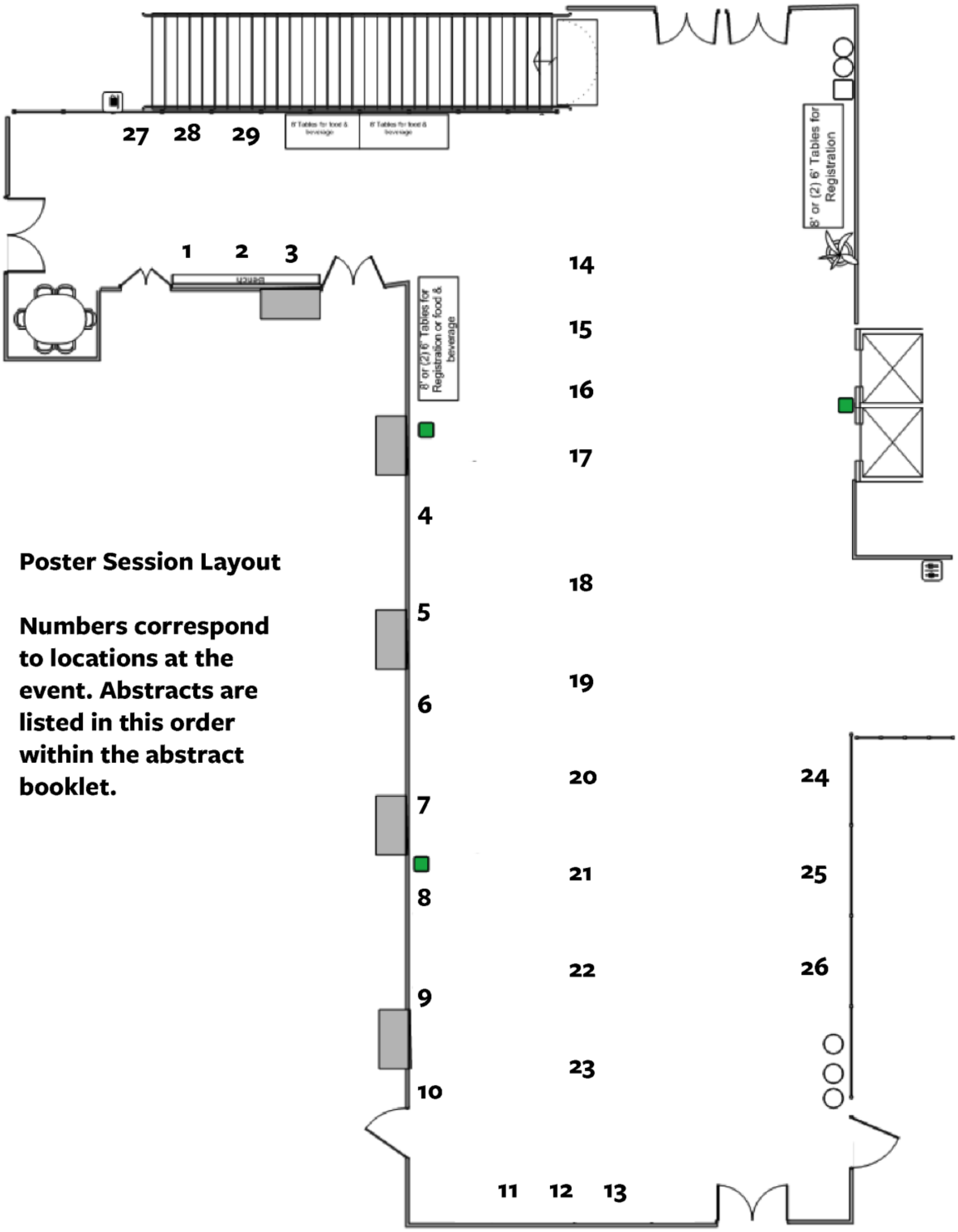

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Introduction of the present Earthquake Early Warning system for the Shinkansen

Session I: Global Implementation Status
Tuesday September 4th, 2014

Masaki Nakamura[1], Yuki Kotera[1], Koji Tamaribuchi[1], Yasuyuki Yamada[1], Shinpei Adachi[1], Masahiko Morimoto[1], Mitsuyuki Hoshiba[1]
[1]Meteorological Research Institute, Japan Meteorological Agency

The Earthquake Early Warning of Japan Meteorological Agency

We review the operation of nationwide Earthquake Early Warning (EEW) of JMA. Then we show its performance of the cases of the 2011 Great East Japan Earthquake (Mw 9.0) and its aftershocks. After that, we present some lessons from the experience and future plans to improve the system.

JMA began to operate the EEW nationwide in October 2007. We predict seismic intensities and arrival times of S waves after determining the hypocenter by a combination of several techniques; the magnitude by maximum displacement amplitudes. The main part of the system uses 220 stations. The JMA EEWs are updated repeatedly as available data increases with elapsed time.

The JMA seismic intensity scale is based on instrumental measurements which consider not only the amplitude but also the frequency and duration of the shaking. The scale has 10 degrees. Intensities of 5 and 6 are divided into 2 degrees, namely 5-lower, 5-upper, 6-lower and 6-upper, respectively. Intensity 1 corresponds to the ground motion that people can barely detect and 7 is the upper limit. There are 2 categories for the JMA EEW. The first one is 'forecast' for the limited users, and the other is 'warning' for the public. We issue the forecast in the case where the estimated maximum intensity exceeds 2, or estimated magnitude is larger than 3.5. We announce the warning through TV and cell phones to the general public when we predict the maximum intensity 5-lower or larger to the areas where the estimated intensities exceed 3. The forecast is updated whenever it is necessary, but we provide the updated warning only when the estimated intensities become 5-lower or larger from less than 4 in some areas, and limit it within 60 s after the first detection.

The warning of the EEW was disseminated 30 s after the Mw 9.0 event occurrence, which was 8 s after the first detection. The estimated magnitude was 7.2 at the time and the warning was issued only for Tohoku. We could provide the warning before the arrival of S-waves for all warning areas. However, the actual magnitude was 9.0 and the wide area was ruptured. The under estimate of the magnitude and the extent of the source region caused the under estimate of intensities. Especially, in Kanto, we observed 6-upper, but we could not provide the warning for the public. The warning was provided for the public only once, but the updated information was provided only to the limited users. We issued the EEW totally 15 times for the event. Finally the EEW estimated M 8.1, 105 s after the first detection.

Aftershocks sometimes occurred simultaneously over the wide region. Then, the system became confused and did not always determine the hypocenter parameters correctly. In 49 days after the main shock to April 28, 2011, 70 EEWs were announced to the public, but actual observed intensities did not exceed 2 at any stations in 17 cases.

To overcome those problems, Tamaribuchi *et al.* (2014) developed a new algorithm to classify multiple concurrent events for EEW. Their approach used the particle filter method and the method estimated the hypocenter, the origin time and the magnitude in the probabilistic framework, using trigger times, maximum amplitudes, epicentral distances and incident angles of the waveforms for the likelihood function. Furthermore, we will also introduce the real-time pseudo seismic intensity by Kunugi *et al.* (2008), by which we will be able to monitor the extent of the strong motion field and to evaluate the calculated hypocenter parameter. We developed another new method to forecast seismic intensities directly using observed intensities, which was a simplified version of Hoshiba (2013). As mentioned above, the current JMA EEW system is based on the calculated hypocenter parameter. We have the idea of a hybrid method using the conventional method and the new method of monitoring the real-time intensities. We have already simulated some events and were sure that the hybrid method worked well.

Moreover, JMA began to provide long period ground motion information, using the observed waveform at each station, on JMA web site March, 2013. Furthermore, we also begun to investigate the long period ground motion forecast aiming at establishing an earthquake early warning for long period ground motion (Ogami *et al.*, 2014).

References: Hoshiba, 2013, DOI: 10.1002/jgrb.50119. Kunugi *et al.*, 2008, Zisin2. Ogami *et al.*, 2014, the abstract of this meeting. Tamaribuchi *et al.*, 2014, Zisin 2, submitted.

John Clinton[1], Aldo Zollo[2]
[1]ETH Zurich
[2]Department of Physics, University of Naples Frederico II

An Overview of Earthquake Early Warning Efforts in Europe through the prism of REAKT

We provide an overview of the state of Earthquake Early Warning efforts in Europe within the context of the EU project REAKT, which is due to end in 2014. Recent scientific algorithm developments from key laboratories are presented. The status and plans of EEW implementations at seismic networks across Europe are discussed. Major work engaging end-users has been undertaken during REAKT, and we highlight the successes and forecast next steps. Finally, we describe efforts to build common EEW services for the European networks, such as an open EEW alert software agnostic of EEW algorithm and an EEW testing framework.

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Earthquake Alerts - From Black Magic to Science and Engineering

On Friday, April 18th, 2014, Mexico experienced a 7.2 magnitude earthquake that lasted approximately 30 seconds originating in the Guerrero state that was felt by millions, and not a single life was lost. That was not a fluke occurrence or blind luck. It was because Mexican government officials had been working diligently since 1985 to develop an earthquake detection and warning system to better protect the Mexican population. This session will examine how Mexico created a system in which earthquake detection sensors are integrated with an emergency mass notification network that provides warning to the mass population of an impending shock wave, sometimes of up to a minute or more. Mexico utilizes a network of thousands of small radios that automatically process signals from detection units and generate alerts in the form of broadcast sirens and automated messages that give recipients warning to take safety precautions. The system is in place in radio and t.v. broadcast stations, schools, and other public facilities. Overall, the system detects an earthquake, calculates its strength, determines when and where it started, identifies which locations could be affected, estimates how much time the locations have before the P-wave (primary wave) hits, and provides warning to the general public at each location before they feel the impact. Furthermore, to cut down on false alarms or alert fatigue, the scope of the warning system is determined by the strength of the earthquake as measured by the initial sensors so that only government agencies and emergency services are alerted to earthquakes 5.0 or above on the Richter scale. Earthquakes that are larger than 6.0 activate the mass notification system that alerts the general public and only to those areas that need the warning. Mexico is now examining the feasibility of expanding the network to become an all-hazards warning system that would encompass other events such as tsunamis and flooding and utilize existing IP-enabled networks to generate texts, push notifications, pop-up alerts on desktops and laptops, and to allow for the exchange of rich data such as images, videos and maps on mobile devices.

Join this session to learn about Mexico's process for developing an integrated earthquake detection and warning system, in hopes that the same network can be developed and applied to other areas of the world.

Douglas Given[1], Richard Allen[2], Tomas Heaton[3], John Vidale[4]
[1]United States Geological Survey
[2]Berkeley Seismological Laboratory
[3]California Institute of Technology
[4]University of Washington

ShakeAlert: Public Earthquake Early Warning for the United States

Earthquake Early Warning (EEW) is a proven use of seismological science that can give people and businesses outside the epicentral area of a large earthquake up to a minute to take protective actions before the most destructive shaking hits them. EEW systems are currently operating in several counties including Mexico, Japan, Taiwan, Italy, China, Turkey and Romania. Since 2006 several organizations have been collaborating to create such a system in the United States. These groups include the US Geological Survey, Caltech, UC Berkeley, the University of Washington, the Southern California Earthquake Center, the Swiss Federal Institute of Technology, Zürich, the California Office of Emergency Services, and the California Geological Survey. It is the goal of USGS and its partners to create and operate an Earthquake Early Warning system for the highest risk areas of the United States beginning with the west coast.

A demonstration version of the system, called ShakeAlert, began sending test notifications to selected users in California in January 2012. In August 2012 San Francisco's Bay Area Rapid Transit district began slowing and stopping trains in response to strong ground shaking. The next phase of the project is to transition from the current demonstration system to a production prototype for the west coast. ShakeAlert leverages the considerable physical, technical and organizational earthquake monitoring infrastructure of the Advanced National Seismic System (ANSS).

While significant progress is being made with current limited funding, a fully functional, robust, public EEW system will require substantial new investment and development in several areas. First, high-quality sensors must be installed with sufficient density to ensure they are near all possible source faults. To this end ANSS regional nets are upgrading and augmenting their existing sensor networks on the west coast as funding allows. Second, data telemetry from those sensors must be engineered for speed and reliability. Next, robust central processing infrastructure is being designed and built. Also, computer algorithms to detect and characterize the evolving earthquake must be further developed and tested. This effort was accelerated when the Gordon and Betty Moore Foundation funded USGS, Caltech, UCB and UW to advance EEW. Every available means of distributing alerts must be used to insure the system's effectiveness. ShakeAlert developers have created an internet-based UserDisplay application and a smartphone app based on Google Cloud Messaging. In addition, USGS has applied for authorization to alert over FEMA's Integrated Pubic Alert and Warning System (IPAWS). ShakeAlert partners are also working with private companies to develop a variety of alert distribution channels and end user implementation capabilities. Finally, because policy makers, institutional users, and the public must be educated about the system, social scientists and communicators are determining how to communicate the alerts most effectively.

Progress is also being made in several areas related to EEW. High-precision real-time GPS position data is becoming available on a large scale and algorithms are being developed to use these data to rapidly characterize the fault rupture as it propagates. This is critical to properly correctly estimate ground motions from large earthquakes that rupture long stretches of fault zones. New, advanced seismological and geodetic algorithms are being developed including specialized methods for the Cascadia megathrust. Joint development projects with private companies being used to encourage commercial EEW applications. And Federal, State and local agencies are working out their roles and responsibilities in building and operating the system and educating users about its uses and limitations.

There is much more to be done and funding the creation and operation of this new capability is a challenge, however, Federal, State and local governments along with private partners share the goal of building an EEW system before the next big earthquake rather than in its aftermath.

Session II: Big Earthquakes
Thursday September 4th, 2014

Maren Böse[1,2], Claude Felizardo[2], Tomas Heaton[2], Egill Hauksson[2]
[1]ETH Zurich
[2]California Institute of Technology

Real-time performance of FinDer during the 2014 M5.1 La Habra earthquake, Los Angeles and M6.0 American Canyon/Napa EQs

The Finite-Fault Rupture Detector algorithm FinDer has been designed to provide real-time estimates of fault-rupture extent during moderate to large earthquakes (Böse *et al.*, 2012). Compared to traditional point-source algorithms, the information on source-finiteness is expected to enhance ground-motion predictions as needed for earthquake early warning. Conceptually, FinDer is based on a rapid near-far source classification of observed high-frequency ground-motions and comparison with a set of pre-calculated templates. FinDer is an important extension of the currently implemented point-source algorithms (tauc-pd Onsite, Virtual Seismologist, and ElarmS) in the Californian ShakeAlert system. Even though FinDer has not been fully integrated into ShakeAlert yet, we are running the algorithm California-wide in real-time test mode and have gathered important real-time performance data over the past months. Most remarkable is the performance of FinDer during the 2014 M5.1 La Habra earthquake, Los Angeles. Though effects of source-finiteness for an event of this magnitude are expected to be small, both the FinDer real-time predicted 2D rupture dimensions and orientation agree surprisingly well with the observed SW-NE oriented isoseismals and aftershock distribution, and thus providing an important proof-of-concept of the algorithm.

Ronni Grapenthin[1], Ingrid Johanson[1], Richard Allen[1]
[1]Berkeley Seismological Laboratory

Operational Real-time GPS enhanced Earthquake Early Warning

Moment magnitudes for large earthquakes derived in real-time from near field seismic data are underestimated due to instrument limitations, ground tilting, and saturation of frequency/amplitude-magnitude relationships. Real-time high-rate GPS resolves the build-up of static surface displacements with the S-Wave arrival, thus enabling the estimation of slip on a finite fault and the event's geodetic moment. Recently, a range of high-rate GPS strategies has been demonstrated on off-line data. Here, we present the first operational system for real-time GPS-enhanced earthquake early warning as implemented at the Berkeley Seismological Laboratory (BSL) and currently running on data for Northern California.

The BSL generates real-time position estimates operationally using data from 62 GPS stations (BARD, PBO, USGS) in Northern California. A fully triangulated network defines 170+ station pairs for processing with the software trackRT. The BSL uses G-larmS, the Geodetic Alarm System, to analyze the positioning time series, and determine static offsets and pre-event quality parameters. G-larmS derives and broadcasts finite fault and magnitude information through least-squares inversion of the static offsets for slip. This Python implementation tightly integrates seismic alarm systems (CISN ShakeAlert, ElarmS) as it uses their P-wave detections to trigger its processing; quality control runs continuously.

To test our approach, we add offsets due to synthetic slip on the Hayward fault to real-time data. We are able to recover input slip and magnitude. Additionally, we replay high-rate GPS data from Southern California that recorded the 2010 Mw7.2 El Mayor-Cucapah earthquake. These data include dynamic motion due to S-waves and surface waves. Again magnitude and slip are well recovered.

To scrutinize our assumptions about strike, dip, timing and quality of location estimates (from the seismic system), we perturb these parameters at the respective stages in the processing. The findings depend highly on station coverage and the processing is most sensitive in densely instrumented areas. For a surface rupture on the Hayward Fault with the current GPS network, we suggest, for instance, that slip for an earthquake occurring within small bounds of our assumptions, i.e. strike= 320 +/-5 deg, dip= 90 +/- 3 deg, mislocation within 3 km orthorgonal to surface trace (depending on station coverage) will be well recovered. Outside of these bounds, however, slip and magnitude recovery can be poor at relatively good fit of the model to the data. Along dip partitioning of the slip distribution can have particular impact on slip and magnitude recovery if not accounted for in the inversion.

In the case of California and other places with onshore crustal faults, the worst-case scenario is undoubtedly the surface rupture of a strike-slip fault under a dense GPS network. Finite fault model solutions and magnitude recovery will degrade if the location is mis-estimated by the triggering system such that individual stations are on the wrong side of the model fault. This highlights a problem with the fault province approach G-larmS currently implements. However, it also shows that relying solely on a fault catalogue and selecting the nearest fault to the ShakeAlert location will cause similar problems. Ultimately, finite fault algorithms in settings of crustal faults within a dense network should make an effort to solve for location, strike and dip of the fault surface.

Timothy Melbourne[1], Walter Szeliga[1], Marcelo Santillan[1], Craig Scrivner[1], Frank Webb[1]
[1]Pacific Northwest Geodetic Array, Dept. of Geological Sciences, Central Washington University

Real-time GPS monitoring of the Cascadia megathrust

We have developed a comprehensive real-time GPS-based seismic monitoring system for the Cascadia subduction zone based on 1- and 5-second point position estimates computed within the ITRF08 reference frame. A Kalman filter stream editor that uses a geometry-free combination of phase and range observables to speed convergence while also producing independent estimation of carrier phase biases and ionosphere delay pre-cleans raw satellite measurements. These are then analyzed with GIPSY-OASIS using satellite clock and orbit corrections streamed continuously from the International GNSS Service (IGS) and the German Aerospace Center (DLR). The resulting RMS position scatter is less than 3 cm, and typical latencies are under 2 seconds. Currently 71 coastal Washington, Oregon, and northern California stations from the combined PANGA and PBO networks are analyzed. We are now ramping up to include all of the remaining 400+ stations currently operating throughout the Cascadia subduction zone, all of which are high-rate and telemetered in real-time to CWU. These receivers span the M9 megathrust, M7 crustal faults beneath population centers, several active Cascades volcanoes, and a host of other hazard sources.

To use the point position streams for seismic monitoring, we have developed an inter-process client communication package that captures, buffers and re-broadcasts real-time positions and covariances to a variety of seismic estimation routines running on distributed hardware. An aggregator ingests, re-streams and can rebroadcast up to 24 hours of point-positions and resultant seismic estimates derived from the point positions to application clients distributed across web.

A suite of seismic monitoring applications has also been written, which includes position time series analysis, instantaneous displacement vectors, and peak ground displacement contouring and mapping. We have also implemented a continuous estimation of finite-fault slip along the Cascadia megathrust using a NIF-type approach. This currently operates on the terrestrial GPS data streams, but could readily be expanded to use real-time offshore geodetic measurements as well. The continuous slip distributions are used in turn to compute tsunami excitation and, when convolved with pre-computed, hydrodynamic Green functions calculated using the COMCOT tsunami modeling software, run-up estimates for the entire Cascadia coastal margin. Finally, a suite of data visualization tools has been written to allow interaction with the real-time position streams and seismic estimates based on them, including time series plotting, instantaneous offset vectors, peak ground deformation contouring, finite-fault inversions, and tsunami run-up. This suite is currently bundled within a single client written in JAVA, called *GPS Cockpit,* which is available for download.

Yoshie Kawazoe[1], Masaki Nakamura[1], Koji Aizawa[1], Shigeki Aoki[1], Hirokazu Sakihara[1], Gota Kubo[1], Jyunpei Uratani[1], Mitsuyuki Hoshiba[2]
[1]Japan Meteorological Agency
[2]Meteorological Research Institute, Japan Meteorological Agency

Information on long-period ground motion of the Japan Meteorological Agency

Earthquakes with larger magnitudes usually generate larger long-period ground motions. When the natural period of a high-rise building is close to the predominant period of ground motion, resonance happens and the top of the building is severely shaken longer than surface of the Earth. Today, more and more people spend a lot of times in high-rise buildings especially in metropolitan areas. If great earthquake occurs, many people in high-rise buildings will be affected by long-period ground motion.

To notify people of such situations and facilitate effective countermeasures, Japan Meteorological Agency (JMA) started to provide information on long-period ground motion from March, 2013. Based on questionnaires to tenants of high-rise buildings, it has become clear that difficulty of people's activities depends on the velocity of floor movement, and we classified the intensity of long-period ground motion into four on the basis of velocity. To get the classification, we use waveforms observed by 660 JMA seismic intensity meters on the surface of the Earth, which are automatically sent to the JMA system. To estimate shaking at higher floors from wave forms on the surface of the Earth, we simulate the shaking of buildings by absolute velocity response spectrum of the period between 1.5 and 8.0 seconds which causes a significant resonance of buildings with 45 meters or higher. The information is available on the JMA website (http://www.data.jma.go.jp/svd/eew/data/ltpgm/) with various kinds of contents including intensity of long-period ground motion, absolute velocity and acceleration response spectrum, acceleration and velocity waveforms and intensity scale on long-period ground motion in each period.

Furthermore, we have begun to investigate the long-period ground motion forecast aiming at establishing an earthquake early warning (EEW) for long-period ground motion. There are 4 possible kinds of methods. The first one is the method using hypocenter parameters determined by conventional EEW, the distance attenuation function and gains at stations, which is similar to the conventional EEW of JMA. The second method is based on observation results of past large earthquakes and simulation results of anticipated mega quakes, using hypocenter parameters determined by conventional EEW. The third one is the method through wave field forecast using waveforms of high density stations. The forth one is the method using a transfer function between stations and observation data in real time manner. Probably we will combine some kinds of the above methods. Now we are investigating attenuation relationships of response spectrum because it can calculate response spectrum at any given seismic parameter and calculate fast. We will introduce some attenuation relationships and their features.

Sarah E. Minson[1], Jessica R. Murray[2], John Langbein[2], Joan S. Gomberg[2]
[1]California Institute of Technology
[2]United States Geological Survey

Real-time inversion for finite fault slip models and rupture geometry based on high-rate GPS data

We present a semi-analytical Bayesian inversion methodology for determining both the spatial distribution of slip and the orientation of the fault plane in real-time based on high-rate GPS data. There are three main advantages to this source modeling methodology. The first is that, by using a Bayesian approach, we can obtain a stable solution for what is generally a poorly-constrained inverse problem, and we can do this without the use of non-physical smoothing constraints. Second, because our methodology is semi-analytical, and thus computationally inexpensive, we can estimate the slip model and fault geometry, along with the uncertainties associated with our estimate, in real-time as the earthquake rupture evolves, making this inversion approach particularly useful for earthquake early warning. Third, since we solve for the full finite fault slip model and fault plane orientation, the inversion results could potentially be used to produce better shaking forecasts and tsunami hazard assessments and for other earthquake rapid response needs. We will present our inversion methodology and the results of a series of performance tests using data from both scenario events and real earthquakes including the 2011 great Tohoku-oki earthquake. In these tests, we are able to recover both the fault plane orientation and a coarse distributed slip model for each event. We are also able to determine the total moment released by the earthquake rupture as it evolves. Because our semi-analytical inversion methodology is very computationally efficient, the latency associated with estimating the source model is controlled by the duration of the rupture and the time needed for information to propagate to the receivers and not by the computational cost of the source modeling.

Lingsen Meng[1], Richard Allen[1], Jean-Paul Ampuero[2]
[1]Berkley Seismological Laboratoy
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Application of Seismic Array Processing to Earthquake Early Warning

Earthquake early warning (EEW) systems that issue warnings prior to the arrival of strong shaking are essential in mitigating earthquake hazard. Currently operating EEW systems work on point-source assumptions and are of limited effectiveness for large events, for which ignoring finite source effects results in magnitude underestimation. Here, we explore the concept of characterizing rupture dimensions in real time for EEW using small-aperture seismic arrays located near active faults. Back tracing array waveforms allows us to estimate the extent of the rupture front (as a proxy of the rupture size) and directivity in real-time, providing complementary EEW capabilities for M>7 earthquakes to existing EEW systems. We implement it in a simulated real-time environment and analyze the 2004 M6 Parkfield earthquake recordings by the UPSAR array and the 2010 M7.2 El-Mayor Cucapah earthquake recordings by strong motion sensors in San Diego. We find it important to correct for the bias in back-azimuth induced by dipping structures beneath the UPSAR array, based on data from smaller events. Our estimated rupture lengths are 30% shorter than those inferred from other studies, but still reasonable for EEW purpose. We attribute this difference to rupture directivity effects and the limited field of view of a single array. The accuracy of the approach may be improved with a network of arrays with overlapping fields of view. We demonstrate this by tracking the 2011 Tohoku earthquake rupture with two clusters of Hi-net stations in Kyushu and Northern Hokkaido. The obtained results are consistent with teleseismic back-projection results and yield reasonable estimates of rupture length and directivity. Compared to other proposed finite-fault EEW approaches, the array method is less affected by the coarseness of a GPS or seismic network and provides a high frequency characterization of the rupture which yields more suitable predictors of ground shaking for certain structures.

Session III: New Concepts in EEW
Thursday September 4^{th}, 2014

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Numerical Shake Prediction for Earthquake Early Warning: Data-assimilation, Real-time Shake-map, and Simulation of Wave Propagation

In many methods of the present Earthquake Early Warning (EEW) systems, hypocenter and magnitude are determined quickly and then strengths of ground motions are predicted. The M9.0 Tohoku earthquake, however, revealed some technical issues with the methods: under-prediction at large distance due to the large extent of the fault rupture, and over-prediction due to confusion of the system by multiple aftershocks occurred simultaneously. To address these issues, a new method is proposed for EEW, in which distribution of current ground motion is estimated precisely in real time (real-time Shake-map) applying data-assimilation technique, and then the future wavefield is predicted time-evolutionally using simulation of seismic wave propagation. This method is based on a simulation of physical process from the precisely estimated initial condition. This method, therefore, corresponds to 'numerical shake prediction', on the analogy to 'numerical weather prediction' in meteorology. Examples applying the proposed method to The 2011 Tohoku Earthquake (M9.0) and The 2004 Mid-Niigata Earthquake (M6.8) indicate that the proposed method gives precise and rapid prediction of ground motion in a real time manner.

Gokcan Karakus[1], Thomas Heaton[1]
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A Waveform Envelope-Based Reality Check Algorithm in Early Warning

Current earthquake early warning systems usually make magnitude and location predictions and send out a warning to the users based on those predictions. We describe an algorithm that assesses the validity of the predictions in real time. Our algorithm monitors the envelopes of horizontal and vertical acceleration, velocity, and displacement. We compare the observed envelopes with the ones predicted by Cua & Heaton's envelope ground motion prediction equations. We define a 'test function' as the logarithm of the ratio between observed and predicted envelopes at every second in real time. Once the envelopes deviate beyond an acceptable threshold, we declare a misfit. Kurtosis and skewness of a time evolving test function are used to rapidly identify a misfit. Real-time kurtosis and skewness calculations are also inputs to a Linear Discriminant Analysis that ultimately decides if there is an unacceptable level of misfit. This algorithm is designed to work at a wide range of amplitude scales; it works for both small and large events.

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Small and large earthquakes: evidence for a difference in rupture initiation

The main objective of our study is the investigation of the physical grounds of earthquake early warning to establish whether it is possible to determine the final earthquake size from the first few seconds of recorded signals, with a special focus on the real-time magnitude estimate of large events. For the real-time magnitude estimate two Early Warning (EW) parameters are usually measured within 3-4 seconds of the P-wave signal. These are the initial peak displacement (Pd) and the average period (τc). Here we propose an evolutionary approach for the magnitude estimate, based on the progressive expansion of the P-wave time window, until the expected arrival of the S-waves.

The methodology has already been applied to the 2011, Mw 9.0 Tohoku-Oki earthquake records and showed that a minimum time window of 25-30 seconds is indeed needed to get stable magnitude estimate for a magnitude M ~8.5 earthquake. We extended the analysis to a larger data set of Japanese earthquakes with magnitude between 4 and 9, using a high number of records per earthquake and spanning wide distance and azimuth ranges. We analyze the relationship between the time evolution of EW parameters and the earthquake magnitude itself with the purpose to understand the evolution of these parameters during the rupture process and to investigate a possible different scaling for both small and large events. The results of this analysis show that the initial evolution of peak displacement is different between small and large earthquakes, thus suggesting that the evolution of P-wave peak displacement holds information regarding the early stage of the rupture process and may be a proxy for the final size of the event. In particular, we show that the initial increase of P-wave motion is more rapid for small earthquakes that for larger ones, thus implying a longer and wider nucleation phase for large events. Our results indicate that earthquakes breaking in a region with a large critical slip displacement value have a larger probability to grow into a large size rupture than those originating in a region with a smaller critical displacement value.

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A P-wave, threshold-based method for Earthquake Early-Warning

A strategy for an on-site Early-warning system has been developed and tested using a database of Japanese earthquakes in the magnitude range between 4 and 9. The key element is the real-time, continuous measurement of peak amplitude parameters (Pd, Pv, and Pa) along the vertical component of the P-wave signal, starting from the P-picking time. Both Pd, Pv and Pa can be used as a proxy for the final peak ground velocity (PGV), which can be, in turn, related to the instrumental intensity at the recording site. The observed parameters are compared to threshold values, prior established through empirical regression analyses on a wide strong motion data bank. As soon as the threshold values are exceeded, a local alert level can be issued at the recording site, based on a decisional scheme. The performance of this methodology has been evaluated by defining successful, missed, and false alarms, and counting their percentage of occurrence on Japanese earthquake records. The overall performance turned out to be very good, with a very small percentage of false alarms and a small number of missed alerts. Here we propose a probabilistic approach to improve the performance of the system. The idea is the combination of Pd, Pv, and Pa to reduce the number of false alarms and to minimize the missing alerts. Different approaches to combine the three parameters have been tested, from the simple arithmetic mean to more complex combinations (such as weighted average, linear and non-linear combinations). A probabilistic approach for the alert issue has been also tested. Here we present preliminary results of the analysis, showing that the performance of the system improves when the combination of two (Pd, Pv) or even three (Pd, Pv, Pa) is used, with respect to the use of a single parameter. Finally we show an offline application of the method to a number of moderate size events occurred in Italy during the past decade and massively recorded by the Italian strong motion network.

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MyShake: Building a smartphone seismic network

We are exploring the possibility of building a new type of seismic network using smartphones. The accelerometers in smartphones can be used to record earthquakes, the GPS unit can give an accurate location, and the built-in communication unit allows transfer of data. In order to build this network, we developed an application for android phones and a back-end server to record the acceleration data in real time. These records can be sent back to a server in real time, and analyzed at the server. We evaluated the performance of the smartphone as a seismic recording instrument by comparing them with high quality accelerometer data while located on controlled shake tables for a variety of tests. We also explore the noise floor and sensitivity if smartphone accelerometers. We collect daily human activity data recorded by volunteers, and comparing that data to the shake table data, we developed algorithms to distinguish earthquakes from daily human activities on the smartphones. These all form the basis of setting up a new prototype smartphone seismic network in the near future. We expect that such networks will provide an important supplement to existing traditional networks for both scientific research and real-time applications including earthquake early warning.

Teron Moore[1], Benoit Pirenne[1], Andreas Resenberger[1]
[1]Ocean Networks Canada

Geohazard early warning at Ocean Networks Canada: the WARN project

Ocean Networks Canada (ONC) operates cabled ocean observatories (VENUS and NEPTUNE Canada) off the coast of British Columbia, as well as in the Arctic in Cambridge Bay, NU. Together those systems represent a new generation of coastal and deep ocean facility that supports research as well as operational oceanography. Most recently, ONC has received funds to exploit further the capabilities of its cable technology and of its Oceans 2.0 data management system to deliver on Smart Oceans BC: a integrated coastal information system that will provide early geohazard warning, navigation aid in the form of localized sea state indices, as well as marine mammal incident mitigation.

The Web-enabled Awareness Research Network (WARN), part of Oceans 2.0, enables the early detection of geo-hazards such as tsunamis and earthquakes. WARN implements fast event detection and correlation from the data streams of an arbitrary number of networked sensors distributed on land and offshore. Using the Common Alert Protocol, WARN delivers alerts to stakeholders interested in programming a reaction to the alerts. The alerts contain basic information that computer models can use to assess risks for populations and infrastructure. The models communicate their results to the authorities' warning systems with seconds to minutes to spare before an earthquake or tsunami hits. WARN can moreover feed simulated events to risk assessment and impact prediction models to enrich their scenarios database.

This presentation will focus more on the earthquake early warning capabilities of WARN and describe the sensors and their distribution, the P-Wave detection algorithms selected and finally the overall architecture of the system, tuned towards delivery of alerts.

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A Filter Bank Approach to Earthquake Early Warning

Earthquake Early Warning (EEW) is a race against time. The longer it takes to detect and characterize an ongoing event, the larger is the blind zone—the region where a warning arrives only after the most damaging ground motion has occurred. The problem is most acute during destructive medium size earthquakes, where damaging ground motion is confined to a small zone around the epicenter. An ideal EEW algorithm, which is fast enough to reliably provide relevant alerts for such scenario events, would have to exploit available real-time information in a more optimal way than what is currently done by existing algorithms. In this study we present a novel approach to EEW, which fully mines the broadband frequency content of incoming waveforms. We extend the Virtual Seismologist method of Cua and Heaton, 2007 to an evolutionary EEW algorithm that starts parameter estimations at the P-wave onset on the first station. We use a filter bank with minimum phase delay filters, which allows us to use frequency information from each frequency band at each triggered station at the earliest possible time. With an extensive dataset of near-field earthquake waveforms we demonstrate the potential of such a processing scheme to infer earthquake source parameters in real-time with high accuracy.

Poster Session
Thursday September 4th, 2014

#1

Sarah Minson[1], Benjamin Brooks[1], Craig Glennie[3], Jessica Murray[2], John Langbein[2], Susan Owen[4], Thomas Heaton[1], Robert Iannucci[5], Darren Hauser[3]
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[2]United States Geological Survey
[3]NCALM, University of Houston
[4]Jet Propulsion Laboratory
[5]Carnegie Mellon University, Silicon Valley

Crowd-Sourced Global Earthquake Early Warning

Although earthquake early warning (EEW) has shown great promise for reducing loss of life and property, it has only been implemented in a few regions due, in part, to the prohibitive cost of building the required dense seismic and geodetic networks. However, many cars and consumer smartphones, tablets, laptops, and similar devices contain low-cost versions of the same sensors used for earthquake monitoring. If a workable EEW system could be implemented based on either crowd-sourced observations from consumer devices or very inexpensive networks of instruments built from consumer-quality sensors, EEW coverage could potentially be expanded worldwide. Controlled tests of several accelerometers and global navigation satellite system (GNSS) receivers typically found in consumer devices show that, while they are significantly noisier than scientific-grade instruments, they are still accurate enough to capture displacements from moderate and large magnitude earthquakes. The accuracy of these sensors varies greatly depending on the type of data collected. Raw coarse acquisition (C/A) code GPS data are relatively noisy. These observations have a surface displacement detection threshold approaching ~1 m and would thus only be useful in large Mw 8+ earthquakes. However, incorporating either satellite-based differential corrections or using a Kalman filter to combine the raw GNSS data with low-cost acceleration data (such as from a smartphone) decreases the noise dramatically. These approaches allow detection thresholds as low as 5 cm, potentially enabling accurate warnings for earthquakes as small as Mw 6.5. Simulated performance tests show that, with data contributed from only a very small fraction of the population, a crowd-sourced EEW system would be capable of warning San Francisco and San Jose of a Mw 7 rupture on California's Hayward fault and could have accurately issued both earthquake and tsunami warnings for the 2011 Mw 9 Tohoku-oki, Japan earthquake.

#2

Beth Pratt-Sitaula[1,2], Robert Butler[3], Robert Lillie[4], Nancee Hunter[4], Bonnie Magura[5], Roger Groom[5], Chris Hedeen[6], Jenda Johnson[7], Shelley Olds[2], Donna Charlevoix[2]
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[2]UNAVCO
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[7]Lava Video Productions

Educator professional development as a component of earthquake and tsunami readiness and early warning systems

The Cascadia EarthScope Earthquake and Tsunami Education Program (CEETEP) is helping to mitigate the effects of these potential disasters through collaboration building and professional development for K-12 teachers, park and museum interpreters, and emergency management outreach educators in communities along the Oregon and Washington coast (2013-2016). Through this project nearly 150 coastal Cascadia educators will be introduced to critical knowledge about (among other things) earthquake monitoring and earthquake early warning systems. In collaboration last year with UNAVCO, CEETEP developed an animation explaining how GPS and seismic systems can work in concert to greatly enhance earthquake early warning systems for Cascadia and other subduction zone areas (https://www.youtube.com/watch?v=wx0L8ppwmm0&list=PLzmugeDoplFOot41MIBBZiLYBCB0M-p1P). When full-scale earthquake early warning systems are implemented, they will need to go hand in hand with extensive public education campaigns. Science and preparedness educators are key collaborators in this endeavor. The knowledge of how to run effective professional development programs for such educators will greatly enhance outreach efforts.

Initial results from CEETEP are very encouraging. The first two of six planned workshops were held in August and October of 2013 in northern coastal Oregon. Results show that participant content knowledge improved from 50% to 86% over the course of the workshop. Similarly, confidence in teaching about workshop topics increased from an average of 2.8 to 5.2 on a 6-point scale. Participant optimism about the efficacy and tractability of community-level planning also increased from 5.7 to 7.4 on a 9-point scale. Nearly 90% of participants continued to be active with the program through the time of the March 8, 2014 Share-a-thon and presented on a wide range of activities that they and their learners had undertaken related to earthquake and tsunami science and preparedness.

Tens of thousands of Oregon and Washington residents live within severe earthquake-shaking and tsunami-inundation zones, and millions of tourists visit state and federal parks in these same areas each year. CEETEP is strengthening readiness capabilities providing these community-based workshops that bring together all of these professionals to review the basic science of earthquakes and tsunamis, learn about EarthScope and other research efforts that monitor the dynamic Earth in the region, and develop ways to collectively engage students and the general public on the mitigation of coastal geologic hazards. This type of educator engagement will be critical to future implementation of early warning systems.

#**3**

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Visualizing Emergency Response Under Extreme Motions

This work visualizes emergency response under extreme motions, in the CAVE of the Visualization Laboratory at Marquette University. The visualization (a) displays ground motions (from the science community), (b) inputs these motions to structural models (from the engineering community) and illustrates the resulting responses, (c) translates structural responses to damage states of building elements, (d) creates a virtual room subjected to the perception associated with such earthquake shaking, and (e) introduces the human element of emergency response in this immersive environment. Building upon previous work on earthquake simulations, performance-based earthquake engineering (PBEE), building information modeling (BIM), and earthquake awareness, this study integrates elements of PBEE and BIM within the CAVE environment to provide visual information for decision making. Real-time or near real-time information via earthquake early warning (EEW) and structural health monitoring (SHM) further facilitates response within a limited time frame.

#4

Laurence Withers[1], Murray McGowan[1], Nathan Pearce[1], Horst Rademacher[1]
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A New Instrumental Approach to Earthquake Early Warning

Over the last decade digital data telemetry has led to vast improvements in the quality of the data collected by seismic networks and has substantially increased the reliability of such networks. Nowadays full waveform data with sampling rates of several hundred sps are routinely transmitted, received and processed in quasi real-time without major glitches. However, the ever growing number of Earthquake Early Warning (EEW) systems places completely new demands on seismic networks. In those systems time is of the essence and every second counts to make a warning successful. Here we present a new data acquisition system, which was designed with EEW in mind. It is capable of substantially reducing the time it takes for mission critical parameters to reach an EEW processing and alarm center.

Currently, most digitizers used in the remote stations of seismic networks are capable to sample the incoming analog waveform data at one or more sampling rates. Depending on the communications protocol, the digital data are then bundled into packets. Once a packet is ″full″, the digitizer will send it to the receiver, in most cases an acquisition computer in the data center. From there the data are transferred to processing computers, where the parameters critical for EEW are computed. These parameters include, but are not limited to, peak ground acceleration (PGA), peak ground velocity (PGV), spectral intensity (SI) as well as estimates of the amplitudes and periods of the wavetrain necessary to predict the magnitude of an event. Depending on the structure of the packets governed by the telemetry protocol, the design of the telemetry network, the way incoming data are handled within a data center and the algorithms used to calculate the EEW parameters, it can take up to tens of seconds between the first detection of an earthquake and the availability of these parameters to decision makers.

To substantially reduce this time we have developed a new data acquisition system, which can function as a classic data logger as well as an EEW warning unit. Using very streamlined data processing we have reduced the intrinsic latency within the units. In addition we calculate relevant EEW parameters continuously and directly at the remote station immediately after digitization of the anolgue signal. Besides using pre-programmed well established algorithms we have also made provisions, that user defined code can be remotely programmed onto the unit in order to optimize the calculation of the parameters needed for a specific EEW system. We are also using a new data streaming concept call ″gdi-link″, which further increases the speed with which EEW parameters are transmitted to a data center.

In our poster we will introduce the new data acquisition system and demonstrate its capabilities.

#5

Michael Jackson[1], Paul Passmore[1], Leonid Zimakov[1], Jared Raczka[1]
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Innovative, High Resolution, Integrated Real-time GNSS and Seismic Recorder for Earthquake Early Warning Systems

One of the fundamental requirements of an Earthquake Early Warning (EEW) system (and other mission critical applications) is to quickly detect and process the information from the strong motion event, i.e. event detection and location, magnitude estimation, and the peak ground motion estimation at the defined targeted site, thus allowing the civil protection authorities to provide pre-programmed emergency response actions: Slow down or stop rapid transit trains and high-speed trains; shutoff of gas pipelines and chemical facilities; stop elevators at the nearest floor; send alarms to hospitals, schools and other civil institutions.

An important question associated with the EEW system is: can we measure displacements in real time with sufficient accuracy? Scientific GNSS networks are moving towards a model of real-time data acquisition, storage integrity, and real-time position and displacement calculations. This new paradigm allows the integration of real-time, high-rate GNSS displacement information with acceleration and velocity data to create very high-rate displacement records. The mating of these two instruments allows the creation of a new, very high-rate (200 Hz) displacement observable that has the full-scale displacement characteristics of GNSS and high-precision dynamic motions of seismic technologies. It is envisioned that these new observables can be used for earthquake early warning studies and other mission critical applications, such as volcano monitoring, building, bridge and dam monitoring systems.

We developed an integrated GNSS/Accelerograph system, model 160- 09SG, which consists of REF TEK's fourth generation electronics, a 147-01 high-resolution ANSS Class A accelerometer, and a Trimble GNSS receiver and antenna capable of real time, on board RTX Precise Point Positioning with satellite clock and orbit corrections delivered to the receiver directly via L-band satellite or IP (Internet Protocol). The RTX technology leverages compressed orbit and clock corrections in real-time data from Trimble's global tracking network allowing the GNSS receiver to process data at the site thus eliminating the need to transmit raw data to a processing facility.

The test we conducted with the 160-09SG Recorder is focused on the characteristics of GNSS and seismic sensors in high dynamic environments, including historic earthquakes replicated on a shake table, over a range of displacements and frequencies. The main goals of the field tests are to explore the optimum integration of these sensors from a filtering perspective including simple harmonic impulses over varying frequencies and amplitudes and under the dynamic conditions of various earthquake scenarios.

#**6**

Henry Berglund[1], Frederick Blume[1]
[1]UNAVCO

Real-time GNSS Positioning, A High-Precision Kinematic Testing

The use of high-rate and real-time GNSS measurements for hazards monitoring and scientific applications is still in its infancy and there is great potential for its integration with strain, gravity and seismic measurements. Many commercial vendors and public agencies now offer real-time positioning services that provide sub-decimeter accuracy, with some approaching the sub-centimeter level. As GNSS network operators begin transitioning into offering real-time products, they will need to consider a number of factors including but not limited to: cost, position accuracy, solution latency, network topology and bandwidth. Periodic evaluation of real-time positioning systems will need to be conducted in order to optimize their integration into hazard-monitoring and multi-disciplinary networks. Controlled outdoor kinematic and static experiments provide a useful method for evaluating real-time systems, helping to identify system limitations, and characterize performance and reliability.

Recently released real-time precise point positioning (PPP) services such as Trimble′s RTX or Leica′s VADASE promise ~4 cm accuracy with 95% confidence. These positioning clients can run onboard a GNSS receiver where it obtains orbit and clock corrections via cellular network or satellite. Trimble′s corrections are generated using its proprietary global tracking network while Leica utilizes IGS real-time products. Trimble also offers a RTX server client that collects and processes data streams from multiple receivers, and commercial server-based packages such as RT-Net are also in use. GNSS network operators are currently evaluating both receiver- and server-based types of clients for hazard monitoring applications.

To characterize the kinematic performance of real-time positioning algorithms, UNAVCO has developed a portable low-cost antenna actuator. We have performed tests using controlled 1-d antenna motions and will present comparisons between these and other post-processed kinematic algorithms including GIPSY-OASIS and TRACK. In addition to kinematic testing, long-term static testing of Trimble’s RTX service is ongoing at UNAVCO and will be used to characterize the stability of the position time-series produced by RTX. A receiver-based RTX client was enabled at the Plate Boundary Observatory site P041 in June, 2013. Position estimate analysis for this and other PBO stations using the server-based RTX client will be presented for comparison.

#7

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An Alternative Funding Model for Earthquake Warning

If earthquake warning is to become a reality in California, the extant question of how to fund the system must be answered. Securing funding through state and federal appropriations processes is difficult and can take several years from the initial lobbying effort to the receipt of funds. Should this be accomplished, an even greater problem is the uncertainty of maintaining this funding over many years, during which an earthquake warning system may demonstrate limited benefits in the absence of a major earthquake. It is therefore prudent to seek alternative sources of funding to develop and maintain earthquake warning systems.

We propose that all vulnerable populations in California can be afforded the protection of earthquake warnings without burdening unduly those groups that perceive limited value in these warnings. There exists already within the state a subset of the population, primarily certain commercial enterprises and heavy industry, which derives extremely high value from earthquake warnings, and has the capacity and the willingness to pay for them commensurately. Some of the revenue from these user fees can be directed toward subsidy and grant programs for needy populations that, while they derive value from earthquake warnings, cannot afford to pay for them.

User fees can support the ongoing operation of the system, but there is also an alternative funding source for building the system out in the first place. Because commercial entities perceive sufficient value in earthquake warning, there is significant private capital investment interest in supporting the initial deployment. Furthermore, in a properly managed earthquake warning model, some revenue from user fees can also be directed toward maintenance of the research networks and even toward research programs to advance the state of earthquake warning science. We propose a strategy for accessing these alternative funding sources and harnessing private capital for the development and ongoing support of earthquake warning efforts, both in the private and academic sectors.

#**8**

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[4]Institut de Physique du Globe de Paris—Département de Seismologie
[5]University of Florida

Earthquake early warning systems with high-precision gravity strain meters

We investigate a new concept of Earthquake early warning system based on the detection of gravity perturbation during the fault rupture. We show that a high-precision gravity-strain meter designed to observe signals at 0.1 Hz and above can detect prompt gravity perturbations from fault rupture, i.e. within a few seconds after the onset of the rupture, and at distances of more than 100km to the hypocenter. The analysis is based on an original analytical time-dependent model of gravity perturbations from fault rupture, which is further validated via comparison with numerical simulations. We show that this new gravity-based warning system could reduce the size of the blind zone of the EEWS and increase warning times.

#9

Heon-Cheol Chi[1], Jung-Ho Park[1], In-Seub Lim[1], Yun Jeong Seong[1], Youngchai Kim[1]
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Discrimination of teleseismic-relevant false alarm by geometrical distribution of triggered stations

The real-time test result of Earthquake Early Warning (EEW) system in Korea on 2013 showed that most of false alarms were related to the teleseismic events. Even though the events were triggered at almost all stations, the partial association results in one local event or even three local events. This teleseismic-relevant false alarm is caused by logical co-relation during association procedure and the corresponding geometrical distribution of associated stations is crescent-shaped. Seismic stations are not deployed uniformly, so the expected bias ratio varies with evaluated epicentral location. This ratio is calculated in advance and stored into database, called as TrigDB, for the discrimination of teleseismic-origin false alarms. Together with conventional spatial density of triggered station, TrigDB was very efficient to reject teleseismic-relevant false alarms quickly without loss of local weak events.

#10

Shin Aoi,[1] Hiromitsu Nakamura[1], Takashi Kunugi, Wataru Suzuki[1], Hiroyuki Fujiwara[1]
[1]NIED, Japan

Realtime ground-motion monitoring system—Combination of 'Kyoshin monitor' and EEW

Time history of the ground motions of K-NET and KiK-net is basically recoded by an event triggering system and the data are sent to the DMC (Data Management Center at Tsukuba) by non-continuos telephone lines, which are connected only after the earthquake. On the other hand, several kinds of strong motion indexes for the KiK-net and some K-NET stations, such as peak values of acceleration, velocity and displacement, real-time seismic intensity, and response spectra are continuously calculated at stations and immediately transmitted through the continuous line to the DMC every second. By visualizing these observed strong-motion indexes, we have realized a realtime ground-motion monitoring system, which makes it possible to grasp the current ground motion of Japanese Islands. We call this system 'Kyoshin monitor', because 'Kyoshin' means strong motion in Japanese. We have combined the 'Kyoshin monitor' with EEW information. In this system, the seismic intensity distribution predicted from EEW is overlapped on the map with the observed one-second-interval indexes. This system also shows the epicenter and the circles indicating the arrival time of P- and S-wave estimated by the EEW on the map.

#11

Leonid Zimakov[1], Paul Passmore[1], Phillip Davidson[1]
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Acquisition Hardware for Rapid Seismic Event Notification System

The key requirements for Rapid Seismic Event Notification System are:
1. Quick delivery of digital data from seismic station to the acquisition and processing center;
2. Data integrity for real-time earthquake notification in order to provide warning prior to significant ground shaking

These two requirements are met in recently modified REF TEK 130 series seismic Recorder.
1. The modified data acquisition algorithm in the enhanced 130 Recorder allows output digital data every 0.2 sec. This is a significant reduction in the time interval required for real-time transmission of the currently available digitizers. The packet size varies depending on the sampling rate.
2. Modified REF TEK Protocol Daemon (RTPD) receives the digital data and acknowledges data received without error. It forwards this 'good' data to processing clients.

The 130 Recorder keeps tracks of what data has not been acknowledged and re-transmits the data giving priority to current data. The modified telemetry algorithm in the 130 Recorder provides a unique opportunity for customers to meet the critical requirements of the Earthquake Early Warning System to detect strong ground shaking at one or several locations and transmit the detected event for processing and notification ahead of the seismic energy affects the populated area.

Detailed acquisition algorithm and results of data transmission via different communication media are presented.

#**12**

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PRESTo2.0: An integrated on-site and regional early warning system for Italy

With more than 750 accelerometric stations installed over all the active seismic zones, target cities and strategic infrastructures, Italy has the potential for a nation-wide early warning system, although the communication network and data sharing must be expanded and improved. A significant number of these stations are nodes of the RAN (Italian Accelerometric Network) managed by the Italian national emergency management department (Dipartimento della Protezione Civile, DPC), whose data are used for emergency response services. In the framework of the European project REAKT (Strategies and tools for Real Time Earthquake RisK ReducTion), we worked at a feasibility study on the implementation of the EEW software PRESTo (PRobabilistic and Evolutionary early warning SysTem) for earthquake early warning on the Italian accelerometric network (RAN). Indeed, PRESTo is a highly configurable and easily portable platform for Earthquake Early Warning. The system processes the live accelerometric data streams from the nodes of a seismic network to promptly issue an alert message containing the estimates of location and magnitude of detected earthquakes while they are occurring, as well as ground shaking prediction at a regional scale.

PRESTo 2.0 is the second generation of the EWS which fully integrates the regional and the on-site components. In particular, the measured P-peak displacement and characteristic period (Pd, τc) provide an alert level at the site, while their measurements at several stations in the epicentral area can be used to identify the potential damage area in a few seconds after the event origin. Alarm messages containing this information can reach target sites before the arrival of destructive waves, enabling automatic safety procedures.

Here, we present the results for a feasibility and performance study of a nation-wide, Early Warning System in Italy based on the accelerometric array RAN and the PRESTo_2.0 EW system. This has been assessed by playing-back the strong motion records of Italian earthquakes with M larger than 5, occurred during the past decade. In addition the performance of the EWS has been investigated through a statistical approach, which has been implemented considering a nation-wide grid of synthetic sources located at the nodes used to derive the seismic hazard map in Italy. By considering a virtual testing period of 50 years, each grid's node is considered as a seismic source capable of generating a sequence of earthquakes with magnitude varying according the seismogenic zones properties to which it belongs. Then, the EW algorithm is run on the sequences of synthetic data created for each of the grid's points considering the present-day RAN configuration, and the network performance in terms of lead-time, errors in event location and magnitude determination has been therefore evaluated.

#**13**

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Earthquake Early Warning capabilities of regional seismic networks

The performance of an Earthquake Early Warning (EEW) system strongly depends both on the EEW algorithm and the available seismic network infrastructure. Assessing the performance of an EEW algorithm can therefore not be decoupled from the capability of the underlying seismic network. In this context we present an analysis of the EEW capabilities of six real-time regional networks running the Virtual Seismologist (VS) as implemented in the real-time monitoring software SeisComP3. The networks are the Swiss Seismological Service, the National Institute for Earth Physics in Romania, the Icelandic Meteorological Office, the University of Patras Seismological Laboratory in Greece, the Kandilli Observatory and Earthquake Research Institute in Turkey, and GeoNet in New Zealand. We analyzed the speed and accuracy of the first available VS magnitude and location estimates, with a special focus on the latencies produced by the network geometry, data telemetry and processing. This detailed description of time delays associated with major parts of the EEW system then allows us to create a model of expected alert times for any potential hypocenter within a region of interest.

Our results provide an overview of the EEW systems that allows identification of the weakest links in the alert chain and possibly plan network and algorithmic improvements to head towards an optimal and effective EEW system in each area. This is of particular importance in order to provide potential funding bodies with an accurate cost-benefit analysis.

We also demonstrate how the VS empirical magnitude relationship, derived on the basis of shallow Southern Californian seismicity (Cua, 2005), are applicable in widely different tectonic settings, including regions with deep earthquakes.

#**14**

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ElarmS: Rapid accurate alerts across California

The ElarmS methodology and algorithms are currently part of the ShakeAlert demonstration system in California, are being tested in the US Pacific Northwest and South Korea, and will be implemented for testing in Israel in the coming year. The methodology is a network-based approach to early warning in that it requires several seismic stations to detect P-waves before an alert is issued. Earthquakes are located, and the magnitude is estimated based on P-wave amplitude information. Both amplitude and frequency content are used to screen out triggers from teleseismic earthquakes. The alerts are distributed to test users across California who receive an estimate of the shaking intensity at their location and the time until that shaking will start.

We assess performance in California. Over the last year, ElarmS successfully alerted on all significant earthquakes (M>=4.5, 10 earthquakes) and generated no false alarms. This includes events in Los Angeles, Santa Rosa, offshore Eureka, and the southern Sierra. The magnitude estimates were within 0.5 magnitude units in all cases. The largest event was the M6.8 event offshore of Eureka. The initial ElarmS magnitude estimate was M6.3 with a location 7 km from the true (offshore) location. ElarmS also alerted on all of the larger (M>=4.5) aftershocks. The speed of the alert depends on the quality of the seismic network around the epicenter. For the M5.1 Los Angeles Le Habra event the alert was 4.2 sec after the origin time, this is typical for events in the Los Angeles region. For the Santa Rosa event the alert was 6.8 sec after the origin time, 10.8 for the southern Sierra event, and 25.7 for the (offshore) Eureka earthquake. Comparing the performance of ElarmS across the state for a wider range of magnitudes (M>=3) the effect of variable seismic network quality is very apparent. The performance is good to excellent in the San Francisco Bay and Los Angeles areas where station coverage is densest. In the greater San Francisco Bay Area of the 38 M>=3.0 events reported by the ANSS, 5 were missed (all in the Geysers Geothermal Area) and there were no false events. In the Los Angeles region, of the 35 M>=3.0 events, 4 were missed and there were 2 false events.

Ongoing development of earthquake warning capabilities by the UC Berkeley group includes an effort to reduce the event detection and alerting times further, development of a complementary GPS-based event characterization methodology for the largest earthquake called G-larmS (see Grapenthin, Johanson, Allen, Operational Real-time GPS enhanced Earthquake Early Warning), and the development of a smartphone based warning capability (see Kong, Allen, Schreier, MyShake: Building a smartphone seismic network).

#15

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Increasing Warning Times for the Onsite Earthquake Early Warning Algorithm

An important source of latency in earthquake early warning (EEW) algorithms is the time window required to estimate EEW parameters following a P wave detection. We investigate whether the detection time for the τc - Pd Onsite algorithm can be reduced by estimating EEW parameters on shorter waveform windows. The Onsite algorithm is currently one of three EEW algorithms implemented in ShakeAlert, the earthquake early warning system being developed for the west coast of the United States. Onsite uses the ground-motion period parameter (τc) and peak initial displacement parameter (Pd) to estimate the magnitude and expected ground-shaking of an ongoing earthquake. The current implementation of Onsite requires 3 sec of the P waveform data before issuing a magnitude estimate. We test the performance of Onsite for a range of window lengths between 0.5-5 s using a suite of waveform records of local earthquakes recorded in California. We will investigate using a time-dependent waveform window that provides very fast and increasingly more reliable estimates of τc and Pd for use in the Onsite algorithm.

#16

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Performance assessment of VS earthquake early warning algorithm in the Eastern Caribbean Region

The Virtual Seismologist (VS), as included in SeisComp3, is an earthquake early warning (EEW) algorithm that provides near-instantaneous estimates of earthquake magnitude immediately after SeisComp3 locations become available. In this study we have tested the software package SeisComP3 in the Eastern Caribbean Region, a region composed by small-size islands characterized by a complex seismotectonic setting with crustal, volcanic and large subduction earthquakes (MMaxObs=8.0 with focal depths up to 200 km).

The accuracy and robustness of location and magnitude estimates obtained with SeisComp3/VS have been assessed by offline playbacks of some earthquake scenarios. Broadband synthetic seismograms (0-10 Hz) have been computed from the identified earthquake scenarios using the broadband ground motion simulation method developed at the University of California at Santa Barbara, which uses an extended kinematic model of the seismic source with correlated random source parameters based on dynamic rupture models. The synthetic seismograms have been computed at seismic stations located in the Eastern Caribbean Islands as well as in North-Eastern Venezuela. The computed values of peak ground acceleration (PGA) have then been compared with Zhao et al. (2006)'s ground-motion prediction equation (GMPE), which turned out to be able to satisfactorily predict the intensity of ground shaking in the region. Thus, this GMPE has been used to compute in 'real-time' the PGA at selected critical infrastructures expected from near-instantaneous estimates of epicentre location and magnitude for a number of earthquake scenarios. Eleven infrastructures located in Trinidad & Tobago, Barbados and Antigua & Barbuda have been identified as the sensitive objectives of the study. They include hospitals, public utilities (e.g. electricity, water, telecommunications, sewerage), airports, seaports, an oil refinery and a natural gas industrial company. These infrastructures have been selected as a result of interviews and purposely-developed questionnaires distributed to the officials of a longer list of potential sensitive objectives spread throughout the Eastern Caribbean Islands in order to assess whether they could be interested in EEW information.

#**17**

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A seismogeodetic approach to earthquake early warning in Cascadia

We present an operational plan for implementing combined seismic and geodetic time series in an earthquake early warning system for Cascadia. The Cascadian subduction zone presents one of the greatest risks for a megaquake in the continental United States. Ascertaining the full magnitude and extent of large earthquakes is problematic for earthquake early warning systems due to instability when double integrating strong-motion records to ground displacement. This problem can be mitigated by augmenting earthquake early warning systems with real-time GPS data, allowing for the progression and spatial extent of large earthquakes to be better resolved due to GPS's ability to measure both dynamic and permanent displacements. The Pacific Northwest Seismic Network (PNSN) at the University of Washington is developing and testing an integrated seismogeodetic approach to earthquake early warning. The first implementation of the system is to provide warnings for Cascadia megathrust earthquakes. Regional GPS data are provided by the Pacific Northwest Geodetic Array (PANGA) at Central Washington University. Precise Point Positioning (PPP) solutions are sent from PANGA to the PNSN through JSON formatted streams and processed with a Python-based quality control (QC) module. The QC module also ingests accelerations from PNSN seismic stations through the Earthworm seismic acquisition and processing system for the purpose of detecting outliers and Kalman filtering when geodetic and seismic instruments are collocated. The QC module outputs time aligned and cleaned displacement waveforms to ActiveMQ, an XML-based messaging broker that is currently used in seismic early warning architecture. Earthquake characterization modules read displacement information from ActiveMQ when triggered by warnings from the Cascadian implementation of the ElarmS earthquake early warning algorithm. Peak ground displacement and P-wave scaling relationships from Kalman filtered waveforms provide initial magnitude estimates. Additional modules perform more complex source modeling such as centroid moment tensors and slip inversions that characterize the full size and extent of the event. We also test numerous synthetic earthquakes in the Pacific Northwest to operationally investigate the interweaving of the ShakeAlert seismic early warning methods and our seismogeodetic algorithms. We anticipate that our seismogeodetic methods will find wide applicability in other regions with sufficiently dense geodetic instrumentation.

#18

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Early status of earthquake early warning on the Island of Hawaii

Earthquakes, including large damaging events, are as central to the geologic evolution of the Island of Hawai`i as its more famous volcanic eruptions and lava flows. Increasing and expanding development of facilities and infrastructure on the island continues to increase exposure and risk associated with strong ground shaking resulting from future large local earthquakes. Damaging earthquakes over the last fifty years have shaken the most heavily developed areas and critical infrastructure of the island to levels corresponding to at least Modified Mercalli Intensity VII. Hawai`i's most recent damaging earthquakes, the M6.7 Kiholo Bay and M6.0 Mahukona earthquakes, struck within seven minutes of one another off of the northwest coast of the island in October 2006. These earthquakes resulted in damage at all thirteen of the telescopes near the summit of Mauna Kea that led to gaps in telescope operations ranging from days up to four months.

With the experiences of 2006 and Hawai`i's history of damaging earthquakes, we have begun a study to explore the feasibility of implementing earthquake early warning systems to provide advanced warnings to the Thirty Meter Telescope of imminent strong ground shaking from future local earthquakes. One of the major challenges for earthquake early warning in Hawai`i is the variety of earthquake sources, from shallow crustal faults to deeper mantle sources, including the basal décollement separating the volcanic pile from the ancient oceanic crust. Infrastructure on the Island of Hawai`i may only be tens of kilometers from these sources, allowing warning times of only 20 s or less. We will assess the capability of the current seismic network to produce alerts for major historic earthquakes, and we will provide recommendations for upgrades to improve performance.

#19

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Kinematic slip inversion and tsunami forecast with regional geophysical data

Rapid kinematic slip inversions immediately following earthquake rupture are traditionally limited to teleseismic data and delayed many hours after large events. Regional data such as strong motion is difficult to incorporate quickly into images of the source process because baseline offsets render the long period portion of the recording unreliable. Recently it's been demonstrated that high rate GPS can potentially produce rapid slip inversions for large events but is limited to very long periods. With an example of the 2011 M9 Tohoku-oki event we will demonstrate that the optimal on-the-fly combination of GPS and strong motion through a seismogeodetic Kalman filter produces reliable, broadband strong motion displacement and velocity waveforms that can be used for kinematic inversion. Through joint inversion of displacement and velocity waveforms we will show that it is possible to obtain a broadband image of the source. Furthermore, we will also show that it is possible to include offshore geophysical observables such as sea surface measurements of tsunami propagation from GPS buoys and ocean bottom pressure sensors into the kinematic inversion. These data better constrain the shallowest part of rupture. We will use the time-dependent deformation of bathymetry predicted from the inversion results as an initial condition for tsunami propagation and inundation modeling. Finally, we will demonstrate that it is possible to reproduce the inundation pattern along the coastline as observed from post-event surveys.

#20

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Acquisition, processing, and modeling of real-time high-rate GPS data at USGS in Menlo Park for improved Earthquake Early Warning

For most earthquakes of magnitude less than ~6, real-time GPS positions are too noisy to aid in Earthquake Early Warning (EEW), and currently implemented EEW algorithms based on seismic data alone should provide the most robust warnings. However, for larger events, which generate larger surface offsets, GPS data can provide a direct measurement of displacement that stays on scale and has sufficient precision. In such situations, the GPS observations may enable more accurate estimation of magnitude and rupture extent than seismic data.

The USGS Earthquake Science Center (ESC) in Menlo Park currently obtains real-time data from approximately 100 GPS stations in Northern California. These stations, which span the San Andreas fault system from the Mendocino Triple Junction to San Juan Bautista, are operated by USGS-Menlo Park, UC Berkeley, and UNAVCO. Current real-time GPS efforts for EEW at the ESC are concentrated in three areas: 1) development of software tools for monitoring and trouble-shooting data acquisition and data quality, 2) evaluating the latency and precision of position estimates obtained through real time processing, and 3) implementation of the BEFORES algorithm (Minson et al, 2014) for real-time finite fault inversion.

The ESC in Menlo Park operates eight GPS sites in the San Francisco Bay area; these sites transmit data using radio telemetry either directly or via links to the Northern California Seismic Network (NCSN) microwave telemetry system. Line-of-sight telemetry operated independently of commercial communication providers, while not always possible, avoids data outages caused by cellular network overload following a major earthquake. The remaining sites for which we process data use a variety of communications including radio links, frame relay, and cell modem. We conduct centralized real-time processing of raw, 1 Hz data in Menlo Park to obtain position estimates for each station using two software packages, TrackRT and RTNet. We have developed web-based software for monitoring a variety of state-of-health, data quality, and latency metrics as well as for real-time and static plotting of processed station positions.

For EEW applications, real-time GPS positions must have low latency and good short-term repeatability. We process data in two modes: differential (requiring a reference station) and Precise Point Positioning (PPP), which provides absolute positions. The differential solutions typically have latencies of less than 5 seconds with 99.5% of the horizontal position estimates having less than 10 mm RMS averaged over 1 minute; these are adequate for EEW applications. Generating PPP solutions requires satellite clock corrections, which are obtained in real time from an outside source. Our testing of real-time PPP demonstrates precision that is nearly identical to that of the differential solutions, but the PPP latencies are unacceptably high, often exceeding 50 seconds due to delay in delivery of the clock corrections. New technology allows computation of PPP solutions onboard GPS receivers in the field, and initial tests indicate that latencies sufficiently low for EEW are achievable.

The BEFORES algorithm (Minson et al., 2014) uses Bayesian analysis to determine the best-fitting coseismic fault orientation and slip distribution (from which moment and rupture extent are obtained) at each data epoch. BEFORES has been tested extensively on both simulated and real data (retrospectively) for a variety of earthquakes. We are now focusing on three aspects of its implementation: 1) receiving real-time earthquake locations from independent seismic EEW algorithms, 2) synchronization and quality control of real-time GPS position streams that are obtained through multiple TCP/IP connections and transmitted to BEFORES, and 3) optimizing the computation of elastic Green's functions. Completion of these tasks, along with additional tests using waveforms of simulated earthquakes superimposed on real data, will prepare the algorithm for implementation in the Decision Module and further testing as part of the broader EEW system.

#21

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Examination of the relative site amplification factor of OBS and their real-time correction: examples of Sagami Bay OBS, NIED

Hoshiba (2013, JGR) proposed a method for real-time prediction of ground motion based on real-time monitoring as the next-generation EEW. Real-time correction of site amplification is one of the important factors in this method. Ocean Bottom Seismograph (OBS) will provide valuable information to grasp ground motion propagation from ocean area. However, it is necessary to correct the site amplification factor of OBS for applying real-time monitoring method. In this study, we evaluate relative site amplification factor of Sagami Bay OBS (NIED, Eguchi et al., 1998, MGR), which is the closest OBS to land stations, and examine the effects of real-time correction to predict ground motion of land station from OBS.

The averaged spectral ratio of a station-pair from many events can be regarded as the relative site factor when the hypocentral distances to the station-pair are much larger than the distance of those stations. In this study, we use the waveform data from the Sagami Bay OBSs and adjacent land stations (K-NET and KiK-net, NIED), and select the dataset with the hypocentral distance which is greater than 100km. And, we compare Fourier spectra from the waveforms of S-wave portion (20s) on OBSs with those on adjacent land stations as the relative site factors. In examples of the relative site factors of OBSs to KNGH23 (KiK-net borehole station), the amplification factor of the horizontal component is greater than that of the vertical component for frequencies 1-10Hz. We conclude that the site effects of OBSs characterized by such a low velocity sediment layers causes those amplification factors.

In order to examine the effect of frequency-dependent relative site amplification factor, we compare the accuracies of predicted JMA seismic intensity using the spectral ratio with those using the average of JMA seismic intensity (frequency-independent factor). We design the causal digital filter (Hoshiba, 2013, BSSA) having similar amplitude property to relative site factor for the station pair. And we use the real-time processing of JMA seismic intensity (Kunugi et al., 2008, Zisin 2) to estimate seismic intensity from observed and predicted waveforms. Both of the techniques are applicable in real-time. We consider the RMS of residual between observed and predicted seismic intensities as the accuracy of site correction of each station pair. In the case of prediction of seismic intensities from OBSs data to land stations, the average RMS of frequency-dependent method are smaller than that of frequency-independent method. Similar results are also obtained at pairs of land station. These results indicate that the frequency-dependent site factor is crucial factor to predict seismic intensity from OBS data, and also show that OBS can be used as front stations in the method for prediction of ground motion based on the real-time monitoring.

Acknowledgments: Strong motion acceleration waveform data were obtained from K-NET and KiK-net of NIED.

#22

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Prototype of a Real-Time System for Earthquake Damage Estimation in Japan

J-RISQ, a real-time system for earthquake damage estimation, was developed provide information by combining amplification characteristic data for subsurface ground accumulated in the course of the development of the Japan Seismic Hazard Information Station (JSHIS), basic information on population and buildings, methods for predicting ground motion, methods for assessing building damage, and strong motion data observed by K-NET and KiK-net in real-time. J-RISQ estimates spatial ground motion distribution from seismic intensity information sent at different timing for observation stations, estimates population exposure to seismic intensity and building damage using estimated ground motion as input, and provides information to users via Web browser or email using Web GIS. J-RISQ estimation is based on intensity data obtained at different timing to ensure recency by updating results when it receives new data and updates results when it receives estimation results. J-RISQ provides and collects information using questionnaires from users on actual motion and damage situations. We have operated the system on trial from 2010 and estimated over 500 earthquakes in real-time. As a result, the system provides the first report 30 seconds after it receives intensity information at a certain level or larger, thus showing sufficient performance from the perspective of providing immediate information.

#23

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A general introduction of the earthquake early warning system in Wenchuan, China

Since Wenchuan earthquake in 2008, a dramatic progress on EEW has been made by the Institute of Care-life (ICL). The research on EEW by ICL covers sensing, ideas of installing the stations, analysis of the seismic waves for EEW, application of EEW messages for both students and some life-line projects, such as subways, nuclear power stations, and high speed trains. So far, over 3000 EEW alerts have been triggered, and thus tested, by actual earthquakes. Indeed, the EEW alert has triggered the evacuation of students in a school in 2013. Indeed, innovative work is done to suppress false alarms and missed alarms, to initiate the move of delivering EEW messages to the public, to push the application of EEW in China.

#**24**

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Next-Generation Model Averaging for Earthquake Early Warning

The earthquake early warning (EEW) system currently under development in the western U.S. is built on the principle of operating multiple independent EEW algorithms independently and then averaging these results into a single real-time estimate of earthquake source properties. This model averaging mechanism is referred to as the decision module. We will present a performance review of the currently operating EEW algorithms and decision module estimates. We then suggest potential improvements to the decision module to both improve performance with the existing EEW algorithms and to prepare for new EEW algorithms that are starting to come online. This next generation decision module would weight the contribution of different algorithms in different earthquake scenarios based on their performance in the past using Bayesian model class selection with a new likelihood model for combining the different algorithms' results.

#25

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Bayesian updating with ETAS in Earthquake Early Warning

We propose to adapt information on aftershock sequence in the earthquake early warning systems (EEWS) because earthquakes cluster in time and location. The potential occurrence times and locations of aftershocks can be predicted by the epidemic-type aftershock sequence model (ETAS). We show that by applying the prior information provided by ETAS in the Bayesian updating process of EEWS, we can significantly improve the epicenter estimation process, especially in the regions with sparsely populated stations. As an example, the epicenter estimation for the aftershock events from the 1992 M 7.2 Landers is performed using ETAS to illustrate the possible implementation on the current EEWS. As a result, we show that including the information provided by ETAS could significantly decrease the size of the blind zone of the EEWS and increase warning times. For instance, in an aftershock sequence most triggers at the closest stations will turn out to be real earthquake and warning can be issued after observations of only one or two stations.

#26

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A Note on Rapid Source Estimation

One of the big advantages of 1D modeling over 3D modeling is the separation of radiation patterns into vertical and azimuthal functions. Thus, the simple grid search performed by the Cut-And-Paste (CAP) from a library of Green's Functions is very fast. We show that a few P-waveforms at the nearest stations can prove effective in predicting the entire seismograms for small events, M < 6, for a number of different environments including basins.

Larger events can be recognized either by their extended P-wave train and/or their longer period CAP inversions. However, this approach does require specific libraries for various epicenters, which can be obtained by a combination of existing 3D models with local small event calibration for shallow structure. We demonstrate such a procedure on a few Imperial and Los Angeles basin events as well as the recent Fontana event near the San Andreas Fault.

#27

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Earthquake early warning response to the May 24, 2014 northern Aegean earthquake (**MW=6.9**)

Combining real time waveform data from Turkish seismic networks (KOERI, TUBITAK, AFAD, KOU) including the Greek stations provides an excellent coverage for precise and fast location of the earthquakes taking place in NW Turkey and Northern Aegean. The seedlink server module of widely known SeisComP3 data acquisition program allows such data exchange. The continuous on-line data from these stations is used to provide real time warning for emerging potentially disastrous earthquakes.

KOERI (Kandilli Observatory and Earthquake Research Institute) operates a seismic network in Marmara Sea region (NW Turkey) consisting of 40 broadband and 30 strong motion inland and OBS stations which has a good topology for regional EEW studies. Besides, 10 strong motion station EEW seismic network is deployed for mainly threshold based studies.

The Virtual Seismologist in SeisComP3 and the PRESTo regional EEW software are the two regional EEW algorithms that have been recently setup at KOERI data center to generate the EEW signal. Onsite EEW applications are underway for more than a decade. The early warning signal is communicated to the appropriate servo shut-down systems of the recipient facilities, that automatically decide proper action based on the alarm level.

An earthquake with Mw=6.9 occurred in the Northern Aegean on 24 May 2014 12:25 local time (UTC +3) approximately 30 km north-west of Gökçeada (Imbros) Island resulting in strong ground motion in the region. The earthquake has been felt in Marmara and Aegean regions of Turkey, primarily in Çanakkale, Balıkesir, Edirne and Istanbul. Strong ground shaking was widely felt across Turkey, Greece and Bulgaria including the major cities of Çanakkale, Thessaloniki, Edirne, Plovdiv, İzmir and İstanbul. However, with the exception of Çanakkale no damage has been reported in these cities. The maximum intensity of ground shaking felt on land was VI-VII on the EMS'98 scale. This level of shaking has the potential to cause light damage to buildings and moderate damage to vulnerable structures.

Owing to the dense seismic network the first estimation of the epicenter was done in 35 seconds after the origin time of the earthquake and the information was immediately released supplying about 50 seconds leading time for Istanbul located about 300 km away from the epicenter. Having received the EEW signal from KOERI, ELER (Earthquake Loss Estimation Routine) has been triggered for the Earthquake Hazard and Loss estimation. RT-ELER has automatically produced the intensity map of the event (**http://www.kandilli.info**). The first intensity estimation of the event was VII in the epicentral region, VI in the nearby islands and V, IV on the Greek and Turkish coasts.

#28

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Implementation of EEWS to Istanbul natural gas network

Istanbul Earthquake Early Warning and Rapid Response System (IEEWRRS) has been deployed in 2002 by Kandilli Observatory and Earthquake Research Institute (KOERI). Currently, the system has 10 on land and 5 sea bottom strong motion Earthquake Early Warning (EEW) stations and 110 strong motion Earthquake Rapid Response (ERR) stations with real-time data transmission capability. Although the system is under operation over 10 years, the interest of the industry to the system is very recently. In 2012, Istanbul Natural Gas Distribution Company (IGDAS) has started to a project of "IGDAS Earthquake Risk Reduction System" collaboration with KOERI. Even though the project had several stages and purposes, the main aim was to have a real-time risk reduction system for the whole natural gas network. In this study, the Earthquake Monitoring Network task of the project and its integration with the existing IEEWRRS will be clarified.

IGDAS network includes 1,383km steel pipeline and 13,000km PE pipeline. The network also contains 11 RMS stations, 693 district regulators, 487 valve rooms and 626,364 service boxes. The total number of user of IGDAS is over 4million.

The following sub-tasks have been carried out within the IGDAS Earthquake Risk Reduction System project, Earthquake Monitoring Network.

- Installation of 110 strong motion stations into the IGDAS district regulators,
- Development of a real-time strong motion data processing algorithm for the strong motion stations,
- Transmission of EEW information to IGDAS district regulators strong motion stations,
- Development of shut-off algorithm for the IGDAS district regulators,
- Development of the algorithm for the integrated near real-time ShakeMap for the IGDAS district regulators strong motion stations (110) and KOERI ERR stations (110).

The real-time implementation of the integrated system follows 4 stages as below:

1) Real-time ground motion data transmitted from 110 IGDAS and 110 KOERI stations to the IGDAS Scada Center and KOERI.
2) During an event EW information is sent from IGDAS Scada Center to the IGDAS stations.
3) Automatic Shut-Off will be applied at IGDAS district regulators, and calculated parameters will be sent from stations to the IGDAS Scada Center and KOERI.
4) Integrated damage maps will be prepared immediately after the earthquake event.

At present, the system is under operation and the improvement works are ongoing. It is believed that with the well introduction of this and similar systems to the community, awareness of the public and industrial sector to the Earthquake Early Warning Systems will increase.

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Attenuation model of peak P-wave displacement for California

False alarms due to larger magnitude estimates is one of the big problems in earthquake early warning systems. An algorithm is needed to track actual shaking while strong ground motion propagates. A ground motion attenuation model based on peak P-wave displacement may be helpful, however, this is insufficiently studied in literature. In this study, I developed two ground motion attenuation models which have a similar functional form to Boore et al, 2009 and Boatwright et al, 2003 using calibration dataset of Southern and Northern California earthquakes. Both models use initial magnitude and epicenteral distance from initial earthquake location of EEWS as inputs to calculate peak P-wave displacement at stations. Comparing regression equations to determine magnitude in California, both model statistically superior in mean, standard deviation of residuals and determination of coefficient. Finally, I gave an offline example how to identify false magnitude calculation and how proposed models can be implement to existing EEWS in California.

Applications of EEW
Friday September 5th, 2014

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Participatory decision making: From earthquake early warning to operational earthquake forecasting

The deployment of Earthquake Early Warning systems should involve the active participation of stakeholders sharing the seismic safety benefits, as well as the various costs. One of the advantages of this societal engagement is public education. There is more to earthquake preparedness than earthquake engineering. An EEW alarm in a hospital may allow time for delicate operations to be briefly suspended, and for infirm patients on their feet to sit down.

Many potential EEW actions, such as these, have low costs in the event of an occasional false alarm. The same holds for Operational Earthquake Forecasting (OEF) actions. Just as an EEW alarm does not have to shut down a critical installation, an OEF does not have to shut down a city. Earthquake preparedness should vary according to temporal changes in the ambient seismic hazard. During a time of elevated hazard, a wide range of low cost preparedness measures can be taken, with stakeholder participation, to mitigate earthquake casualty risk.

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Early insights into earthquake early warnings in the Pacific Northwest

A key lesson from prior research on hazard warnings is that people need actionable information on what to do, not just that there is a threat. With the seconds to minutes of lead time that earthquake early warnings may provide, accomplishing this will require setting the stage for action by working with communities and institutions to develop goals, procedures, and expectations. This talk characterizes initial phases of EEW development in the Pacific Northwest of the U.S. based on prior risk interpretation and action research and initial interviews with and surveys of Pacific Northwest Seismic Network leaders and affiliates. Research funded by U.S. NSF EAR-1331412

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Introduction of the present Earthquake Early Warning system for the Shinkansen

The bullet train in Japan (Shinkansen) has utilized Earthquake Early Warning (EEW) using P-wave information for over 20 years in order to halt the trains safely during earthquakes. Railway Technical Research Institute (RTRI) developed a first system, the Urgent Earthquake Detection and Alarm System (UrEDAS, Nakamura, 1988) which was introduced to the Shinkansen in 1992. Afterward, RTRI developed a new system for the Shinkansen (Ashiya, 2002) and replaced the UrEDAS with the new system from 2004 to 2006 (Yamamoto et al., 2011b, in this paper, we call this new system 'the present system'). Over the 200 seismic stations for the present system are currently installed in Japan. The number is still increasing due to the extensions of the Shinkansen routes.

The present system basically consists of four kinds of instruments (Track-side seismometer, Distance-track seismometer, Central server, and Monitoring PC); (1) The Track-side seismometers are installed along the rail tracks. This seismometer has two important roles. The one is to alarm to directly stop the Shinkansen by shutting off the power supply to the trains, in case that it is judged from the M-Δ method (Nakamura et al., 2005) that the railway structure of its area is expected to be damaged, or in case that the shaking level exceeds a threshold of seismic intensity. The other is to inform the Central server about the peak value of seismic intensities immediately after earthquakes in order to inspect the damage of the railway structure efficiently; (2) The Distance-track seismometers are installed at locations where are far from the railway, in order to detect the occurrence of earthquakes as rapid as possible. The analyzed information is transmitted to the Track-side seismometer via the Central server; (3) The Central server receives the information from the seismometers and transmits them to the other seismometers as needed. Furthermore, it transmits all of the information, including trouble of the instrument, to the Monitoring PC. The Central server and the seismometers are connected using the TCP/IP protocol; (4) The Monitoring PC compiles the information and displays them for Shinkansen operators.

Both the Track-side and Distance-track seismometers independently estimate earthquake parameters (epicenter location and magnitude) from using the B-Δ method (Odaka et al., 2003) and the Principal Component Analysis (Noda et al., 2012) within 1 second in the shortest. Each seismometer determines the epicenter location at first, and then estimates the magnitude from the epicentral distance and amplitude by using a pre-defined attenuation relation. It should be pointed out that the information of the earthquake parameter used in the present system is predicted on the single-station algorithm for faster warning. Recently, the present system has started utilizing the JMA (Japan Meteorological Agency)-EEW information (Hoshiba et al., 2008), in order to improve the redundancy of the system.

The present system has experienced some large earthquakes since its installation, including the 2011 great Tohoku earthquake. According to Yamamoto and Tomori (2013), it was confirmed that 27 operating Shinkansen trains were safely halted during the great Tohoku earthquake by the alarm information from the present system.

RTRI keeps on conducting practical approaches to improve the performance of the present system (e.g. Yamamoto et al., 2011a). We are now developing a next generation EEW system for the Shinkansen, which is equipped with some new techniques (e.g. C-Δ method, multi-station algorithm, etc).