ShakeAlert: Using early warnings for earthquakes along the US West Coast

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In 2016, the ShakeAlert earthquake early warning (EEW) system for the US West Coast progressed from demonstration to production prototype operations. This progress has been funded by the US Geological Survey and the Gordon & Betty Moore Foundation. Earthquake early warning (EEW) is the ability to detect an earthquake quickly and provide a few seconds of warning before destructive shaking starts. Alerts from an EEW system can improve resilience if their recipients have developed plans for responding and act on them. During the demonstration phase, beta-test users from critical industries and institutions in US West Coast states were recruited for the EEW system, to observe the alerts produced, think about actions their organization could take and provide feedback for improving the system. With the advent of the prototype production system, some users are developing and implementing actions - planned responses to an alert that would protect lives and reduce losses. We also continue to test and develop alert delivery mechanisms, procedures and products. Our most effective collaboration has been with the Bay Area Rapid Transit District (BART). Since 2012 the BART system has been using EEW information to automatically slow trains. BART receives alerts via the internet and feeds them into the train operating system. In both the 2014 South Napa (M6) earthquake and a M5 earthquake near The Geysers, CA, the BART operations center received EEW alerts from ShakeAlert and their automatic actions worked as planned. Most recently, PG&E, a northern California gas and electrical power company has begun a pilot project to explore and implement personal and automatic actions to ensure staff safety and improve resilience. Other pilot project participants include additional mass transit organizations and utilities, emergency management offices at various levels of government, school districts, pipeline operators, mass media organizations such as radio and television, and medical centers.

Keywords: Earthquake Early Warning, Seismology, earthquakes and society, rapid earthquake information

Real-Time Risk Reduction Through Early Warning, Earthquake and Volcano Monitoring in Southern California, USA

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More than 20 million people live in southern California, astride the Pacific and North America plate boundary. Caltech and USGS operate the Southern California Seismic Network (SCSN) to provide timely disaster mitigation in the form of early warning, event notification, ShakeMap, and other data products.

The earthquake early warning (EEW) project (ShakeAlert) analyzes SCSN data to identify the P-waves of earthquakes and issue warnings. The ShakeAlert prototype production system has been operating in a test mode for more than a year. Two point source algorithms report rapid earthquake magnitude and location that are received by UserDisplay and cell phone apps operated by pilot users. In the future, finite source algorithms will be added to the system to improve performance for the largest events.

Real-time processing provides accurate magnitudes and hypocenters within two minutes. Within 5 minutes, an accurate ShakeMap of the peak amplitudes of shaking provides a geographical view of potential damaging shaking for emergency responders. In the same time frame, a seismic moment tensor to identify the causative fault and evaluate tsunami hazards is available. In the case of unusual activity, seismologists provide near real-time situational awareness to warn civic authorities of increased hazards levels. We also operate seismic swarm detectors to identify possible onset of volcanic activity, alerting civic authorities.

The SCSN processes data real-time and routinely archives more than 15,000 earthquakes every year; in case of a large sequence, it may archive more than 60,000 events per year. The Southern California Earthquake Data Center (SCEDC) archives the data and facilitates the use of the SCSN data for scientific research, earthquake engineering, and public communication. All 80TB of data produced by the SCSN are freely distributed via the SCEDC; waveform data are made available online within minutes of the occurrence of an earthquake. The magnitude completeness level since 1981 is M1.8, on average, within the SCSN reporting region. The template-matching catalog that is being constructed for the SCSN will have a completeness level of approximately M0.0, as template matching detects 20 to 30 times more events than the regular catalog.

The performance goals of the SCSN are to deliver data for earthquake early warning (EEW) processing within 0.5 sec as well as a continuous stream of data for archiving and future processing. The SCSN records real-time seismic data from more than 500 stations. To capture data on scale, these stations have 24-bit digitizers with a variety of sensors, including strong motion, broadband, and short-period sensors. By using two sensors at each station, the SCSN has the capability of recording data on scale for a magnitude range from < M0 to > M8. To ensure timely data delivery and redundancy in data communications the SCSN uses cell modems, microwave, radio, and satellite links for data communications. We use various tools to monitor the state of health of stations, primarily to detect data latency, and sudden changes in data quality. To ensure data integrity the SCSN uses virtual private networking (VPN) to secure data delivery from remote stations. For data processing we use AQMS and earthworm software, and parametric data are stored in an Oracle database. Metadata are maintained in

the Station Information System Database (SIS), which is a relational database designed to store equipment inventory and produce metadata information in a variety of formats, including dataless SEED and station XML metadata information.

To take advantage of publicly available cloud computing facilities, we have already migrated some of our operations into the Amazon web services cloud (AWS). We plan to distribute products from the AWS and maintain a long-term archive in the AWS Glacier facility. This will significantly reduce the vulnerability of SCSN and SCEDC operations during future earthquakes in southern California.

Keywords: earthquake monitoring, earthquake early warning, seismicity & seismic network, data processing, security & cloud computing, ShakeMap, Reducing risk from natural hazards

An International Platform on Earthquake Early Warning Systems under the aegis of UNESCO

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The Sendai Framework for Disaster Risk Reduction 2015-2030 recognizes the need to "substantially increase the availability of, and access to, multi-hazard early warning systems and disaster risk information and assessments to the people by 2030" as one of its global targets (target "g"). While considerable progress has been made in recent decades, early warning systems continue to be less developed for geo-hazards and significant challenges remain in advancing the development of these systems for specific hazards, particularly for sudden onset hazards such as earthquakes. An earthquake early warning system helps in disseminating timely information about potentially catastrophic earthquake hazards to the public, emergency managers and the private sector to provide enough time to implement automatized emergency measures. In recent years, earthquake early warning systems have been developed independently in few countries. Provided that, in many instances, the development of such a system still requires further testing, increased density coverage in seismic observation stations, regional coordination, and further scientific understanding, there is a strong need to enhance the technical and operational capacities required for these systems and to further understand their implications for policy. In an effort to address this gap, in December 2015, UNESCO launched the "International Platform on Earthquake Early Warning Systems". The main objective of the Platform is to assess the current state of the art in the development and implementation of earthquake early warning systems worldwide, and to foster dialogue and international cooperation for capacity building around these systems. Here we will discuss the opportunities and challenges for the establishment of earthquake early warning systems around the world, as well as the aim, objectives and expected contributions of this newly established Platform.

Keywords: Earthquake, Early Warning, Geo-hazards

Testing a real-time GNSS-based earthquake and tsunami early warning system

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The goal of GNSS-based earthquake early warning (EEW) is to estimate magnitude, without saturation, and fault finiteness for the largest, most damaging earthquakes. This is especially important for tsunamigenic earthquakes, where slip on a finite fault can be used to guide local tsunami hazard warning in real-time. Because large events (M>6.5) are infrequent, geodetic algorithms are not regularly exercised and tested. It is therefore necessary to assess the performance of such algorithms using synthetic earthquakes and geodetically-recorded earthquakes worldwide. We will discuss the testing and performance of the Geodetic Alarm System (G-larmS) using both real and synthetic earthquake data. G-larmS has been in continuous operation since 2014 using event triggers from the ShakeAlert EEW system and real-time position time series from a triangulated network of GPS stations along the west coast of the United States. G-larmS uses high rate (1 Hz), low latency (<~5 s), accurate positioning (cm level) time series data from a regional GPS network and P-wave event triggers from the ShakeAlert EEW system. It extracts static offsets from real-time GPS time series upon S-wave arrival and performs a least squares inversion on these offsets to determine slip on a finite fault. During its 3 years of operation, G-larmS has only been tested in real-time by the 2014 M6 Napa, California earthquake. We therefore develop a catalog of 1300 Cascadia megathrust scenarios and 4000 individual ruptures on 25 faults in California built from realistic 3D geometries in order to test the system. Synthetic long-period 1Hz displacement waveforms were obtained from a new stochastic kinematic slip distribution generation method (Fakequakes). Waveforms are validated by direct comparison to peak P-wave displacement scaling laws, peak ground displacement GMPEs obtained from high-rate GPS observations of large events worldwide, and NGA-West2 spectral acceleration GMPEs at 10s period. In addition to the synthetic catalog, we also run real-time simulations for the recent M7.6 Melinka, Chile earthquake and the 2011 M9 Tohoku-Oki earthquake. We use the resulting finite fault sources to simulate tsunami hazards and demonstrate the usefulness of geodetic-algorithms for tsunami early warning.

Keywords: Earthquake Early Warning, Tsunami Early Warning

揺れの数値予報：経験的な地震動予測式に対応した距離減衰の導入
Numerical Shake Prediction for Earthquake Early Warning: Introduction of attenuation relation consistent with empirical GMPEs

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　Hoshiba and Aoki (2015) により提案された"揺れの数値予報"は，新しい地震即時予測の手法であり，従来の震源情報（震源位置とマグニチュード）の即時推定に基づく方法と異なり，震源情報を必要としない．それに代わって，データ同化手法を用いて地震波動場の現状を正確に把握し，その後に，波動伝播の物理（波動伝播シミュレーション）を用いて未来の波動場を予測するものである．これは，気象分野の天気の数値予報の考え方に近い．

　この揺れの数値予報は，近い未来（つまり，近傍の予測点）の予測に対しては，従来の震源情報に基づく方法よりも精度の高い予測を示したが，遠い未来（遠い予測点）では必ずしもそうではなかった．これは，Hoshiba and Aoki (2015)では，2次元での波動エネルギー($\tilde{}$振幅^2)の伝播のシミュレーションを用いたためである．波動エネルギーの距離減衰は，2次元では(距離)$^{-1}$に比例するが，3次元では(距離)$^{-2}$である．多くの経験的な地震動予測式（GMPE）の距離減衰は，この-1と-2乗の間にあることが多く，実際，現在，気象庁が現在緊急地震速報で用いているものは，-1.72乗である．なお，波動エネルギー伝播のシミュレーションを3次元で計算することはそれほど難しくはないものの，問題は，地震観測は地表（つまり，2次元）に限られていることであり，この場合，データ同化を行ったとしても地表付近にしか作用しない．

　この2次元と3次元の違いを克服し，(-1)と(-2)の間の任意の距離減衰関係を仮想的に実現するために，距離減衰に新たなパラメータを導入した．これにより，経験的なGMPEと等価な距離減衰関係を与えることが出来る．そして，遠い未来においても精度のよい予測が可能となる．

　2004年中越地震や2016年熊本地震などを例に取り，予測結果を示す．

キーワード：地震動予測、緊急地震速報、地震動予測式
Keywords: prediction of seimic ground motion, earthquake early warning, GMPE

Reducing risks from earthquakes: earthquake alert and site-effective action in industries

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Expectations for earthquake early warning (EEW) are somewhat replacing that for earthquake prediction in the past. Alerts of strong hits can be delivered from a big network system to areas that may be affected, but only seconds before arrivals. Nonetheless, people in public may overly expect a timely accurate warning, and criticize it when the actual ground motions turn to be different from EEW. There are many algorithm developments that attempt to resolve issues related to accurate prediction of ground-motions using big network operations with a station interval of ˜20 km in real-time. However, the spatial resolution covered by a big network is typically on the order of ˜10 km while the variation of actual ground motions can be in a much smaller scale. Our exploratory studies have shown short wavelength variation of ground motions recorded by a dense local network (˜1.5km) that also depends on the incident azimuths of seismic waves to sites. This situation evokes concerns about EEWs provided by a big network and issues of on-site monitoring systems. In high-tech industries buildings were generally built with a conventional earthquake-resistant design that meets a high standard building code and are supposed to have the strength to avoid structural collapses. In addition they are more concerned about how to protect the contents in the company buildings, expensive equipment and machines from strong ground shaking. Machines may be in operation with high speeds and/or high voltage current etc. that are vulnerable to strong shaking. It may take more than seconds to fully stop the operations after the switches are turned off with an alert. If the machines are damaged, they could leak hazardous chemicals. There are many other issues in addition to EEW to make earthquake safety in industries. I will discuss a case study of site-effective seismic safety configuration at a high-tech company.

Keywords: Earthquake Alert, Site Effective Action

A Rapid Earthquake Detection Algorithm for Earthquake Early Warning: A Bayesian Approach using Single Station Waveforms and Seismicity Forecast

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The utility of Earthquake Early Warning (EEW) relies on the robust and rapid classification of near-site earthquake source signals from noise and teleseismic arrivals. We propose a new method to achieve this, which uses the three-component acceleration and velocity waveform data and Epidemic-Type Aftershock Sequence (ETAS) seismicity forecast information in parallel, producing the posterior prediction by combining the predictions from the heterogeneous sources using a Bayesian probabilistic approach. We collected 2,446 three-component strong-motion records for training and testing. The rapid prediction is available as quickly as 0.5 s after the trigger at a single station, achieving a precision of 98% at the first prediction with the classification accuracy increasing with time. The leave-one-out validation method also demonstrates confidence of robust performance for future earthquake signal detections. Our new strategy has shown promising results and the implementation of this methodology could provide significantly faster and more reliable EEW warnings to regions near the earthquake's epicenter where the strongest shaking is observed.

Identification of nonlinear response and estimation of S-wave amplifications at ocean bottom seismograph sites in Sagami Bay area, Japan

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Deployments of large scale ocean bottom networks that comprise seismometers and pressure gauges (e.g., DONET in the Nankai Trough area, S-net in the Japan Trench area) are expected to contribute to earthquake and tsunami early warnings by prompt detection of earthquakes at subduction zones. The amplification effects of soft sediments at the ocean bottom seismograph (OBS) sites on the overestimation of the displacement-amplitude-based magnitudes have already been discussed (Hayashimoto and Hoshiba 2013; Nakamura et al. 2015). On the other hand, Hayashimoto et al. (2014) analyzed nonlinear site effects at three Off-Kushiro OBS sites which showed that recordings having PGA 100 cm/s^2 or greater display the nonlinear site response. Because the OBS sites are located on soft sediments, the sites may undergo large deformations during major earthquakes causing unpredictable site response. In this paper, we investigated nonlinear site effects and site amplifications at six K-NET OBS sites namely KNG201, KNG202, KNG203, KNG204, KNG205, and KNG206 located in Sagami Bay area of Japan. We employed the method of Wen et al. (2006) to identify the nonlinearity and the equation proposed by Noguchi and Sasatani (2011) to quantify the degree of nonlinearity. The methodologies use horizontal-to-vertical spectral ratios of S-wave recordings to identify and estimate the degree of nonlinearity (DNL). Our results showed that strong-motion recordings having horizontal vector PGA greater than 50 to 150 cm/s^2, depending on site, display clear signatures of nonlinear site response. For PGAs > 100 cm/s/s, peak frequencies of strong-motions are found to be shifted between about 20 % and 55% of the peak frequencies of weak-motions in the analyzed data ranges (PGA ˜ 450 cm/s/s). Similarly, the reduction of spectral ratios occurs by about 5 % to 70 % of the weak-motion peak spectral ratios. After identifying the thresholds for nonlinear response, we used the S-wave part of horizontal components having PGAs smaller than the thresholds to estimate amplifications at 0.2 Hz to 20 Hz by spectral inversion method. Our results showed amplification factors of about 10 to 50 at frequencies between 0.2 Hz and 10 Hz. In the case of strong shakings, the amplification factors may be substantially modified by nonlinear response and this effect should be investigated for real time application of the recorded motions. We describe in detail the data, methodology, and results of our study for identification of nonlinear site response at the OBS sites in (Dhakal et al., 2017).

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Keywords: Nonlinear site response, Ocean bottom seismograph, Site amplification

Automatic Shutdown System in Gas Regulators for Real-Time Seismic Risk Reduction of a Populated City: Bursa, TurkeyAutomatic Shutdown System in Gas Regulators for Real-Time Seismic Risk Reduction of a Populated City: Bursa, Turkey

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Bursa is a city located within a region of first grade earthquake risk, and it has occasionally suffered devastating and massive earthquakes for more than 2000 years. After a large disastrous earthquake in Izmit in 1999, many earth scientists are expecting the next large earthquake on the western extension of the Izmit earthquake rupture zone. Bursa is located south of the western end of the 1999 earthquake rupture and there are many active faults in and around Bursa. Bursa has now almost three million inhabitants, many heavy/industrial factories and historical monuments. Most of the people are using natural gas for heating, cooking and production in their buildings. Bursagaz is an inner-city gas distribution company and they are aware of the high seismic risk in Bursa city, so, they want to reduce causalities, fires and explosions in their natural gas district regulators and main pipelines. For these reasons, we have started to install accelerometers inside some of the main gas regulators and set up an algorithm for initiating an automatic gas shutdown system into their network for reducing the seismic risk in the city. We plan to install seismic instrumentation within a four-year-project and each year the seismic network will be growing by installing new accelerometers. We are also testing different algorithms to reduce false alarms aiming at a more secure and robust shutdown system. There are five different active fault lines in and around Bursa city having potential for creating M6.5 or larger earthquakes. Our first aim is to install accelerometers inside the inner city regulators located on and next to the main fault crossing highly populated regions of Bursa city center as a priority. By installing accelerometers very close to the active fault, we can detect PGAs more quickly and effectively. In the first phase of the project, we installed 15 accelerometers in the field and provided data collection and processing algorithm software in Bursagaz central building. All digital data are transferred by using GSM lines to this data center. In the second phase of the project, we installed another 10 accelerometers along the second active fault located in the Bursa city center. The project has not completed yet. During third and fourth project phases, the total number of accelerometers will be reach up to 50 within 2 years. At present, Bursagaz has 163 district regulators working in the city and all these regulators are connected to the company center with online SCADA communication system. Our main idea is to install one accelerometer at the central regulator and controlling at several district regulators in the surrounding to this instrument. Whenever the processing algorithm detects a certain level of acceleration due to a moderate or large earthquake, it will firstly observe PGA values for each single instrument and then calculate PGA values by using attenuation relationships for all regulators to finally compare these values with predefined threshold values. In case of exceedance of a threshold level, a shut-off signal will be send to those district regulators having higher PGA values than their threshold values. The installed algorithm will also calculate and estimate damage information in gas distribution infrastructure and create damage distribution maps very quickly and correctly. This information will be send to Bursagaz Technical and Emergency Response Teams that they could take all necessary actions to mitigate the disaster quickly and effectively. Our second aim is to use

Bursagaz seismic network as a core unit of Bursa City Earthquake Early Warning and Rapid Response System. The project team is going to cooperate with local authorities to integrate their system with the national network and increase the number of accelerometers for having a better station coverage for implementing an early warning and rapid response system for Bursa. To this aim, ArNET seismic network is integrated with Bursagaz network. Thus ArNET data of fifteen online seismic stations will be combined with Bursagaz data in the Bursagaz operation center. The SEISAN and SeisComp data acquisition and automatic location software are already installed and at present local earthquakes are monitored and located automatically. We are still working on the improvement of the system to reduce false alarms and time delays of information about location and magnitudes of earthquakes. Installation procedure of Bursagaz Real-Time Seismic Risk Reduction System, algorithms of automatic shutdown system, integration of seismic monitoring network, recorded events, system response, combination and integration with earthquake early warning and rapid response system will be discussed.

Keywords: seismic risk, early warning and rapid response, shutdown system

A new methodology for Earthquake Early Warning (EEW) by a high-dense seismic network

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Many of current EEW systems issue estimated intensity distribution maps according to empirical attenuation relationships which require information of source parameters and focal distance. These information are determined based on point source model which is not applicable for finite source model of large earthquakes. EEW is essential for the source area of inland earthquakes where heavy damages are expected. In most cases, EEW is issued lately in the source area which described as a "blind zone". Seismic networks, in case of Japan, are deployed for the determination of hypocenter at about 20-30 km interstation distance. That span delays the detection of P-wave arrivals by about 3-4 s. It should be suitable for the real time monitoring of seismic phenomenon that transfer on about 2.7 km/sec of the rupture, 3.5 km/sec of S waves and 6.0k m/sec of P-waves velocities. In this study, we present a new methodology for EEW which uses peak ground acceleration (PGA) estimated from P wave portion, taking advantage of the differential velocity (i,e., ~1.73) and the amplitude ratio (i,e., ~1/5) of P and S-waves. The efficiency of this method suggests the distribution of a high-dense seismic network of 5 km interstation distance, considering a span distance less than that of velocity of P-wave (i,e., 6 km/s). The slowness analysis of P waves tells information of the rupture starting point and its depth. Firstly, peak ground acceleration (PGA) on free surface is estimated from the maximum P-wave amplitude in one-second time step until the arrival of S-wave at the first detected station, and then adjusted to that on the engineering base (PGA_E) by eliminating the site effect. The S wave detection is performed by the amplitude comparison method of the synthesized amplitude of the two horizontal components and the vertical component. Secondly, we estimate PGA_E on far site from a relevant attenuation relationship and adjusted to PGA considering site amplification. Finally, we issue real-time intensity map in every second time step till the declining of PGA. The described method is useful to improve EEW system and also to perform disaster estimation immediately after the occurrence of large event, in order to avoid data extrapolation and the time consuming waveform inversion analysis.

Keywords: EEW, PGA, PGAE, P estimation, blind zone, real time intensity

強震動P,S 相のPGA比に対する距離減衰式
The Attenuation Relation for Ratio of S- PGA to P-PGA

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１．始めに

　緊急地震速報の利便性は、予測の早さと精度の高さにかかっている。その目的を達成するため気象庁から発信される緊急地震速報に加えるに、評価点に設置したいわゆるオンサイト地震計データを使う方法が提案・実施されている。我々はＰ波を使いＳ波の大きさを予測する方法を追及している。（藤縄ら、2003）。評価点に届いたＰ波の大きさを計測し、主要動（Ｓ波）の強さを,経験的係数（S/P比、α係数）を使い予測するものである。評価点でのα係数は、あらかじめ実測値により作成したデータベースを使うこととしているが、新たに任意の評価点での係数α求める距離減衰式を作成した。

２．方法：

　評価点での地震動の強さは、伝搬中の減衰と散乱、評価点の非線形効果を含んだ地盤効果などを勘案した距離減衰式によって記述される。放射効果は断層との相対関係で決まるが、従来平均値（Ｓ波の場合は、0.69）が使われてきた。ここでは、個々のサンプル地震の断層パラメータ（発震機構解、方位角、すべり角、射出角）を使う。任意の方向の地震波（P,S）の大きさは、点震源モデルでは解析的に表されており（Aki and Richards, 2002）、それを使う。係数αは、Ｓ波がゼロになる方向が特異点となるので、除外・平滑化を導入した。減衰効果は幾何減衰、粘性・散乱減衰の効果に分解され、多くの研究成果がある。ここでは川瀬・松尾（2004）の結果を初期値として採用する。サイト効果は線形近似の範囲で地盤増幅率の大きさで表現されるが、ここでは、防災科研の250ｍメッシュのDBを使う。非線形効果は、藤本・翠川（2006）の結果を使い地盤増幅率、最大速度から算出する。最大速度の算出は、司・翠川（1999）の関係式により求める。このように従来の研究成果で得られているパラメータを初期値とし、残差最小の条件で最適パラメータの第２近似を算出する。

　その値を使って理論値の第１近似を、地震区(i)の補正値ν_iを考慮した第2近似、地震区(i)・サイト(j)に対応する補正 ε_{ij}を施した第3近似を求める。

　サンプル地震として、首都圏直下型地震と想定されている東京湾北部地震、多摩直下地震、元禄型関東地震、立川断層地震、東海地震に限定し、推定されている破壊域で起きた地震を抽出した。現時点では、マグニチュード（Mw）が4程度、最大で6.5、最小が3.2,全地震データ数は54である。評価点に近いK-NET観測点でのデータをダウンロードし、P、S相の最大加速度、計測震度相当値、卓越周波数、パラメータ（α）及び、発震機構パラメータを使いα値を算出した。その結果を報告する。

３．結果

　求めたα係数は、東京湾北部地震(3.7±1.8)、元禄関東地震(3.5±1.8)で、デフォルト値（3.4）に近く、立川直下地震では6.0±1.7でデフォルト値より大きく、東海地震では5.1±1.1と大きめ、多摩直下地震では2.2±1.5と小さい結果となった。

　要因分析の結果、これまで距離減衰式で無視されてきた放射効果が主要ファクターであることが分かった。さらに、従来の散乱減衰として径方向（評価点と震央を結ぶ方向）の成分だけが考慮されてきたが、横方向の減衰効果を考慮しなければ、観測結果を説明できないことが判明した。その横方向の減衰係数QtをS波のQ値Qsの1/nと仮定した。Ｑｐに関しては、報告されている結果に相当のばらつきがあることから、Qsの1/mとし、n, mを観測と予測の残差が極小となるという条件で求めた。その結果、最適パラメータは、Qso=93, Qpo/Qso＝2/3, S,P波の幾何学的減衰の冪数n_s=n_p=0.69, Qt=Qs/5、という結果となった。

４．結論

　実用化に耐える精度（計測震度の数分の１程度）でα係数が予測できる距離減衰式を作成できた。任意の評価点でのα値は、震源パラメータ、発震機構、震源との相対位置の入った理論距離減衰式を使い、１次近似値α_1がもとまり、さらに破壊域に対する補正項ν、破壊域と評価点で決まる補正項εを考慮することで、それぞれ、第２近似値α_2, α_3がえられる。これにより、P波の強さから主要動の強さをより高い精度で推定できることが分かった。

キーワード：地震早期警報、強震動予測、P,S 相のPGA比、距離減衰式、放射影響、2次元減衰

Keywords: Earthquake early Warning, strong motion forecast , Ratio of S- PGA to P-PGA, Attenuation Relation, Radiation Relation, 2D dissipation

高周波地震波を用いた噴火規模の即時推定：噴火微動の震源振幅に基づく噴煙高度の予測式

Realtime estimation of eruption size using high-frequency seismic waves: empirical relations to predict eruption height from the seismic source amplitude of eruption tremor

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　噴火時に噴火規模を迅速に把握し、伝達することは、火山周辺の住民や自治体が適切な行動をとるために重要である。噴火規模は噴出量と噴煙高度に基づいて推定されるが、噴火中にこれらを即時的に推定することは難しい。一方、噴火に伴って発生する微動や爆発地震は常時観測ができるが、噴火現象との関係については定量的な理解が進んでいない。そこで我々はこれまでに、即時的な噴火規模の推定法を確立することを目的として、日本などの複数の火山を対象に、噴火微動・爆発地震と噴煙高度の関係を高周波地震波に着目して調べてきた。その結果、最大噴煙高度が、噴火微動では、震源での最大振幅の大きさに相当する量である震源振幅(A_s)のおよそ1/4乗に比例し、またこの関係が噴煙の上昇過程に基づいた噴煙高度モデルと類似していることを明らかにした。これらの結果は、A_sの値から噴煙高度を推定できる可能性を示唆している。そこで本研究では、A_sを用いた即自的な噴煙高度の推定の可能性について検討したので、その結果について報告する。

　即時的な噴煙高度予測を考えた場合、観測波形の各時刻の振幅からA_sを推定し、最大噴煙高度とA_sのべき乗関係を用いて噴煙高度を推定する必要がある。しかし、最大噴煙高度とA_sのべき乗関係は最大振幅に対してのみ成立するものであり、どの時刻の振幅に対しても常にこのべき乗関係が成立するか確認することが必要となる。そこで、噴煙高度とA_sを時系列で比較した場合の関係性を調べた。比較には、2011年1月26〜27日に霧島新燃岳で発生したサブプリニー式噴火の噴煙高度データを用いた。これは気象レーダにより10分間隔で測定されたもので、噴火活動がP1〜P3の3つのフェイズに分かれていた。一方、震源振幅についても同様に3つのフェイズに分け、5-10Hzのエンベロープ波形に対して10秒窓で平均振幅を求め、震源距離と非弾性減衰の効果を補正し、時系列化した震源振幅A_sを推定した。そして噴煙高度データと時間間隔を合わせるために、A_sについて10分毎の最大振幅を求め、10分間隔の時系列データとした。

　上記のデータを比較した結果、噴煙高度(H)が6㎞以上の場合には、噴煙高度とAsの関係が最大噴煙高度とA_sのべき乗関係に比較的合っていた。一方Hが6㎞以下の場合では、A_sとHの関係はべき乗関係では表せず、かつ最大噴煙高度とAsのべき乗関係から推定される値よりもHの値が小さくなることが分かった。さらにA_sがある値を下回ると、$H=0$となるような下限値が存在することが分かった。またこの結果を、トゥングラワ火山での最大噴煙高度とA_sの関係と合わせて整理したところ、A_sと噴煙高度の関係性が、A_sの値に応じて①A_sが下限値を下回り噴煙が上がらない場合、②対流圏下層まで上昇する場合、③対流圏上層に達する場合の3つに変化することが分かった。そしてこれらのHとA_sの関係を用いて推定した噴煙高度と、実際の噴煙高度の測定値を比較したところ、比較的良く推定値が測定値を再現できた。

　噴煙の上昇過程に基づくと、これらの噴煙高度とA_sの関係性について以下のように解釈できる。噴煙は火口で与えられた浮力と運動力を原動力として上昇するが、これらの原動力は高度とともに減衰していく。そのため噴煙がさらに上昇し続けるためには、乱流によって周囲の大気を取り込み膨張し、浮力を獲得することが必要となる。このとき大気の取り込み速度は、噴煙の上昇速度に比例する。上昇速度は噴出率によって決まるので、噴出率が大きい場合には、与えられた運動量の影響が減衰しても、噴煙は乱流によって十分な浮力を獲得し、対流圏上層または成層圏まで上昇することができると考えられる。このように浮力のみに依存して噴煙が上昇するとき、プリニー式噴火では、噴煙高度が噴出率の1/4乗に比例するということが理論的に知られてい

る。さらに噴出率がA_sと比例関係にあると考えると、噴煙高度がA_sの1/4乗に比例するべき乗関係が成立する。一方、噴出率が小さい場合には噴煙は効率的に乱流が起こせず、十分な浮力を獲得することができない。よって噴煙は運動量のみを原動力として上昇するため、噴煙高度とA_sの関係がべき乗関係で表せず、さらに噴煙上昇が対流圏下層で止まってしまうと考えられる。このような対流圏上層と下層で噴煙高度とA_sの関係が異なるという考察結果は、上記に示した解析から得られたHとA_sの関係と整合的である。よって、A_sの値に応じて3つの噴煙高度とA_sの式を使い分ければ、高周波地震波の解析から即時的な噴煙高度の推定が可能であると考えられる。

不均質構造を考慮した「揺れの数値予報」：2016年熊本地震を例に
Numerical Shake Prediction incorporating heterogeneous structure: a case for the 2016 Kumamoto Earthquake

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　地震動予測に影響を与えるファクターは、主に震源・伝播経路・観測点近傍の増幅特性(サイト特性)、の3つに大別することができる。これらの影響は、震源情報によらない地震動即時予測手法である「揺れの数値予報」(Hoshiba and Aoki, 2015)ではそれぞれ次のように取り入れられている。

　・サイト特性は、時系列フィルタ(例えばOgiso et al., 2016)によって補正

　・震源や伝播経路に由来する地震動の不均質な分布は、観測地震動をデータ同化で適切に内挿することによって、初期値に取り込める

　一方、Hoshiba and Aoki (2015)では、初期値から未来の波動場を予測する際に、一様な速度・減衰構造を用いている。予測を行う段階においても、不均質な速度・減衰構造を取り入れれば、地震動の予測精度の向上が見込まれる。本研究では、「揺れの数値予報」スキームにおいて、未来を予測する段階に不均質構造を取り込めるように拡張し、2016年熊本地震を対象に地震動即時予測シミュレーションを行い、不均質構造を取り入れることの効果を検討した。

　Hoshiba and Aoki (2015)では、波動伝播は輻射伝達理論に基づいて2次元空間で計算されている。ここで必要な構造パラメータは非弾性減衰・散乱減衰・速度構造の3つである。本研究では、非弾性減衰と散乱減衰はMultiple Time Lapse Window法 (MLTWA, Hoshiba, 1993)を用いて、Carcole and Sato (2010)に基づいて推定した。得られた減衰構造は、特に九州地方の活火山や活断層周辺で非弾性減衰や散乱減衰が強いという特徴があった。また、MLTWAを行った際の観測点ごとの見かけ速度を内挿することによって、暫定的な2次元速度分布を推定した。

　得られた速度及び減衰構造を用いて、2016年熊本地震の最大地震(Mj7.3)の地震動即時予測シミュレーションを行った。均質媒質を利用した場合に比べ、不均質な減衰・速度構造を考慮することによって震度予測の残差のRMSが10秒後予測の場合で約15%程度改善された。また、20秒後予測の場合には改善の度合いは10秒後予測の場合より高くなった。これらの結果は、「揺れの数値予報」スキームにおいて、より猶予時間の長い予測を行おうとした場合には不均質構造が重要な役割を果たすことが示唆される。

　不均質な非弾性及び散乱減衰構造の推定手法にはまだ改良の余地があるが、従来はテクトニクスと関連付けられて議論されてきたMLTWAによって推定された不均質構造は、地震動即時予測にとっても有用な先験情報となりうる。

波動場予測手法に基づく緊急地震速報のためのリアルタイムP相識別処理
Real-time P-phase discriminator for earthquake early warning based on wavefield-estimation methods

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　M8を超えるような巨大地震発生時の緊急地震速報の予測精度を向上させるために，揺れの数値予報(Hoshiba and Aoki, 2015)やPLUM法（小寺・他，2014）といった，震源推定を介さずに波動場から波動場を直接予測する手法が提案されている．しかしながら，これらの波動場予測手法は，S相による強震動に頼って予測しているのが現状であり，その前に得られるＰ相の情報を活用できていない．従って，Ｐ相の情報を直接予測に活用できれば，より予測の迅速性を高められると期待される．本発表では，V/Hを用いたごく単純なP相検出器を導入し，同検出器とPLUM法とを組み合わせた場合の性能について考察する．

1. Ｐ相の識別方法について
　地震波の自動フェーズ検知に関する先行研究の多くは，polarityを活用している（例えばRoss and Ben-Zion, 2014）．本研究では，リアルタイム計算の実装が容易な「V/H（加速度の上下動と水平動合成の比）」に着目し，P相の検出を試みる．地震の発生状況によらず「V/H」を連続的に計算し続け，「V/H≧1.0」を満たしたときに「P相を観測している」と判定する．この単純なP相検出器を，①東北地方太平洋沖地震，②熊本地震M6.5，③熊本地震M7.3の事例へ適用し，有効性を評価した．①～③のいずれにおいても，初動部分のP相は明瞭に見えることが分かった．また，①では破壊開始点近傍のSMGA (Asano and Iwata, 2012)に伴うP相をいくつかの観測点で検出できた（図a）．③では，大分県で発生したM5.7程度の誘発地震によるP相も確認できた（図b）．一方で，理論Ｓ波直後に「V/H≧1.0」を満たす観測点が存在したり，①における福島県沖付近のSMGAのP相が明瞭に検知できなかったりなど，改善の余地があることを示す現象もいくつか見られた．

2. PLUM法への適用について
　上記の「V/H」によるP相検出器を，PLUM法の予測計算に組み込むことを考える．Ｐ相部分の計測震度は，Ｓ相部分の計測震度よりも1.0程度小さいことが報告されている（Yamamoto et al., 2008）．この性質をもとにすると，PLUM法の予測計算は次のように修正できる：（１）（観測地点におけるＳ相の予測）まず，「V/H≧1.0」である観測点に対して，観測リアルタイム震度に「+1.0」を加える．（２）（PLUM法の通常計算）その後，予測対象点の半径30km以内の観測リアルタイム震度を集め，その最大値を予測値とする．このＰ相を活用したPLUM法を，①東北地方太平洋沖地震，②熊本地震M6.5，③熊本地震M7.3の事例へ適用した．警報第１報の発表タイミングに注目すると，①では５秒，②および③では１秒の迅速化が見込めることが分かった．また，最終的な震度の予測精度は，①～③いずれも大きな変化はなかった．これは，観測リアルタイム震度を嵩上げしたことによる過大評価の悪影響はそれほど顕著でないことを示している．
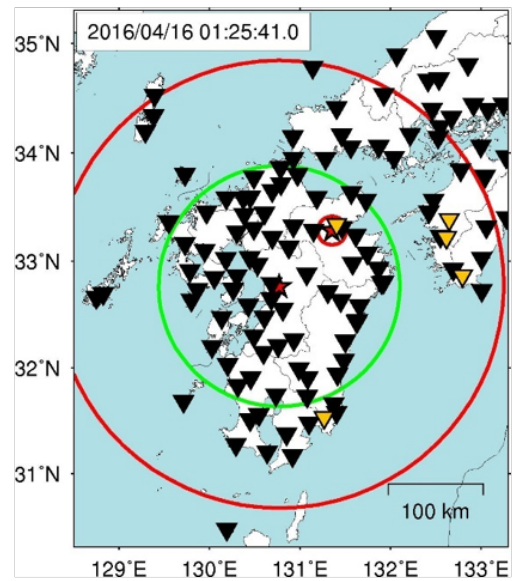
キーワード：緊急地震速報、P相識別、PLUM法、揺れの数値予報、SMGA、誘発地震
Keywords: earthquake early warning, P-phase discrimination, PLUM method, numerical shake prediction, SMGA, induced earthquake

(a) Tohoku-oki earthquake (Mw 9.0)

(b) Kumamoto earthquake (Mj 7.3)
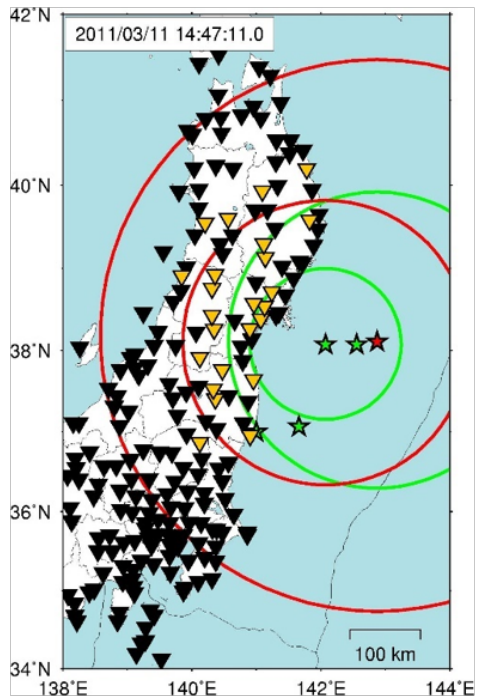
★ : initial rupture point (JMA hypocenter)
★ : SMGA (Asano and Iwata, 2012)
— : theoretical P wave
— : theoretical S wave
▽ : station where $V/H \geq 1.0$

★ : JMA hypocenter
— : theoretical P wave
— : theoretical S wave
▽ : station where $V/H \geq 1.0$

Accuracy of real-time GPS/Acoustic measurement using a slackly moored buoy

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Coseismic geodetic data near the source region of an offshore large earthquake is crucial for the real-time estimation of its magnitude and source mechanism. GNSS network enables us to obtain onshore geodetic data in real-time. In offshore area, seafloor pressure gauge network (e.g. DONET) provides offshore geodetic data in vertical component. However, offshore geodetic data in horizontal component cannot be obtained in real-time because a seafloor positioning by means of GPS/Acoustic (GPS/A) method is carried out only by a campaign style using a research vessel. For the real-time detection of seafloor crustal movement associated with a large earthquake in subduction zone, we have developed a real-time GPS/A seafloor positioning system using a moored buoy. The buoy is moored by a slack cable which is 1.5 times longer than the water depth against strong current. The seafloor positioning is performed at unpredictable position due to drifting of the buoy, which is generally apart from the array center. This is a unique drawback of buoy observation compared to ship observation because this results in significant systematic positioning error. Therefore, we assess the accuracy of the GPS/A positioning for this ill-conditioned survey.

We have tested the system over a year in Kumano-nada, Nankai Trough and obtained the data for seafloor positioning in real-time as follows. A single acoustic ranging, which consists of continuous 11 pings with 65 sec interval, was carried out once a week and optionally on-demand. This sequence totally amounts to 102 times of ranging during the trial. The buoy position during acoustic ranging was estimated using kinematic PPP technique. The data for seafloor positioning were transmitted to the land station via iridium Short Burst Data service. Due to the low bite rate of the satellite communication, the data were automatically pre-processed and compressed within the buoy. It takes about ten minutes to transmit the compressed data for seafloor positioning after acoustic ranging, while GPS raw data and acoustic waveform data were stored in the buoy logger for technical purpose.

Using the data transmitted in real-time, we can estimate the seafloor array position for each ping. We regard the two standard deviations of the estimated array positons as the accuracy of the GPS/A positioning, because actual movement during the trial is negligible compared to the error. The final accuracy is 0.9/0.7 m in EW/NS component, which is significantly larger than that using a vessel (~0.1 m). During the trial, the buoy is randomly located within a ~4 km radius around the array while a vessel can stay on the above the array center. Apart from the array center, the error propagation of the observation data (e.g. the buoy position, travel time) arises due to uncertainty of the array geometry. Then, we classified the accuracy into two types; the buoy is within or out of the array. The former is 0.3/0.3 m while the one of the latter is 1.0/0.8 m. The seafloor crustal deformation associated with offshore large earthquakes (~M8) on the above of source area is considered to amount to a few meters. For the detection of it, we should improve the accuracy when the buoy is out of the array. There is room for the improvement also by re-determining the array geometry more precisely.

キーワード：GPS/音響結合方式、係留ブイ
Keywords: GPS/Acoustic measurement, Moored buoy

電子基準点リアルタイム解析システム（REGARD）による断層モデル即時推定結果
GEONET real-time analysis system for rapid finite fault modeling

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　国土地理院は全国約1,300ヶ所に設置された電子基準点から構成されるGNSS連続観測網（GEONET）を運用している．GEONETでは，国土地理院（茨城県つくば市）の解析センターにおいて電子基準点で観測された1秒サンプリングのGNSS観測データをリアルタイムで収集し（一部を除く），解析を行い，その結果を観測データとともに一般に提供している．また，リアルタイムデータは，ネットワークRTKのための補正情報の生成や，リアルタイム解析技術の研究等のために利用されている．

　GEONETリアルタイム解析の重要性は平成23年（2011年）東北地方太平洋沖地震（Mw 9.0）の発生により大きく高まった．地震規模がM8を超えるような巨大地震において短周期地震計データから推定された地震規模は飽和することが指摘されている（Ozaki, 2011）．一方で，地震規模は地殻変動量に基づいて推定することもでき，短時間で地震時の地殻変動を得ることが可能なGNSS観測データのリアルタイム解析を用いた地震規模の即時推定技術について，現在大きな期待が寄せられている．

　国土地理院では東北大学との共同研究で，GNSS観測データのリアルタイム解析技術，地殻変動検知技術，矩形断層モデル及びすべり分布モデル推定技術等を組み合わせた地震規模即時推定システム（REGARD）を開発した．

　REGARDの運用を開始して以降，平成28年（2016年）4月に熊本地震が発生した．4月14日21時26分にM6.5の地震，15日0時03分にM6.4の地震，16日1時25分にM7.3の地震など複数の地震が時間的に近接して発生したが，REGARDの1秒単位のリアルタイム解析により時間分解能が向上したことから，それぞれの地震が地殻変動を伴っていたことが明らかとなった．また，4月16日のM7.3の地震では，REGARDによって電子基準点「長陽」で南西方向に約1m，「熊本」で東北東に約80cmの移動など，非常に大きな地殻変動が観測され，これは GEONETの定常解析の結果と比較して，水平成分は概ね±5cm程度の範囲で一致していた．REGARDの即時推定結果では，地震発生から58秒後に気象庁CMT解のMwと概ね整合するMw6.85が得られ、6分後には布田川断層帯に沿った領域に矩形断層モデルが求まった．

　また，2016年10月21日には鳥取県中部でM6.6の地震，11月22日には福島県沖でM7.3の地震が発生した．これらの地震においても地殻変動が観測され，断層モデルが推定されている．しかし，推定された断層モデルは鳥取県中部の場合はやや長大であり，福島県沖の場合は共役な断層であった．いずれの地震でも地殻変動量が小さく適切な断層モデルが推定できなかったものと思われる．

キーワード：GEONET、リアルタイムキネマティックGPS、リアルタイム
Keywords: GEONET, RTK-GPS, real-time

Near-field tsunami forecasting from offshore pressure data in association with the earthquake early warning
Near-field tsunami forecasting from offshore pressure data in association with the earthquake early warning

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Effective mitigation of tsunami disasters requires tsunami forecasts that are made in real time and the provision of timely evacuation warnings to affected communities. Tsushima et al. (2014) developed tFISH/RAPiD, which is the initial sea surface height distribution estimated from rapidly acquired GNSS data provides robust finite source size information that is incorporated into an offshore tsunami data inversion for reliable tsunami predictions along the near-field coast. In contrast, it is slightly difficult to obtain the reliable initial sea surface height distribution for M7 class earthquakes in the offshore region by RAPiD because of the difficulty of the accurate estimation of small coseismic displacement field compared with more large events.

Based on these backgrounds, we have developed an alternative algorithm that improves near-filed tsunami forecasting based on offshore tsunami data after an earthquake by incorporating earthquake early warning (EEW) data. Basic scheme is the same with the tFISH/RAPiD, we estimate the initial sea surface height distribution using the EEW data. We assumed that the single rectangular fault deduced from the scaling law between the earthquake magnitude and the fault dimension.

We retrospectively applied tFISH/EEW to the 2011 Sanriku-Oki earthquake (March 9, 2011, Mw 7.2) based on the actual ocean bottom pressure (OBP) record and EEW information. The predicted results immediately after the earthquake (˜2 to 3 min) the arrival times and wave heights of the first tsunami wave along the near-field coast could be predicted more accurately than the estimation based only on offshore tsunami data. After more time, the estimated initial sea surface distribution by the tFISH/EEW had continuously changed, and it was similar to that based on offshore tsunami data alone.

We will discuss more detail characteristic and its ability of the tFISH/EEW algorithm based on the various case studies.

キーワード：Earthquake Early Warning、Ocean bottom Pressure、Tsunami early warning
Keywords: Earthquake Early Warning, Ocean bottom Pressure, Tsunami early warning

沖合水圧記録の順解析による津波波源即時推定手法の検討
Rapid estimation of tsunami source information based on forward analysis of real-time data from dense offshore observation network

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　津波波源の情報は、観測データをインバージョン（逆解析）することで求める手法が一般的に用いられている。津波の即時予測においても、地震波もしくは津波波形のインバージョンにより求めた震源もしくは波源情報に基づいてフォワード計算を行ったりデータベースから適切なシナリオを選んだりすることで、沿岸の津波高や到達時間を予測している。事後の解析においては、津波波源の情報を求めるのに時間的制約がないため、例えばローカルミニマムに陥っていないか等の確認を手動である程度時間をかけて行うことが出来る。一方で、即時予測においては、沿岸に津波が到達するまでの短時間で逆解析を行う必要があり、誤った解を求めてしまう可能性が高くなる。そこで逆解析を用いずに、地震・津波観測監視システム（DONET）や日本海溝海底地震津波観測網（S-net）等の大規模な海域観測網で得られる沖合の水圧記録を順解析することで津波波源を即時に推定することを試みる。ひとつには、観測された津波の波高分布の重心位置（Tsunami Centroid Location; TCL）を求めることでおおよそ波源の位置を推定出来る可能性があることが分かっている（Yamamoto et al., 2016, EPS）。また、予め計算しておいた津波シナリオと観測データを比較し、相関係数を求めることで津波波源の位置及び形状を推定できる可能性があることが示されている（Yamamoto et al., 2016, GRL）。本発表では、模擬データを用いたこれらの手法の検討に加えて、実際に観測されたデータを用いた検討結果について報告する。

キーワード：即時推定、津波、S-net、DONET
Keywords: Rapid estimation, Tsunami, S-net, DONET