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Key Points:
- A new method to detect events for earthquake early warning is presented
- This approach will help to reduce false alerts
- This method does not require complex signal processing techniques

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Automatic earthquake confirmation for early warning system

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Abstract Earthquake early warning studies are shifting real-time seismology in earthquake science. They provide methods to rapidly assess earthquakes to predict damaging ground shaking. Preventing false alarms from these systems is key. Here we developed a simple, robust algorithm, Authorizing GRound shaking for Earthquake Early warning Systems (AGREEs), to reduce falsely issued alarms. This is a network threshold-based algorithm, which differs from existing approaches based on apparent velocity of *P* and *S* waves. AGREEs is designed to function as an external module to support existing earthquake early warning systems (EEWSs) and filters out the false events, by evaluating actual shaking near the epicenter. Our retrospective analyses of the 2009 L'Aquila and 2012 Emilia earthquakes show that AGREEs could help an EEWS by confirming the epicentral intensity. Furthermore, AGREEs is able to effectively identify three false events due to a storm, a teleseismic earthquake, and broken sensors in Irpinia Seismic Network, Italy.

1. Introduction

Earthquake early warning systems (EEWSs) are shifting earthquake science toward real-time event detection and data processing [*Kuyuk and Allen*, 2013a, 2013b; *Kuyuk et al.*, 2014; *Satriano et al.*, 2010]. These systems are minimizing the time needed to calculate source parameters of earthquakes (essentially, location, and magnitude) to within a few seconds of their occurrence. While the EW methodologies are becoming more accurate in terms of real-time source characterization, an important challenge remains minimization of false alarms [*Böse et al.*, 2013], which have a negative economic impact and generate the so called "cry-wolf syndrome" within the community.

EEWSs are generally conceived as network-based (regional) or as single-station-based (on-site) methodologies. A *P* wave, network-based EEWS consists of a seismic network located near active faults, while target sites to be alerted are far away from it. The early portion of recorded *P* wave signals is used to estimate the relevant source parameters (event location and magnitude) and to predict the expected ground shaking (peak ground velocity and peak ground acceleration, PGA) at the target sites by using ground motion prediction equations. The *P* wave, on-site approach, instead, consists of a single sensor located nearby the target structure to be alerted. Here the *P* wave is directly used to predict the ensuing peak ground motion at the same site, possibly bypassing the estimation of earthquake location and magnitude.

There are essentially two main attempts to increase the reliability of alert declaration in network-based EEWS: (i) increasing the number of stations required for the warning declaration and (ii) increasing the ground motion thresholds to be overcome prior to declaring an event. Both strategies may result in decreasing the issuance of false warnings; however, using these strategies, the available lead time (e.g., the time available for security actions, before the arrival of strong ground shaking waves) is reduced, with an intrinsic trade-off between the number of false alarms and those of correct warnings. Most of the network-based approaches require a minimum of four triggered stations for the warning confirmation. They all rely on accurate *P* wave detection at stations and association algorithms, which automatically measure the *P* wave arrival times and convert them into the earthquake location. Incorrect and imprecise detection may cause false alarms or large uncertainties in source parameters.

More sophisticated algorithms to deal with false alarms have been developed and tested. The concept of "apparent velocity," for example, is generally used in network-based approaches to discriminate false

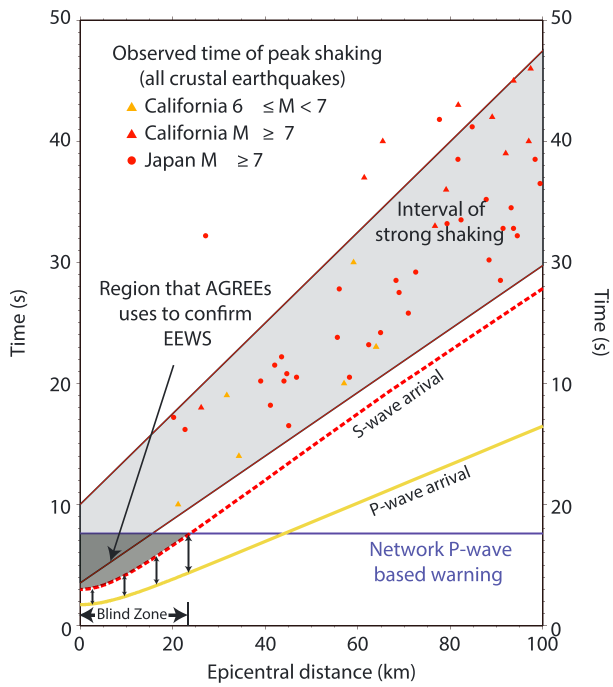

Figure 1. Time-distance plot illustrating the relative timing of seismic arrivals and warnings. The *P* wave and *S* wave arrival times are plotted as a function of epicentral distance for an earthquake with a hypocenter at 10 km depth. The light gray shaded region shows the interval of strong shaking based on observations from crustal earthquakes with depths of 21 km or less. The time of peak ground shaking is calculated for all available stations in nine $M > 6$ earthquakes from Japan and California. The blue horizontal line at 7.6 s is the warning of regional EEWS (after the origin time). It assumes that *P* wave front reaches 32 km (at 5.6 s) and that 2 s of *P* wave is required to estimate magnitude. This means that the blind zone (an area where *S* wave and/or strong shaking has already reached) is ~23 km from the epicenter at this time. AGREEs uses the available strong shaking observed within the blind zone (dark gray region) to confirm alerts before they are issued. (Figure modified from *Allen* [2011]).

events among real earthquakes. With the existing filters, false alarms are definitively reduced, but we need alternative approaches in order to decrease further.

In this study we developed an algorithm called Authorizing GRound shaking for Earthquake Early warning Systems (AGREEs) that is a discriminator specifically designed for EEWS. AGREEs could be integrated into existing EEW platforms to confirm correct alerts and prevent the issuance of false warnings. AGREEs is a straightforward algorithm that couples the real-time earthquake information provided by the EEWS platform with the real-time measurement of the impending ground motion.

2. Methodology

AGREEs is designed to support existing EEWSs, although it is not a *P* or *S* wave-based algorithm. Instead, the ground motion is continuously monitored but without discrimination between different phases. It simply uses observed amplitude of the ground motion to calculate intensities at a station. It then converts station intensities to the epicentral intensity of an earthquake. It is specifically conceived to support a network-based approach and, in its actual configuration, cannot be applied to a single-station methodology. AGREEs is based on a straightforward, efficient algorithm to confirm the alert delivered by an EEW platform in case of a real earthquake and reduce (or even eliminate) the incidence of false alarms.

Most EEWSs use *P* wave information to estimate location and magnitude of an earthquake. Some *S* wave information is also often available within a few seconds of the earthquake origin time at very close stations and could be used to better constrain the source parameters [*Lancieri and Zollo*, 2008]. However, as the real-time identification of the *S* phase is difficult to implement in real-time automatic algorithms, *S* waves are seldom used in EEW estimations.

The light gray area in Figure 1 shows the interval time of strong shaking reaching any station in the network. Apparent velocities of *P* wave and *S* wave are shown in yellow and red, respectively. Due to telemetry and processing delays and because portions of the *P* wave are required for the source parameter computation, EEWSs usually have a blind zone around the epicenter where the *S* wave arrives ahead of or coincident with the warning issuance. AGREEs exploits the strong shaking already felt within the blind zone to confirm network *P* wave-based warnings (dark gray shaded area).

In order to proceed, AGREEs requires the earthquake location as input and we assume here that this is correctly provided by the existing EEW platform, through the first *P* wave arrival times (Figure 2). Once the earthquake location is released, AGREEs measures the instantaneous peak acceleration value of ground motion and calculates the associated intensity at stations around the epicenter, according to the conversion table of *Wald et al.* [1999] (Figure 3). The acceleration is computed along the ground motion vector and is updated

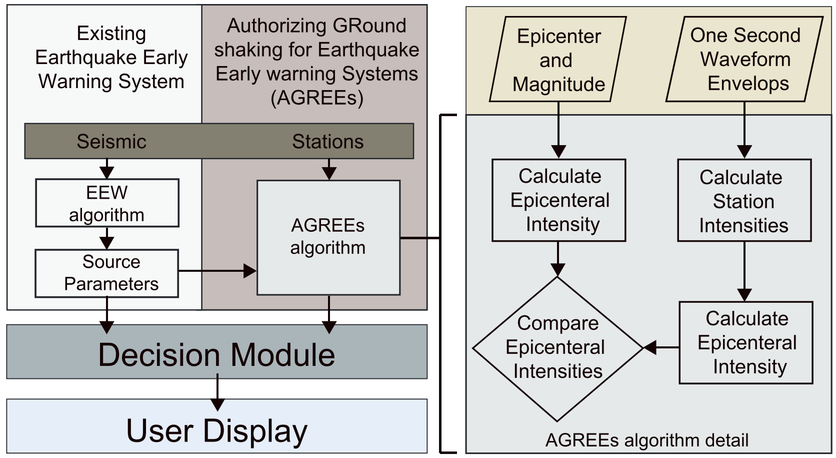

Figure 2. Flow chart of AGREEs that can be cooperated with existing EEWS. AGREEs requires the earthquake source parameters and station waveforms as input. AGREEs calculates the associated intensity at stations around the epicenter and averages the intensities. The average value of intensity is compared with existing EEWS in order to check whether the forecasted peak ground motion through the magnitude and location of the earthquake is appropriate or not. Based on the deviation between the expected and the observed peak ground acceleration, this information is fed back to the decision module of EEWS in order to confirm or cancel the warning.

every second so that continuously refined intensity estimates are delivered. AGREEs then averages the intensities at the closest three, five, and seven stations and creates three concentric circles whose radii correspond to distance of the third, fifth, and seventh closest station, respectively. The user interface of AGREEs then colors each circle according to the color-coded intensity plot shown in Figure 3. These three circles and variable numbers of stations act as filters on top of the regular EEWS and work separately in case of failure of any of them. The average value of intensity is updated at each second and is fed back to EEWS in order to check whether the forecasted peak ground motion through the magnitude and location of the earthquake is appropriate or not. AGREEs compares the expected and the observed peak ground acceleration and feeds this information back to the EEWS in order to confirm or cancel the warning.

To validate the proposed approach, we tested the algorithm in different situations and compared the results with the performance of the PRESTo EEW platform. PRESTo is a free and open source software platform for earthquake early warning [*Satriano et al.,* 2010] (http://www.prestoews.org) that was developed at the University of Naples and implements both a regional and an on-site method. PRESTo continuously processes the live streams of three-component acceleration data from the stations of the Irpinia Seismic

Perceived Shaking	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
Potential Damage	None	None	None	Very Light	Light	Moderate	Moderate / Heavy	Heavy	Very heavy
Peak Acc. (% g)	<0.17	0.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
Peak Acc. (cm/s^2)	<2	2-14	14-38	38-90	90-177	177-334	334-638	638-1216	1216
Instrumental Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Attributed Colors									

Figure 3. Example of threshold levels at stations. Stations are flagged by exceedance of predefined thresholds. Threshold values vary and can be chosen according to application or device.

Network (ISNet), in Southern Italy, deployed in the seismogenic area of the $M_s = 6.9$, 23 November 1980 event. The real-time experimentation of PRESTo started back in 2009, producing a bulletin of more than a hundred low-magnitude events (http://isnet.fisica.unina.it). The performance of the regional approach to EEW implemented in PRESTo was evaluated by comparing the real magnitude and origin time of each event from the manually revised ISNet Bulletin with respect to the final estimates obtained in real time by PRESTo [*Zollo et al.*, 2014]. Most of the earthquakes are correctly declared, and a small number of missed alarms were caused by communication problems among stations. However, a relatively large percentage of false alarms have been declared by PRESTo (about one fifth of the analyzed events) and are essentially associated with storms (which in case of adverse weather conditions may be incorrectly declared as seismic events) and with relatively close teleseismic events (which are incorrectly declared as local events since the hypocentral searching is restricted to the region covered by the location grid encompassing ISNet) [*Zollo et al.*, 2013].

3. Testing AGREEs

Here we tested two real earthquakes, the 2009 M_w 6.3 L'Aquila and the 2012 M_w 5.9 Emilia earthquake. We also tested three false events recorded by ISNet network. The first one is a false alert event triggered by a distant earthquake (an earthquake in Greece, approximately 600 km from the center of ISNet network). The second is a false event generated by a broken sensor and noise at close stations. The last one is a false event declared by PRESTo due to a storm.

3.1. Application 1: L'Aquila Earthquake

We simulated the 2009 M_w 6.3 L'Aquila earthquake offline using 19 stations from the RAN (National Accelerometric Network) network. This was a favorable test case for AGREEs, with very dense station coverage around the epicenter. Two stations are within 2 km from the epicenter, and another four stations are within 4 km. The earthquake data were processed by simulating real-time data streaming of records through PRESTo and AGREEs.

The earthquake was simulated in PRESTo by playing back the available three-component accelerograms. In this simulation, we neglect the telemetry latencies to understand the response of the system. The first estimate of location and magnitude was available 7.0 s after the actual origin time, which is just 4.5 s after the first *P* wave arrival at station AQU. The very first magnitude estimate is affected by a large uncertainty as it basically relies on a single station: GSA. After just 1 s from the first alarm, a good estimate of the source parameters was available; i.e., it is in good agreement with the actual values and affected by a small uncertainty. From that instant onward, the estimates converge to the final values, with errors of the order of 1 km for epicenter and depth and 0.1 for magnitude. Figure 4a shows normalized waveforms for the closest seven stations. Gray shaded areas indicate the ground motion before the *P* wave-based PRESTo alarm, which is given 7 s after the origin time.

At the time of the first alert, AGREEs creates three circles and calculates the intensities in each disk (Figure 4b). An epicentral intensity of 8 is computed by AGREEs; intensities of 7 and 6 are determined for the outer circles. In this case both PRESTo and AGREEs produced exactly the same intensity information at the epicenter at the time of the alert. Thus, AGREEs confirmed the (accurate) PRESTo alert.

3.2. Application 2: Emilia Earthquake

As a second case study, we selected the M_w 5.9, 2012, Emilia earthquake, which was the second largest event in Italy in the last decade. The near-field station distribution is rather sparse compared to L'Aquila. The closest station is 13 km away and there are no other stations within 30 km of the epicenter. For the simulation, we used the seven closest stations. Their normalized waveforms are shown in Figure 4c. *P* wave onsets are drawn as vertical bars on each waveform. The first EEW information is released 11 s after the origin time. At this time, both AGREEs and PRESTo declared an instrumental intensity of 7 in the epicentral area. The intensity drops down to 6 and 5 in the adjacent circles containing the closest 5 and 7 stations, respectively.

3.3. Application 3: False Alert Due To Teleseismic Earthquake

We applied the algorithm to the accelerometric data of a magnitude 5.8 earthquake that occurred in Greece on 29 August 2014, approximately 600 km from the center of ISNet network (http://www.emsc-csem.org/Earthquake/earthquake.php?id=397390). At that time, some of the stations of ISNet network were

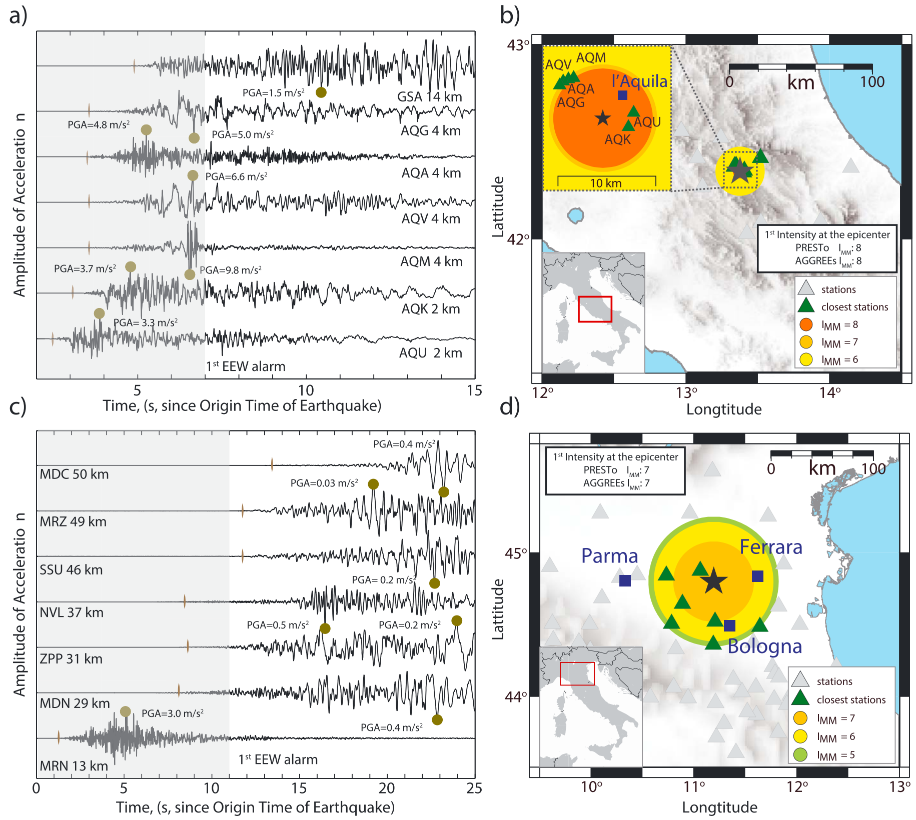

Figure 4. Plots show the waveforms of the seven closest stations for the two test events and results from AGREEs at the time of the first alert from *P* wave-based PRESTo. (a, b) $M_W = 6.3$ L'Aquila 2009 and (c, d) $M_W = 5.9$ Emilia 2012 earthquakes. On the waveform plots, the gray region shows the data collected before the PRESTo alert was issued. AGREEs calculates intensities using observed peak accelerations within this shaded region. The waveforms are normalized according to their PGAs and ordered according to their epicentral distances. The maps show AGREEs intensity estimations at the time of the first alarm. Intensities from both algorithms at the epicenter match exactly for both earthquakes.

triggered by the *P* wave front propagating northward and PRESTo declared a *M* 3.7 event at the southeast border of the network (Figure 5b). Using the estimated magnitude, PRESTo estimated an intensity of 3 at the epicenter. While the event was obviously a real seismic event, the real-time source parameters were wrong and, in this sense, the alert was a "false" event in the bulletin. Based on the maximum amplitudes of the waveforms at stations around the PRESTo event location at the time of the PRESTo alert, AGREEs did not observe the required threshold and declared an epicentral intensity of 1, i.e., not felt. Therefore, AGREEs could have been used to prevent the declaration of a false alert.

3.4. Application 4: False Event Due To a Broken Sensor

Another testing case for AGREEs was given by a false *M* 6.1 event declared by PRESTo on 15 June 2014. In its actual configuration, PRESTo requires six stations to be triggered within a short time window. This threshold has been specifically configured for the Irpinia region, where the rate of seismicity is rather low and most of the events are micro-to-small earthquakes ($0.5 < M < 3$). The triggering condition has been set after trial and error analysis and has been found to balance the incidence of false alarms and the automatic detection of small events ($M < 2$). On 15 June, due to the simultaneous occurrence of triggers associated with very small events, the triggering condition was met. Meanwhile, the strong motion sensor installed at station BSC3 was broken. As a result of these two conditions, an event was created. Initially, it had a magnitude of 1.6, but then the magnitude increased to a final magnitude of 6.1 and located in the middle of the network, due to triggers from the broken sensor (Figure 5d).

We played back the accelerometric data through AGREEs and found that the algorithm could prevent a false alert. For the entire duration of the simulation, based on the peak acceleration at the three closest stations

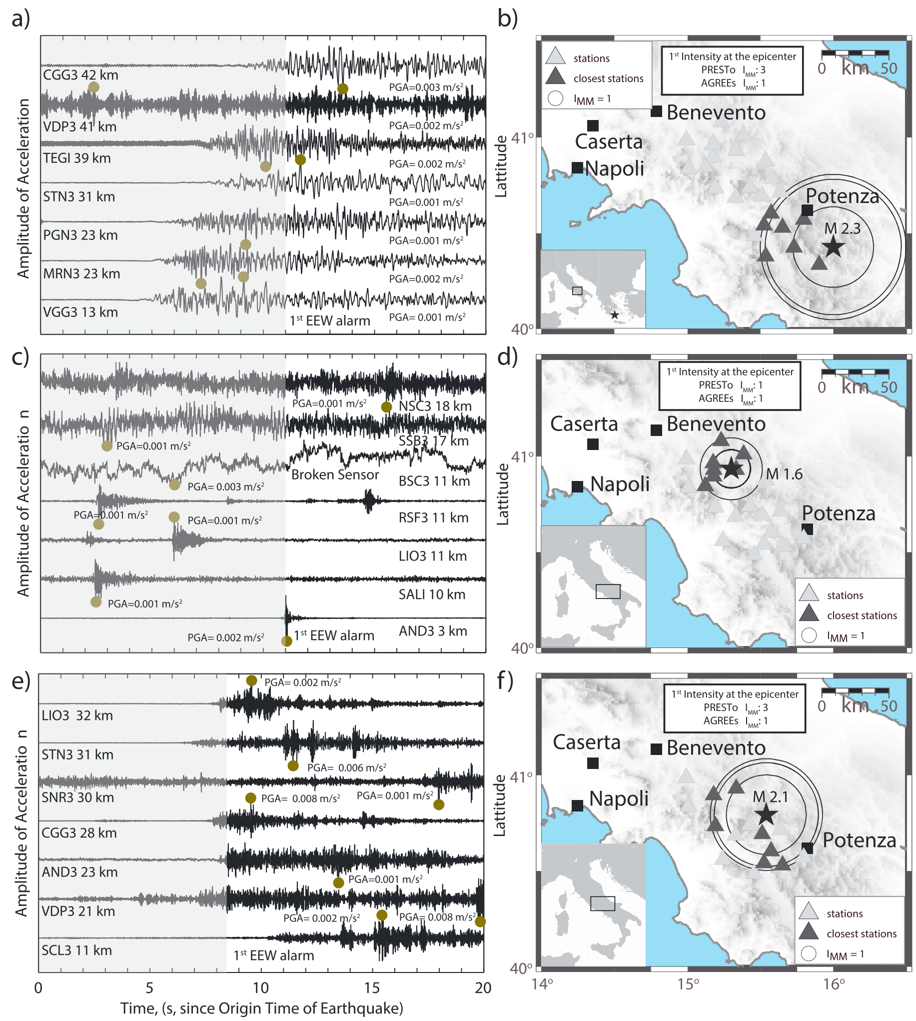

Figure 5. Similar plots to Figure 4 but for the three false events. Waveform plots show data for the seven closest stations to the estimated (false) epicenter for each event, and the map figures show the results of AGREEs at the time of first magnitude solution by PRESTo. (a, b) $M = 3.7$ false event due to a teleseismic earthquake in Greece ($M_W = 5.8$), (c, d) $M = 6.1$ false event due to one broken sensor and spurious triggers, and (e, f) $M = 2.1$ false event due to weather noise. On the waveform plots, the gray region shows the data collected before the PRESTo alert was issued. AGREEs calculates intensities using observed peak acceleration within this shaded region. The waveforms are normalized according to their PGAs and ordered according to their epicentral distances. The maps show AGREEs intensity estimations at the time of first alarm. Intensities from both algorithms at the epicenter match exactly for both earthquakes. AGREEs's intensity solutions in each instance are zero.

around the epicenter, AGREEs declared an expected epicentral intensity of 1, meaning no shaking. At the time of the first alert declaration, AGREEs did filter the M 1.6 event because both PRESTo and AGREEs declare intensities of 1 at the epicenter. However, when the magnitude increased to 6.1, there is a mismatch between the PRESTo and AGREEs intensities, with AGREEs reporting intensity 1, while the PRESTo alert predicted strong shaking. So AGREEs could have been used to prevent the false alert because the reported large amplitude at the broken sensor was inconsistent with the amplitudes at other closer stations.

3.5. Application 5: False Event Due To Storm

A common problem for real-time seismic networks, both for routine seismicity monitoring and EEW, is the erroneous, spurious picks due to storms or bad weather conditions. On 19 November 2013, PRESTo declared a magnitude 2.1 false event in the middle of the network caused by the occurrence of a storm (Figure 5f). With eight station triggers, PRESTo created an event with an initial magnitude of 1.7 and a final magnitude of 2.1. Again, we simulated the event and played back its accelerometric data with the AGREEs algorithm. As in the previous case, AGREEs did not report any event; i.e., the epicentral intensity estimate never exceeded 1, and the alert released by PRESTo could be quickly canceled/suppressed.

4. Discussions and Conclusion

The EEW requirement of fast, real-time data processing, combined with ambient noise, lightning, device failures, etc., can result in poor estimation of source parameters (location and magnitude) which may, in turn, lead to false and missed alarms. In terms of risk management, missed and false alarms reduce the effectiveness of EEWS and both have direct and indirect costs. The reliability of EEWS can be maximized by using a combination of warnings from many stations (i.e., the regional approach) and by improving the redundancy of the system (for example, with multiple algorithms, running in parallel).

With the purpose of reducing the declaration of false events, here we developed and tested a straightforward tool that can be used as a real-time discriminator between false events and real earthquakes for which an alert is needed. AGREEs is not intended to be a separate EEW system, essentially because it needs a reliable real-time earthquake location estimate to work properly. It has been specifically conceived to provide a complementary methodology for the alert declaration and to support the existing EEW platforms. Among them, for example, PRESTo or ElarmS-2, or any algorithm in the California Integrated Seismic Network ShakeAlert EEWS, could benefit from AGREEs, to improve their performance. The idea is to directly incorporate AGREEs into an existing EEW system, or to have AGREEs separately running as the last module/check, before the warning is released.

Because the algorithm is based on the continuous, real-time observation of actual ground shaking, it cannot generate false events but can only intervene on the prediction released by the primary platform. The greater the number of stations available in the epicentral region, the more accurate the shaking estimate at epicenter. AGREEs is favorable over a single-channel threshold-based approaches because single stations may have issues with noise, clipping, overvoltage, etc. Rather than a single station, AGREEs adds layers to quantify and verify impending ground shake by adding various distances and thresholds in a network.

We applied the methodology to some test cases, including two earthquakes in Italy and three false events declared by PRESTo, running at ISNet network. AGREEs successfully detected both L'Aquila and Emilia earthquakes and confirmed epicentral intensity with PRESTo. Furthermore, the three false events declared by PRESTo could be canceled by AGREEs.

As for the computational aspects, the real-time data processing of AGREEs is straightforward and the required data transmission is small compared to other EEWS and in many cases already available. AGREEs does not perform complex operations (such as filtering the waveforms or performing real-time integration), but it only requires one peak value per second. In its current version, AGREEs uses acceleration waveforms, but there is no reason not to include velocity and displacement waveforms including GPS displacement data series [*Grapenthin et al.,* 2014]. Real-time data streaming from cell phones could also be used.

Most active EEWS use either the frequency content or the displacement of the *P* wave. However, unforeseen signals such as records from broken sensors or clipped signals may result in irregular and meaningless signals. This may cause false events or errors in source parameters such as overestimated magnitude. Because AGREEs uses peak acceleration, it will be an alternative companion for *P* wave-based EEWS.

One remaining question that must be answered before AGREEs can be implemented is how similar the *P* wave-based intensity and observed intensity estimates must be for AGREEs to allow an alert to be issued. In the examples of this study, both PRESTo and AGREEs have given the same intensity estimates at the epicenter. How big the difference in the intensity estimates could be for the alert to proceed is a choice that EEWS operators need to make. Simulations could be used to estimate likely uncertainties and differences.

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