# *Improving Location of Offshore Earthquakes in Earthquake Early Warning System*


## by Hsin-Chih Hsu, Da-Yi Chen, Tai-Lin Tseng, Yih-Min Wu, Ting-Li Lin, and Hsin-Chieh Pu



## ABSTRACT

We proposed an effective approach to improve the accuracy of offshore earthquake location in the earthquake early warning (EEW) system of Taiwan. The EEW system was built upon Geiger's method for earthquake location that requires a set of initial estimates (epicenter, depth, and origin time). Because the initial epicenter highly depends on the locations of inland stations, for far offshore events the final solution falls effortlessly into a local minimum which may far away from the actual position. To solve this problem, an approach for choosing a better initial epicenter was proposed. We added predefined initial epicenters on the offshore area and then implemented several programs running Geiger's method simultaneously. Each of the programs adopted a different predefined initial epicenter. The best earthquake location is given by the most timesaving run, assuming that the solution is converged most efficiently related to the closest distance between the initial and true epicenters. The modified method has been tested with the online EEW system from June 2016 to July 2017 for offshore east Taiwan. A total of 60 earthquakes with magnitudes ranging from 3.3 to 6.0 were detected successfully. The results were compared with the estimations from the original EEW system, showing that our proposed method for offshore earthquakes is able to reduce location error by about 4.9 km on average.

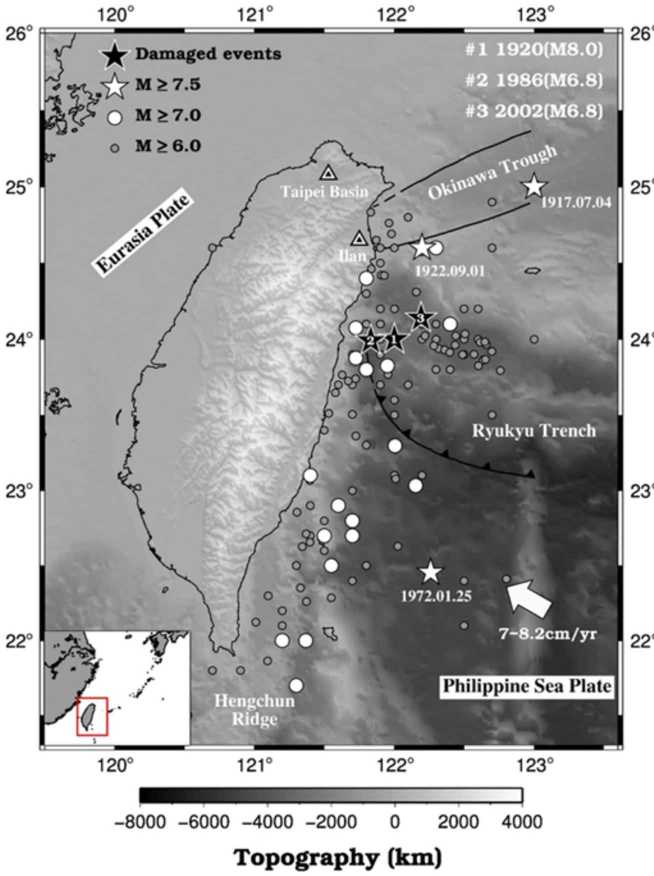

## INTRODUCTION

Taiwan is located on the collision zone between the Philippine Sea plate (PSP) and the Eurasia plate (EP) and is one of the most seismically active regions in the world. In the eastern offshore area of Taiwan, the PSP subducts northward underneath the EP along the Ryukyu trench, causing numerous large earthquakes with magnitude above 7.0 in the past (Fig. 1). Subduction zone earthquakes in general can cause large ground shakings to the Taipei metropolitan area and caused severe damages due to the amplification effect (Huang *et al.*, 2010). For example, the ground shakings from the 1986 $M_w$ 6.8 ($M_w$ 7.3) earthquake and the 2002 $M_w$ 6.8 ($M_w$ 7.7) earthquake caused damage to buildings or caused buildings to collapse. The largest instrumentally recorded earthquake of $M_w$ 8.0 ($M_w$ 7.7) in Taiwan may have also caused some damage at that time (moment magnitudes were recalculated by Theunissen *et al.*, 2010). Moreover, according to the geodetic data, the plate interface in this area is fully locked and has potential to produce $M_w$ 7.5–8.7 tsunami earthquakes (Hsu *et al.*, 2012). Therefore, it is important to enhance the ability of earthquake monitoring and to accelerate the speed of earthquake notification for offshore earthquakes of eastern Taiwan (Kao, 1998; Wu *et al.*, 1999).

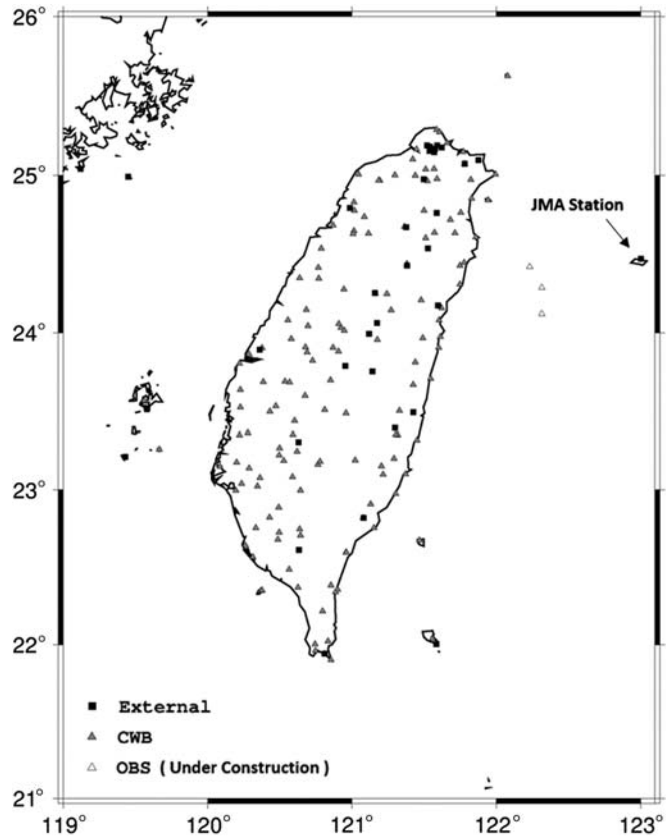
To reduce earthquake hazard from offshore east Taiwan, one of the most practical approaches is to develop an earthquake early warning (EEW) system that issues warnings to citizens and facilities automatically before ground shakings hit the target areas. Making as much lead time as possible for a warning notification before the arrival of ground shaking is a crucial task for a successful EEW system. When earthquakes occurred on land and near target areas, the lead time is quite small or even not available. On the contrary, when earthquakes occur in far offshore area, a lead time of tens of seconds is possible. This is especially true for subduction zone earthquakes with magnitude larger than 7.0, because the ground shaking would be large enough to cause damage to land. The 2011 $M_w$ 9.0 Tohoku earthquake demonstrates that the EEW system is useful for mitigating earthquake damage, for example (Hoshiba *et al.*, 2011).

The Central Weather Bureau (CWB) of Taiwan has developed the EEW system for about two decades. The initial EEW system was based on the strong-motion seismic network transmitting real-time data via telephone line with 16-bit amplitude resolution and 50 Hz digitization (Wu *et al.*, 1999). Because the original design of the procedure aimed for a quick warning notification after earthquake occurrence, a short time window of only 10 s after $P$-wave arrival was adopted for magnitude determination and only the nearest stations triggered by epicenter were used for source parameter determination (Wu and Teng, 2002). With this approach, alarms were issued by the EEW system after about 22 s of processing time on average, and the EEW messages were only available for limited agencies.

Recently, the greatly improved EEW system of CWB has started to release EEW messages to the general public, after the upgrade of the seismic network and the modification on algorithms for earthquake monitoring. The CWB Seismic Network (CWBSN) consists of strong motion, short period, and broadband stations, which had been fully upgraded to 24 bit in




▲ **Figure 1.** The distribution of the eastern offshore historical earthquakes from 1900 to 2017 with depth less than 40 km, provided by the Central Weather Bureau (CWB) earthquake catalog. The event number 1 is the largest earthquake in the history. The events 2 and 3 caused a lot of damages in Taipei basin due to site effect. The color version of this figure is available only in the electronic edition.



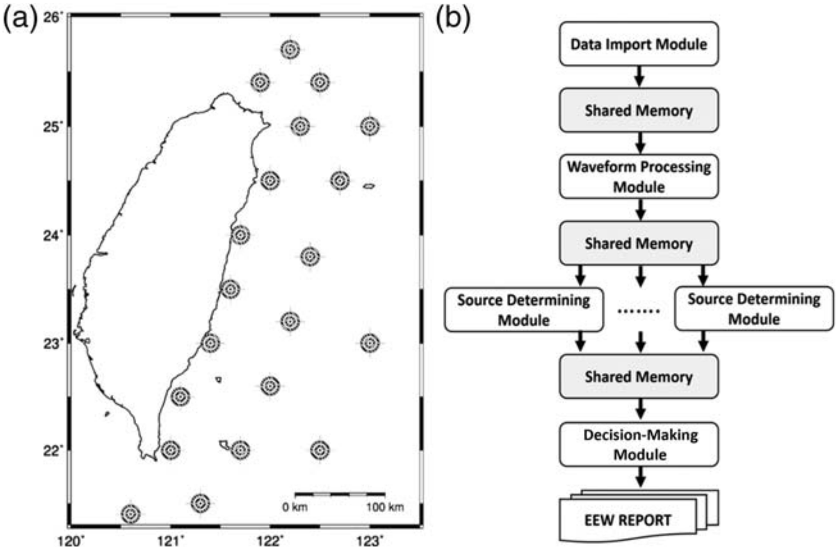

▲ **Figure 2.** The station distribution of the CWB seismic network. Solid squares represent stations operated by external institutions. Solid triangles represent stations operated by the CWB. Open triangles represent cable-based ocean-bottom seismometers (OBSs) that were not used in this study. JMA, Japan Meteorological Agency.

data resolution and 100 Hz in sampling rate by 2012. To improve station density, the CWB incorporates more broadband stations into the current CWBSN, mainly those in Taiwan Island from the Institute of Earth Sciences of Academia Sinica. One station distributed on the eastern offshore area by the Japan Meterological Agency is also included for better coverage. Figure 2 shows the station distribution of the CWBSN and those incorporated in this study. All of the real-time seismic data streams are integrated by Earthworm software, developed by the U.S. Geological Survey (Johnson *et al.*, 1995).

The Earthworm software is one of the most popular earthquake monitoring systems worldwide because it has complete functions for data acquisition, exchanging, processing, archiving, and it is free of charge (Johnson *et al.*, 1995). The software was designed as modularity and scalability (Johnson *et al.*, 1995), meaning that users can establish any kind or any size seismic monitoring system, depending on their requirements. In addition, users are able to customize their systems because the Earthworm software is open source. Nowadays, many seismic monitoring centers have created their own Earthworm modules for specific earthquake monitoring purposes (Olivieri and Clinton, 2012).

With the Earthworm platform, Chen *et al.* (2015) established a new EEW system called the Earthworm-based alarm reporting (*e*BEAR) system in CWB. This innovative system, adopting *P*-wave information for the determination of earthquake location and magnitude, is able to provide EEW messages about 15 and 30 s after inland and offshore earthquakes occurred, respectively. The CWB started to send EEW messages to schools in 2014 and to the general public via television and cell phone in 2016.

In the *e*BEAR EEW system of CWB, the estimations of earthquake locations were developed based on Geiger's method (Geiger, 1912) using a 1D two-layered velocity model for calculating travel time of each triggered station (Lee and Dodge, 1992; Chen, 2015). Occasionally, the location determined by the EEW system shows large location error for offshore earthquakes. In the EEW system, the initial epicenter, given by the centroid of trigged stations, may be far away from the actual epicenter due to poor station coverage. This erroneous initial epicenter may lead to final solution in the local minimum rather than the true location. Moreover, the location




▲ **Figure 3.** System configuration of the proposed approach. (a) The distribution of the 20 predefined initial epicenters. (b) Data flow of the new system adopting the proposed approach in this study. When an earthquake occurs, the waveform processing module will provide *P*-wave arrival time and put it into the shared memory. A total of 20 source determining modules were receiving those parameters and estimating source parameters in parallel. Earthquake messages from these modules were sent to the same shared memory. Finally, the decision-making module will choose the most timesaving run as the result for the earthquake early warning (EEW) report.

error may further cause incorrect estimation in magnitude. Consequently, the predicted ground motions could be overestimate or underestimate that means the EEW system would issue false alarms or miss to issue alarms. In this study, we proposed an approach in providing a suitable initial epicenter for an offshore earthquake based on the iterative procedure of Geiger's method. The EEW system of Taiwan can be benefit from the improvement of offshore earthquake location.

## AN APPROACH FOR CHOOSING SUITABLE INITIAL EPICENTER

Geiger's method is a linearized iterative process for earthquake location (Geiger, 1912). In each iteration, the method minimizes the travel-time residuals between the theoretical prediction and the observation of the seismic phases at triggered stations. After giving a set of initial parameters including epicenter, focal depth, and origin time, the differences between the set of the initial parameters and the expected true parameters are determined and be used to adjust the trial parameters in the next iteration. This procedure is iteratively performed until the residuals fall below certain predefined criteria. Finally, the estimated source parameters are given.

For an earthquake occurred within a seismic network, the initial epicenter, given by the centroid of triggered stations, could be close to the actual epicenter. This algorithm, however, may fail when earthquakes occurred outside and far away from a seismic network. Even if the initial epicenter is given by the nearest station (Lee and Valdes, 1985) or the centroid of triggered stations, the position of the initial epicenter is still far away from the actual epicenter. In this case, it is difficult to reduce the travel-time residuals in the iterations. It may lead the solution converges to a local minimum. The resulting large location errors for offshore earthquakes are our main concerns that need to be improved.

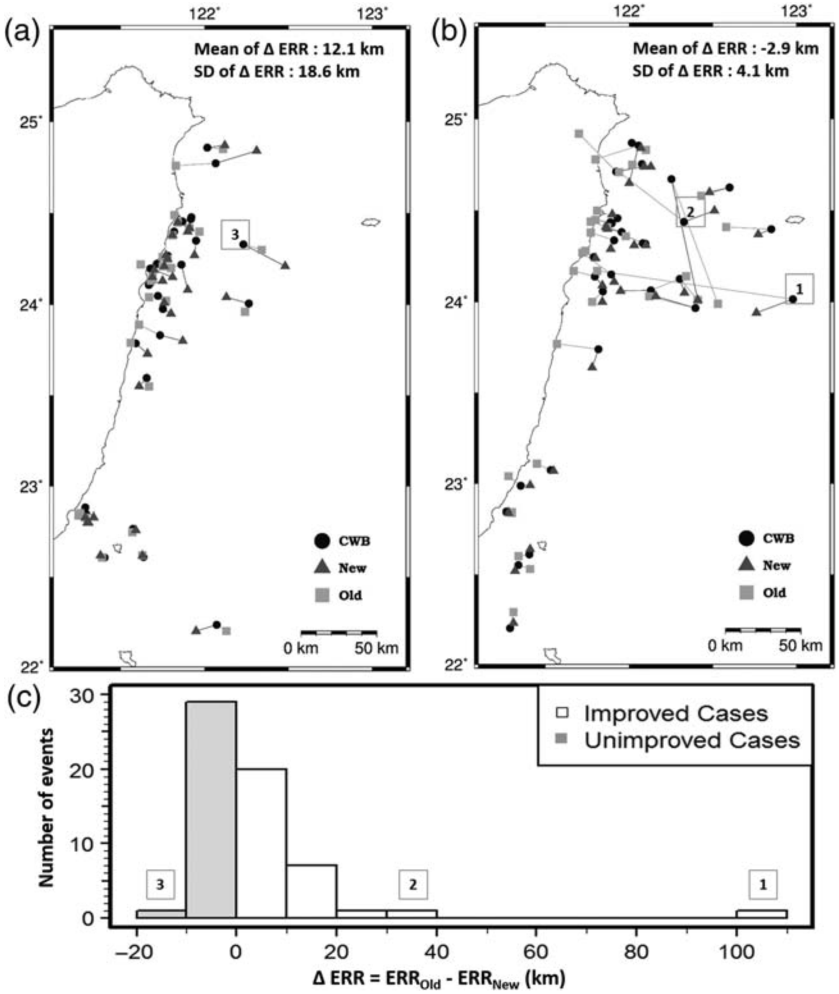
In principle, when an initial epicenter is close to the actual epicenter, the earthquake location can be well determined. However, the lack of triggered stations in the offshore area makes it difficult to choose one initial epicenter that is close to the actual epicenter in advance. To solve this problem, we can predefine several initial epicenters in the global space and assume that one of them must be closest to the actual epicenter. The idea is that if one of the predefined epicenters is closest to the actual epicenter then the program running Geiger's method with this predefined one will be the most timesaving run.

If the predefined initial epicenters were not dense enough, the estimated epicenter from the proposed method could be wrong because the initial hypocenter location is very close to a local minimum travel-time residual, and the global travel-time minimum is relatively far from the initial locations. If the chosen initial epicenter was close to the global travel-time minimum (because of dense predefined epicenters), the final estimated epicenter should be near the chosen initial epicenter. Therefore, we proposed the constraint that the distance between the estimated epicenter and the chosen initial epicenter should be less than the interval of each predefined epicenter.

## SYSTEM CONFIGURATION FOR IMPLEMENTING THE NEW APPROACH

The current *e*BEAR EEW system of Taiwan has been developed on the Earthworm software and consists of three developed Earthworm modules for the purpose of EEW (Chen *et al.*, 2015). One is the waveform process module, which picks *P*-wave arrivals and measures amplitude in a certain time window after the *P*-wave arrival. Second is the source determining module, which associates *P*-wave arrivals for the estimations of earthquake location and magnitude. The third is a decision-making module, which receives earthquake messages from the second module and chooses some of them as EEW messages to issue to the public.

For the current system, the source determining module may provide an incorrect earthquake location for offshore earthquakes, because the module takes the centroid position of all triggered stations as an initial epicenter for the iterative linearized procedure of Geiger's method. In our new approach, we assumed the initial depth to be 30 km, which is equal to the




▲ **Figure 4.** Comparisons of epicenter locations in the old and new EEW systems. (a) Cases for unimproved estimates of epicenters from the new system. (b) Cases for improved estimates of epicenters from the new system. (c) Histogram of the difference between $ERR_{New}$ and $ERR_{Old}$ for improved and unimproved cases. Symbols mark the locations determined from the new system (solid triangles), old system (solid squares), and the CWB relocated earthquake catalog (solid circles). Numbers in the open squares indicate outliers in (c) corresponding to earthquake locations in (a) and (b). SD, standard deviation.

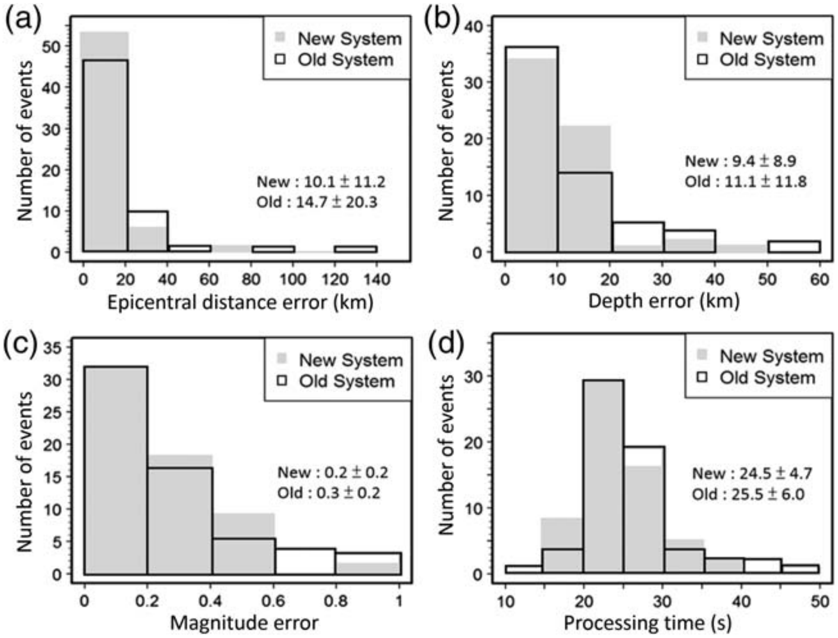
average focal depth of the eastern offshore earthquakes in Taiwan. The initial origin time of the earthquake is provided by the *P*-wave arrival of the first triggered station. To improve the initial epicenter, we added 20 predefined epicenters on the eastern Taiwan offshore area, shown in Figure 3a. Each of them was adopted from one source determining module, respectively. Figure 3b illustrates the flow of processing to produce a EEW report. After the data streaming in through the data import module, *P*-wave arrivals were picked automatically on the seismic waveforms by the waveform processing module and then written into a shared memory. The shared memory passed information regarding *P*-wave arrivals to a total of 20 source determining modules, which were implemented for earthquake location in parallel using predescribed initial epicenters. When the root mean square of the travel-time residuals is less than 0.8, the earthquake report will be generated by each module and sent to the same shared memory successively. The decision-making module reads messages from the memory, filters them by checking the number of triggered stations (at least 13 stations), and then takes the earliest result as the EEW message.

Traditionally, three kinds of criteria are considering for evaluating location estimations, including number of stations, station coverage gap, and travel-time residuals. The station coverage gap is a good indicator of the quality of hypocenter estimation, but for offshore earthquake this factor is usually large. The travel-time residuals have been considered in the source determining module. Therefore, in the decision-making module, we only used number of triggered stations as criteria, which corresponds to the quality of hypocenter more directly than comparing with others.

## PERFORMANCE OF THE SYSTEM IMPLEMENTING THE NEW APPROACH

To calibrate the new system that applies the proposed approach for choosing the best initial epicenter in Geiger's method, we implemented an online test with the CWBSN and other stations as shown in Figure 2. From June 2016 to July 2017, the system detected 60 earthquakes with magnitude ranging from 3.3 to 6.0. In addition, the old system, which applies centroid position of all triggered stations as initial epicenter in Geiger's method, was also implemented at the same period. Comparisons of the earthquake location and processing time in the new system with those in the old system were discussed here. The processing time is defined as the time between the occurrence of an earthquake and the time the EEW system issues the earthquake alarm.

To analyze the accuracy of epicenter, we use the earthquake catalog maintained by the CWB staff as a standard reference to compare the results produced from the new and old system. We define the distance between the epicenter determined from the new system and from the catalog as $ERR_{New}$ (in which ERR denotes error), the distance between the epicenter determined from the old system and from the catalog as $ERR_{Old}$, and the difference between $ERR_{New}$ and $ERR_{Old}$ as $\Delta ERR$. In 30 cases (50%), hypocenter locations from the new system are closer to the catalog than those from the old system (Fig. 4b; $\Delta ERR$ is about 12.1 km in average for these 30 events). This indicates that the proposed algorithm can effectively improve the accuracy of offshore earthquake location. Using event numbers 1 and 2 in Figure 4b as examples, the location error can be reduced by the new system about 100 and 30 km, respectively (Fig. 4b,c).




▲ **Figure 5.** Performance comparisons in the old and new EEW systems; (a) epicenter error, (b) depth error, (c) magnitude error, and (d) processing time. Symbols mark the distribution of the new system (solid bars) and old system (open bars). Average and standard deviation of the performance in the old and new EEW system are also shown.

Although there are 30 unimproved cases in which the locations from the old system are more accurate than those from the new system, the overall average $\Delta$ERR is about −2.9 km, which is comparable with the average error inland and can be considered an acceptable value. However, there is still one worst case (event number 3) for which the location error is increased 17 km from the new system (Fig. 4a,c).

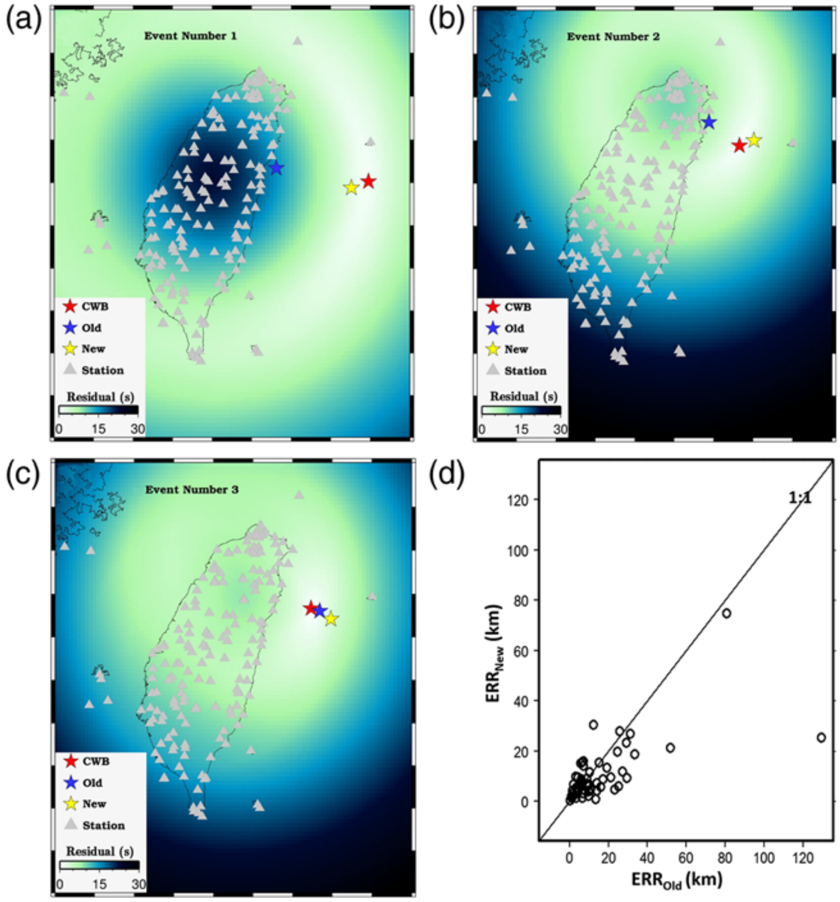
Figure 5 illustrates the performance comparisons of the new and the old system, including processing time and error of epicenter, depth, and magnitude. In terms of epicenter locations (Fig. 5a), the new system has less or equivalent chance to produce the epicenter error from 15 to 75 km and has no error larger than 75 km. In other words, extremely large errors in epicenters are avoided in the new system. As indicated by Figure 5b, the new system also has slightly smaller errors in focal depth, most of which are within 20 km. The new system produces magnitude that are more consistent with the CWB results and reduces the frequency of reporting extremely overestimated magnitude (0.65–0.85), as in Figure 5c. Figure 5d compares the processing time for the 60 earthquakes in the old and new system. Overall, we can conclude that the new system is able to improve the estimations of epicenter, focal depth, and magnitude according to the means and standard deviations, although the processing time improved insignificantly by 1 s in average.

## DISCUSSION

Two strategies are typically used to deal with the earthquake location problems in early warnings. One is a linearized iterative method, such as Geiger's method (Geiger, 1912). This method requires a prior estimate for the next iteration until the process reaches the convergent state. The advantage of this method is timesaving in computation, but the disadvantage is that the solution is seriously affected by the prior estimate. An incorrect prior estimate may lead to a local minimum solution and cause an incorrect earthquake location. The other approach is a direct grid-search method, which has been implemented in the EEW system (Rydelek and Pujol, 2004; Satriano *et al.*, 2008; Sheen, 2015). This method does not need a prior estimate, but finds solutions in a global solution space. The advantage of the direct grid-search method is that the solution is less affected by the outlier of the picks. The disadvantages are that the accuracy depends on the grid size and it is time consuming.

The proposed system in this study is a hybrid system of the grid-search method and Geiger's method. First, we predefined 20 initial epicenters that are similar to the grid-search method, then with each of the predefined epicenters we performed Geiger's method simultaneously. The most timesaving run of those will provide the epicenter estimation. To better understand the advantages of the proposed method, Figure 6a–c shows the travel-time residual maps using 5 km by 5 km mesh over the whole Taiwan area. Event numbers 1 and 2 are the most improved cases in our study because the proposed method can provide solutions in the area with global minimum. The old method, however, keeps the estimated epicenters trapped in the area with local minimum (nearby the area with higher residuals on land), shown in Figure 6a,b. On the other hand, sometimes the old method provides a solution in the area with global minimum. In this case, the difference between the epicenters, estimated by both the new and the old method, is small, as shown in Figure 6c. In summary, the new method provided better estimated epicenters than the old method. Figure 6d shows the relationship between the epicenter error of the old system ($ERR_{Old}$) and the epicenter error of the new system ($ERR_{New}$). When the epicenter error of the old system is larger than 15 km, almost all records are under the 1 by 1 line. This means that the epicenter error of the new system is less than that of the old system.

In practice, the new method and the old method will be performed together in the EEW system. When an earthquake occurs, the *P*-wave arrivals will be picked and put into the shared memory by the waveform processing module. The source determining modules running the new method and the one running the old method will read the same picks from the shared memory and perform location estimations separately. Then, the decision-making module will adopt the most timesaving result. If earthquakes occurs in an offshore area, the source determining module running the new method will




▲ **Figure 6.** Performance comparisons between the old and new EEW systems. Travel-time residual map using 5 km by 5 km mesh over the whole Taiwan area for event numbers (a) 1, (b) 2, and (c) 3; and (d) relationship between $ERR_{New}$ and $ERR_{Old}$. $ERR_{Old}$ is the epicenter error of the old system compared with the CWB catalog; $ERR_{New}$ is the epicenter error of the new system compared with the CWB catalog. The color version of this figure is available only in the electronic edition.

provide results first. In contrast, if earthquakes occurs in an inland area (i.e., within the seismic network), the source determining module running the old method will provide the result first. Therefore, even though the event location is unknown in the early stage of the EEW operation, the EEW system still can use the old method for inland earthquakes and the new method for offshore earthquakes.

## CONCLUSIONS

Accurately locating offshore events is a big challenge for EEW system. Because of the limited station coverage and few available arrivals, the EEW system may provide poor earthquake locations in the initial reporting stages. The contribution of this study is that our algorithm basically joins the concept of direct grid search with the linearized iterative earthquake locating method. We proposed an approach that searches the best initial epicenter on a global space by concurrently implementing programs based on Geiger's method. The most timesaving run provides the best earthquake location. This approach can prevent local minimum solution and reduce location error, with a slightly shorter processing time. More initial epicenters may be able to accelerate the speed of convergence in Geiger's method procedure. In the future, we can further take advantage of the Earthworm software by implementing more source determining modules simultaneously to reduce not only location error but also processing time.

## DATA AND RESOURCES

Records used in this study were collected from the Central Weather Bureau Seismic Network (CWBSN) of Taiwan. Access to the waveforms records can be obtained from the owners on request (http://www.cwb.gov.tw/eng/index.htm, last accessed January 2018).

## ACKNOWLEDGMENTS

The software program Generic Mapping Tools (GMT; Wessel and Smith, 1998) and R (R development core team, 2016) were used in this study and are gratefully acknowledged. This work was supported by the Ministry of Science and Technology, Taiwan. The authors are also grateful to two anonymous reviewers for their valuable suggestions, which have significantly improved the article.

## REFERENCES

Chen, D. Y. (2015). Development and study of Earthworm platform for earthquake early warning in Taiwan, *Doctoral Dissertation*, Department of Geosciences, College of Science, National Taiwan University, Taipei, Taiwan, 124 pp.

Chen, D. Y., N. C. Hsiao, and Y. M. Wu (2015). The Earthworm based earthquake alarm reporting system in Taiwan, *Bull. Seismol. Soc. Am.* **105,** 568–579, doi: 10.1785/0120140147.

Geiger, L. (1912). Probability method for the determination of earthquake epicenters from the arrival time only, *Bull. St. Louis Univ.* **8,** 60–71.

Hoshiba, M., K. Iwakiri, N. Hayashimoto, T. Shimoyama, K. Hirano, Y. Yamada, Y. Ishigaki, and H. Kikuta (2011). Outline of the 2011 off the Pacific coast of Tohoku earthquake ($M_w$ 9.0)—Earthquake early warning and observed seismic intensity—, *Earth Planets Space* **63,** 547–551, doi: 10.5047/eps.2011.05.031.

Hsu, Y. J., M. Ando, S. B. Yu, and M. Simons (2012). The potential for a very large earthquake along the southernmost Ryukyu subduction zone, *Geophys. Res. Lett.* **39,** doi: 10.1029/2012GL052764.

Huang, Y. L., B. S. Huang, K. L. Wen, Y. C. Lai, and Y. R. Chen (2010). Investigation for strong ground shaking across the Taipei basin during the $M_w$ 7.0 eastern Taiwan offshore earthquake of 31 March 2002, *Terr. Atmos. Ocean. Sci.* **21,** 485–493, doi: 10.3319/TAO.2009.12.11.01(TH).

Johnson, C. E., A. Bittenbinder, B. Bogaert, L. Dietz, and W. Kohler (1995). Earthworm: A flexible approach to seismic network processing, *IRIS Newsletter* **14,** 4.

Kao, H (1998). Can great earthquakes occur in the southernmost Ryukyu Arc-Taiwan region? *Terr. Atmos. Ocean. Sci.* **9,** 487–508.

Lee, W. H. K. and D. A. Dodge (Editors) (1992). A course on: PC-based seismic networks, *U.S. Geol. Surv. Open-File Rept. 92-441*, 535 pp.

Lee, W. H. K., and C. M. Valdes (1985). HYPO71PC: A personal computer version of the HYPO71 earthquake location program, *U.S. Geol. Surv. Open-File Rept. 85-749*.

Olivieri, M., and J. Clinton (2012). An almost fair comparison between Earthworm and SeisComp3, *Seismol. Res. Lett.* **83,** 720–727.

R Development Core Team (2016). *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria, available at http://www.r-project.org/ (last accessed September 2017).

Rydelek, P., and J. Pujol (2004). Real-time seismic warning with a two-station subarray, *Bull. Seismol. Soc. Am.* **94,** 1546–1550.

Satriano, C., A. Lomax, and A. Zollo (2008). Real-time evolutionary earthquake location for seismic early warning, *Bull. Seismol. Soc. Am.* **98,** 1482–1494.

Sheen, D.-H. (2015). A robust maximum-likelihood earthquake location method for early warning, *Bull. Seismol. Soc. Am.* **105,** 1301–1313.

Theunissen, T., Y. Font, S. Lallemand, and W. T. Liang (2010). The largest instrumentally recorded earthquake in Taiwan: Revised location and magnitude, and tectonic significance of the 1920 event, *Geophys. J. Int.* **183,** 1119–1133.

Wessel, P., and W. H. F. Smith (1998). New, improved version of Generic Mapping Tools released, *Eos Trans. AGU* **79,** 579.

Wu, Y. M., and T. L. Teng (2002). A virtual sub-network approach to earthquake early warning, *Bull. Seismol. Soc. Am.* **92,** 2008–2018.

Wu, Y. M., J. K. Chung, T. C. Shin, N. C. Hsiao, Y. B. Tsai, W. H. K. Lee, and T. L. Teng (1999). Development of an integrated earthquake early warning system in Taiwan-case for Hualien earthquakes, *Terr. Atmos. Ocean. Sci.* **10,** 719–736.

*Hsin-Chih Hsu*[1]
*Da-Yi Chen*
*Hsin-Chieh Pu*
*Seismological Center*
*Central Weather Bureau*
*Taipei 10048, Taiwan*
*hchsu@scman.cwb.gov.tw*
*dayi@scman.cwb.gov.tw*
*pu@scman.cwb.gov.tw*

*Tai-Lin Tseng*
*Yih-Min Wu*[2]
*Department of Geosciences*
*National Taiwan University*
*Taipei 10617, Taiwan*
*tailintseng@ntu.edu.tw*
*drymwu@ntu.edu.tw*

*Ting-Li Lin*
*Department of Earth Sciences*
*National Cheng Kung University*
*Tainan 70101, Taiwan*
*ljegay1111@gmail.com*

Published Online 28 February 2018

[1] Also at Department of Geosciences National Taiwan University, Taipei 10617, Taiwan.

[2] Also at Institute of Earth Sciences, Academia Sinica, Taipei 11529, Taiwan.