Magnitude Estimations in Earthquake Early Warning for the 2010 JiaSian, Taiwan, Earthquake

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INTRODUCTION

On 4 March 2010, the JiaSian earthquake ($M_W = 6.0$ and $M_L = 6.4$) struck southern Taiwan. It was the largest earthquake in the region in nearly fifty years, since the 1964 Paiho earthquake ($M_L = 6.3$). According to the damage report by the Taiwan National Fire Agency, there were 96 people injured, but thankfully no deaths. However, hundreds of buildings, including school buildings, were required to be immediately evaluated for structural safety. The hypocenter of the 2010 JiaSian earthquake is shallow (about 23 km, given by the Central Weather Bureau [CWB], Taiwan) and is located within less than a few tens of kilometers to populated areas (Kaohsiung and Tainan counties) on its western side, coinciding with the direction of the mainshock rupture (Figure 1). Therefore, the JiaSian earthquake provides an opportunity to examine the performance of the current earthquake early warning system (EEWS) operated by CWB and also test two new proposed magnitude estimation methods in the EEWS (Lin and Wu 2010a, 2010b).

The two most commonly adopted types of EEWSs at the present time are regional and onsite warning systems. In regional EEWSs, the ground shaking characteristics (either P or S waves) recorded by seismic sensors or a network close to the epicenter are used to calculate the earthquake hypocenter and magnitude and then to estimate strong ground motions at distant target areas. For onsite EEWSs, the initial P-wave motion is used to predict the ground motions of the later S and surface waves (which commonly have higher amplitudes or destructive energy than that of the initial P-wave motion) at the same site. Generally, the onsite EEWS is faster but less accurate than the regional EEWS (Wu and Kanamori 2005a, 2005b).

A sub-network method based on the regional EEWS approach has been in operation for practical real-time earthquake monitoring since 2001 in Taiwan (Wu *et al.* 1999; Wu and Teng 2002; Hsiao *et al.* 2009). The pre-configured sub-network is a subset of the Rapid Earthquake Information Release System (RTD; Wu *et al.* 1997, 2000). The RTD network consists of 109 seismic stations, and each station is equipped with a three-component, force-balance accelerometer (Figure 2). The whole Taiwan region is divided into five sub-networks, and each sub-network consists of 32 RTD stations (Figure 2). The fundamental argument behind the sub-network method is that empirically the determinations of the event location and magnitude with a practically sufficient accuracy are mostly controlled by the stations close to the epicenter (less than 60 km) in EEWS. The average response time of the sub-network system is about 20 seconds (Hsiao *et al.* 2009). The sub-network approach has a "blind zone" with a radius of 70 km centered in the epicenter, in which warnings cannot be issued in a timely manner (Hsiao *et al.* 2009). The method of magnitude estimation in the present sub-network operation is based on the waveforms of the first 10 seconds after the earliest *P* arrival among the sub-network stations (M_{L10}, Wu *et al.* 1998).

Based on the initial three-second window of the first *P*-wave arrival on the high-pass (0.075 Hz) filtered vertical displacement seismogram, the average period (τ_c, Kanamori 2005; Wu and Kanamori 2005a; Wu *et al.* 2007; Wu and Kanamori 2008a, 2008b) and the dominant period (τ_p^{max}, Nakamura 1988; Allen and Kanamori 2003) are also used to estimate earthquake magnitude operating in parallel with the sub-network approach in the current EEWS design in CWB (Hsiao *et al.* 2009). Compared with the sub-network approach, the τ_c and τ_p^{max} methods are more oriented to the onsite one.

Lin and Wu (2010a) derived a peak-ground-acceleration (PGA) attenuation relationship with the epicentral distance using the accelerograms recorded by the Taiwan Strong Motion Instrumentation Program (TSMIP) stations and used this attenuation relationship to define a so-called "M_{pga} magnitude" of earthquakes. The PGA attenuation with the epicentral distance is given as

$$\log_{10} PGA = -0.395\log_{10}(r) + 0.125M_{pga} + 1.979\ , \qquad (1)$$

where r is the epicentral distance in km. They found that the M_{pga} magnitude corresponds well with M_W provided that there are a sufficient number of PGA readings. The TSMIP (Liu *et*

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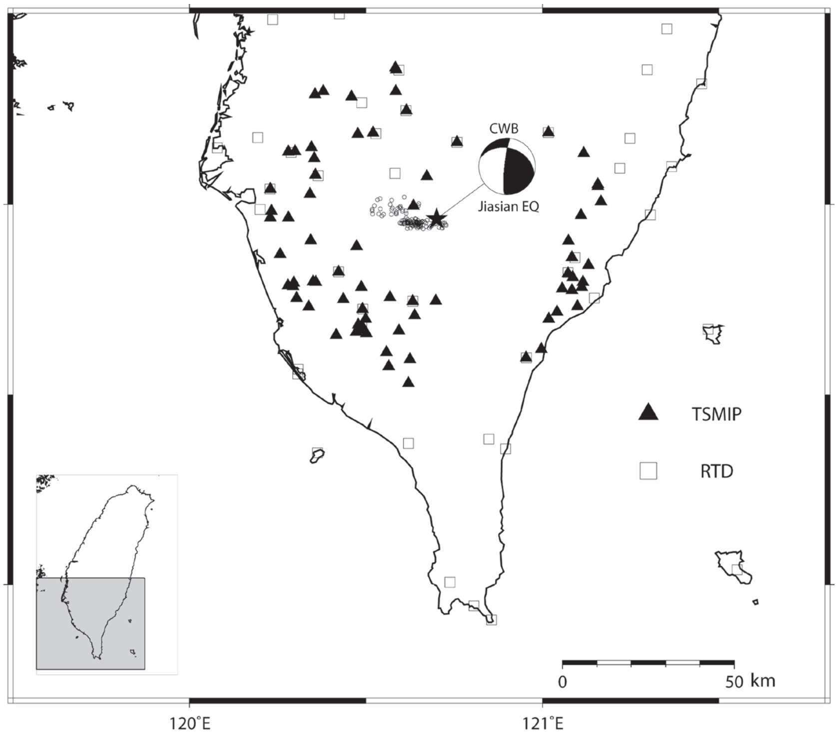
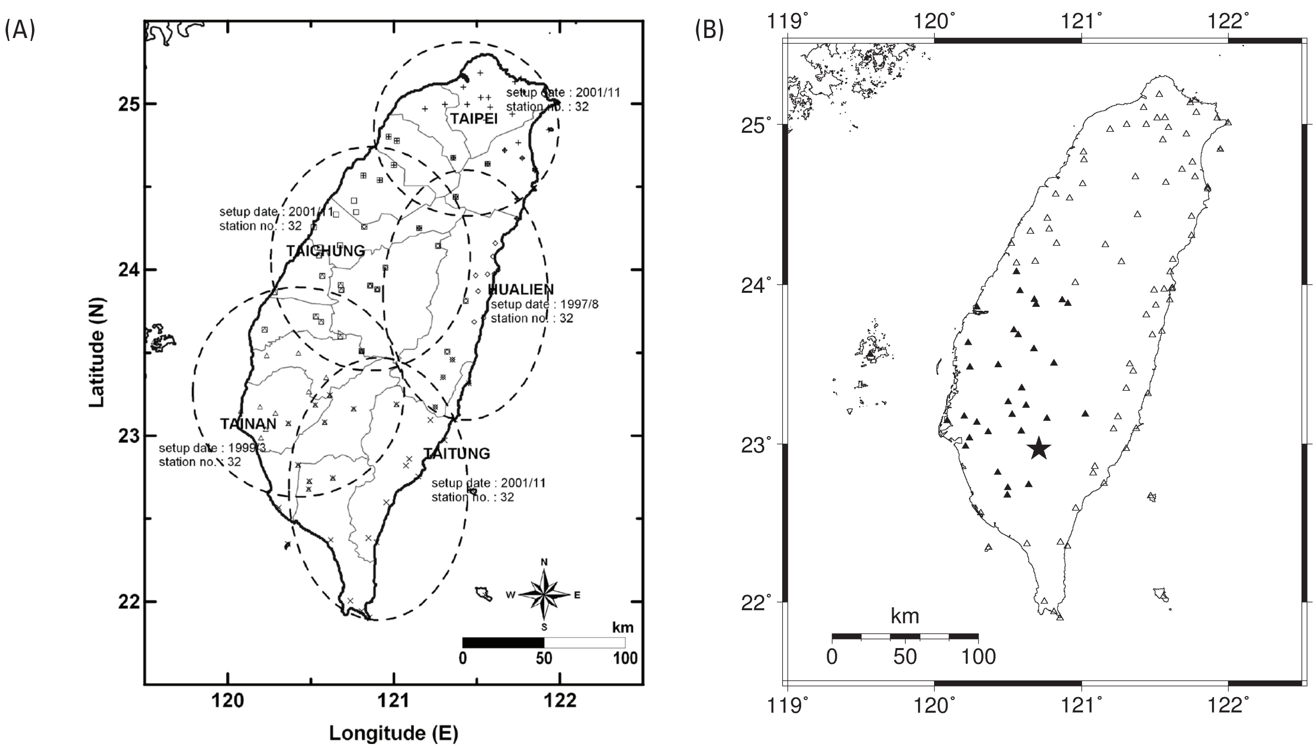
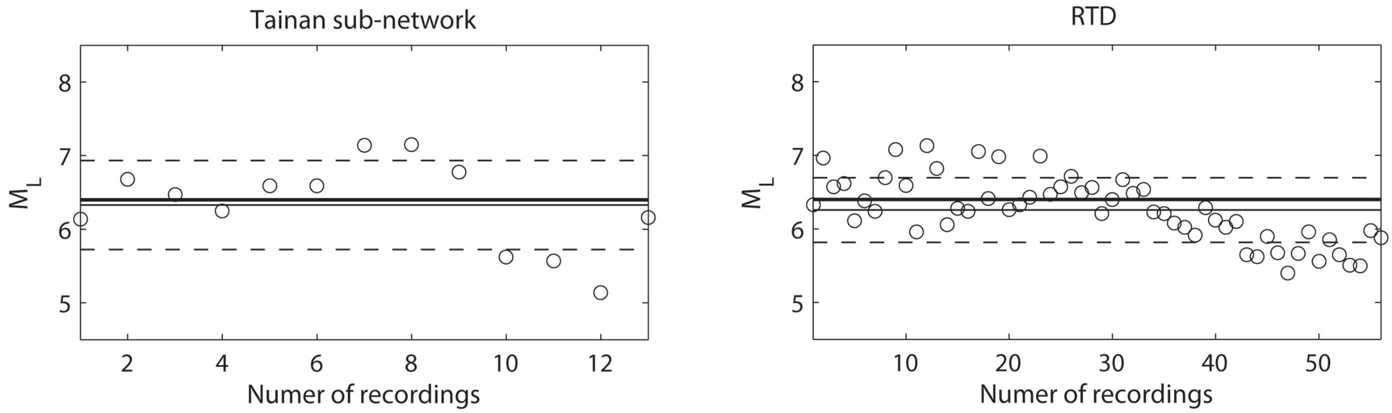


▲ **Figure 1.** Locations of the TSMIP (solid triangles) and RTD (open squares) seismic stations. The epicenters of the 2010 JiaSian mainshock and the aftershocks within two hours following the mainshock are shown as the star and the open circles, respectively. The fault mechanisms given by BATS (Broadband Array in Taiwan for Seismology), CWB, USGS (United States Geological Survey), and Global CMT (centroid moment tensor) solutions all suggest a thrust mechanism with the fault plane most likely striking in the NW-SE direction and dipping about 30–40° to the northeast.



▲ **Figure 2.** A) Station distribution of the RTD network and five pre-configured sub-networks. The dashed circles delineate the general coverage ranges of each sub-network. B) The 13 triggered RTD stations (solid triangles) used to estimate the M_{L10} by the sub-network approach.



▲ **Figure 3.** The estimated earthquake magnitudes in M_L for the 2010 JiaSian mainshock given by the Tainan sub-network (13 recordings) and the whole RTD system (56 recordings). The triggered stations are arranged according to their increasing epicenter [epicentral?] distances. The thick lines represent the CWB reported magnitude ($M_L = 6.4$) and the thin lines show the final estimated magnitudes with one standard deviation plotted in the dashed lines.

al. 1999) operated by CWB consists of more than 800 seismic stations densely distributed throughout the Taiwan island as of 2008 (Figure 1). The TSMIP has a station spacing of about 5 km throughout most populated areas, except for the high-relief mountain ranges.

Using the accelerograms recorded by the TSMIP stations, Lin and Wu (2010b) also found that the logarithms of the areas inside a variety of PGA contours ranging from 100 to 400 Gal (1 Gal = 1.0 cm/s^2) have a linear relation to the corresponding earthquake magnitudes. The empirical area-magnitude relationship is expressed as

$$M_W = 1.95 \log A + 0.006P - 1.619, \tag{2}$$

where A is the area covered by one specific PGA (P in Equation 2) contour. They proposed that this area-magnitude relationship could be used to rapidly estimate earthquake magnitude without knowing the earthquake location while providing adequate seismic station density.

In this study we show and compare the magnitude estimations from the sub-network stations (M_{L10}), PGA attenuation relationship (M_{pga}), and the area-magnitude relationship for the 2010 JiaSian earthquake, since the new magnitude estimate methods are based on the regional EEWS approach. We propose that the two new regional-oriented EEW magnitude estimation methods (Lin and Wu 2010a, 2010b) might be implemented into real-time, online EEW practice in the future enhancement of the EEWS.

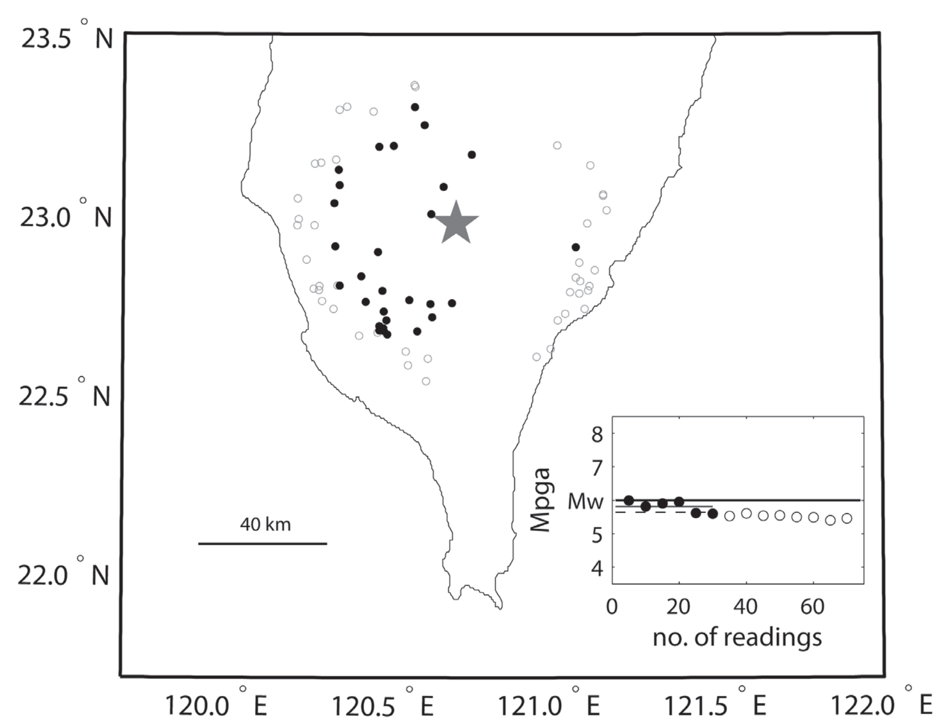
MAGNITUDE ESTIMATIONS

The epicenter of the 2010 JiaSian earthquake is closer to the RTD stations of the Tainan sub-network (Figure 2B) than to any others; hence the first real-time magnitude estimation of the 2010 JiaSian earthquake by CWB was computed from the simulated Wood-Anderson waveforms of the Tainan sub-network stations. There are a total of 13 stations of the Tainan sub-network (Figure 2B) and 56 stations of the whole RTD network that were triggered during the 2010 JiaSian mainshock.

Figure 3 compares the resulting earthquake magnitudes in M_L given by the Tainan sub-network and the whole RTD system. The magnitudes estimated by the Tainan sub-network and the whole RTD system are 6.33 and 6.26 with a standard deviation of 0.60 and 0.44, respectively. The reporting times after the original time of the event of the Tainan sub-network and the whole RTD system are 27 and 48 seconds, respectively. The comparison of the estimated magnitudes of the Tainan sub-network and the whole RTD demonstrates that using only stations close to the epicenter is accurate enough for magnitude estimation for practical EEWS purposes; however, the EEWS processing time is significantly reduced.

Figure 4 shows the resulting estimates of magnitude inverted by the PGA attenuation relationship with the epicentral distance (Lin and Wu 2010a). The estimated magnitude in M_W of the 2010 JiaSian mainshock is 5.81 with a standard deviation of 0.17 using the closest 30 PGA readings of the TSMIP stations with epicentral distances less than about 40 km. The actual PGA recording times after the occurrences of the event are between 15 and 20 seconds for stations with epicentral distances from 35 to 50 km.

Figure 5A plots the PGA contours for 200, 250, and 300 Gal recorded by the TSMIP stations of the 2010 JiaSian mainshock. The areas enclosed by these three levels of PGA contours are calculated and then used to estimate the magnitude in M_W in light of Equation 2 (Lin and Wu 2010b). The estimated magnitudes by the three PGA contours using Equation 2 is shown in Figure 5B. The estimated magnitudes by the three PGA contours are satisfactorily close to the reported magnitude ($M_W = 6.0$), especially for the 300-Gal contour (estimated $M_W = 5.96$), which still has the estimated magnitudes ranging between 5.78 and 6.12 if considering ±20 percent variation in the area. The furthest distance to the epicenter of the 300-Gal contour is between 35 and 40 km with the actual PGA recording times between 15 and 17 seconds.



▲ **Figure 4.** The estimated magnitude inverted by the PGA attenuation relationship (Equation 1). The estimated magnitude in M_W of the 2010 JiaSian mainshock is 5.81 (thin line in the inset) with a standard deviation of 0.17 (dashed lines in the inset) using the closest 30 PGA readings (solid circles in the map) of the TSMIP stations with epicentral distances less than about 40 km. The star shows the epicenter of the 2010 JiaSian mainshock. The open circles in the map show the other TSMIP stations with available PGA readings.

DISCUSSION AND CONCLUSIONS

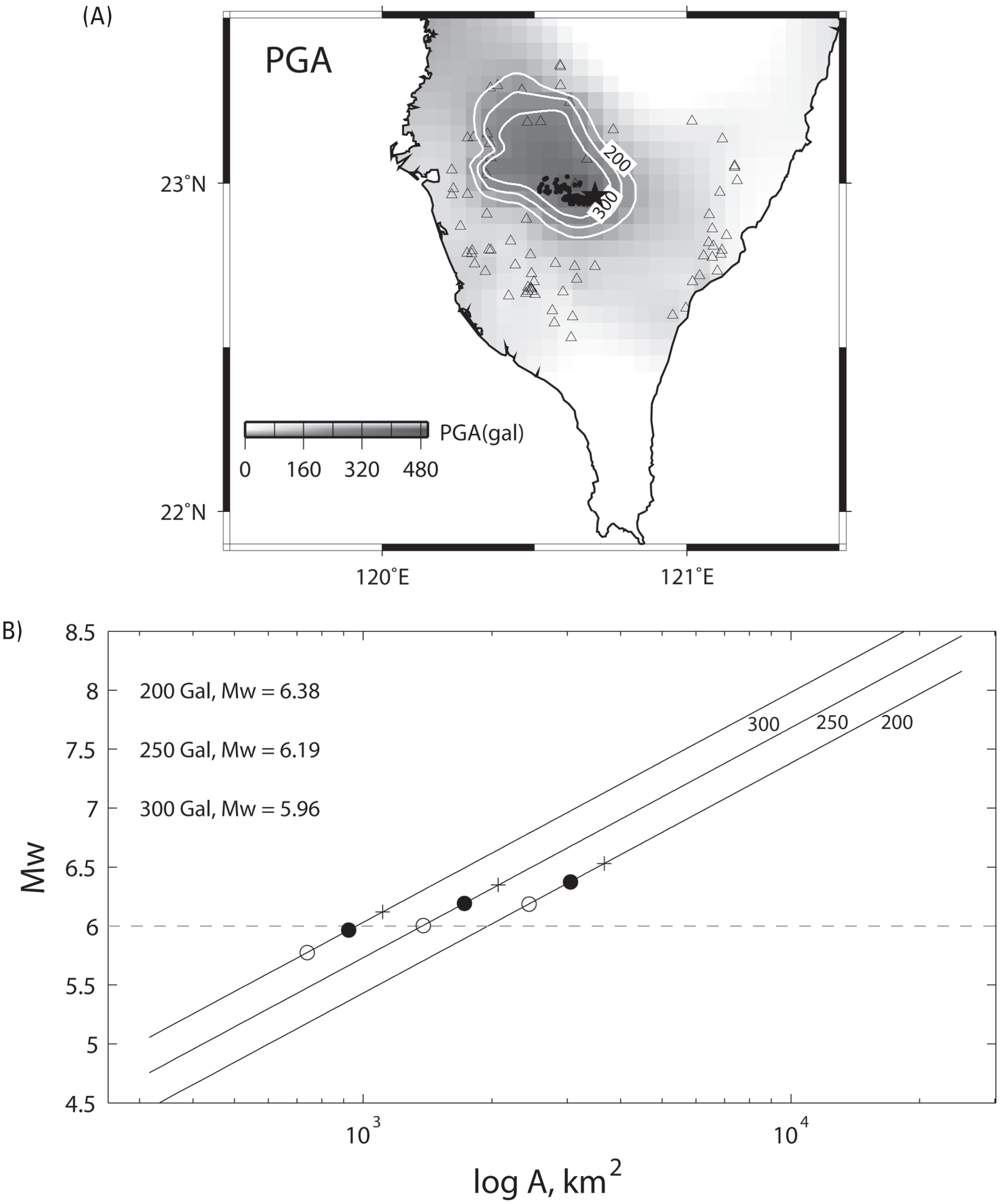
We have presented the online, real-time magnitude estimations for the 2010 JiaSian earthquake by the regional-oriented sub-network approach currently operating in CWB and offline test for two new regional-oriented magnitude methods (Lin and Wu 2010a, 2010b) using the TSMIP stations.

The magnitudes given by the new magnitude methods are fairly close to the reported magnitude for EEWS purposes. However, the source rupture duration during the online processing for the new magnitude estimation methods needs to be considered since PGA is used in the computations. In the case of the 2010 JiaSian earthquake, the actual PGA recording times are between 15 and 20 seconds for those stations with epicentral distances from 35 to 50 km. Considering the computation time, the expected online processing time for this study event should be less than 25 seconds.

According to Wells and Coppersmith (1994), the rupture duration for a magnitude 7 earthquake is 20 seconds, and for an earthquake with magnitude less than 6.5 is under 10 seconds. However, the actual rupture duration for a given magnitude event can vary by a factor of 2 or 3 (Olson and Allen 2005). Limited by the rupture duration, the new magnitude estimation methods (Lin and Wu 2010a, 2010b) seem to be more suitable for earthquakes with magnitudes less than 6.5. But even an earthquake with a magnitude 6.0 occurring at shallow depth and adjacent to a highly populated area or a vulnerable site is capable of causing severe damage.

One valuable merit of the magnitude estimation by the area-magnitude relationship (Figure 5) is that the event location is not a prerequisite parameter during the process. Therefore, any error or uncertainty in the event location does not transfer into the magnitude estimation, unlike the other two methods that rely on the parameter of the event distance. In other words, the other two methods have to wait for earthquake location information to proceed with the magnitude estimation algorithms, which inevitably consumes more EEW processing time. Another merit of this method is that it is directly related to the level of surface ground shaking, and hence it is inherently suitable for the purpose of the EEWS and rapid reporting systems. The level of surface ground shaking is the most important controlling factor in an earthquake's damage potential.

Finally, we propose that the two new regional-oriented EEWS magnitude estimation methods (Lin and Wu 2010a, 2010b) might be implemented into real-time, online EEWS practice in the future enhancement of the EEWS to build more redundancy in the rapid magnitude estimation. In real application, the capabilities of the two methods heavily depend on the spatial density of seismic stations. The EEWS research group at the National Taiwan University is now developing a prototype MEMS (micro-electro-mechanical systems) accelerometer (the "*P*alert" EEW sensor; http://www.sanlien.com.tw) specifically designed for EEWS purposes. The "*P*alert" EEW sensor is miniature, cost-saving, and ideal for recording near-field, high-frequency ground motions. The "*P*alert" EEW sensor can provide real-time three-component acceleration, integrated



▲ **Figure 5.** A) The PGA contours in southern Taiwan of the 2010 JiaSian earthquake. The star and the solid circles show the epicenters of the 2010 JiaSian mainshock and the aftershocks within two hours following the mainshock, respectively. B) The resulting magnitudes estimated by the empirical area-magnitude relationship (Equation 2) are indicated by the solid circles. The plus (+) signs and the open circles limit the magnitude fluctuations within ±20 percent variation in the area. The dashed line plots the reported magnitude.

velocity, and displacement. Once an earthquake is detected by an automatic *P*-picker algorithm (Allen 1978) embedded in the "*P*alert" EEW sensor, the sensor will also compute the peak displacement amplitude, P*d*, from the first three seconds of the *P* wave (Wu and Kanamori 2005b, 2008a, 2008b; Wu *et al*. 2007) and accordingly send an earthquake alarm signal. At the moment, about 20 of the "*P*alert" EEW sensors have been installed in one elementary school in Hualien, a high-seismicity region in eastern Taiwan, to conduct a field test. The two new magnitude estimation methods will gain more accuracy and practical possibilities once our in-development EEW seismic sensor has been extensively installed.

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