Development of an integrated onsite earthquake early warning system and test deployment in Zhaotong, China

Chaoyong Peng a,b,*, Xiaoyi Zhu b, Jiansi Yang a, Bing Xue b, Yang Chen b

a Institute of Geophysics, China Earthquake Administration, Beijing 100081, China
b Institute of Earthquake Science, China Earthquake Administration, Beijing 100036, China

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ABSTRACT

Earthquake Early Warning System (EEWS) is one of the effective ways to mitigate earthquake damage and can provide few seconds to tens of seconds of advanced warning time of impending ground motions, allowing for mitigation measures to be taken in the short term. In the present paper, we develop an integrated onsite EEWS called EDAS-MAS, which is based on the physical characteristics of the P-wave velocity greater than S-wave velocity. The instrument is a single device which includes a 3-channel MEMS accelerometer, a data acquisition unit, seismological processing, and three types of alarms. Two types of magnitudes are computed by using \( c - Pd \) values and the estimated hypocentral distance. It can directly raise the warning to the public when the magnitudes exceed the predefined thresholds, providing longer effective warning time and reducing the “blind zone” range. Although a majority of the reported events were small earthquakes and a relative high false alarms rate existed in the test, the results have shown the capabilities of the prototype EDAS-MAS for EEWS and are of practical importance for the design and optimization of the system.

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1. Introduction

Earthquake early warning system (EEWS) is one of the most effective ways to mitigate earthquake damage, which is able to take full advantage of the existing seismic monitoring network resources. It is used to describe real-time earthquake information that has potential to provide warning prior to significant ground shaking. This is possible by rapidly detecting the energy radiating from an earthquake rupture and estimating the consequent ground shaking that will occur in later time either at the same location or some other locations. It can provide a few seconds to tens of seconds of advanced warning time of impending ground motions, allowing for mitigation measures to be taken in the short term.

The concept has been around for as long as we have had electric communications but it is only in the last two decades that the necessary instrumentation and methodologies have been developed (Nakamura, 1988; Espinosa-Aranda et al., 1995). In particular, a rapid acceleration in the development and implementation of EEWS has been seen in the last eight years, fueled by a combination of seismic network expansion, methodological development, and awareness of the increasing threat posed by earthquakes paired with desire by the seismological community to reduce risk. A lot of effort for EEWS has been invested in different countries and regions, including southern California (Allen and Kanamori, 2003; Wu et al., 2007; Böse et al., 2008; Allen et al., 2009; Böse et al., 2009; Cua et al., 2009; Köhler et al., 2009), Japan (Nakamura, 1988, 1996, 2004; Horiuchi et al., 2005; Nakamura and Saita, 2007; Hoshiba et al., 2008; Brown et al., 2009; Kamigaichi et al., 2009; Sokolov et al., 2010), Taiwan (Wu and Teng, 2002; Hsiao et al., 2009; Chen et al., 2012), Mexico (Espinosa-Aranda et al., 1995; Goltz and Flores, 1997; Espinosa-Aranda et al., 1999; Suárez et al., 2009), Turkey (Erdik et al., 2003; Alcik et al., 2009; Fleming et al., 2009), Romania (Wenzel et al., 1999; Ionescu et al., 2007), Italy (Zollo et al., 2006; Weber et al., 2007; Olivieri et al., 2008; Zollo et al., 2009) and China (Peng et al., 2011). Meanwhile, studies on the properties of seismic waves and strong ground motion have provided scientific grounds for the implementation of EEWS such as \( \tau_{c} \) (Nakamura, 1996; Allen and Kanamori, 2003), \( \tau_{c} \) (Kanamori, 2005), \( Pd \) (Zollo et al., 2006; Wu and Kanamori, 2005,2008b; Lin et al., 2011) and \( Pv \) (Wurman et al., 2007).

There are two different approaches to realize EEWS: regional warning and onsite warning. In regional warning systems, traditional seismological methods are used by a network of stations to determine the locations and magnitudes of earthquakes and to estimate the ground motion in the region involved. In onsite warning systems, the initial ground motion at a single station is directly raised the warning to the public when the magnitudes exceed the predefined thresholds, providing longer effective warning time and reducing the “blind zone” range. Although a majority of the reported events were small earthquakes and a relative high false alarms rate existed in the test, the results have shown the capabilities of the prototype EDAS-MAS for EEWS and are of practical importance for the design and optimization of the system.
By now, there are just a few types of onsite warning systems, such as UrEDAS in Japan (Nakamura, 1988, 2004; Nakamura and Saita, 2007), Palert & i-touch system developed in Taiwan (Chen, 2011) in recent years. Most of the systems utilize the initial 3 s of P wave to estimate source parameters and trigger onsite alarm according to the preset thresholds. As the first generation of onsite EEWs, UrEDAS uses real-time data transferred from the observing system to estimate seismic parameters on a computer for early warning. For the Palert & i-touch system, it is composed of two instruments. The Palert is a three-component MEMS accelerometer and estimates seismic parameters on itself, while the i-touch will get three Palerts estimated seismic parameters for early warning. In this paper, we develop a new type of onsite warning systems called EDAS-MAS which includes a 3-channel MEMS accelerometer, a data acquisition unit, seismological processing, and three types of alarms. It can directly raise the warning to the public, providing longer effective warning time and reducing the “blind zone” range. The instrument is built on Linux 2.6.32 operating system and uses STA/LTA algorithm to automatically detect seismic events. When an earthquake occurs, $\tau_c$, $P_d$, and $M_{SG}$ values and the hypocentral distance will be evaluated by using the initial 3 s of $P$ wave. If the estimated $M_{SG}$ and $M_{SG}$ exceed the predefined thresholds, an alarm will be raised through LCD display, sound, and SMS.

2. Applied algorithms

2.1. Automatic seismic event detection

Automatic detection of seismic event is one of the most important seismological processing steps. An effective automatic detection can ensure the correctness of earthquake event recordings and reduce the follow-up data processing workload of digital earthquake observation. In principle, triggering can be performed using any real-time algorithm, under the constraint that it cannot be done with any method that requires data after the trigger itself, since by definition such data is unavailable at the time of the trigger (Wurman et al., 2007). Therefore, methods such as autoregressive pickers (Sleeman and van Eck, 1999) and pickers based on wavelet transforms (Zhang et al., 2003), are not practically suitable for early warning applications even though they are more precise than a simple short-term/long-term average (STA/LTA) algorithm (Baer and Kradolfer, 1987; Schweitzer et al., 2002; Trnkoczy, 2002; Trnkoczy et al., 2002).

For this reason, we adopt STA/LTA that is a classical seismic event detection algorithm in EDAS-MAS. Its basic principle is to process filtered seismic signals in two moving time windows: A short-time average window (STA) and a long-time average window (LTA). The STA is used for measuring the instant amplitude of the seismic signal and watching for earthquakes. The LTA is used to deal with the current average seismic noise amplitude. The STA/LTA can be calculated from filtered seismic signals as follows:

$$STA = \frac{1}{l_w} \int_{t}^{t+l_{m}} |x(t)| dt$$

(1)

and

$$LTA = \frac{1}{l_w} \int_{t}^{t+l_{m}} |x(t)| dt$$

(2)

where $l_m$ is the length of the short-time average window, $l_w$ is the length of the long-time average window, $x(t)$ is the filter seismic signal and $t$ is arbitrary time.

2.2. $\tau_c$–$P_d$ Method

$\tau_c$ method is a more rapid positioning algorithm developed by Kanamori (2005) based on Nakamura (1988) method, Allen and Kanamori (2003) method. It uses data during the initial 3 s of the $P$ waves to determine magnitude. The efficiency of EEWs can be greatly improved by this method. It can be represented as

$$\tau_c = 2\pi \sqrt{\int_{t_0}^{t_1} \frac{u^2(t) dt}{\int_{t_0}^{t_1} u^2(t) dt}}$$

(3)

where $u(t)$, $\dot{u}(t)$ are the ground-motion displacement and velocity from the vertical component record, respectively. The integration is taken over the time interval $(0, t_0)$ after the onset of the $P$-wave. Usually, $t_0$ is set at 3 s. $\tau_c$ can be used as a parameter representing the average period of the initial portion of the $P$ wave. If it is assumed that waveform in the initial 3 s s is $P$ wave, Brune source model (Brune, 1970) of small earthquakes can be used to prove that the calculated period parameter $\tau_c$ is the corner period of $P$ wave. $\tau_c$ approximately represents the $P$ wave pulse width which increases with the magnitude and can be used to estimate the event magnitude.

Another important element of EEW is to estimate the strength of $S$ wave shaking at a site from the initial $P$ waves at the same time. $P_d$ (Wu et al., 2007; Wu and Kanamori, 2008) which is defined as the maximum amplitude of a 2nd order high-pass Butterworth filtered vertical displacement during the initial 3 s of the $P$ wave is used to estimate the PGV at the same site. The relations between $P_d$ and the earthquake magnitude are statistically gained by using the strong motion records of earthquakes occurred in the Southern California and reveal that there is a good correlation between $P_d$ and PGV/PGA. Therefore, parameter $P_d$ can be used as a criterion to estimate seismic intensity in the warning target area. Furthermore, another fact that the event is most likely to be a destructive earthquake with magnitude greater than 6.0 when $\tau_c > 1$ s and $P_d > 0.5$ cm is also discovered.

3. Design and implementation

A block diagram of EDAS-MAS is shown in Fig. 1, with some technical details listed in Table 1. It consists of a sensor, three analog-to-digital converter (ADC) modules, a field programmable gate array (FPGA), an ARM CPU and a number of peripheral components. The sensor is used for picking signals from ground motion, which will be converted into digital signals through ADC. Then they will be organized into specified formats in FPGA and transferred to the ARM CPU by SSC. The CPU will use linear FIR filters to process these data and store them into a big ring buffer in Linux kernel. Applications can read data from kernel by Linux device interface and use them for storing, estimating seismic parameters, showing, and so on. All components are bought off-the-shelf, leading to EDAS-MAS being much less expensive (about 5000 RMB per unit) than standard seismometers. The components of each block, as well as the software running except the seismological processing onto the ARM CPU will be explained in more detail in Sections 3.1 and 3.2, respectively. The seismological processing will be described in Section 3.3.

3.1. Hardware implementation

A custom designed PCB board containing each hardware component has been fabricated. Special attention has been given on minimizing the board dimensions ($200 \times 130$ mm). Many test points and LEDs have been added in order to simplify the debugging process of the hardware.

The sensors include three accelerometers arranged to provide three-component (X, Y, and Z) data. The accelerometers are based on MEMS sensors called LIS344ALH which has a dynamically user selectable full-scale of $\pm 2 \text{g}, \pm 6 \text{g}$ and is capable of measuring
accelerations over a maximum bandwidth of 1.8 kHz for all axes. Here we select \( \pm 2 \) g as the full-scale, then its sensitivity is \( \frac{V_{dd}}{5} \) \( \pm 5\% \) and its zero-g level is \( \frac{V_{dd}}{2} \) \( \pm 5\% \) where \( V_{dd} \) is 3.3 V under 25°C.

To the ADC modules, low-power AD7684 which is a 16-bit, charge redistribution, successive approximation, PulSAR™ ADC that operates from a single power supply, VDD, between 2.7 V and 5.5 V is chosen. It contains an internal conversion clock and a serial, SPI-compatible interface port. The part also contains a low noise, wide bandwidth, short aperture delay, track-and-hold circuit. The sampling rate is 400 samples per second (sp). EP1C3 is selected as the FPGA, which is one of the Cyclone® field programmable gate array family based on a 1.5-V, 0.13-μm, all-layer copper SRAM process, with densities up to 20,060 logic elements (LEs) and up to 288 Kbits of RAM. All data from ADC will be coded in FPGA to distinguish between X, Y, and Z and transferred to the CPU by SSC.

EDAS-MAS uses at91sam9263 processor at 240 MHz which incorporates the ARM926EJ-S kernel. This processor runs the Linux 2.6.32 operating system with 2.6.32-at91 patch on which all embedded software is run. There is one slot for a CompactFlash card which acts as the hard disk (currently 8 GB in size, but easily increased). 32 MB Nand Flash is used for storing the YAFFS file system compiled within Busybox1.1.3.

Three modes of network communications are provided in EDAS-MAS, which are WLAN (wireless local area network, 2.4 GHz), 3G and 10/100 M LAN. The WLAN card is VT6656 which is USB standard compliant and 230 mA@3.3 V in 802.11 g mode. HUAWEI EM770 Datacard/Modem is used when in 3G communication mode. EM770 is a wireless terminal of the PCMCIA or Express or USB interface, supporting many standards. The user can choose one of these three communication modes in the actual applications.

A LCD module called AT056TN53 with size of 5.6 in. and resolution of 640x480 is designed in EDAS-MAS for showing real-time waveform, system parameters and seismic parameters. When an earthquake occurs, it will flicker for alarm. In order to operate the LCD interface, a touch screen with its control card, ADS7843, is used. The ADS7843 is a 12-bit sampling ADC with a synchronous serial interface and low on-resistance switches for driving touch screens. A measurement of the current Y position of the pointing device is made by connecting the X+ input to the ADC, turning on the Y+ and Y− drivers, and digitizing the voltage on X+. A sound card called AD1981B is also integrated into EDAS-MAS for sound alarm when an earthquake is detected.

### 3.2. Software functions

Except the seismological processing, the software operating on the EDAS-MAS currently consists of the following:

- Custom-built Linux operating system: The operating system for EDAS-MAS is Linux 2.6.32 with 2.6.32-at91 patch. In order to meet our demands, most codes for device drivers are deleted, only device drivers for serial ports, USB ports, SCSI ports (for CF

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**Table 1**

<table>
<thead>
<tr>
<th>Technical specifications of the various components that make up the EDAS-MAS.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accelerometers (MEMS LIS344ALH chip)</strong></td>
</tr>
<tr>
<td>Bandwidth</td>
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<tr>
<td>Sensitivity</td>
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<tr>
<td>Measurement range</td>
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<tr>
<td>Output noise</td>
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<tr>
<td><strong>Digital acquisition</strong></td>
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<td>Number of channels</td>
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<tr>
<td>AD converter resolution</td>
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<td>Input voltage range</td>
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<tr>
<td>Sample rate</td>
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<tr>
<td>Signal bandwidth (-3 dB)</td>
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<td>Timing</td>
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<td>Timing accuracy</td>
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<tr>
<td>Temperature range</td>
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<tr>
<td><strong>System processing modules</strong></td>
</tr>
<tr>
<td>Power supply</td>
</tr>
<tr>
<td>CPU</td>
</tr>
<tr>
<td>Output sample rate</td>
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<td>DRAM (dynamic random access memory)</td>
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<td>Operating system</td>
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<tr>
<td>Storage</td>
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<td>Power consumption</td>
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<td>Safety features</td>
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<td>User interface</td>
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<tr>
<td>Connectivity</td>
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<td>BIOS</td>
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**Fig. 1.** A schematic overview of the architecture of EDAS-MAS.
card), MTDBLOCK, FLASH, LCD, Touch screen, Sound card and network are remained. The file system programs like VFAT, NFS, YAFFS are also remained. Several of new device drivers are added to the system to support real-time data FIR filtering & buffering, WatchDog, temperature measurement, environmental monitoring and power management, etc. The ARM Cross Compiler 4.3.2 is used to compile the configured Linux codes. The U-Boot is selected to be the boot program. It occupies the initial address of the boot flash memory. When the system is powered on, it will run firstly to initialize hardware, to load the Linux kernel and to hand over control to Linux. After the Linux kernel startup is complete, the system will enter into the BusyBox environment through User/Password input. The BusyBox implements 90% Linux system commands, including ftp, http and telnet. All these together form the custom-built Linux operating system and need 30 MB Nand flash space to keep it.

- Data recording: The program that continuously reads the real-time data streams from the kernel buffer through the driver interface, archives them into files (1 file per hour) and stores the files in CF card. When the CF card has only 5% free space, the oldest files will be deleted until the used space is less than 70%.
- Real-time data service: This program is designed for supplying data to network centers (physical or virtual). Two types of services are designed to meet different needs. The implementation of them is based on the connection oriented protocol, TCP/IP. One type of services is to transfer real-time data per second while the other one called fast data service can provide low-latency (100 ms) real-time data service.
- System monitoring: The system temperature, voltage and the CF card READ-ONLY state will be checked per 10 s. The touch screen state will also be checked. If there is no touch operation more than 15 min, the LCD back light will be closed automatically. When someone clicks the touch screen, it will be opened again.
- LCD display: The program uses MiniGUI libraries for displaying. It contains three interfaces: the main interface displays three-component real-time waveforms which displaying length can be adjusted and displaying size can be zoomed in/out and centered; the system parameters interface displays the current configured parameters including longitude, latitude, network address, sampling rate, phase, voltage, temperature and the CF card states; the seismic parameters interface displays each calculated results and trigger time of the latest earthquake.
- Time service: Using NTP for system time service (Zhao et al., 2008). 3 times of the data standard deviation is used as a threshold to eliminate the singular data (means jumping out of the normal range). The system time will be adjusted per 1 min according to the calculated clock offset.

3.3. Seismological processing

EDAS-MAS is developed with the primary goal for performing real-time seismological analysis of EEW. Considering the early warning requirement of issuing ground-motion estimates as quickly as possible, and the fact that EDAS-MAS is composed of low-cost components, the general scheme designed for real-time processing involves the local, relatively simple, rapid, and robust analysis of data (Fig. 2). However, before the seismological processing proceeds, the 400 Hz real-time data transferred from the FPGA through SSC will be extracted and filtered by a FIR 135th
order low-pass linear filter into 200 Hz and 100 Hz, respectively. In order to reduce the CPU load, the extracting and filtering algorithms are coded in ARM assembly language. Loop unrolling and caching multiple data for filtering at one time are also adopted. 200 Hz and 100 Hz data are copied to ring buffers contained in the Linux kernel which can store 20 sec data and these data can be accessed dot by dot for STA/LTA detection.

The sequence of the processing undertaken by EDAS-MAS starts with the filtering of the accelerometer data using a 4th order bandpass (0.1–15 Hz) Butterworth filter, which is followed by the STA/LTA detection of the earthquake’s initial P waves (Section 2.1). An EDAS-MAS is triggered when the signal-to-noise ratio for P waves (SNRP) exceeds a predefined value, which must be set, as well as the STA and LTA width, for each station to best suit the local environmental seismic noise conditions. We employ the recursive formulation developed by NORSAR (Schweitzer et al., 2002; Trnkoczy et al., 2002), where the SNRP is updated at every data point. In order to make sure that the P- and not S-wave is picked, an event end threshold is set as 1.3 times of the LTA value which is frozen at the moment of the P-wave trigger. If the STA value is bigger than this value, we believe that the event is still in progress. Otherwise, the event is end.

Immediately after triggering, the original acceleration records are integrated to find velocity and displacement, and the double-integrated displacements are filtered using a high-pass recursive Butterworth filter with a corner at 0.075 Hz as empirically suggested by Kanamori (2005) and Wu and Kanamori (2005,2008b) in order to remove the long period drift. The peak acceleration amplitude $P_a$, peak velocity amplitude $P_v$, and $P_d$ are determined from the vertical components of the acceleration and the filtered velocity and displacement waveform within the 3-s window after the P arrival. $c$ is also determined from the 3-s vertical-component waveform after the P arrival. The hypocentral distance $R$ is obtained from a parameter $B$ whose logarithmic value is linearly proportional to $–\log(R)$ (Odaka et al., 2003). The parameter $B$ can be calculated from

$$\text{Acc}(t) = Bt \times \exp(-At)$$  \hspace{1cm} (4)

where Acc is the acceleration amplitude, $t$ is the time after the P-wave arrival, $B$ is the slope of the initial part of the $P$ waves, and $A$ is related to the amplitude variation with time. At this point, equations $M_{pa} = 4.748 + 1.371 \times \log(P_d) + 1.883 \times \log(R)$  \hspace{1cm} (5)

and $M_{tc} = 4.218 \log_{10}c + 6.166 \pm 0.385$  \hspace{1cm} (6)

will be used to estimate the two types of magnitudes (Wu et al., 2007). When the estimated $M_{tc}$ and $M_{pa}$ values exceed the predefined thresholds, an alarm will be released through LCD display, sound, and SMS.

### 4. Experiments and analysis

#### 4.1. Test deployment

The first test-bed deployment of EDAS-MAS was carried out with 12 stations installed in Zhaotong, Yunnan (Fig. 3) in March 2012. Zhaotong is located in the Xiaojiang Fault Zone, which is the boundary of Sichuan-Yunnan active block and stable Yangtze block. Since 1500, more than 10 earthquakes with magnitude greater than 6 have occurred in the Yunnan section of the Xiaojiang Fault, such as the 1833 Songming (6 September, $M=8.0$) and 1970 Tonghai (5 January, $M=7.7$, 15,621 people were killed and 32,431 people disability). Fig. 3 shows the location of the instruments. All the instruments are installed on the walls of apartment buildings. The nodes are powered sometimes by mains power with battery backup, or by PoE with battery backup, or in some cases by solar panels, again with battery backup. The 12 stations are named as ST1 to ST12. In order to get as many as possible EEW reports, low thresholds are set for triggering, with both $M_{tc}$ and $M_{pa}$ greater than 3.0.

#### 4.2. System performance: magnitude estimation and warning time

From 5 March 2012, to 20 October 2012, the average effective EEW reports for each station were 22 times within distance range between 45 and 56 km. All earthquakes are the main shock and aftershocks of the 2012 Yiliang Ms 5.7 earthquake (Fig. 3a). The network catalogs were provided by the China Earthquake Networks Center (CENC) and were used as ground-truth information for the EEW-determined events.

![Fig. 3. (a) Location map of Zhaotong, where the test-bed EDAS-MAS is situated. The red solid circles show the mainshock and aftershocks of 2012 Yiliang earthquake Ms 5.7. (b) The locations of 12 stations for the test EDAS-MAS.](image-url)
Fig. 4 shows a weak relationship between $M_{\text{c}}$ and $M_{\text{L}}$ with a standard deviation 1.45. For events with lower magnitudes, the $\tau_c$ values tend to have larger scattering, and many of them are unreasonably large. Even after removing values above 10 s that are considered unreasonable for the high pass filter with a 0.075-Hz corner frequency, the scattering is still too large. One of the reasons for the scattering in the data may be the low signal-to-noise ratio (SNR) of the strong-motion waveforms recorded by EDAS-MAS systems with a 16-bit resolution and a full scale of $\pm$ 2 g. However, the results of Wu et al. (2007) using earthquakes in Southern California show a clear scaling between $\tau_c$ and magnitude. The discrepancy between the two studies may be the result of the difference in equipment. In Wu et al. (2007), most of the stations used are equipped with both high-gain broad-band velocity and low-gain FBA sensors with signals digitized at 100 or 80 samples per second with a 24-bit resolution. In comparison to the new developed EDAS-MAS, the combination of broad-band and strong-motion sensors in earthquake monitoring can provide signals with higher SNR and still record large events with large dynamic range. In a separate study by Shieh et al. (2008) using the Japanese K-net strong-motion array records with a sampling rate of 100 Hz at a 24-bit resolution and a full scale of $\pm$ 2 g, a good scaling was observed between magnitude and $\tau_c$. Even though the strong-motion sensors record signals with lower SNR than broad-band sensors, the combination of the 24-bit resolution and their data selection of only 6 nearest records from each event with $M_{\text{L}}$ equal to or larger than 6 provides a good SNR for their analysis. Results from these studies indicate that $\tau_c$ may be too sensitive to the SNR, as indicated by Wu et al. (2007).

The relationship between $M_{\text{Pd}}$ and $M_{\text{L}}$ shown in Fig. 5 has proved that the $P_d$ attenuation relationship with the hypocentral distance (Wu and Zhao, 2006; Wu et al., 2007) can be used in the tested area. For event greater than M 4.0, the two types of magnitudes show relatively good coincidence. However, this relation underestimates the magnitude by about 0.3 units on average. This provides an average calibration for the EEW magnitude estimator. For all the events, the average magnitude difference was approximately 0.4 magnitude units. One factor leading to the magnitude difference is the $P_d$ attenuation relationship with the hypocentral distance. This relationship should be reconsidered in a future study.

As to the warning time, because all the events are the Yiliang main shock and its aftershocks, the warning times for these events are almost the same. The average warning time for these events is 8.1 s. Fig. 6 shows the measured records of the main shock at ST3, with the south–north orientation and east–west orientation shown from top to bottom, and the vertical acceleration duration record. The time warnings were issued is 3.2 s after $P$ arrival and the time of maximum vibrations is 12.4 s. Therefore, the effective warning time is 9.2 s while ST3 is located 51 km from the epicenter.

4.3. Dealing with false alarms: a practical perspective

A problem with the prototype EDAS-MAS is its false alarm. For events greater than M 3.5, there were 23 triggered reports during 5 March 2012 to 20 October 2012, among which 9 events were false alarms, yielding a rate of 39%. Among them, the biggest false alarm is an “M 6.2 earthquake” reported by ST8, ST9, and ST10 at 14:53:21 on 1 May 2012. These false alarms were caused primarily by abnormal signals recorded at approximately the same time by the stations.

In future work, the instruments will be connected together to exchange seismic information for early-warning decision-making, careful calibration and evaluation of the system will be performed, technical methods for frequency-domain processing to recognize and discriminate abnormal signals will be used, and time-space coherence of all triggered stations will be automatically analyzed. Additionally, by increasing the triggering threshold for magnitude and number of triggered stations, the false alarm rate will be decreased.

5. Conclusions

This paper has presented the development of a new instrument for onsite earthquake early warning called EDAS-MAS which
includes a 3-channel MEMS accelerometer, a data acquisition unit, seismological processing, and three types of alarms. It can directly raise the warning to the public, provide longer effective warning time and reduce the “blind zone” range. The system is built on Linux 2.6.32 operating system and STA/LTA algorithm is used to automatically detect seismic events. When a seismic event is detected, \( \tau_c - \tau_d \) values and the hypocentral distance will be evaluated by using the initial 3 s of \( P \) wave. When the estimated \( M_f \) and \( M_{ld} \) values exceed the predefined thresholds, an alarm will be raised through LCD display, sound, and SMS.

From the results in this study, we found that \( \tau_c \) do not show a good scaling relation with the magnitude due to its sensitivity to the SNR. Thus, \( \tau_c \) as an indicator may not be suitable for the onsite EEW using the EDAS-MAS system. On the other hand, \( P_d \) is found to be a good indicator for the destructiveness of an earthquake. Of course, the practical implementation of this new system still has to be validated through more earthquakes. Meanwhile, other thresholds, such as \( P_v \) and intensity, should be included in this system. Although a majority of the reported events were small earthquakes, using the network catalog as calibrating information we can evaluate the magnitude estimation (for the low-magnitude range). The result is of practical importance for the design and optimization of the system. Minimizing false alarms and missing reports is also important. As time elapses, ongoing evaluation, calibration, and optimization of the system may make the system more reliable. In addition, intensity evaluation will be included in the next version and information appropriate for ShakeMap-type output will be generated for higher resolution maps, allowing us to make neighborhood-scale loss assessments.

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