A Dedicated Seismic Early Warning Network: 
The Mexican Seismic Alert System (SASMEX)

by Gerardo Suárez, J. M. Espinosa-Aranda, Armando Cuéllar, Gerardo Ibarrola, Armando García, Martín Zavala, Samuel Maldonado, and Roberto Islas

ABSTRACT

The Mexican Seismic Alert System (SASMEX) initiated operations in 1993. It was the first to broadcast seismic early warnings to the general population. Today, SASMEX is composed of 97 monitoring stations that straddle practically the whole subduction zone of Mexico. The system also includes strong-motion instruments that monitor the seismicity within the subducted Cocos plate. These earthquakes are located inland, close to the major population centers of Mexico. The monitoring stations are linked to control and distribution centers that receive, decode, and broadcast the alerts by a redundant telecommunications network. The dissemination of the early warning alerts is done through low-cost radio receivers, subscribing television and radio stations, and, in Mexico City, by the system of municipal loudspeakers installed in the streets throughout the city. From 1993 to 2017, the network has recorded 6896 earthquakes and has issued 158 seismic early warnings. The more recent examples of successful seismic alerts are the two earthquakes that occurred in Mexico in September 2017. In the case of the great Tehuantepec earthquake of 7 September 2017 (MW 8.2), SASMEX gave almost 2 min of warning prior to the arrival of the strong-motion seismic waves in Mexico City. The second case was the Morelos earthquake of 19 September 2017 (MW 7.1). The short epicentral distance to Mexico City of ~120 km allowed only few seconds of warning prior to the arrival of the S waves.

Electronic Supplement: Table listing all the early warning alerts issued publicly by Mexican Seismic Alert System (SASMEX) in all the cities subscribing to the system.

INTRODUCTION

The 1985 earthquake was a turning point in the development of seismology and earthquake engineering in Mexico. The morning of 19 September 1985, Mexico City woke up to a large earthquake that lasted for several minutes. The resulting damage was unprecedented, in both human and material losses (e.g., Anderson et al., 1986; Rosenblueth, 1986; Esteva, 1988). The extent of the devastation was unexpected, considering the relatively long distance between this subduction zone earthquake and the city. The reason is that the soft clays, on which Mexico City is built, produce large amplifications of the incoming waves that result in large and long-lasting accelerations of the ground (e.g., Bard et al., 1988; Kawase and Aki, 1989; Ordaz and Singh, 1992; Wirgin and Bard, 1996; Reinoso and Ordaz, 1999).

The possibility of a future great earthquake to the south of Mexico City led the scientific community to propose in 1986, the creation of a seismic alert system (SAS) for Mexico City (Consejo Nacional de Ciencia y Tecnología [CONACYT] and National Research Council, 1986). The development of a seismic early warning system was one of the several measures taken to improve the readiness and resilience of the city to future earthquakes along the subduction zone, on the Pacific coast of Mexico. To this end, in 1991, the Centro de Instrumentación y Registro Sísmico, A.C. (CIRES, Center for Instrumentation and Seismic Recording) developed the SAS to warn the population of Mexico City. CIRES is a nonprofit organization. The government of Mexico City decided at the outset to use this legal figure to decentralize the system and offer it administrative and technical autonomy, under the supervision of the city government.

The objective was to detect and identify potentially large earthquakes using a dedicated network of free-field strong motion (FS) stations distributed along the coast, to warn the population of the capital city of Mexico of destructive incoming waves (Fig. 1). It was estimated that the time difference between the opportune identification of an earthquake in the subduction zone and the arrival of strong motion of the ground in the city would give ample time to evacuate schools and low-rise buildings. CIRES was mandated from the beginning to develop and manufacture its own instruments designed specifically for a seismic early warning system.

In Mexico City, the system allows a warning time between 60 and 120 s prior to the arrival of the S waves from subduction...
earthquakes. This time of opportunity allows putting in place public measures designed to reduce human losses in the city. For example, schools conduct regular evacuation exercises to benefit from this long warning time. SAS started operations in an experimental manner in 1991 and began to function formally as a public service to the city in 1993. Alerts would be given out whenever two or more stations recorded ground-motion amplitudes above $M_b 5.5$. The system, originally called SAS, was composed of 12 strong-motion sensors distributed along the southeastern end of the Guerrero gap (Fig. 1). In this part of the subduction zone, immediately to the south of Mexico City, the last earthquake with magnitude $M_w > 7.0$ took place in 1911. Therefore, it is assumed that an important accumulation of stress exists in this segment of the coast of Guerrero (McCann et al., 1979; Singh et al., 1981).

On 14 May 1993, the Mexican early warning system detected an $M 6$ earthquake in the subduction zone and gave an advanced warning to Mexico City of $\sim 60$ s, prior to the arrival of the strong-motion seismic waves. This successful result during the testing phase prompted the local authorities of the city to disclose the early earthquake warnings publicly. Thus, SAS became the first early seismic warning system worldwide to issue alerts publicly (Lee and Espinosa-Aranda, 2003).

Almost 10 yrs after the disastrous earthquake of 1985, SAS correctly identified the Copala earthquake of 14 September 1995 ($M_w 7.3$) as potentially damaging to Mexico City. An alert was issued, giving a warning time of 70 s to the population of Mexico City, prior to the arrival of the strong shaking. Many schools were promptly evacuated in a timely manner, proving the usefulness and functionality of the system. A few years later, a damaging earthquake on 15 June 1999 ($M_w 6.7$) caused important damage in the state of Oaxaca, in southeastern Mexico. As a result, the government of Oaxaca gave CIRES the responsibility to build a seismic early warning system in this region (Espinosa-Aranda et al., 2009). This system became known as Sistema de Alerta Sísmica de Oaxaca (SASO) (Fig. 1). SASO and SAS were fused in 2012 to form the integrated Mexican seismic early warning system called SASMEX (Cuéllar et al., 2014).

In 2010, SASMEX initiated a project to expand its coverage. From the 12 original stations commissioned in 1991 along the southern coast of the state of Guerrero, the system now
covers practically the whole subduction zone. Thus, thanks to funding from the federal disaster prevention institutions Fondo para la Prevención de los Desastres Naturales (FOPRE- DEN) and from the government of Mexico City, 97 strong-motion stations monitor the subduction zone of Mexico, from the Isthmus of Tehuantepec to the end of the Rivera plate subduction zone, beneath western Mexico (Fig. 1). Additional strong-motion stations, located inland, were added to the system. These stations monitor in-slab earthquakes that occur within the subducted Cocos plate. These earthquakes are more infrequent than subduction events to the south, and are generally of smaller magnitude. Nonetheless, they are also potentially damaging not only to Mexico City but also to other population centers in central Mexico.

To date, SASMEX has issued 158 seismic alerts culled from 6896 detected earthquakes (© Table S1, available in the electronic supplement to this article). This article presents an overview of the system, its basic components, and the communication networks that confirm it. It also reviews the performance of the system during the past 26 yrs of operation and evaluates the contribution that the system has made to the strong-motion catalog of Mexico.

**TECHNICAL CHARACTERISTICS OF THE MEXICAN EARLY WARNING SYSTEM**

According to the United Nations, an early warning system must be centered on the people at whom the alert is targeted and comprise four interrelated elements: (1) knowledge of the risk involved; (2) effective means of dissemination and communication of the alerts; and (4) an adequate response capability of the population (United Nations, 2006). Furthermore, to be an effective earthquake early warning system, the operational segment must be capable of being activated within a few seconds after the detection of a seismic event and to disseminate the alert in the shortest possible time. The detection process should be part of a continuous and automatic monitoring activity. The dissemination and communications instrumentation processes should be linked to well-structured engineering procedures with the goal of attaining the highest rate of data availability, system reliability, and resilience. In the design of the SASMEX network, these considerations were taken into account in the design and operation of the main components of the system: the seismic sensing stations, the communications network, the collection and control nodes, and the decision-making algorithms that decide in real time the magnitude ranges of the earthquakes detected by the strong-motion sensing stations (Fig. 2).

**The Monitoring Field Stations**

As mentioned above, in the initial stage of SASMEX, the coverage included only part of the Guerrero gap (Fig. 1). The first years of operation showed that several earthquakes located outside of the instrumented region were strongly felt also in Mexico City. Clearly, SASMEX was unable to issue timely alerts for these earthquakes, raising uncertainty in the population about the reliability of the system. For example, the 1999 Tehuacán, Puebla, earthquake ($M_w$ 6.9) had an epicenter located ~200 km away from the closest SAS stations. Because of the long distance of the epicenter to the closest SAS station, the early warning issued did not give an effective time of opportunity. As a result of this unfavorable situation, funding allowed the expansion of the network in 2012. Today, SASMEX has 97 FS stations (Fig. 1).

The FS stations consist of triaxial accelerographs and the corresponding communications equipment. Since the beginning, the FS instrumentation has been subjected to a continuous process of technological improvement and modernization. The original instruments built by CIRES were digitizers with 10-bit resolution and a 50-Hz sampling rate. Today, the FS stations of the network have 12-bit digitizers and sample at a rate of 100 Hz. A third generation of instruments is now under final testing and ready to be deployed in the coming months. The new digitizers will have a 24-bit resolution with an embedded Linux computer sampling at 100 Hz. All of these FS stations are designed and manufactured by CIRES. The seismic equipment is continuously modernized as funding permits.

The distribution of stations was designed considering the unusually shallow depth of the subduction zone earthquakes. The FS stations form a front line along the Pacific coast of Mexico with an average spacing of 25 km (Fig. 1). This station spacing ensures that the $S$–$P$ times are less than 3–4 s. The inland stations, monitoring the in-slab earthquakes, are distributed with an average interstation distance of ~40–60 km. The site selection of the FS stations was made taking into consideration the local seismic, geological, and soil dynamic conditions. A background seismic noise analysis was performed to select the final location of an FS site. Sites where the background seismic noise was high in the 1–10 Hz band were avoided. Additional elements, aimed at strengthening the resilience and reliability of the network, such as physical security, communications line of sight and ease of access, for example, were also taken into account in the final selection decision. Figure 3 shows a picture of a typical FS station in the town of El Cortés, to the south of Mexico City.

**Structure and Topology of the Communications Network**

When an earthquake is detected, the data generated by the FS stations are sent as a distributed system to collection centers located in the cities receiving the seismic alert. SASMEX uses redundant platforms to channel the early warning information: radios, satellite links, and private Internet links form the backbone of the telecommunications network. The redundant communications are designed to guarantee the data availability and reliability of the system (Fig. 4).

The FS stations issue the warning parameters using VHF, UHF, and HF unidirectional radio links, via two different communication channels. This dual transmission is designed to reduce the possibility of interference of the alerting signal by other radio communication systems in the vicinity of the FS stations or near the repeater sites. The radio communication system is also designed by CIRES and has similar maintenance
procedures and environmental and security protection as the FS stations of the system.

The radio transmitters are kept offline to save power. They are automatically turned on when the algorithms running in the FS stations detect the need to issue an early warning broadcast. Once open, the radio link offers a high-power communication path to relay the coded alerting message. The alerting message is coded to prevent hacking of the system and the broadcast of false or spurious alerts. The same communications protocol holds for the routine transmission of the state of health parameters from all FS and radio repeater sites. The standby capability of the radio links is designed to reduce the electrical power demand, making it possible to operate exclusively with an independent energy supply based on solar panels.

The alert messages sent by the sensing stations are received by central control and broadcasting systems called EASAS (acronym in Spanish of Alternate Emission Stations of the Seismic Alert System). One of their functions is to receive and decode the digital messages sent from the FS stations. These data are then used to make the decision whether or not to activate an earthquake early warning. As explained in more detail below, when two or more stations confirm the required magnitude range an alert is disseminated. In other words, the EASAS need at least two neighboring FS stations to confirm the presence of an earthquake of the established magnitude range to broadcast an alert. EASAS are installed in all cities subscribing to SASMEX. In addition, based on the scheduled state of health messages sent by the FS stations, the EASAS generate logs summarizing information on the operational performance of the FS station based on the state of health reports.

**Dissemination of Seismic Early Warning Alerts**

In 1991, CIRES was instructed by the Mexico City authorities to broadcast preventive alerts to owners of dedicated receivers of the system in case of an earthquake with body-wave magnitude $5.0 < m_b < 6.0$. In the case of earthquakes $M_b \geq 6.0$, SASMEX was instructed to relay public alerts that, in addition of being received by the dedicated receivers, would be broadcast via the radio and television stations that volunteered since 1993 to disseminate the seismic alert to the public (Espinosa-Aranda et al., 1995). Since 2012, the preventive alert threshold was raised to $M_b \geq 5.5$. Local authorities in other cities define their own alerting levels according to their particular situation; for example, in Oaxaca, the preventive alert was defined for magnitude estimation of $5.0 \leq m_b < 5.5$, and for public alert when $M_b \geq 5.5$. All alerts share the same siren sound.
According to the current regulations in Mexico City, the broadcast of an earthquake early warning must be made within 5 s of the decision to alert, regionalized, and aimed at the largest number of people as possible. The new regulations also prescribe that the devices that receive the seismic alert must meet specific technical criteria to be in acceptable conditions to emit the seismic alert. Also, the law requires that seismic early warning devices should be installed at all strategic buildings such as hospitals, public offices, and security buildings. SASMEX disseminates the seismic alerts in the form of a siren sound through five technologies:

1. Several radio and TV stations broadcast public alerts of strong earthquakes. Audio switches are installed at all cooperating radio and television stations that remotely trigger the early warning signals. The switches are controlled and operated exclusively by SASMEX.

2. Dedicated radio receivers built by CIRES, called SASPER, integrate a receiver of the seismic early warning signal with loudspeakers that broadcast both preventive and public alerts. Independent radio links are used to disseminate the alert via these devices.

3. A modified version of multihazard radio receiver system from the National Weather Radio of the National Oceanographic and Atmospheric Administration (NOAA) using the Specific Area Message Encoding (SAME) protocol (Fig. 5).

4. Recently, the government of Mexico City made the decision to issue all seismic early warnings though the system of public loud speakers distributed throughout the city. The city of Oaxaca also uses seven large loudspeakers since 2003.

5. After the September 2017 earthquakes, the government of Mexico City launched as an experiment a cell phone application called 911 CDMX. This app will be used to measure potential delays between the warning issued by the server and the reception by individual cell phones. This will allow judging the applicability of this alert broadcasting technology in the future.

Since 1993, several radio and TV stations that are part of the Broadcasters Association of the Mexico City Valley broadcast the public seismic alerts. In addition, television channels 7, 11, 13, and 22 in Mexico City, and channel 34 in the Toluca Valley, also relay the warning signals. In the cities of Chilpancingo, Acapulco, Oaxaca, and Puebla, several local radio and TV broadcasters volunteered to broadcast the seismic alerts.

To ensure the timely and reliable dissemination of the early warning alerts, all broadcasters accepted the use of remotely controlled switches independently operated by SASMEX. These switches automatically substitute the regular programming with the official sound signal of the alert. The unique, high-pitched and clearly identifiable signal, warning of an impending earthquake has a 60-s duration. Television broadcasting of the seismic alerts constitutes an excellent resource, particularly during the periods of highest public ratings. This allows warning to a large segment of the population. To date, 28 AM, FM, and TV channels disseminate the warnings in Mexico City and in the Toluca Valley; 9 radio and 2 TV stations do likewise in Oaxaca City. In the cities of Chilpancingo and Acapulco, over 100 users, including radio and TV stations, schools and emergency response institutions receive SASMEX warnings (Table 1).

In 1993, SASMEX developed a dedicated radio, called SASPER. This was the first mechanism used by SASMEX to receive and broadcast seismic alerts. SASPER is operated and supervised by CIRES. It is also used, in a modified version, as a control system to retransmit the earthquake early warnings to other communication systems. Although SASPER has a very high level of reliability, manufacturing costs are high and few units were installed. The users of SASPER devices are mainly authorities, universities, and schools. Emergency response and civil protection institutions use SASPER radio receivers to prepare emergency vehicles and initiate the evacuation of their facilities and parking lots. There are now ∼300 users using this equipment in Mexico City, including the Red Cross and the firefighters.

Since 2008, SASMEX incorporated as part of its alert dissemination devices, a low-cost multihazard radio called SAR-
MEX, which is a modified version of the National Weather Radio of the NOAA (Fig. 5). These radios use NOAA Weather Radio-Specific Area Message Encoder technology (NWR-SAME) based on the norm established by Federal Emergency Management Agency in the United States, to ensure that alerts are received only by radios located in the targeted locations. CIRES modified and improved these radio receivers to be able to receive and to broadcast the seismic warning signals in less than 3 s. SARMEX were used for the first time during the earthquake of 27 March 2009 (M 5.3).

All schools in Mexico City that are located on the soft lacustrine soils have SARMEX radios in every classroom. Today, 89,000 SARMEX devices are in use in the cities of Acapulco, Chilpancingo, Morelia, Puebla, Oaxaca, and Mexico City. In 2013, this radio was used in a pilot test by the Mexican Navy (Secretaría de Marina) as the means of transmitting alerts from the Mexican Tsunami Early Warning System.

On 19 September 2015, as part of the activities commemorating the destructive 1985 earthquake, more than 6700 loud speakers installed throughout Mexico City were incorporated to the SASMEX dissemination system. The loud speakers prioritize seismic warnings over any other task. Ten days after the system was inaugurated, a preventive alert was issued of an M 5 earthquake off the cost of Guerrero. These loud speakers broadcast both preventive and public alerts and 98% of the loudspeakers are turned on within 5 s. In downtown Mexico City, one of the more vulnerable parts of the city, the loudspeakers emit the alert in less than 2 s. It is estimated that the loudspeakers may reach up to 25 million people.
QUALITY ASSURANCE AND DATA AVAILABILITY

Clearly, FS stations in an earthquake early warning system should operate 24 × 7, with a high level of data availability. To guarantee the operation of the stations, the instruments are protected against salinity, atmospheric phenomena, and vandalism. To guarantee its operational capability and the early detection of problems or potential failures, the FS stations follow a routine to report oral prerecorded messages and a written log file twice a day, describing state of health parameters.

The FS stations are powered by solar panels and use fiber optics links to the local radio transmitter, which is the first element of the communication system network. All failure and damage reports are transmitted to both the EASAS and to the central data management center in Mexico City. HF, VHF, and UHF radio links are used to report both the routine status messages and the eventual seismic warning data. The operational procedures establish that when a malfunction is detected, the technical maintenance staff should arrive at the FS site within 24 hrs of the confirmed report to conduct the repairs. The seismic sensor has several algorithms to perform self-diagnostics that recognize unusually high level of urban noise or induced vibrations. The detection algorithms identify stations with persistently high seismic noise and downgrade their contribution in the alerting criteria.

ALERT ISSUANCE CRITERIA

The process to issue an early seismic warning signal is initiated in the strong-motion stations installed in the field (FS). These stations continuously calculate the parameters used to detect a potentially large earthquake based on the algorithms developed by CIRES. The stations along the subduction zone run in parallel the 2(tS–tP) and tS–tP algorithms (Cuéllar et al., 2017a).

To issue an alert, these algorithms measure various parameters and the seismic energy released in the period twice the time between the P and the S phases, in the first case, and within this time window in the latter case. The sensing stations of SASMEX have no absolute time signals, as they were designed specifically for the purpose of a seismic alerting system and not to locate the earthquakes. The arrival-time detection of the P and S waves is determined based on two independent methodologies.

Since the beginning of operations in 1991, SASMEX has used an algorithm, which, based on the seismic energy released in the period 2(tS–tP), discriminates and classifies the magnitude. The algorithm bases its decision on two parameters: (1) the amplitude of the cumulative average squared acceleration and (2) the instantaneous rate of growth of the seismic energy. The resulting values of these two parameters are mapped to a set of curves calibrated with earthquakes of known magnitude. At the time that the algorithm was designed, it made use of magnitude $m_w$. Recently, Cuéllar et al. (2017a) made a detailed performance evaluation of this algorithm demonstrating its robustness in classifying earthquakes in the magnitude bins prescribed by the Mexican authorities to issue early warning seismic alerts; Cuéllar et al. (2017a) describe in detail the algorithm design and performance. The sensing stations of SASMEX have no absolute time signals, as they are designed specifically for the purpose of a seismic alert.

More recently, CIRES developed an algorithm designed to reduce the time necessary to issue an early warning. The new algorithm takes half of the time to conclude the decision-making process relative to the 2(tS–tP), by measuring the seismic energy released in the coda of the P wave during the time lapse S–P. The so-called $tS−tP$ algorithm is based on two parameters: (1) the logarithm of the peak ground acceleration, $\max(a(tS−tP))$, and (2) the logarithmic cumulative acceleration $SA(tS−tP)$. The model is built using a learning machine process that iteratively parameterizes in segments the linear fit of $\max(a(tS−tP))$ and $SA(tS−tP)$ to $M_w$ values determined from calibration earthquakes (Cuéllar et al., 2017b). The FS stations on the coast run the two algorithms in parallel. The decision to issue an alert is taken by the first algorithm that meets the pre-established criteria. For example, in the case of the recent 7 September 2017 earthquake ($M_w 8.2$), the $tS−tP$ algorithm was the first to trigger the alert.

THE HISTORY OF EARLY WARNINGS ISSUED

During its 26 yrs in operation, SASMEX has identified and recorded 6896 earthquakes ranging in magnitude from $4 < M_w < 8.2$. The largest earthquake by far recorded by the SASMEX network is the 7 September 2017 Tehuantepec earthquake. Of these earthquakes, SASMEX has broadcast 158 seismic early warnings to the various cities subscribing
to the system. In Mexico City, in particular, the system has issued 103 alerts; 32 of them have been public alerts for earthquakes $M_w > 6$, and 70 for moderate earthquakes $5.5 < M_w < 6$ (Table S1).

These statistics beg for the question: What is a successful seismic early warning alert? Clearly, a false alert is one issued when there is no earthquake. Another case is the omission of issuing an alert when a large earthquake occurs. Clearly, the purpose of an early warning system is not to produce a parametric seismic catalog with accurately estimated magnitudes, particularly for large earthquakes. The algorithms, however, should be able to avoid underestimations or overestimations of magnitude within an adequate probabilistic range. Clearly, to accurately estimate the magnitude in the range $5.5 < M_w < 6$, during the very short time necessary by an early warning system, is extremely difficult (Iglesias et al., 2007; Suárez et al., 2009).

During its 26-yr history, SASMEX has issued only one false alert. It took place on 16 November 1993, during the first months of the operational stage of SAS. In fact, in the view of its technical experts, the system was launched publicly before it was fully tested, due to the governmental need to demonstrate the existence of a seismic early warning system serving Mexico City. Admittedly, in the more difficult issue of issuing preventive alerts, the system has at times broadcast preventive alerts for earthquakes that are smaller than $M_w 5.5$. In this case, however, the reaction of the population has been generally positive.

Defining magnitude thresholds to issue alerts is particularly difficult in Mexico City. People in the areas underlain by soft shale in the central part of the city are subjected to ground motion that is many times larger than the acceleration felt in the high regions surrounding the city. Thus, earthquakes that may be strongly felt by people in downtown Mexico City may be overlooked in the highlands of the valley. As a result, when citizens perceive that an earthquake occurred, even when the ground motion experienced was smaller than expected, they tend to trust the alert. The opposite is certainly unacceptable, when an earthquake is strongly felt and no alert sounds. SASMEX has never had this situation.

The performance of the $2(t_S-t_P)$ algorithm is illustrated by the results of the systematic tests conducted by Cuéllar et al. (2017a). These tests demonstrate that this algorithm is a robust and effective tool for a seismic early warning system. The tests conducted on the 59 acceleration records of 31 earthquakes with at least two or more accelerograms and with $M_w \geq 6$ indicate that in all cases, with the exception of one strong-motion record, the events are classified as $M_w \geq 6$. Thus, the algorithm shows a high level of reliability and robustness. Although the algorithm underestimates the magnitudes of large and great earthquakes, these events are identified and classified as $M_w \geq 6$. During the expansion phase of SASMEX, from 2013 to 2015, the magnitude of two earthquakes ($M_w < 6$) was overestimated and a public alert was issued.

Similar results were obtained also for the $(t_S-t_P)$ algorithm that is now running in parallel at the FS stations. The performance of $t_S-t_P$ algorithm was tested as a warning tool using 89 earthquakes in the Mexican subduction zone from 1985 to 2017 that met the criterion of having at least two stations within 70 km from the epicenter. The results show that 79 were correctly screened. The magnitude of six events was underestimated and four were underestimated. Those that were not correctly estimated had very unfavorable distances from the epicenter to the closest stations. Cuéllar et al. (2017b) describes in detail the design of the algorithm and the performance tests.

### DATA GENERATED BY THE SASMEX NETWORK

SASMEX was conceived and designed as a seismic early warning system for Mexico City. Throughout the years, several other cities in southern and western Mexico saw the usefulness of having a seismic alert and the system grew gradually. During its operation, it has successfully warned of incoming seismic waves of the largest events in the region and has become a crucial tool of the civil protection efforts in the country against seismic phenomena (Table 2).

During the course of its operation, SASMEX has recorded 6896 earthquakes, which have generated 14,750 accelerograms of both subduction earthquakes and events occurring within the subducted Cocos plate beneath the continent (Table 2). Accelerograms recorded by SASMEX and by the strong-
motion network of Mexico City, also operated by CIRES are being restructured. As an example of the data gathering potential of the SASMEX network of instruments, with the current number and distribution of FS stations, on average the network records 35 earthquakes and 70 accelerograms per month. The data are available with the previous permission of the Oaxaca and Mexico City authorities to interested users in the engineering and scientific community. In the early years, the system used fax and e-mail to communicate results. Nowadays, it uses e-mail, webpages, social networks, and RSS services. An educational and outreach effort to the public is made through several social media listed in the homepage of CIRES website (see Data and Resources).

SUMMARY AND CONCLUSIONS

Although Mexico City is relatively far from the large earthquakes that occur in the subduction zone, the particular characteristics of the soil in Mexico City presented a unique opportunity to design and build a seismic early warning system. The city has a history of being damaged by large earthquakes and the distance to the seismic sources allows an unusually long time of opportunity prior to the arrival of the strong shaking. Thus, the construction of an early warning system was one of the priorities to improve the seismic resilience of Mexico City. As such, it became the first system in the world to issue seismic alerts to the public.

Since the initiation of formal operation in 1993, SASMEX has successfully operated, warning the population of Mexico City of impending large earthquakes.

The addition of other cities in southern and western Mexico, which now subscribe to the alerting system, has posed several challenges. The first is the need to characterize and to rapidly estimate the magnitude of earthquakes that occur within the subducted Cocos plate that lie very close to population centers in central Mexico. Second, there was a need to improve the detection algorithm to more rapidly decide when to issue an alert. A new algorithm was developed that uses the first 3 s of the $P$-wave coda to decide whether or not to issue an alert. Its future implementation will help in a more rapid decision-making process. Finally, CIRES has maintained a steady vocation to improve and modernize the design and operational procedures of the engineering infrastructure, to ensure the reliable and effective operation of the integrated components.

The more recent examples of the performance of SASMEX were during the 8 and 19 September 2017 Tehuantepec ($M_w$ 8.2) and Morelos ($M_w$ 7.1) earthquakes. The 8 September earthquake is the first with a magnitude $M_w > 8$ that has occurred in Mexico since the inception of the seismic early warning system. The earthquake was recorded and rapidly classified as a very large event. A public warning was issued almost 2 min prior to the arrival of the strong shaking in Mexico City. The average peak ground acceleration measured by the Accelerographic Network of Mexico City (RACM) in the soft soil for this earthquake was 28 cm/s$^2$.

In contrast, the 19 September Morelos earthquake took place at an epicentral distance $\sim 120$ km from Mexico City and at a focal depth of $\sim 60$ km. The incoming seismic waves were detected on the strong-motion instruments installed to monitor this type of in-slab seismicity (Fig. 1). The alert was issued as soon as the $S$ waves reached the monitoring stations above the hypocenter. However, considering the proximity of the hypocenter, the advance warning was issued when the population of Mexico City was already experiencing the strong shaking induced by the incoming $P$ waves.

Average peak ground accelerations in the soft shales induced by the 19 September earthquake were 116 cm/s$^2$; however, in the transition zone, between the soft shales and the highlands, peak ground accelerations of 220 cm/s$^2$ were observed. The 19 September earthquake contrasts the differences in warning time available in Mexico City for earthquakes coming from the subduction zone and from nearby events, that will offer imminently a short warning time. The new 3 s algorithm will help in the future reduce the warning time for in-slab events.

The continuous technological improvement and modernization of the infrastructure and of the software, including the algorithms used in the detection and classification process ensures the continued operation of SASMEX in a reliable, effective, and resilient manner to face the challenges of warning the important cities now using the alert of future large earthquakes.

DATA AND RESOURCES

The historical catalog of all seismic early warning alerts issued by Mexican Seismic Alert System (SASMEX) is available in http://www.cires.org.mx/sasmex_historico_es.php (last accessed January 2018). The other data on the educational and outreach effort can be found at http://www.cires.org.mx (last accessed January 2018).

ACKNOWLEDGMENTS

The authors express their gratitude to the governments of Mexico City and of the state of Oaxaca, the institutions that provide funding to the Mexican Seismic Alert System (SASMEX) network, for use of their data. Special thanks are due to Guadalupe Rico, Sandra Ramos, Marisela Palomino, Cecilia Hernández, and Arminda Rangel for their invaluable support in collecting and structuring the data presented in this article. Anaid Galicia ably drafted the figures. The authors acknowledge the constructive comments made on the original manuscript by Men-Andrin Meier, two anonymous reviewers, and Associate Editor Brendan Crowell.

REFERENCES


Gerardo Suárez
Instituto de Geofísica, UNAM
Ciudad Universitaria
04510 Mexico City
Mexico
gerardo@geofisica.unam.mx

J. M. Espinosa-Aranda
Armando Cuéllar
Gerardo Ibarrola
Armando García
Martin Zavala
Samuel Maldonado
Roberto Islas

Centro de Instrumentación y Registro Sísmico (CIRES)
Anaxagoras 814
Colonia Narvarte
03020 Mexico City
Mexico
maranda@unam.mx
cuellar@cires.org.mx
g.ibarrola@cires-ac.mx
a.garcia@cires-ac.mx
m.zavala@cires-ac.mx
s.maldonado@cires-ac.mx
r.islas@cires-ac.mx

Published Online 7 February 2018