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The IGN MEMS Accelerographs Record the First Accelerograms in Different Locations in the Lorca City

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Abstract: A recent earthquake (13 December 2018, Mag. 3.5) has allowed the recording 11 accelerograms from a network microelectromechanical systems (MEMS) low-cost accelerograph Silex. The National Geographic Institute of Spain (IGN) has built this kind of equipment and has installed in the Lorca City. The epicenter of the earthquake is only approximately 6 km from Lorca. This is important because an earthquake hit this city on 11th May, 2011. This earthquake caused nine deaths, more than 400 injured people and a loss estimated about $1 billion. We have also got records from two commercial accelerograhs GeoSig GMSPlus and GeoSig GSR-18 in two different stations in Lorca and we have been able to compare these signals with signals from Silex. We have studied carefully the records from places where peak accelerations are noticeably higher than in other locations. We have seen that the waveforms of these records have different features and we think that the effect sites are very important. Finally we have also compared the peak acceleration with macroseismic intensity obtained from questionnaries. We have checked there is no clear correlation between instrumental acceleration and macroseismic intensity at least for earthquake with small magnitudes.

Key words: MEMS, low-cost, high dynamic range, peak acceleration and macroseismic intensity.

1. Introduction

In this paper we want to show the first recorded data of the Silex accelerograph network which started to be deployed in the city of Lorca in 2015. Most Silex accelerographs of the network were installed in February 2017. The National Geographical Institute of Spain (IGN) has currently installed eleven Silex accelerographs.

The main goal of this project is to densify the current accelerographs network, allowing us to solve the lack of data in many critical places like Lorca and its surrounding areas. In order to achieve this target, we manufactured a low-cost accelerometer device with a resolution of about 4 mg with real-time data transmission and with a reliable communication protocol, minimizing all possible costs (approx. $500).

The current accelerographs network from the National Geographic Institute has more than 100 devices. These devices are commercial devices with high dynamic range, based on “Feedback” systems. However, this network is not enough to cover very special critical location well. As the destructive May 11, 2011 hit Lorca there was only one accelerograph in Lorca city [1].

Significant variations in the measured peak ground acceleration (PGA) can be found just in an area of a few hundred squared meters. This enormous spatial resolution requires the deployment of a large number of measuring equipment and it is not possible for budgetary reasons.

Displaying a PGA vs. epicentral distance graph versus all the recorded accelerograms in Spain, in Fig. 1, we can see the lack of accelerograms for epicentral distances of less than 10 km and with a PGA of about 100 mg. According to Fig. 1, and by means of extrapolation, this lack of data belongs to accelerograms for earthquakes range between 3.6 and 4.0 magnitudes and for epicentral distances lower than 10 km.

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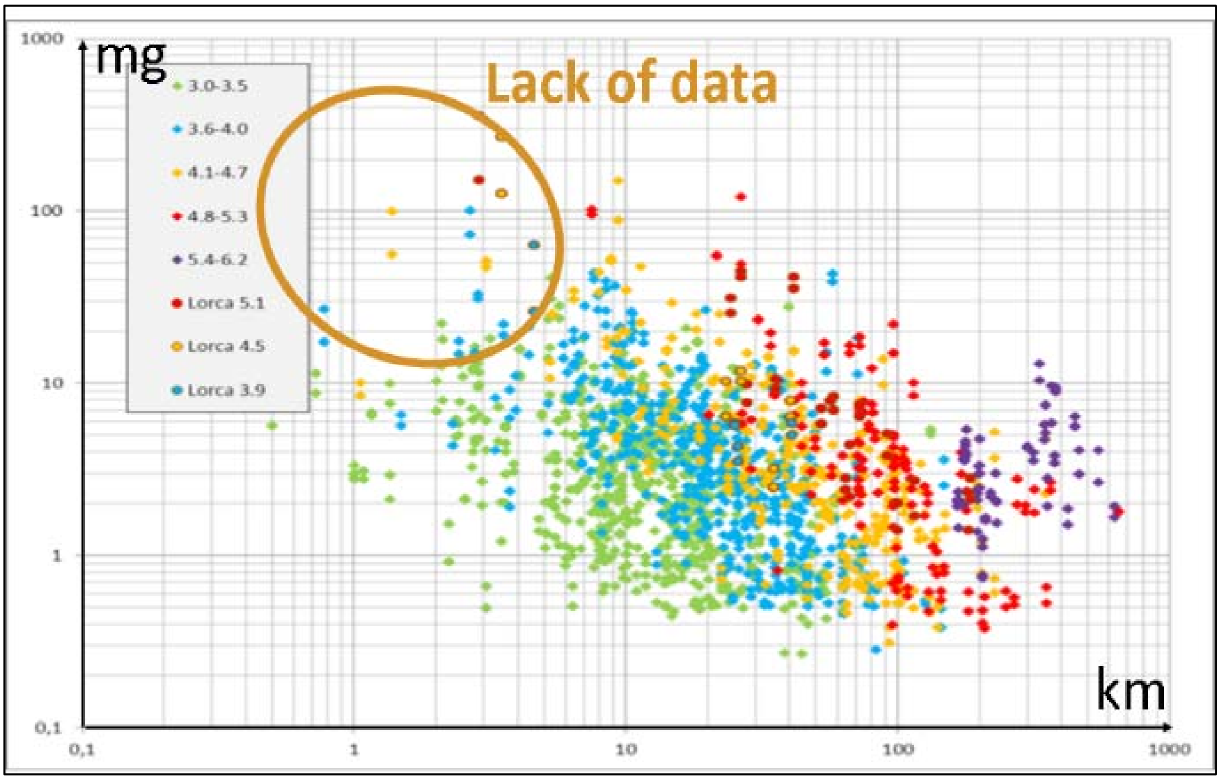

Fig. 1 PGA horizontal values (mg) vs. epicentral distance (km), of almost all of the Spanish Seismic Network (IGN-SSN) accelerograms, until approximately May 2013. We have circled the area with lack of acceleration data.

2. Deployment

2.1 History

Every part of the development process has been done in IGN: design, manufacturing and assembly of this low-cost accelerometer based on MEMS (microelectromechanical systems) technology. Many different departments were involved in it with their knowledge, such as Astronomical Yebes Observatory [2], Geophysical Toledo Observatory (at the beginning of this project), and National Seismic Network (NSN) along with others private companies like EDINTEC [3]. They have developed all the integrated digital signal processing (DSP), the development of a protocol for efficient and reliable communications based on UDP internet protocol, acquiring server software and its integration with Seiscomp analysis software. Seiscomp delivers automatic PGA and PGV (Peak Ground Velocity) data in XML format for the Shakemap application [4].

MEMS accelerometers are capacitive micro sensors where the displacement of a tiny mass produces a change in the capacitance of a micro capacitor. Residual gas sealed inside the device generates motion damping of its components.

Fields such as automotive, missile tracking, smartphone, etc. have been using this technology for years, and its applicability in the field of seismology seems already to have been demonstrated [5, 6].

After studying several MEMS-based accelerometers, we decided to use the three-axis accelerometer from ST Microelectronics, LIS331DLH. This accelerometer is one of the most used accelerometers in the world, including mobile devices (like the iPhone), which makes its wide availability on the market one of its biggest advantages. It is produced in LGA (Land Grid Array) encapsulation (whose dimensions are extremely small 3 mm × 3 mm × 1 mm), Fig. 2. We need special machines to weld these chips. Insyte firm has done this. LIS331DLH has an operating range from -40 °C to

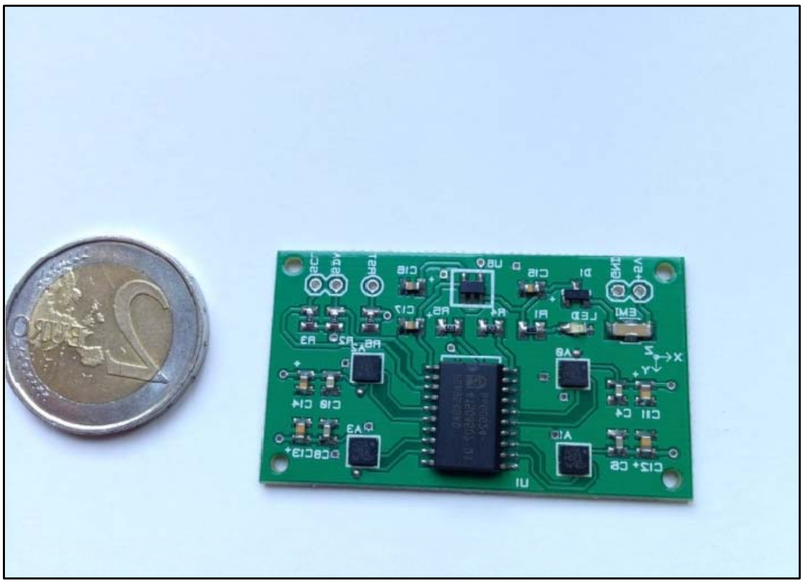

Fig. 2 Last PCB board version, with four different MEMS accelerometers (A1, A2, A3 and A4).

Fig. 3 The last encapsulation of Silex accelerograph.

85 °C. As it is a three-axis accelerometer, we can obtain acceleration in the three components (X, Y, Z), the converter is a 12-bit ADC and via I2C or SPI bus that allows the data output. Although the device allows multiple sampling scales and sampling rates, we have chosen the lowest scale (± 2 g), and the maximum sampling rate that allows (1 kHz).

SILEX general specifications are as follows.

Time acquisition: GPS or NTP;

Data transmission: UDP via GPRS or Ethernet;

Oversampling: 1,000 sps (samples per second) converted to 100 sps;

Combined resolution: 3.06 mg using three MEMS sensor and oversampling;

Memory store: 30 minutes files/1.04 MB/100 sps.

In Fig. 3, you can see the equipment in its final appearance.

At the beginning, we installed several of them in different places across Spain using different ways of data transmission. Every installation has very unique conditions. We wanted to check our devices working in quite different environments. Before sending a Silex device to the field, we compare its output with a commercial accelerograph (Guralp CMG-5T) with a known output using a vibratory table (Fig. 4) belonging to CEDEX Institute.

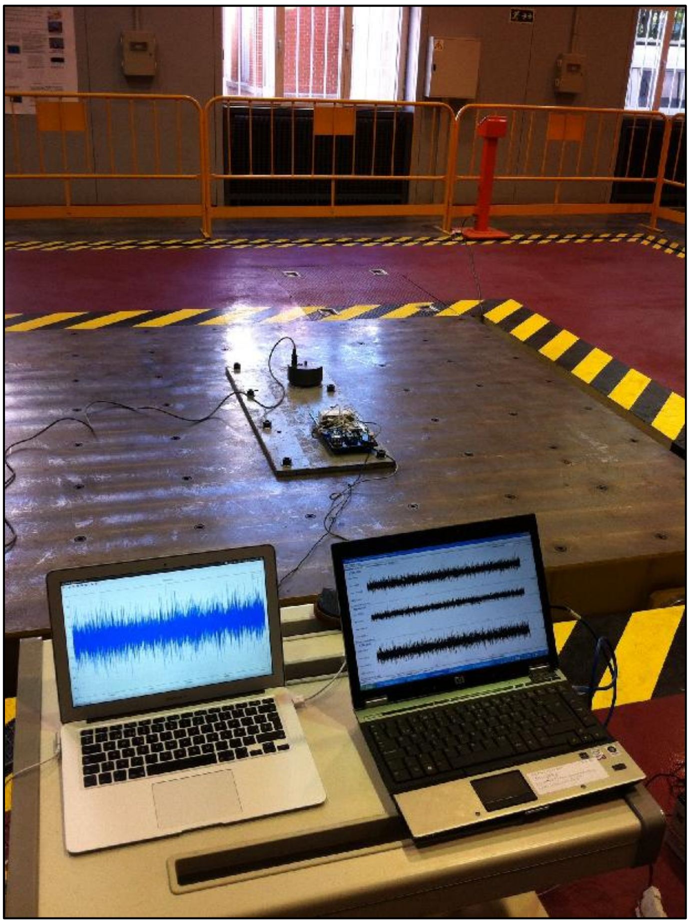

Fig. 4 Test in a vibratory table allows comparing the signal from accelerograph Silex and a Guralp CMG-5T.

2.2 Installation

We are currently receiving data from Silex devices in the Azores Island, in Observatories of Astronomy in Norway and Finland (Finnish Geospatial Research Institute) and even in Lima (Peru) (Fig. 5).

2.3 The First Waveform from an Actual Earthquake

IGN had installed a Mobile Broadcast VSAT Data (UMV), among other portable stations, in the seismic series of Torreperogil in Jaen, in December 2012. UMV consisted of a CMG-5T accelerometer Guralp (+ trident digitizer Nanometrics 24 bit). We installed a Silex (with MEMS technology) accelerometer very close to the UMV Guralp accelerometer at the end of March 2013. The Guralp accelerometer was buried in the cemetery grounds at Torreperogil, and the Silex accelerometer was installed approximately 50 meters away from the Guralp one in a neighbouring cemetery building on a concrete floor.

The MEMS accelerometer transmitted data via GPRS (general packet radio service) to software based on SeiscomP located in the CRD (Data Reception Centre) in Madrid. See the ofcomparison both signals in Fig. 6.

We finally present a graph (Fig. 7) with the total amplitude envelope of the acceleration vector of the accelerograms recorded by both accelerometers, in order to correct any mistakes produced by the lack of guidance from both sensors and signal smoothing.

2.4 Densifying the Current Strong-Motion Network

Currently, the IGN is deploying several devices focused on areas such as Alhama fault at Murcia region

Fig. 5 Different locations where Silex are installed in the world.

(southeast of the Iberian Peninsula) and Aran Valley in the Catalonian Pyrenees. This new network is a densification of the existing accelerographs network (based on standard commercial accelerometers), and volunteer citizens offer their own home as suitable installation locations (Fig. 8).

After conversations held with the civil protection service of Lorca, there is a mutual interest in putting these accelerographs in different public and private schools, and Secondary Education Institutes in the city of Lorca. We will name this new series with the letters "SX00". The Council of Lorca allowed IGN to install these devices that will join with three previously installed devices named "Series SX900".

2.5 Installation of Silex Network in the Lorca City in February 2017

As we mentioned before, the Silex equipment has been installed in schools and secondary schools taking advantage of the local area network (LAN) of the centers. The data arrive at the Data Reception Center in Madrid through the internet. Silex devices also record data locally in an SD card so we can recover them in case of a communication disruption.

Our goal is to deliver a quick and easy installation network while minimizing costs, by installing the accelerographs in the ground floor of small buildings.

We fixed most of them to the ground with a bolt. We used resistant double-face tape when we were not able to drill a hole on the floor. Fig. 9 shows an example of installation, Silex SX004.

Students can watch the real-time waveform from the devices installed in their Education Centers. They only have to connect with our SeedLink server in Madrid (Fig. 10). This is vital for citizens to become aware of the risks of an earthquake.

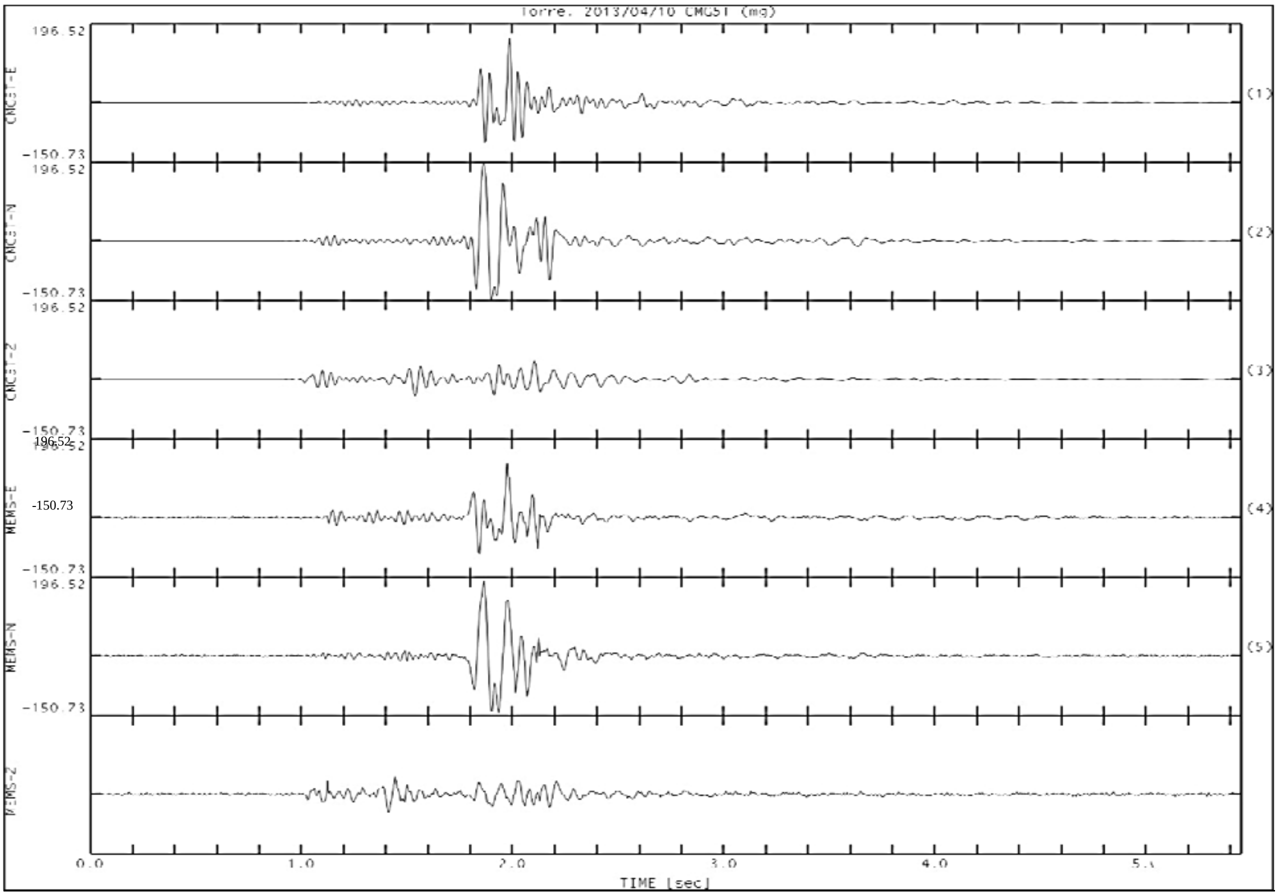

Fig. 6 Comparison of real seismic signals in the same scale and amplitude (mg) of the accelerograms recorded by the Guralp CMG-5T accelerometer and the MEMS device. The earthquake is of a magnitude 3.3 earthquake at Torreperogil (Jaén) on April 10, 2013. The epicentral distance is about 2.2 km. All records received the same data processing: baseline correction (with regression line), Hamming window (10%) and a non-casual Butterworth low-pass filter, fc = 30 Hz, and 4 sec. Acceleration is in mg.

In Fig. 11, we can see a map of Lorca city with the locations of the accelerographs.

We can see the epicenter of earthquake on December 13th, 2018, Magnitude 3.5, Fig. 12.

3. Results

3.1 Peak of Acceleration from Devices

We can observe in Fig. 13 waveforms of commercial GMSPlus from GeoSig and Silex LA10A in CIFEA Station (SX010). They are in the same location very close to each other. We can compare the three components and amplitudes (peak acceleration). GMSPlus records 200 samples per second and Silex 100 samples per second. We only corrected the signals of line base (linear regression) with no filtering.

The Vertical (Z) components from both accelerographs are not so similar, since vertical components of this small earthquake have fewer signals than horizontals. Silex S/N ratio is very low.

In Fig. 14 we zoomed in the first seconds of the signal from the earthquake.

Figs. 15 and 16 are velocity and displacement correspondingly after integrating both accelerograms GMSPlus and Silex LA10A (SX010). We always apply line base correction. Previously to obtain the velocity from GMSPlus, a Butterworth Filter, High Pass, fc = 1 Hz. Two (2) poles non-causal were applied, in order to remove very long periods in the integrated signal. For the same reason, the same filter was applied to the velocity signal from Silex to get the displacement.

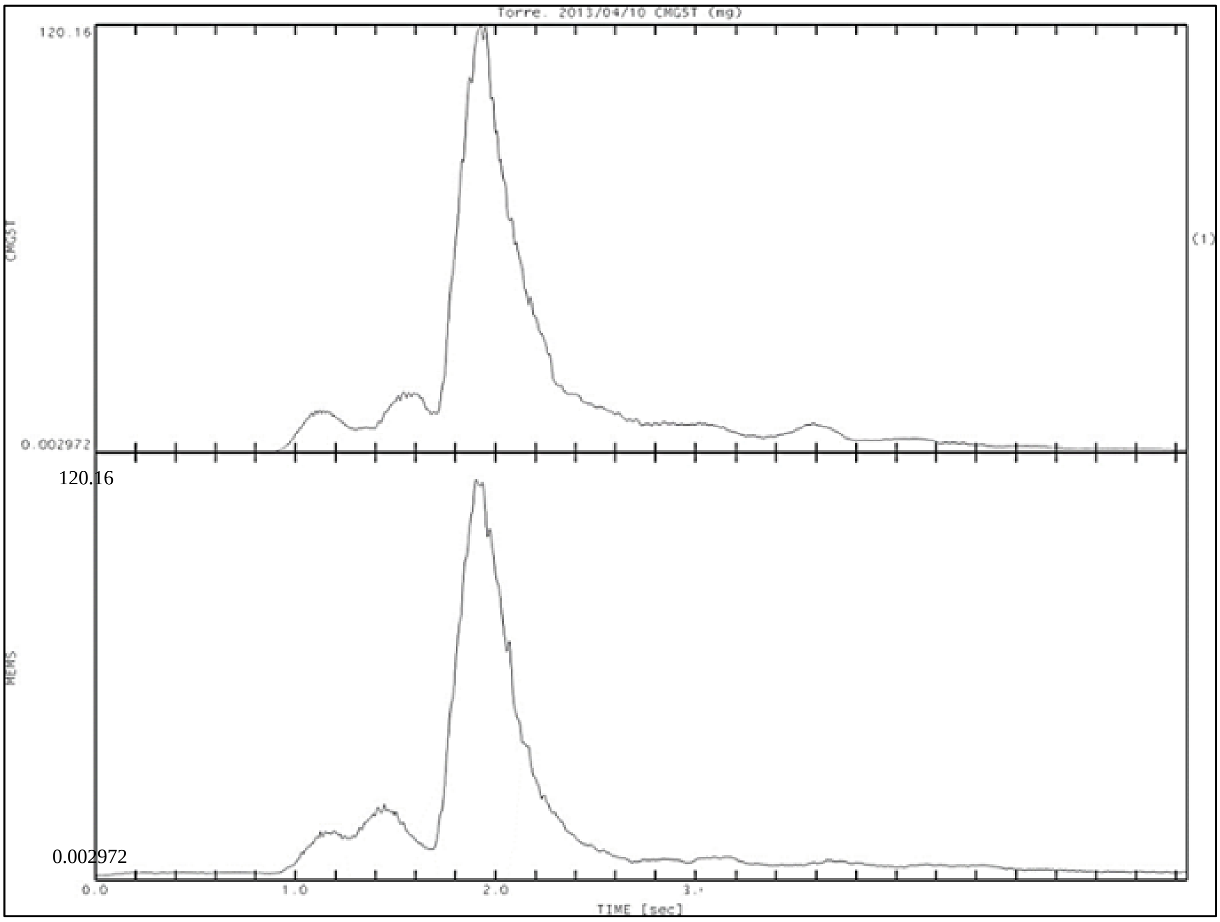

Fig. 7 The envelopes of signals from both CMG-5T and Silex accelerographs.

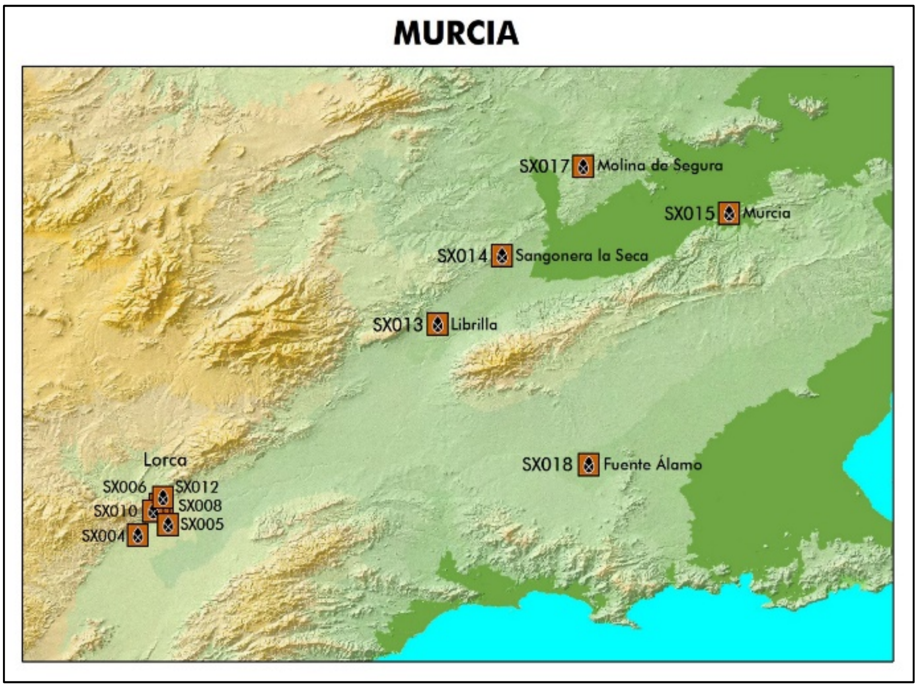

Fig. 8 Map of installations of Silex in Murcia province.

Fig. 9 Example of an installation: Silex SX004.

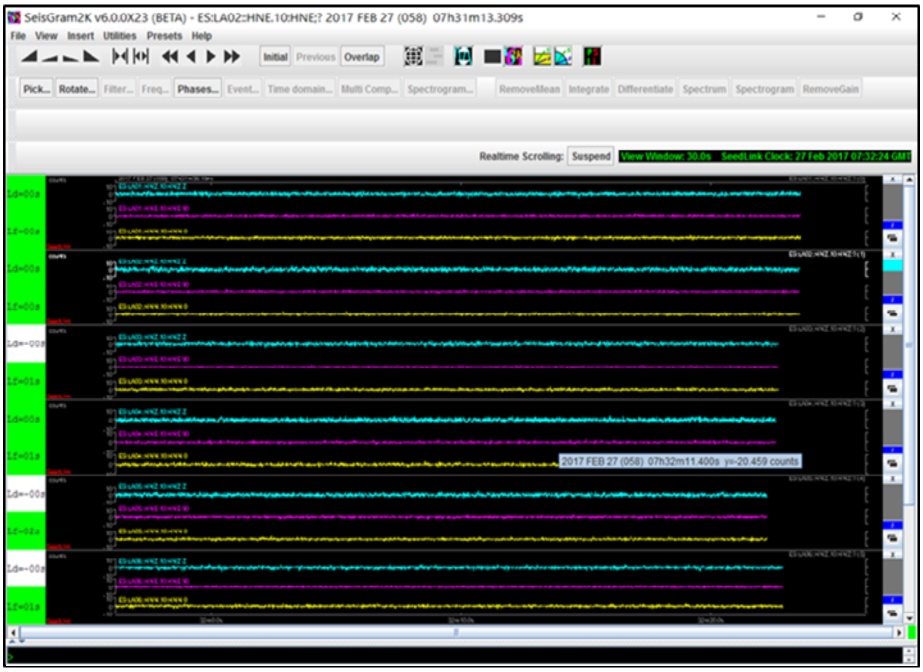

Fig. 10 The Education Centers can watch the waveform in real time.

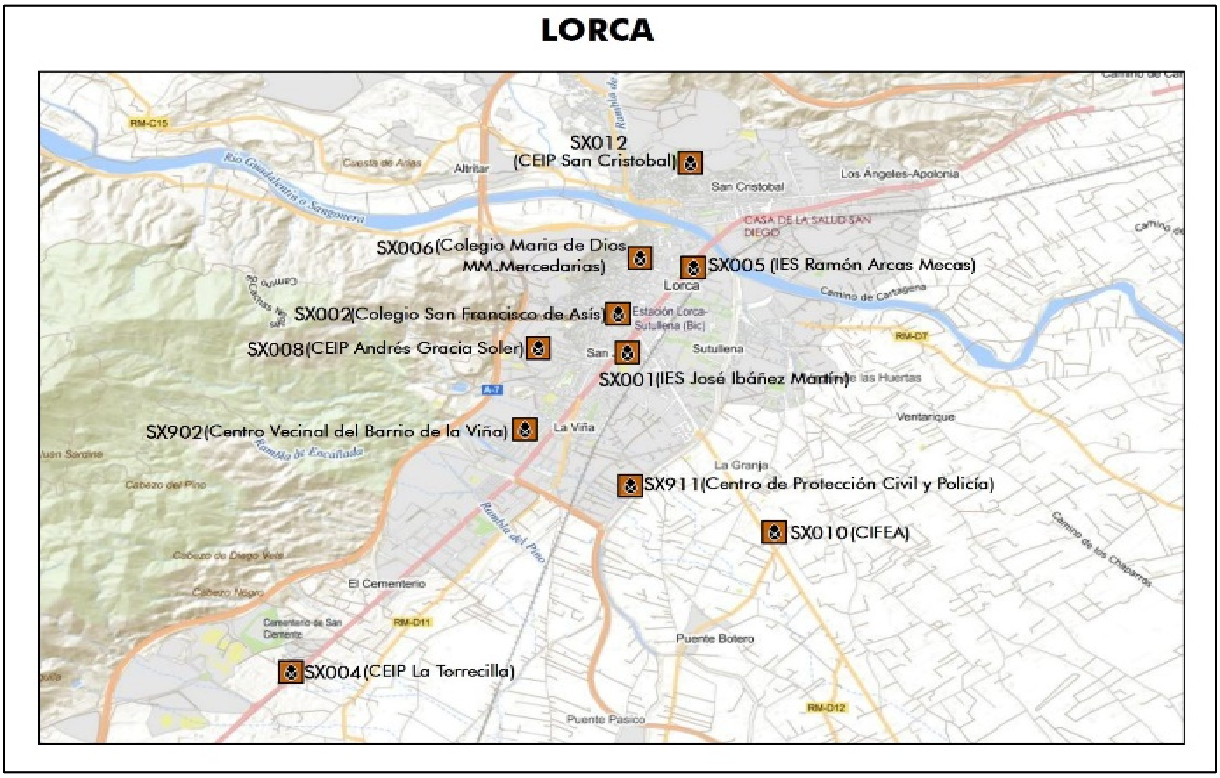

Fig. 11 Silex installed in the city of Lorca and surroundings.

Fig. 12 The map shows epicentral location of earthquake on December 13th, 2018, with a red star.

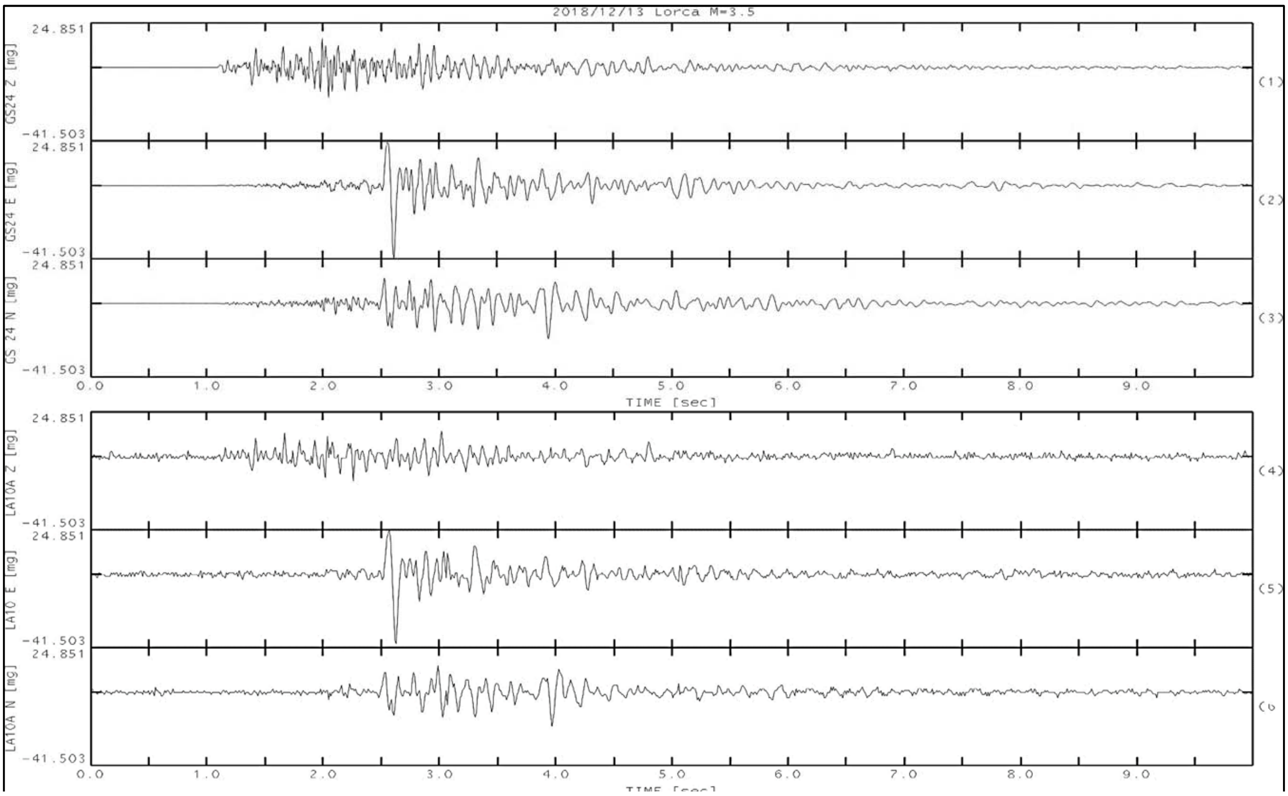

Fig. 13 Accelerograms from GMSPlus (GS) and Silex LA10A (SX010), in the same location (CIFEA). Components Vertical (Z), East (E) and North (N). Units in mg.

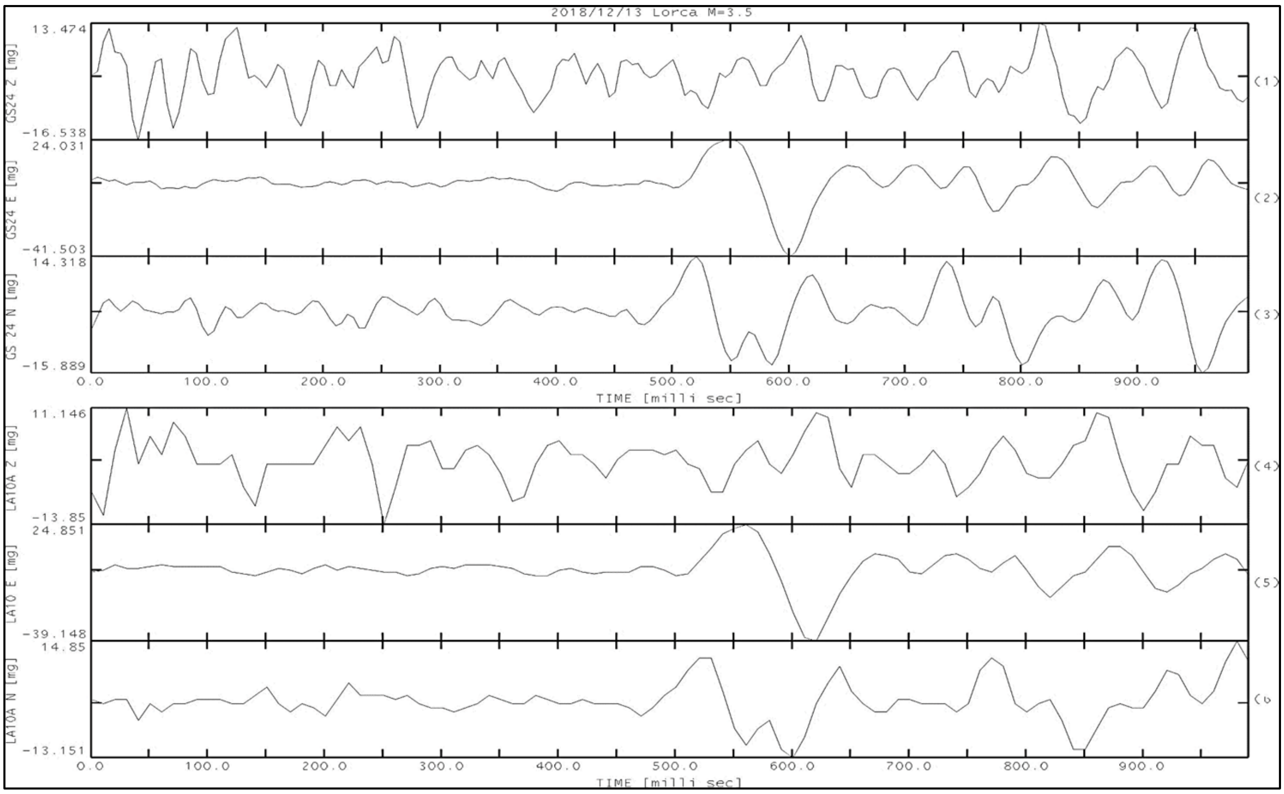

Fig. 14 Zoom of the first seconds of accelerograms from GMSPlus (GS) and Silex LA10A (SX010), in the same location (CIFEA). Components Vertical (Z), East (E) and North (N). Units in mg.

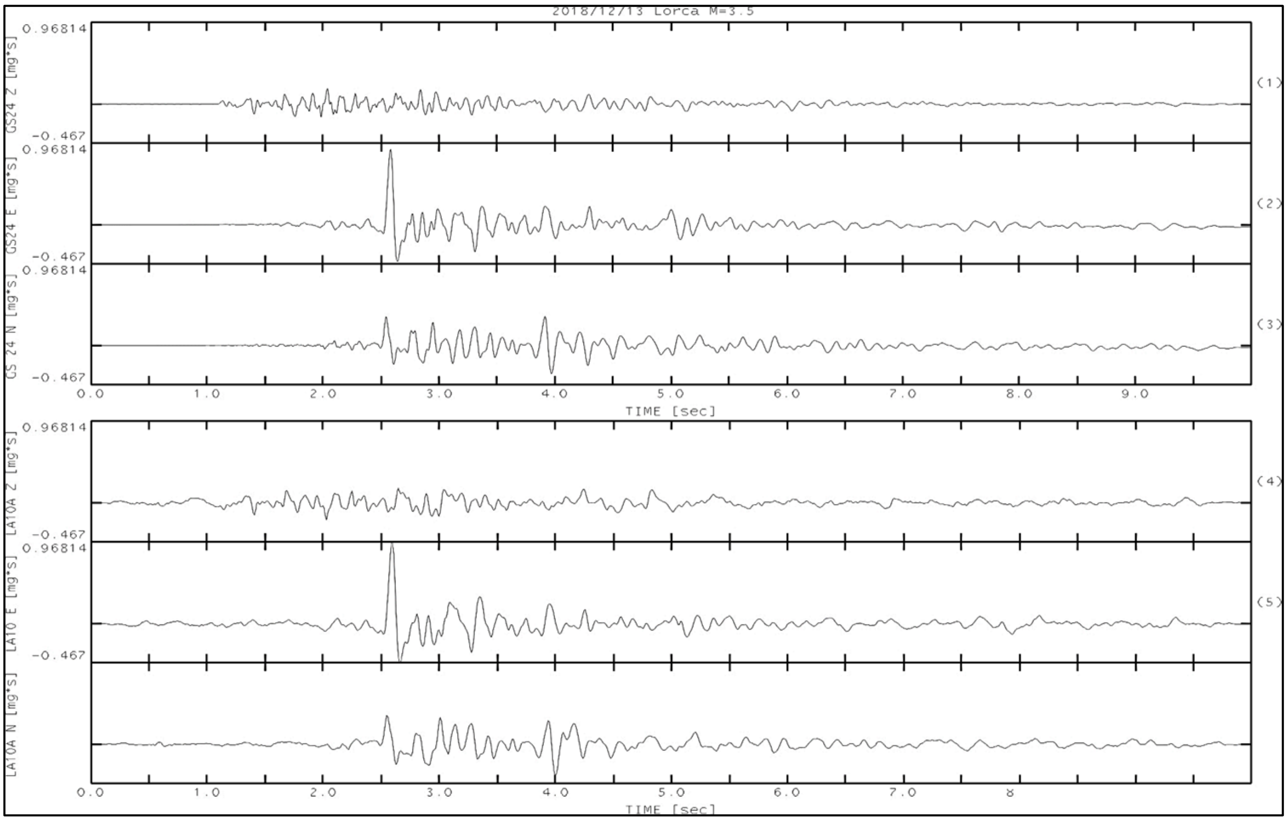

Fig. 15 Velocity (integrating the acceleration) from GMSPlus (GS24) and Silex LA10A (SX010), in the same location (CIFEA). Components Vertical (Z), East (E) and North (N). Units in mg·s. See the text.

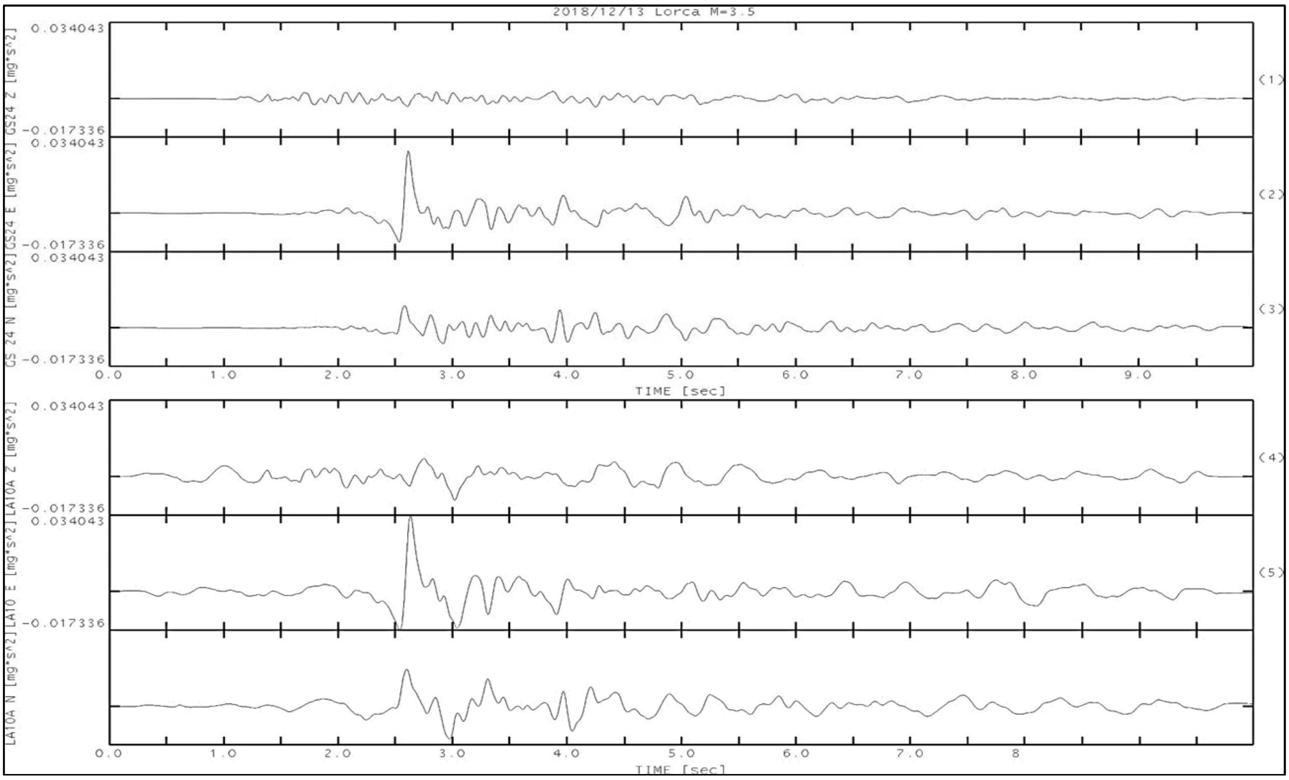

Fig. 16 Displacements (integrating the velocity) from GMSPlus (GS24) and Silex LA10A (SX010), in the same location (CIFEA). Components Vertical (Z), East (E) and North (N). Units in mg·s^2. See the text.

In Figs. 17-19 we can observe the Fourier spectrum from accelerograms GMSPlus and Silex LA10A, for components Vertical (Z), East (E) and North (N) respectively.

Fig. 20 presents signals from Silex M0002 and M0008. These devices are in the same location, in the Barrio de la Viña (SX902), one next to the other. They present an acceleration peak of about 100 mg. And the signals are almost exactly the same, allowing us to be very confident about the data received from both devices.

We can see the accelerograms obtained from other locations in Figs. 21-28. Some of them show peaks of amplitudes of about 25 mg. Others have very low amplitudes of about 8 mg. They are very close to their resolution limits. The Silex LA04A (SX004) in CEIP La Torrecilla has a surprising amplitude of 115 mg (Fig. 23).

Finally, in Fig. 29, we can observe the recording of the GSR-18 from GeoSig commercial accelerograph at the Court (Juzgados, LOR). This equipment was the first one installed in Lorca city, and it recorded a PGA over 600 mg when the mentioned Lorca earthquake hit on May 11, 2011. The install location is of hard rock where the Castle of Lorca is placed.

In Table 1, we can observe the acceleration peak from every accelerograph, for a better comparison. In this table, we highlight with blue color the most important information.

3.2 Spectral Division of Horizontal Components by Vertical Components

We can observe the waveform of accelerograms from Silex LA04A (Fig. 23), and Silex M0002 and M008 (Fig. 20). They present different characteristics from other locations (Figs. 13, 21, 22, 24-29): higher peak acceleration and lower frequencies.

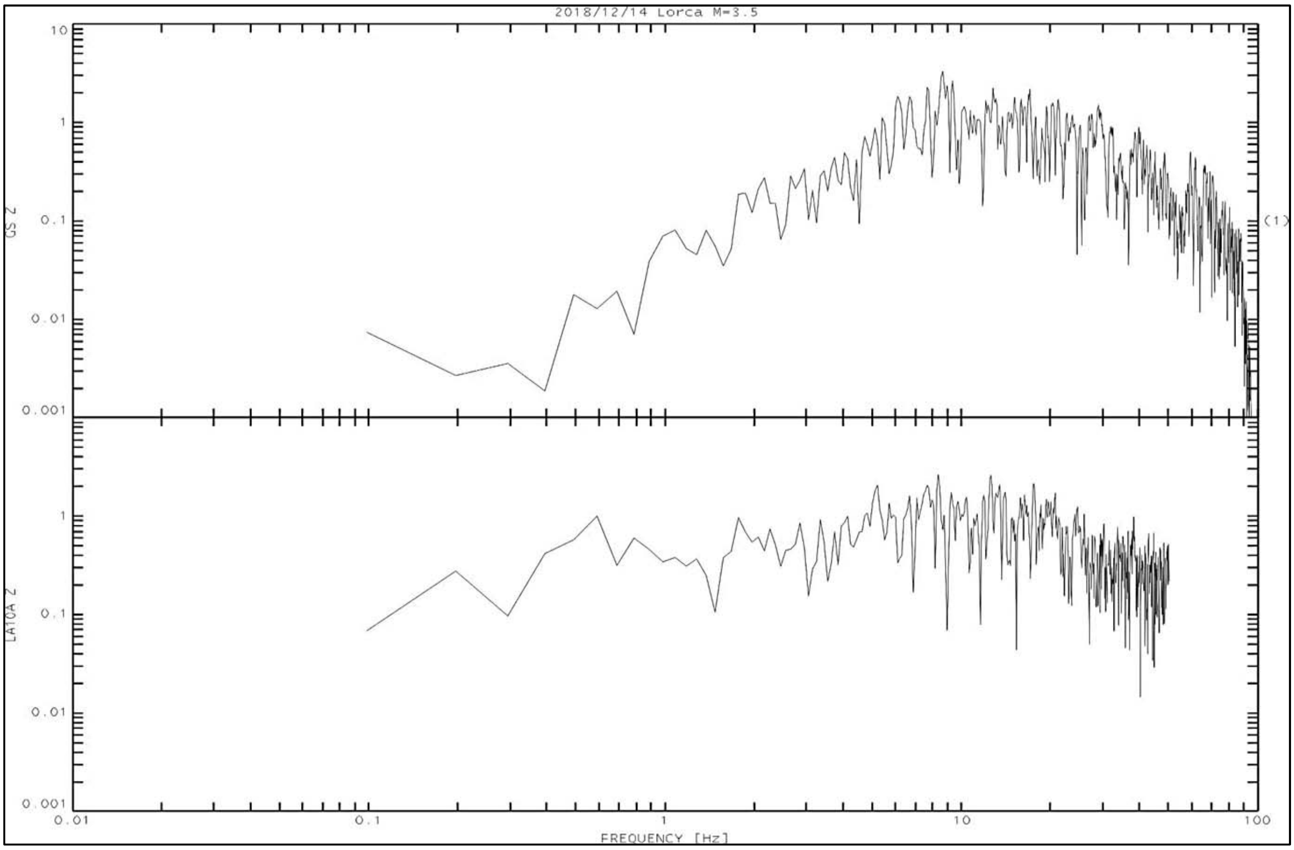

Fig. 17 Spectrum from GMSPlus (GS) and Silex LA10A (SX010), in the same location (CIFEA). Component Vertical (Z). Units in mg·s. See the text.

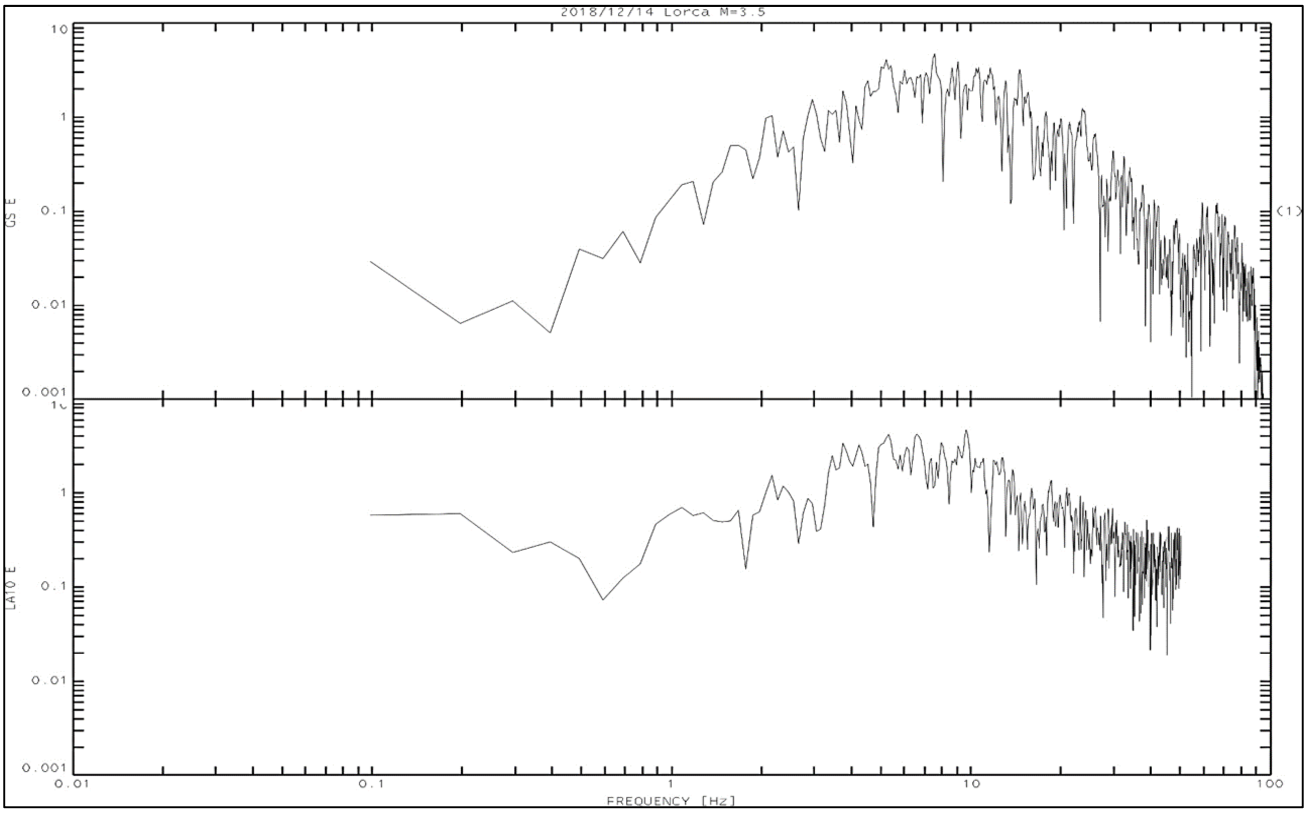

Fig. 18 Spectrum from GMSPlus (GS) and Silex LA10A (SX010), in the same location (CIFEA). Component East (E). Units in mg·s. See the text.

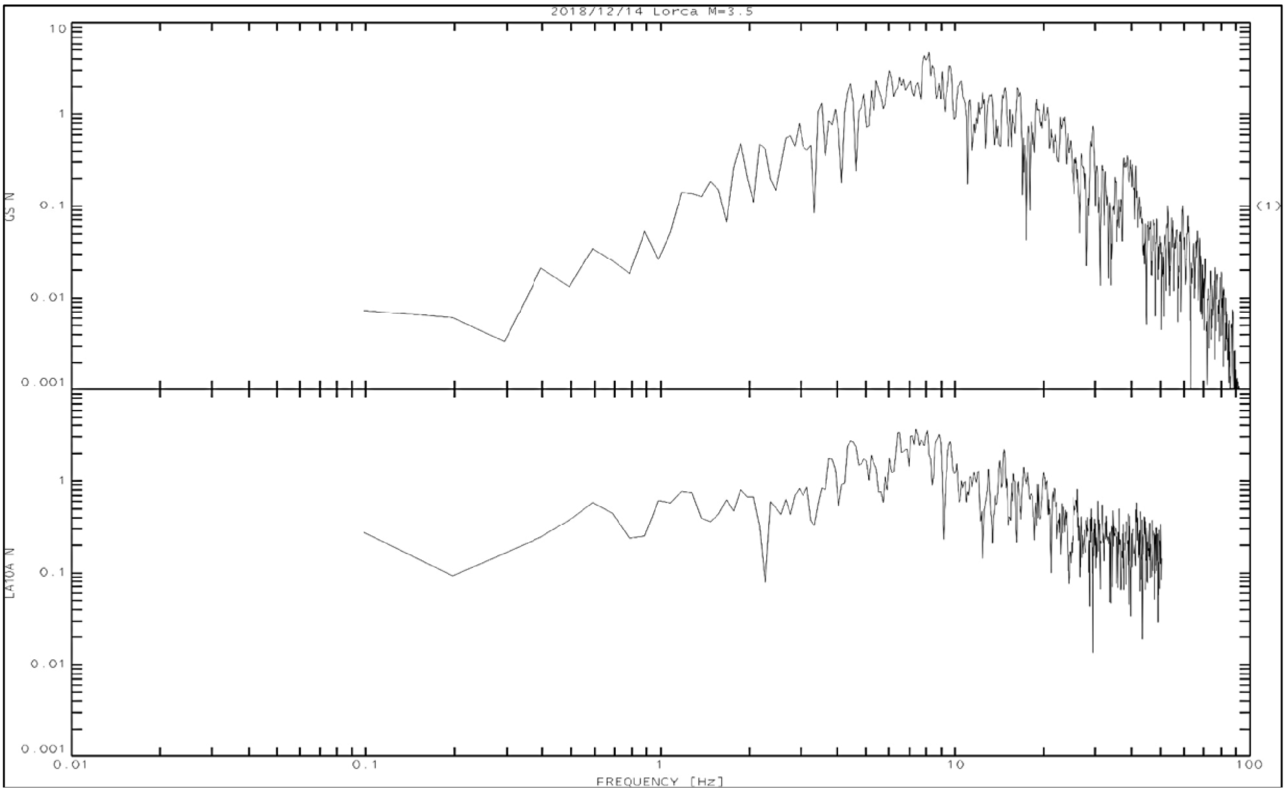

Fig. 19 Spectrum from GMSPlus (GS) and Silex LA10A (SX010), in the same location (CIFEA). Component North (N). Units in mg·s. See the text.

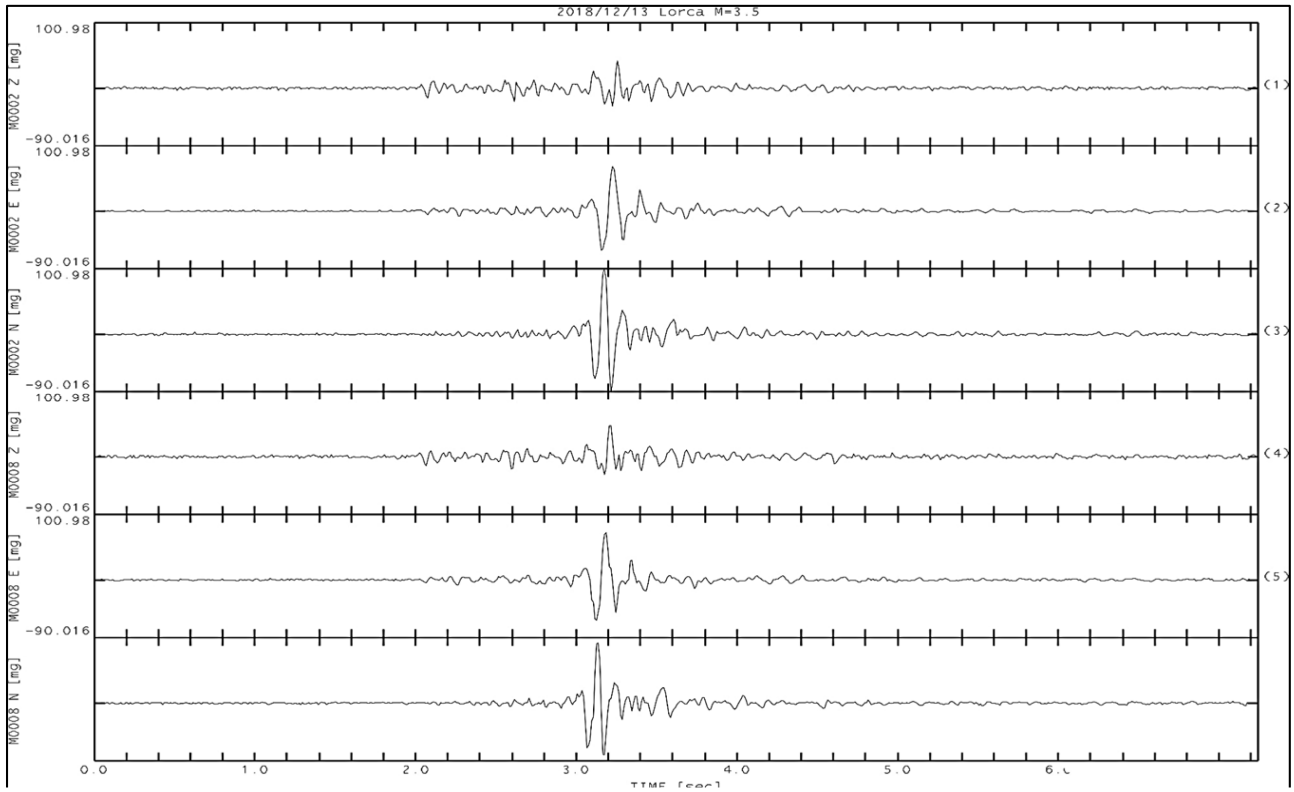

Fig. 20 Accelerograms from Silex M0002 and Silex M0008, in the same location (SX902). Components Vertical (Z), East (E) and North (N). Units in mg.

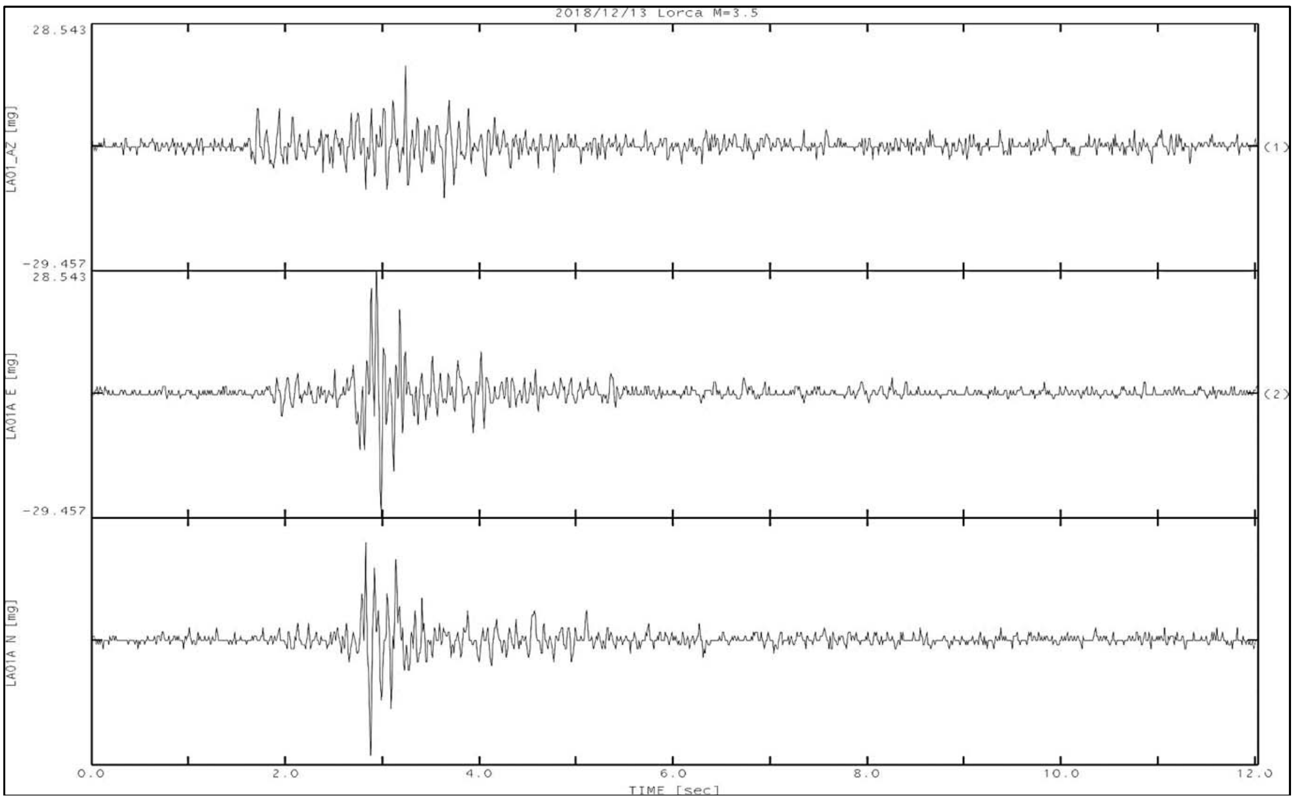

Fig. 21 Accelerograms from Silex LA01A in IES Jose Ibañez Martin (SX901). Components Vertical (Z), East (E) and North (N). Units in mg.

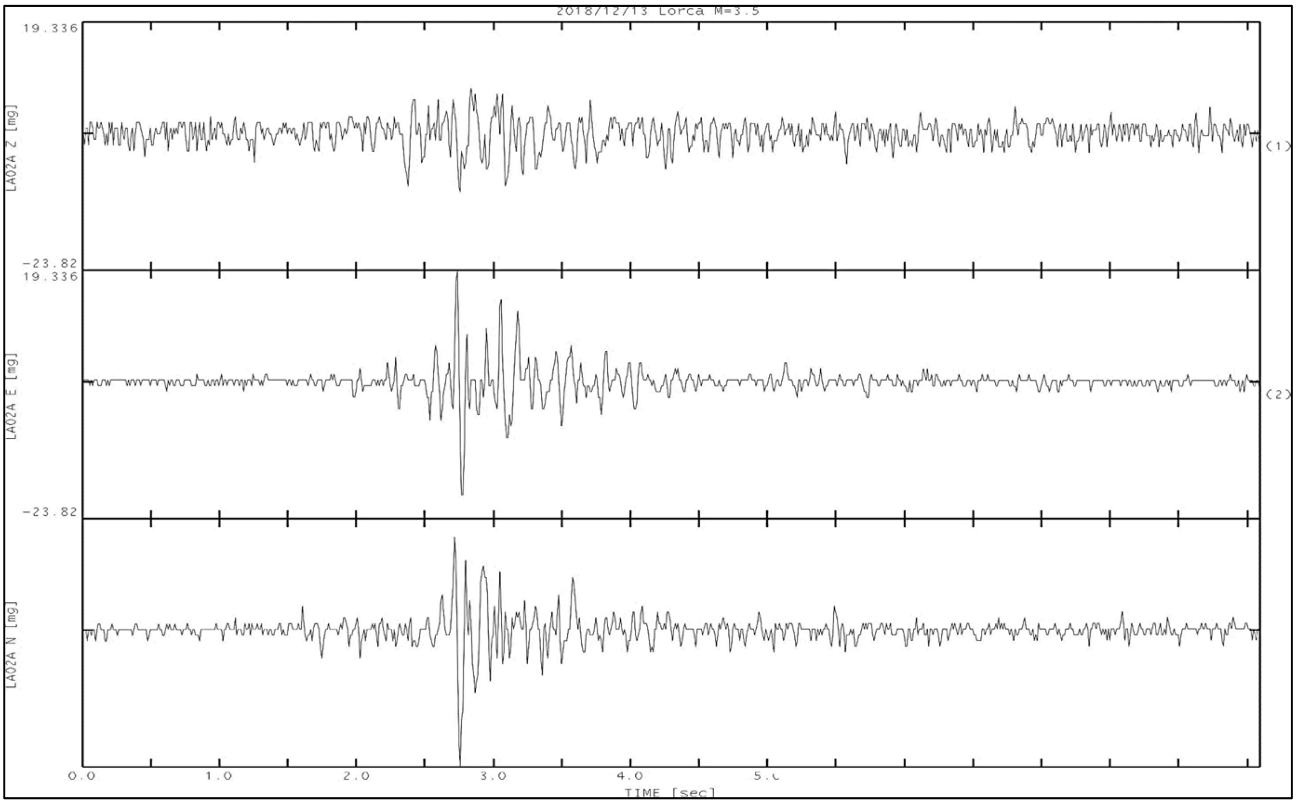

Fig. 22 Accelerograms from Silex LA02A in Colegio San Francisco de Asis (SX002). Components Vertical (Z), East (E) and North (N). Units in mg.

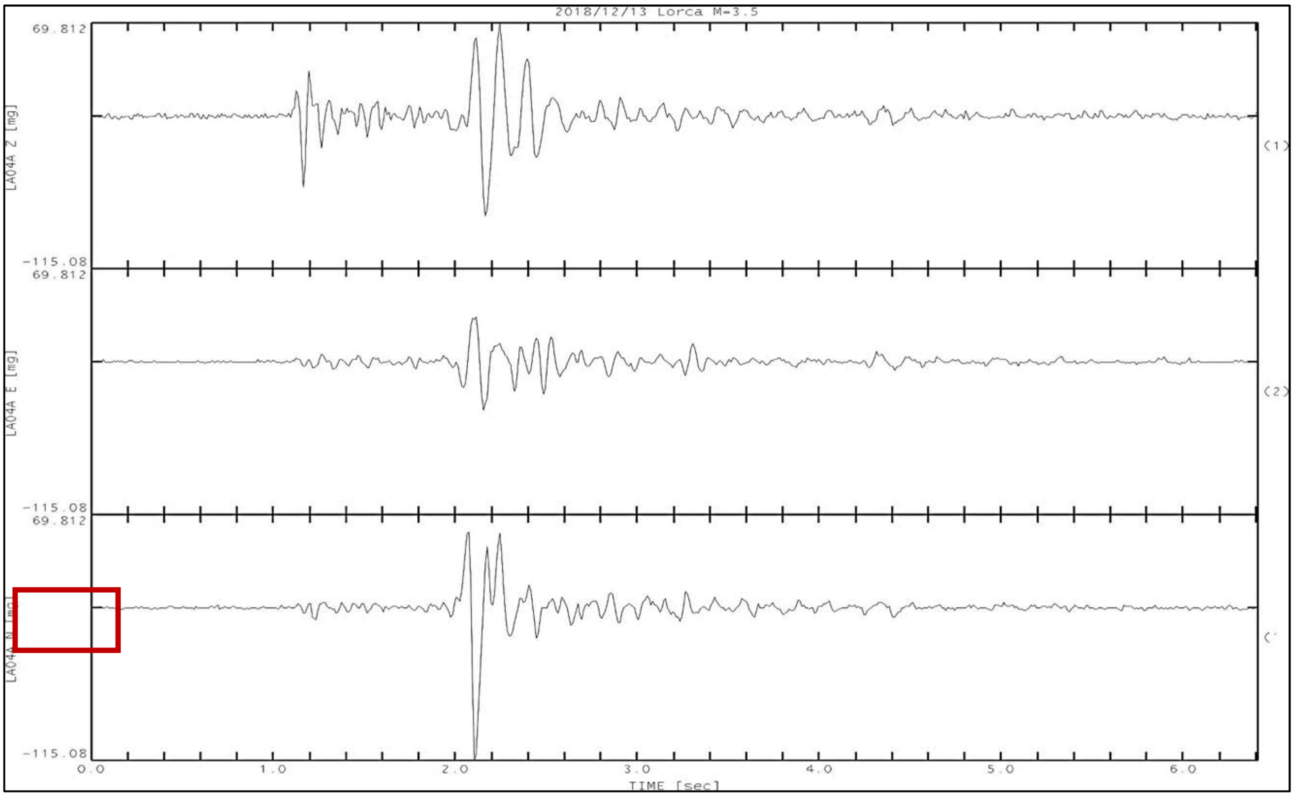

Fig. 23 Accelerograms from Silex LA04A (SX004) in CEIP La Tordecilla (SX004). Components Vertical (Z), East (E) and North (N). Units in mg. Peak Acc. = -115 mg.

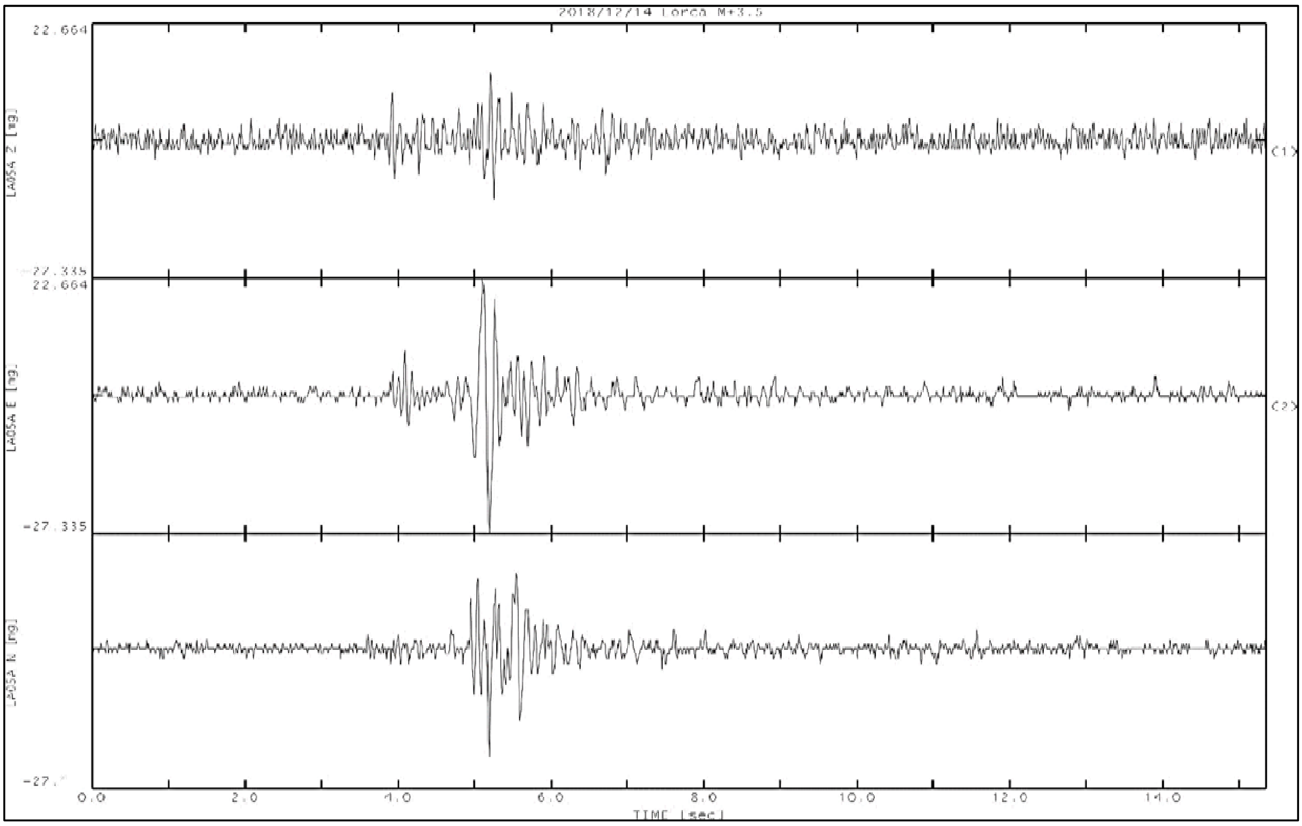

Fig. 24 Accelerograms from Silex LA05A in IES Ramon Arcas Meca (SX005). Components Vertical (Z), East (E) and North (N). Units in mg.

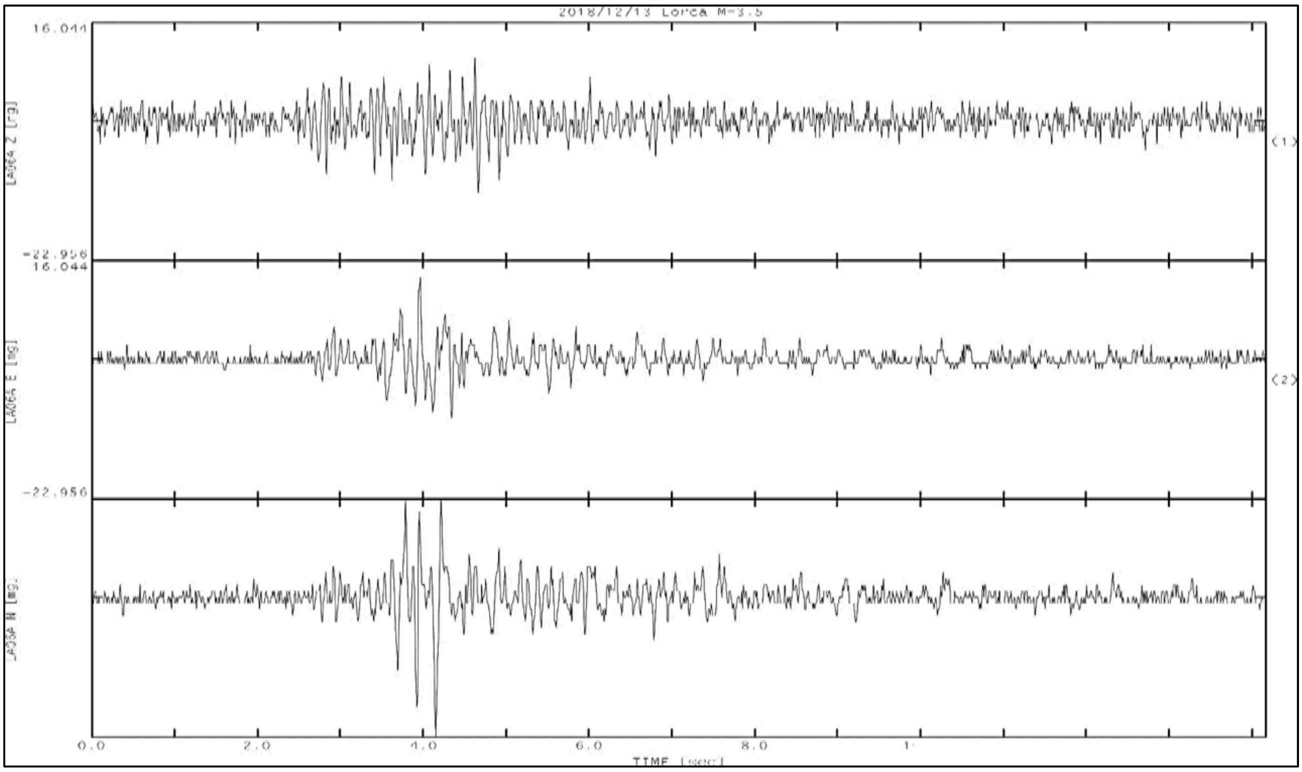

Fig. 25 Accelerograms from Silex LA06A in Colegio Maria de Dios MM. Mercedarias (SX006). Components Vertical (Z), East (E) and North (N). Units in mg.

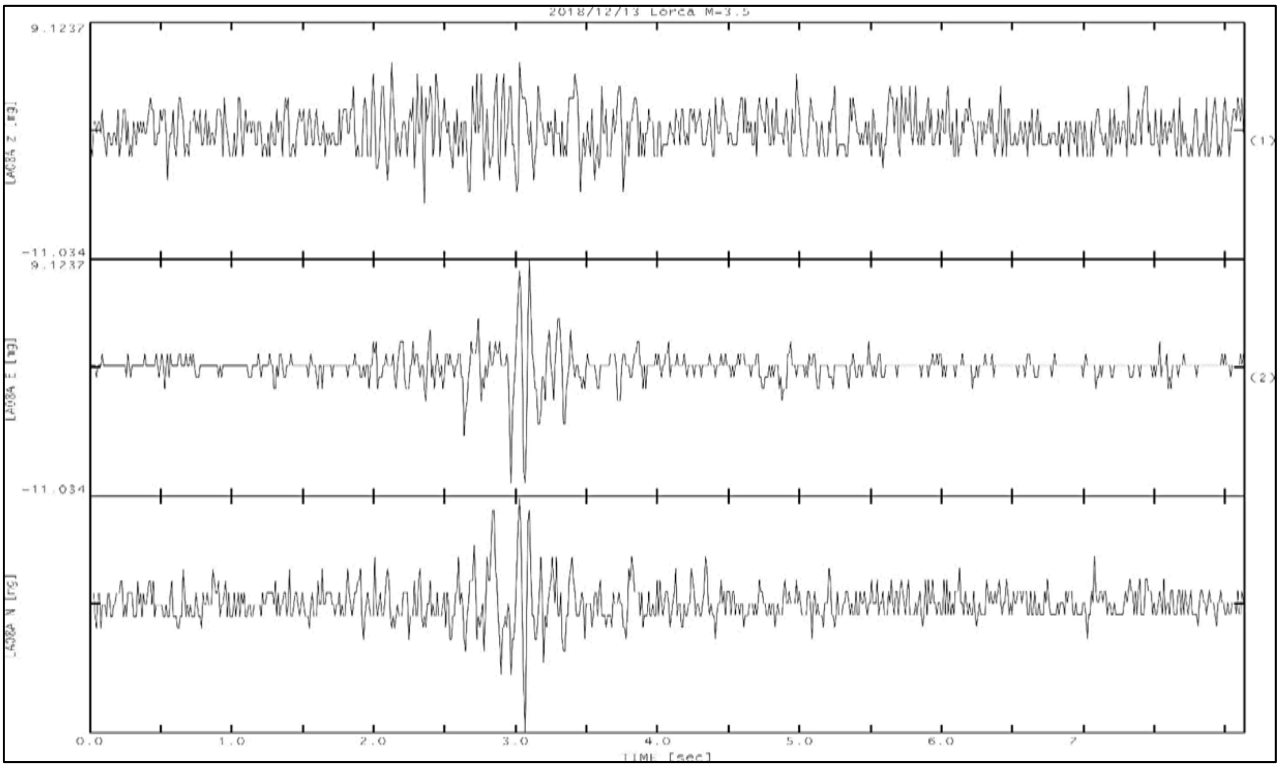

Fig. 26 Accelerograms from Silex LA08A in CEIP Andres Garcia Soler (SX008). Components Vertical (Z), East (E) and North (N). Units in mg.

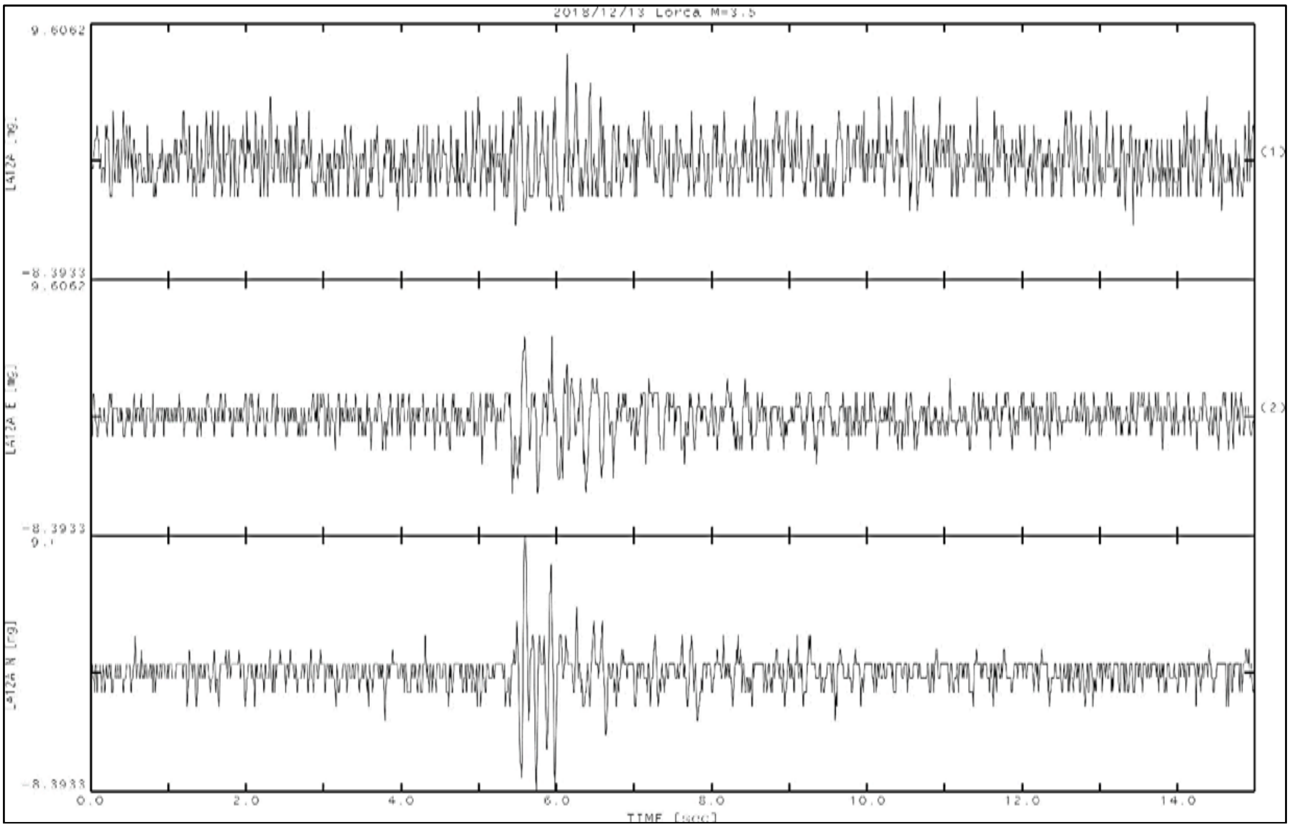

Fig. 27 Accelerograms from Silex LA12A in CEIP San Cristobal (SX012). Components Vertical (Z), East (E) and North (N). Units in mg.

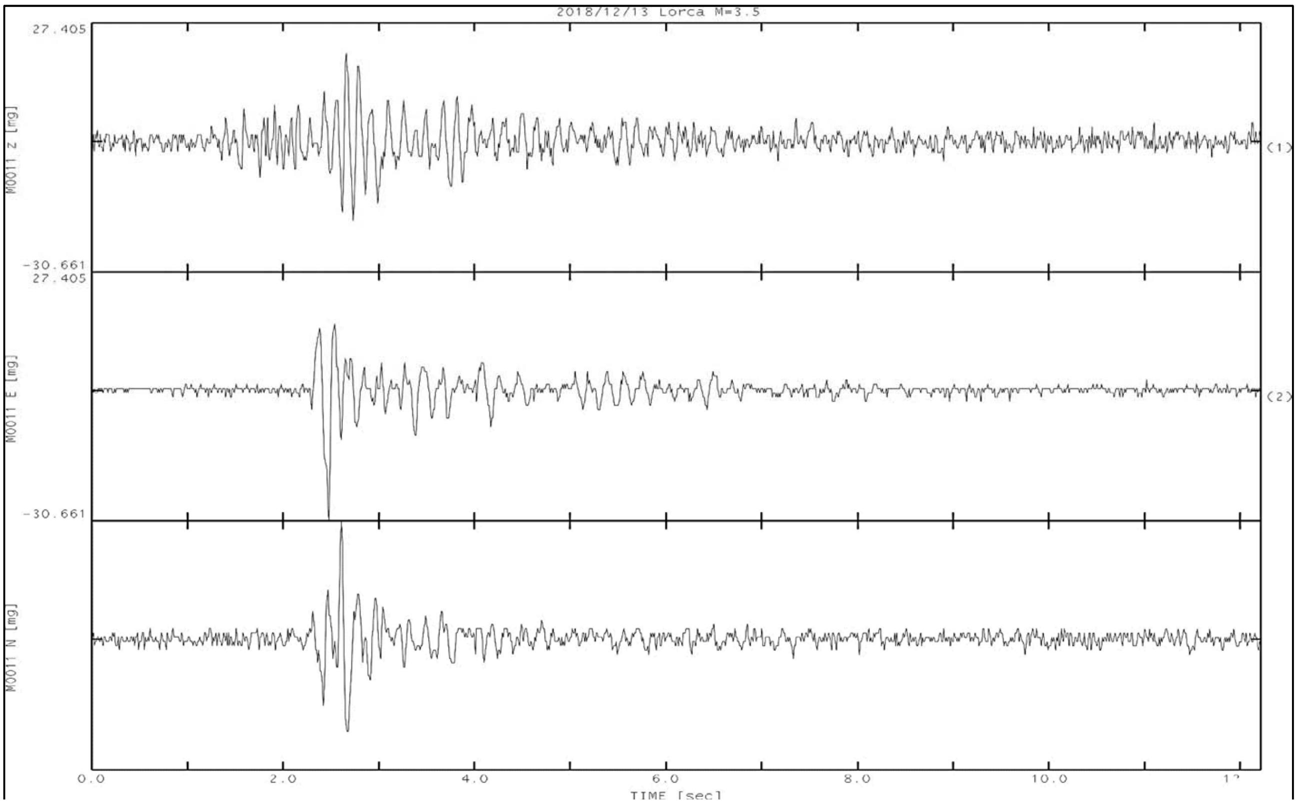

Fig. 28 Accelerograms from Silex M0011 Police and Civil Protection Centre (SX911). Civil Protection and Police Center. Components Vertical (Z), East (E) and North (N). Units in mg.

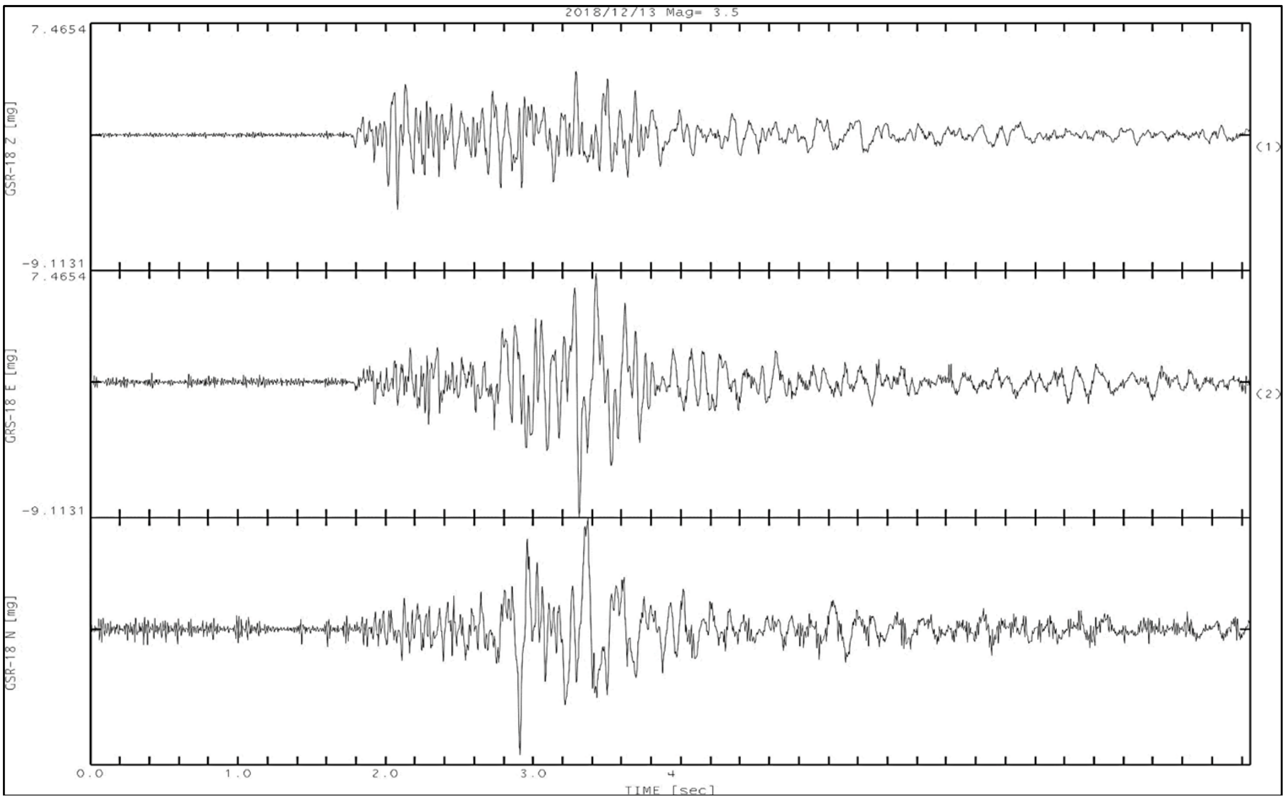

Fig. 29 Accelerograms from GSR-18 from GeoSig in Los Juzgados (LOR). Court. Components Vertical (Z), East (E) and North (N). Units in mg.

Table 1 Values of peak of acceleration from accelerographs installed in Lorca city.

Silex	Station	Peak Acc. (mg)	Silex
LA01A	SX001	-29 (E)	IES José Ibáñez Martín
LA02A	SX002	-24 (N)	Colegio San Francisco de Asís
LA04A	SX004	-115 (N)	CEIP La Tordecilla
LA05A	SX005	-27 (E)	IES Ramón Arcas
LA06A	SX006	-22 (N)	Col. María de Dios MM. Mercedarias
LA08A	SX008	-9 (N)	CEIP Andrés Gracia Soler
LA012A	SX009	+10 (N)	CEIP San Cristóbal
M0011	SX911	-31 (E)	Centro de Protección Civil y Policía
M0002	SX902	+100 (N)	Centro Vecinal Barrio de la Viña
M0008	SX902	+93 (N)	Centro Vecinal Barrio de la Viña
LA010A	SX010	39 (E)	CIFEA

E—East, N—North, Z—Vertical.

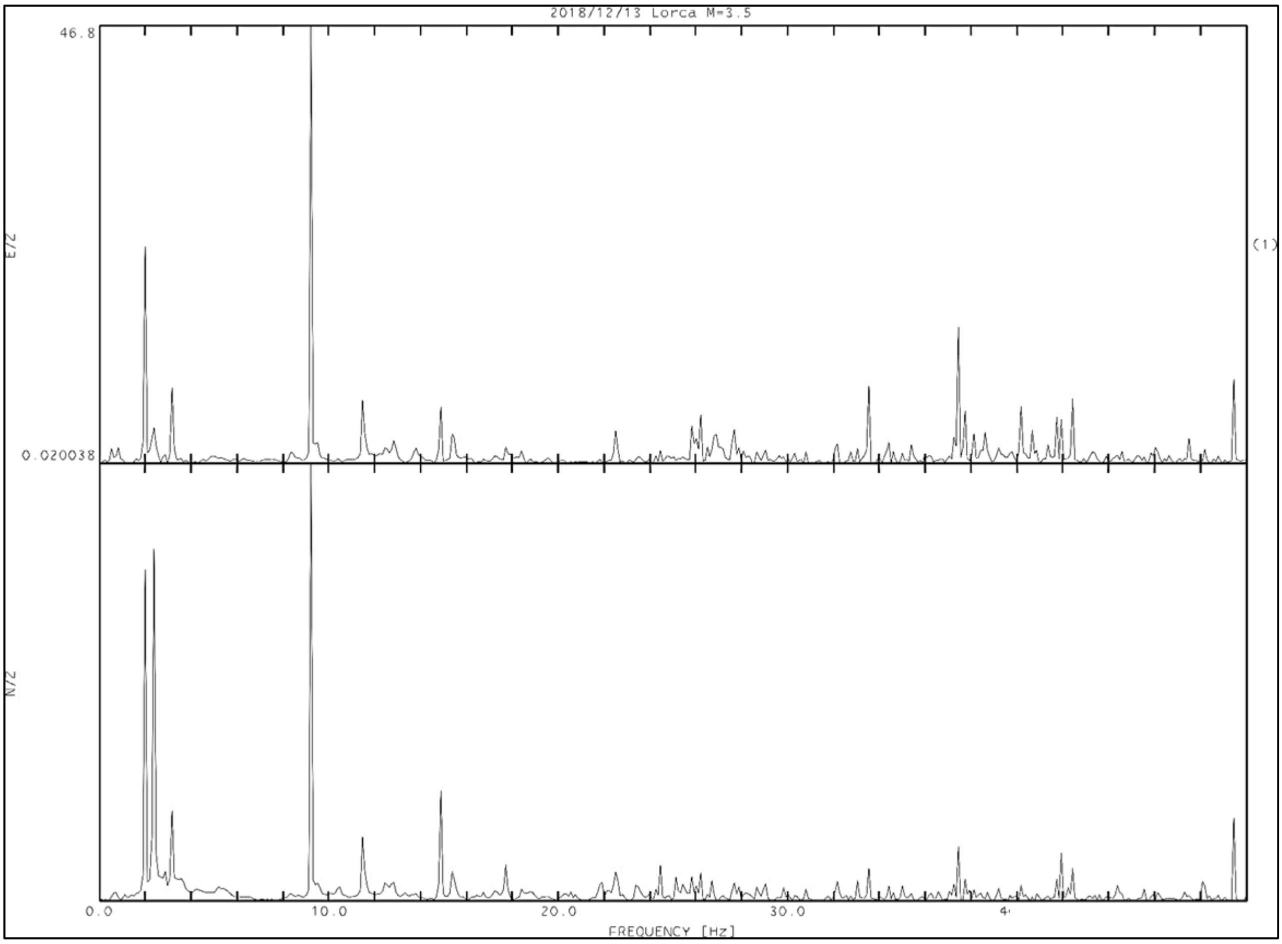

Fig. 30 Spectral division of the horizontal components (East and North) by the vertical component respectively. For accelerograms from Silex LA04A.

We address this problem by applying Nakamura method, so we divide horizontal components (East and North) by vertical components for Silex LA04 (CEIP La Tordecilla). In Fig. 30, we can observe that there are several remarkable peaks in specific frequencies. This spectral ratio is very characteristic of a location where there is high amplification, as it might be a soft layer over a deep layer of hard rock.

4. Values from Macroseismic Intensity

4.1 Values from Forms

We now present several maps of Lorca city and its surroundings along with the seismic intensity. Fig. 30 shows that the maximum intensity for the earthquake is about IV (except outliers).

4.2 Discussion: Seismic Intensity versus Acceleration Peaks

In the map shown in Fig. 31, El Barrio de la Viña is highlighted with a red square, which is the most affected neighborhood of the May 2011 earthquake. We can observe that this neighborhood does not have outstanding values of intensity. There are even fewer questionnaires received compared with other areas. Why inhabitants are less aware of the earthquake in Barrio la Viña area?

In Fig. 32 and 33, we can observe that there is no easy correlation between acceleration data received from our devices and intensities received from questionnaires, so we would probably not be able to calculate the potential hazard of the neighborhood only by analyzing macroseismic intensity information.

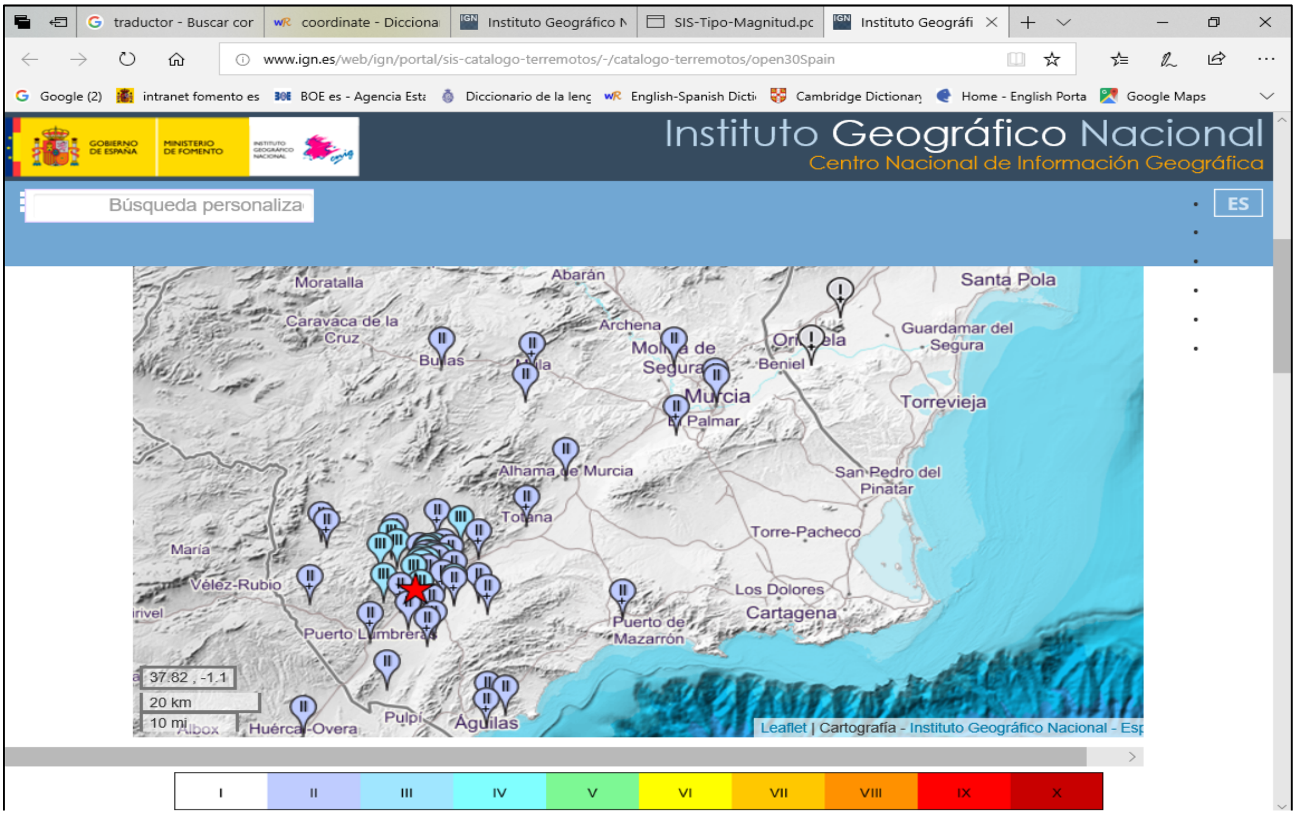

Fig. 31 Current (January 28, 2019) map of the IGN web page of seismic intensity of Lorca province for earthquake December 13, 2018. Imax. = IV.

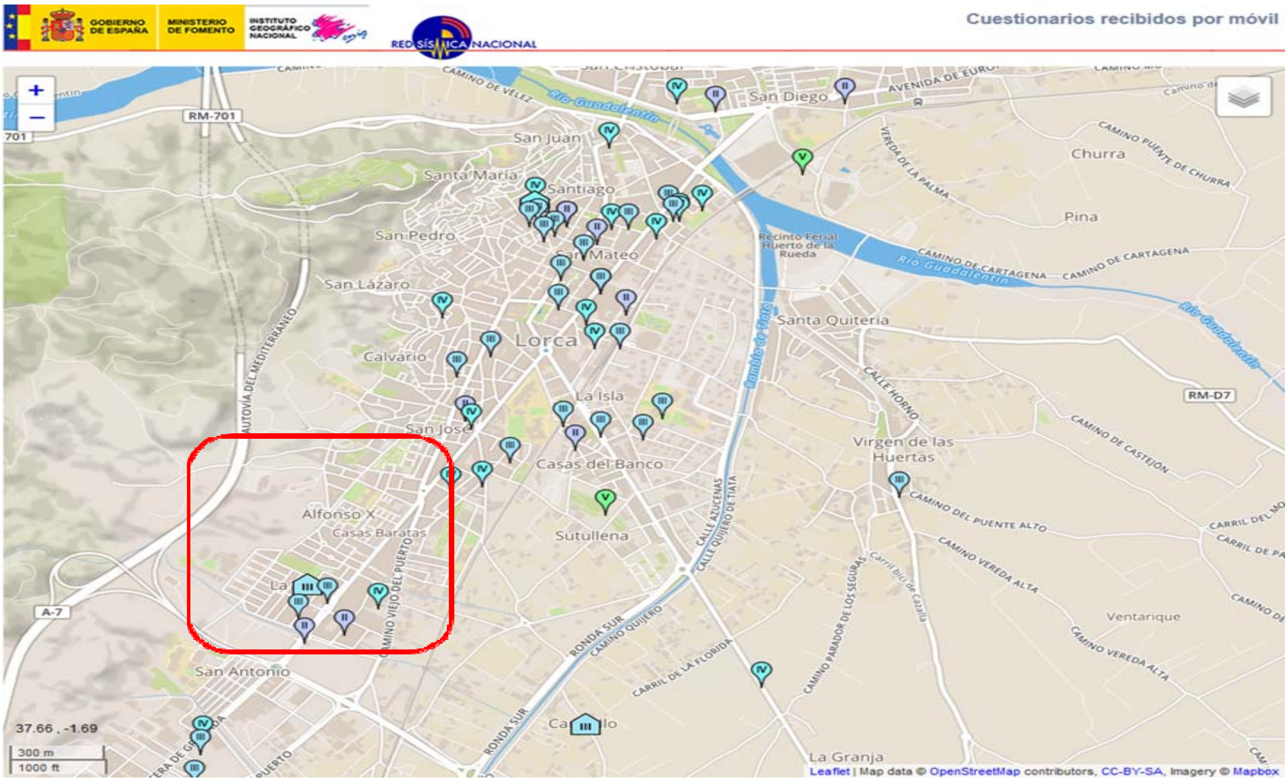

Fig. 32 Map of seismic intensity of Lorca for earthquake December 13, 2018. Values from questionnaires of IGN's smartphone app and IGN web page for eight days after earthquake. Imax. = IV (except outliers).

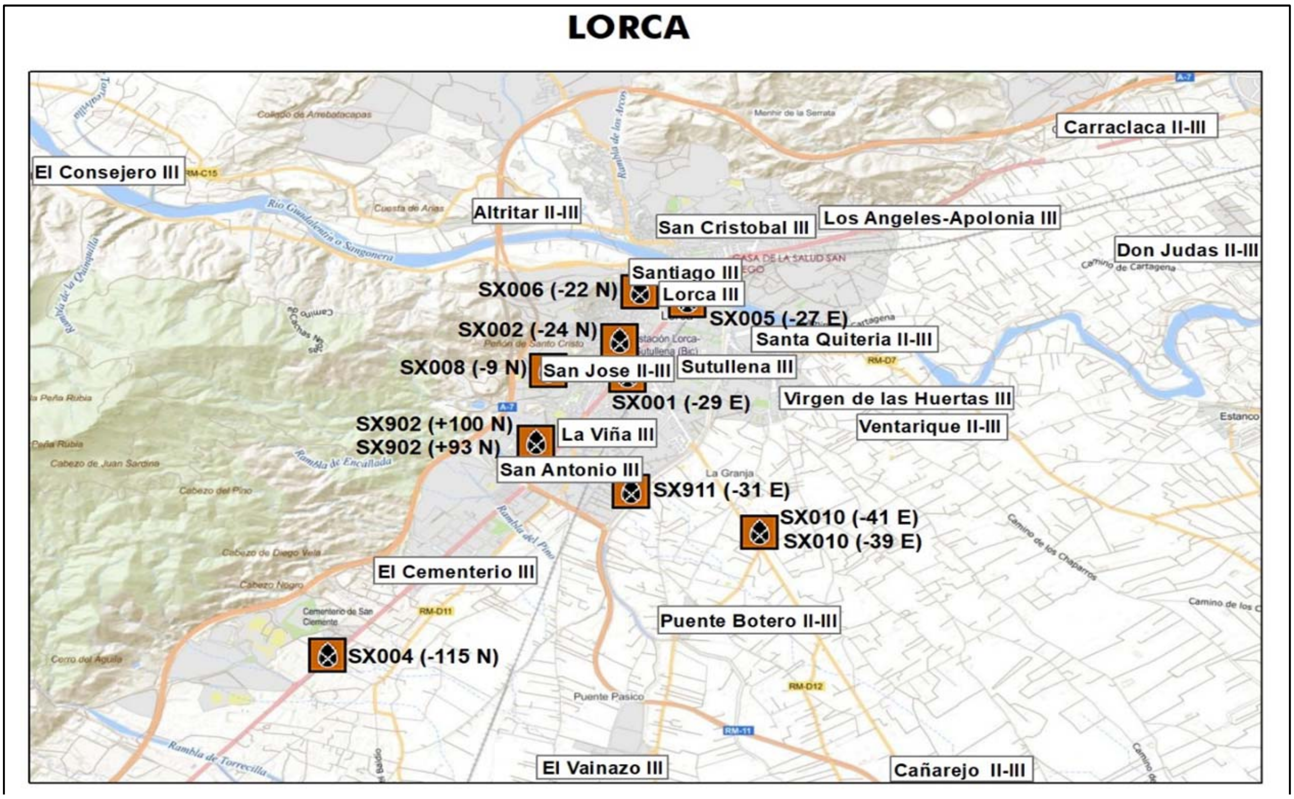

Fig. 33 Map of Lorca for earthquake December 13, 2018, comparing average intensity values from the different borough and instrumental acceleration values. Imax. = III.

5. Conclusions

The usefulness of MEMS accelerographs to improve the output from the Shakemap software has been confirmed [5].

From this paper, we have proved the necessity of having many values of instrumental acceleration to assess dangerous areas which might suffer the quake effects. We think macroseismic intensity is not enough at least obtained from small or middle earthquakes (they are the majority in the seismic catalogs) to assess the hazard and potential damages.

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