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High-density seismic network for monitoring Alentejo region (Portugal) and Mitidja basin region (Algeria)

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Abstract

The seismic sensor network Alentejo (SSN-Alentejo) brings a new approach in seismological survey based on networked low-cost sensors and acquisition systems. It is developed by the Earth Sciences Institute (*Instituto de Ciências da Terra*, University of Evora) to bring the most dense seismic sensor network ever deployed in Portugal. By combining high-sensitive sensors with low-cost sensors, this novel network aims to improve the characterisation of seismic activity in the region, by augmenting existing sensing and monitoring capabilities, enabling the opportunity to observe, for the first time in Portuguese territory, real-time monitoring of the seismic activity in high resolution. In this study, we start by describing the seismicity along the occidental border between the Eurasian-Nubian plates, including the two regions of our interest: the Arraiolos region, in Portugal, and the Mitidja basin, in Algeria. We then present our work in designing and implementing a high-density sensor network, including low-cost sensor systems and server platforms. The conducted tests have proven the feasibility of the overall platform, including its detectability capability. Future work includes the deployment of the sensor network in the Alentejo region. Since seismogenic zones such as the Mitidja or Chelif basins in Algeria will also benefit from having a high-density network, we will also seek collaboration with Algerian institutions.

Keywords High-density seismic network · Seismic sensors · MEMS · Accelerometers · Seismology

Introduction

Seismic events can be extreme and severe threats to humanity, causing a heavy death toll, serious destruction and damage. Being no exception, the Iberian Peninsula and the North of Africa—part of the Ibero-Maghrebian region between the Gulf of Cadiz and Algeria—share the Eurasian-Nubian plate boundary that corresponds to a well-defined narrow band of seismicity, where large earthquakes occur (Ousadou and Bezzeghoud 2019).

Helping to understand these phenomena, seismic networks have been deployed in increasing number, filling in the gaps in the global coverage and improving our understanding of the physical processes that cause earthquakes. Portugal, in particular, has made a significant effort to develop the Broadband Portuguese seismic network integrating seismological stations from various institutions supporting real-time monitoring of the earthquake activity (Caldeira et al. 2007). Between 2010 and 2012, the WILAS (West Iberia Lithosphere and Asthenosphere Structure) project integrated a temporary network of 20 sensors in the Portuguese national network resulting in a total of 55 stations spaced on average by 50 km (Veludo et al. 2017; Custódio et al. 2014). These stations continuously recorded measurements at frequencies up to 100 Hz, thus collecting a large volume of high-quality data of densely distributed broadband stations that can be used to image the Earth's inner structure with unprecedented resolution (Palomeras et al. 2014). More recently, the Arraiolos seismic network (in Alentejo) was deployed comprising 14 broadband stations (CMG 6TD, 30s) of the Institute of Earth

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Sciences of Evora, Portugal (Instituto de Ciências da Terra or ICT), and temporarily extended with 21 short-period stations (CDJ, 2.0 Hz) of the Dom Luiz Institute of Lisbon, Portugal (Instituto Dom Luiz or IDL) within a 20-km radius (Wachilala et al. 2019).

Continuing the trend to increase seismic monitoring resolution by deploying more seismic stations, the United States deployed several very-high-density seismic networks with the capability of recording the propagation of seismic activity in high resolution. This methodology allowed displaying seismic wave propagations in space and time (i.e., evolutive *Shakemaps*): in 2001 and 2002, the California Institute of Technology (CalTech) deployed more than 5200 stations spaced by 100 m with the main purpose of conducting seismic survey to better define the Long Beach Oil Field (Inbal, Clayton and Ampuero 2015). In addition, the CalTech established the Community Seismic Network (CSN), an earthquake monitoring system based on a dense array of low-cost acceleration sensors (more than 1000) aiming to produce block-by-block strong shaking measurements during an earthquake (see http://csn.caltech.edu/, last accessed 2020/08/14). The University of Southern California's (USC) Quake-Catcher Network (QCN) began rolling out 6000 tiny sensors in the San Francisco Bay Area, being part of the densest networks of seismic sensors ever devoted to study earthquakes in real time (see https://quakecatcher.net/, last accessed 2020/08/14).

High-density networks also present several challenges for the state of the practice in seismology. According to Addair et al. (2014), the traditional techniques used in seismology use a processing paradigm that was developed in the 1980s when average computer processing power was a tiny fraction of what is commonly available now. The huge data volume generated by high-density networks demands for research on the application of data-intensive processing techniques like big data and artificial intelligence (e.g., clustering, pattern matching and correlation) in seismology. We expect that a high-dense network-enabled seismic network operating in the principle of "live" data brings the opportunity to explore new applications in seismology, including real-time earthquake detection, more accurate characterisation (high resolution) of strong earthquake motion and the generation of *Shakesmaps* in near real time.

This chapter addresses the seismotectonic context of the regions of interest, namely, the region of Arraiolos, which is located in the north of Evora (Portugal) and the Ibero-Maghreb region, specifically the zones of the Mitidja basin, in Algeria, and the development of a high-dense seismic sensor and, in particular, SSN-Alentejo. It presents the design of the seismic network system, including the sensor platform component and the implementation of the server platform, followed with an analysis of the seismic activity detectability of the sensor platform. The chapter finalises by presenting the planned deployment of the large-density network in Portuguese territory and the rational for its deployment in the Mitidja basin (Algeria), involving a collaboration with Algerian institutions.

Seismotectonic context

Along the border between the Eurasian-Nubian plates, in the section that extends from the islands of the Azores to the Strait of Gibraltar and the Ibero-Maghreb region, different tectonic contexts are distinguished. The interaction between Iberia and Africa results in a complex region located in the western part of the boundary between the Eurasian and Nubia plates. The seismic activity within the region thus results from the transition from an oceanic border (form the Azores to the Gorringe Bank (NE Atlantic), to a continental limit where Iberia and Nubia collide (see Fig. 1).

The plate boundary is very well defined in the oceanic part, from the Azores islands along the Azores-Gibraltar fault to west of the Strait of Gibraltar (approximately 12° W). From 12° W to 3.5° E, including the Ibero-Maghreb region and extending to the western part of Algeria, the border is more diffuse and forms a wide area of deformation (e.g. Bezzeghoud and Buforn 1999; Borges et al. 2001; Buforn et al. 2004; Borges et al. 2007).

The characteristics of the seismicity recorded in the region suggests the division of the western part of the Eurasia-Nubia limit, from the Middle Atlantic crest in the west, to Algiers in the east, in six zones (see Buforn et al. 2004; Bezzeghoud et al. 2014): these zones are characterised by a faulting mechanism variability based on seismicity and focal mechanisms (Bezzeghoud et al. 2014).

Specifically for this study, aiming towards a more detailed characterisation of the seismic activity in the area, we focus our analysis on two specific regions: the region of Arraiolos, which is located in the north of Evora (Portugal) (see Fig. 1, area A), and the Ibero-Maghreb region, specifically the Mitidja basin region, in Algeria (see Fig. 1, area B).

Arraiolos Region, Portugal In the Arraiolos region, located north of Evora in Portugal, an earthquake occurred on the 15th of January 2018 with a ML = 4.9 located at a depth of 11 km. This was the biggest recorded earthquake in the area. A mapping of the seismic activity registered in the area between 1961 and 2018 is illustrated in Fig. 2.

This seismic event has raised a number of interesting questions about the tectonic characterisation of this region.

The seismic activity in the Arraiolos region has been historically moderate, being assumed to be generated by the slow plate movement of Iberia. Geological and seismological studies have been conducted in the region (Wachilala et al. (2019), Araújo et al. (2018); Matias et al. (2019); however, the

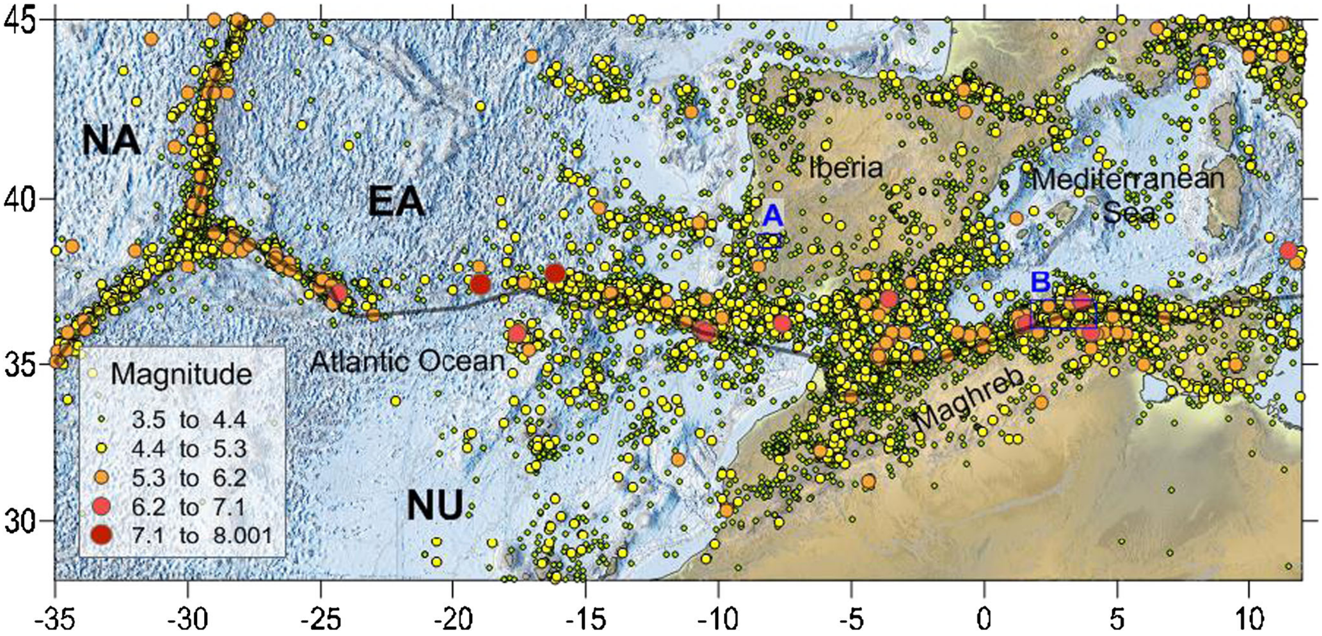


Fig. 1 Map of the seismic activity along the western border of the Eurasian (EU) and Nubian (NU) plates, between 1926 and 2020. NA = North American plate. The two regions of interest are shown with two letters: A (Arraiolos) and B (Mitidja basin). Seismicity data is from the International Seismological Centre (2020). Bathymetry and topography data are from the GEBCO Grid (2020) The limit between the Eu and Nu plates is provided by Bird (2003)

seismotectonic interpretations have been difficult to derive from the existing tectonic knowledge and seismic data. The known mapped faults in the region do not seem to be linked to the recently observed seismic activity, and thus the identification of its probable associated faults is yet to be resolved. Given the increased—previously unknown—degree of seismotectonic complexity of the region, it becomes necessary to improve the seismic and tectonic knowledge of this region by, as envisaged by SSN-Alentejo, deploying additional seismic sensors, increasing the resolution of the recorded seismic activity and, consequently, producing a more detailed seismic characterisation of the region.

Mitidja Basin Region, Algeria In the Ibero-Maghreb region, the Tell Atlas of Algeria is known to be formed by a complex system of faults. The Mitidja basin experienced several disastrous earthquakes such those of Algiers 1365 and 1716, Blida 1825, Mouzaia 1867 and more recently Tipasa-Chenoua 1989 and Zemmouri 2003. According to several studies (Buforn et al. 2004; Ousadou and Bezzeghoud 2018), the Tell Atlas,

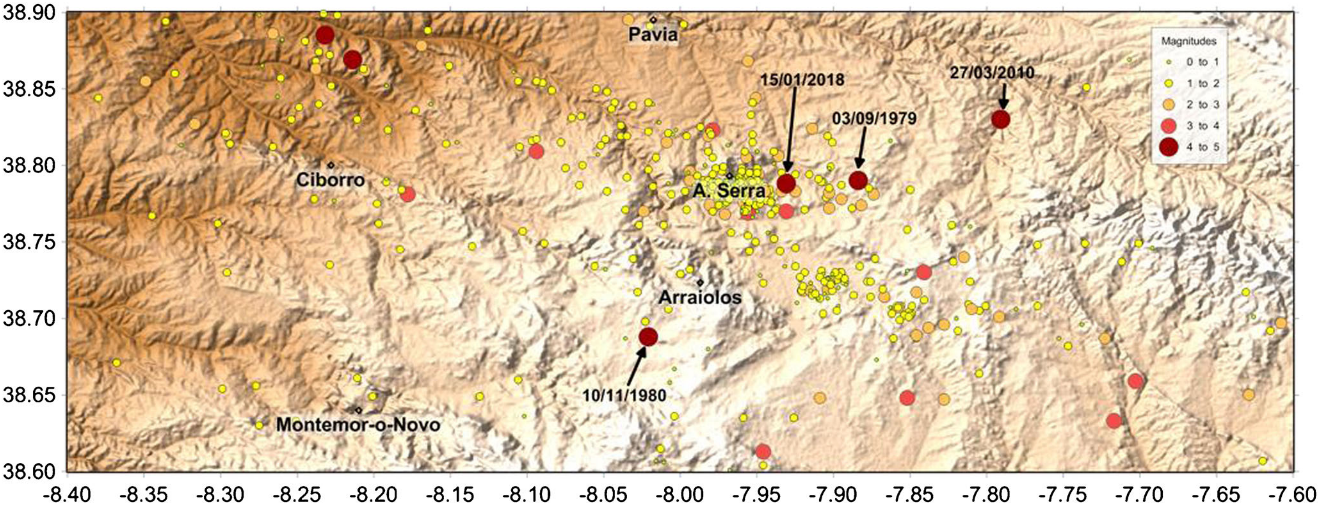


Fig. 2 Map of the recorded seismic activity in the Arraiolos Region, Portugal, between 1961 and Mars 2018, which marked some of the main shocks in the region, including the recent seismic sequence associated with the 15 January 2018 shock ($M = 4.9$). Seismicity source: IPMA (Portugal) catalogue

along the thrust system accommodates 2–3 mm/year shortening of the 5–6 mm/year obtained for the global plate movement. The Mitidja basin region yields a very active seismic activity, as depicted in Fig. 3 (bottom) for the period 1910–2020. Therefore, having the capability to provide a better characterisation of seismic activity through high-resolution mapping from a high-density network, as in SSN-Alentejo, will improve the seismic and tectonic knowledge of this region. This basin is bounded by two important fault systems: the south Mitidja basin and the Sahel fault in the north. In this seismotectonic framework (Fig. 3), both western and eastern edges of the Mitidja basin experienced destructive earthquakes (e.g. Ayadi and Bezzeghoud 2015; Maouche et al. 2011; Benfedda et al. 2017), with the 1989 Tipasa earthquake (Mw 6.0) (Bounif et al. 2003) and the 2003 Zemmouri earthquake, respectively (Santos et al. 2015; Ayadi et al. 2003).

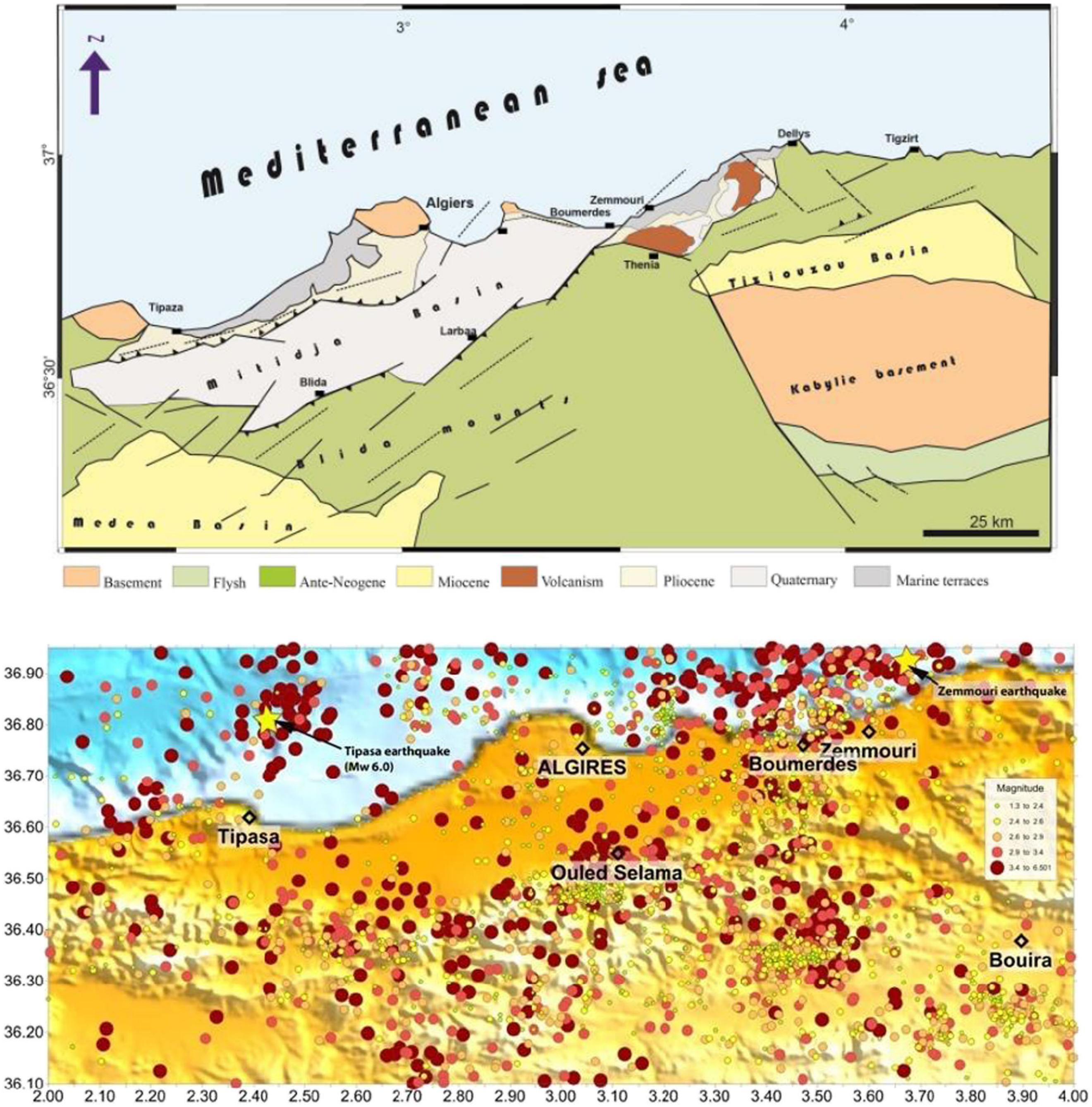


Fig. 3 Top: geological and tectonic background of the Mitidja basin bounded by thrust fault systems (adapted from Ayadi et al. 2003); bottom: seismicity map of Mitidja basin region, Algeria, between 1910 and June 2020. The figure shows a high number of moderate to strong earthquakes distributed over a densely populated region such as Algiers. The 1989 Tipasa (Mw 6.0) and the 2003 Zemmouri earthquakes are highlighted by yellow stars. Seismicity source: International Seismological Centre (2020), online Bulletin

SSN-Alentejo: high-density seismic networks

In the last years, sensors and sensing network technology evolved at a fast pace, resulting in improved performance (resolution, sensibility and processing capacity), operation (energy efficiency, operation time) and connectivity (broadband communications), at significant cost reduction. Low-cost microelectromechanical (MEM) accelerometers, in particular, demonstrated the capability of generating relevant data for seismic analysis in dense deployment contexts (Lainé and Mougenot 2014).

The seismic sensor network Alentejo (SSN-Alentejo) developed by ICT brings the most dense seismic sensor network ever deployed in Portugal. This novel network aims to improve the characterisation of seismic activity in the region and to improve earthquakes' assessment.

Between 2020 and 2021, the SSN-Alentejo will deploy a monitoring network of 60 sensors to generate significant volumes of live data and advance seismology knowledge. The sensors will be distributed in a mesh configuration spaced on average 10 km and covering an area of about 5000 km^2. The density proposed for the network abides to the findings of Clayton et al. (2011). Furthermore, as recommended by Evans et al. (2003), the project opts for a cost-effective network configuration, combining high-performing broadband stations and low-cost sensors.

The seismic network design

The seismic network system for SSN-Alentejo was built by a team of researchers of the ICT. It was designed to operate with *live* data (generated by seismic sensors) and be highly scalable (support a high number of sensors). The design identifies three main functional elements: *producers* of seismic data (i.e. *sensors*), *servers* that collect and store seismic data and *consumers* of seismic data (i.e. users or *clients*). The network is an underlying element that provides connectivity between elements. The system is assumed to be always connected and available.

A general view of the seismic network is shown in Fig. 4, illustrating several connected sensors, clients and servers.

A goal of the seismic network is to provide global access to its resources (i.e. sensors and servers) via the *Internet*. It therefore will rely on many of the latter's components (e.g. routers and gateways).

The sensor and server components are described next.

Sensor platform component

Recent developments in microelectromechanical systems (MEMS) have enabled the mass production of small-size accelerometers with potential applications in numerous areas, including seismology. Capacitive accelerometers, in particular, are highly popular due to reduced cost, their simple structure and the ability to integrate the sensor close to the readout electronics. When subjected to an acceleration, the inertial mass shifts cause a proportional change in capacitance. By measuring the capacitance change, the acceleration can be calculated.

The application of MEMS accelerometers to seismology has met a number of applications (Scudero et al. 2018):

i MEMSs for seismological study and earthquake observation
j MEMS-based seismic monitoring networks
k MEMSs for seismic surveys

Early applications explored the presence of MEMS accelerometers in computers (specifically in hard disc drives) that, connected to a distributed computing network, could be used to build a network of sensors to detect and monitor earthquakes, like the QCN (Cochran et al. 2009). As the underlying technologies to build connected MEMS systems become more accessible and affordable, dense seismic networks using dedicated MEMS sensors are being deployed, as the case of CSN and the urban MEMS seismic network in the Acireale Municipality (Sicily, Italy) (D'Alessandro et al. 2014).

In order to properly exploit its data, it is important to take into account MEMS benefits and limitations, as summarised next (Farine et al. 2003; Evans et al. 2014; Manso et al. 2017). MEMS accelerometers:

- Provide adequate sensitivity, noise level, and range (measured in g) to be applicable to earthquake strong-motion acquisition ($M > 3$), thus also limiting the "resolution' capability. However, the high level of instrumental self-noise that increases as frequency decreases limits their application in the study of low-frequency weak-motion forces
- Are well fit to measure high-frequency (> 40 Hz) ground motion since their resonant frequency (typically above 1 kHz) is far above the seismic band pass
- Measure the gravity acceleration component, thus providing a useful reference for sensitivity calibration and tilt measurement
- Have high acceleration ranges (several g) and are capable to sustain high acceleration (several hundred g) without being damaged
- When compared with broadband seismometers, MEMS may have an advantage in detecting weak high-frequency signals, while the broadband seismometers have the advantage in detecting weak signals at low frequencies
- Can have useful applications such as earthquake early warning, seismic hazard assessment map and security applications.

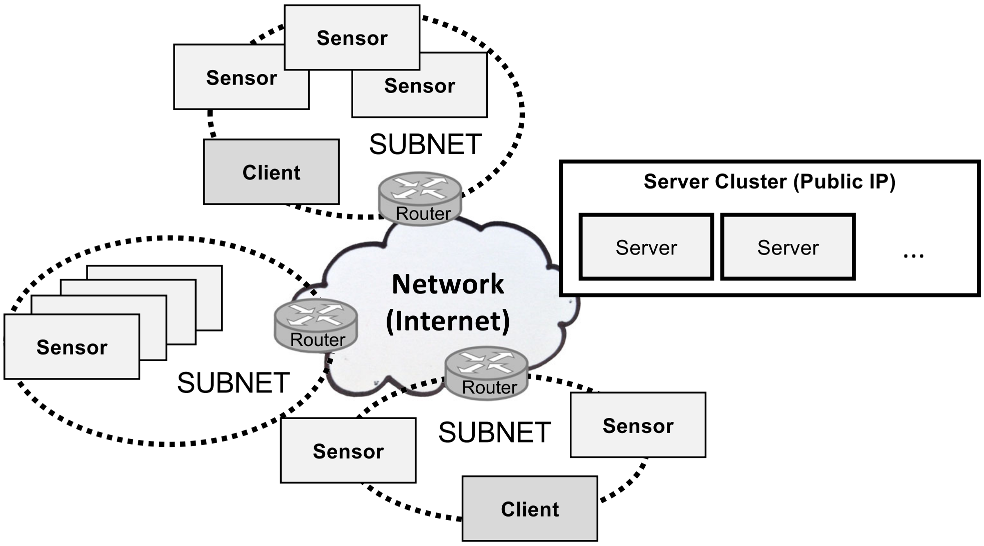


Fig. 4 General view of the seismic network

Analysis of MEMS accelerometers Seismology is most interested in measuring weak ground motion at low frequencies (e.g. distance teleseismic events), while sometimes dealing with moderate to large local events that exhibit medium and strong ground motion at high frequencies. The type of instruments used in seismology, their main purpose and scope is presented in Table 1.

It is quite challenging for a single seismometer to cope with a wide range of signals, inevitably having to set compromises between sensitivity and range: even broadband seismic sensors with a 160-dB dynamic range will clip in the presence of a magnitude 9 earthquake whose maximum dynamic range is around 220 dB (Tunc et al. 2012). Installing strong-motion accelerometers helps overcoming this limitation and thus provides valuable measurement data for seismologists.

Based on Havskov and Ottemoller (2010)

In this regard, when selecting MEMS accelerometers for seismological purposes, the following parameters should be taken into account:

- *Range*: Specifies the minimum and maximum acceleration values it can measure. It is often represented relative to g (e.g. ± 2 g).
- *Resolution*: Specifies both (i) the degree to which a change can be detected and (ii) the maximum possible value that can be measured. In the case of a digital sensor, it is expressed in bits. For example, a sensor with 16 bits resolution is able to quantify 65,536 possible values. If the scale is set to ± 2 g (hence, a 4 g range), the minimum possible change that can be detected is about 61 μg.
- *Sensitivity*: Specifies the ratio of the sensor's electrical output to mechanical input, thus representing the smallest absolute amount of change that can be detected by a measurement. It is typically used in analogue sensors. It can be measured in V/g or in counts/g.
- *Noise density*: Accelerometers are subject to noise produced by electronic and mechanical sources. Since they have a small inertial mass, noise increases at low frequencies. The noise density is often represented in terms of power spectral density (PSD) and is expressed as g/√Hz. It varies with the measurement bandwidth: when multiplied by it, the resulting value represents the minimum acceleration values that can be resolved.
- *Bandwidth*: Specifies the frequency range that the sensor operates in. It is limited to the natural resonance frequency

Table 1 Seismology instruments: purpose and characteristics

Seismology instrumentation	Passive short-period (SP) sensors	Active BB sensors	MEMS accelerometers
Main purpose	Local earthquakes. Global observations of P waves	Suited for all seismological observations. Global observations	Retrieve unclipped observations near the earthquake (suitable for strong motion) Can replace SP sensors for local earthquakes Supports very high frequencies Not suited for low frequencies (< 1 Hz) and weak motion (M < 2).
Frequency Spectrum	Linear for velocity between 1.0 and 100 Hz	Linear for velocity between 0.01 and 50 Hz	Linear for acceleration in frequency band (e.g. 0–1000 Hz) however is limited at low frequencies due to the presence of sensor noise

of the mechanical structure of the accelerometer itself, which is typically very high (> kHz).
- *Sample rate*: Specifies the number of measurements (samples) per second.

Moreover, for purposes of high-dense deployments, other factors are also relevant:

- *Size*: Specifies the physical dimensions of the sensor. MEMS accelerometers are supplied embedded in small chips (order of mm).
- *Power consumption*: Specifies the required power to operate. Usually is very low (order of µA).
- *Cost*: Refers to the cost to purchase a MEMS accelerometer. Prices vary according to the sensor performance. Cost tends to decrease as new (improved) models are launched over time.

For the selection of MEMS accelerometers for SSN-Alentejo, target values were defined as presented in Table 2.

Moreover, in the context of high-dense networks, it is important to consider factors that impact the overall cost, including manufacturing and assembling aspects. As such, the assessment considers the following requirements:

- *Digital sensor*, facilitating direct data read (i.e. no need for an analogue-to-digital converter, no need for any signal pre-conditioning or pre-processing, signal is less exposed to external noise)
- *Cost* (for 3-axis measurements). Two other important parameters are intrinsic in most MEMS:
- *Size* (MEMS accelerometers are embedded in very small chips (in the order or mms))
- *Power* (MEMS accelerometers operate using small currents (in the order of mA or less))

Resorting to online resources and marketplaces, several MEMS accelerometers were analysed based on openly available information, such as product datasheets. The sensors selected for prototyping and evaluation purposes are the following:

- Analogue ADXL355, a 3-axis digital sensor with 20-bit resolution, noise density (PSD) of 25 µg/√Hz and moderate cost (~ 35€). (source: https://analog.com)
- Freescale MMA8451Q with 14-bit resolution, noise density (PSD) of 99 µg/√Hz and low cost (~ 2€). (source: https://www.nxp.com)
- Invensense MPU-6050 with 16-bit resolution, noise density (PSD) of 400 µg/√Hz and low cost (~ 2€). (source: https://www.invensense.com)
- ST Electronics LIS3DHH with 16-bit resolution, noise density (PSD) of 45 µg/√Hz and low cost (~ 7€). (source: https://www.st.com)

Sensor platform implementation The sensor platform contains the sensor component as well as additional other components in order to achieve the functionalities required to operate in a network-enabled environment. The platform should incorporate microcontroller and processing capabilities in order to (i) deliver the capability to function autonomously (i.e. no need to connect to external computers to operate), (ii) connect to an IP-based network and be a low-cost platform (Manso et al. 2016).

The microchip ESP8266 (https://www.espressif.com/en/products/hardware/socs, last accessed 2020/08/14) is low-cost (each unit is below 5€) and covers several needs: it has a fast and programmable microcontroller (up to 160 MHz) and embedded Wi-Fi capabilities and supports a wide range of programming libraries (see https://www.arduino.cc/en/reference/libraries). Moreover, time synchronisation can be achieved by means of the Network Time Protocol (NTP). NTP can keep time accuracy of all machines within the same subnet within 1 ms (NTP 2003). The ESP8266 also contains a limited amount of flash memory (up to 3Mbits) that can be used to store sensor data.

The sensor platform based on ESP8266 has been demonstrated to work with several MEMS accelerometers (coping

Table 2 MEMS accelerometers: parameters and target values

Parameter	Target	Notes
Range	2 to 4 g	Increasing range reduces sensitivity. It is thus advisable to select a small value
Resolution	16-bit or above	-
Noise density	Below 100 µg/√Hz (below 400 µg/√Hz acceptable for prototyping and testing)	This is a critical parameter that is currently the main limiting factor in the application of MEMS in seismology. The target value reflects the current state of the art of the low-cost MEMS market
Bandwidth (and sample rate)	100 Hz or above	Increasing the bandwidth increases the noise density

with up to 200 samples per second), connect to an IP-based network (using the wireless Wi-Fi protocol) and stream data to a server component.

Server component

The server component main functions are to collect and store data received from sensors and to provide access of sensor data to clients (Manso et al. 2017).

Importantly, since a single server supports a limited number of sensors, servers can be deployed in a cluster configuration. In this way, several server instances can be deployed (as required) in order to be able to connect more sensors. Servers propagate information regarding registered sensors among other servers within the cluster as a mechanism to ensure that any server (and any client) can access any sensor.

The server component runs an HTTP server that can be accessed by sensors over a local network or the Internet and used to send measured data. In this regard, the *WebSocket* protocol (Fette and Melnikov 2011) is selected due to its capability to handle high data throughput and its easy integration with Internet-based technologies.

The server component also incorporates a HTTP web server module that allows clients (subscribers) to visualise, retrieve and/or process sensor data. Clients are fully decoupled from the server, can be implemented in different languages and can have different purposes.

The server code is implemented in node.js since it is event-driven and its non-blocking I/O model delivers high performance and scalability. It can also take advantage of multiple CPU cores and parallel processing in handling sensors and clients requests.

Visualisation and event detection tools

The SSN-Alentejo also delivers visualisation and data processing tools exploiting "live" sensor data. Users (*clients*) can use Internet browsers to access the SSN-Alentejo server and visualise the location of sensors, as well as their connection status.

Figure 5 illustrates a simulated scenario of 4 deployed sensors in Evora. Note that sensors are displayed as a circle over a map, thus allowing to visualise their location in space. A colour code is used as follows:

- Green: the sensor is connected and providing data.
- Orange: the sensor has triggered a seismological event.
- Blue: the sensor is registered but is not providing data.

The figure shows two connected sensors (green colour), one registered sensor (blue colour) and one sensor detecting an event (orange colour).

Visual artefacts, such as varying a sensor circle's radius and/or colour based on MMI or other properties, and the use of spatial heat maps can be explored for improving the interpretation of the high-dense network measurements. Interesting implemented examples of the presentation of seismic-related information from high-dense networks are the following:

- Caltech's experience with seismic sensor networks and CSN was employed to monitor campus buildings in the Los Angeles region. The system generates a map displaying the recorded peak acceleration in campus buildings in order to assess potential damage and risk of collapse (see: http://csn.caltech.edu/lausd).
- The MyShake platform is built on existing smartphone technology to detect earthquakes and issue warnings (Allen et al. 2019). The platform aggregates earthquake activity into clusters that are displayed over a map, allowing to visualise areas with high earthquake activity.

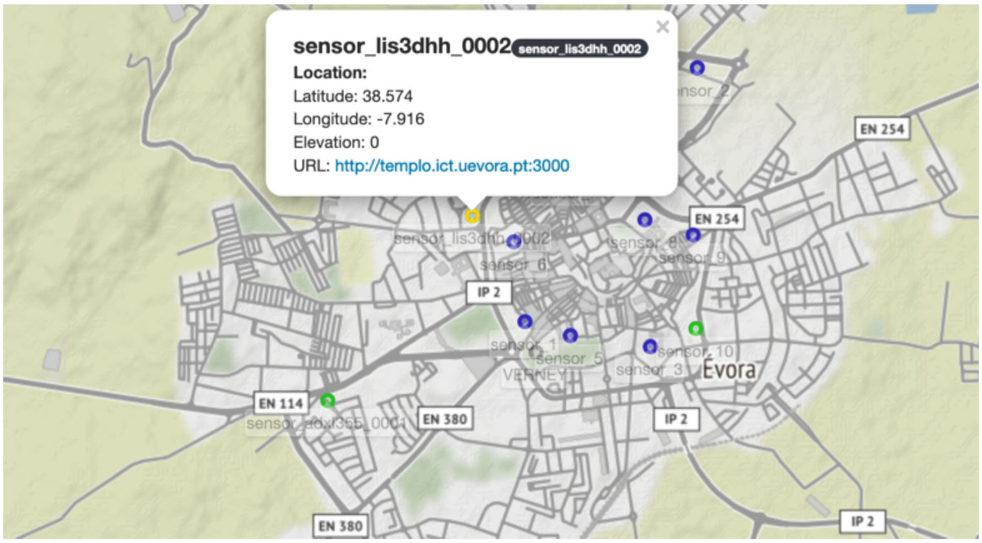
In a scenario of a high-dense network, it will be possible to register a large number of events containing time, location and intensity (MMI) of seismic events (and thus generate *Shakemaps*) as they occur. Referring recent research concerning the 4.9 ML seismic event in Arraiolos, Portugal (Marreiros et al. 2019), the generation of the associated *Shakemap* was delayed due to (1) the lack of availability of seismic data in real time and (2) the need to increase the observation points in space, by collecting feedback from human observers (thus, highly subjective). The SSN-Alentejo will fill the above gap by providing with high amounts of sensor data in quantified form.

Detectability

In this subsection, we present an estimate of the detectability threshold of a seismic sensor prototype platform developed for the SSN-Alentejo, evidencing its relevant and applicability in the field.

The seismic sensor prototype platform, herein named SN.LIS3, used the LIS 3DHH accelerometer operating with a 100-Hz sampling frequency. The platform was deployed and connected to the SSN-Alentejo for several days. The sensor platform was at rest.

In order to estimate the detectability of SN.LIS3, a record of about 1 h and 30 min length was extracted from the SSN-Alentejo database. Date and time were chosen so that no significant seismic activity occurred and cultural noise was as small as possible (i.e. night). We applied a Butterworth low-pass filter with corner frequency in order to eliminate the high frequencies less present in the earthquake records. The result is illustrated in Fig. 6.



sensor_lis3dhh_0002

Location:

Latitude: 38.574

Longitude: -7.916

Elevation: 0

URL: http://templo.ict.uevora.pt:3000

Fig. 5 Visualisation of a small sensor network deployment. The figure shows the sensors' location and connection status (green, connected; blue, registered; orange, activity detected). A sensor was coloured in orange because an event was being detected and recorded

Considering the average noise of the records and defining a criterion for detection signal/noise equal to 5, we estimate a detectability peak ground acceleration (PGA) threshold for SN.LIS3 of 4×10^{-4} m/s^2.

Considering a typical ground motion prediction equation (GMPE) proposed by Atkinson and Boore (2006), the SN.LIS3 detectability threshold, depending on the earthquake magnitude and epicentral distance, is depicted in Fig. 7.

Based on the calculated PGA threshold, we can conclude that:

- SN.LIS3 can detect a magnitude 3 earthquake having an epicentral distance less than 100 km.
- SN.LIS3 can detect a magnitude 4 earthquake having an epicentral distance less than 500 km.
- SN.LIS3 can detect a magnitude 5 earthquake having an epicentral distance less than 1000 km.

The detection capability is quite promising considering the seismic activity in the regions of interest (see Figs. 1, 2 and 3). Our future work will continue the performance analysis of the sensor prototypes using other accelerometers, such as the ADXL355 that is known to have a better signal-to-noise ratio.

Applications

The SSN-Alentejo is composed by accelerometer sensors capable of recording ground motions depending on the event's magnitude and distance (see previous section "Detectability"). Moreover, saturation is unlikely to occur in these instruments because the limit of saturation is of the order of 1 g (9.8 m/s^2), unlike traditional seismometers that are designed to measure weak motions over narrow ranges. The network-enabled high-density seismic network generates data in real time and explores the accelerometers' good sensitivity, high resolution and generous bandwidth, enabling the following applications:

a) Seismic detection (strong motion) for near and "far" earthquakes (far being in the order of hundreds of km), being less likely to saturate compared with traditional equipment. The network allows to study the seismic processes (earthquakes localizations and seismic source study, including the study of focal mechanisms) related to the occurrence of seismic events belonging to sedimentary basin structure.

b) Study local events and characterise the structure of the seismogenic zone by performing waveform analysis of nearby small events (weak motions) and ambient noise. The network will enable us to characterise sedimentary basin structures,

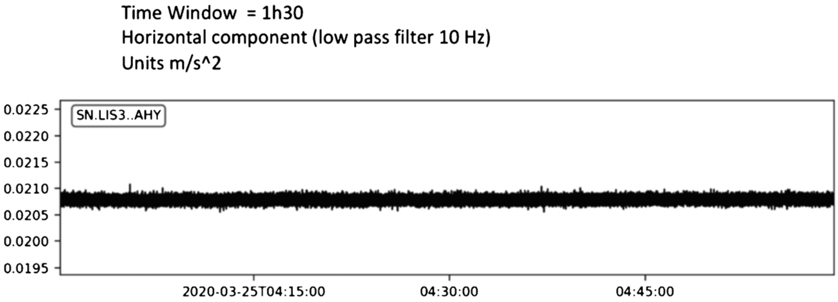


Fig. 6 Time record of the horizontal component recorded by the seismic sensor platform prototype using LIS 3DHH

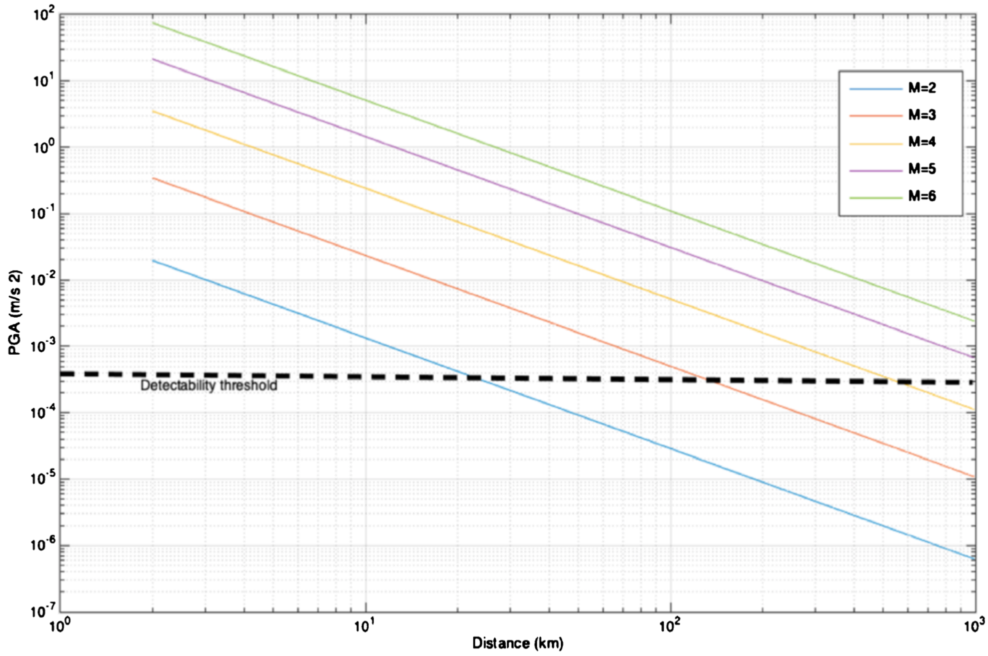


Fig. 7 Detectability threshold for the SN.LIS3. PGA for magnitudes from $M = 2$ to $M = 6$ and epicentral distances to 1000 km, GMPE proposed by Atkinson and Boore (2006)

locate near earthquakes and get seismic source by inverting the waveforms, calculating focal mechanisms, performing local seismic tomography and studying the attenuation of seismic waves using ambient noise or seismic waveforms.

c) Analyse the impact produced by human activity and cultural noise on buildings and monuments: *Urban seismic noise* is usually dominated by *traffic* and industrial activity with peak frequencies below 25 Hz. A continuous exposure to urban tremors can cause a cumulative and progressive degradation on fragile buildings and monuments, which could cause irreparable damage in human heritage. If installed in buildings and monuments, the SSN-Alentejo produces information allowing to determine structural integrity risks.

d) *Shakemap* generation in near real-time. *Shakemaps* provide an estimate of *ground motion* amplitudes (maximum displacement, velocity or acceleration) caused by earthquakes. These maps can be used by civil protection authorities, decision-makers and local organisations (public or privates) for post-earthquake response, including assessing structural integrity risks in buildings and slopes. To be effective, these maps need to be *immediately* generated, thus requiring peak ground motion data in near real time, as generated by the SSN-Alentejo.

e) Provide to the scientific community with new open-access high-resolution seismic data for studying seismic-related phenomena and for developing methodologies useful to discriminate between natural and induced events (Stabile et al. 2020; Serlenga and Stabile 2019; Havskov et al. 2012).

f) Facilitate access to education in seismology, resulting from open-access to low-cost technology that can be installed in high schools and integrated in projects and activities.

Conclusion

The SSN-Alentejo represents a reinforcement of sensing and monitoring capabilities, enabling the opportunity to explore for the first time in Portuguese territory the high-resolution observation of seismic activity. In particular for the identified two regions of interest, namely, Arraiolos (Portugal) and Mitidja basin (Algeria), we argued that there is a need to overcome the existing limitations in monitoring seismic activity by deploying additional seismic sensors, increasing the resolution of the recorded seismic activity and, consequently, producing a more detailed seismic characterisation of the region. This is a necessary step to improve the seismic and tectonic knowledge in the regions.

After the occurrence of the recent magnitude 4.9 earthquake in Arraiolos, a temporary network of about 40 stations was deployed for a few weeks (Fig. 8a) that has now been reduced to almost 15 permanent stations (Fig. 8b). The SSN-Alentejo will deploy 60 connected sensor platforms, increasing the regional seismic network to about 65 stations, enabling a high-resolution seismic characterisation (Fig. 8c). In addition, the SSN-Alentejo will be used to monitor ground motion activity (might be caused by natural and/or human activity) in high detail of Evora City, considering its high patrimonial value and cultural heritage. As it can be clearly visualised in Fig. 8, the SSN-Alentejo brings a significant increase in the monitoring of seismic activity in the area of interest.

The high-dense network-enabled seismic network operating in the principle of "live" data will bring the opportunity to explore new applications in seismology, including real-time earthquake detection, more accurate characterisation (high

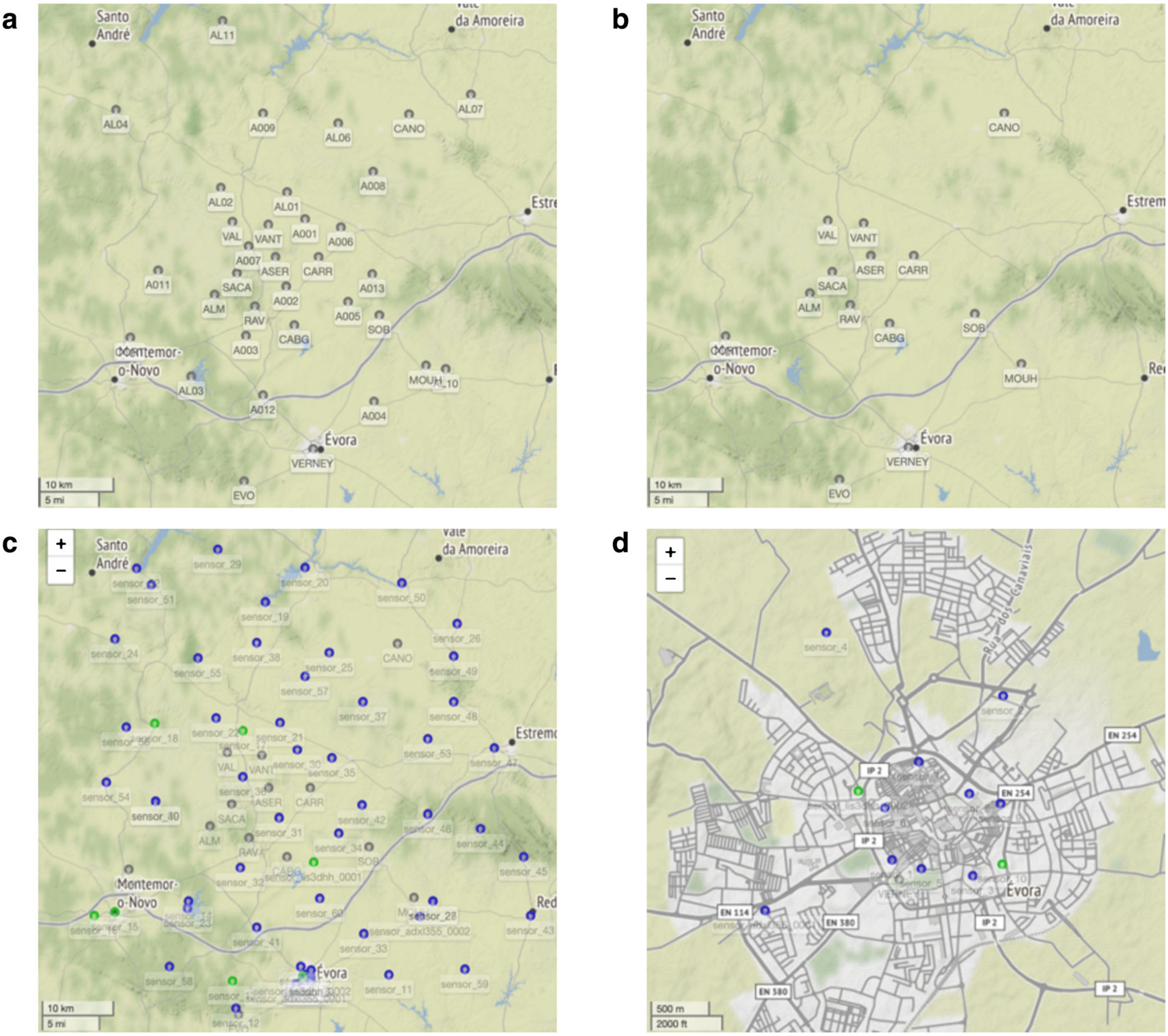


Fig. 8 Different phases of the seismic network in Alentejo (includes the Arraiolos region) and the SSN-Alentejo planned deployment. (**a**) Temporary seismic network deployed in the Arraiolos region after the earthquake. About 60 connected stations. (B) Current seismic network in the Arraiolos region. Less than 15 connected stations. (C) SSN-Alentejo: planned deployment of additional 60 sensors, resulting in about 75 stations in total. (D) SSN-Alentejo: planned deployment for the Evora City. Sensor density is increased to monitor ground motion activity that may impact cultural heritage and historical buildings

resolution) of strong earthquake motion and the generation of shakemaps in near real time.

Moreover, based on Addair's findings (Addair et al. 2014), novel and redesigned algorithms exploiting parallel computational-intensive techniques will allow applying machine learning techniques and pattern matching-based processing that are much more sensitive than the power detectors used in current seismic systems, making them especially relevant in the presence of noise and weak signals such as those present in slowly deforming regions, namely, Alentejo (Fig. 8).

Importantly, these high-density networks bring, in general, enormous potential to better understand seismogenic zones such as the Mitidja or Chelif basins in Algeria. It is our aim to explore a deployment resorting to our close relationship with several Algerian institutions such as the Algiers and Oran universities as well as the Centre National de Recherche Appliquée en Génie Parasismique (CGS) and the Centre de Recherche en Astronomie Astrophysique et Géophysique (CRAAG).

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