ACADEMIA | Letters

Monitoring the Earth: the Near-Future Developments in Seismology

Mourad Bezzeghoud
Marco Manso

University of Évora, Portugal

Seismology deals with the study of the activity of physical forces responsible for the origin of earthquakes and the seismic waves generated within the Earth. All structures located from the center of the Earth to its surface are the subject of study in this discipline. Seismology therefore pursues the understanding of the Earth's internal structure and the physical processes that cause earthquakes, resorting to advanced instruments for observation and measurements. This paper presents an overview of important milestones in the seismological field, followed by revolutions in the instrumentation and observation of seismological events.

The Earth

Earth is our natural habitat. Human beings and economic and social development depend on the planet's resources, which are not inexhaustible. In fact, the way resources will be managed during the 21st century will be decisive: only their moderate and rational exploitation will allow the Earth to host and sustain the 10 billion human population estimated for the end of this century. Developing a thorough knowledge and understanding of the functioning of our planet is therefore essential to develop our society in a harmonious and sustainable way. It is also our legacy to teach future generations our understanding of the Earth.

The Earth is a fascinating "entity" and discovering it from a physical point of view is an even greater adventure. Understanding its structure, its dynamics and its shape imposes answering questions across different domains, because several physical phenomena of different

Corresponding Author: Mourad Bezzeghoud, mourad@uevora.pt
Citation: Bezzeghoud, M., Manso, M. (2021). Monitoring the Earth: the Near-Future Developments in Seismology. *Academia Letters*, Article 581. https://doi.org/10.20935/AL581.

scales are involved, from "astronomical" scale (e.g., interaction with other celestial bodies) to "atomic" scale (e.g., radioactive emission).

In the 20th century, the acquisition and analysis of massive amounts of observations and information was made possible by progresses in instrumentation, electronics and information technology. However, as opposed to Jules Verne's novel "Journey to the Center of the Earth", so far, knowing the interior of our planet is only possible through observations and records made on the surface, i.e., indirect observations.

The Physics of the Earth

Our knowledge of the Earth's interior was still rudimentary at the beginning of the 20th century [1], especially when compared with the scientific advances obtained about the "infinitely small" (discovery of radioactivity by Bequerel in 1896; identification of the electron by Thomson in 1897; formulation of the quantum theory by Planck in 1900) and "infinitely large" (theory of gravitation by Newton in 1687; foundations of celestial mechanics by Laplace in 1799; formulation of the theory of general relativity by Einstein in 1915). Knowledge of the interior of the Earth mainly results from work conducted in the 20th century: in 1887 John Milne (1850-1913) identified the crust, Lord Rayleigh, Lord Rutherford and Emil Wiechert the mantle; the limit between the crust and the mantle was defined by Andrya Mohorovicic in 1909 (discontinuity of Mohorovicic/Moho); in 1906, Oldham's remarkable work determined the size of the Earth's outer core; Beno Gutenberg (1889-1960), in 1912 in his doctoral thesis, defined the boundary between the outer nucleus and the mantle. This interface between the asthenosphere and the endosphere is called Gutenberg's Discontinuity; in 1926, Sir Harold Jeffreys (1891-1989) discovered that the outer core is liquid; in 1936 Inge Lehman (1888-1993) provided the key for the identification of the Earth's inner core; inner core which, in 1946, is identified as solid by Keith Edward Bullen (1906–1976). In 1935, H. Jeffreys and K.E. Bullen published the famous travel time tables of the seismic waves that bear their names (Jeffreys-Bullen tables) and which served as a reference for seismologists and geophysicists for half a century. The previously mention discoveries about the structure of the Earth, from John Milde to K.E. Bullen, were based on the study of earthquakes and the propagation of seismic waves. It is also important to underline one of the great steps taken to understand internal geodynamics, due to the Irish Robert Mallet (1810-1881) and to the French, Alexis Perrey (1807-1882) and Count Fernand Jean Batiste Marie de Montessus de Ballore (1851-1923) who dedicated a significant part of their work to the collection of information regarding earthquakes that occurred throughout the planet. The revolutionary discovery of the ocean floor expansion in 1963 by Drummond Hoyle Matthews and his student Fred J. Vine, also in-

Corresponding Author: Mourad Bezzeghoud, mourad@uevora.pt
Citation: Bezzeghoud, M., Manso, M. (2021). Monitoring the Earth: the Near-Future Developments in Seismology. *Academia Letters*, Article 581. https://doi.org/10.20935/AL581.

dependently brought by Lawrence Morley, were essential elements for the acceptance of the Plate Tectonics theory .

Recording earth motion and earthquakes - the first (r)evolution in high-density deployments

Seismic events can be extreme, and severe threats to humanity. Helping to understand these phenomena, seismic networks have been deployed in increasing number, filling in gaps in the global coverage and improving our understanding of the physical processes that cause earthquakes. Several countries have made significant efforts to deploy Broadband seismic networks incorporating seismological stations supporting real-time monitoring of the earthquake activity. However, these stations are installed several kilometers from each other, thus limiting the overall spatial resolution of the observations. It is important to highlight that the revolutionary contribution of broadband seismic instrumentation, in which principles of feedback accelerometers and zero-length leaf spring were implemented. Construction, functionality and measurement results of the first vertical STS-1 broad-band (BB) seismometer was published by Wielandt and Streckeisen [2] and the advancing the STS-1 to a novel digital Very-Broadband-Seismograph (VBB) was published by Wielandt and Steim [3].

A paradigm change occurred in the United States with the deployment of high density seismic networks with the capability to record the propagation of seismic activity in high resolution: The California Institute of Technology established the Community Seismic Network 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 [4]. The University of Southern California's Quake-Catcher Network began rolling out 6000 tiny sensors in the San Francisco Bay Area, being part of the densest network of seismic sensors ever devoted to study earthquakes in real time [5].

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, as well as the generation of Shakemaps (i.e., spatial representation of ground motion amplitudes).

Low-cost sensors: the second (r)evolution and the near-future developments

In the last years, sensors and sensing network technology evolved at a fast pace, resulting

Corresponding Author: Mourad Bezzeghoud, mourad@uevora.pt
Citation: Bezzeghoud, M., Manso, M. (2021). Monitoring the Earth: the Near-Future Developments in Seismology. *Academia Letters*, Article 581. https://doi.org/10.20935/AL581.

in improved performance, operation and connectivity at significant cost reduction. Low-cost Micro-Electro Mechanical Systems (MEMS) accelerometers, in particular, demonstrated the capability to generate relevant data for seismic analysis in dense deployment contexts [6].

MEMS technology has enabled the mass production of small size accelerometers. 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.

In order to properly exploit its data, it is important to take into account MEMS benefits and limitations [7-10]. MEMS accelerometers have adequate range (several times the standard gravity *g*), sensitivity and frequency response (typically around 1k Hz) but exhibit high-levels of instrumental self-noise. As such, they are especially fit to measure strong seismic activity (M>3), high frequencies (>40 Hz) and can measure the gravity acceleration component. Importantly, MEMS accelerometers complement broadband seismometers in what regards strong motion and high frequency measurements.

In Portugal, as part of the SSN-Alentejo project [11], the University of Évora is planning a deployment of up to 300 network-enabled stations in the Évora region, complementing the existing network that is comprised by 15 broadband stations. SSN-Alentejo will be used to monitor ground motion activity - caused by natural and/or human activity - in high detail, including in Évora city given its high patrimonial value and cultural heritage.

The network-enabled high-density seismic network generates data in real-time enabling the following applications [9]:

- Seismic detection (strong motion) for near and “far” earthquakes (far being in the order of hundreds of kms).

- Study of local events and characterize the structure of the seismogenic zone by performing waveform analysis of nearby small events and ambient noise.

- Analyze 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.

- Generation of *Shakemaps* that can be used by civil protection authorities for post-earthquake response, including assessing structural integrity risks in buildings and slopes.

Corresponding Author: Mourad Bezzeghoud, mourad@uevora.pt
Citation: Bezzeghoud, M., Manso, M. (2021). Monitoring the Earth: the Near-Future Developments in Seismology. *Academia Letters*, Article 581. https://doi.org/10.20935/AL581.

- Provide to the scientific community with new open-access high-resolution seismic data.
- 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

Seismology is a relatively young scientific discipline, that has significantly evolved since the beginning of the 20th century, benefiting from significant advances in theories and technology. Broadband seismic networks brought the capability to perform real-time monitoring of the earthquake activity and subsequent high-density deployments allowed further increasing spatial resolution of the observations for a more accurate characterization (high resolution) of earthquake motion. Recent developments in low-cost MEMS accelerometers have found numerous real-world applications, including in seismology and risk hazard assessment of buildings and human heritage. Being low-cost, it facilitates their widespread adoption enabling the deployment of high-density networking providing high resolution observation and massive amount of data that may feed intensive processing techniques like big data and artificial intelligence, applying machine learning techniques and pattern matching-based processing that are much more sensitive than the power detectors used in current seismic systems [12] making them especially relevant in the presence of noise and weak signals.

The deployment of high-density network-enabled seismic networks represents an important step in our road towards understanding the functioning of the Earth, including its internal structure and physical processes that cause earthquakes, while at the same time contributing towards a safer and more sustainable society.

Corresponding Author: Mourad Bezzeghoud, mourad@uevora.pt
Citation: Bezzeghoud, M., Manso, M. (2021). Monitoring the Earth: the Near-Future Developments in Seismology. *Academia Letters*, Article 581. https://doi.org/10.20935/AL581.

References

[1] Bezzeghoud M. (2012) *Viagem ao interior da Terra*, in Ana Maria Silva, Araújo, A., Reis, A., Morais, M., Bezzeghoud, M (ed.) *Two Decades of Earth Science Research*. Centro de Geofísica de Évora Celebration of 20 Years. ISBN: 78-989-95091-4-6.

[2] Wielandt E., Streckeisen G. (1982) *The leaf-spring seismometer: design and performance*, Bull. seism. Soc. Am., 72(6), 2349–2367.

[3] Wielandt, E., Steim, J.M. (1986) *A digital very broad band seismographe*, Annales Geophysicae, 4, B, 3, 227-232.

[4] See http://csn.caltech.edu/, accessed 2021/01/15

[5] See https://quakecatcher.net/, accessed 2021/01/15

[6] Lainé J. and Mougenot D. (2014). *The Leading Edge*. November 2014. Special Section: Sensor technology and nanotechnology. DOI: 10.1190/tle33111234

[7] Evans J, Allen R, Chung A, Cochran E, Guy R, Hellweg M, Lawrence J (2014). *Performance of Several Low-Cost Accelerometers*. Seismological Research Letters, 85, 1, January/February 2014. DOI: 10.1785/0220130091

[8] Farine M, Thorburn N, and Mougenot D (2003). *General applications of MEMS sensors for land seismic acquisition. Is it time?* The 2003 CSPG/CSEG convention. Canada.

[9] Manso M., Bezzeghoud M., Caldeira B. (2017) *Design and Evaluation of a High Throughput Seismic Sensor Network - Tools for Planning, Deployment and Assessment*. In Proceedings of the 6th International Conference on Sensor Networks - Volume 1: SENSORNETS, ISBN 978-989-758-211-0, pages 129-134. DOI: 10.5220/0006127701290134

[10] Manso, M., Bezzeghoud, M., Borges, J., Caldeira, B., Abdelhakim (2020) *High-density seismic network for monitoring Alentejo region (Portugal) and Mitidja basin region (Algeria).* Arab J Geosci 13, 976. DOI: 10.1007/s12517-020-05972-w

[11] See https://www.uevora.pt/en/Research/projects?id=3812, accessed 2021/01/15. The SSN-Alentejo project is funded by the Science Foundation of Portugal (FCT) under grant number ALT20-03-0145- FEDER-031260.

[12] Addair T, Dodge D, Walter W, and Ruppert S (2014). *Large-scale seismic signal analysis with Hadoop*. Computers & Geosciences 66, 145–154. DOI: 10.1016/J.CAGEO.2014.01.014

Corresponding Author: Mourad Bezzeghoud, mourad@uevora.pt
Citation: Bezzeghoud, M., Manso, M. (2021). Monitoring the Earth: the Near-Future Developments in Seismology. *Academia Letters*, Article 581. `https://doi.org/10.20935/AL581`.