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D4.6 Key scientific questions for future network design

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Authors	Michel Campillo, Université Grenoble Alpes Fabrice Cotton, GFZ Potsdam Aldo Zollo, University of Naples Federico II Frederic Tilmann, GFZ Potsdam Andreas Rietbrock, Karlsruhe Institute of Technology Rosemary Fayjaloun, Université Grenoble Alpes and all the participants of the workshop (see page 19)
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Table of Contents

Summary

As part of the SERA EU project (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe, task 23.4 Assessment of network design), a workshop (Potsdam, 21-23 November 2018) has been organized to evaluate the immediate impact of the new technologies and the expected long-term science evolutions that cross the boundaries of traditional seismological research. The needs of the seismological community have been first evaluated through a questionnaire sent to the participant's teams before the workshop. 26 researchers representing 10 countries were present. This questionnaire has been used to 1) identify critical databases and instrumentation pools required to tackle key scientific questions and operational demands, 2) discuss the potential scientific impact of new sensor network technologies 3) compare the level of European seismological networks with Japanese and US networks. These questionnaires and the meeting presentations have contributed to identifying the priorities of future European seismological instrumental pools and networks. These suggestions and the associated roadmap are identifying the following priorities: 1) support the development of European Multi-sensor Observation Sites (EMOS), in order to concentrate the efforts at a level where it can be transformational and be able to test new technologies in real conditions; 2) develop coordinated on-shore-off-shore experiments to characterise the structures responsible for megaquakes; 3) build European instrument pools of instruments related to new technologies (Distributed Acoustic Sensing, rotational sensors, nodal dense arrays) that are underrepresented at national levels. The paper finally suggests a series of experimental tests and data-analysis approaches that have been identified as important to evaluate the potential of emerging technologies: imaging resolution of present and future seismological networks, potential of Distributed Acoustic Sensing (DAS) technology, evaluation and comparison of most popular low-cost seismological sensors, limits of seismological networks deployed in urban or industrial environments, key potential improvements of European on-line databases.

1 Introduction

New types of seismological instrumentation and deployment modes (distributed acoustic sensing in optical fibre, rotational sensors, massive deployments of low cost sensors) will be widely available in upcoming years. The vast amount of data that will be generated requires new computing paradigms, which are also needed to leverage the new methods emerging from computing science, often collectively referred to as data science. As part of the SERA EU project (Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe, task 23.4 Assessment of network design) a workshop (Berlin and Potsdam, 21-23 November 2018) has been organized to evaluate the immediate impact of these new technologies and the expected long-term developments in our science, which cross the boundaries of traditional seismological research. Based on this, this report aims to lay out the foundations of a roadmap for future European scientific and technological research in seismology.

The needs of the seismological community have been first evaluated through a questionnaire sent to the participant's teams before the workshop. This questionnaire has been used to 1) identify critical databases and instrumentations pools required to tackle key scientific questions and operational demands, 2) discuss the potential scientific impact of new sensors, and 3) compare the level of European seismological networks with Japanese and US networks. The first part of the present paper summarizes the feedback received through the questionnaires and meeting presentations.

In the second part, the priorities of the European seismological instrument pools are formulated based on identified major, leading edge research themes. Based on these, this report makes recommendations and the foundations of a roadmap in order to guide the improvement (or redesign) of European seismological networks and highlight new capabilities, which will be required to make rapid progress in addressing one or more science grand challenge questions.

2 European seismology at the frontier: lessons learned from a community survey

- Question 1. Science frontiers. Which seismological data are missing to tackle key scientific questions? Which are the weaknesses of actual databases?

The importance of near-fault system observations has been stressed in many questionnaires. High density observation systems at specific pilot-sites (European Multi-sensor Observation Site 'EMOS'), instrumented with multi-parametric sensor networks, are needed to potentially detect and compare the preparation phase of small-moderate-large earthquakes, analyse the mechanisms controlling the initiation and evolution of seismic ruptures and pre- or post-seismic phenomena.

Such 'EMOS' strategy is not new and the feedbacks of previous and present experiments are the basis for a discussion of the evolutions toward the new generation of seismological observatories of active faults. This new generation will include boreholes sensors (to improve the detection threshold of low magnitude earthquakes), high-rate GPS stations, rotational and high-dynamics sensors able to record both small and large earthquakes and associated shaking. The next generation of near fault monitoring systems should also include off-shore instruments (OBS, cables) and leverage temporary deployments of Large-N arrays (seismic antennas with hundreds of nodes) to obtain detailed structural information. Because of anthropogenic induced seismicity issues and the development of mega-cities, this new generation of "EMOS" monitoring systems should be also fully operational in urban and industrial environments (and not only in quiet environments). This new generation should also take advantage of datasets from fibre-optic cables, building and lifelines and monuments monitoring.

Science frontiers in seismology are related to more complete exploration of growing volumes of observations. The feedbacks show that the seismological community is facing with a cultural change: we are moving from a "download" culture to data-mining and assimilations methods which imply a strong coupling between High Performance Computing (HPC) and large datasets. The next big challenge will be to bring the data to HPC, or bring HPC to the data, an emerging Data Science. Speed of access and ability to treat and store large intermediate results or data on dedicated platforms is becoming a key issue. New approaches of data-mining also imply the need for seamless inter-operability between datasets collected by different instruments and communities (e.g. geodesy and seismology) and between various institutions.

- Question 2. Operational seismology. Which seismological data are missing to improve our operational goals (detection, early warning, rapid response, hazard assessment)? Which are the weaknesses of actual databases?

Seismic hazard studies are becoming region and site specific. Dense instrument pools are needed to increase the density of observations in cities but also on active faults or volcanoes. "Act local but think global": the development of physics-based prediction models implies the integration of large experimental data both at the local scale (e.g. to define velocity and attenuation models) and at the global scale (e.g. to define the probability distribution of seismic rupture parameters). Hazard models and the databases used for volcanic and earthquake hazard predictions have to be fully open and transparent.

New early warning and rapid response systems imply the development of automated, real time (certified deadline for data transmission smaller than a second) monitoring systems and the real-time validation and integration of crowd-sourcing data. The next generation of early warning systems will integrate new sensor technologies (e.g. high-rate GPS integrated with strong motion sensors, near-source surface and borehole seismic arrays, fibre optic cable sensors, rotational sensors, integrated super-conducting gravimeters and broadband seismometers) and processing methods to track and image the rupture while it is ongoing (e.g. real-time dynamic/kinematic modelling and waveform simulation, neural networks and LM for EEW signal processing, P-wave based mapping of the potential damage zone, assimilation techniques to space time prediction of peak ground motion), experiment the massive exploitation of low-cost accelerometers in smartphones and improve their use for alert services during emergencies. There is now a wealth of information available rapidly after an earthquake from seismology, geodesy, satellite imagery, sea-level measurements, as well as crowd sourced information (videos of the tsunami, landslides…) (e.g. Bossu et al., 2018). The right analysis and visualization tools to fully exploit these interdisciplinary datasets are, however, still missing.

- Question 3. New sensors and network development: A game changer for European Earth Sciences? Do we need new types of sensors or simply more sensors? Which new sensors for which applications?

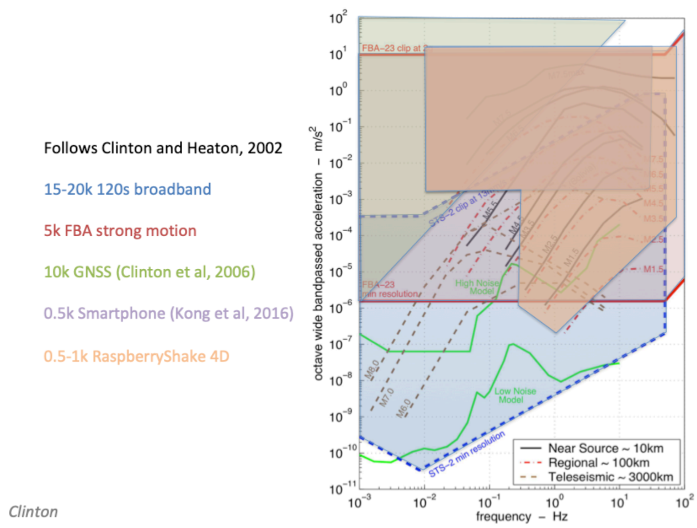

Figure 1: Adapted from Clinton and Heaton (2002). Frequency-amplitude plot for octave-wide band-passes of ground-motion acceleration. The dashed blue lines give the dynamic range of the STS-2. The areas shaded with light blue are regions of frequency-amplitude space that are recorded by the FBA-23 but not by the hypothetical low-gain broadband seismometer. Noise levels are the USGS high- and low-noise models (Peterson, 1993). The pink area shows recent tests performed by the SED.

Two major game changers have been identified: the exponential increase of the number of sensors which can nowadays be deployed (see Table 2) and the emerging use of new type of sensors (e.g. rotational, fibre-optic cables). These new types of sensors seem to emerge quickly during the last few years and some of them can results in important breakthroughs (e.g. detection of P-waves and discrimination of P & S wave signals at near source distances using rotational sensors).

Cheap sensors (e.g. Kong et al., 2016, Cochran et al., 2018) for dense deployment are a reality and their use will naturally increase, simply because it is possible, affordable and has shown excellent results in exploration. The survey results show however the need to better test and characterize the instrument response of these low cost sensors (**Error! Reference source not found.** shows some preliminary test developed by the Swiss Seismological Service). The questions of the cost and usability of DAS technology is stressed by many questionnaires. The development of DAS interrogators (versus the use of commercial ones) has also been also raised. Better instrumentation of the seafloor and of remote/extreme areas inland remains an important challenge and the need to deploy sensors on the seafloors is identified as a priority but there is no consensus on the technical solutions. The development of new technologies (e.g. MERMAID, use of marine cable) is seen as major step forward for offshore seismology, but detailed tests are still ongoing.

- Question 4. How do European networks/services/databases compare with others (US, Japan)?

European seismological network are evaluated as less dense and homogeneous compared with those from US and Japan. The networks now operated by China are also very impressive compared to the European situation. European distributed databases are improving quickly thanks to major initiatives like EPOS. The support / expertise of European services (ORFEUS, EMSC and EPOS) in both scientific and infrastructural projects are fully acknowledged. European databases however still contain less data and seem to be a little bit less “efficient” than the US centralized data centre (IRIS). In other words, the community strongly believes in EIDA but the impression is that the user experience is still better at IRIS. This might only be a perception based on past experience but also the result of a larger and regular funding of IRIS compared to European institutions in charge of data-dissemination. European seismological services seem also to have a strong emphasis on the Euro-Mediterranean region compared to US services that have a more global perspective. Several replies stress the lack of a unique pool of mobile instruments in Europe, which makes organization of large-scale experiments complex.

- Question 5. Let’s dream… How would you invest a 5 million € (or more) additional funding?

Most replies identify the need to develop natural laboratories for the analysis of processes (e.g. preparation and development of earthquakes or volcanic eruptions) with multi-parametric sensor networks (accelerometers, borehole-, short period- and broadband seismometers, GPS, strainmeters, geochemical probes). These natural laboratories are also seen as ideal test-beds for new technologies. The development of European pools of sensors for dense array deployments and the deployment of a European-wide permanent array including offshore sensors are also identified as key potential investments. The development of a stationary satellite carrying an optical seismometer based on image interferometry is also suggested for the future.

3 Strategies at the European scale

3.1 Key and common targets

The seismological community is facing with scientific questions that are relevant for the community preparedness to seismic risk reduction and resilience post-disaster. There is a fundamental need to assess the factors that control earthquake initiation and propagation. Besides improved event detection capabilities, this implies a precise knowledge of the structure from the scale of the shallow fault system, to deeper crust and lithosphere. The impact of transient deformations for the seismic appeared also to be a key issue for hazard evaluation. Furthermore, in recent years it became clear that understanding the shallow subsurface (the ’first km’) is necessary in order to give a sound local evaluation of the hazard. At the same time, seismic investigation of the shallow subsurface is a source of information on this critical zone between solid Earth and its fluid envelope. This covers issues related with water resources and their evolution, climate change, meteorology, and in general the relation between solid Earth and its environment. It also has implication for evaluating geotechnical parameters such as soil and slope stability, the later being relevant for evaluating the hazard from triggered or spontaneous landslides.

Keeping in mind the large range of fundamental and applied topics related with seismological observations, the scientists gathered in Potsdam discussed a plan that encompasses all of the raised fundamental questions which requires a joint effort at the European scale.

To summarize the rich discussions, and in accordance with the final remarks, we present their summary in two sections. The first one is a mostly focused on geological object of common interests (EMOS) where efforts of all kinds could be directed with new observational strategies (density, multi-parameter observations, new instruments…) and a large community implied in deployment and data analysis. The second one concerns the needs for shared instrument pools.

3.1.1 European Multi-sensor Observation Site (EMOS)

Near Fault Observatories

The community has already run Near Fault Observatories (NFOs) with some unquestionable successes. Based on these experiences, it is timely to envision larger experiments associating all observations and providing widely the data required to tackle the big scientific challenges of earthquake occurrence and of related hazard (fault structure at depth, low magnitude seismicity, surface deformation, fluid transfer, temporal changes, ground motion variability & surface geology…). A specific interest of NFOs is their importance for both fundamental research into earthquake preparatory phase, initiation and propagation as well as fault evolution, and operational issues such as earthquake early warning and rapid damage assessment. European sites should associate those two aspects, meaning that they should build upon existing initiatives. The consensus was to set a very limited number of sites, in order to concentrate the efforts at a level where a European initiative can make a difference in comparison with the present-day distributed efforts. The number has to be defined with respect to the actual means of the community and the most important scientific questions. EPOS should now be the common framework and platform for developing such a new infrastructure initiative.

What we expect from an EMOS is a description of fault structure, seismicity, deformation, fluids movement etc. in unprecedented detail over at least a decade. This could be achieved by concentrating in a small region the classical instruments of seismology, magnetotelluric equipment, geodesy, but also new instrumentations. EMOS should be the place for testing and developing the instruments of the future, and eventually to use them for long-term observations. We consider the deployment of very dense arrays (including borehole sensors) of nodes or ‘cheap’ stations, and durable installation of optical fibres, in addition to backbones of broadband and rotation sensors.

The scientific questions behind these efforts include different aspects. In addition to studying the ruptures of moderate-large events with the potential to cause damage, we have to look at rupture phenomena at the small scale but field conditions in order to successfully transfer knowledge from lab experiments into the study of natural or induced earthquakes. By decreasing the minimum magnitude of earthquakes that we can detect and characterize, we can investigate the extremely fine crackling occurring on and around a potentially causative fault. We can move from a static description of the fault zone to a dynamic view. Together with time and space evolution of seismicity and 4D imaging makes it possible to track the fluid migration and changes of stress and/or friction on the fault.

For these goals, the quantitative analysis of the observations requires high quality data and a precise characterization of the recording sites, opening avenues for more applied research into ground motion variability (site effects, micro-zonation). The understanding of the multi-scale, physical/chemical processes responsible for earthquakes and faulting requires considering phenomena that intersect different research fields (the road of integration; https://www.epos-ip.org/near-fault-observatories-europe-road-integration-why-do-we-need-nfos).

The EMOS are the opportunity to integrate multi-parameter data (geodetic, hydrological, meteorological and geochemical...). by combining diverse observations for example related to mantle-crustal and seasonal fluids (e.g. rain), in influencing or responding to the occurrence of slow and fast as well seismic and aseismic deformation processes.

It was noted that volcanoes share a lot of similarities with fault systems beside their hazardousness and that they represent also the same challenges for multi-sensor data processing and modelling and merging remote sensing data. Geothermal and underground repository sites should also be considered.

Large seismogenic structures

The precise evaluation of seismic hazard at the continental scale requires knowledge of the major tectonic structures responsible for large earthquakes in the past. For example in the European Union territory, at least two zones with major historical earthquakes have to be studied: the system of transform faults in the Atlantic likely responsible for the 1775 and 1941 earthquakes offshore Lisbon (Figure 2) and the Hellenic subduction (Figure 3) in the Crete region (megaquakes of 365 and 1856 AD).

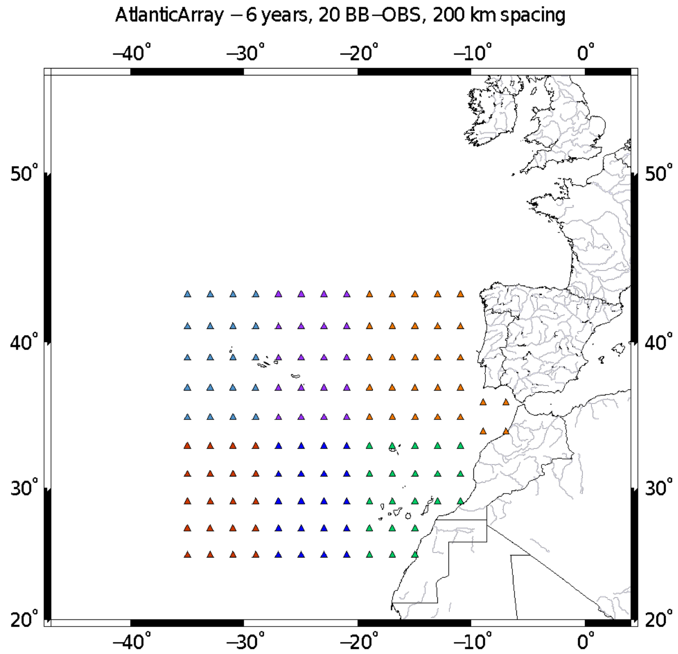

Figure 2: A proposition for a European project "Atlantic Array" to investigate the structures responsible for the mega earthquakes offshore Portugal. Depending on the availability of OBS from different national pools the array could be covered by multiple deployments (from S. Custodio).

The 1755 event is the most destructive historical earthquake in Europe, but its source processes remain essentially unknown, including the devastating tsunami associated with it. The region is also the locus of elusive mantle earthquakes and the geodynamical behaviour of faults (e.g., Gloria fault), the Azores triple junction and hotspots in the region are poorly understood. With these cases, we see the need for offshore observations to image the structures and record the seismicity.

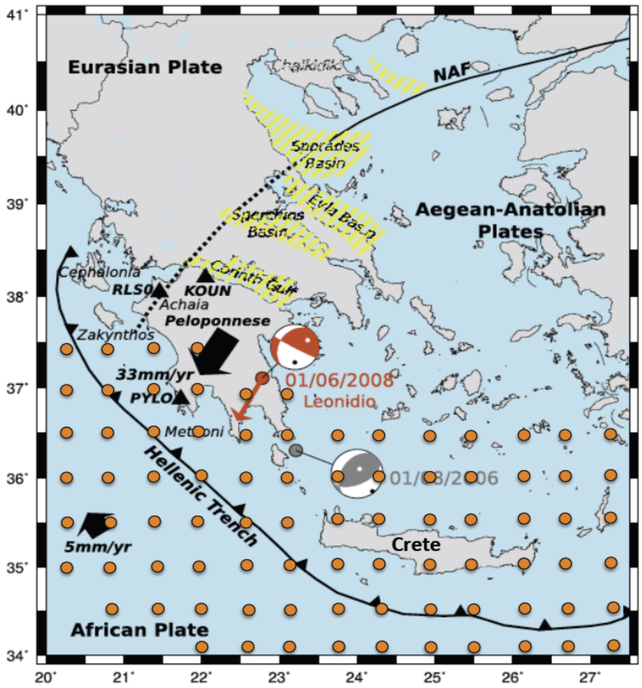

Figure 3: A proposition for a European project to investigate the structures responsible for the mega earthquakes in the Hellenic subduction.

The technical solutions that have been proposed are: 1) temporary deployments of OBS, 2) floating buoys (MERMAID project, Sukhovich et al. (2015)), and 3) use of sea bottom cables (e.g Tilmann et al., 2017; Marra et al. 2018). Solution 3) does not appear realistic at this stage for the EU community until further technical developments driven by hazard mitigation needs have been carried out. Solution 2) has already shown its capability of recording significant events but it seems difficult to produce very precise locations or to use match filter / template approaches due to the constant changes of position. Large deployments of OBS together with inland stations seems still the most feasible approach at this stage to tackle these issues of critical importance. The limiting factor for ambitious deployments is often ship time as well as the prohibitive costs in terms of batteries and insurance payments. This is exacerbated by the higher noise levels for at least the horizontal components in most frequency bands, which necessitates longer deployment times compared to land stations. However, technical progress in the efficiency of data loggers and seismometers have led to a significantly increased endurance of OBS, the newest models of which can now operate autonomously for up to two years. An initiative at European scale could allow for deploying large arrays for one or two years to significantly improve our knowledge of seismic activity in these regions.

3.1.2 Instrument pools at the European scale

In the discussion, it was clear that the science of earthquakes is also advancing with portable arrays. These arrays are used both for planned deployments with a high station density in a target region and for rapid installation when an opportunity appears: seismic swarms, triggered seismicity, post seismic intervention. This issue is discussed in this section.

The needs for action at European level are driven by the scientific questions we are going to solve in the next decades. The composition of instrument pools has to be defined for these applications. Again, the objectives are earthquake source physics, imaging of internal structures of the Earth and investigation of the critical zone between solid Earth and the atmosphere. These objectives are strongly linked, of course. We know also that our knowledge is limited and that much of our progress has been data driven during the last decades. The development of new observation tools is by itself a part of the prospective if it opens novel insights into Earth processes and structures (sensitivity, detection, new observables…).

Onshore and offshore observations are at different levels of difficulty. The discussion has shown that offshore observations are dramatically missing for precise structural imaging and detailed seismicity studies of some of the most active fault zones in Europe (transform faults off shore Spain and Portugal, subduction in Crete, and Calabria, fault in coastal regions of the Mediterranean…). The OBS deployments require expensive cruises that limit the number of projects. It seems difficult to consider separately the construction of a European pool of instruments and the availability of ships. However, they represent the most reliable way to get necessary data for achieving our scientific goals with techniques developed for onshore studies. The use of buoys (drifting seismic recorder and follow-up) could provide valuable information for global and regional imaging. Their usefulness for local seismicity studies has to be assessed.

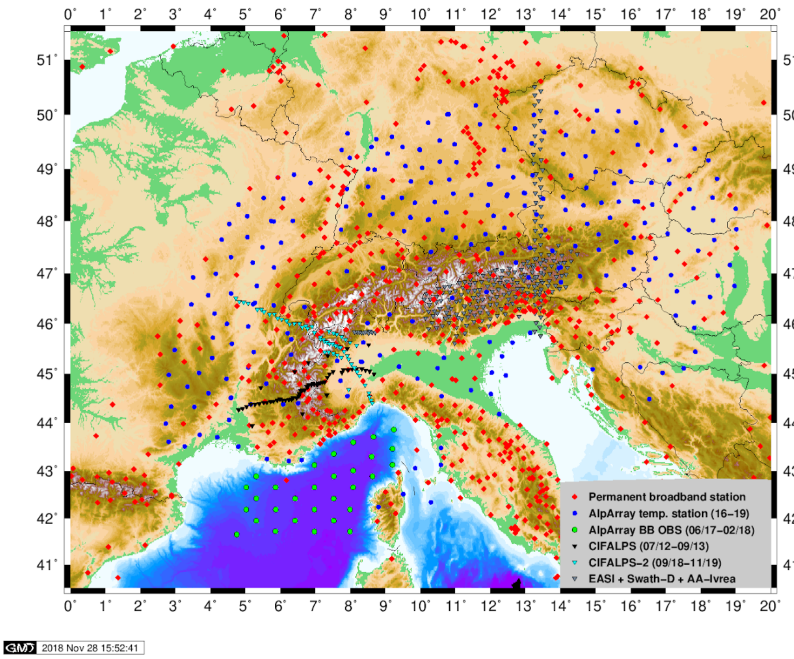

Figure 4: Topographical map of the greater Alpine area and the geometry of the AlpArray Seismic Network (Courtesy of Anne Paul).

Several large combined onshore BB and OBS deployments by European teams have been carried out successfully, with contributions of several national pools (e.g. RHUM-RUM, AlpArray Seismic Network (Figure 4)). A first goal for the future is to improve the integration of the existing instrument pools and coordinate their use at the European level. The present cooperation to share BB and SP stations at EU level is good and could be further optimized. As for the locations, we keep in mind the several initiatives already existing. We need to develop a clear framework for accessing existing instrumental pools based on federative projects with wide participation.

While a European pool of mobile seismological instruments was seen as desirable in the long term, the ad-hoc combination of national pools was perceived by most participants to work reasonably well in practice, with coordination of funding having been at least as large an issue in AlpArray. In order to facilitate and enhance the access to the available European mobile seismic pools, a new website (http://msp-epos.ictja.csic.es) has recently been made available to researchers in the mainframe of EPOS-IP. A new European pool of instruments should therefore not replicate national pools by encompassing mostly broadband and wideband sensors but should focus on the new types of instrumentation that is not yet sufficiently represented at national levels. . We have identified three key technical developments relevant for seismic recording:

-'nodal' dense arrays

-DAS (optical fibre)

-rotation sensors

Another aspect is the use of sensors-of-opportunity or provided by citizen science opportunities (accelerometers in smartphones, school seismology projects...) which, by definition, are not included in instrument pools, but present their own opportunities and challenges in terms of data collection and dissemination.

Nodal arrays

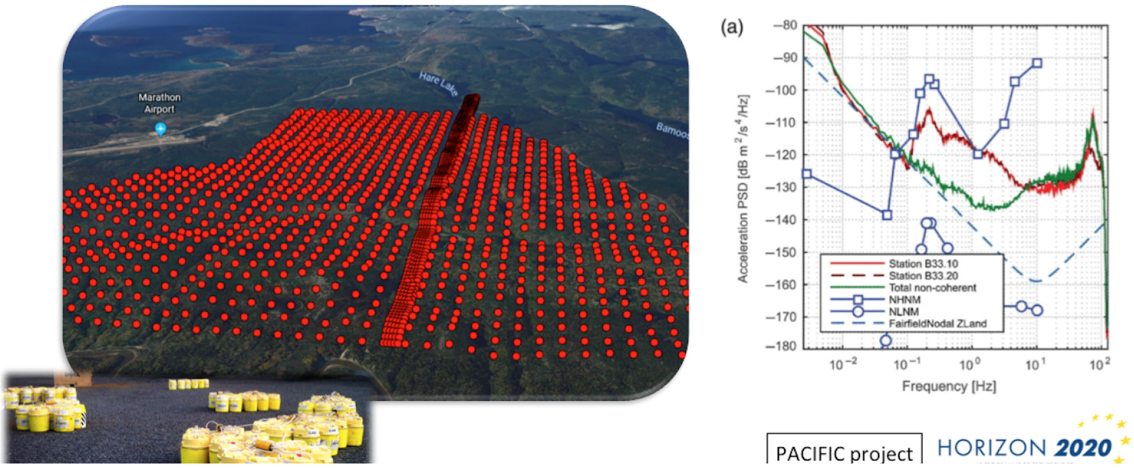

Figure 5: Example of deployment of 1200 sensors for the H2020 project PACIFIC (courtesy of F. Brenguier)

Arrays have been used for a long time but technical advances driven by the exploration industry make it now possible to deploy rapidly thousands of sensors (Figure 5). The potential of these arrays has not been fully investigated so far. Small dense arrays produced structural images of the critical zone and the upper crust in unprecedented detail with passive imaging techniques. They allow to considerably enhance the signal to noise ratio for detection and to perform effective beam-forming. The novelty is in the number of sensors made possible by the simplicity of use. One of the present-day limitations with ready-to-go products is the limited time of continuous recording (about 1 month); however, technical solutions exist (e.g. 'Cube') to extend the recording time to several months and three-component recordings. Thorough tests have to be carried for these large dense array configurations, particularly for installation and data extraction.

DAS

Distributed Acoustic Sensing (DAS) is an optical method using optic-fibre and its defects as a sensor of deformation. Very convincing examples (e.g. Jousset et al., 2018) have shown that wave measurements can be made along a commercial telecommunication fibre that can be several tens of kilometres long (Figure 6). The strain rate can be measured continuously along the fibre with metre scale and kHz resolution. Dedicated or existing fibres can be transformed into a dense array, offering new opportunities, like changing the position of the points of sensing along the fibre just by software, or re-measuring along the same fibre after years for time-lapse imaging.

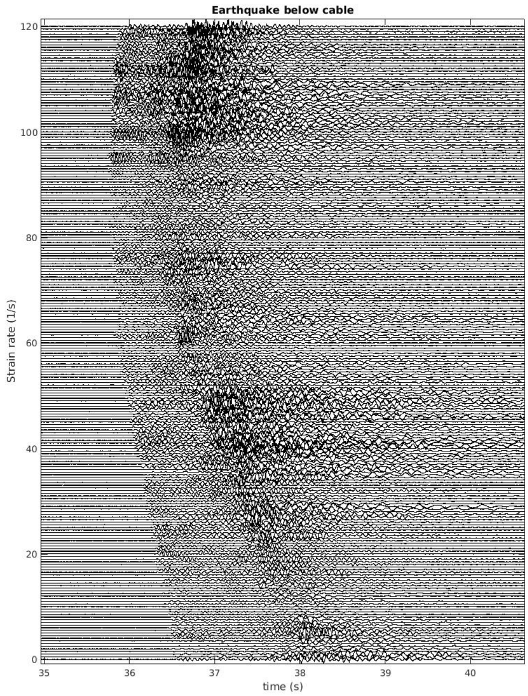

Figure 6: Example of the records of a Magnitude 1 earthquake located about 3.5 km beneath a 10 km long fibre. (Jousset et al., 2018)

Fibres are now becoming the standard in borehole measurements, at least if only the vertical component is needed. Its limit in the present-day application in seismology is the absence of availability of opto-electronic interrogator systems for distributed acoustic sensing that could be adapted for long time monitoring and the various requirements of our field experiments. An effort at the European scale would permit to get a series of units to be shared between EMOS and temporary experiments, or to develop a new device specific to our needs. A series of permanently buried fibres (including boreholes) should be installed at the ESS that can be used to realise the promises of the technology. A key issue is to demonstrate that a fibre can be used repeatedly over the years for 4D imaging.

Rotational sensors

Portable 6C-stations with the technology of interferometric fibre-optic gyroscope allow for single-point broadband measures of rotation (Figure 7), independent of translational motions (Sollberger et al., 2018). While the rotation around the z-axis can theoretically also be deduced from the spatial derivatives of the records of surface arrays, this is limited to a single axis, and a narrow period band imposed by the array geometry. Rotational sensors allow the measurement of surface wave dispersion at a single point and are highly sensitive to earthquake source properties, having shown far better source reconstructions in synthetic tests then even twice the number of conventional sensors (which would result in an equal total number of components). Furthermore, with the rotation components, the contamination of long period horizontal components of translational sensors by dynamic tilt can be corrected.

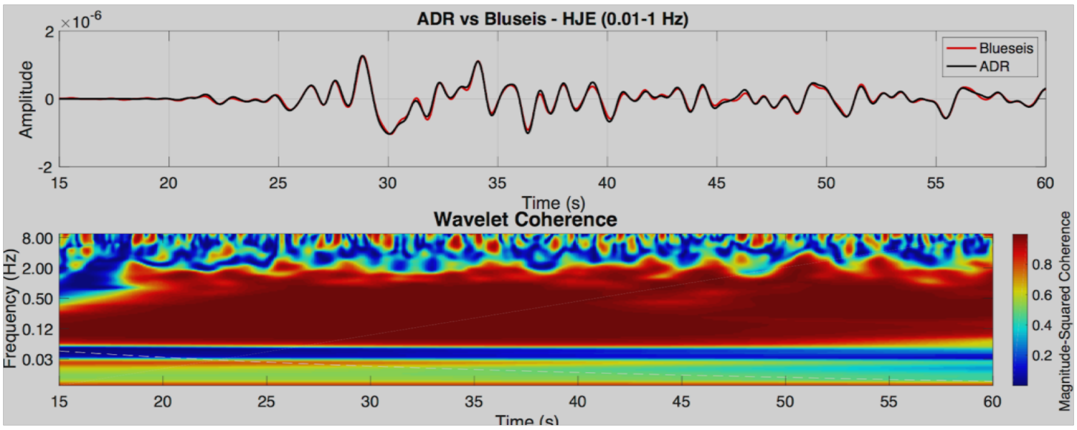

Figure 7: Comparison of the rotation measured by a single rotation sensor with the array derived rotation for a magnitude 5.4 at 58 km of epicentral distance (reproduced from J. Wassermann, 2018)

The limitations are the still high cost of this technology, the intrinsically high level of instrumental noise (see Figure 8), and the relatively high power consumptions that make temporary deployments over longer time periods challenging.

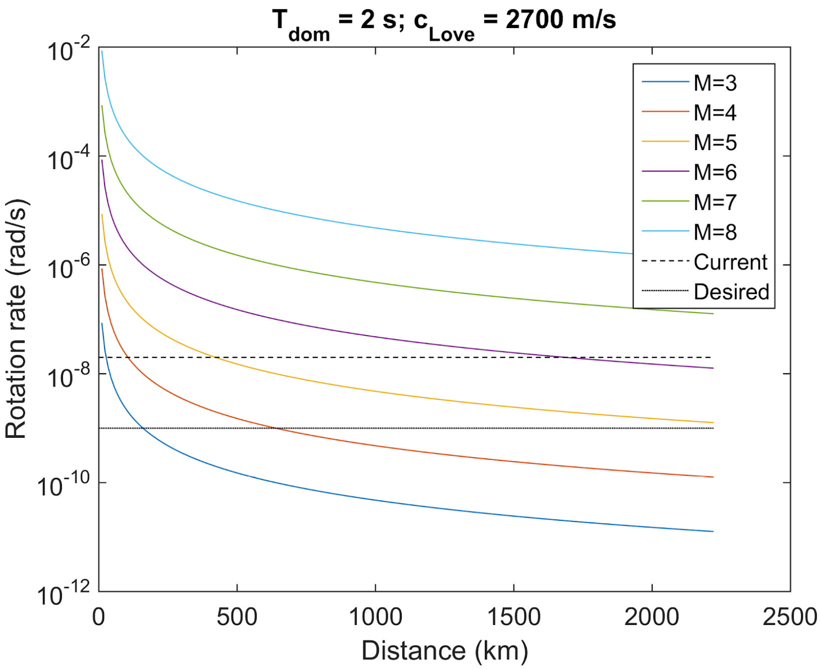

Figure 8: Estimated Love rotation vs distance for different magnitude and present-day and expected instrumental noise. From J. Wassermann (personal communication, 2018).

A comprehensive strategy could include a backbone of high quality instruments, well-tested sensors (BB and rotation sensors) complemented by numerous lower quality sensors (nodes, mems…) or DAS. A pool of rotation sensors at the European level could complement the national BB pools as part of the backbones of the future deployments. Rotation sensors should be installed at the EMOS to provide further constraints on source and rupture mechanism.

Cheap sensors?

The issue of the need for high data quality versus the number of sensors is discussed among the participants. It seems also clear that proper bench marking of all different instrument types is needed in a transparent and trusted way so that the right instrumentation can be made available to future studies. Low noise observatories like the Black Forest Observatory (BFO) could be ideally suited to act as instrument testing facility for the wider community. The instrumentation of specific sites or structures with cheap equipment (mems..) does appear to be in need of European level action, except regarding the data dissemination.

Use of station pools

The scientific goals justifying station pools are of two natures: imaging and characterizing the Earth interior at all scales, and studying the expressions of the Earth's dynamics (earthquake, volcanic eruptions...). These scientific goals impose adapted implementation strategies. Long-term (1-5 years) temporary deployments are needed for regional imaging (e.g. AlpArray). We know also that the discoveries will arise from our capacity to catch the opportunities of observing the processes at work: spontaneous or triggered seismic crisis, volcanic activity... A subset of stations could be available for specific short-term localized studies and kept at ESs the rest of the time for their optimal use, although this model should be evaluated in terms of the relative costs of the instruments and the cost of installation/de-installation under tight time constraints.

3.2 Data Management

Geophysical observational systems evolve rapidly, implying a spectacular increase in the volume and diversity of data. Our infrastructures evolved simultaneously so far but, with the continuous growth of data, we foresee the need for adjusting our analysis tools. In parallel with the growth of the data set, we also increased the variety of our analysis and needs for analysis of continuous data rather than pre-determined windows: noise cross-correlations, time-lapse seismic velocity variations, slow earthquakes (SSE, tremors, LFE), signals generated by ocean/atmosphere, ice-quakes… The present-day "download strategy" multiplies the data volume by the number of users. An alternative approach should therefore be to bring computing resources like HPC to the data centres, for example for systematic detection and signal classification.

For an optimal scientific exploitation of the observations, the data has to be open access and follow FAIR principles (Findable, Accessible. Interoperable, Reusable). With the new huge data sets (dense arrays, DAS), it is possible that full data sets can no longer be offered for download. Instead dedicated reduced data sets can be offered in standardised format to different user communities, and it should be possible to run user-defined work flows on the full data sets, somewhat akin to the approach of Google Earth Engine for remote sensing data . All datasets should be fully interoperable with datasets acquired by other communities to understand the relation between the solid Earth and its fluid envelope (e.g. water content and its evolution, climate change, meteorology), as is envisaged by the EPOS project.

4 Conclusions and Recommendations

The discussion has first contributed to identify important technical issues (which could be solved within the next months) in order to evaluate the potential of emerging technologies:

- How dense is dense? What is quantitatively the improvement on imaging fault zone structure at depth provided by denser local arrays together with using full waveform inversion (FWI)?

- What is the sensitivity and signal to noise level of DAS data in the different frequency ranges of interest for the project and how well are the cables coupled to the underlying ground? Can we repeat a measurement on a fibre after years in view of monitoring changes at different depth levels?
- What are the capabilities of cheap sensors? Can we gather the different instrumental tests made with 'cheap' sensors by members of the group, or published?
- Can we detect and characterize small earthquakes in an urban noisy environment? Shall we compare the recordings at the surface and in a borehole of low magnitude triggered events at the depth of interest (e.g. 6 km with the case of injection beneath Helsinki).

These questionnaires and the meeting presentations have also contributed to identifying the priorities of future European seismological instrumental pools and networks. The European seismological community has recently greatly enhanced permanent networks and fielded large experiments with some unquestionable scientific successes. Based on these experiences, it is timely to envision larger experiments associating all observations and providing widely the data required to tackle the big scientific challenges of earthquake occurrence and of related hazard (fault structure at depth, low magnitude seismicity, surface deformation, fluid transfer, temporal changes, ground motion variability in relation to surface geology…). The scientific questions are driving the following priorities:

- Support the development of a few EMOS, in order to concentrate the efforts at a level where the project can make the difference and also test new technologies,
- Develop coordinated land-sea experiments to characterize the structures responsible of megaquake offshore,
- Build a European pools of instruments related to the new technologies (Distributed Acoustic Sensing, rotational sensors, nodes) that under-represented at national levels.

How do we get there? How do we build consensus on where to focus? The governance is out of the scope of the present paper (already constituted bodies exist at the European level) and these developments have to be defined with respect to the actual means of the community and within EPOS which is the common framework and platform for the development of such new instrumental projects.

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6 Appendices

Table 1: List of participants

NAME	INSTITUTE
Remy BOSSU	EMSC
Florent BRENGUIER	Université Grenoble Alpes, CNRS
Michel CAMPILLO	Université Grenoble Alpes, CNRS
Carlo CAUZZI	Swiss Seismological Service
Lauro CHIARALUCE	INGV
John CLINTON	Swiss Seismological Service
Fabrice COTTON	GFZ Potsdam
Susana CUSTODIO	Faculdade de Ciências da Universidade de Lisboa
Jordi DIAZ	ICTJA - CSIC Barcelona
Bernard DOST	KNMI - Netherlands
Antonio EMOLO	University of Naples Federico II
Rosemary FAYJALOUN	Université Grenoble Alpes
Ana FERREIRA	University College London
Philippe JOUSSET	GFZ Potsdam
Hayrullah KARABULUT	Boğaziçi University
Andreas RIETBROCK	Karlsruhe Institute of Technology
Nikolai SHAPIRO	Institut de Physique du Globe de Paris
Karin SIGLOCH	University of Oxford
Sebastian Specht	GFZ Potsdam
Nikos THEODOULIDIS	ITSAK - Thessaloniki
Frederik TILMANN	GFZ Potsdam
Jerome VERGNE	Université de Strasbourg
Joachim WASSERMANN	LMU München
Aldo ZOLLO	University of Naples Federico II
Charlotte KRAWCZYK	GFZ Potsdam

Table 2: European seismology at the frontier: numbers and facts from recent studies and experiments

EXPERIMENT (REFERENCE)	NUMBERS AND FACTS
LB3D - A Dense Urban Seismic Network in Long Beach (Lin et al., 2013)	5200 short period stations over a square of 10kmx10km, 6 months of continuous data
Pacific project (Brenguier et al., 2018)	1200 nodes, 5 days
French nodal seismic pool (courtesy of F. Brenguier)	100 nodes, 5Hz, 3C, 1500euro per node
Low-Frequency Earthquakes in Guerrero, Mexico massive detection from continuous seismic data (Frank et al., 2016)	1,849,486 LFEs detected over 2.5 years, 1120 unique sources, 2000 LFEs per day on average
International Maule Aftershock Deployment – IMAD (Rietbrock et al., 2012; Beck et al., 2014)	200 stations (mainly broadband), 670 selected events for optimizing spatial and depth resolution, 38,000 P wave onset times, 14,000 S wave onset times, 1TB of continuous high frequency data accessible through IRIS (or Liverpool)
The Ocean frontier (Courtesy of K. Sigloch)	4% of the stations registered at ISC are in the oceans (mostly on islands) Price of a ship for OBS deployment: 20/50 keuros per day Lifetime of MERMAIDs: 3-5 years, cost ~30k€.
Event detection and hypocenter location from eight years of continuous waveform data (IPOC network Chili). Sippl et al., 2018.	101,601 double-difference relocated earthquake hypocenters. 1,200,404 P and 688,904 S phase picks
GEOFON (GFZ global network of permanent broadband stations (courtesy of F. Tilmann)	GEOFON data holdings 90 TB, current growth 8TB/year
DAS (courtesy of F. Tilmann)	4 weeks of acquisition: 50TB
Harmonized local magnitude scale for Europe using the European Integrated Data Archive (EIDA) Bindi et al. (in preparation)	12700 earthquakes, 2800 stations, 600000 records
Ground-motion variability analysis (Bindi et al., 2018)	1760 earthquakes, 545 stations, 500000 records
EIDA (courtesy of F. Tilmann)	500 TB
TopoIberia-Iberarray deployment (https://doi.org/10.7914/SN/IB)	200+ broad-band stations deployed in Iberia and N. Morocco (2007-2014). 6 Tb aprox
Orogen-Maupassacq deployment (Aquitanian basin) (https://doi.org/10.7914/SN/XD_2017) Reference: Chevrot et al, 2019, Geophysical Research Abstracts Vol. 21, EGU2019-12707, 2019	500 nodes, 6 months continuous acquisition + 40 broad-band stations
Mobile Seismic Pool website (http://msp-epos.ictja.csic.es)	Searchable database of the mobile seismic pools available in Europe (broad-band, short period, nodes)

Contact

Project lead	ETH Zürich
Project coordinator	Prof. Dr. Domenico Giardini
Project manager	Dr. Kauzar Saleh
Project office	ETH Department of Earth Sciences
	Sonneggstrasse 5, NO H62, CH-8092 Zürich
	sera_office@erdw.ethz.ch
	+41 44 632 9690
Project website	www.sera-eu.org