DELIVERABLE

D4.7 Strategies for future network design (update of deliverable 4.6 delivered on April 2019)

Work package	WP4
Lead	CNRS
Authors	Michel Campillo, Université Grenoble Alpes Fabrice Cotton, GFZ Potsdam Aldo Zollo, University of Naples Federico II Frederik Tilmann, GFZ Potsdam Andreas Rietbrock, Karlsruhe Institute of Technology Rosemary Fayjaloun, Université Grenoble Alpes Charlotte Krawczyk, GFZ Potsdam and all the participants of the workshop (see page 19)
Reviewers	-
Approval	Management Board
Status	Final
Dissemination level	Public
Delivery deadline	30.04.2020
Submission date	27.04.2019
Intranet path	DOCUMENTS/DELIVERABLES/SERA_D4.7_Strategies_Network_Design.pdf

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1 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 characterize the structures responsible for megaquakes, and improve long-term monitoring of the offshore domain; 3) build European instrument pools of instruments related to new technologies (Distributed Acoustic Sensing DAS), 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 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. Additionally, international efforts to equip newly-laid submarine telecommunication cables with high precision accelerometers and pressure sensors and the use existing or abandoned submarine cables for remote probing techniques - such as DAS and optical interferometry - hold great potential for improving large-scale seismic monitoring of the ocean floor.

2 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 computer science and statistics, 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 instrumentation 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 lays out the foundations of a roadmap in order to guide the improvement (or redesign) of European seismological networks and highlight the new capabilities that will be required to advance the forefront of seismological research.

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.

The paper finally presents the results of field tests and tests with simulated data that highlight the potential of the emerging technologies to tackle new research questions: 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.

3 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 characterise the preparation phase of small-moderate-large earthquakes, and 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 experiences of previous and present experiments and observatories reported in the questionnaire form the basis for a discussion of the priorities for the new generation of seismological observatories on 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 (ocean bottom seismometers (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 on highly active fault systems, this new generation of "EMOS" monitoring systems should not only be placed in quiet environments but be fully operational in urban and industrial environments (and). This new generation should also take advantage of datasets from fibre-optic cables, building and lifelines and monuments monitoring.

Advancement of the frontier in seismological research relies critically on the more complete exploration of growing volumes of observations. The collected feedback shows that the seismological community is on the verge of undergoing a cultural change: we are moving from a "download" culture of working with pre-selected datasets to application of data-mining and assimilation methods, which rely on huge datasets and collections thereof. A strong coupling between High Performance Computing (HPC) and data archives is thus needed. The next big challenge will be to bring the data to HPC, or bring HPC to the data. 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 and archived not only by different institutions but increasingly by different communities, using entirely different instruments and data standards (e.g. geodesy and seismology).

- 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 (models are taking into account the regional properties of earthquakes and wave propagation). 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 earthquake early warning (EEW) 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 Machine Learning for EEW signal processing, prediction of the potential damage zone based on backprojection and application of assimilation techniques to improve 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 (including photos of earthquake damage but also videos of triggered effects such as tsunamis and 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?

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 result 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 SERA survey results show, however, the need to better test and characterize the instrument response of these low cost sensors (Figure 1 shows an overview of preliminary test results). 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 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 floating pressure sensors - Stokstadt 2019; use of submarine cable telecommunications cable – Howe et al. 2019) is seen as major step forward for offshore seismology, but detailed tests are still ongoing, and funding concepts for these new types of trans-national infrastructures need to be developed.

- 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. Many of the distributed European data centres are federated within the European Integrated Data Archive (EIDA). The services offered 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 is frequently 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

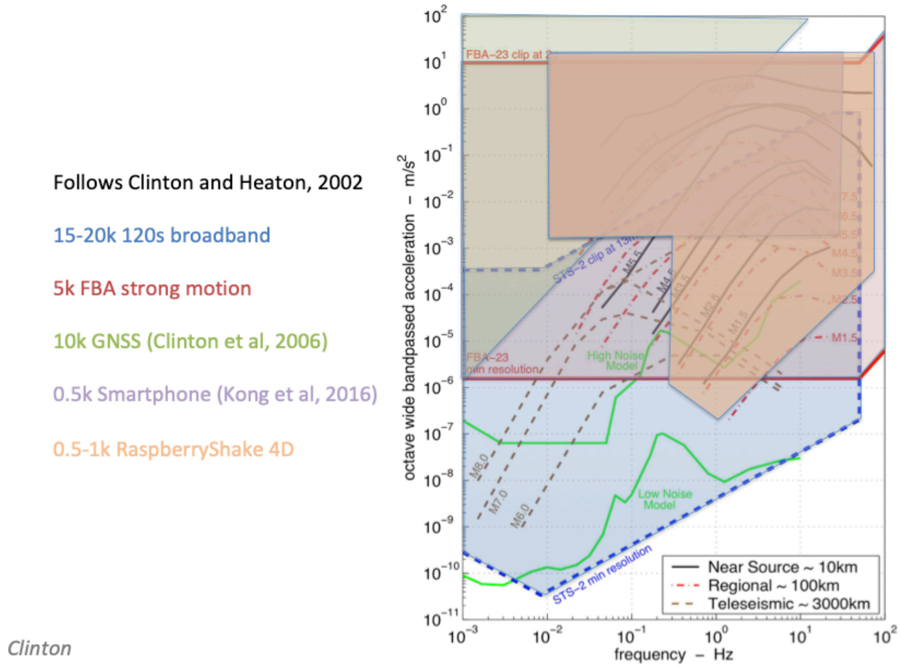

Figure 1. Sensitivity ranges of different types of seismic instrumentation, adapted from Clinton and Heaton (2002). Green lines indicate USGS high- and low-noise models for reference (Peterson 1993). The range for the Raspberry Shake is based on recent tests performed by SED, otherwise results are from Clinton and Heaton (2002), or as indicated in the legend. Numbers in front of instrument types in the legend on the left indicate the approximate price range (in €). The dotted lines gives the empirically observed signal maximum levels for local, regional and teleseismic earthquakes at a specific nominal distance (indicated at the bottom right) to give an impression of what magnitude earthquakes are recordable with the different instrumentations.

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 a device for measuring ground motion based on image interferometry is also suggested for the future.

4 Strategies at the European scale

4.1 Key and common targets

The seismological community is facing several scientific challenges relevant for the community preparedness to seismic risk reduction and resilience post-disaster. First, 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 cycle appears also to be a key issue for time-dependent hazard evaluation. Furthermore, in recent years it became clear that understanding the shallow subsurface (the 'first km') is necessary in order to provide a sound local evaluation of the hazard. At the same time, seismic investigation of the 'critical zone', the shallow subsurface is a prerequisite for understanding the interaction between the solid Earth and its fluid envelope. This line of investigation covers issues related to water resources and their evolution, climate change, meteorology, and in general the relation between the solid Earth and its environment. It also has implication for evaluating geotechnical parameters such as soil and slope stability, which are key elements for evaluating the hazard from triggered or spontaneous landslides.

Keeping in mind the large range of fundamental and applied topics, which can be addressed with seismological observations, the scientists gathered in Potsdam discussed the strategies and priorities for European seismology.

To summarize the rich discussions, and in accordance with the final remarks, we present their summary in two sections. The first one refers to a geographically focused geological target of common interest, a European Multi-sensor Observation Site (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 is concerned with instrumentation and how to organise its use.

4.1.1 European Multi-sensor Observation Site (EMOS)

Near Fault Observatories

The community has already operated Near Fault Observatories (NFOs) for many years, with some unquestionable successes. Based on these experiences, it is timely to envision a larger-scale effort, associating all observations and providing widely the data required to tackle the big scientific challenge of earthquake occurrence and its related hazard (fault structure at depth, low magnitude seismicity, surface deformation, fluid transfer, temporal changes, ground motion variability & surface geology, and petrophysical property behaviour). 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 for applied research for 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 mostly nationally or bilaterally driven distributed efforts. The number has to be defined with respect to the actual needs 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, fluid movement in unprecedented detail with an operational lifetime of at least a decade. This could be achieved by concentrating in a small region the classical instruments of seismology, magnetotellurics, geodesy, but also new types of instrumentation. In addition, EMOSs should be the place for testing and developing the instruments of the future, with the target to eventually integrate them into the observatory infrastructure for long-term-monitoring. 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 backbone networks of broadband and rotation sensors, as the most promising strategy for developing the seismological observation infrastructure at these sites.

The scientific questions behind these efforts include different aspects. In addition to studying the ruptures of moderate to large events with the potential to cause damage, we have to look at rupture phenomena at the small scale *in situ* 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. By combining analysis of the time and space evolution of seismicity with 4D imaging we will be able to track the fluid migration in and around the fault and understand how it affects the stress and/or frictional properties along the fault.

For these goals, high quality data and a precise characterization of the recording sites are required, which will also open avenues for more applied research into ground motion variability (site effects, micro-zonation). The understanding of the multi-scale physical and 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 (geologic, geodetic, geophysical, hydrological, meteorological and geochemical) into an understanding of the various fluid systems, for example mantle-crustal derived and meteoric fluids (e.g. rain), and how they influencing and respond to slow and fast, aseismic and seismic deformation processes.

New technical solutions for the imaging and petrophysical characterization of the uppermost kilometres comprise not only new sensors, but also increased utilization of active seismic measurements using shear waves with the perspective to close the gap to geotechnical needs. In addition to potentially better resolve structural images, the derivation of shear moduli becomes feasible through shear-wave velocity profiling, as well as the characterization of stable and unstable regions by introducing additional seismic attributes (Wadas et al. 2020). Coupling such information in the future with hydrological and meteorological information in a NFO would enable critical zone understanding and forecasting the effects of fluids on fault zone development and behaviour.

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).

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.

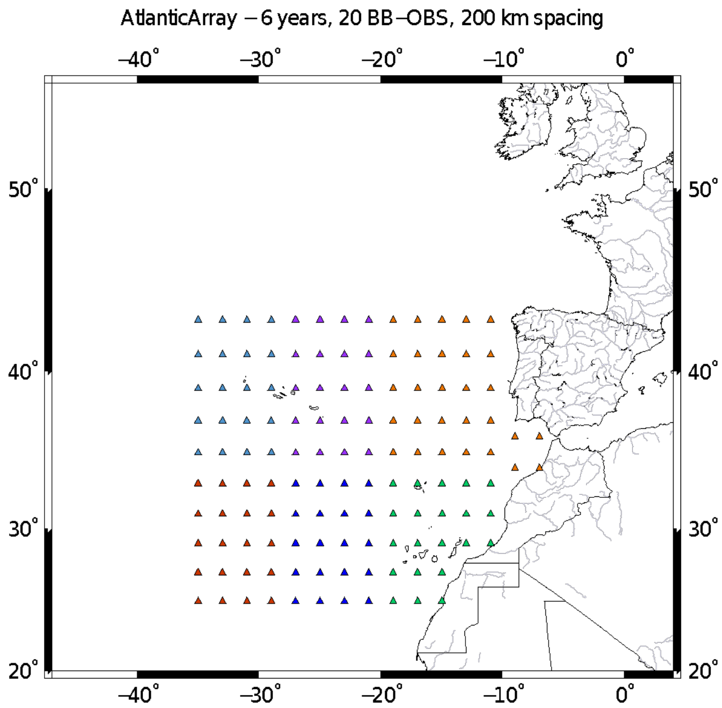

Figure 2. A proposition for a European project "Atlantic Array" to investigate the structures responsible for the mega earthquakes offshore Portugal. Depending on the availability of OBS from different national pools the array could be covered by multiple deployments (from S. Custodio).

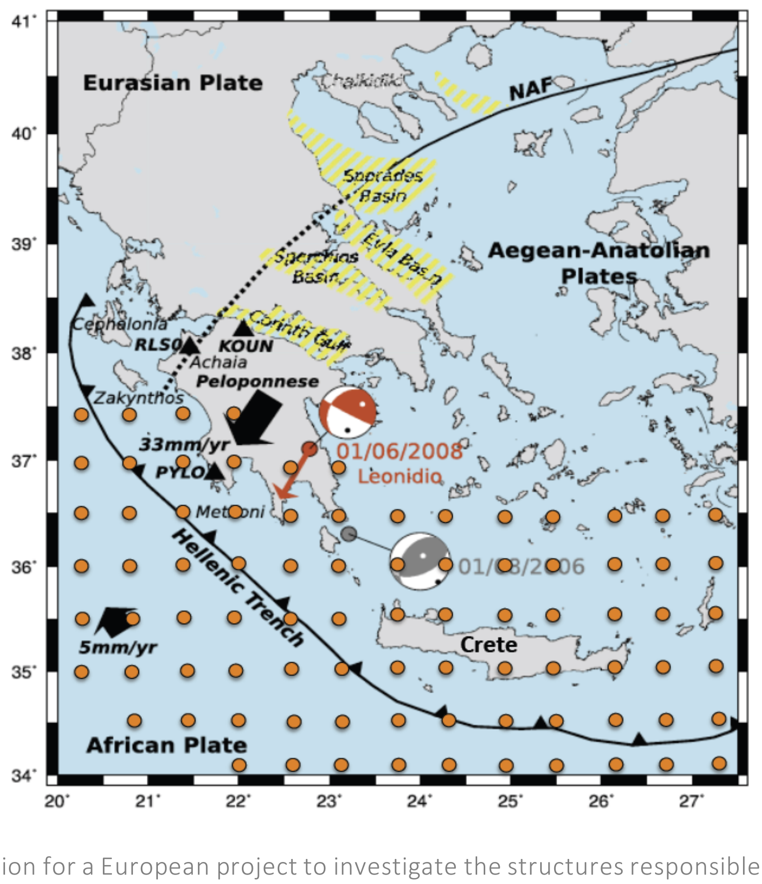

Figure 3. A proposition for a European project to investigate the structures responsible for the mega earthquakes in the Hellenic subduction.

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, Howe et al. 2019, Marra et al. 2018). Solution 3) is more suitable for long term monitoring as two-dimensional coverage cannot readily be achieved. Furthermore, regulatory and financial hurdles still need to be overcome. 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 still seem 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 achieve deployment of a large array encompassing even up to 100 instruments for one or two years to significantly improve our knowledge of the structure and seismic activity in these regions.

4.1.2 Instrument pools at the European scale

In the discussion, it was generally agreed that advancement of the science of earthquakes continues to benefit greatly from portable arrays. These arrays are used both for planned deployments with a high station density in a target region and for rapid installations when an unpredictable and relatively short-lived phenomenon of interest appears: seismic swarms, anthropogenically triggered seismicity, aftershock sequences. This issue is discussed in this section.

The need for action at the European level is driven by the scientific questions we are going to solve in the next decades. The composition of instrument pools has to be optimized for the most promising applications. Again, the objectives are earthquake source physics, imaging of internal structures of the Earth and investigation of the critical zone linking the solid Earth to the hydrosphere and 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 can by itself drive forward scientific insight if it opens novel insights into Earth processes and structures (by increasing sensitivity leading to improved resolution, lower detection limits for active processes, and possibly the detection of entirely new phenomena, or by enabling entirely new types of observables…).

Onshore and offshore observations are at different levels of difficulty. The discussion has shown that offshore observations are critically important 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…) but are too rarely realized, at least at large-scale. Long-term OBS deployments have complicated logistics requiring at least two expensive cruises (for deployment and recovery) and consumables (batteries) represent a substantial cost. Also this limits the number of projects. It therefore seems difficult to consider the construction of a European pool of instruments separately from the availability of ships and funding. Nevertheless, OBS experiments 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 pressure sensors transmitting recorded data in triggered mode) represents an innovative approach that could provide valuable information for global and regional imaging but their usefulness for local seismicity studies has yet to be assessed.

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 – Stähler et al. 2016, AlpArray Seismic Network - Hetényi et al. 2018, also see Fig. 4). A first goal for the future is to improve the

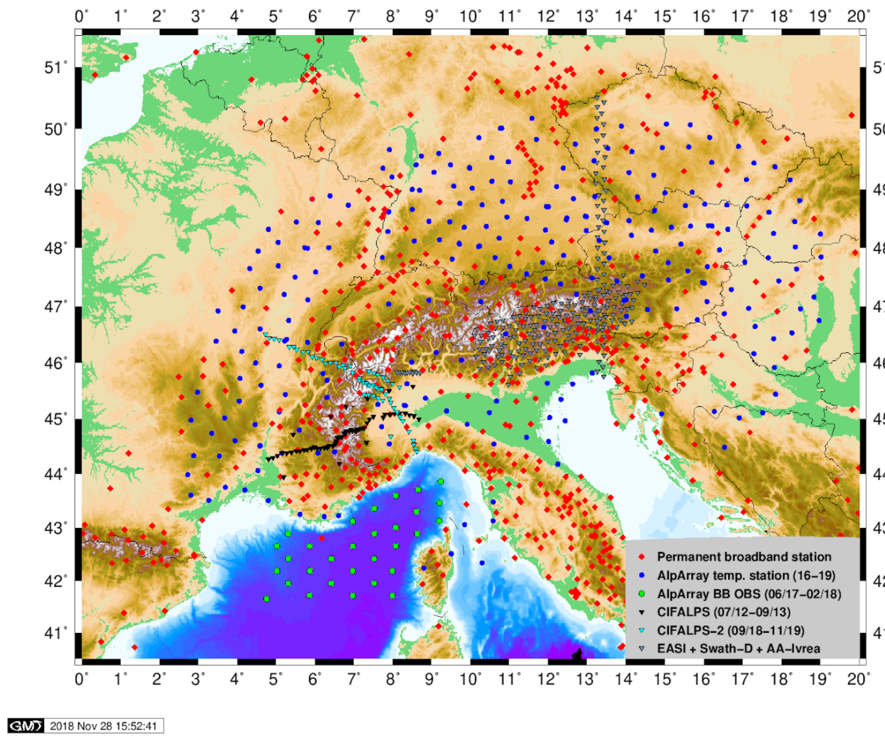

Figure 4. Topographical map of the greater Alpine area and the geometry of the AlpArray Seismic Network (Courtesy of Anne Paul).

integration of the existing instrument pools and coordinate their use at the European level. Presently, sharing of BB and SP stations at EU level largely is based on cooperation of individual research group. Building on the experience from several large-scale initiatives already existing, most notably AlpArray, we need to develop a clear framework for accessing existing instrumental pools based on federated 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 the bigger challenge 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 as an outcome of the EPOS-Implementation Phase project. 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

Arrays have been used for a long time but technical advances lowering the power requirements of GPS receivers and data loggers have resulted in the development of small portable instrumentation combining sensor and data recording in one autonomous unit (a so-called node). These developments were driven by the exploration industry but now allow also academic projects to deploy rapidly thousands of sensors (Figure 5). The potential of these arrays has not been fully investigated so far. Small dense arrays have 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 of small events and to perform effective beam-forming from sub-arrays offering the potential of enhanced imaging with converted and reflected phases in recordings of micro-seismicity. 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 for modular systems (e.g. 'Cube') that extend the recording time to several months with external battery packs and allow for application-driven flexibility in sensor choice, e.g. enabling a mix of 5 Hz geophones and 1 Hz short period seismometers. A downside of the modularity that the deployment is not quite fast as for the nodal systems, but still very easy compared to conventional systems, and a good mode of operation could be experiments combining the power of nodal and modular systems (e.g. Roux et al. 2018). Thorough tests have to be carried for these large dense array configurations, particularly for defining efficient installation and data extraction standard operating procedures.

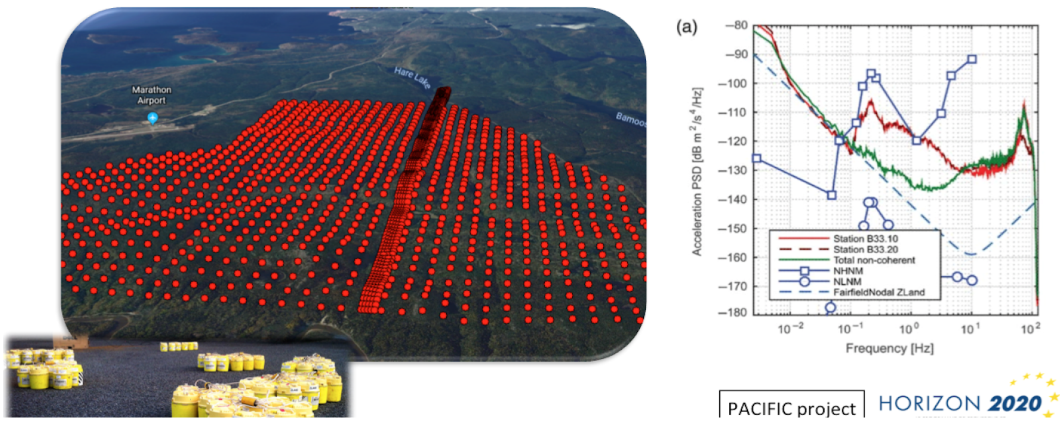

Figure 5. Example of deployment of 1200 sensors for the H2020 project PACIFIC (courtesy of F. Brenguier)

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.

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 high cost 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

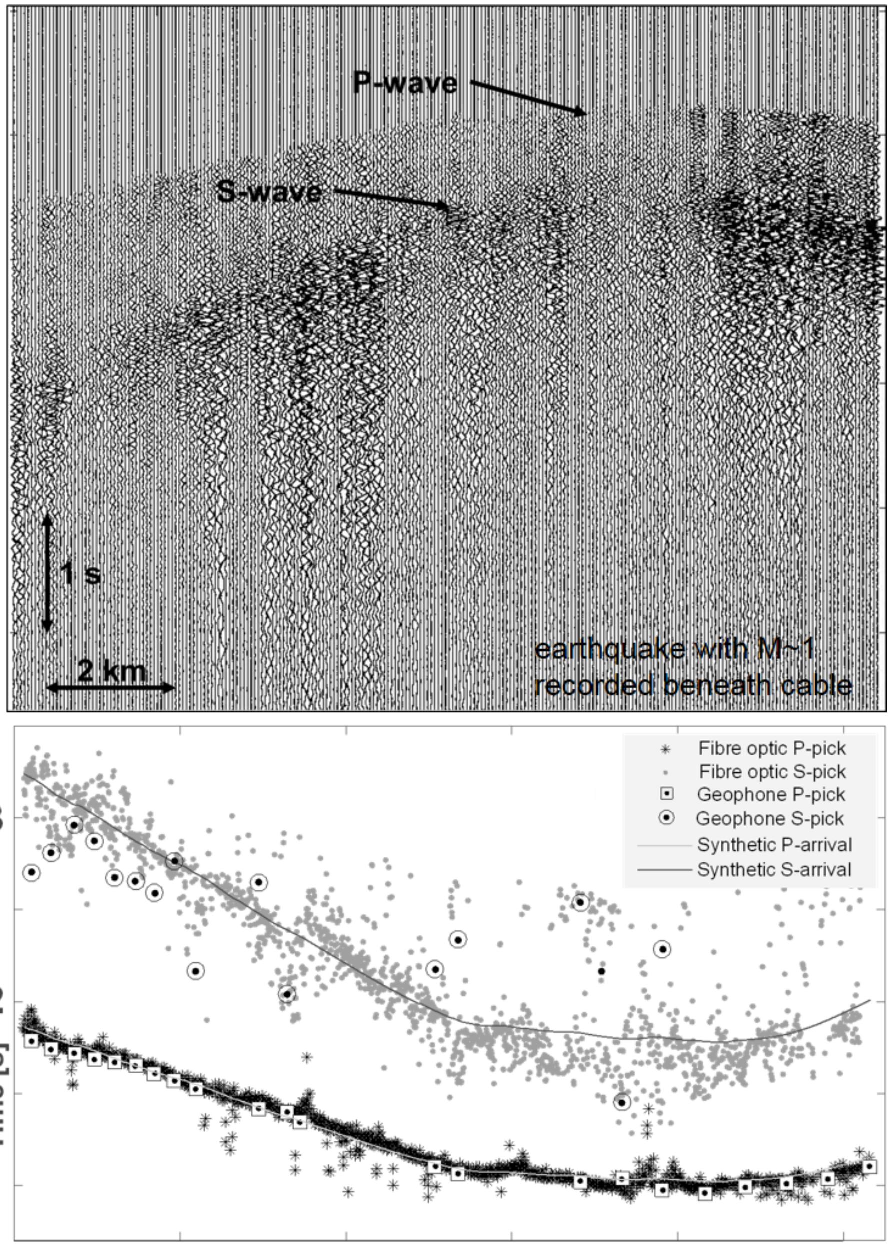

Figure 6. Example of the records of a Magnitude 1 earthquake located about 3.5 km beneath a 10 km long fibre. (Jousset et al., 2018)

device specific to our needs. A series of permanently buried fibres (including boreholes) should be installed at the EMOS sites 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

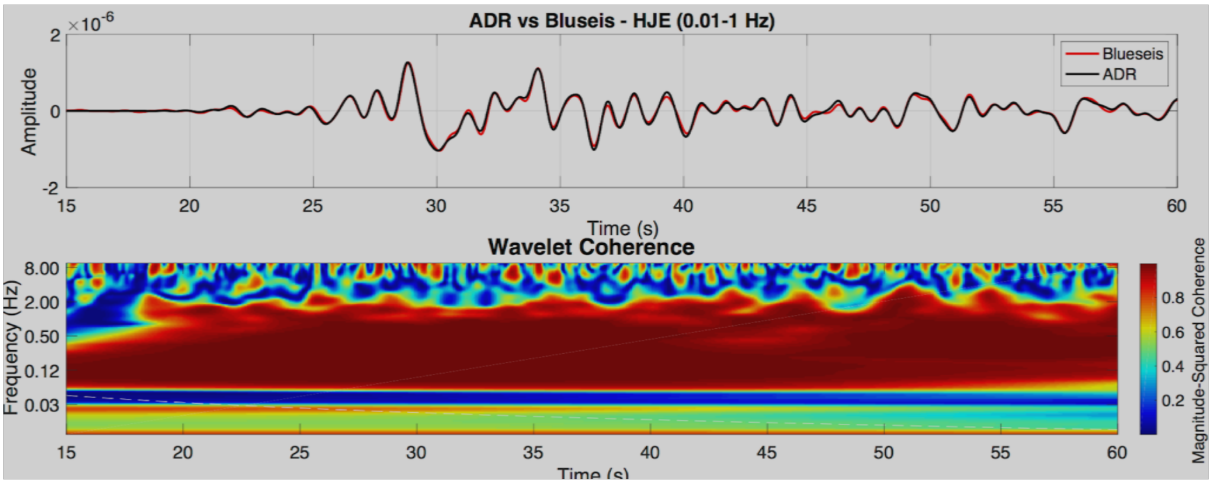

Figure 7. Comparison of the rotation measured by a single rotation sensor with the array derived rotation for a magnitude 5.4 at 58 km of epicentral distance (reproduced from J. Wassermann, 2018)

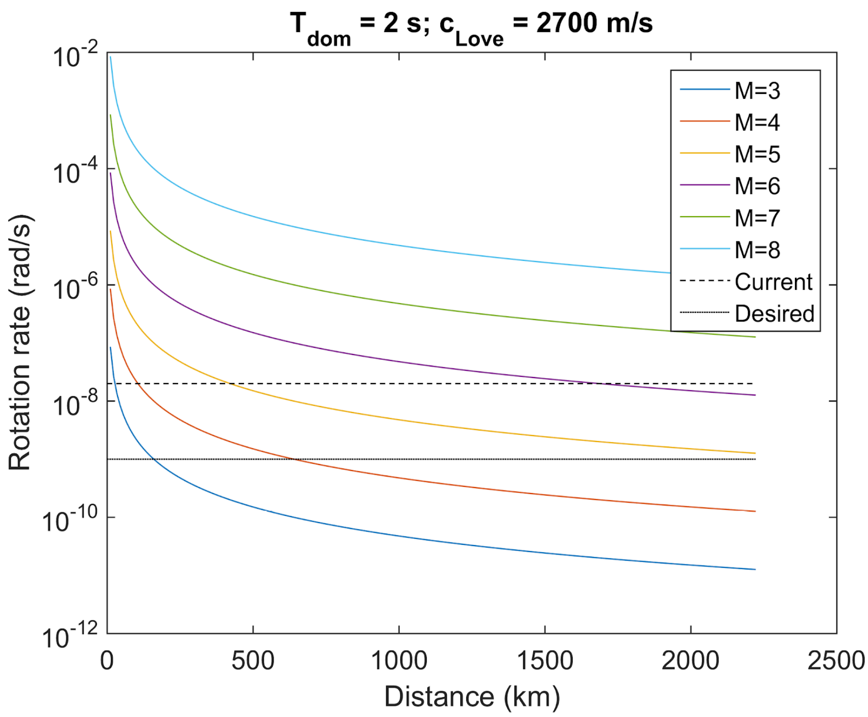

Figure 8. Estimated Love rotation vs distance for different magnitude and present-day and expected instrumental noise. From J. Wassermann (personal communication, 2018).

in an equal total number of components) (Reinwald et al. 2016). Furthermore, with the rotation components, the contamination of long period horizontal components of translational sensors by dynamic tilt can be corrected.

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.

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 trade-off between the need for high data quality versus a high density of observations with a large number of lower quality sensors was discussed among the participants. An outcome of these is that proper bench marking of all different instrument types is needed in a transparent and trusted way so that the right instrumentation can be chosen for future studies based on a clear understanding of its strengths and limitations. Low noise observatories like the Black Forest Observatory (BFO) are 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.

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 (earthquakes and non-volcanic tremor, volcanic unrest, landslides…). These scientific goals impose adapted implementation strategies. Intermediate-term (1-5 years) temporary deployments are needed for regional imaging (e.g. AlpArray and its planned follow-up AdriaArray). We know also that discoveries will arise from our capacity to catch the opportunities of observing transient processes at work, e.g., natural or anthropogenically triggered seismic swarms, volcanic activity, processes in the critical zone such as increased landslide activity after disturbance by a major earthquake. A subset of stations should therefore be reserved for specific short-term localized studies and kept prepared for ready deployment, although this mode of operation should be evaluated in terms of the relative costs of the instruments and the cost of installation/de-installation under tight time constraints.

4.2 Submarine monitoring with telecommunications cables

Although OBS deployments are a powerful way to image Earth structure and seismicity below oceanic regions, they are limited in the period of observation (1-2 years with current technology and taking into account realistic limitations for ship time) and cannot provide real-time data, so cannot be used for earthquake or tsunami early warning. This is a particularly pertinent shortcoming, as the largest earthquakes and tsunamis tend to originate below the submarine forearcs of convergent plate boundaries.

Attaching instrument packages to submarine cables is the obvious solution, and although single cabled ocean bottom seismometers have been operated for two decades or more, e.g. H2O in the middle of the Pacific Ocean, which operated from 1999 for a few years off a donated abandoned (co-axial) telecom cable (Butler et al. 2000), and several operational seafloor observatories as part of the EMSO initiative (http://emso.eu/), which, however, are often located in near-shore areas. Currently, serious long-term, low-latency seismic monitoring in the offshore domain requires dedicated seafloor cables connecting multiple sites. Due to the prohibitive cost of such cables, such projects have only been realised at large scale offshore Japan (DO-Net, S-Net) and on the Cascadia plate offshore north-western North America (Ocean Networks Canada and Ocean Observatory Initiative). Although there is interest in other countries (e.g., Chile, Indonesia), the required funding levels are not easy to reach. Submarine communications cables offer a possible less costly alternative, and could also provide monitoring of large ocean basins. Several initiatives are working to advancing this basic idea. Here three fundamentally different basic concepts have to be distinguished.

- *SMART cables.* Commercial communication cables need repeater units every 50-100 km (Fig. 9). In the SMART cable concept, these repeaters are additionally equipped with a scientific payload consisting of an accelerometer, pressure and temperature sensors, which can be harnessed for both seismological and oceanographic applications (Howe et al. 2019). The charm

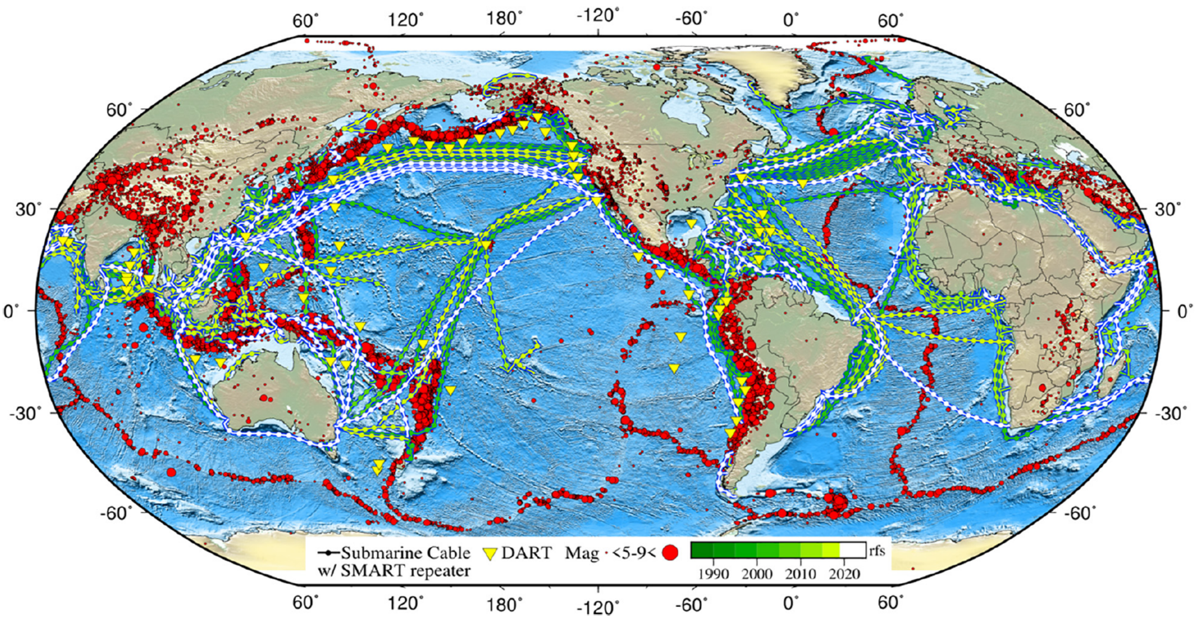

Figure 9. Current and planned cable routes (green: present, white: in progress) spanning the global oceans, together with global seismicity. For illustrative purposes repeaters are only shown every 300 km. In reality, repeaters would be placed at distances of 50-100 km, i.e., at 3-6 times the density shown. Figure from Howe et al. (2019). Earthquake locations: NEIC, Cable Routes TeleGeography's Telecom Resources.

of this concept is that the bulk of the cost of the cable laying and operation is borne by the telecom operators, although this implies that the scientific community would have no say in the cable routing, and the instrumentation needs to be able to withstand the rough environment in routine cable laying operations. The main technical challenges on the sensor side are the provision of low power accelerometers sufficiently sensitive to capture moderate to small earthquakes and the long term stability of the pressure sensors (the latter less of an issue for seismic and tsunami related applications, but highly relevant for seafloor geodesy and climate applications). Initial studies indicate the impact of such a system on tsunami early warning and global tomography (Tilmann et al. 2017), but a large impact of wide-spread monitoring of offshore areas off convergent margins on the understanding of subduction zone seismogenesis can be expected. Potentially more cumbersome than the technical challenges are the regulatory and financial challenges in building a business case for these types of cable installations. A Joint Task Force of the ITU, WMO and UNESCO is advancing this concept, and recommends a 'wet demonstrator', an deployment of a prototype of a few `SMART repeaters' under realistic conditions as a stepping stone towards the commissioning of a whole transoceanic cable.

- *Submarine DAS.* A DAS interrogator unit can be attached to the onshore landing site of a submarine cable. The general promise of DAS technology has already been explained above, and there is no fundamental reason not to apply it in the offshore region. This approach is particularly attractive for cables, which are not in operational use ('submarine dark fibre'), making the entry barrier low. The principle viability of this technology has already been demonstrated with pilot projects, e.g. offshore Belgium (Williams et al. 2019) and France (Sladen et al. 2019). Analysis proceeds equivalently to onshore DAS, although of course the recorded wavefield is strongly affected by Scholte waves induced by opposing gravity waves (this is true for all submarine recording system in the corresponding frequency range, though). The most important limitation is that the current practical range of DAS interrogators is ~50 km so it is limited to near-shore regions, although the rapid technical development of interrogators might push out this range in the near future. Furthermore, the current cost of interrogators make this approach more suitable for temporary experiments rather than long-term monitoring, but this can also change, as the price of interrogators is coming down.

- *Optical interferometry.* This technique represents a very recent technical developed by metrology institutes where the change in the total length of a long fibre connection is measured through the time of flight (Marra et al. 2018). This technique has great potential as in principle it should be possible to interrogate the whole length of a trans-oceanic cable, although so far the recording of seismic waves has only been carried out with much shorter cables. The measurement represents the spatial integration of strain/strain rate along the cable, and therefore requires adaptions of the algorithms usually employed by seismologists. Whereas there are theoretical possibilities laid out by Marra et al. (2018) to locate the sites of disturbances along the cable based on the speed-of-light limitation for information transfer, they yet have to be demonstrated in practice.

All three approaches are worthwhile pursuing, as they cover individual niches, where they have clear advantages. From a purely technical perspective, the SMART cable concept is relying on the most mature technology and is arguably the best method for establishing long term ocean floor observations far from shore, but progress with the financial aspects and ability to influence the planning of submarine cable projects has been slow. Optical interferometry shows great promise but the exciting proof-of-concept observations reported in Marra et al. (2018) need to be followed by further tests showing the usability of this technique for actual seismicity monitoring and structural imaging tasks and new analysis approaches need to be developed. The application of DAS technology to near-shore observations has a low barrier of entry, relatively speaking, and is likely to become a widely used tool for studies of continental margins.

4.3 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 analysis methods, implying an increased demand for analysis of continuous data rather than predetermined 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 developed to tie computing resources like HPC closer to the data archives, for example for systematic detection and signal classification on massive datasets. This approach will require engagement with the major HPC centres.

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 standardized formats to different user communities (e.g., by converting native DAS data to mseed for monitoring applications, and SEG-Y for imaging), 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 for the EPOS ERIC (European Infrastructure Consortium).

Discussion about optimal data management strategies of large data sets (e.g. DAS and Large-N) started in the context of the European Open Science Cloud projects as well as within the FDSN where a survey is being carried out involving potential users.

5 Conclusions and Recommendations

The discussion has first identified 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? How stable is this coupling, i.e., will we be able to repeat a measurement on a fibre after years in order to monitor changes at different depth levels?
- What are the capabilities of cheap sensors? Can we gather the results of 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, improved data access and fielded large experiments with some unquestionable scientific successes. Based on these experiences, it is timely to envision larger experiments associating multiple 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 they can make a substantive difference; the EMOS should also serve as a test bed to test new technologies,
- Develop coordinated land-sea and monitoring infrastructure experiments to characterize the structures responsible for megaquake earthquakes offshore,
- Build a European pool 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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7 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
Charlotte KRAWCZYK	GFZ Potsdam
Andreas RIETBROCK	Karlsruhe Institute of Technology
Nikolai SHAPIRO	Institut de Physique du Globe de Paris
Karin SIGLOCH	University of Oxford
Sebastian von 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

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 hypocentre location from eight years of continuous waveform data (IPOC network Chili). Sippl et al. 2018.	101,601 double-difference relocated earthquake hypocentres. 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)

8 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