Seismic Waveform Data from Greece and Cyprus: Integration, Archival, and Open Access

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Abstract

The National Observatory of Athens data center for the European Integrated Data Archive (EIDA@NOA) is the national and regional node that supports International Federation of Digital Seismograph Networks and related webservices for seismic waveform data coming from the southeastern Mediterranean and the Balkans. At present, it serves data from eight permanent broadband and strong-motion networks from Greece and Cyprus, individual stations from the Balkans, temporary networks and aftershock deployments, and earthquake engineering experimental facilities. EIDA@NOA provides open and unlimited access from redundant node end points, intended mainly for research purposes (see Data and Resources). Analysis and quality control of the complete seismic data archive is performed initially by calculating waveform metrics and data availability. Seismic ambient noise metrics are estimated based on power spectral densities, and an assessment of each station's statistical mode is achieved within each network and across networks. Moreover, the minimum ambient noise level expected for strong-motion installations is defined. Sensor orientation is estimated using surface-wave polarization methods to detect stations with misalignment on particular epochs. A single data center that hosts the complete seismic data archives with their respective metadata from networks covering similar geographical areas allows coordination between network operators and facilitates the adhesion to widely used best practices regarding station installation, data curation, and metadata definition. The overall achievement is harmonization among all contributing networks and a wider usage of all data archives, ultimately strengthening seismological research efforts in the region.

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Supplemental Material

Introduction

The understanding of the physical mechanisms that cause earthquakes, volcanic eruptions, tsunamis, surface and submarine landslides, and ultimately the seismic response of engineered structures and lifelines necessitates two elements: on the one hand, the timely and long-term availability of high-quality data and observations, and, on the other hand, tools that model their evolution in space and time. Accessing such data, which are gathered through multidisciplinary research infrastructures (RIs), can be instrumental to new findings

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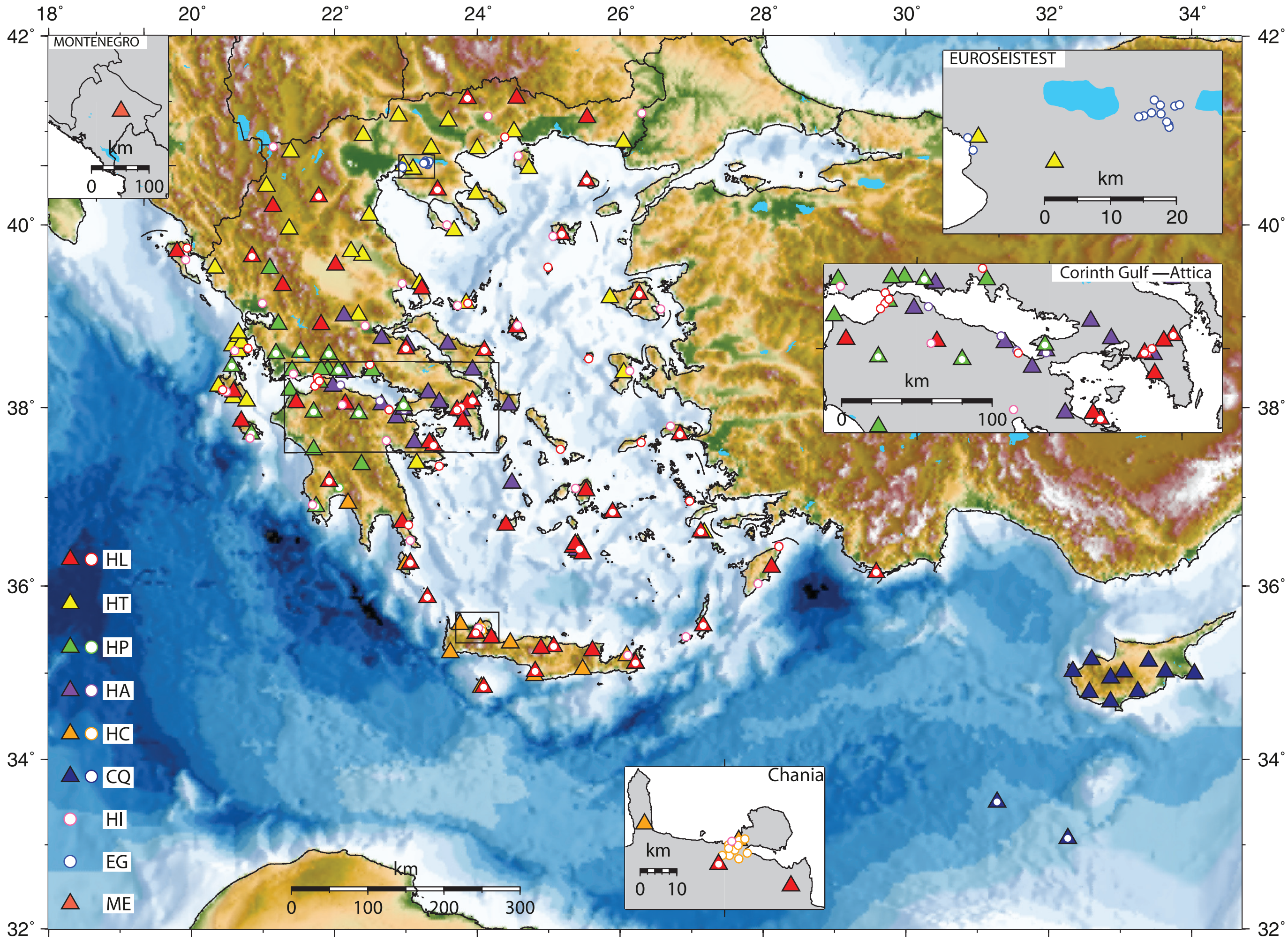

Figure 1. Map of open and active stations distributed through National Observatory of Athens data center for the European Integrated Data Archive (EIDA@NOA) in October 2020. Triangles indicate broadband (BB) stations, and circles indicate strong-motion (SM) sensors or stations. Stations are color coded by network according to the legend. Inset maps show, from north to south, respectively, enlarged maps of Montenegro, the EUROSEISTEST earthquake engineering experimental facility near Thessaloniki, the Corinth Gulf and Athens metropolitan area, and the area of Chania (Crete).

and breakthroughs in Earth science as well as earthquake engineering, leading to more effective disaster prevention and hence societal benefit. To this end, the Hellenic Plate Observing System (HELPOS) project was launched in 2017. It is an initiative arising from the current need, on a Greek and European level, for a comprehensive RI that will help integrate earth science and engineering. This initiative integrates the highly advanced, yet up to now scattered, national facilities into one distributed, coherent multidisciplinary RI, complementing other large-scale RIs within Europe, for instance, the European Plate Observing System, European Research Infrastructure Consortium (EPOS-ERIC; see Data and Resources).

The European Integrated Data Archive (EIDA), an initiative within Observatories and Research Facilities for European Seismology (ORFEUS), is a federated European data center archiving and providing access to seismic waveforms and respective metadata originating across European RIs. EIDA operates through distributed regional nodes, which supply data from designated regions. Regional EIDA nodes systematically dedicate resources toward the support, operation, and further development of EIDA and its services. The regional node hosted by the National Observatory of Athens' Institute of Geodynamics (NOAIG) integrates waveform data from seismic stations located across Greece, the Balkans, and the southeastern Mediterranean (Fig. 1).

In 2007, a national project was initiated, aiming to unify the main seismic networks in Greece into a single Hellenic Unified Seismic Network (HUSN). Initially, the unified network consisted of the HL backbone network and the three regional networks with network codes HT, HA, and HP (all network codes defined here are assigned by the International Federation of Digital Seismograph Networks (FDSN) to facilitate unique identifiers, see Data and Resources). In 2020, the HUSN memorandum of understanding (MoU) was extended to include HC network and the strong-motion (SM) network HI. Nowadays, all networks under HUSN exchange near-real-time waveform data for most of their stations through SeedLink, and those data are freely available through EIDA@NOA. Network operations are coordinated through a dedicated HUSN forum (phpBB open-source software) and use a cloud-based storage system (ownCloud file server hosted at NOA) to synchronize metadata exchange.

The implementation and operation of the EIDA@NOA node is the first attempt on a national level, to provide the global scientific community with unlimited and unrestricted access to waveform data archives for the region. Thus, NOAIG is willing to host and serve, as a dedicated regional EIDA node, data from all the seismic networks that belong to HUSN, as well as networks and temporary deployments from neighboring countries in the Balkans southern Caucasus and northern Africa.

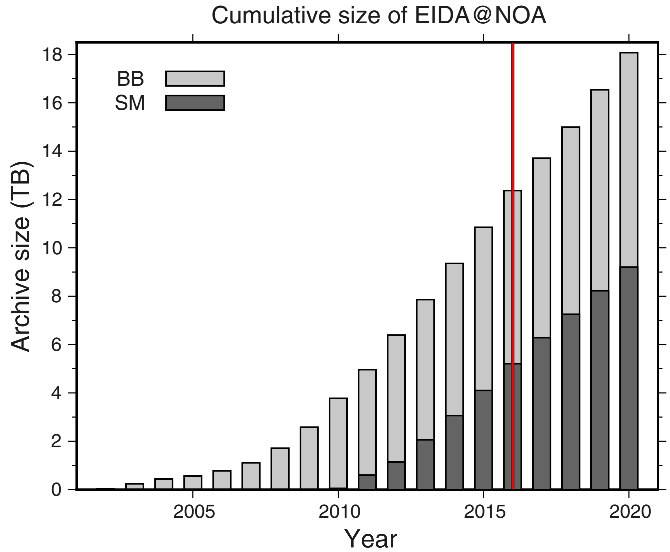

Figure 2. Evolution of the EIDA@NOA data archive for BB and SM stations. The red line indicates the year 2016, when the node became operational. The color version of this figure is available only in the electronic edition.

EIDA@NOA—National and Regional Node in the Southeastern Mediterranean

Since 2015, NOAIG is committed to an open-data policy for the entirety of its broadband seismic network (HL) and for selected SM stations (about 50% of the available SM stations in continuous transmission mode). Waveform data archives from these stations have been included in the Institute's EIDA@NOA node, established in May 2016. At that initial stage, data were also available from other networks in Greece (HP, HC, and EG) and Cyprus (CQ). Two stations from HA network were added in 2017, whereas, data from the entire HA network were added in 2018. In 2018, through the HELPOS infrastructural project, the node itself became national, and data from the remaining regional Greek networks were also included. The entire HT network was added in 2018, with a secondary route to GeoForschungsZentrum (GFZ) for certain stations that were already being distributed. Finally, 30 stations from the nationwide SM HI network were added in 2018. EIDA@NOA also distributes one station from Montenegro (network ME, see Data and Resources). Data from networks outside Greece (CQ: Cyprus and ME: Montenegro) are distributed through bilateral MoUs between NOA and the respective institutes.

Available channels and epochs

The earliest data that are available, at least, for the majority of stations date back to 2010, when most HL stations were upgraded and the channel sampling rate was extended from 50 to 100 Hz. At this time, NOAIG provided HH (100 samples per second) streams. Since then, any change at the station concerning the sensor, data logger, orientation, and, so forth, defines a new metadata epoch. HUSN was also made fully operational in 2010. In addition, most HL and HI SM stations were upgraded to continuous mode broadband accelerometers, during 2010, to be distributed in HN streams. At present, EIDA@NOA distributes only the highest sampling rate from each sensor. A considerable effort is underway to backfill all waveform archives from contributing networks, including all available data before 2010 (Fig. 2). In addition, EIDA@NOAIG is prepared and willing to host all temporary deployments in Greece and the southeast Mediterranean that are not already stored in other EIDA nodes.

Latency and licensing

EIDA@NOA distributes data targeted at research purposes only (i.e., not operational, such as early warning, ShakeMaps, structural monitoring, loss estimation, which is often an official mandate for certain agencies at national level). This is why data are provided with a latency ranging from 30 min to 24 hr, according to independent agreements with each network operator. The seismic data delay is applied at two levels: first, a global delay of 30 min from the current time is performed for all distributed seismic records, by setting the appropriate SeisComP parameters, and then a network-specific delay of 24–48 hr for the CQ network is achieved via the Operating System's copying utilities in an autoscheduled manner.

Data archives are licensed under a Creative Commons Attribution 4.0 International License, that is, the user can share (i.e., "copy and redistribute the material in any medium or format") and adapt (i.e., "remix, transform, and build upon the material for any purpose, even commercially"), providing appropriate credit.

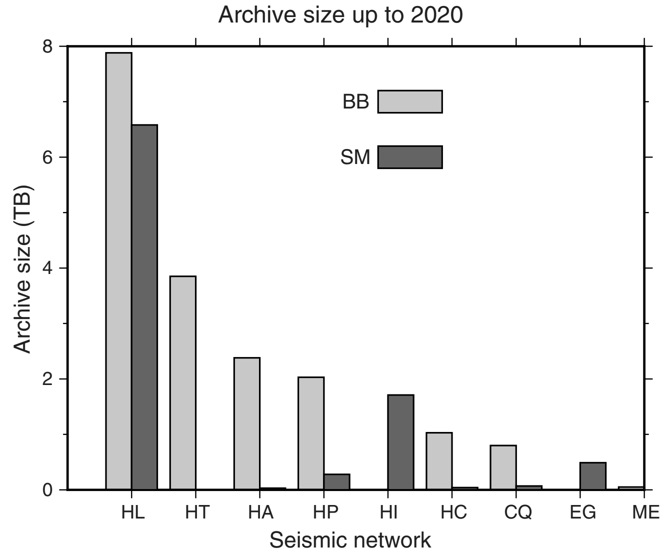

Figure 3. Data archive size per network for BB and SM stations up to 2020.

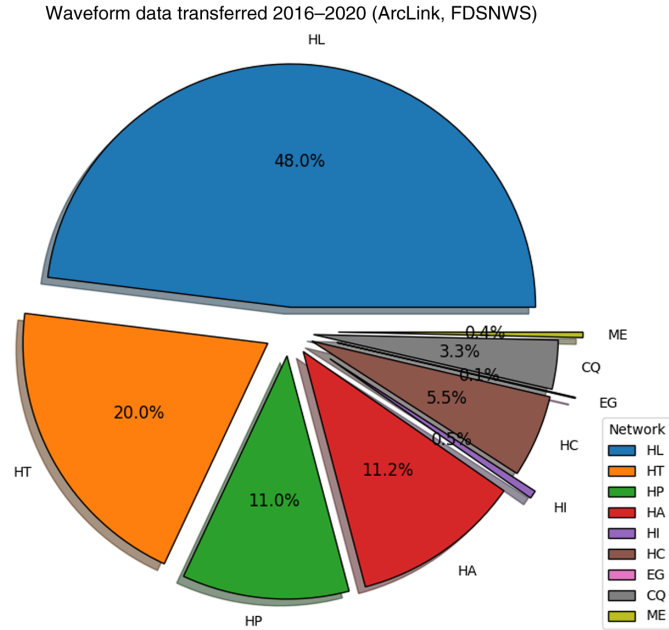

Figure 4. Percentage of data dissemination per network distributed since 2016 through EIDA@NOA. Total volume of disseminated data is ∼44 TB. FDSNWS, International Federation of Digital Seismograph Networks webservices. The color version of this figure is available only in the electronic edition.

Data archiving and dissemination

At present, EIDA@NOA delivers 11 seismic networks and two virtual networks. The total number of distributed stations is 315, with 255 stations in operation, seven embargoed, and 39 closed. In addition to these, the HUSN is distributed via the _HUSN virtual network code, which unifies the seismological networks of Greece (HL, HT, HP, HA, HC, and HI). In addition, in collaboration with the French Réseau sismologique et géodésique français (RESIF), distribution of data from the multidisciplinary near-fault observatory (NFO) of Corinth Rift Laboratory (CRL) are orchestrated via the NFO CRL virtual network (CL, HP, HA, and HL). At present, EIDA@NOA holds about 27 TB of data, growing by about 3 TB per year (Fig. 2). An addition of several tens of terabytes of data from the inclusion of SM stations from the entire data holdings of HI and HL networks is expected in 2020–2021. Figure 3 shows EIDA@NOA data holdings per network. Most broadband data are available from networks HL (∼8 TB) and HT (∼4 TB). Most SM data are distributed from networks HL (∼6.5 TB) and HI (∼2 TB).

Restricted stations are not served through the node. Embargoed stations from temporary deployments and experiments are released on a yearly basis, following certain timelines (maximum 2 yr after data acquisition) and on the condition that the data must remain in EIDA after the end of the experiment. Apart from HP network, all HUSN temporary deployments use existing permanent network codes.

Up to 2020, EIDA@NOA served more than 45,000 unique requests, disseminating, approximately, 44 TB since 2016 (16.5 TB in 2020). Figure 4 shows the percentage of data per network disseminated since 2016.

EIDA@NOA infrastructure

EIDA@NOA currently supports three redundant EIDA node end points, as follows:

- primary end point (see Data and Resources),
- secondary end point (see Data and Resources), and
- tertiary end point (see Data and Resources).

Primary and secondary end points are deployed in different geographical areas in Athens, Greece. The primary one is located in the NOA campus of Penteli, Attica and the secondary one in the NOA campus of Thissio, Athens, and they are exclusively maintained by NOA personnel and infrastructure. Waveform data archiving at both end points are preserved under separate network file system storage systems. A third end point is also delivered by National Infrastructures for Research and Technology (Greek Research and Technology Network [GRNET]), by its Infrastructure as a Service named okeanos-knossos, which is part of GRNET's cloud facilities. The waveform data archiving for that particular end point is maintained under the GRNET infrastructure (see Data and Resources). All three archives synchronize with each other to maintain data consistency. At present, EIDA@NOA is working on a deployment of a centralized end point proxying the data requests to all three aforementioned EIDA redundant end points. This implementation is meant to provide both fault tolerance and the ability to load-balance requests to the individual end point copies.

Webservices (WSs)

NOA, as a member of the EIDA federation, publicly distributes three primary data types (waveforms, station metadata, and waveform quality metrics). These data are provided by the following three WSs, respectively:

- FDSNWS—dataselect (for retrieving miniSEED waveform data) (see Data and Resources)
- FDSNWS—station (for retrieving station metadata and instrument characteristics) (see Data and Resources)
- EIDAWS—WFCatalog (for retrieving quality metrics for the waveform data) (see Data and Resources)

In addition, EIDA@NOA exposes the following WS, for guiding clients and users to determine its data holdings positions:

- EIDAWS—routing (for requesting routes of various data and services between EIDA nodes) (see Data and Resources).

As part of the EIDA federation, NOA participates with its WSs as the southeastern Mediterranean end point to the recently released EIDA Federator WS (see Data and Resources). A federator is a unified single-access point that retrieves waveform archives, station metadata, and quality-control-related information across all EIDA data holdings (i.e., data centers), in a distributed manner. Using a single request, the user is able to retrieve all data independently from whichever data center is curating them and whether it is distributed by a single or by multiple data centers. At present, EIDA@NOA is examining the use of an internal EIDA Federator instance (along with a routing service instance) for distributing seismic data of the primary, secondary, and tertiary end points, under a central end point. In this way, the internal mechanism of the Federator paves the way for having a rapid manual route alteration, in case of a failover of the higher-priority end point or having a load balance of the requests (per seismic network) to the respective serving end point.

Finally, with its 24/7 monitoring service, NOAIG distributes its event catalog publicly. These data are provided by the following WS and contain "earthquake-type" events from 2010 onward:

- FDSNWS—event (for retrieving event parameters and related data) (see Data and Resources)

EIDA@NOA utilities

EIDA@NOA runs a well-tested webinterface (see Data and Resources), providing an easy-to-handle graphical user interface (GUI). It has also deployed four web utilities, based on ORFEUS software for serving its local data, although, enriching them with additional features to serve specific NOA needs. These web tools are the following:

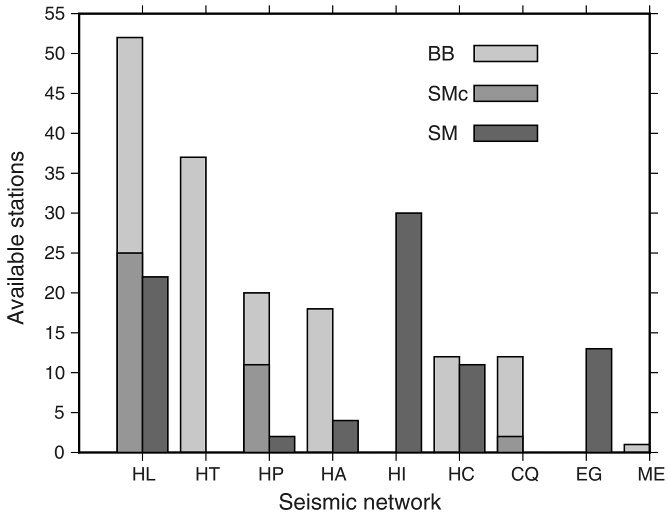

Figure 5. Number of stations per network for BB, collocated SM (SMc), and SM stations available through EIDA@NOA.

- a graphical interface showing daily data availability (see Data and Resources),
- a graphical interface showing daily waveform metrics (see Data and Resources),
- a graphical interface for viewing waveform data (see Data and Resources), and
- a graphical interface showing instrument response characteristics (see Data and Resources).

Seismic Networks

In the following, we briefly describe each distributed network separately.

HL network

The Hellenic seismic network (HL) is the nationwide backbone network operated by NOAIG (Fig. 5). Monitoring the seismicity in Greece and the adjacent region started by installing the first seismographs in Athens in 1899 (see Comninakis *et al.*, 1987). Good records have been produced from 1912 onward, when the horizontal Mainka-type seismometers were installed (1910), followed by the horizontal and vertical Wiechert-type seismometers (1924 and 1928, respectively). In 1997, an upgrade from analog to digital instrumentation was implemented, and, by 2002, most operating stations were acquired in near-real-time mode through SeedLink (Melis and Konstantinou, 2006). At present, HL operates 52 permanent broadband seismic stations and 146 stand-alone SM stations. Among those, the HL network cooperates stations in Greece, in collaboration with the GE (eight stations), the MN (four stations), and HP (one station) networks, by sharing either equipment or telemetry costs. Station HL/MN.IDI is the auxiliary certified International Monitoring

System seismic station of the Comprehensive Nuclear-Test-Ban Treaty Organization (assigned treaty code AS036). The HL network covers mainland Greece, large and remote islands, and all active volcanoes of the Hellenic Arc (Santorini, Nisyros, Milos, and Methana). As operator of the HL network and coordinator of the HUSN, NOAIG operates a 24/7 monitoring service and contributes picked phases and event locations to the International Seismological Centre (ISC) and the European-Mediterranean Seismological Centre (EMSC-CSEM).

Broadband seismic stations are equipped with a variety of seismic sensor types. About 25 of the broadband stations also include a collocated SM sensor (Figs. 1 and 4) and 14 with Global Navigation Satellite Systems (GNSS) stations. A typical distance between collocated sensors is of the order of a few meters. At present, all seismic stations are being upgraded, to include broadband seismometers (>60 s) and collocated SM sensors. Near-future infrastructure efforts will focus on densifying the seismic network coverage in areas close to the Hellenic subduction zone, by installing a seismic array and stations with collocated broadband, SM, rotational, and GNSS sensors (the PANhellenic GEophysical Observatory of Antikythera [PANGEA] initiative recently funded by the European Investment Bank).

The SM instrumentation program in Greece started in the early 1970s by NOAIG. By the end of the 1980s, the network was largely expanded, installing instruments mainly in large Greek cities. By 2006, the network had been upgraded with telemetry at all sites, with instruments in triggering mode. From 2008 onward, a major equipment upgrade allowed continuous recording at 200 samples per second and near-real-time transmission, to incorporate stand-alone SM stations in the NOAIG seismic monitoring system (Kalogeras *et al.*, 2011).

Various HL network temporary deployments are also shared through EIDA@NOA. These include the aftershock sequence deployments after the 2014 Cephalonia, 2014 Lesvos, and 2019 Western Attica events, as well as dense deployments in the eastern Corinth Gulf, the Saronikos Gulf, in western Greece, and around Methana volcano (see Table S1, available in the supplemental material to this article).

Detailed information on the networks operated by NOAIG and the related data dissemination services can be found at their websites (see Data and Resources).

NOAIG has assigned a Digital Object Identifier (DOI) for the HL seismic network (see Data and Resources). Table S1 describes the location, sensor, and vault type at each station included in the NOAIG EIDA node (see also Fig. 1).

HT network

The seismic network of the Department of Geophysics of the Aristotle University of Thessaloniki (AUTH) has been operating since 1 January 1981. Originally, it consisted of eight stations, all of them in central Macedonia, and now covers most of mainland Greece, as well as a number of islands in the Ionian and Aegean Sea (Fig. 1). The data have been digitally recorded and processed since the first day of operation, with digitization originally taking place at the central seismological station (THE). Starting in 2003, it was gradually upgraded with broadband seismometers and digital transmission of data via Transmission Control Protocol - User Datagram Protocol/Internet Protocol (TCP-UDP/IP). The network has been part of HUSN, since 2007, and, contributes its data to the national EIDA node, since 2018 (Fig. 5).

The HT network has a 24/7 monitoring service, contributes manually and automatically picked phases and epicenters to EMSC-CSEM, and publishes a monthly bulletin of seismicity. It currently operates 37 broadband and eight short-period single-component stations.

AUTH has assigned a DOI for the HT seismic network (see Data and Resources). Table S2 describes the location, sensor, and vault type at each station included in the NOAIG EIDA node (see also Fig. 1).

HP network

The University of Patras seismic network started its operation in the 1990s. At that time, it was called University of PATras Seismic NETwork (PATNET) and was of analog type. PATNET remained in operation for more than 10 yr and recorded significant events in the area (e.g., the 1993 Patras and the 1995 Egion earthquakes, see, e.g., Tselentis *et al.*, 1996; Plicka *et al.*, 1998). PATNET was replaced in the 2000s by Patras Seismological Laboratory NETwork (PSLNET), a seismic network based on broadband sensors and digital telemetry. PSLNET stations are installed around western Greece, the Corinth Gulf, the Peloponnese, and the Ionian islands (Fig. 1). PSLNET (code HP in FDSN) is part of HUSN, and all its data are freely available through the national EIDA node since 2016 (Fig. 5). Most seismic stations also have a SM sensor (Fig. 5), whereas, two of them have additional GNSS receivers.

Besides the permanent network, two temporary deployments are also shared through the EIDA@NOA node, namely, the Trichonis Lake (YB_2007, see Data and Resources) and the Lefkada 2015 (X5_2015, see Data and Resources) temporary networks. Both networks were installed soon after a strong event, to monitor its aftershock sequence. In the case of Trichonis Lake network (Sokos *et al.*, 2010), eight short-period stations were installed for a period of 25 days after the mainshock, whereas, for the case of Lefkada, six stations were installed for a period of two months.

PSLNET has assigned a DOI for the HP seismic network (see Data and Resources). Table S3 describes the location, sensor, and vault type at each station included in the NOAIG EIDA node (see also Fig. 1).

HA network

The HA network, or Athenet, is the seismological network of the Seismological Laboratory of the National and Kapodistrian

University of Athens (SL-NKUA), founded in 1931. The first seismological network of SL-NKUA was called Volos Network (VOLNET) and was installed during 1983 and 1984 in central Greece, composed of nine analog stations (Papadimitriou *et al.*, 1993). The Cornet telemetric seismological network, which was installed by SL-NKUA in 1995, was the first digital permanent network in Greece, operated in the eastern Gulf of Corinth. In June 2008, the HA network was integrated into HUSN, mainly covering the region of central Greece (Fig. 1).

The HA network is primarily distributed across central Greece (Fig. 1), with several stations along the coasts of the Gulf of Corinth, not only around its eastern part but also around the western part, where it complements the CRL network (see Data and Resources). The majority of HA stations were installed between 2007 and 2010.

The Rio-Antirrio Strong Motion Network (RASMON) accelerometric array was initially installed in 1991 across the Gulf of Corinth in the framework of EU and National research projects. During the last decade, RASMON was composed of 11 stations, five of which off-line and six on telemetry with data retrieval upon request. At present, four stations have been upgraded to real-time streaming of continuous data, shared with HUSN partners and through the EIDA@NOA node.

SL-NKUA also installed temporary stations in Santorini during the 2011–2012 volcanic unrest (Kaviris *et al.*, 2015; Papadimitriou *et al.*, 2015) and in western Attica, near Athens, during the 2019 seismic activity (Kapetanidis *et al.*, 2020). The data were shared in real time with HUSN and distributed through EIDA@NOA.

SL-NKUA has assigned a DOI for the HA seismic network (see Data and Resources). Table S4 describes the location, sensor, and vault type at each station that has been included in the NOAIG EIDA node (see also Fig. 1).

HC network

The Hellenic Seismological Network of Crete (HSNC) is the network operated by the Institute of Physics of the Earth's Interior and Geohazards and the United Nations Educational, Scientific and Cultural Organization (UNESCO) Chair on Solid Earth Physics and Geohazards Risk Reduction, Hellenic Mediterranean University Research Center, located along and focuses on the Hellenic Arc front monitoring (Fig. 1). The network (FDSN code HC) started operating in 2004 with triggering records, whereas, the first continuous data started in 2006. In the initial phase, there were four stations installed in each major city of Crete Island. Between 2004 and 2012, the network expanded to 12 stations (Hloupis *et al.*, 2013; Chatzopoulos *et al.*, 2016). During the past few years, and aiming to contribute to HUSN under the HELPOS project, the main focus of HSNC is to improve the quality of station conditions. Stations close to anthropogenic noise sources were relocated or upgraded with new, free-field bunkers.

In 2015, the HSNC started operating a permanent, dense, urban SM network in Chania basin. The sensors are set to monitor ground vibration in continuous mode, with a high sampling rate of 250 Hz. The first six installations were fully completed by the end of 2015, and the remaining ones completed in 2016.

HSNC has assigned a DOI for the HC seismic network (see Data and Resources). Table S5 describes the location, sensor, and vault type at each station included in the NOAIG EIDA node (see also Fig. 1).

CQ network

During 2012–2013, the Cyprus Geological Survey Department (GSD) completed a full rebuild of its seismological network, to meet the latest technological advances in seismology (Nanometrics, 2017). Today, the Cyprus digital seismological network (FDSN code CQ) consists of 13 permanent seismological stations (11 inland stations homogeneously covering the island, and two offshore ocean-bottom stations) and 17 new SM stations in various permanent and temporary deployments. Two seismological centers support the operation of the network for the continuous monitoring and evaluation of the local seismicity of Cyprus, and the dissemination of earthquake information to the public.

Inland seismological stations are broadband seismometers installed in 1 m deep vaults (see Table S6). The communication between the remote stations and the seismological centers is bidirectional, enabling remote monitoring and maintenance of the stations. The 11th inland station is a permanent GEOFON broadband station (GE.CSS), which has been operational since 1998. Each offshore station (owned at the moment by CSnet International Inc.) comprises a Güralp tripod ocean-bottom seismometer (OBS) installed with probe penetration of about 0.2 m into the seafloor. The OBSs use a real-time, cabled oceanographic node system, which transports data in real time to clients such as the Cyprus Seismological Network.

The seismological centers (main and backup) support the reception of continuous local seismological data in real time, the storage, processing and sharing of the data. They also receive real-time data from about 70 international seismological stations. A system that supports the automatic processing of the data and the dissemination of preliminary results (via SMS, e-mail, and website) is also operational. The seismological centers also operate and support an interactive open-access website (see Data and Resources) with manually processed earthquake information and live monitoring of station recordings (see Data and Resources). On a daily basis, picked phases and hypocenters are contributed to EMSC-CSEM, and information on every processed seismic event is posted on Twitter (@CY_earthquakes).

GSD of Cyprus has assigned a DOI for the CQ seismic network (see Data and Resources). Table S6 describes the location, sensor, and vault type at each station included in the NOAIG EIDA node (see also Fig. 1).

HI SM network

The Institute of Engineering Seismology and Earthquake Engineering (ITSAK) operates a SM network that spans the whole Greek territory, consisting of about 250 accelerographs of various triggering systems and resolutions. The backbone of the HI network is a network of 120 SM stations in continuous mode, equipped with broadband accelerometers (Margaris *et al.*, 2014). Furthermore, ITSAK operates a network of 4 six-channel borehole systems in Thessaloniki and one 15-channel borehole system in Cephalonia, providing continuous recordings both on surface and at various depths within boreholes. All real-time instruments provide continuous transmission at 100 samples per second and, in the case of accelerations higher than 0.05*g*, additional waveforms at 200 samples per second. ITSAK also operates special accelerographic arrays, for the monitoring of buildings, bridges, and valleys at several sites in Greece. In most cases, data recorded by these instruments are stored locally and downloaded in situ.

At the moment, only the data of 30 out of the 120 SM stations are disseminated via EIDA@NOA node (Fig. 1). Table S7 describes the location, sensor, and vault type at each station distributed through the node.

In addition to operating the aforementioned networks, ITSAK provides a number of data dissemination services. The recordings from the real-time free-field network are used for the automatic near-real-time generation of ShakeMaps for earthquakes in the southern Balkan region with $M_w \geq 4.0$ (see Data and Resources). In addition, an extensive data archive with unified processed SM data for the time period 1982–2016 is publicly available for engineers and geoscientists (see Data and Resources). Finally, in cases of major disastrous events, ITSAK is committed to publishing earthquake reports useful to public authorities, engineers, and other stakeholders (see Data and Resources).

Detailed information on the networks operated by ITSAK and the related data dissemination services can be found in the website (see Data and Resources) and in Margaris *et al.* (2014) and Scordilis *et al.* (2018).

ITSAK has assigned a DOI for the HI seismic network (see Data and Resources). Table S7 describes the location, sensor, and vault type at each station included in the NOAIG EIDA node (see also Fig. 1).

EG SM network

The SM network EG has been operating since 1993 in the Mygdonian basin, 30 km north-northeast from the city of Thessaloniki. Initially, the network consisted of 10 triaxial 12-bit and 19-bit surface and downhole accelerographs operating in trigger mode (Fig. 1). The stations were installed along a 6 km long, north–south-trending section of the central part of the Mygdonian basin, between the villages of Profitis and Stivos. The network operated with this structure for about 10 yr, and significant studies were conducted using the events it recorded (Raptakis *et al.*, 1998; Chávez-García *et al.*, 2000). From 2002 onward, the network was continuously upgraded, with new instrument installations along the east–west direction of the basin, relocation and/or replacement of existing stations, and new communication facilities. This also led to a 3D basin model (Manakou *et al.*, 2010). At present, the EG network covers an area of about 40 km^2 in the central Mygdonian basin and comprises 20 triaxial 24-bit surface and downhole accelerographs at different depths, monitoring on a 24/7 basis (see Data and Resources, Pitilakis *et al.*, 2013). Data from most of the EG stations are distributed in real time through the EIDA@NOA node (Fig. 5).

EUROSEISTEST has assigned a DOI to the EG seismic network (see Data and Resources). Table S8 describes the location, sensor, and vault type at each station included in the NOAIG EIDA node (see also Fig. 1).

Data Quality Control

A single data center that hosts the complete seismic data volumes and their respective metadata from networks that cover similar geographical areas allows massive calculations on data metrics and quality. In this way, a coordination process that follows widely used best practices on station installation, data curation, and metadata definition is performed to achieve harmonization among all contributing networks.

Noise analysis—networks MNLM

The characteristics of ambient noise across Greece, as recorded by HUSN, have been investigated by Evangelidis and Melis (2012). Those authors computed power spectral densities (PSDs) and the respective probability density functions (PDFs) for a total of about 110 broadband stations based on continuous data recordings spanning 4 yr, namely 2007–2010. The HUSN minimum mode noise model (designated as HMLNM) constitutes the highest-probability ambient noise level across Greek territory. For the purposes of this article, the 2020 study has been extended to include all seismic stations currently in operation and data holdings of EIDA@NOA, and thus the HMLNM has been re-estimated (see Table S9). Separate minimum mode noise models have been estimated for each network and compared against the new HMLNM (Fig. 6). In general, modes at high frequencies vary considerably, because they are mainly affected by station proximity to sources of anthropogenic noise (see Lecocq *et al.*, 2020).

Station and network modes at the microseismic band (2–10 s), which is affected by sea–weather conditions at local seas (Aegean, Ionian, and eastern Mediterranean) or at much longer distances (North Atlantic), are concentrated at similar levels with no significant dispersion. At longer periods, only networks that operate wider broadband sensors (>60 s) in combination with good seismic vault construction (see Tables S1–S8) and thermal insulation follow the minimum noise levels as defined by HMLNM. Stations with constant elevated noise levels

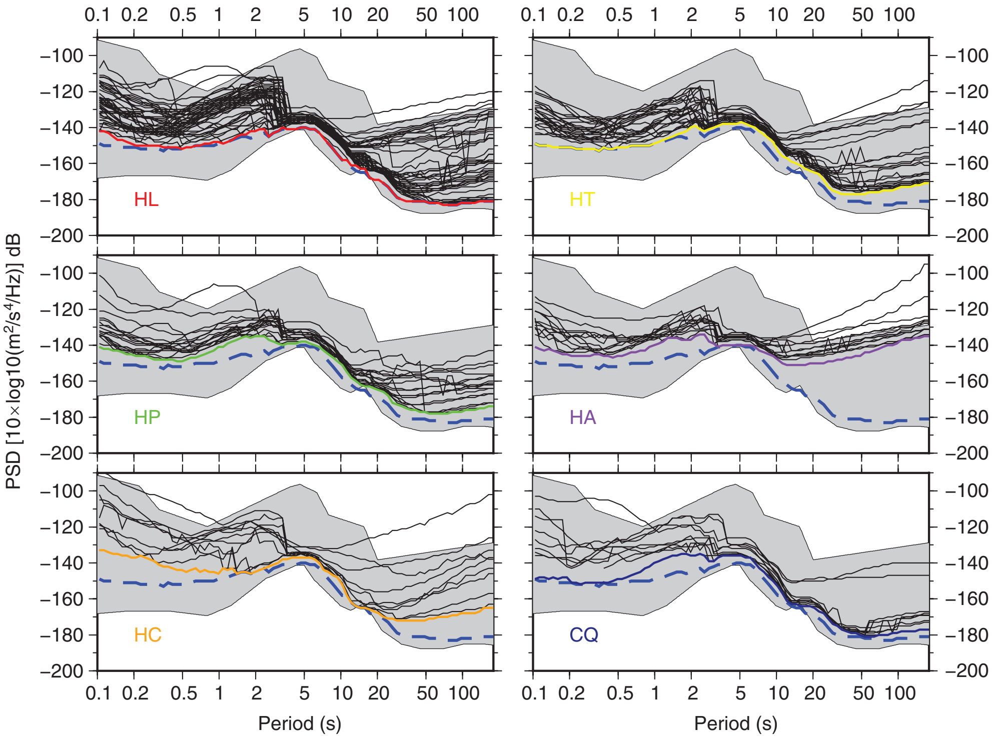

Figure 6. Minimum probability density function (PDF) mode noise levels for each BB seismic network distributed through EIDA@NOA, calculated as the minimum of all station individual modes (thin lines) currently operating on the same network. The overall PDF mode noise model (Hellenic Unified Seismic Network [HUSN] minimum mode noise model [HMLNM]) is also plotted (blue-dashed lines). The gray shadow marks the area between Peterson (1993) new low- and high-noise models. PSD, power spectral density.

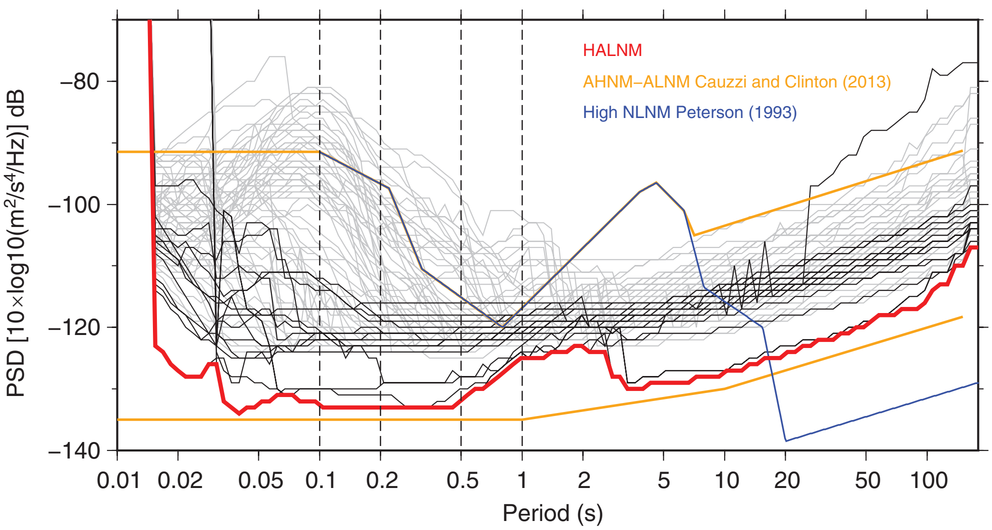

Figure 7. Minimum PDF mode noise levels for Hellenic seismic network (HL) SM stations distributed through EIDA@NOA (Hellenic accelerometer low-noise model [HALNM], red bold line), calculated as the minimum of all station individual modes currently operating. Thin gray lines mark stand-alone SM station modes, and thin black lines mark SMc sensors installed at BB seismic stations. Orange lines show the accelerometric high (AHNM) and low (ALNM) noise models of Cauzzi and Clinton (2013). The blue line marks the high-noise model of Peterson (1993). NLNM, new low-noise model.

across all bands usually correspond to cases in which either the vault was poorly constructed or the site was poorly chosen. Such observations can inform the decisions of network operators, who may then proceed to make structural improvements or even relocate a station.

The minimum PDF noise levels for HL SM (accelerometer) stations distributed through EIDA@NOA are also calculated (Hellenic accelerometer low-noise model [HALNM], Fig. 7). It represents the minimum of all SM station individual modes currently in operation (see Table S10). Each station can be classified by comparing its mode with HALNM at different periods (0.1, 0.2, 0.5, and 1 s). Stations with low noise across all frequency bands tend to be collocated with broadband sensors and installed in free-field seismic vaults on bedrock. From Figure 7, it is clear that the minimum level of noise defined by the HALNM is mainly determined by a very few collocated sensors paired with high-resolution data loggers (Earthdata PS6-24). The remaining HL SM stations, all of which have the same data logger type, show higher levels of noise than HALNM and than the accelerometer low noise model (ALNM) of Cauzzi and Clinton (2013). This is not related to site conditions and reveals that the data logger resolution is being met. A re-estimation of HALNM, including all SM stations from HI, HP, and EG networks, would not decrease the minimum levels of noise, because these stations are installed within urban areas, sedimentary basins, and soft rocks, and have the same type of sensors and data loggers as

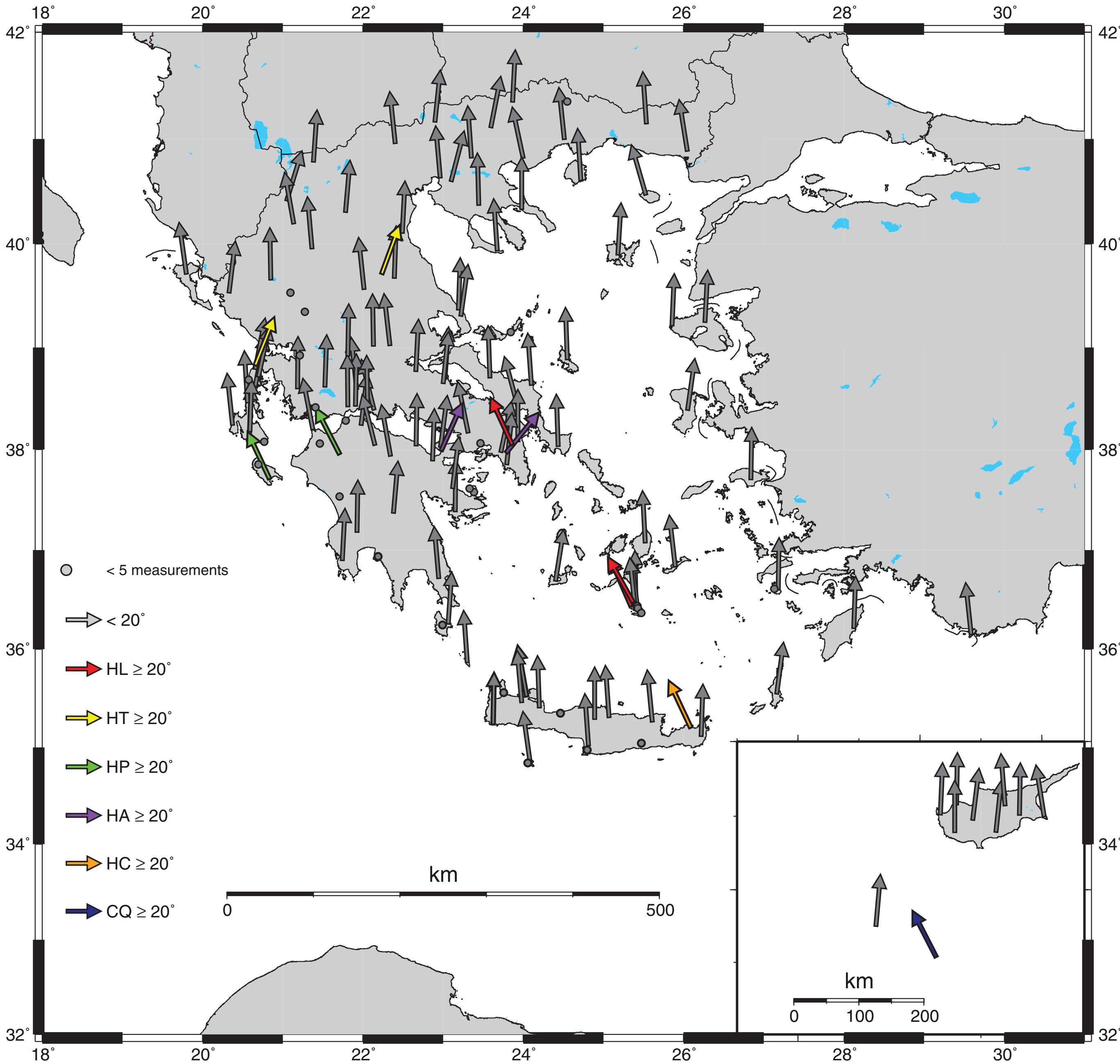

Figure 8. Map showing the obtained sensor orientations of all EIDA@NOA BB stations. Colored arrows indicate stations with misorientations greater than 20° (red, HL network; yellow, HT; green, HP; purple, HA; orange, HC; and blue, CQ). Only stations that have measurements for more than five events are shown. Inset map shows the results for broadband stations in the Republic of Cyprus (inland) and for the two OBS locations that lie within its exclusive economic zone (offshore).

the HL network (see Tables S1–S8). Thus, HMLNM for SM sensors (HALNM) represents the targeted ambient noise level expected in Greece, as recorded by few high-quality 24 bit data loggers and SM sensors installed in optimum conditions (see Table S10).

Sensor misorientations

Broadband sensor orientation is examined using the procedure proposed by Petersen *et al.* (2019) based on the Rayleigh-wave-polarization method. For each station distributed through EIDA@NOA, records from a number of shallow teleseismic events are analyzed. The radial (R) component is rotated and then compared to the vertical (Z) component by cross correlation for a specified time window that includes the surface waves. The best estimate of the true sensor orientation is computed by maximizing the cross-correlation coefficient of the correction angle (0° corresponds to no rotation correction). This procedure is applied to all event–station pairs, and the results of multiple events are combined by computing the median value for each station. In Figure 8, colored arrows indicate station misorientations greater than 20°. Only stations that have measurements for more than five events are shown. The selected teleseismic waveforms have been filtered between 0.03 and 0.1 Hz. Up to October 2020, stations HL.PTL, HL.SAP3, HL.SAP4, HT.TSLK, HT.TYRN, HP.DRO, HP.LTHK, HA.ATHU, HA.LOUT, HC.STIA, and CQ.OSC2 were identified as having a misorientation greater than 20° for the entire EIDA@NOA data holdings. A routine process that uses any new candidate high-signal-to-noise ratio event will improve the resolution of the method at all EIDA@NOA stations. The new azimuths are added in the metadata as separate epochs. Moreover, there is a planned HUSN initiative to detect, describe in metadata, and correctly orient all deployed sensors using highly accurate gyrocompass technology.

Conclusions

EIDA@NOA shares data from 11 seismic networks (nine of which permanent) and from two virtual networks. Since 2016, committed to an open-data policy, it provides unlimited and unrestricted access, for research purposes, to waveform data archives from Greece, Cyprus, southeastern Mediterranean, and the Balkans. Up to the end of 2020, the total number of broadband and SM stations is 315, with 255 operating, seven embargoed, and 39 closed. Data archives are stored and served at three redundant EIDA node end points. Primarily, waveforms, waveform quality metrics, and station metadata are distributed through dedicated FDSN and EIDA WSs. Various services include an easy-to-use GUI through a dedicated webinterface and graphical interfaces and tools to expose data availability and waveform metrics. Moreover, seismic ambient noise metrics are estimated based on PSDs. Access to these allows users to assess the quality of recordings at each station and network separately. Such plots and metrics can be valuable to network operators, since they can indicate cases of possible sensor malfunction, or where a station might need improvement. Optimum levels of minimum-expected noise levels are also indicated for broadband and SM deployments. Records of teleseismic events are used to detect sensor misorientations. Finally, free and unlimited access to the complete waveform archives from a single data center in the region allows coordination and harmonization, following ORFEUS and FDSN best practices. These actions will strengthen and fully exploit seismological research efforts in the region. EIDA@NOA is willing to host and serve, as a regional EIDA node, any other seismic network, or temporary deployment from the Balkans, southeast Mediterranean, and southern Caucasus.

Data and Resources

The facilities of National Observatory of Athens (NOA) data center, and specifically the National Observatory of Athens data center for the European Integrated Data Archive (EIDA@NOA) Observatories and Research Facilities for European Seismology (ORFEUS) node (http://eida.gein.noa.gr), were used to access all waveforms and related metadata shown in this article. We used data from the HL (National Observatory Of Athens, Institute of Geodynamics (1997)), HT (Aristotle University of Thessaloniki Seismological Network (1981)), HP (University of Patras, Geology Department (2000)), which is cooperating certain stations jointly with the Charles University in Prague, HA (University of Athens (2008)), HC (Institute of Physics of the Earth's Interior and Geohazards, UNESCO Chair on Solid Earth Physics and Geohazards Risk Reduction, Hellenic Mediterranean University Research Center (former Technological Educational Institute of Crete) (2006)), CQ (Geological Survey Department Cyprus (2013)), HI (Institute of Engineering Seismology Earthquake Engineering (ITSAK) (1981)), EG (Research Unit Of Soil Dynamics, Civil Engineering Dept, Aristotle University (1993)), and ME (Sector for Seismology, Institute of Hydrometeorology (1982)) networks. Information about Corinth Rift Laboratory (CRL) network is available in Corinth Rift Laboratory Team and RESIF Datacenter (2013). The Generic Mapping Tool (GMT) mapping software (www.soest.hawaii.edu/gmt; Wessel and Smith, 1998) was used for figure preparation. The supplemental material for this article comprises a separate comma-separated variable (CSV) table for each network, which reports information for each seismic station as served from EIDA@NOA WSs at the end of 2020 (Tables S1–S8); a README file that describes seven different types of installation for broadband and strong motion stations; the EIDA@NOA minimum mode noise model of all broadband station modes, as the new representative noise model for Greece and Cyprus (Hellenic Unified Seismic Network [HUSN] minimum mode noise model [HMLNM]) (Table S9); and the minimum value of all strong-motion HL station modes, as the new representative noise model for accelerometers in Greece (Hellenic accelerometer low-noise model [HALNM]) (Table S10). Information about European Plate Observing System, European Research Infrastructure Consortium is available at https://www.epos-ip.org/. Data about International Federation of Digital Seismograph Networks (FDSN) are available at https://www.fdsn.org/networks/. Data about primary end point are available at https://eida.gein.noa.gr, secondary end point at https://eida2.gein.noa.gr, and tertiary end point at https://eida.grnet.noa.gr. Information about Greek Research and Technology Network (GRNET) infrastructure is available at https://okeanos-knossos.grnet.gr. Data about FDSNWS—dataselect (for retrieving miniSEED waveform data) are available at https://eida.gein.noa.gr/fdsnws/dataselect/1, FDSNWS—station (for retrieving station metadata and instrument characteristics) at https://eida.gein.noa.gr/fdsnws/station/1, EIDAWS—WFCatalog (for retrieving quality metrics for the waveform data) at https://eida.gein.noa.gr/eidaws/wfcatalog/1, EIDAWS—routing (for requesting routes of various data and services between EIDA nodes) at https://eida.gein.noa.gr/eidaws/routing/1, and FDSNWS—event (for retrieving event parameters and related data) at https://eida.gein.noa.gr/fdsnws/event/1. EIDA@NOA runs a well-tested webinterface at http://eida.gein.noa.gr/webdc3. Information about EIDA Federator webservice is available at eida-federator.ethz.ch. Data about a graphical interface showing daily data availability are available at http://eida.gein.noa.gr/availability, daily waveform metrics at http://eida.gein.noa.gr/metrics, for viewing waveform data at http://eida.gein.noa.gr/waveform, and instrument response characteristics at http://eida.gein.noa.gr/response. Data about the networks operated by

National Observatory of Athens' Institute of Geodynamics (NOAIG) and the related data dissemination services can be found at https://bbnet.gein.noa.gr and https://accelnet.gein.noa.gr. Information about ShakeMaps is available at http://shakemaps.itsak.gr. The data archive with unified processed strong-motion data for the time period 1982–2016 is publicly available for engineers and geoscientists at http://ghead.itsak.gr. Data about Institute of Engineering Seismology and Earthquake Engineering (ITSAK) are available at http://www.itsak.gr/news/categories/24. Information on the networks operated by ITSAK and the related data dissemination services is available at http://www.itsak.gr/en/page/infrastructures/networks/acc_network. At present, data about EUROSEISTEST are available at http://euroseisdb.civil.auth.gr. Information about Trichonis Lake is available in Sokos (2007), and information about Lefkada 2015 is available in Sokos (2015). Data about seismological centers are available at www.gsd-seismology.org.cy, and data about live monitoring are available at www.moa.gov.cy/gsd. All websites mentioned in the article were last accessed in January 2021.

Declaration of Competing Interests

The authors acknowledge there are no conflicts of interest recorded.

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