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Investigation of the central Adriatic lithosphere structure with the AlpArray-CASE seismic experiment

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The tectonics of the Adriatic microplate is not well constrained and remains controversial, especially at its contact with the Dinarides, where it acts as the lower plate. While the northern part of the Adriatic microplate will be accurately imaged within the AlpArray project, its central and southern parts deserve detailed studies to obtain a complete picture of its structure and evolution. We set up the Central Adriatic Seismic Experiment (CASE) as a AlpArray Complementary Experiment with a temporary seismic network to provide high-quality seismological data as a foundation for research with state-of-the-art methods and high-precision seismic images of the controversial area. The international AlpArray-CASE project involves four institutions: the Department of Earth Sciences and the Swiss Seismological Service of ETH Zürich (CH), the Department of Geophysics of the Faculty of Science at the University of Zagreb (HR), the Republic Hydrometeorological Service of the Republic of Srpska (BIH) and Istituto Nazionale di Geofisica e Vulcanologia (I). The established temporary seismic network will be operational for at least 18 months. It combines existing permanent and temporary seismic stations operated by the involved institutions together with newly deployed temporary seismic stations, installed in November and December 2016, managed by ETH Zürich and INGV: five in Croatia, four in Bosnia and Herzegovina and one in Italy. We present our scientific aims and

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network geometry as well as the newly deployed stations sites and settings. In particular, the new stations show favourable noise level (power spectral density estimates). The new network improves considerably the theoretical ray coverage for ambient noise tomography and the magnitude threshold shown in the Bayesian magnitude of completeness threshold map.

Keywords: AlpArray, Adriatic microplate, Dinarides, lithosphere, seismic networks, noise level

1. Introduction

The investigation of the Apennines-Alps-Carpathian-Dinarides orogenic system is the main target of the international AlpArray collaborative initiative (www.alparray.ethz.ch). Its ambitious goal is to provide exceptionally high-quality geophysical and seismological data that, with unprecedented resolution (Hetényi et al., 2018), will allow mapping of the lithosphere and the mantle and will provide a new homogeneous earthquake catalogue. New and consistent geodynamical and tectonic models of this complex area will be produced by analysing and combining the AlpArray datasets and scientific studies. Just to the southeast of the AlpArray border lies a region where, despite its high seismic hazard, there is limited modern instrumentation and consequently scientific understanding: the central Adriatic Sea and the Dinarides. This area is the target of the *Central Adriatic Seismic Experiment* (CASE).

Tectonics in the wider Adriatic Sea region and the Dinarides is the result of the interaction between the European and the African plates together with the Adriatic microplate (Adria). In particular, the Adriatic microplate forms the upper plate in the collision front in the Western and the Central Alps, whereas it acts as the lower plate in the Apennines and the Dinarides (*e.g.* Vignaroli et al., 2008, 2009; Handy et al., 2015). Although the general framework is not disputed, the details about the interaction of Adria with the European mainland are not well constrained and remain controversial, especially in the central and the southern part of the Dinarides. From a kinematic point of view, Oldow et al. (2002) proposed that Adria is divided into two blocks by the Gargano–Dubrovnik fault line, which experiences considerable recent seismicity. Battaglia et al. (2004) confirmed their findings. The crustal thickness and structure under the Dinarides are poorly resolved, and are dominated by large seismic transition zones that are not obviously linked to the tectonic structures observed at the surface (Herak and Herak, 1995; Šumanovac, 2010; Stipčević et al., 2011). Most investigations model a relatively narrow belt of thick crust (> 40 km) following the main axis of the Dinarides and thinning rapidly towards the Pannonian basin and the Adriatic Sea (*e.g.* Skoko et al., 1987; Šumanovac, 2010). Stipčević et al. (2011) applied the receiver functions analysis to the Dinarides and reported that the Mohorovičić discontinuity is considerably deeper than suggested in previous studies, indicating some of the thickest crust in Europe. As with the crustal structure, little is known about the deeper structure of the Dinaric collision zone. Recent teleseismic tomographic images (Bijwaard and Spakman, 2000; Piromallo and Morelli, 2003; Koulakov et al., 2009) show a shallow high-velocity anomaly beneath the central and the southern Dinarides reaching approximately 200 km of depth. Most interpretations suggest this represents underthrusting of the Adriatic microplate beneath the Dinarides (Ustaszewski et al., 2008; Schmid et al., 2008; Ustaszewski et al., 2010; Handy et al., 2015; Šumanovac, 2015). Moreover, by analysing GPS measurements, Bennett et al. (2008) argued for an ongoing subduction process of the Adria lithosphere beneath the central and the southern Dinarides whilst simultaneously proposing a best matching fault plane solution for the large regional earthquakes. Some studies (Schefer et al., 2011; Matenco and Radivojević, 2012) even suggested a collisional subduction accompanied by the slab roll-back. Tomographic images available in the recent studies do not allow for a unique interpretation due to poor ray coverage. The recent SKS-splitting analyses of Subašić et al. (2017) suggest that – unlike the situation in *e.g.* the Alps – the fast axis orientation in the mantle beneath the central and southern Dinarides is perpendicular to the mountain chain of the Dinarides. These observations may be explained by the preferred lattice orientation of mantle minerals generated by the asthenospheric flow directed SW–NE to SSW–NNE through the slab-gap beneath this part of the Dinarides. Moho maps have been compiled (*e.g.* Tesauro et al., 2008; Molinari and Morelli, 2011; Spada et al., 2013), but such compilations suffer from the lack of data in the Dinarides and surrounding areas, which results in Moho depths and crustal structure estimations with high uncertainties. At shallower depth, the crustal structure of this area is still under debate due to the sparsity of seismic stations and available data. Anisotropy in the crust was determined by Lokmer and Herak (1999), who also found the fast axis to strike SW–NE, most probably as a results of dilatancy-induced cracks aligned in the direction of the maximum tectonic stress.

The studied area is one of the seismically most active parts of both Adria and the Dinarides. The Dinarides are characterized by moderate to strong seismicity with rare occurrence of strong earthquakes. The majority of the recorded events occurred on reverse and strike-slip faults along the Dinaric strike. One of the largest events in this region was the Great Dubrovnik Earthquake from 1667, which produced intensity IX on the EMS scale (Herak et al., 1996; Markušić et al., 2017). According to Croatian Earthquake Catalogue (updated version of Herak et al., 1996), several earthquakes with local magnitude greater than 6.0 have occurred in the recent past: M_L = 6.0 and I = VIII MSK (Medvedev-Sponheuer-Karnik macroseicmic intensity scale, Medvedev et al., 1964; Medvedev, 1978; Ad-hoc Panel, 1981) on 5 September 1996 near Ston-Slano (Markušić et al., 1998); 11 January 1962 near Makarska with M_L = 6.2 and I = VIII °MSK; M_L = 6.2 and I = VIII–IX °MSK on 29 December 1942 near Imotski; and 2 July 1898 with I = IX MSK near Sinj (estimated M_L = 6.7). A strong earthquake happened on 15 April 1979 offshore Montenegro with Mw = 7.1 (Benetatos and Kiratzi, 2006). According to Ivančić et al. (2018), this area is in a phase of stress accumulation and it seems to be close to reaching the critical level of strain. In the middle of the Adriatic Sea, near Jabuka Island, on 27 March 2003 an earthquake of local magnitude 5.8 was recorded (Herak et al., 2005). This was the last of three major events in the area between Jabuka and Palagruža islands with $M_L \geq 5.0$ in the past 40 years. Herak et al. (2005) noted that the Central Adriatic Sea shows significantly higher seismic potential than generally assumed.

Because of its key role in the Mediterranean plate tectonics, the central Adriatic Sea and the Dinarides deserve a detailed study that, combining different methodologies, will allow a more complete picture of the debated Adriatic

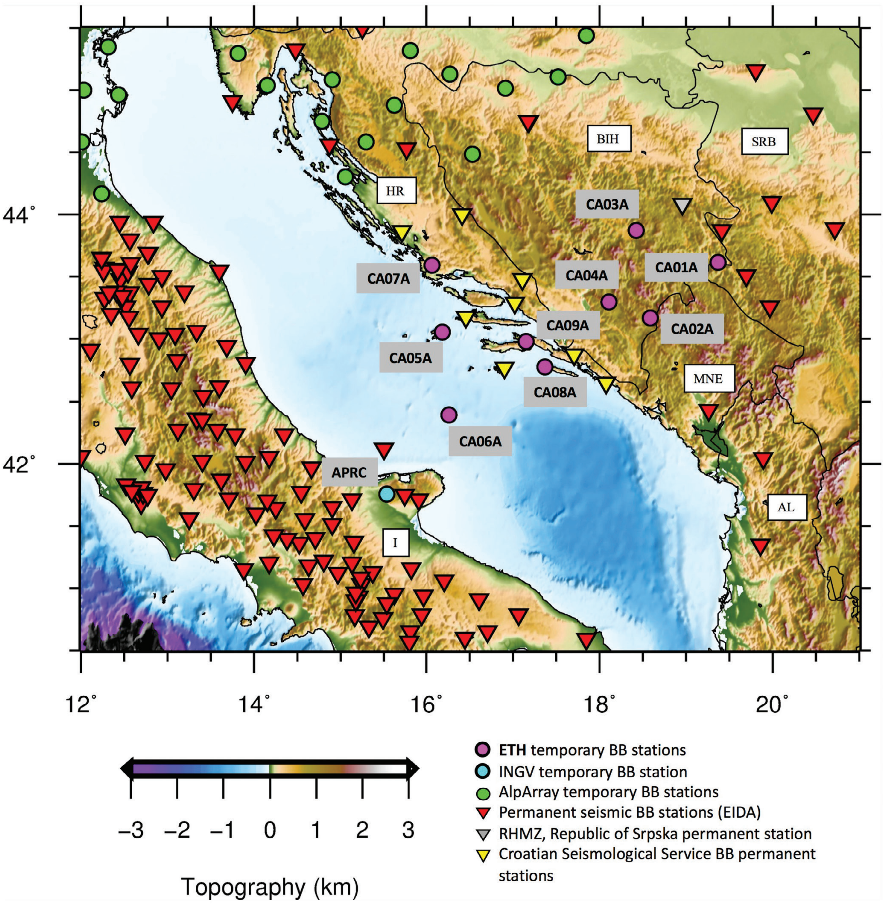

Figure 1. Map of the AlpArray-CASE broadband seismic stations, with the permanent stations in EIDA (red triangles), the AlpArray-CASE temporary stations (magenta and cyan circles), the permanent broadband stations within the Croatian Seismological Network (yellow triangles), the permanent broadband station owned by the Republic Hydrometeorological Service of the Republic of Srpska (grey triangle) and the AlpArray temporary station (green circles).

microplate structure and its evolution. The relationship with the neighbouring mountain chains and the full knowledge of its 3D lithosphere structure, as well as the recent seismicity, require better understanding, which is only possible with new high-quality and high-resolution seismic data. While the northern parts of Adria and the Dinarides will be imaged in detail within the AlpArray project, the central and southern parts are targeted in this project.

The primary goal of the AlpArray-CASE project is to improve our knowledge on the 3D seismic structure and seismotectonics of this area by recording high-quality broadband seismic data. In this work we describe the project in terms of scientific aims, network design and network performance. The CASE project is carried out by four institutions: the Department of Earth Sciences and the Swiss Seismological Service of ETH Zürich (CH), the Department of Geophysics with the Croatian Seismological Survey of the Faculty of Science at the University of Zagreb (HR), the Republic Hydrometeorological Service of Republic of Srpska (BIH) and Istituto Nazionale di Geofisica e Vulcanologia (I). This collaboration established a temporary broadband seismic network that will be operational for at least 18 months starting from November 2016. The network is composed of existing permanent and temporary seismic stations operated by the institutions involved in addition to nine newly deployed temporary seismic stations owned and maintained by ETH Zürich in Croatia and Bosnia and Herzegovina, and one owned by INGV in Italy (Fig. 1). The CASE temporary deployment is supported entirely by the Swiss-AlpArray SINERGIA project. In this work, we focus on the description of the locations and the characteristics of the newly installed station.

2. The AlpArray-CASE project: Scientific goals and seismic network geometry

In this section we describe the main scientific goals, the methods we will apply to analyse the dataset, the network geometry and its characteristics. The design of a seismic temporary experiment, especially its network geometry, involves careful balancing and compromising between the pursued scientific aims, morphological and political constraints, anthropogenic noise, instrument availability, work force and sustainability. A crucial point for a successful experiment is the quality of the seismic stations, determined by site selection, instrumentation and installation techniques and we describe them here for the CASE experiment.

2.1. Scientific aims

The AlpArray-CASE project has the main ambition to answer fundamental questions on the structure, the geodynamics and the tectonics of the central part of Adria and the central and the southern Dinarides. How does the 3D lithosphere structure look like? Which is the topography of the Mohorovičić discontinuity? What regional-scale velocity structures (isotropic and anisotropic) are present within the lithosphere? How is the anisotropy related to the geodynamic of the region? Which are the links between the lithosphere structures and the tectonic evolution of the region? How does the seismicity associate with the 3D structure?

The broadband nature of the CASE seismic network allows us to pursue these goals by applying seismic methods such as receiver functions (*e.g.* Stipčević et al., 2011, Belinić et al., 2018), ambient noise tomography (*e.g.* Molinari et al., 2015), SKS-splitting (*e.g.* Salimbeni at el. 2008, 2013; Subašić et al., 2017), attenuation measurements (*e.g.* Dasović et al., 2013, 2015; Majstorović et al., 2017), high-precision earthquake location (*e.g.* Diehl et al., 2009a), local earthquake tomography (*e.g.* Husen and Kissling 2001; Diehl et al., 2009b) and full waveform tomography (*e.g.* Tromp et al., 2005; Fichtner et al., 2013). The results of these investigations will further lead to a better understanding of the geodynamics and the tectonics of the whole area in relation to other orogenic systems.

2.2. Network constraints and geometry

The seismic array (Fig. 1) is specifically designed for these scientific aims and, in particular, for ambient noise tomography, local earthquake tomography and receiver functions. However, the network geometry is limited by the presence of the Adriatic Sea, and by political and safety constraints. In particular, to resolve the crustal structure in the region covered by the Adriatic Sea we will apply ambient noise tomography exploiting also the permanent stations in Italy (INGV seismic network stations). We installed a station on Palagruža Island and stations in Bosnia and Herzegovina in order to resolve the Moho topography with receiver function studies and to infer the seismic anisotropy in the upper mantle along the SW–NE profile, from the Italian peninsula across the Adriatic Sea to the Dinarides. Moreover, the new station in the middle of the Adriatic and a denser network along the Croatian coast will greatly help to reduce the minimum magnitude detection threshold and increase the ray path coverage in local earthquake tomography and seismic noise studies (Fig. 2b). The network geometry has been designed to optimally achieve the above mentioned scientific purposes, keeping a compromise between the local noise sources and the morphology of the area (presence of the Adriatic Sea and of islands only near the Croatian coast), the number of available temporary broadband stations and political boundaries.

The Swiss-AlpArray SINERGIA project covered the costs of the deployment and operation of nine temporary stations from the SEG/SED mobile seismic station pool, while a site (APRC station) in Gargano region, Italy, was upgraded from short-period to broadband sensor thanks to INGV internal funding. The AlpArray-CASE temporary network code is 8X and the station names follow the convention CAYYA, where YY stands for the number of station. The last letter is typically A, unless the station is moved, when it is replaced by B, C etc. as needed (AlpArray Seismic Network, 2015, 2016; Table 1 shows the stations loca-

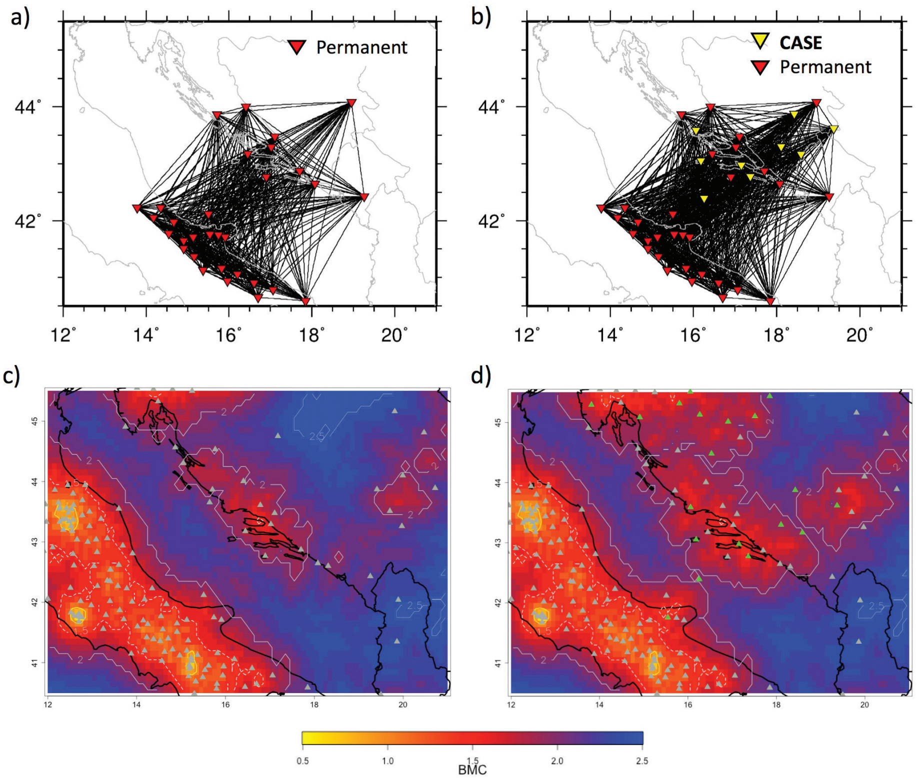

Figure 2. Theoretical ray coverage for the ambient noise tomography study without (*a*) and with (*b*) the AlpArray-CASE temporary stations. As illustrative example, we considered here only some of the surrounding permanent stations. The ray coverage greatly increases in the Central Adriatic microplate and SE Bosnia and Herzegovina. Bayesian magnitude of completeness map following Mignan et al. (2011) before (*c*) and after (*d*) the installation of the AlpArray and the AlpArray-CASE stations.

tion coordinates, operating start and expected end time together with installation site characteristics.

We determined the locations of the temporary stations following the uniform coverage rule: we took into account the already existing permanent broadband stations (owned by the Department of Geophysics with the Croatian Seismological Survey and by the Hydrometeorological Service of the Republic of Srpska), the temporary AlpArray station currently deployed (green circles in Fig. 1) and we filled the gaps with the AlpArray-CASE temporary stations (magenta circles in Fig. 1). We had to consider the limitations arising from political boundaries – also within Bosnia and Herzegovina, the accessibility of the sites (many regions are not accessible or are hardly reachable during winter season), the chance to get the permission to install a seismic station and the morphology of the dry land in the Adriatic Sea, extending from Italian coast to the Dinarides, as well as local

Table 1. List of the temporary AlpArray-CASE stations installed for the temporary experiment, with station name, coordinates, start and expected end time, type of housing and sensor (STS – Streckeisen, TC – Trillium Compact) and country of deployment. The network code is 8X (http://eida.ethz.ch/fdsnws/station/1/query?&net=8X&station=&format=text) for all stations except APRC for which it is IV (see http://www.orfeus-eu.org/stationbook/).*

Station name	Lat. [°N]	Lon. [°E]	Elev. [m]	Site name	Start time (yyyy-mm-ddThh:mm:ss)	Expected end time (yyyy-mm)	Country	Housing class	Sensor sits on	Sensor type
CA01A	43.6176	19.369	482	Rudo	2016-11-14T19:30:00	2018-09	BIH	Free-field	cement	STS-2
CA02A	43.1695	18.5854	1050	Klinje	2016-11-15T15:30:00	2018-09	BIH	Building	cement	STS-2
CA03A	43.8754	18.4239	686	Sarajevo – Grdonj	2016-11-14T19:00:00	2018-09	BIH	Building	cement	STS-2
CA04A	43.2989	18.1029	893	Nevesinje	2016-11-15T16:30:00	2018-09	BIH	Urban Free-field	cement	STS-2
CA05A	43.0537	16.1836	315	Lissa, Vis	2016-11-10T17:00:00	2018-09	HR	Urban free-field	cement	STS-2
CA06A	42.3927	16.2545	140	Palagruža	2016-12-16T17:00:00	2018-09	HR	Urban free-field	cement	STS-2
CA06B	42.3926	16.2555	144	Palagruža	2017-09-06T16:00:00	2018-09	HR	Urban free-field	cement	STS-2
CA07A	43.5905	16.0578	261	Vinovac	2016-11-12T13:00:00	2018-09	HR	Urban free-field	cement	STS-2
CA08A	42.7750	17.3627	77	National Park Mljet	2016-11-11T17:00:00	2018-09	HR	Urban free-field	cement	STS-2.5
CA09A	42.9775	17.1532	203	Orebić, Pelješac Peninsula	2016-11-11T15:00:00	2018-09	HR	Building	cement	STS-2.5
APRC	41.75738	15.5431	672	Apricena	2017-03-28T13:00:00	-	I	Urban free-field	cement	TC

noise. The distribution of the islands is not uniform in the Adriatic Sea and almost all of them are located on the eastern side, in Croatia: Palagruža Island (HR) is the only accessible island in the centre of the Adriatic and is therefore a crucial spot to collect new seismic data. Ocean Bottom Seismometer (OBS) could also have been an interesting solution to reach a uniform coverage of the region of interest. Unfortunately, at the moment, aside from the prohibitive cost, this option is not viable due to the presence of very thick sediment basins in a relatively shallow sea (~100 m depth) and because of the high fishing rate that makes the OBS deployment very risky. The coverage of the Adriatic Sea with OBS might be the target of a next temporary experiment, when with advancing developments, new technical solutions may allow a safe deployment of seismic instruments in these particular conditions.

Among the nine temporary Swiss stations, five are located in Croatia, and four in Bosnia and Herzegovina. We covered the most distant islands from the Croatian coast: Vis (CA05A), Mljet (CA08A) and Palagruža (CA06A/CA06B). Despite its crucial position in the middle of the Adriatic Sea between Italy and Croatia, continuous seismic data have never been acquired in Palagruža Island until the AlpArray-CASE project. Inland, one crucial temporary station is the station in Sarajevo (CA03A), where the instrumental seismic data acquisition started as early as 1904.

The network includes also eight permanent stations owned by the Department of Geophysics with Croatian Seismological Survey, and the data from these stations have been made available within the project. To give an idea of the improved ray coverage obtained with the final configuration of the AlpArray-CASE network, in Figs. 2a and 2b we plot the theoretical ray coverage for the ambient noise tomography study with and without the temporary stations, respectively. For such study we expect to be able to reach a horizontal resolution of 10 km × 10 km at least. We calculated the Bayesian magnitude of completeness (BMC) threshold map, following Mignan et al. (2011), for the first order estimation of the minimum possible magnitude of completeness for the network geometry without (Fig. 2c) and with stations deployed within the AlpArray and the AlpArray-CASE project (Fig. 2d). For simplicity, because we are only interested in estimating the improvement, we considered the parameters and the attenuation relation optimized for the Swiss network (Kraft et al., 2013). From Figs. 2c and 2d, we can see that the AlpArray-CASE temporary stations decrease the minimum magnitude detection level to ~ 0.5–1.5 in many areas, especially in the central Adriatic Sea and to the south and the southeast of the Bosnia and Herzegovina, allowing an improvement of the earthquake detection rate.

The AlpArray-CASE project's seismic network follows the same high-quality standards defined within the AlpArray Seismic Network deployment (see AlpArray technical strategy, www.alparray.ethz.ch/organisation/documents/), extensively described in *e.g.* Molinari et al. (2016), Fuchs et al. (2016) and Govoni et al. (2017). According to these standards, the allowed median value of the site noise-level for the noise should be 20 dB lower than the New High Noise Model (NHNM; Peterson, 1993) from 20 Hz up to 100 s, excluding the microseismic peak (5–20 s). One exception is made for the long period (20–100 s) horizontal components for which the noise level can be up to 10 dB lower than NHNM. A detail description of the AlpArray-CASE stations performances with respect to these guidelines can be found in the Section 4.

3. Site selection and station design

The site scouting was based on compromises between the available budget, manpower, political and dry-land geography. For site selection, we followed the basic principles outlined in Molinari et al. (2016) and our final site selection normally gravitated towards sites with optimal balance between all these requirements. In general, free-field vaults were not an option due to financial and time constraints. We preferred sites in small building with solid foundations outside the main villages or small towns and far away from obvious noise sources like highways, railways, industries and other anthropogenic noise sources. Furthermore, the optimal site had to be equipped with an existing power supply and a good mobile signal for data transfer. Preferably, the planned sites were to be located in sparsely-populated region except at the coast in summer season when the tourist activity is not negligible. As previously mentioned, due to the dry-land configuration four sites are located relatively close to the sea where the elevated sea noise is unavoidable. The site selection started in the office with internet search of possible sites and contacts with local authorities and/or the private owners in order to get the permission to install an instrument. Before the final installation, we always visited the potential sites (with the exception of Palagruža Island) and we performed noise measurements in order to select the less noisy location. Other criteria influencing the final site selections were also the possibility to get installation permission and safety of the location.

Our final selected sites count seven sites in small isolated one-story rarely-used buildings, one site in a monastery in Orebić (HR) and one site in the middle of a large city (Sarajevo) in a building owned by the Federal Hydrometeorological Institute of Federation of Bosnia and Herzegovina built in the early 1900s to host the first seismographs. In the Republic of Srpska (BIH), we selected three sites that already host short-period sensors owned and operated by the Republic Hydrometeorological Service.

Most of the stations are situated in the External Dinarides and placed on limestone and dolomite rocks, originating from the Adriatic Carbonate Platform with the carbonate deposits reaching up to 8 km thickness in these areas (Vlahović et al., 2005 and references therein). Two eastern stations (Sarajevo and Klinje) lie in the Internal Dinarides (Bosnian flysch zone) or just on the border between the Internal and the External Dinarides, while the most eastern-one (Rudo) lies deep in the Internal Dinarides, in the Dinaric ophiolite zone

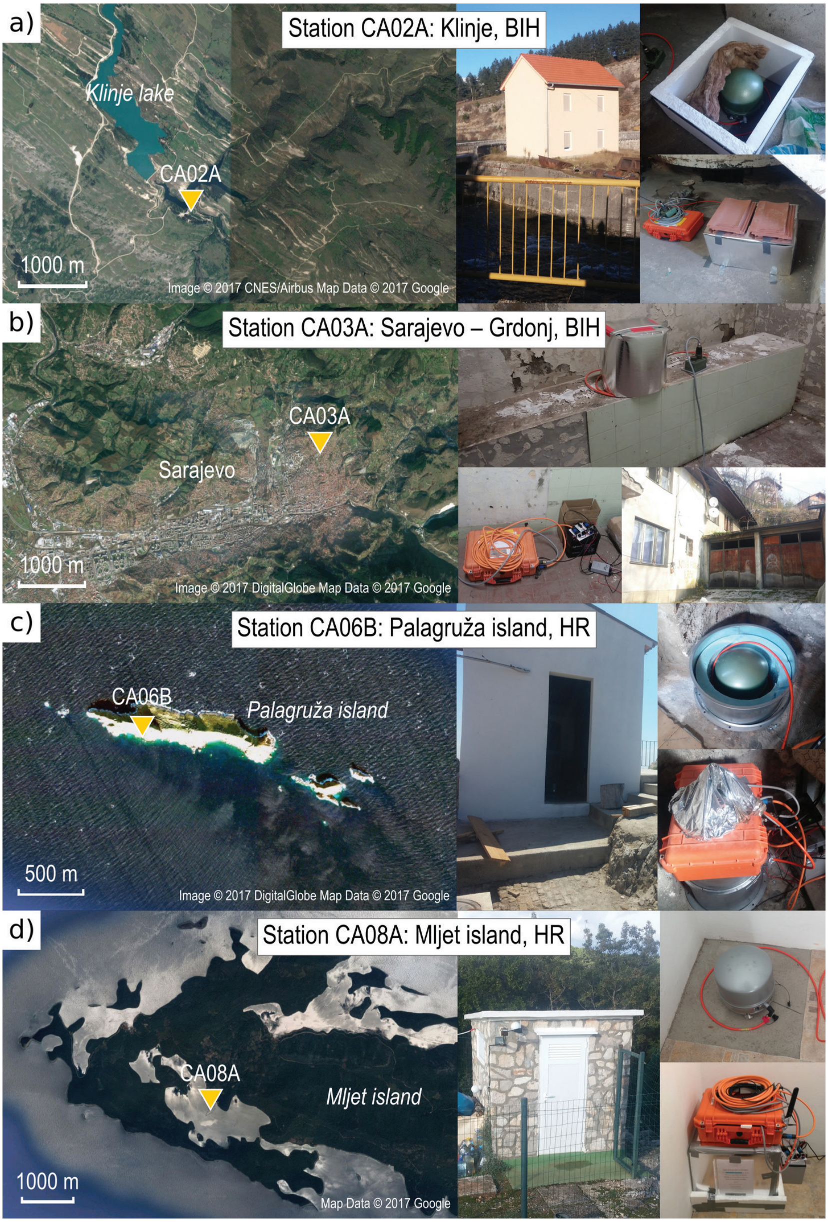

Figure 3. Examples of site location and installation configurations for four housing types (rows). Pictures to the left show the station's position on Google Earth (yellow triangles). Pictures to the right display the photographs of each installation site and the building that hosts the instruments. The stations are: (*a*) CA02A in Klinje, Bosnia and Herzegovina; (*b*) CA03A in Sarajevo, Bosnia and Herzegovina; (*c*) CA06B on Palagruža Island, Croatia; (*d*) CA08A in the Mljet National Park on Mljet Island, Croatia.

(Hrvatović, 2006). Only one station is located on the Adriatic microplate (Palagruža Island).

We have three sensor housing types in our temporary deployment (as described in Molinari et al., 2016): free-field (1), urban free-field (5) and building (3). Examples of building sites are shown in Fig. 3. An example of free-field station is the CA01A in Rudo (BiH) in which we occupied a seismic vault previously built for a short-period sensor. All the urban free-field sites are very small isolated one-story buildings (< 3 m × 3 m) with the high building's natural frequency that should be negligible at the long-period horizontal components: an example is the CA08A station in Mljet (Fig. 3d). Only one station was powered by solar panels with data transmission in quasi-real-time, while the rest have main power and transmit data in real time to the ETH EIDA node.

The AlpArray-CASE temporary station design is similar to the one adopted for the Swiss AlpArray deployment (see Molinari et al., 2016; Fig. 2). Instrumentation on the CASE temporary stations consists of a STS-2 or STS-2.5 (120 s) sensor, Taurus 3-channel 24 bit digitizer with > 141 dB dynamic range (100 sps sampling rate), GPS antenna, AnyRover mobile access router (Dual-Modem High-speed LTE and WLAN Router) for real-time data communication, mobile antenna 4G-LTE and at least 65 Ah battery. On Palagruža Island for the first ten months of operation, when power supply was not available, the station (CA06A) was powered by two solar panels with 30 W peak power, 17.6 V voltage and 1.68 A current each. All stations support real-time data stream with mobile data traffic except at the site powered by solar panel where the data is transferred daily only in a single two-hour-long time window if the mobile signal is good. As sensor thermal insulation, which is very important to avoid temperature jumps that can affect the signal quality especially of STS-2/STS2.5 sensors, we used polystyrene lining or boxes filled with mineral wool in most of the sites (see Fig. 3). All the installations are secured following the best practises for installations of broadband sensors, STS-2 in particular (*e.g.* Hutt and Ringler, 2009). The sensor orientation is determined using a compass. However, we are aware of possible errors due to unexpected local disturbance of the magnetic field, especially in buildings.

4. Installation and network performance

The installation of the nine temporary stations was performed between 10 November and 16 December 2016. The station CA06A on Palagruža Island was relocated on 6 September 2017 due to poor data quality to CA06B in a neighbouring hut next to the lighthouse on the same day. The logistic problem of access to this site (weather and sea condition mainly) and the waiting time to get the permission to install the station in the new site delayed the relocation for 5–6 months. At the time of writing, we have collected more than 14 months of data

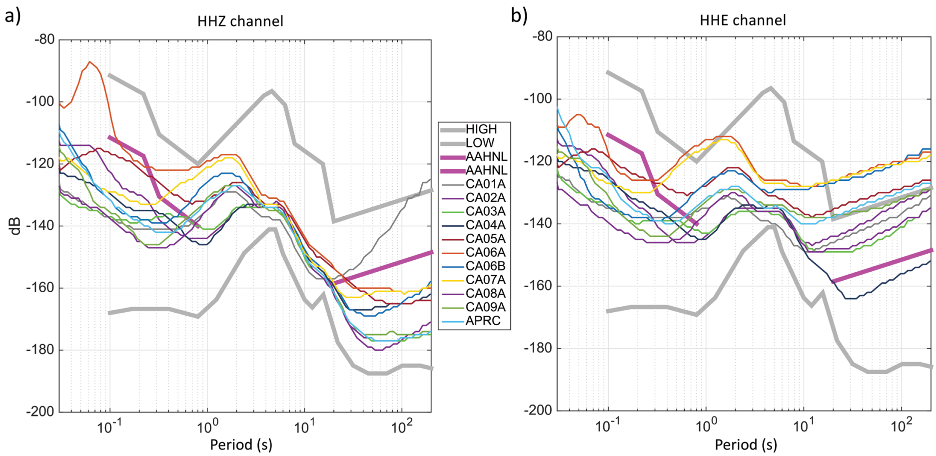

Figure 4. Median curves of the power spectral densities for the AlpArray-CASE stations during the period from November 2016 to January 2018. Each line represents a single station. The thick grey lines correspond to the NHNM and NLNM models, and the thick magenta line is the AlpArray noise level requirement. (*a*) Vertical component and (*b*) East-West horizontal component.

from all temporary stations and five months of data from the CA06B on Palagruža retrieved mainly by real-time communications.

We have calculated the distribution of seismic power spectral density (PSD) using the direct Fourier method (Cooley and Tukey, 1965), using the Obspy software package (Krischer et al., 2015) based on McNamara and Buland (2004). The probability density functions (PDFs) of the PSD are particularly important to identify the ambient noise conditions as high-probability occurrences and it is nowadays a standard tool to examine the overall station quality and the level of Earth noise at each site as well as to identify artefacts related to station operation and episodic cultural noise.

To evaluate the quality of a station, we compare the median of the PSD with the New High Noise Model (NHNM) curves (Peterson, 1993) and with the AlpArray noise requirements curves. Excluding the microseismic frequencies, the noise recorded at an AlpArray station should be 20 dB lower than the NHNM, except for the low frequency horizontal component for which the limit is 10 dB less than the NHNM.

A summary of the PSD median for the AlpArray-CASE temporary installations is shown in Fig. 4 for the vertical and E–W components. At short period (T < 1 s) all stations meet the AlpArray noise level requirements for both components. The only exception was the CA06A (the first site on Palagruža Island) that showed a very high noise level, however after its relocation, the CA06B, is now 10 dB lower that the AlpArray requirement. At long periods, the vertical components are all satisfying the requirements with a noise level from 30 to

50 dB lower than the NHNM. The long period horizontal components, however, show higher noise levels: five stations have a noise less or equal to the NHNM and only one station meets the AlpArray requirements. Long period components are highly influenced by atmospheric pressure changes and wind (*e.g.* Webb, 2002), building warping, temperature changes, and sensor-to-ground coupling. In our case, we can relate the high horizontal noise level to the site conditions and location: the noisier stations are in buildings with people walking around, especially during the summer season, on the coast by the sea and/or on narrow windy island. Storms, winds and variation in the weather are all part of the cause for the high noise level. The thermal insulation, especially for pressure and temperature changes, plays a role in these high noise levels and a more solid insulation (rather than our polystyrene box and mineral wool) might improve the performances. The installation type is similar to that described in Molinari et al. (2016) for which we have lower long-period horizontal noise. We believe that the site characteristics in our noisier stations are the main source of noise.

In the following we give a short description for each of the newly deployed temporary sites and their preliminary noise characterization.

CA01A is buried in a 2 m deep cement vault previously built to host a short period seismic sensor. The vault is located in the garden of a house at the outskirts of the small village Rudo (the Republic of Srpska, BIH). The building is used as an office during the working hours. A small river runs 500 m away from the site and the soil is mainly shallow soft river sediment. The sensor has been thermally shielded with mineral wool. The vertical component at both high and low frequency, as well as the high-frequency horizontal components, show a very good noise level meeting the AlpArray (AA) requirements, while the long-period horizontal component noise is higher than the NHNM (Fig. 5a). This is probably due to the tilts caused by cars and people walking around the vault. The thermal insulation is not optimal and might play a role in this high noise level.

CA02A is located in the basement of two-storey building, isolated in the mountain, by the artificial Lake of Klinje (the Republic of Srpska, BIH). The building is rarely used and has a concrete floor. It is situated on the Cretaceous flysch. A small river flows 20 m away and in some period of the year waterfalls are occasionally formed, increasing the high-frequency noise level at the station. Both vertical and horizontal components meet the AlpArray noise requirements (Fig. 5b), especially the vertical component which is very quiet. At high frequencies, vertical component shows two distinct zones with high probability separated by ~ 10–15 dB. The noisier one relates to the formation of the waterfalls in the river. Overall this is a particularly quiet station.

CA03A is installed in Sarajevo (BIH), on the hill to the north-east of the city in a two-storey building owned by the Federal Hydrometeorological Institute of Federation of Bosnia and Herzegovina. The building was built at the beginning of the 20th century to host the first seismographs. There is a 100 m tunnel into the hill with several cement platforms built directly on the bedrock and disconnected from the building. The soil is composed from clay, marl and sands. The

STS-2 is installed on the top of a 0.5 m wide and 3 m long platform at the tunnel entrance (Fig. 3b). We did not occupy the platforms inside the tunnel because of logistic difficulties to connect the GPS and the mobile antenna. The sensor is thermally insulated with mineral wool and a polystyrene box. The noise level is very good; however, there is room for improvement at long-period signals if we move the sensor to the end of the tunnel (Fig. 5c). This station fully meets the strict AlpArray noise requirements.

CA04A is located on the riverside of an artificial lake of Nevesinje (the Republic of Srpska, BIH) in a small one-storey building (3 m × 3 m) that hosts scientific equipment and some devices to monitor the dam. It is situated in the narrow valley on the Quaternary alluvium and limnoglacial sediments. The sensor is insulated within a 6 cm thick polystyrene box. The noise level is higher than on the other stations especially at long periods. The vertical component shows a dual behaviour, with higher noise during the daily hours (Fig. 5d). This is probably due to the traffic along the road 200 m away from the station site, the activity of the nearby dam and an insufficient thermal insulation of the sensor that could be improved.

CA05A is installed on the island of Vis (HR) in an isolated one-storey building, used as storage room, on the top of a hill overlooking the Vis harbour. The terrain is mainly Cretaceous carbonate rocks, mostly dolomites with some limestone. The sensor is placed on a cement floor, under the cardboard box with polystyrene lining. On the vertical component both high and low frequencies show low level of noise and they meet the AlpArray criteria (Fig. 5e), while the long periods on the horizontal component are noisier and exceed the NHNM. This is likely due to the site condition: the building on top of the hill is prone to the tilts due to wind and inadequate thermal insulation which makes it more sensitive to thermal changes than was designed.

CA06A/CA06B is located in the remote island of Palagruža (HR) on Jurassic dolomite, limestone and clastic rock with gypsum. The island is 1.2 km long and 0.5 km wide in the middle of the Adriatic Sea; the only buildings are the lighthouse, a 3 m × 4 m hut next to the lighthouse used periodically as a kitchen, and a very small building in westernmost side of the island that hosts scientific equipment. The latter was chosen for the first installation (CA06A) and the station was powered with solar panels. The noise level at this site is particularly curious: higher noise on the high-frequency vertical component than on the horizontal one (Fig. 5f). After many trials, we concluded that the building is the noise source that was acting as a vibrant membrane due to its specific construction. After 10 months, we moved the sensor (CA06B, Fig. 3c) to the small hut next to the lighthouse (directly built on carbonate rocks). The high-frequency noise for this new site is drastically reduced (Fig. 5g). The sensor is installed on the cement floor in a corner of the hut and insulated with a 6 cm thick polystyrene material inside a metal pot. Horizontal long-period noise level is higher than NHNM mainly due to environmental condition, wind and sea waves. Surprisingly for such a remote location, we have a quasi-real-time communication using a normal mobile phone SIM-card.

CA07A is deployed in a one-storey 10 m × 4 m building used as storage room on mainland in the remote village of Vinovac (HR), 10 m away from the narrow road. The building is built on carbonate rocks, mostly Cretaceous limestone with dolomite. The sensor is thermally insulated with a polystyrene 6 cm thick box

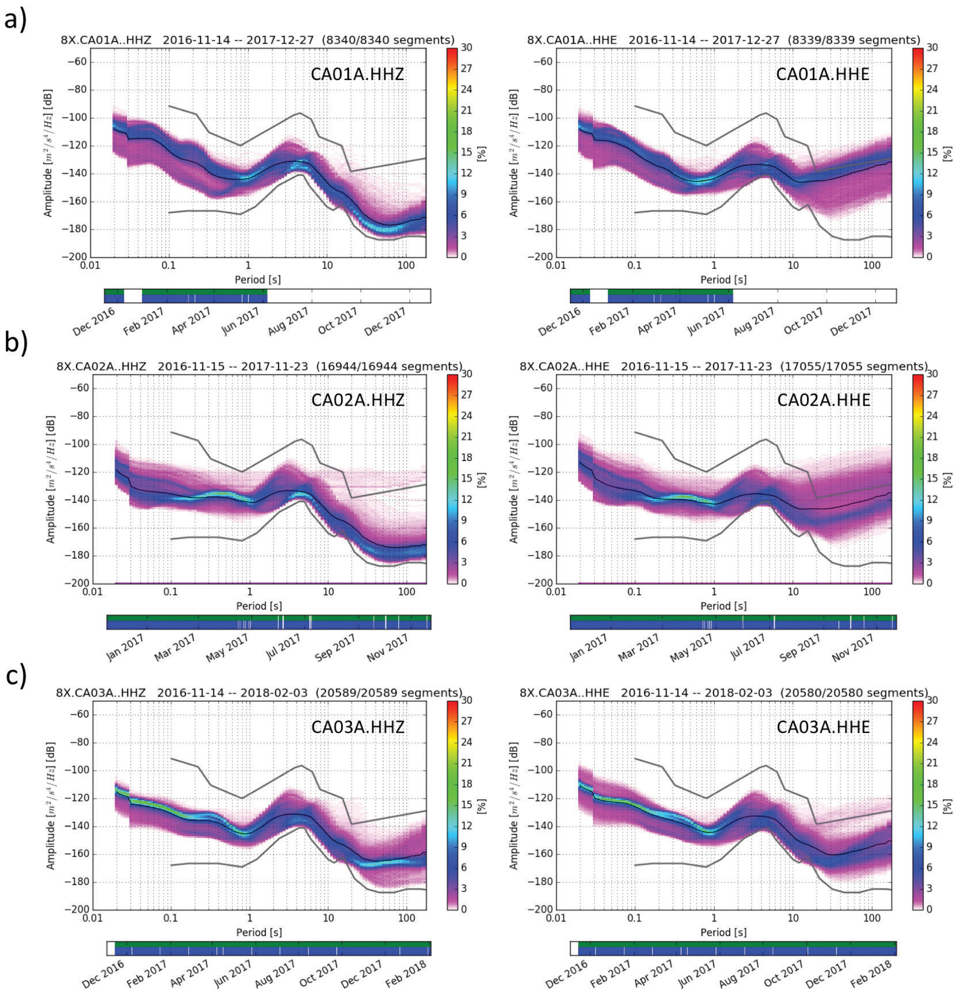

Figure 5. Probability density functions of vertical and E–W components for temporary sites in the AlpArray-CASE experiment (respectively in each sub-panel). Station (*a*) CA01A; (*b*) CA02A; (*c*) CA03A; (*d*) CA04A; (*e*) CA05A; (*f*) CA06A; (*g*) CA06B; (*h*) CA07A; (*i*) CA08A; (*l*) CA09A; (*m*) APRC. The thick grey lines correspond to the NHNM and NLNM models.

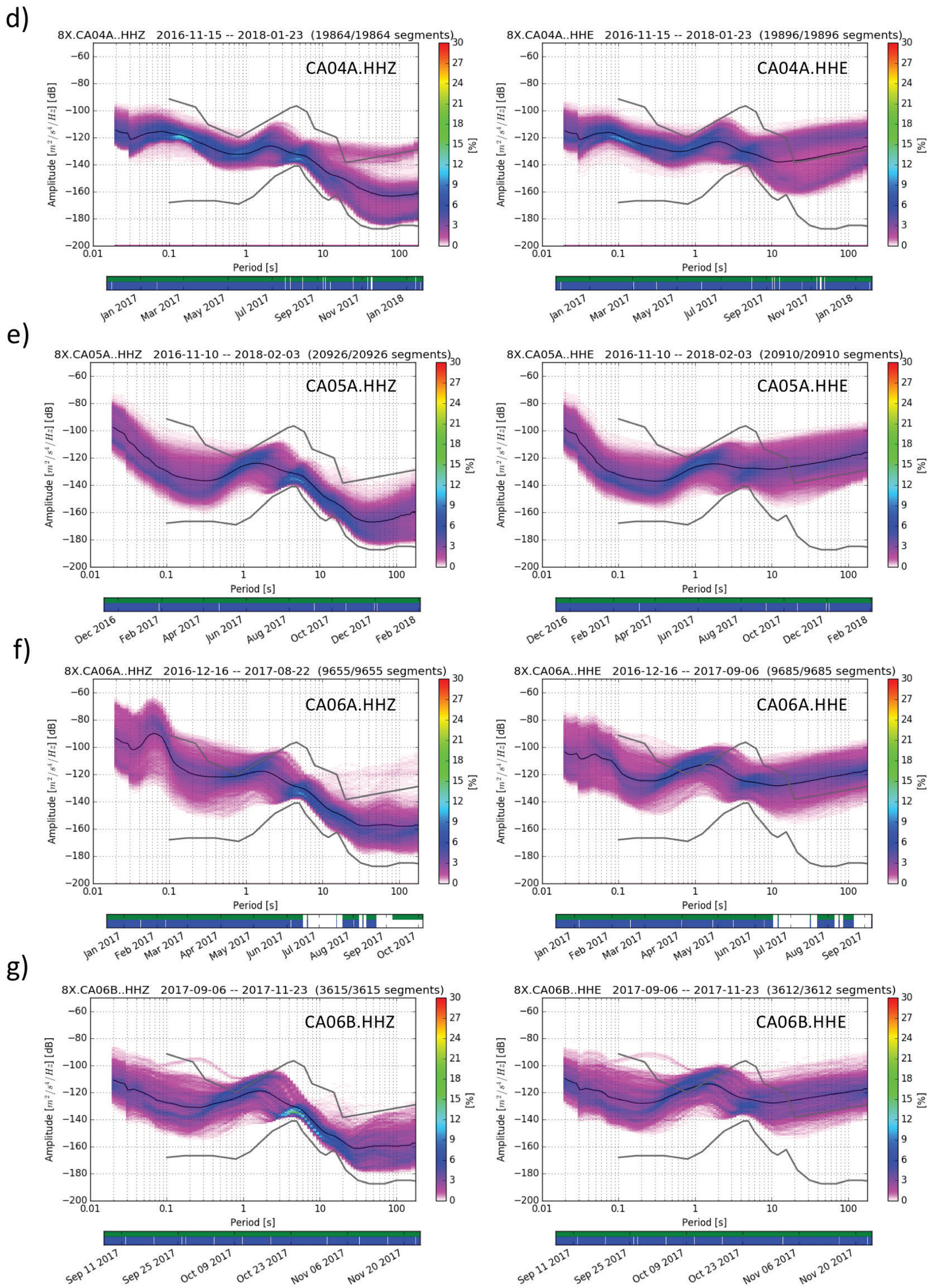

Figure 5. Continued.

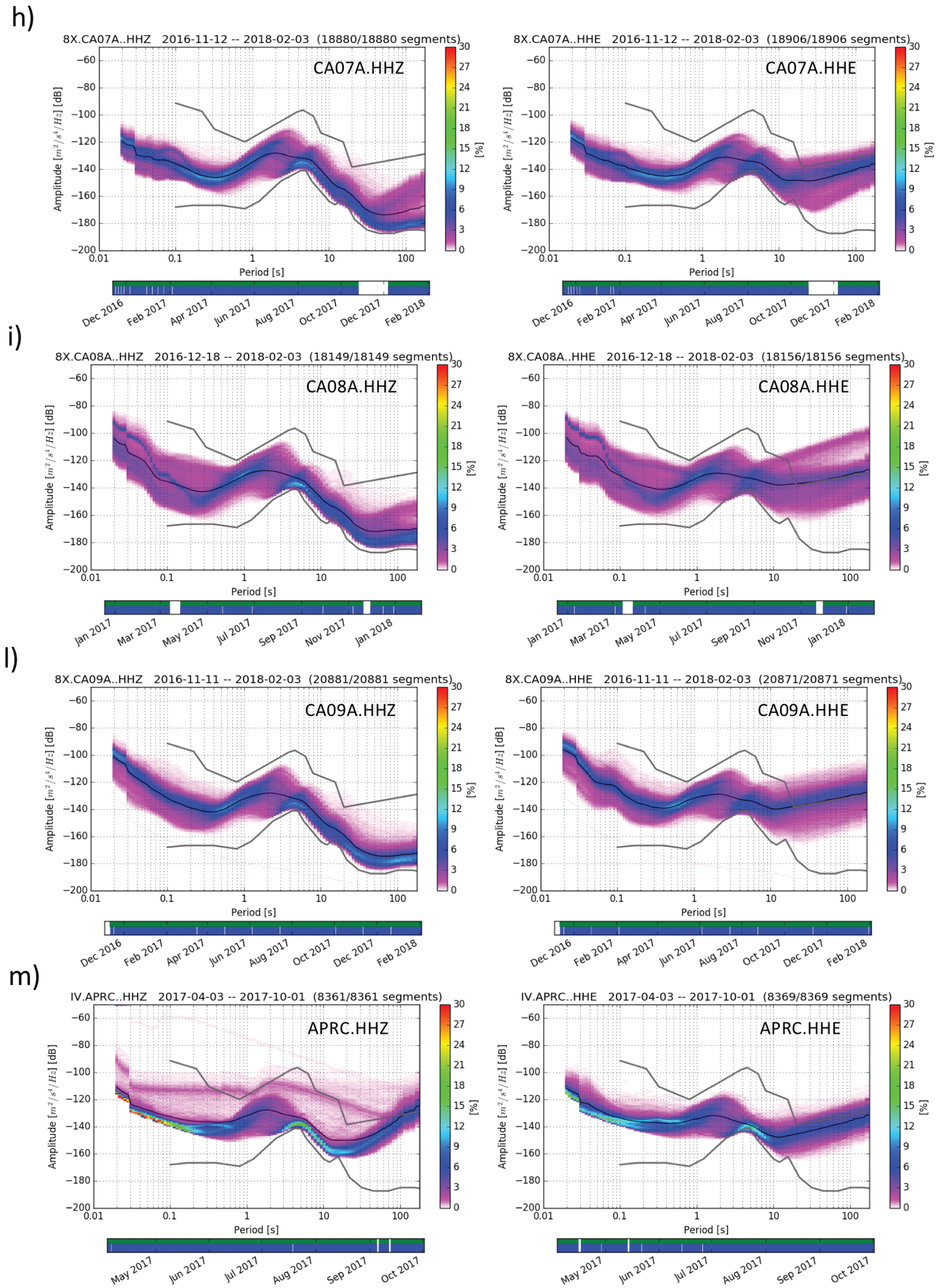

Figure 5. Continued.

wrapped with thin foam insulator with aluminium foil. The station shows low level of noise in all the broad frequency band and all components meet the AlpArray noise requirements, with exception of the horizontal long periods that are, however, lower than the NHNM (Fig. 5h).

CA08A is located in the Mljet National Park on Mljet Island (HR) in a isolated 2 m × 2 m one-storey building in a meteorological observational spot, near the north-western coast of the island, on the Jurassic dolomite rock with some limestone. A meteorological observer visits the site three times per day in order to annotate the meteorological observations which causes an increment of the short-period noise and long-period horizontal noise, but only during the visiting time. The station noise level, however, is acceptable (Fig. 5i).

CA09A is installed in Orebić on Pelješac Peninsula, in a monastery on the top of a steep hill composed by Paleogene dolomite rocks. Two monks live there all year long in the convent. The site is really quiet during winter time and at nights, but in summer time the site is often visited by tourists increasing the noise level. The effect of people walking around is clearly visible on the long-period horizontal components (Fig. 5l). For short periods and long periods at vertical component noise levels are very good and below the AlpArray requirement.

Taking into account that many sites are installed on islands where weather conditions, *e.g.* the wind and the sea waves, drastically contribute to increase the noise level, we consider our temporary installations as successful. The deployment of STS-2s as the standard seismometer for our stations facilitates the collection of best possible long-period data, especially the vertical components.

5. Data completeness, real time monitoring and integration of temporary stations in the seismological services

At the present day the nine stations are included in the daily standard reviewed event detection of the Croatian Seismological Survey (HR) and the Seismic Service of the Republic of Srpska (BIH). The stations are also available in real time for Swiss Seismological Service (SED), ETH Zurich for data quality checking although they are not used for real-time earthquake location. Parameters like GPS conditions, SOH, mass centring, voltage, bandwidth and delay are continuously monitored and archived within the SED monitoring system. The integration in the real-time monitoring is very convenient because it allows a continuous check of the data flow, the detection of station problems (power interruption due to storms, anomalous noise sources, STS-2 masses issues) and enables back-up of the recorded data (whenever the internet connection is stable enough). In Fig. 6 we show the waveforms recorded in real time by the 8X stations for a regional earthquake (M4.5, which occurred in Croatia near Split on 9 December 2016, 12:56:59.8 UTC) and a teleseism (M6.9, occurred on the 24 April 2017 at 21:38:30 UTC in Chile).

At present date, we count eight stations on-line, one off-line due to a problem with the modem, two stations with low bandwidth which do not always transmit

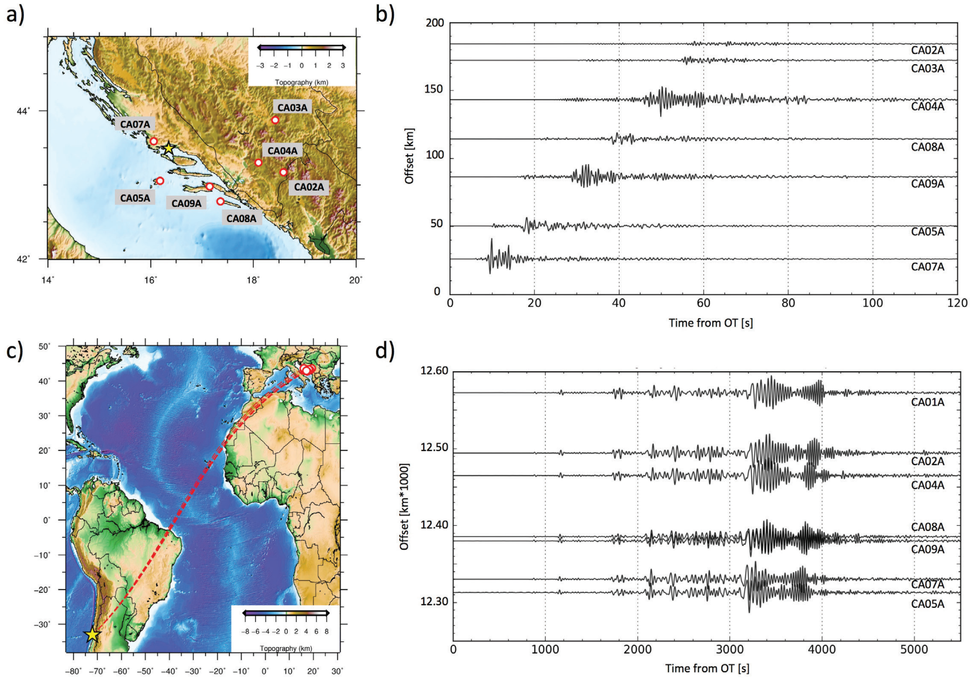

Figure 6. Examples of waveforms recorded by the AlpArray-CASE temporary stations. (*a*) Location (yellow star) of the $M_L = 4.5$ local earthquake occurred in Croatia on 9 December 2016 at 12:56:59.8 UTC and (*b*) associated waveform filtered using a bandpass filter between 0.04 and 2 Hz. (*c*) Location of $Mw = 6.9$ teleseismic event occurred on 24 April 2017 at 21:38:30 UTC in Chile and (*d*) associated waveform filtered using a bandpass filter between 0.009 Hz and 0.4 Hz.

the full seed data but only SOH information, and CA06B that strongly depends on the mobile coverage that varies over time but the connection bandwidth is in general more than acceptable. The data availability (Fig. 7) of the 8X stations is > 85% (excluding the station with low bandwidth). The gaps are constantly filled once the data are manually collected and stored in the database. Large gaps before June 2017 are unfortunately not restorable because of station operation interruptions (mainly power supply interruption).

6. Conclusion

In this paper, we described the concept and the set-up of the AlpArray-CASE project, an AlpArray complementary seismic experiment in the central Adriatic Sea and the central and the south Dinarides. Some of the fundamental questions on the evolution, the current geodynamics and the interaction of the Adriatic microplate and the Dinarides, which would significantly improve the seismic

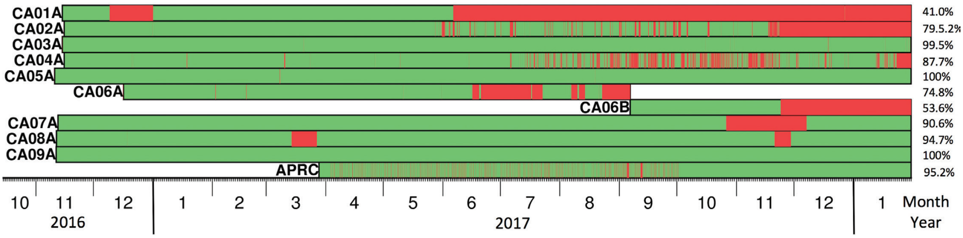

Figure 7. Data availability of the ten AlpArray-CASE temporary stations (8X) from real time communication in the time period from the installation day to the end of January 2018. The gaps are constantly filled once the data are manually collected and stored in the database. Large gaps before June 2017 at stations CA01A and CA08A are unfortunately not restorable because of station operation interruptions (mainly power supply interruption). At the day of writing, station CA01A is off-line; stations CA02A, CA04A and CA06B do not have sufficient communication bandwidth to transmit continuous mseed-files. CA06A was closed on September 2017. Intermittent gaps are mainly due to connection problem (low bandwidth) and will be filled once the data are manually retrieved.

hazard assessment in this seismically very active region, remain unanswered. In order to address these issues, recently developed methods must be applied and these demand high-quality seismic network with optimally designed network geometry. The newly established AlpArray-CASE temporary seismic network fulfils these requirements and finally allows for acquisition of high-quality data set that will be a cornerstone needed for implementation and development of the state-of-the-art methods.

We described the principles and procedures that allow for the collection of top quality seismological broadband data in a region with challenging morphological and lithological subsurface conditions, considering also environmental and political constraints. Furthermore, we showed that our temporary station performance, in general, meets the high AlpArray Seismic Network quality standards in terms of noise level (*i.e.* 20 dB lower than the NHNM for vertical components and 10 dB lower of NHNM for horizontal component), with the exception of horizontal component at low frequency (< 0.1 Hz) for stations installed on islands. Furthermore, the AlpArray-CASE network improves considerably the theoretical ray coverage for the ambient noise tomography study and that we can now expect to reach a horizontal resolution of 10 km × 10 km at least. Moreover, the calculated Bayesian magnitude of completeness threshold expected for the new network configuration indicates decrease of the threshold level for ~0.5–1.0 units of magnitude in many areas, especially in the Central Adriatic Sea and Bosnia and Herzegovina, which is a considerable improvement. The obtained results prove that our network is able to produce high-quality seismic data for the implementation of the methods (*e.g.* receiver functions, ambient noise tomography, local earthquake tomography etc.) that will image complicated crustal and lithospheric structure in the targeted area.

Data availability

Waveform data from all AlpArray-CASE stations (ten temporary and seven permanent stations from the Croatian Seismological Survey) are available through EIDA (http://www.orfeus-eu.org/eida/). Data are restricted to the AlpArray-CASE participants (http://alparray.ethz.ch/en/research/complementary--experiments/case/data-access-citation/) and will be publicly available three years after the experiment ending date. However, all AlpArray-CASE temporary stations are available in real-time for seismological observatories within the AlpArray-CASE region with monitoring and alerting duties.

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SAŽETAK

Istraživanje strukture litosfere u području srednjeg Jadrana seizmičkim eksperimentom AlpArray-CASE

Irene Molinari, Iva Dasović, Josip Stipčević, Vesna Šipka, Dejan Jarić, Edi Kissling, John Clinton, Simone Salimbeni, Snježan Prevolnik, Domenico Giardini, Stefan Wiemer, Terenski tim AlpArray-CASE i Radna skupina AlpArray-CASE

Tektonika Jadranske mikroploče nedovoljno je poznata i djelomično kontroverzna, pogotovo u dijelu gdje Jadranska mikroploča međudjeluje s Dinaridima kao donja ploča. Dok će sjeverni dio Jadranske mikroploče biti detaljno istražen u okviru međunarodne inicijative AlpArray, njezinom srednjem i južnom dijelu potrebno je detaljno istraživanje kako bi se odredila njihova struktura i evolucija. *Central Adriatic Seismic Experiment* (CASE; Seizmički eksperiment u Srednjem Jadranu) započet je kao komplementarni projekt inicijative AlpArray organizacijom privremene seizmološke mreže koja omogućuje prikupljanje seizmičkih podataka visoke kvalitete kao temelja za istraživanje pomoću suvremenih metoda i određivanja seizmičkih slika ovog kontroverznog područja. U međunarodnom projektu AlpArray-CASE sudjeluju četiri institucije: *Department of Earth Sciences* i *Swiss Seismological Service* s ETH Zürich (CH), Geofizički odsjek Prirodoslovno-matematičkog fakulteta Sveučilišta u Zagrebu (HR), Republički hidrometeorološki zavod (Republika Srpska, BIH) i *Istituto Nazionale di Geofisica e Vulcanologia* (I). Ustanovljena privremena seizmološka mreža bit će operativna najmanje 18 mjeseci. Mreža se sastoji od postojećih stalnih i privremenih seizmoloških postaja kojim upravljaju institucije uključene u projekt te novih privremenih postaja instaliranih u okviru ovog projekta. Tim novim postajama upravljaju ETH Zürich i INGV, pri čemu je pet postaja postavljeno u Hrvatskoj, četiri u Bosni i Hercegovini te jedna u Italiji. U ovom radu predstavljamo naše znanstvene ciljeve i geometriju seizmičke mreže kao i postav i svojstva novih postaja. Nove postaje pokazuju povoljnu razinu seizmičkog nemira (spektra snage signala). Novoustanovljena mreža znatno poboljšava prekrivenost područja teorijskim zrakama za tomografiju seizmičkog nemira te smanjuje prag magnitude prikazan na karti Bayesove magnitude potpunosti kataloga potresa.

Ključne riječi: AlpArray, Jadranska mikroploča, Dinaridi, litosfera, seizmološka mreža, razina seizmičkog nemira

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