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The SWATH-D seismological network in the Eastern Alps

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Abstract

The SWATH-D experiment involved the deployment of a dense temporary broadband seismic network in the Eastern Alps. Its primary purpose was enhanced seismic imaging of the crust and crust-mantle transition as well as improved constraints on local event locations and focal mechanisms in a complex part of the Alpine orogen. The study region is a key area of the Alps, where European crust in the north is juxtaposed and partially interwoven with Adriatic

crust in the south, and a significant jump in the Moho depth was observed by the 2002 TRANSALP N-S profile. Here, a flip in subduction polarity has been suggested to occur. This dense network encompasses 163 stations and complements the larger-scale sparser AlpArray seismic network. The nominal station spacing in SWATH-D is 15 km in a high alpine, yet densely populated and industrialized region. We present here the challenges resulting from operating a large broadband network under these conditions and summarize how we addressed them, including the way we planned, deployed, maintained and operated the stations in the field. Finally, we present some recommendations based on our experiences.

1- Introduction

The SWATH-D network is part of the AlpArray collaborative project, which involved 36 European institutions from 11 countries, who collectively operated a network of stations with typical 50 km inter-station spacing called the AlpArray Seismic Network (AASN, Hetényi et al., 2018a), including the permanent networks of partners but also many temporary stations. The design of the AASN is optimized for obtaining images of the plate interaction and sl~~abs~~ **slab** geometries at depth, which requires a footprint far beyond the topographic expression of the Alps. The AASN is also able to recover orogen-wide variations in crustal thickness and seismicity. However, the average station spacing in the AASN limits its resolving capability for imaging details of the collision in the crust and near the transition to the mantle and does not significantly improve the determination of absolute depths for shallow earthquakes. For example, in the Eastern Alps the N-S extent varies between about 170 and 230 km, implying only 4-6 AASN stations are placed along profiles in this region characterized by a complex internal structure (e.g. Schmid et al., 2004). One of the key areas in the Eastern Alps is the

Tauern Window, a block of European derived crustal units surrounded by African derived units only ~40 km wide in N-S direction. A much denser spatial sampling is required in order to model the 3D Moho and crustal structure. It is clear that a deployment with a much higher station density than the AASN requires focus on a smaller target area and can only cover a fraction of the total Alpine orogen.

The SWATH-D focuses on a key area of the Alps where a flip in subduction polarity from south-dipping European plate subduction has been suggested to occur primarily on the basis of prior teleseismic tomographic images at around 12° East (Lippitsch et al, 2003, Handy et al 2014), but the validity of this hypothesis is in dispute (Mitterbauer et a. 2011). In this area, a ~10 km jump in the Moho at the presumed meeting point of Adriatic and European Moho discontinuities has been observed in receiver function images constructed from the N-S TRANSALP passive profile stations (Kummerow et al, 2004), and a diffuse or absent Moho is suspected south and slightly east of the Tauern Window (Spada et al. 2013) in a region with with complex Moho topography (Brückl et al. 2010). Receiver function images from the recent EASI N-S passive profile at 13.5°E were interpreted as evidence for northward directed Adriatic plate subduction (Hetényi et al. 2018b).

The SWATH D network footprint is geared towards constraining the three-dimensional structure in this key region in the Alps and complements, with its elongation in E-W direction, the two N-S profiles TRANSALP and EASI (Figure 1). There are just a few precedents for broadband arrays of the density and footprint of the SWATH D deployment, with maybe the closest example the DANA deployment in Northern Anatolia (DANA, 2012; Poyraz et al, 2015). The high topography of the Alps and the high population density, level of industrial activity and traffic in the valleys of the Alps presented particular challenges. Therefore, we needed to develop an adaptive approach for the station mix, scouting and deployment strategy, which will be described below.

The distribution of earthquakes in the Alps is intrinsically related to plate interaction and crustal collision (see Figure 1 for a map of the SWATH-D region in the context of a coarse tectonic map). The local seismicity obtained up-to-date cannot entirely map the geometry of the local smaller structures and it appears to be no intermediate depth seismicity (International Seismological Centre, 2014). This is most likely due to large inter-station distances and unevenly distributed seismological stations of the permanent networks in the Eastern Alps. The design of the ASSN with station spacing of ca. 50 km (Hetényi et al., 2018a) had been optimized to investigate the slab geometries in the upper mantle and the variation of crustal structures on the large scale but is not suitable to reveal smaller scale features (of about 10 to 15 km size) in the Eastern Alps, including the Moho structure at the point where European and Adriatic plates meet. The station spacing in the AASN also limits the accuracy with which the absolute depths of shallow earthquakes (<~20 km deep) can be determined. Considering that most of the geological variations in the Central and Eastern Alps are taking place within a few kilometers it is necessary to locally provide a much denser network to properly image those features.

With the focus in this area, the SWATH-D experiment was developed as a dense temporary broadband seismic network in the Eastern Alps. The equipment for the SWATH-D array was provided by the Geophysical Instrument Pool Potsdam (https://www.gfz-potsdam.de/gipp) and the DSEBRA array (http://www.spp-mountainbuilding.de/research/project_reports/DSEBRA_2018.pdf). The field work was carried out by an international consortium including the Deutsches GeoForschungsZentrum (GFZ) and the Ludwig Maximilian University of Munich (LMU) in Germany, the Zentralanstalt für Meteorologie und Geodynamik (ZAMG) in Austria and the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) together with the Civil Protection Südtirol and the Civil Protection Trento in Italy.

2-.Network installation and operation

During the preparatory phase, we defined the research area by integrating the SWATH-D within the previously defined AlpArray network, with the aim to focus on the region where there ~~is~~ **are** still ongoing discussions about the features at depth that play a key role or could help to understand the tectonic evolution of the Alpine mountain belt. There was consensus on the importance of the role of the Adriatic plate as well as the Peri-Adriatic and the Giudicarie fault systems and the region of the Tauern Window, where the small scale of geological variation in the Central and Eastern Alps requires denser spatial sampling than provided by the AlpArray deployment. Other experiments in the area, like TRANSALP and EASI provided good quality data in the region but these experiments were profiles with N-S orientation and had a narrow resolution band in the E-W direction. The SWATH-D was then designed as a network to extend these observations in the E-W direction.

2.1. Scouting of the sites and stations deployment

In order to produce clear images from crust to the upper mantle a dense network of seismological stations is therefore required. This is represented by SWATH-D seismological network of 163 stations with an inter-station spacing of ca. 15 km in a region of 120 km x 315 km covering a key area of the Alpine orogeny (Figure 2). The number of stations was defined based on previous knowledge of the region and availability of instruments to be deployed in the field for approximately two years. The large number of stations and the small inter-station distance played a key role in defining not only the geometry of the network but also the logistics necessary to carry out the experiment.

The distribution of the SWATH-D stations within the study region was devised according to a number of steps that led to the final configuration of this dense network. In the first step, the area to be covered was defined, nominal station sites were derived based on an hexagonal closed packed structure, the same as AlpArray. If an AASN station was within a 5 km radius of a nominal SWATH-D site, then this site was deemed occupied and no further deployment planned.

,Q D VHFRQG VWHS µYLUWXDO VFRXWLQJ¶ ZDV SHUIRUPHG E\ FRQVLGHULQJ WKH ORFDO YD topography, accessibility and infrastructure. This was done by using standard navigation tools (for example Google Earth and Open Street maps). Nominal sites that fell in lakes, on glaciers or mountain peaks were moved to more accessible areas. In addition to modifying the site in question, nearby points were also adjusted in order to maintain the required pre-established inter-station separation in a sort of damped domino effect. Scouting of the 163 sites was made by teams that went to the field not only to find a proper place for the installation but also to contact local authorities and private landowners and distribute info-flyers that contained information about the project: a map of the stations planned, the aims of the study, characteristics of the deployment and contact information in case further explanation was needed by the local people. This helped to find a broad acceptance in the population, especially in areas that had experienced significant earthquakes in the past.

Every field team had a list of stations according to a region of scouting where they had the freedom to move the predefined point to a more accessible, more suitable point keeping in mind to respect the inter-station spacing. The teams filled a form, known as scouting sheet or protocol (see Figure S1 in the supp. material) with all relevant information from the point to be used during the deployment phase. The protocol contained information related to the location, access roads, locality, coordinates, description of the site, difficulties or problems that could arise during deployment, availability of electricity and mobile network (3G or 4G). Also the name of the owner or contact person that permitted the installation along with other contact details.

The scouting required many teams working in the field at the same time for nearly two months. They had to deal with a large number of sites per day (4-5 sites were scouted by each team), but the teams were able to operate in the field and manage the time both effectively and efficiently as the scouting was helped by the previous virtual selection of the sites performed during the preparation phase. At the same time, the scouting helped to define the logistics for the deployment phase, as all relevant information needed for the installation were collected. This scouting sheet containing all relevant information about the deployment site (see supp. Material containing all types of sheets used in the field) was entered into a form and transferred later to a digital database. The main requirement for the deployment teams was to perform a daily upload of the information contained in the field protocols to a server where all groups were able to access the updated information online from the field. This was done by using a system for files archiving, share and synchronization that was previously configured in order to manage the field operations database. Thus, the information obtained was backed up immediately by uploading scans or photos of the protocol sheets.

2.2 Deployment and Service of the stations

Following the scouting, the deployment of the instruments was planned following the information collected for each specific site. Having for example a locality with electricity and mobile cellphone network available allowed us to make use of instrumentation that would enable data transfer in real-time. The areas with no mains power or difficult access during the winter months needed a different kind of instrumentation depending on the availability of electricity and mobile network for data transfer. The type of instrumentation used according to availability of electricity and mobile data transmission can be seen in Table 1.

Once the scouting was completed, we divided the SWATH-D network into sites suitable for online stations with power supply and mobile network coverage and sites without sufficient mobile coverage or lack of available mains electricity for offline stations where the data would need to be collected periodically during the service run intervals. Before the trips started, a list of sites was elaborated and the owners were contacted by a person at the office in our central at the GFZ. This person was in charge of contacting the local persons and authorities and make appointments for the teams in the field. This helped to improve the efficiency of the field teams as they were able to go directly to the site knowing they were expected. The contact list with names and phone numbers for almost all stations was part of the information provided to the teams.

The service trips were performed mainly before and after the winter months with some visits in between, in case it was necessary. In some cases, the stations started to have trouble due to power failure as detected by the real-time monitoring system, especially following a weather event like rain and snow storms or lightning strikes affecting the local mains power lines. Other contingencies were related to special cases where the owner requested to move the station to a nearby location due to flooding or collapse of nearby rocks. For more details about the scouting, service, deployment etc., see section 5.1.

The SWATH-D stations were deployed between August and November 2017 while the AlpArray backbone stations were all running by the end of 2017 when the SWATH-D stations were fully installed and the network was running. For this reason, there is a good overlap between both datasets for at least 2 years between 2017 and 2019. For the SWATH-D network, 153 stations were provided by the Geophysical Instrument Pool Potsdam (GIPP) of the GFZ, 10 stations were provided by the German Seismological Broadband Array (DSEBRA) and installed by LMU-Munich in October 2018. The full list of 163 seismic stations from the SWATH-D deployment in the Central and Eastern Alps can be found in Heit et al. (2017) or the GEOFON link: https://geofon.gfz-potsdam.de/doi/network/ZS/2017.

2.2.1 Online stations

The online stations (Type A in Table 1) were mostly installed in protected environments such as basements or huts in private properties or little-used governmental buildings that provided a small spot of approximately 2 m^2 (see Figure 3) with mains and internet signal via mobile network. A few online stations were installed near outdoor weather stations with available power. All online stations were equipped with an Earth Data Recorder EDR-210 data logger and a TELTONIKA RUT 955 router. The data were transmitted to the server at GFZ via the cellphone module of the router and using the standard SeedLink real-time transmission protocol for seismic data (see below for details). When power supply was provided by private persons, an annual contribution was paid in compensation. In order to protect the installation against power surges in thunderstorms, frequent and violent in the high alpine regions, a standard plug-in socket adapter with 13.500 A surge protection was used at most stations, particularly when installed away from the protection of the main residence. This adapter proved to be very useful in at least five cases where direct lightning strikes caused significant damages to electrical items in the homes but did not strike our equipment.

External GPS antennas were placed outside the buildings implying in some cases the necessity of extension cables for proper installation. The sampling rate was fixed at 100 Hz. A total of 44 online stations (from a total 61) in Austria and 45 stations from a total of 100 stations were online. In total, 55 % of the SWATH-D stations were operating and transferring data in real-time.

In order to better resolve the lithospheric structure at the eastern edge of the network, 10 further stations (D154-D163) were added to extend the SWATH-D network in northeast direction (Figure 2, red triangles; type D in Table 1). These stations cover the area of the

Niedere Tauern, where small earthquakes frequently occur. LMU-Munich scouted the sites with the help of colleagues from Vienna (ZAMG) and subsequently, installed and maintained the stations. These stations were equipped with a broadband seismometer, a GPS-antenna (GA-88P) and buffered power supply (Yuasa battery, 12V, 38 Ah and battery charger CTEK MXS 5.0). While almost all DSEBRA stations were connected to a power grid, one station (D159) ran on a solar power system and was equipped with two solar panels (Kyocera KT145-3UC), two batteries (Yuasa, 12V, 65Ah) and a solar charger (SunSaver-20L) (see Figure 3). The seismometers were either buried and covered with soil or wrapped with wool and covered with a bucket to shield them from environmental influences. A mobile router (Teltonika RUT955) with an LTE-antenna (B4BE-7-27-5SP) was used to transfer the station data to LMU-Munich in real-time. The data were directly forwarded to the GFZ via SeedLink protocol and merged into the SWATH-D archive. At the end of the project, gaps in the SeedLink transmitted archive were filled from the recovered local storage media.

2.2.2. Communication and Data Transfer

At each online station a LAN connection between the data logger and the mobile router was established. Each local network has the same design to minimize configuration efforts when exchanging components. The mobile router is the default gateway. An openVPN tunnel provides access from the central server to the station. Therefore the server needs to be reachable from the internet with a public domain. All openVPN tunnels sum up to a virtual private network (VPN), which contains all mobile routers and servers (Figure 4).

For data streaming the seiscomp3 software (https://www.seiscomp.de Hanka et al., 2010) was used server side. This setup also enabled remote control of the seismic network. A copy of the data was also stored locally on the EDR-210 datalogger in order to avoid data loss due to network problem. The real-time data feeds from the online stations were made available via SeedLink protocol from the GEOFON SeedLink server to cooperating partners ZAMG and OGS, which allowed them to include these data into standard earthquake monitoring work-flows (see section 4).

2.3 Offline Stations

Locations where the site failed to provide stable internet connection or there was a lack of mains electricity were equipped with acquisition systems that could run over longer periods of time without being serviced. Sometimes, access roads were closed during the winter months and remained closed for further months due to snow avalanches blocking the accessibility to the sites. In these cases, having autonomous stations proved to be very useful. These so-called offline stations were mainly equipped with a 3C CUBE (Type B in Table 1) and Earth Data Logger (EDL-PR6- GLJLWL]HU\V 7\SH & 7KH &8%(¶V ZHUH DWWDFKHG WR D 7ULOOL &RPSDFW V DQG WKH ('/¶V WR *•UDOS-&0* ESPC (60 s) or Güralp CMG-ESP (120 s) VHLVPRPHWHUV7KH SRZHUVXSSO\ IRUWKH &8%(¶V ZDV SURYL ded only by air (Zinc/Air) batteries (PATURA 9V/200Ah) connected in series to provide 18V/200Ah (Figure 5 B). The EDL-PR6-24's recorders were attached to solar panels and gel batteries. Both kinds of instrumentation were connected to external GPS and had a sampling rate of 100 Hz.

The Zinc/Air batteries need to be well ventilated but are also known to lose effective capacity both in cold or humid conditions. During the initial deployment we buried the batteries, which were enclosed by a sturdy plastic bag, in order to insulate them from the very low surface temperatures during the winter nights and attempted to ensure adequate circulation by taking measures to secure an air pocket above the batteries, with each battery set being ventilated by two short bits of hosepipe connecting the space above the battery to the surface. However, this design did not work as well as expected, probably because the air pocket above the batteries was too small, and also because the environment in the plastic bag was too humid, leading to premature loss of power for many offline stations during the first winter season. However, for a small number of offline stations, the station siting did not allow burial of the batteries, meaning that they were exposed to low temperatures. Nevertheless, these stations were operating through the winter until the next service in spring. Based on these experiences we modified the station design (Figure 5 B-E) for the second winter season by placing the batteries inside plastic boxes (Figure 5 D) and keeping them at the surface, ensuring ventilation by with hosepipes. The air inside the box was then enough to allow a proper functioning of the batteries. The low temperatures experienced showed that the main issue we needed to pay attention to was air circulation inside the box and keeping humidity low. This design performed much better, leading to much reduced data loss for offline stations in the second winter season. The original deployment where the air batteries were placed inside plastic bags without a plastic box showed that 70 % of the stations had lost power during the first 2 months of the installation. The design with plastic boxes proved to be effective as 100 % of the stations were running well and had no power shortages between the service runs. In Figure 5 B-E the installation of the air batteries inside the plastic box with ventilation using hosepipes can be seen. We also add the step by step instructions on how to deal with this kind of air batteries (Figure S7) in the supp. material.

2.4 Data archival

The first step was to collect all the data of the online stations via a dedicated server, which then forwarded the data to both GIPP and GEOFON archives. The process for collecting the offline data needed to be organized according to seasonal variations and road accessibility. After being collected, the data was converted to standard format (mini-SEED) and integrated into the GIPP and the GEOFON archive at the GFZ. The GIPP archive has a full back-up copy of the entire raw dataset and log files from all stations, whereas the GEOFON archive stores the data in standardised formats, and provide all standard EIDA (European Integrated Data Archive) access tools, in particular FDSN web services, for convenient access to selected waveforms.

As is the practice for other complementary AlpArray experiments such as EASI and CASE, the SWATH-D data are initially embargoed. Access is initially restricted to direct national and international partners defined above (Austria - ZAMG, Italy ±OGS, all funded projects of the Priority Program SPP 4D-MB, who are given unlimited access but must declare any active or intended research project in order to allow coordination and avoid duplication of research efforts. Other national or international partners in the AlpArray consortium can request data access, which will generally be granted, if there is no conflict with the research of the PhDs and postdocs from the SPP 4D-MB. The decision on data release is made by the SPP coordinators and SWATH-D partners OGS and ZAMG in consultation with the affected projects. Following the general rules for data gathered with GIPP instruments (https://www.gfz-potsdam.de/gipp), the data will become part of the open data archive of the GIPP and the GEOFON networks four years after the end of the fieldwork, when they will be fully compliant with FAIR (Findable, Accessible, Interoperable, Reusable) principles (Wilkinson et al., 2016). Any user of the data should cite the dataset publication Heit et al. (2017).

3. Routine for data quality control

For quality check and documentation purposes, various summary figures, e.g., regarding probabilistic power spectral densities (PPSD) and the data completeness at each seismic station have been calculated within a toolbox developed at GEOFON.

3.1. Data Completeness

The full dataset from the SWATH-D network is stored at the GEOFON server and accessible by web-service. Data from the two and a half year deployment (between July 2017 and November 2019) can be incomplete due to discontinuous station maintenance during the winter time or due to discontinuous power supply related mainly to heavy rain and extreme weather episodes (i.e. batteries were not recharged) in the case of online stations. In the case of offline stations, missing data is related mainly due to seasonal effects (i.e. snow blocking the access roads, water affecting the batteries or lightning impacting the station). With the exception of several offline stations during the first winter (see section 2.3), most of the stations have a very good performance as can be seen on the output of the Obspy scan function presented as Supplementary Information where the performance of the station is indicated in percentage under the station code. The scan covers the entire time span for all stations and the plot summarizes it all in one overview plot (Figure S2 and the link containing the plot for all stations). To visualize the stations having significant problems and/or large data gaps we present a summarized plot containing only these problematic stations in Figure 6.

3.2 Seismometer misorientations

Some of the stations were installed in cellars or storage rooms that made a proper orientation of the seismometer with a magnetic compass difficult, as it is common for metal parts in buildings to bias in the magnetic north direction. Therefore, we used a fiber-optic gyrocompass (iXBlue Octans) which helps to accurately orientate geophysical sensors. The gyrocompass has an accuracy of 0.1° and proved to be very helpful in many situations where a proper orientation with a magnetic compass was not possible. However, station types A-C were usually installed by several teams working in parallel, and we only had one gyrocompass available, leading to a mixture of stations oriented with the gyrocompass and with a magnetic compass. After a sufficient amount of data, approximately one year had been recorded and archived a modified version of the python based routine by Petersen et al. (2019) has been used for checking the orientations.

This routine is calculating the cross-correlation of the vertical and radial waveforms of teleseismic Rayleigh waves recorded at the SWATH-D seismic stations to detect any deviation of the motion with respect to the Great Circle Path (GCP) direction. 45 teleseismic events with magnitude greater than 6.5 Mw have been selected, with a good distribution in distance and backazimuth. The events considered have been already located and the horizontal components N-E are rotated to the R-T system. The Rayleigh wave motion is expected to be confined in the radial ±vertical plane. Energy on the transverse component at the theoretical arrival time of Rayleigh waves might be interpreted as the result of anisotropy and heterogeneity beneath the stations and along the ray path as well as related to station misorientation. Processing earthquake data with a good distribution in backazimuth and distance allows to discriminate the station misorientation as source of off-GCP path propagation of the observed Rayleigh waves. Figure 7 shows the determined misorientations for those stations with data from more than 5 events. Station D125 shows a misorientation of 180°, which is clearly related to a mistake at installation time. The estimated misorientation was later confirmed in the field during the service trip with the gyrocompass which proved to be an invaluable tool for the assessment of the work performed during the deployment. The correction was only applied in the dataset and HHZ, HHN, and HHE were renamed to HHZ, HH1, and HH2 in the GEOFON database, respectively, and the actual correction noted in the metadata.

A total of 3 stations with misorientation greater than 20° respect to the North and associated uncertainty of less than 10° have been identified by AutostatsQ and confirmed by an additional check of the gyrocompass. The following stations were flagged as having large misorientations by the Rayleigh wave polarisation analysis: D001 (+27°), D116 (-35°) and D125 (180°) measured clockwise in degrees from the North. The metadata of the corresponding stations have been updated according to the measured angles.

3.3 The digital station-book

The installation was documented during the deployment using a form similar to the one used during the scouting where all relevant information are cataloged (see supporting information). Photos of the forms were uploaded to a shared folder in a file sync and backup utility, usually on the same day as the installation. Once the fieldwork was finalized all the information was then uploaded in a digital station-book, a database containing all the additional information about each station (Figure 8). The Station-book was a fundamental tool to check all the details and keep track of modifications made during service visits. Successive visits and services performed at the stations are recorded and can be visualized in a way that all relevant information is displayed. This includes deployment dates and details, dates of visit and service, operators, changes made and replacements performed on site as well as recommendations for the next visit or description of unforeseen problems encountered on the way to the station, but also basic information about the environment (e.g free-field vs in-building, obvious noise sources in the surroundings), in which the stations were deployed.

3.4. Noise analysis

The noise levels encountered by all SWATH-D stations are shown as median curves of the noise probability density functions in Figure 10. Even though the tighter station spacing compared to the AASN implies that there is less flexibility in siting stations and more compromises have to be made with respect to the achievable noise levels, we compare the noise at SWATH-D stations with the maximum noise requirements for AlpArray, which are set to be at 20 dB below the Peterson et al (1993) New High Noise Model (NHNM) for the vertical components and short period horizontal components, and 10 dB below the NHNM for long period horizontal component data (e.g. Fuchs et al., 2016, Molinari et al., 2016). The PDF is the ensemble of PPSD curves and represents the relative density of color coded PPSD values (McNamara & Buland, 2004). The PDFs for all stations is shown in the supplemental material (see Figure S3 and the link to all PPSDs). A map view of the median noise at each station of the SWATH-D network color-coded according to the requirements for the AlpArray noise requirements can be seen in Figure 11.

Anthropogenic induced noise tends to be lower at most offline stations, since sites are preferentially located in areas with little population and usually far away from roads or other type infrastructures. Due to the small inter-station spacing and the configuration of the network some stations, particularly those near houses or at basements in buildings are affected by high frequency signals.

For the vertical components, the majority of stations fulfill the AlpArray noise requirements between 50 Hz and 100 s (e.g., 87% at 30s, and 88% at 0.5 s). At long periods, the noise levels at most stations appear to be dominated by instrumental noise, leading to much better performance of type D (DSEBRA) stations, as they were the only stations to utilise true broadband instruments We note that for the primary science targets of the SWATH-D experiments periods less than 20 s are most relevant, for which all station types showed similar performance.

For the horizontal components, at short periods the horizontal component noise levels are similar to or only slightly higher than those of the vertical components and the majority of stations hit the AlpArray noise targets (80% at 0.5 s), but at longer period the noise levels at nearly all stations exceed those requirements (with only ~25% of stations hitting the target at 30 s), with a significant fraction of stations even exceeding the Peterson NHNM. All station types show a very similar average performance, although the distribution within each group spans a wide range of ~25-30 dB. The poor performance of horizontal components in temporary stations is usually attributed to thermal and tilt noise, which is hard to avoid in the types of installations feasible for high density temporary station deployments, which need to deploy stations in existing structures or use shallow burial for installation.

4. SWATH-D data use in routine seismic analysis: Examples from ZAMG

One of the aims of the SWATH-D network was to improve the location of smaller earthquakes that are sometimes missing in the regional networks due to larger inter-station distances. The data recorded by SWATH-D was used by regional networks in Austria and Italy to improve the completeness of their catalogues. The ZAMG in Austria provides a 24/7 monitoring and analytical service to the Austrian national and provincial Civil Protection authorities, the public and media for possible damages and impacts caused by earthquakes. Through the international data exchange, the data of more than one hundred seismic stations are processed in real-time for issuing automatic alerts. The ZAMG also assists the Civil Protection of Bolzano in the operation of the seismic network of the Autonomous Province of Bolzano - South Tyrol in Italy and provides a 24/7 on call duty service.

During the SWATH-D experiment, a number of earthquakes occurred at Fulpmes, Tyrol (Austria) and were recorded by both the SWATH-D and the ZAMG networks. For the main shock with a magnitude of Ml=3.9 on November 3 rd, 2017, ZAMG provided advice to the civil protection as the strong ground shaking attracted considerable public interest. The ZAMG obtained more than 5700 felt reports and assigned an epicentral intensity of degree V (EMS-98). Slight non-structural damage (hair-line cracks, fall of small pieces of plaster) occurred in a few buildings. Figure 12 shows the recordings of the main shock and the solution for the source mechanism. SWATH-D stations were used to validate the automatic location and to manually constrain the focal depth. The latter is essential for rapid determination of areas with the highest intensities and the probable impacts (e.g. generation of Shake-Maps). For locating events during manual review, the Antelope module dblocsat2 (Bratt & Bache, 1988) with a standard 1D-model (IASPEI, 1991) was used. Picks from 100 P- and S-wave arrivals were identified for the location of the main event, whereas 160 arrivals in total have been associated. Among the 100 arrivals, there were 51 SWATH-D arrivals used to improve the location accuracy.

The source mechanism of the main shock was determined by manual analysis of the first P-arrival polarities, as well as SV to P amplitude ratios. In total, 64 stations were used for the final solution, among them 31 from the SWATH-D network. The software FocMec (Snoke, 2003) was used to calculate the focal mechanism and FPS (Reiter & Lenhardt, 2006; 2017) as a graphical interface. The main shock ruptured as an oblique reverse-faulting with strike slip component on either a plane with strike 205°, dip 47° and rake 29°, or on the equivalent plane with 94° strike, 69° dip and 134° rake.

The seismicity recorded during the AlpArray and SWATH-D experiments as detected by routine seismic analysis at ZAMG is shown in Figure 13. Regions with high seismicity are located near west of the Giudicarie Fault and north of the Insubric Line, along the Inntal Fault and Telfs Fault, along the Mur-Mürz Fault and the Vienna Basin Transfer Fault, at the northern margin of the Lavantal Fault as well as in central Friuli, while regions with low seismicity are found around east of the Giudicarie Fault, east of the Lavantal Fault and south of the Mur-Mürz Fault as well as in the Tauern Window. There is an alignment of earthquakes along the Pustertal-Gailtal Fault. The Fulpmes earthquake described above is close to the Telf Tranverse Fault and the Brenner Fault in the northern edge of the SWATH-D network.

5. Conclusions

We have described the aims and details of the seismological SWATH-D project. The data produced within the frame of this experiment will help to shed light on the intraplate interaction in the eastern Alpine Region more precisely in the area known as the Tauern Window. First results by Mroczek et al. (2020) show a much clearer image of the European and Adria plates, Hofmann et al. (2020) are able to detect minute earthquakes using waveform and template-matching based methods and Jozi-Najafabadi et al. (2019) present new high resolution images of the crustal structure. More results from other groups are starting to be presented. The SWATH-D experiment operated for more than two years and provides a unique data set to the scientific community that will help to improve the completeness of earthquake catalogs and earthquake location and will enhance the resolution of structural models from the Alpine lithosphere. Data from this experiment is at this stage only available for partners (mainly PhD students) but will be open to the scientific community at the end of the embargo period in 2023. The stations from this network contributed data to the local and regional permanent network of earthquake monitoring systems that continuously monitor earthquakes and other seismic disturbances in one of the most seismic active areas in Europe as in the case of ZAMG in Austria and OGS in Italy.

There was a significant technical improvement compared to other temporary deployments performed with GIPP instrumentation in the past as we were able for the first time to put nearly half of the network online for data transmission. This is very helpful as part of the network is operated on real time modus and can be used to improve the location of local earthquakes as was done by ZAMG using data from the SWATH-D but also because it enables monitoring the status of the instruments and the state of health of the network in general. It also allows the immediate use of the data in the different studies. This was particularly useful following extreme climatic events where power lines and communications were affected. By identifying the stations that went offline after such a weather event we were able to move quickly in order to bring them back online and replace damaged instrumentation. The set-up is now being reused in ongoing experiments where site access is difficult, e.g. for an experiment currently being conducted by GFZ in northern Myanmar (Witze, 2019).

By using low-power instruments such as the CUBE recorders and Trillium Compact sensors we were able to install and run stations in areas without electricity, very little sunshine or with large amounts of snow during the winter. By operating many of the stations on a real-time basis we have been able to operate a big seismic network and reduce the costs of service trips Finally, as we interacted with many institutions and colleagues from the region, this achievement must be regarded as a collaborative effort between scientists, technicians, local people and regional authorities that made this experiment successful. Six field teams of 2-3 persons took part during the scouting and the deployment phase (23 persons in total) working between 1-2 weeks and alternating with new participants joining in between. There was an overlap planned for each team with at least one member always remaining in the field. This member of the team was responsible of keeping the standards at the same level and introducing the new team member to the the operations in the field. Each team drove within 2-3 weeks between 4.000 and 5000 km, with some teams reaching 10.000 kilometers during the deployment phase. During the service runs, teams of two operated in the field with nearly 8.000 km driven including departure and return to Potsdam in Germany. During the project duration it is estimated that 180.000 km were driven by all the teams together. A group of at least 10 people operated as support teams in Germany, Italy and Austria and were always available to support the teams in the field by making phone calls or preparing equipment to be replaced.

5.1 Final Recommendations

We divided the work in four steps that involve in each case different levels of work and give some recommendations for each one of them: 1) Scouting 2) Deployment 3) Service and 4) Dismantling

5.1.1 Scouting

Before starting with the scouting it is necessary to properly define the region and collect all information available in order to simplify the traveling during the field recognition (access roads, maps, phone numbers and addresses from local and regional authorities, etc.). As online maps (such as openstreet, google maps, google-earth, etc.) have exponentially developed over the last years, it is of great help to make use of them as this can help in recognizing difficulties in terms of accessibility and even give hints about the infrastructure in the area of future deployment. Pre-scouting the area with the help of such online mapping tools makes the pre-selection of potential sites easier and could be helpful when trying to evaluate the sources of noise in advance.

When all the sites have been defined or pre-selected, it is helpful to hand out all information available to the scouting teams that will be doing the field scouting, the teams should use this opportunity to talk to locals and inform local authorities about the aims of the project. A couple of info-flyers with clear and useful information containing a short description in plain language with some pictures of a similar deployed instrument can make things easy to understand and avoid misunderstandings. It is always advisable to remark that the project has scientific purposes and let the people know if there is any socially relevant information that can be acquired during the investigation (e.g. earthquake data would be of public use, etc).

The crews in the field should operate in teams of two or three max. persons and have well defined tasks for each day. Materials and tools for the field as well as handheld GPS, batteries, camera, etc. should be part of the equipment list, although this has nowadays become largely obsolete with the use of mobile phones. The OpenStreetMap app for mobile phones turned out to be very useful (OSMand on Android), as it provides offline map access, important in valleys where mobile reception can be poor, and makes it easy to upload the coordinates of scouted sites as map markers; in addition the detail of mapping information sometimes exceeds that of commercial online navigation aids. The teams should fill the form for scouting or scouting protocol immediately and write down all the information gathered for each site. An example of our scouting sheet can be found in Figure S1. This Scouting Sheet or protocol needs to be adapted to your own experiment according to the kind of equipment you plan to install.

5.1.2 Deployment

The deployment was done in teams of two or three persons. The crews had the chance to be trained on-site as the deployment was always done with at least one member of the team having experience in the installation of the different instruments. The number of installations per team/day was therefore optimized by reducing the distance and traveling time between stations. Every crew needed to fill up the deployment form (see Figure S4) in order to keep record of the details related to the installation. By keeping the teams closely together they were able to support each other during the fieldwork in case of unforeseen problems. We operated in the field following the rules to guarantee the health, the safety during the work and protecting the environment. Regarding hazard/safety it was particularly important that the teams in the field reminded of the dangers it implies driving long hours in unconsolidated roads and to reduce the amount of off-road driving. In the Alps it is important to pay attention to sudden weather changes and to have proper clothing always available (raincoat, hats or caps, sun screen, sunglasses, working shoes, etc.). Having a first aid kit and contact numbers of other teams in the near as well as knowing the evacuation ways were also part of the safety recommendations provided to the teams.

5.1.3 Service

Regular service runs were of course essential to keep the stations running, especially the offline stations that needed battery replacement and data collection. The service runs were scheduled before and after the winter months as many of the roads were closed for longer periods of time. The service always involved visiting all offline stations plus some online stations that were having troubles. The service routine was sometimes affected by road closures following the winter and a few stations remained for longer periods without battery replacement and/or data collection. Therefore it is always advisable to find an alternative site that is easier to reach all year round. It is always better to contact Landowners before servicing the stations and check accessibility. The list of material needed like voltmeter, batteries, navigation device, and above all it is important to review the previous protocols, either deployment or previous service trips. A copy of our service sheet (Figure S5) can be seen in the supplementary.

5.1.4 Dismantling

The dismantle operation involved many crews working in parallel to collect all stations and the materials from the site. This was done following the instructions and filling the dismantle form (see Figure S6). The procedure was to check and download data to a backup external hard drive and remove all parts of the installation in order to leave no traces of the station on the ground. Many stations operated in areas of national parks and nature reserves, so that leaving no trace was considered of high importance. As in the case of the deployment, it is advisable to contact all partners and local landowners and authorities to inform them about the end of the project. It is always prudent to backup all the data collected before shipping the equipment back to the instrument pool.

Data and Resources

The equipment for the SWATH-D array was provided by the Geophysical Instrument Pool Potsdam (GIPP of the GFZ grant number 201717) (https://www.gfz-potsdam.de/gipp) and DSEBRA (http://www.spp-mountainbuilding.de/research/project_reports/DSEBRA_2018.pdf). Seismic data were collected by the SWATH-D team (GFZ-Potsdam and LMU, Heit et al., 2017, doi:10.14470/MF7562601148). The field work was carried out by an international consortium including the Deutsches GeoForschungsZentrum (GFZ) and the Ludwig Maximilian University of Munich (LMU) in Germany, the Zentralanstalt für Meteorologie und Geodynamik (ZAMG) in Austria and the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) together with the Civil Protection Südtirol and the Civil Protection Trento in Italy. Data are curated and distributed by the GEOFON Data Centre, embargoed until 08.2023 and afterwards available under CC-BY 4.0 License. Data were processed by AutoStatsQ (modified after Petersen et al. 2019) and figures prepared using Generic Mapping Tools (GMTs).

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Tables

Table 1: Instruments type according to availability of mains, mobile data transmission. (*) Online stations type A and D were equipped with Teltonika router (+3.5 W)

Datalogger	Sensor	Power Consumption in Watt (datalogger+sensor)	Mains Electricity	Mobile Data Transmission	Solar Panel	Instrument Type
EDR-210	Güralp 3ESPC 60s	(1.2 W+0.75 W)	X	X	-	A*
CUBE	Trillium Compact 120s	(0.13 W + 0.13 W)	X	X	-	B
EDL-PR6-24	Güralp 3ESPC or ESP 60/120s	(2 W + 0.75 W)	-	-	X	C
Centaur 24-bit	Trillium Horizon, 120s	(0.85 W+0.23 W)	X	X	-	D*

Figure Captions

Figure 1: Generalized tectonic map of the Alps with the Tauern Window in the center. The area of the SWATH-D experiment is highlighted as a red rectangle. The AlpArray backbone network consisting of permanent national stations contributing to AASN (red inverted triangles) and the AASN temporary stations are shown as orange circles. The green line is the transect from the TRANSALP project involving active and passive seismic stations (TRANSALP 2002, 2006; e.g. Lüschen et al. 2004). The blue rectangle indicates the location of the EASI experiment (Hetényi et al. 2018b).

Figure 2: The distribution of stations of the SWATH-D network in the context of Alpine topography. Light blue triangles are real-time stations. Red triangles are SWATH-D real-time stations managed by LMU. Dark blue triangles are offline stations. The station spacing within the network is 12 to 15 km. The AlpArray backbone stations are plotted here as reference (orange circles). The break in the topography color scale from greenish to brownish colors highlights the 800 m contour, which delineates approximately the main Alpine ranges.

Figure 3: Typical installation of a real-time station in a basement. Top left: the green box encloses the datalogger (EDR-210) and the router. The logger is, connected via the white cable with the Güralp seismometer, which is placed below an upturned bucket covered with silver insulation cover (in the background). On the wall the automatic charger (output 12V/DC, 5A) controls the trickle charge to the battery. GPS cable connection to the antenna placed outside of the building and two communication antennas from the router for mobile connection are fixed to the wall. Top right: The EDR-210 unit inside the green box on the left

compartment plus the battery on the right. The box lid has the Teltonika router and a controller attached to it with connection cables. The blue LAN cable is the connection to a portable PC during service check. The white cable is the connection between the datalogger and the router. Bottom left: Installation of a DSEBRA station, the box is equipped with 2 batteries (Yuasa, 12 V, 65 Ah), a solar charger (SunSaver-20L), a data logger (Nanometrics Centaur) and a mobile router (Teltonika RUT955). Bottom right: Alignment and Shielding of a Seismometer (Nanometrics Trillium Horizon, 120s).

Figure 4: Diagram showing the communication between the different stations via VPN to the GFZ data center (DMZ).

Figure 5: A) Deployment of an offline station (CUBE+Trillium Compact) with sensor oriented to the north. The seismometer is connected to the recorder unit (Cube in the green box) and the batteries (orange bag). B): Two Zinc/air batteries are connected in serie (18V) with . C): The batteries are attached to a hosepipe for ventilation purposes. D): The batteries are stored in a plastic box. E): Final step, the box containing the batteries is covered with a orange plastic bag to protect it from water intrusion and the hosepipe and power cable are properly fixed with duct tape and zip ties.

Figure 6: Uptime for a selected group of 15 stations that showed severe problems between August 2017 and October 2019 (see text for more details). D122 shows no data after December 2017 as it was affected by a snow avalanche and re-installed in July 2018 a few hundred meters away from the original site as D122A. Red: are data gaps Blue: data overlaps.

Figure 7: Sensor misorientations in the SWATH-D network as estimated by AutoStatsQ (modified after Petersen et al. 2019) based on the Rayleigh wave polarisation. Red arrows indicate misorientations greater than 20°. The length of the arrow is scaled by the amount of available data and measurements for stations with less than 5 events are not shown. The selected teleseismic waveforms have been filtered between 0.03 and 0.1 Hz.

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Figure 9: Median curves of the power spectral densities for the entire SWATH-D for HHZ (Top) and HHE (Bottom). The noise levels for HHN are nearly identical to the East component and are therefore not shown. Each line on the graphic is one station according to type of instrumentation. A: EDR+Güralp 60sec, B: CUBE+Trillium Compact 120sec, C: EDL+Güralp 60/120sec. D: DSEBRA Stations. Dashed colored lines are the medians over all stations of the respective instrument type. The dotted black lines show the AlpArray noise level requirements. The thicker black lines indicate the new global high and low noise models (Peterson, 1993).

Figure 10: Map views of the median noise of the SWATH-D network on the horizontal components (Z component, upper panels and E component lower panels) for the short period (0.5 s, left panels) and long period (30 s, right panels) bands. Green: station fulfills requirements for the AlpArray maximum noise requirement for the respective band. Yellow to red: station noise above the acceptance level.

Figure 11: Recordings for the Fulpmes Earthquake (Ml=3.9) on November 3rd 2017 used in the routine seismic analysis at ZAMG. The seismograms were high-pass filtered (> 1 Hz) and show P-wave arrivals on the vertical component. The inset presents the source mechanism of the main shock based on the manual analysis of the first P-arrivals, as well as polarities and SV to P amplitude ratios. SWATH-D stations that contributed to the final solution are shown as white and blue rectangles (dilatation, compression) in the graph.

Figure 12: Seismicity recorded during the AlpArray and SWATH-D experiment (2016 ±2019) based on routine seismic analysis at ZAMG. Tectonic lines are based on the results from Decker et al., 2005; Schmid et al., 2004; Hintersberger et al., 2017; and Reiter et al., 2018. Major faults labelled: IL..Insubric Line, GF..Giudicarie Fault, TF..Telfs Transverse Fault, BF..Brenner Fault, IF..Inntal Fault, KF..Katschberg Fault, PGF..Pustertal-Gailtal Fault, LF..Lavantal Fault, SEMP..Salzachtal-Ennstal-Mariazell-Puchberg, MM..Mur-Mürz Fault, VBF..Vienna Basin Transfer Fault, NAT..North Alpine Thrust Fault. The area of SWATH-D is highlighted with the red rectangle. Red star: Fulpmes Earthquake (Ml=3.9) on November 3rd 2017.

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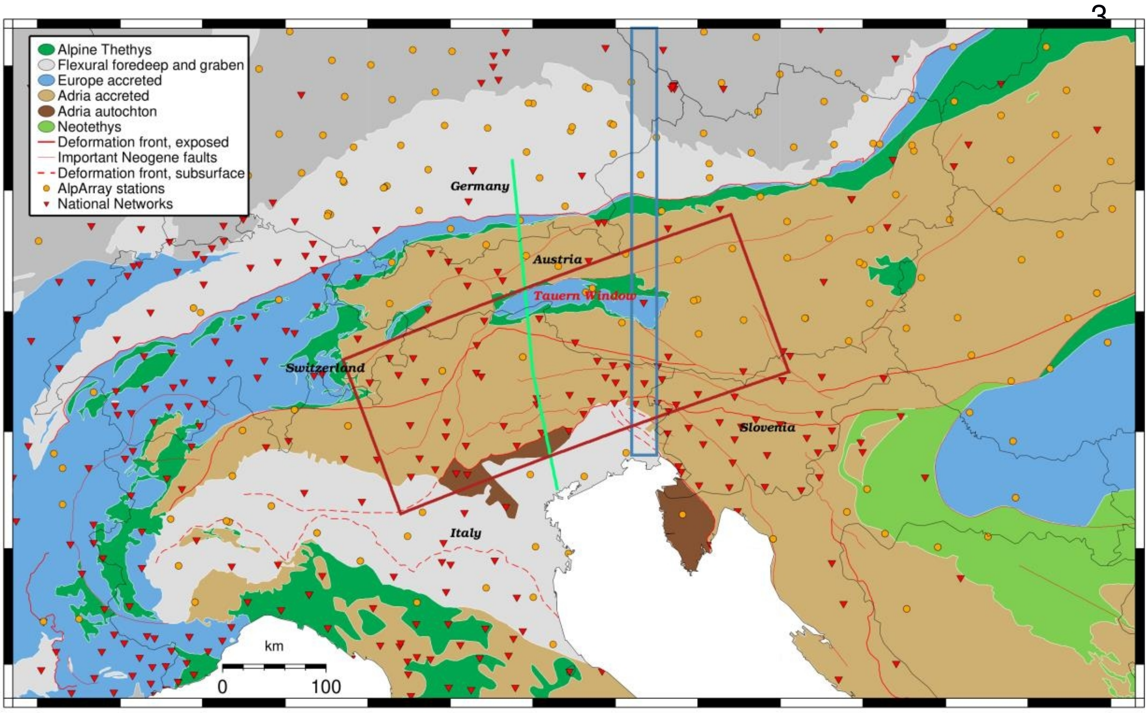

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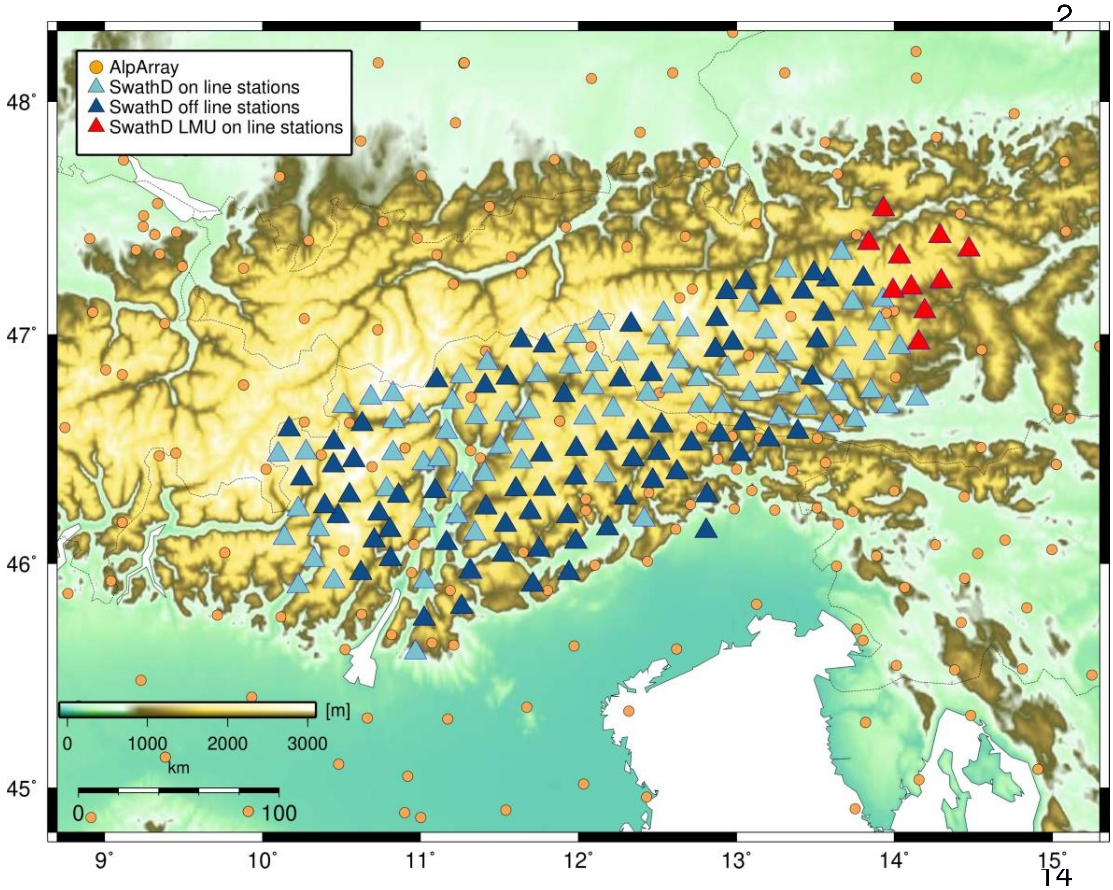

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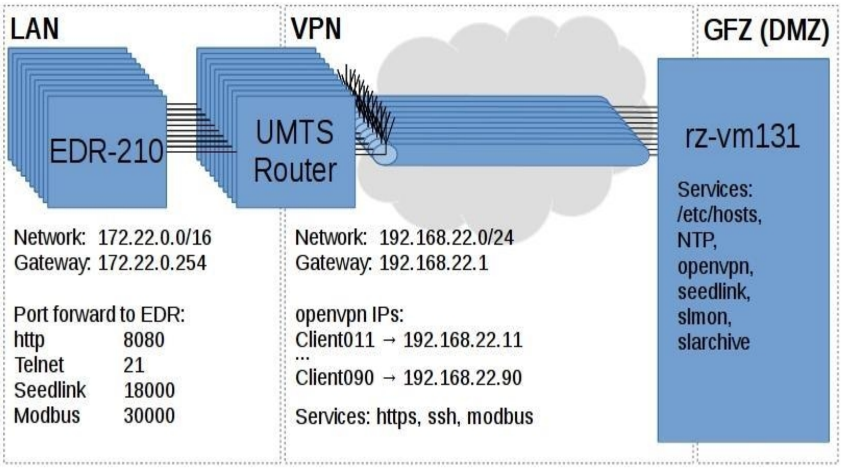

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A)

B)

C)

D)

E)

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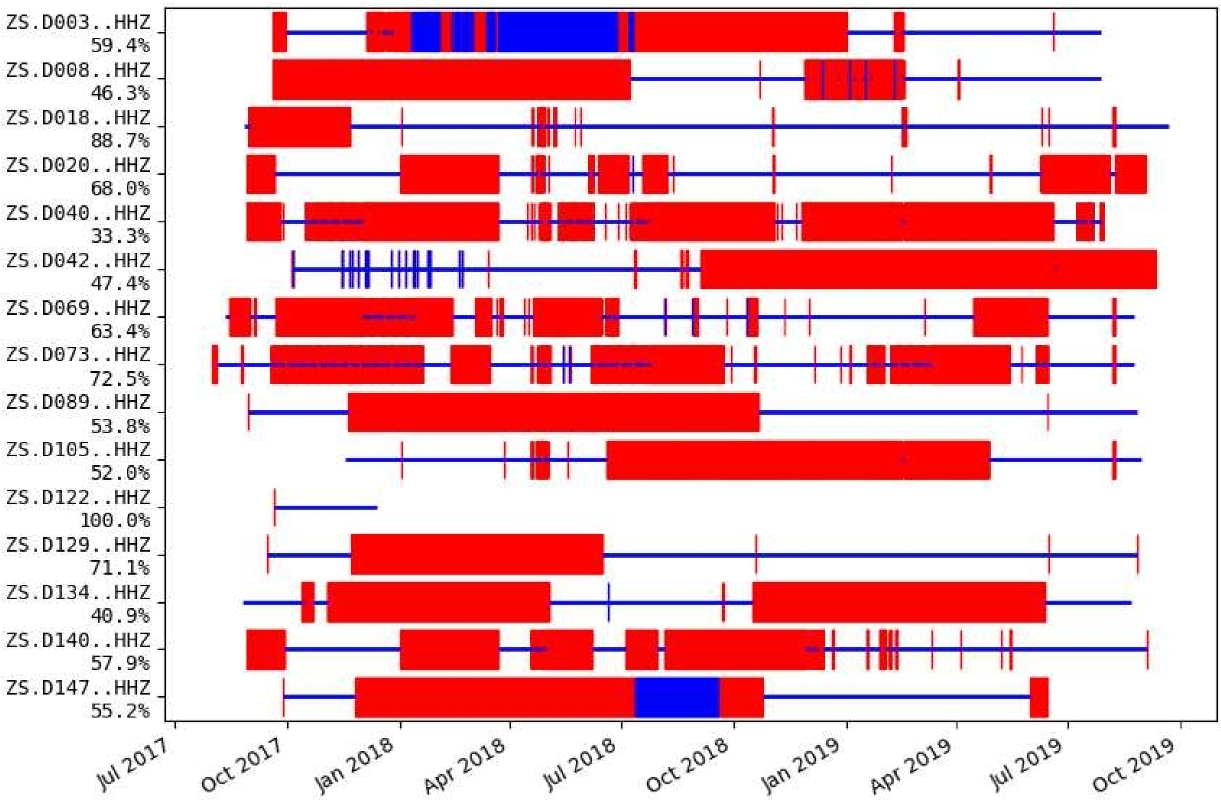
)LJXUHV



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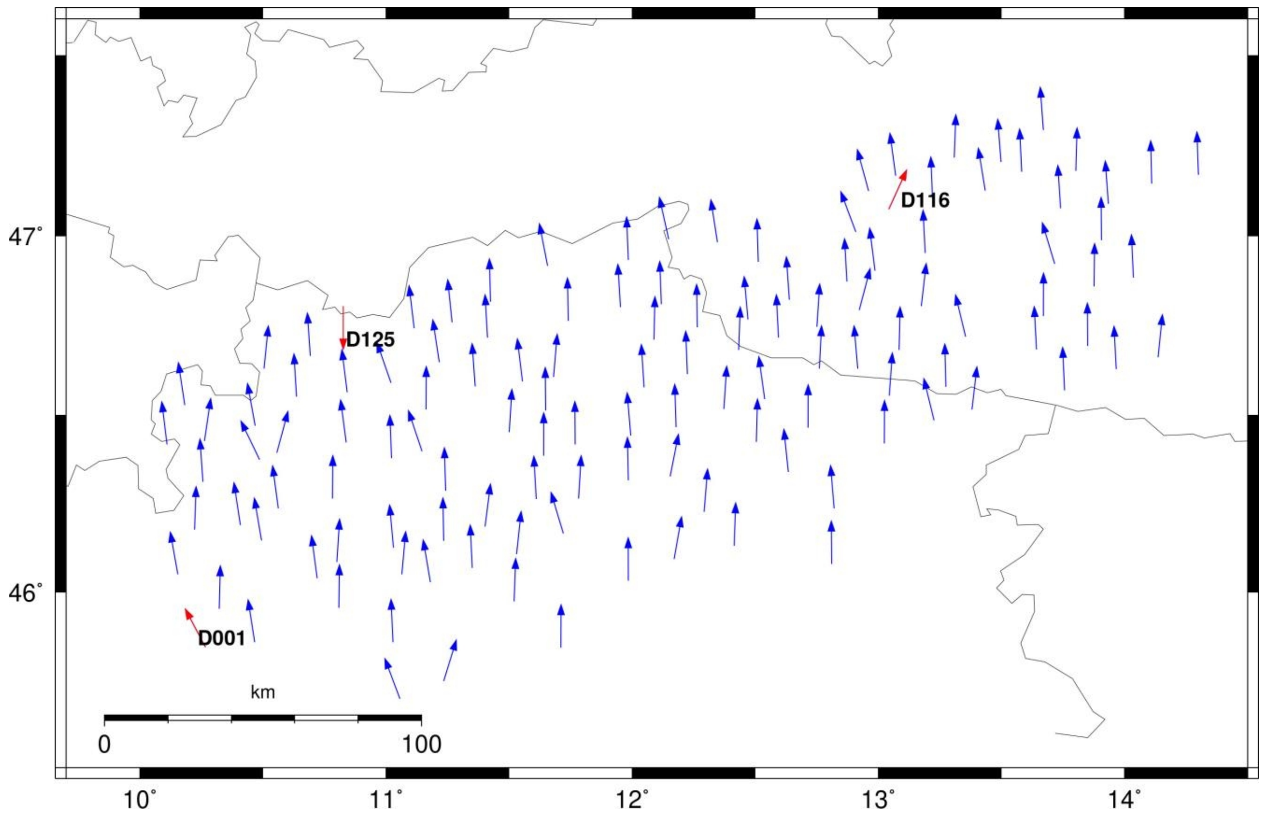

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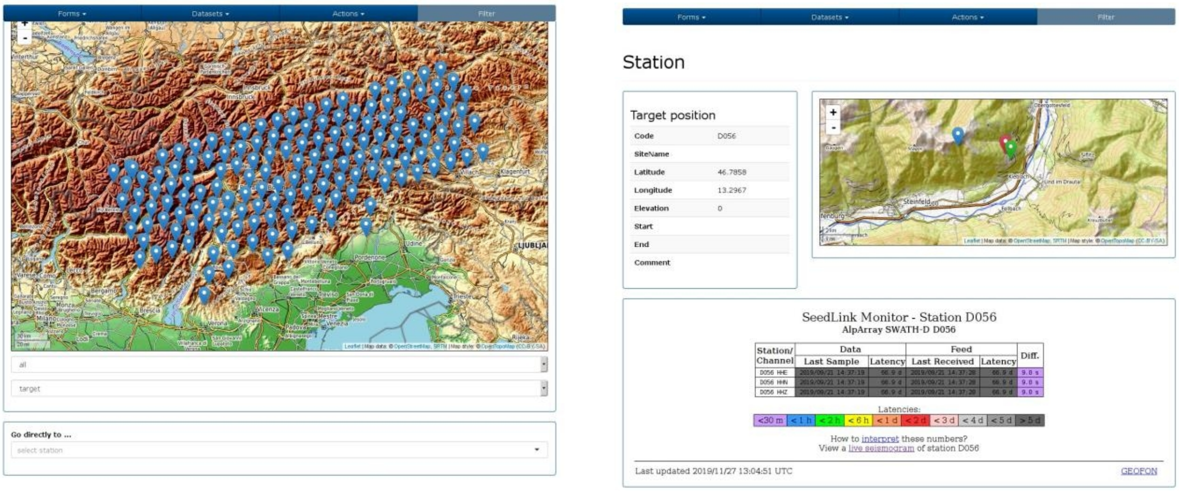

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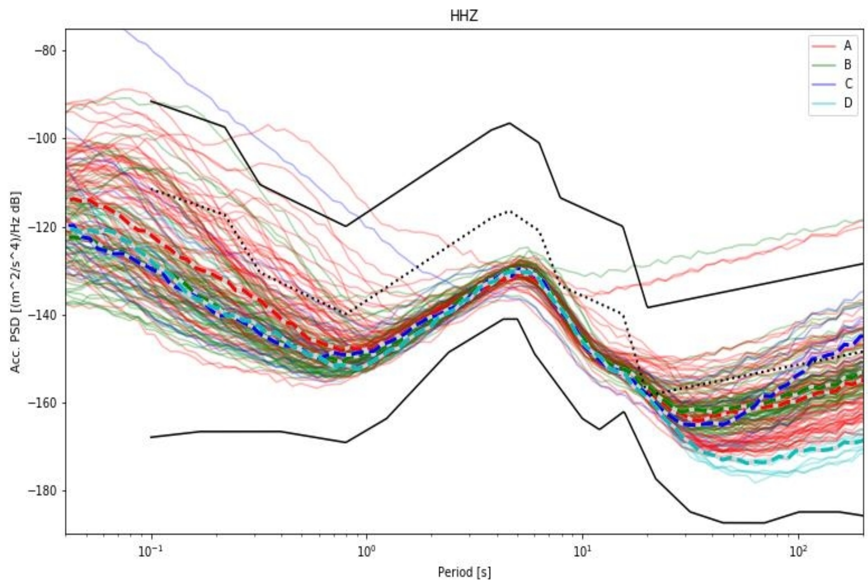

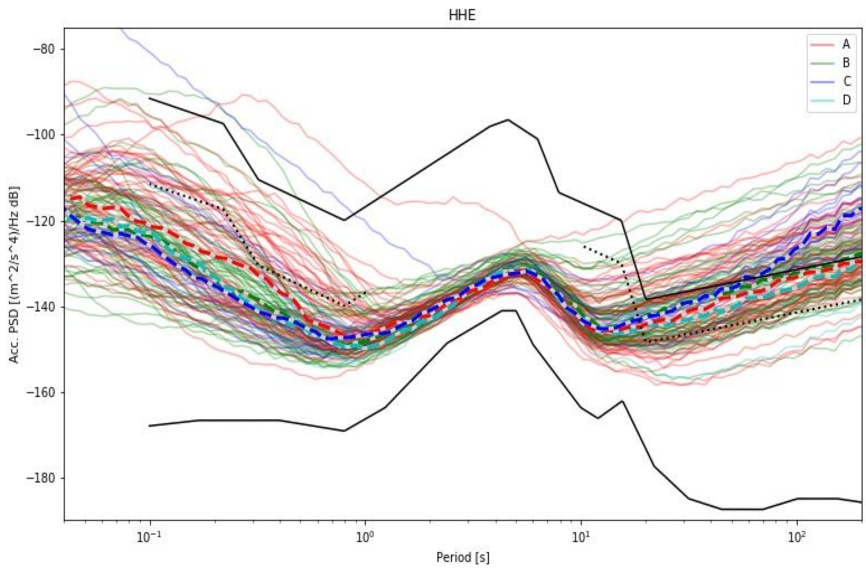

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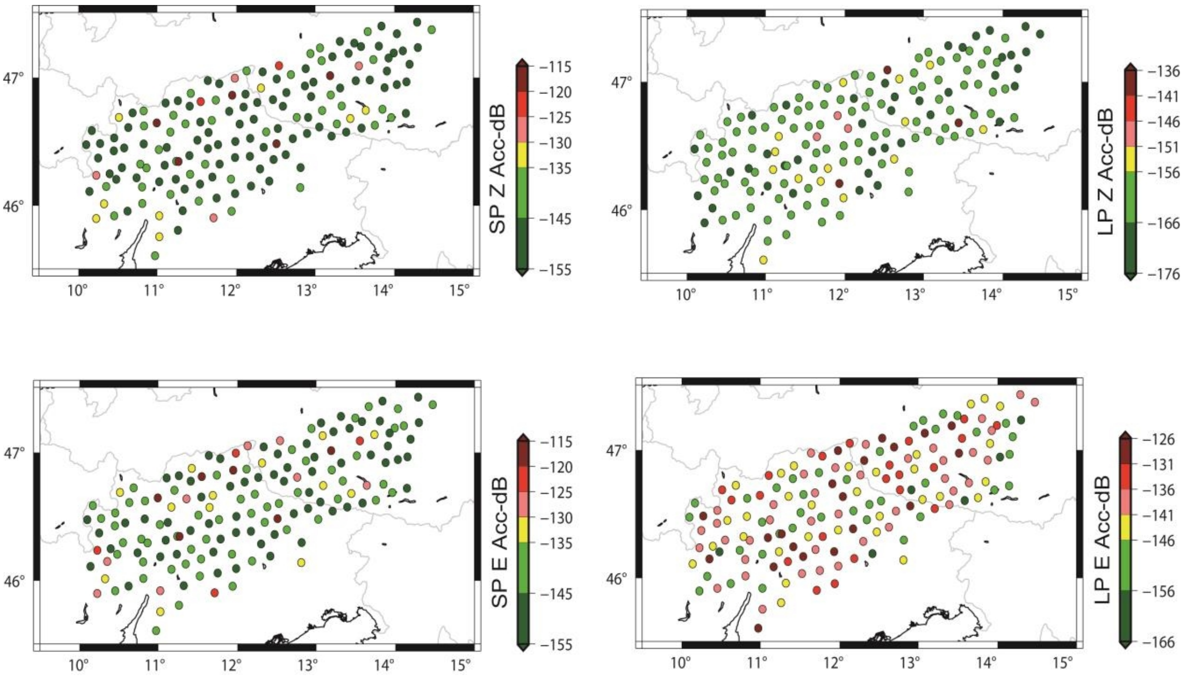

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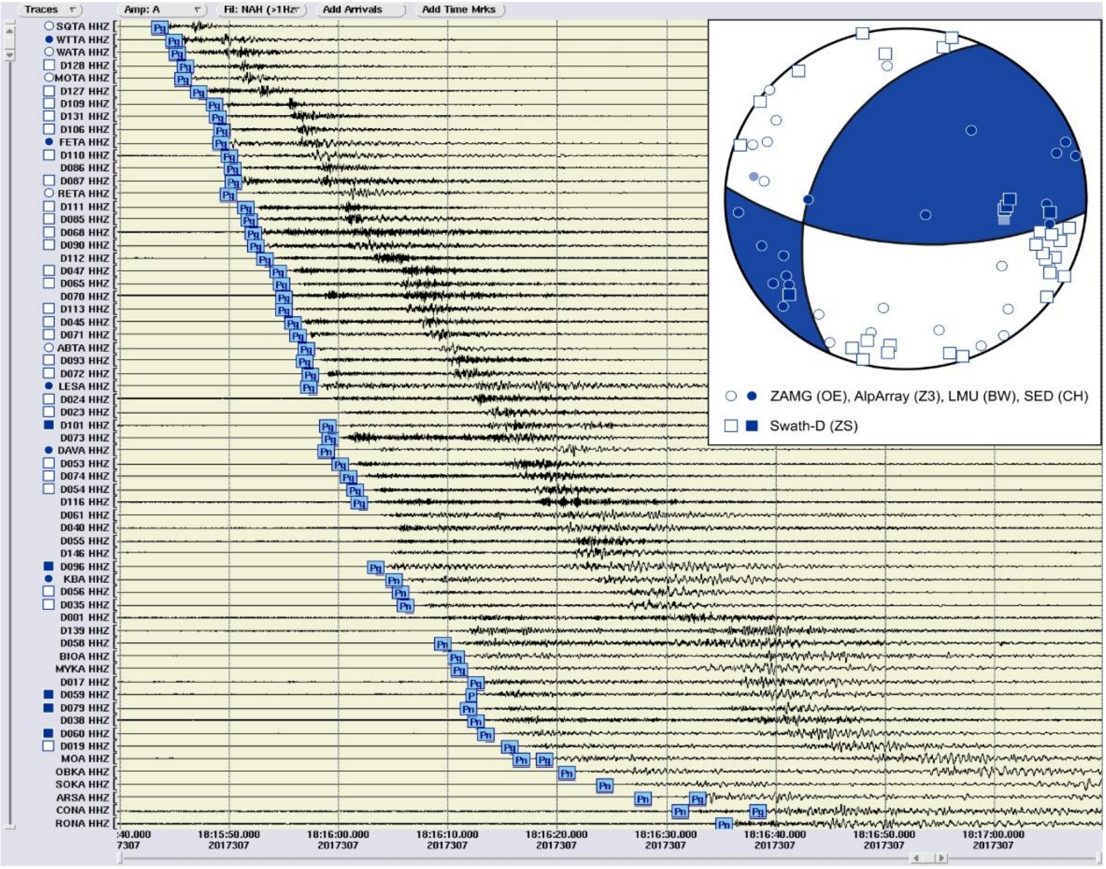

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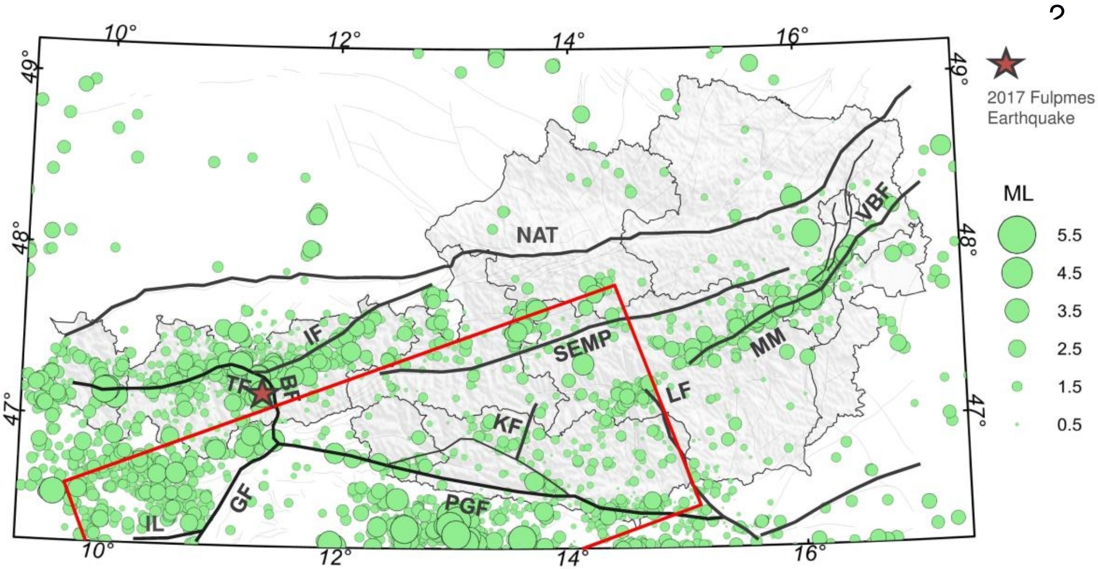

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The SWATH-D seismological network in the Eastern Alps

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2- Freie Universitaet Berlin, Malteserstr. 74 ±100, 12249 Berlin, Germany

3 Istituto Nazionale di Oceanografia e di Geofisica Sperimentale ±OGS, Borgo Grotta Gigante 42/C, 34010 Sgonico (TS), Italy.

4- ZAMG Zentralanstalt für Meteorologie und Geodynamik, Hohe Warte 38, 1190 Vienna, Austria.

5- LMU Universitaet München, Geophysikalisches Observatorium Department für Geo- und Umweltwissenschaften, Ludwigshöhe 8, 82256 Fürstenfeldbruck, Germany.

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(*) corresponding author

Abstract

The SWATH-D experiment involved the deployment of a dense temporary broadband seismic network in the Eastern Alps. Its primary purpose was enhanced seismic imaging of the crust and crust-mantle transition as well as improved constraints on local event locations and focal mechanisms in a complex part of the Alpine orogen. The study region is a key area of the Alps, where European crust in the north is juxtaposed and partially interwoven with Adriatic crust in the south, and a striking jump in the Moho depth was observed by the 2002 TRANSALP N-S profile. Here, a flip in subduction polarity has been suggested to occur. This dense network encompasses 163 stations and complements the larger-scale sparser AlpArray seismic network. The nominal station spacing in SWATH-D is 15 km in a high alpine, yet densely populated and industrialized region. We present here the challenges resulting from operating a large broadband network under these conditions and summarize how we addressed them, including the way we planned, deployed, maintained and operated the stations in the field. Finally, we present some recommendations based on our experiences.

SCOUTING SHEET SWATH D – GFZ - 4D-MB

Arrival Date, Time		Operators:	
Station CODE	Permitters / Land owners / Authority		
SWATH_D_ _ _ **Mobile coverage:** **3G** **4G**	Host name: Building or location: Street & number: Postal code & City: Telephone: E-mail:		
GPS Coordinates Handheld GPS: Set to deci. Deg, note five signif. figs after dec. point; set ellips. to WGS-84	Lat:	Lon:	Elevation:
Site geology / environment (e.g. bedrock, sediments)			
Installation (comment, site sketch overleaf)	Indoor / Vault / Buried GPS: in box / indoor / outside	Power: Solar panels:	
Departure Time			
Comments			

Turn overleaf for site map, sketch, permitting info. Take photos of both sides of deployment sheet as 'backup'. Take site photo.

Please turn over !

Map	**Site Sketch**
Directions to site and site owner house; include names of GPS waypoints where applicable; mark access road turnoffs with waypoints	Show position of buried sensors, data loggers, battery, cables Fence? + photos
Summer **Winter**	

Permitting	
One-off installation fee (if applicable): Monthly fee: Deposit paid: covering until (date): Comments	Space for pasted receipts / notes

Take photos of both sides of deployment sheet as 'backup'

Please turn over !

Figure S1 ±Scouting Sheet

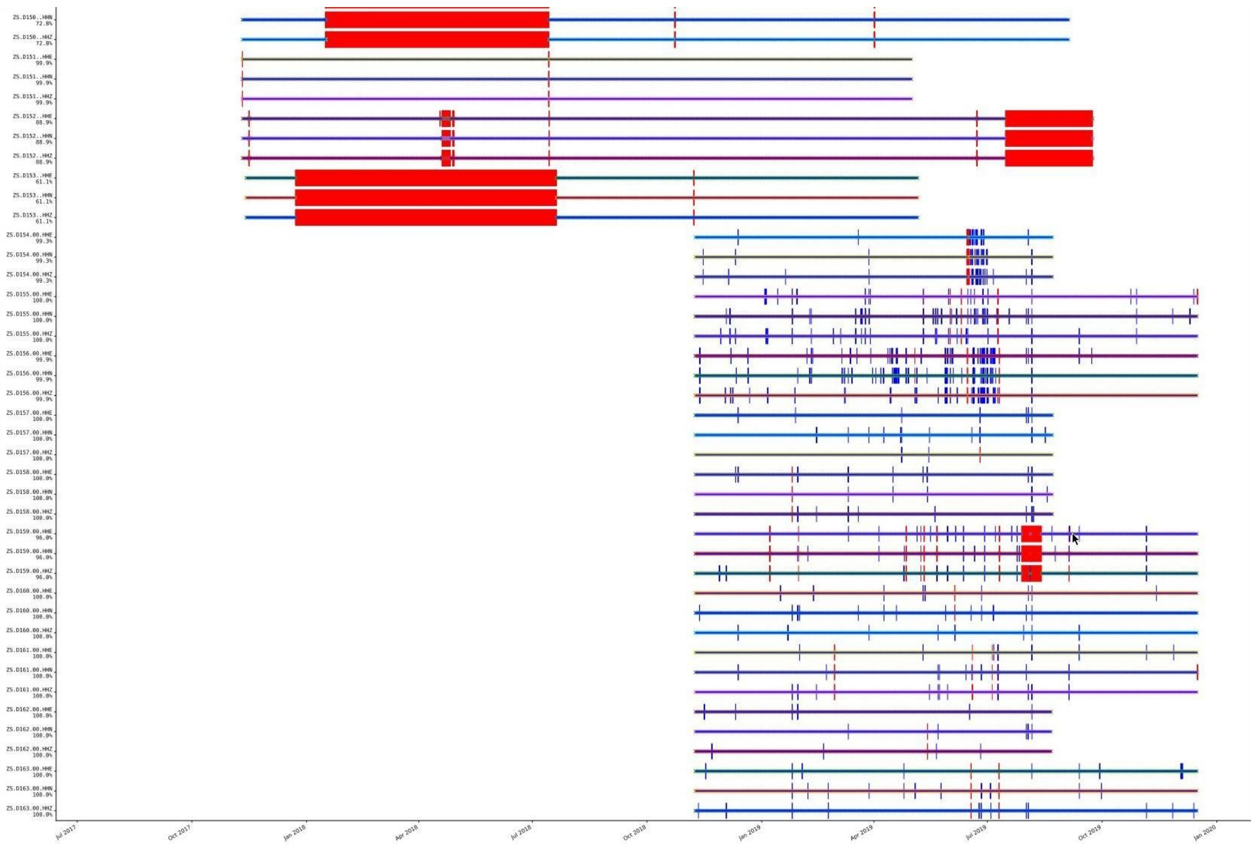


Figure S2 - Obspy Scan showing some stations from the SWATH-D networks: Due to the large number of stations and obvious space issues, only a part including the LMU stations is shown here. The full scan can be downloaded from:

https://nextcloud.gfz-potsdam.de/s/cf5WrZyALnPEKFB

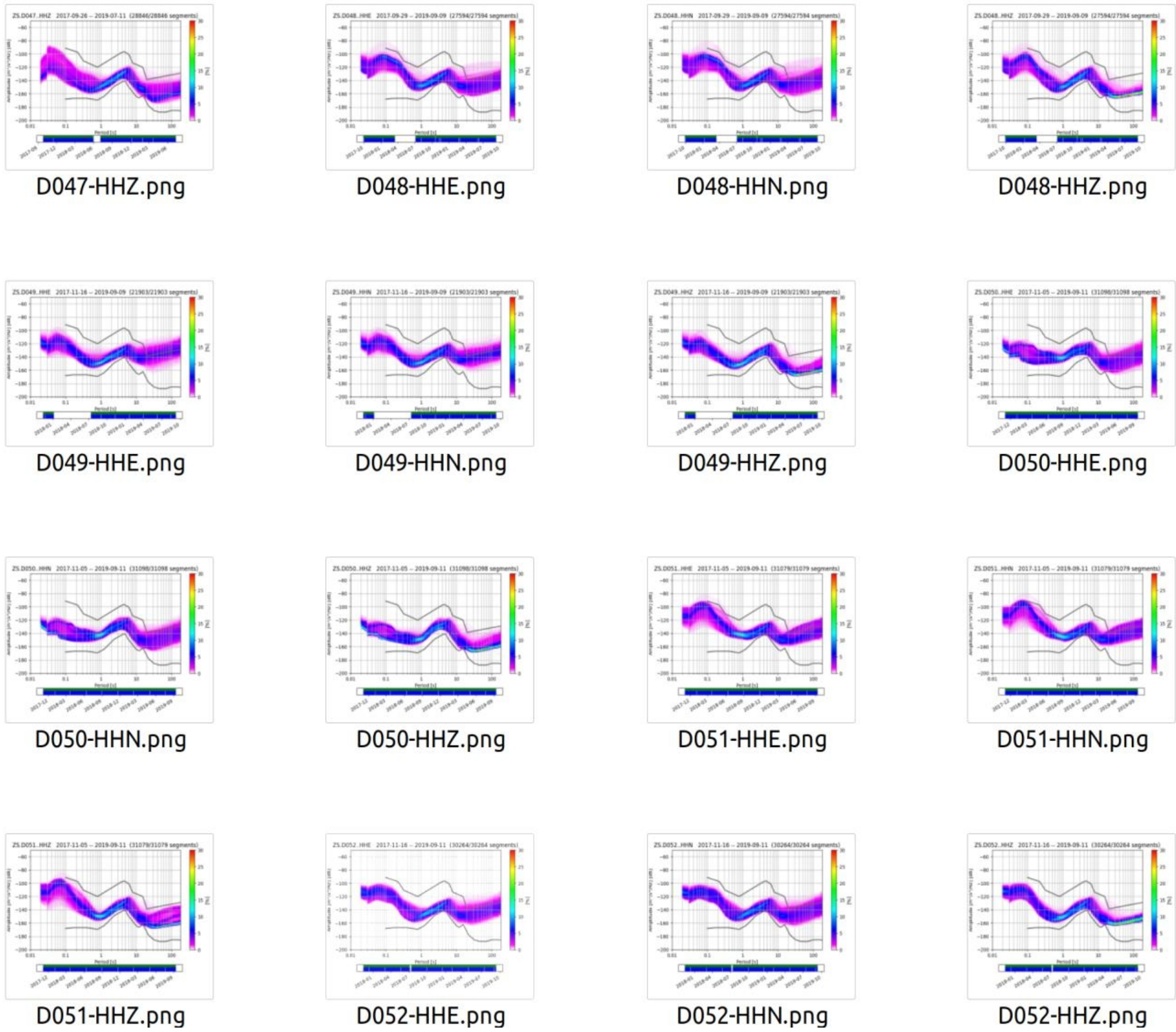


Figure S3 ±Screenshot form a part of the PPSD's from the SWATH-D stations. The file containing all PPSD's is large and includes more than 500 files. It can be downloaded from https://nextcloud.gfz-potsdam.de/s/ngAX9KXXAT7qfpE

II - DEPLOYMENT SHEET EDL / EDR SWATH D – GFZ - 4D-MB

Arrival Date, Time	GMT/ LT	Operators:	
Station CODE SWATH_D _ _ _	EDL # EDR #	EDL IP EDR IP	HD# Size: GB Used: GB
Location: **(e.g. nearby village)**	Battery Type:	Capacity: Ah	Voltage: V
	Charge (underline): Mains Solar: Regulator:	Charger. How many panels?	Grounding: Power: W
Mobile coverage: **3G** **4G** **Potential noise sources:**	Seism. Type: Serial#: Orientation: Magnetic N Assumed local declin: ° True N (compass/gyro/geod) Levelled (bubble)? Locking nuts closed?	Güralp: Unlocked? Centered? Sampling Rate: Hz Monitor: check traces (stomp on floor to test) / mass positions: Z: OK? Baseline: N: OK? Baseline: E: OK? Baseline:	
GPS Coordinates Handheld GPS: Set to deci. Deg, note five signif. figs after dec. point; set ellips. to WGS-84	Lat:	Lon:	Elevation:
Acquisition (read power, temperature from EDL / EDR status)	OK? Power: V Temp: °C	NOT OK Problem:	
GPS (from EDL / EDR)	OK? Sats: Lat: Lon: Date/Time:	NOT OK Problem	
Cable check	GPS, solar cables not squeezed by EDL box? EDL box locked?		
Installation (comment, site sketch overleaf)	Indoor / Vault / Buried GPS: in box / indoor / outside	Burial depths - sensor: cm Logger/Battery: cm	
Modem Nr:	**Tel.Nr:**	**IP:**	
Comments			
Departure Time			

Der Besitzer des Grundstücks/Gebäudes ist nicht verantwortlich bei Verlust und/oder Beschädigung der seismologischen Station.
Il proprietario del terreno/edificio non sarà in alcun modo responsabile della perdita e/o di eventuali danni alla strumentazione sismologica installata temporaneamente nel suo terreno/edificio.

Stationsaufsteller / Tecnico installatore della stazione sismica - Grund-/Gebäude-Besitzer / Proprietario del terreno/edifici

Site map, sketch, permitting info on reverse side

II - DEPLOYMENT SHEET EDL / EDR SWATH D – GFZ - 4D-MB

Site Map	
Permitting	
2017 One-off installation fee (if applicable): covering until (date): Comments	Space for pasted receipts / notes
Permitting	
2018 One-off installation fee (if applicable): covering until (date): Comments	Space for pasted receipts / notes

II - DEPLOYMENT SHEET CUBE SWATH_D-GFZ-4D-MB

Arrival Date, Time	GMT/ LT	Operators:	
Station CODE SWATH_D _ _ _	CUBE# Internal or Ext GPS Antena	Size: GB Used: GB	
Location: **(e.g. nearby village)**	C3-int C3-ext		
	Battery Type:	Capacity: Ah	Voltage: V
	Charge(underline):Mains Solar: Regulator:	Charger: How many panels?	Power: W
Mobile coverage: **3G** **4G** **Potential noise sources:**	Seismometer Type Serial#: Orientation: Magnetic N assumed local decl: ° True N (compass/gyro/geod) Levelled (bubble)? Locking nuts closed?	Güralp: Trillium: Mark: LOCK: Unlocked? Centered? Sampling Rate: Hz Monitor: check traces (stomp on floor to test) / mass positions: Z: OK? Baseline: N: OK? Baseline: E: OK? Baseline:	
GPS Coordinates Handheld GPS: Set to deci. Deg, note five signif. figs after dec. point; set ellips. to WGS-84	Lat:	Lon:	Elevation:
Acquisition (read power, temperature if available)	OK? Power: V Temp: °C	NOT OK Problem:	
Cable check	GPS, solar cables not squeezed?		
Installation (comment, site sketch overleaf)	Indoor / Vault / Buried GPS:in box/indoor/outside	Burial depths - sensor: cm Logger/Battery: cm	
Modem Nr:	**Tel.Nr:**	**IP:**	
Comments			
Departure Time			

Der Besitzer des Grundstücks/Gebäudes ist nicht verantwortlich bei Verlust und/oder Beschädigung der seismologischen Station.
Il proprietario del terreno/edificio non sarà in alcun modo responsabile della perdita e/o di eventuali danni alla strumentazione sismologica installata temporaneamente nel suo terreno/edificio.

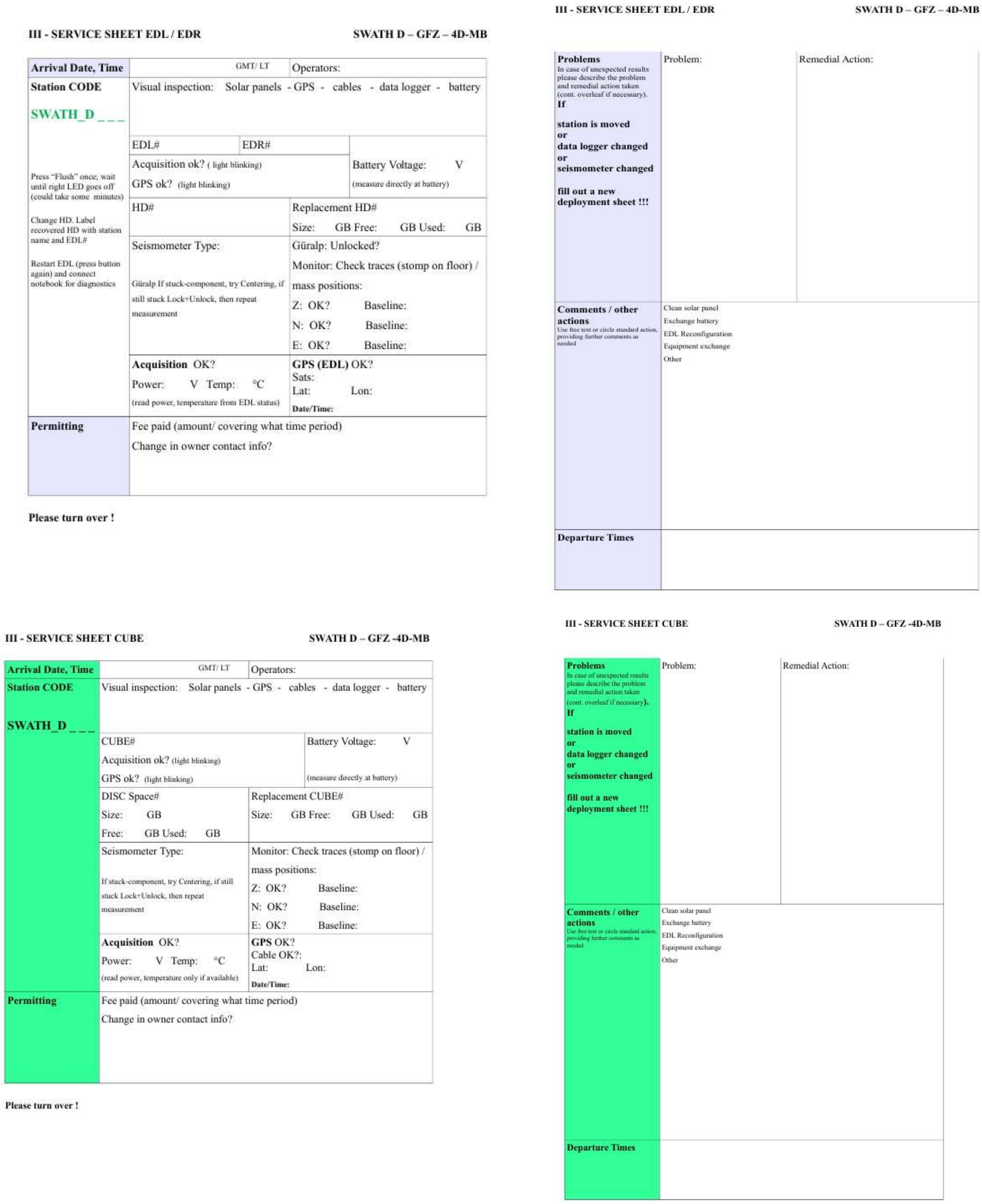
Stationsaufsteller / Tecnico installatore della stazione sismica - Grund-/Gebäude-Besitzer / Proprietario del terreno/edifici

Site map, sketch, permitting info on the reverse side

II - DEPLOYMENT SHEET CUBE SWATH_D-GFZ-4D-MB

Site Map	
Permitting	
2017 One-off installation fee (if applicable): covering until (date): Comments	Space for pasted receipts / notes
Permitting	
2018 One-off installation fee (if applicable): covering until (date): Comments	Space for pasted receipts / notes

Figure S4 ± Deployment Sheet for recorder units type EDR-EDL (Güralp 3ESPC and ESP seismometers). CUBE recorders used Trillium Compact seismometers (see text for details).



III - SERVICE SHEET EDL / EDR — SWATH D – GFZ – 4D-MB

Arrival Date, Time	GMT/ LT	Operators:	
Station CODE SWATH_D _ _ _	Visual inspection: Solar panels - GPS - cables - data logger - battery		
	EDL#	EDR#	
Press "Flush" once; wait until right LED goes off (could take some minutes)	Acquisition ok? (light blinking) GPS ok? (light blinking)		Battery Voltage: V (measure directly at battery)
Change HD. Label recovered HD with station name and EDL#	HD#	Replacement HD# Size: GB Free: GB Used: GB	
Restart EDL (press button again) and connect notebook for diagnostics	Seismometer Type: Güralp If stuck-component, try Centering, if still stuck Lock+Unlock, then repeat measurement	Güralp: Unlocked? Monitor: Check traces (stomp on floor) / mass positions: Z: OK? Baseline: N: OK? Baseline: E: OK? Baseline:	
	Acquisition OK? Power: V Temp: °C (read power, temperature from EDL status)	GPS (EDL) OK? Sats: Lat: Lon: Date/Time:	
Permitting	Fee paid (amount/ covering what time period) Change in owner contact info?		

Please turn over !

III - SERVICE SHEET EDL / EDR — SWATH D – GFZ – 4D-MB

Problems In case of unexpected results please describe the problem and remedial action taken (cont. overleaf if necessary). If station is moved or data logger changed or seismometer changed fill out a new deployment sheet !!!	Problem:	Remedial Action:
Comments / other actions Use free text or circle standard action, providing further comments as needed	Clean solar panel Exchange battery EDL Reconfiguration Equipment exchange Other	
Departure Times		

III - SERVICE SHEET CUBE — SWATH D – GFZ -4D-MB

Arrival Date, Time	GMT/ LT	Operators:	
Station CODE SWATH_D _ _ _	Visual inspection: Solar panels - GPS - cables - data logger - battery		
	CUBE# Acquisition ok? (light blinking) GPS ok? (light blinking)		Battery Voltage: V (measure directly at battery)
	DISC Space# Size: GB Free: GB Used: GB	Replacement CUBE# Size: GB Free: GB Used: GB	
	Seismometer Type: If stuck-component, try Centering, if still stuck Lock+Unlock, then repeat measurement	Monitor: Check traces (stomp on floor) / mass positions: Z: OK? Baseline: N: OK? Baseline: E: OK? Baseline:	
	Acquisition OK? Power: V Temp: °C (read power, temperature only if available)	GPS OK? Cable OK?: Lat: Lon: Date/Time:	
Permitting	Fee paid (amount/ covering what time period) Change in owner contact info?		

Please turn over !

III - SERVICE SHEET CUBE — SWATH D – GFZ -4D-MB

Problems In case of unexpected results please describe the problem and remedial action taken (cont. overleaf if necessary). If station is moved or data logger changed or seismometer changed fill out a new deployment sheet !!!	Problem:	Remedial Action:
Comments / other actions Use free text or circle standard action, providing further comments as needed	Clean solar panel Exchange battery EDL Reconfiguration Equipment exchange Other	
Departure Times		

Figure S5 ± Service Sheet for recorder units type EDR-EDL (Güralp 3ESPC and ESP seismometers). CUBE recorders used Trillium Compact seismometers (see text for details).

IV - DISMANTLE SHEET EDL / EDR **SWATH D – GFZ – 4D-MB**

Arrival Date, Time	GMT/ LT	Operators:	
Station CODE **SWATH_D _ _ _**	Visual inspection: Solar panels - GPS - cables - data logger - battery		
	EDL#	EDR#	
Press "Flush" once; wait until right LED goes off (could take some minutes)	Acquisition ok? (light blinking) GPS ok? (light blinking)		Battery Voltage: V (measure directly at battery)
Change HD. Label recovered HD with station name and EDL#	HD# Size: GB Free: GB Used: GB		
Restart EDL (press button again) and connect notebook for diagnostics	Seismometer Type: Güralp If stuck-component, try Centering, if still stuck Lock+Unlock, then repeat measurement	Güralp: Locked? Monitor: Check traces (stomp on floor) / mass positions: Z: OK? Baseline: N: OK? Baseline: E: OK? Baseline:	
	Acquisition before turning OFF press Flush/WLAN button Power: V Temp: °C (read power, temperature from EDL status) **Date/Time:**		
Permitting	Fee paid (amount/ covering what time period) Change in owner contact info?		

IV - DISMANTLE SHEET EDL / EDR **SWATH D – GFZ – 4D-MB**

Problems In case of unexpected results please describe the problem and remedial action taken (cont. overleaf if necessary). If station is moved, fill out a new deployment sheet	Problem:
Comments / other actions Use free text or circle standard action, providing further comments as needed	Clean solar panel Exchange battery EDL Reconfiguration Equipment exchange Other
Departure Times	

IV - DISMANTLE SHEET CUBE **SWATH D – GFZ -4D-MB**

Arrival Date, Time	GMT/ LT	Operators:	
Station CODE **SWATH_D _ _ _**	Visual inspection: Solar panels - GPS - cables - data logger - battery		
	CUBE# Acquisition ok? (light blinking) GPS ok? (light blinking)		Battery Voltage: V (measure directly at battery)
	DISC Space# Size: GB Free: GB Used: GB		
	Seismometer Type: If stuck-component, try Centering, if still stuck Lock+Unlock, then repeat measurement	Monitor: Check traces (stomp on floor) / mass positions: Z: OK? Baseline: N: OK? Baseline: E: OK? Baseline:	
	Acquisition OK? Power: V Temp: °C (read power, temperature only if available) **Date/Time:**		
Permitting	Fee paid (amount/ covering what time period) Change in owner contact info?		

IV - DISMANTLE SHEET CUBE **SWATH D – GFZ -4D-MB**

Problems In case of unexpected results please describe the problem and remedial action taken (cont. overleaf if necessary). If station is moved, fill out a new deployment sheet	Problem:
Comments / other actions Use free text or circle standard action, providing further comments as needed	Clean solar panel Exchange battery EDL Reconfiguration Equipment exchange Other
Departure Times	

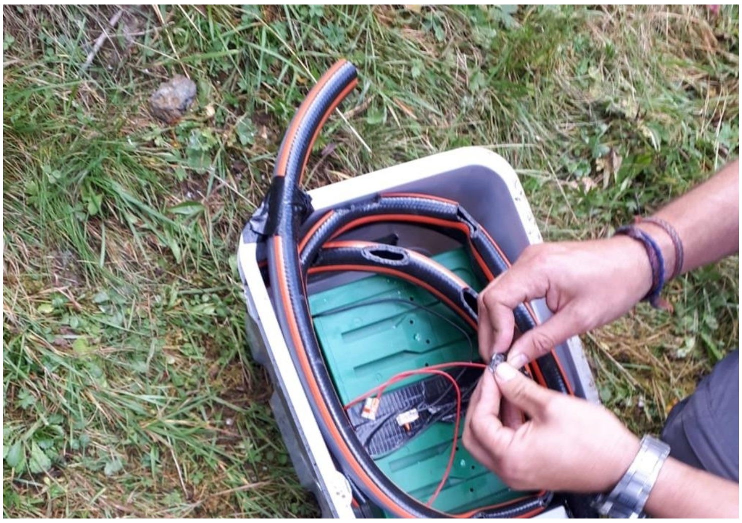
Figure S6 ± Dismantle Sheet for recorder units type EDR-EDL (Güralp 3ESPC and ESP seismometers). CUBE recorders used Trillium Compact seismometers (see text for details).

Figure S7 ±Step by step installation of Zinc/air batteries

1) The battery is supplied with the ventilation holes sealed (9V/200Ah). First remove the seal so that the batteries can start working. Attach both batteries together and connect them in serie (18V/200Ah).

2) Attach a hosepipe with some holes in it to enable proper ventilation.

3) Place the batteries with the hosepipe in a plastic box. Preferably a hard plastic box with cover that can last in the field for the period of deployment.



4) Place the box with the batteries inside a heavy duty plastic bag to protect it from water intrusion. The ventilation hosepipe and power cable are properly fixed with duct tape and zip ties. On the right, the final aspect of the installation with the CUBE box under a green plastic cover for protection