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GA-OGS-ARSO Transfrontier CE3RN AdriaArray Seismicity Experiment (GOAT-CASE) installations and first results

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Abstract

GOAT-CASE experiment aims to evaluate the expected improvement in automatic earthquake localisation in the joint area of NE Italy, Austria and Slovenia, performed by respective authoritative agencies, also members of AdriaArray experiment and virtual network CE3RN. We re-picked P-wave arrival onsets on the seismometer channels of permanent seismic stations, additional AdriaArray stations and additional permanent stations in the joint area plus the 50 km surrounding belt. The onset detections were performed by each member of the experiment for stations within its authoritative area while the detection association was performed centrally. The resulting catalogue was compared against the joint catalogue of manually revised locations as the reference. Only the location parameters were compared in this experiment while the magnitudes were taken from manual catalogues. We used Antelope software for analysis in a similar way as in regular real-time monitoring procedures but with commonly agreed parameters. The comparison of procedures and parameters used by the three agencies was also one of the goals of the experiment. After reviewing the results of the comparison for the first two years of the experiment for events with local magnitude M > 1.5 we conclude that there is observable improvement in earthquake locations. This is reflected by the median distance between automatic and manual locations with the GOAT-CASE result being better than the results of any of the individual agencies. Additionally, we discuss the installation of six temporary stations by OGS in sites already used by the previously successful AlpArray project.

Keywords: AdriaArray; Seismic bulletin; Earthquake location; Seismic network; Earthquake detection

1. Introduction

The Italian National Institute of Oceanography and Applied Geophysics (OGS), GeoSphere Austria (GA, formerly ZAMG) and the Slovenian Environment Agency (ARSO) are the institutions dedicated to real-time seismological monitoring of the north-east of Italy, Austria and Slovenia in collaboration with the respective civil protection authorities. In 2014, OGS, GA (then ZAMG) and ARSO founded the "Central and Eastern Europe Earthquake Research

Network" (CE3RN, 2014; Lenhardt et al., 2021) in order to: 1) formally establish the cross-border network, 2) define the rules of conduct for the management, improvement, extension and expansion of the network, 3) improve seismological research in the region and 4) support civil protection activities. As part of CE3RN, OGS, GA and ARSO have adopted the Antelope software package (Antelope, 2024) for collecting, archiving, analysing and sharing seismological data.

In 2022, the international experiment AdriaArray (AdriaArray, 2022) was launched, following the previously successful experiment AlpArray (Hetényi et al., 2018). AdriaArray is a multinational project to map the Adriatic plate and its active margins in the central Mediterranean with a dense regional array of seismic stations (Fig. 1) to understand the causes of active tectonics and volcanic fields in the region. OGS, GA and ARSO are actively involved in the AdriaArray experiment by providing data from their seismic monitoring networks and – in the case of OGS – also by installing and operating dedicated seismic stations. As part of the AdriaArray experiment, several additional seismic stations have been set up in Austria and north-east Italy. It is therefore to be expected that the additional seismic stations will improve the earthquake localisation capabilities of GA, OGS and ARSO. This certainly applies to Austria and north-east Italy, but also to Slovenia, as a large part of its seismicity lies on the border with Italy.

The GOAT-CASE experiment aims to quantify the expected improvement in earthquake localisation capability in the area encompassing the areas covered by the three agencies and a 50 km surrounding belt (Fig. 2). The underlying methodology is to relocate earthquakes with additional seismic stations and compare the results. The workload for the detections is distributed among the three partners, while the locating procedure is done centrally. An attempt will be made to use artificial intelligence to detect earthquakes and compare the results with the agencies' standard routines.

The AdriaArray experiment is planned to run for 3 years from around mid-2022. In this paper we will illustrate the installations of the additional seismic stations for the AdriaArray project and the results in the seismic bulletins comparisons of the first two years of the experiment, from 01/07/2022 to 30/06/2024.

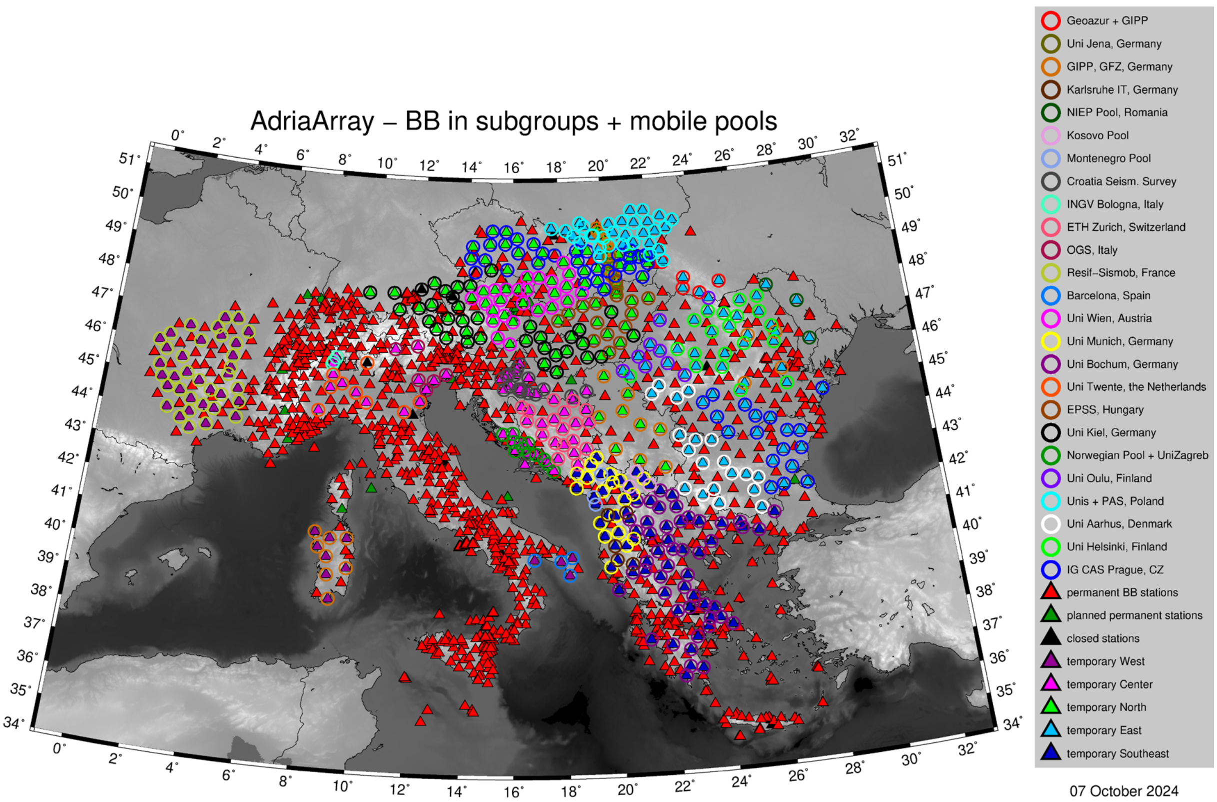

Figure 1. Map of all seismic broadband stations of the AdriaArray, divided into subgroups. The 6 OGS stations belong to the temporary subgroup Centre: see legend for details on colour and shape. Map courtesy of Petr Ferro Kolínský from AdriaArray management via his public GitHub repository.

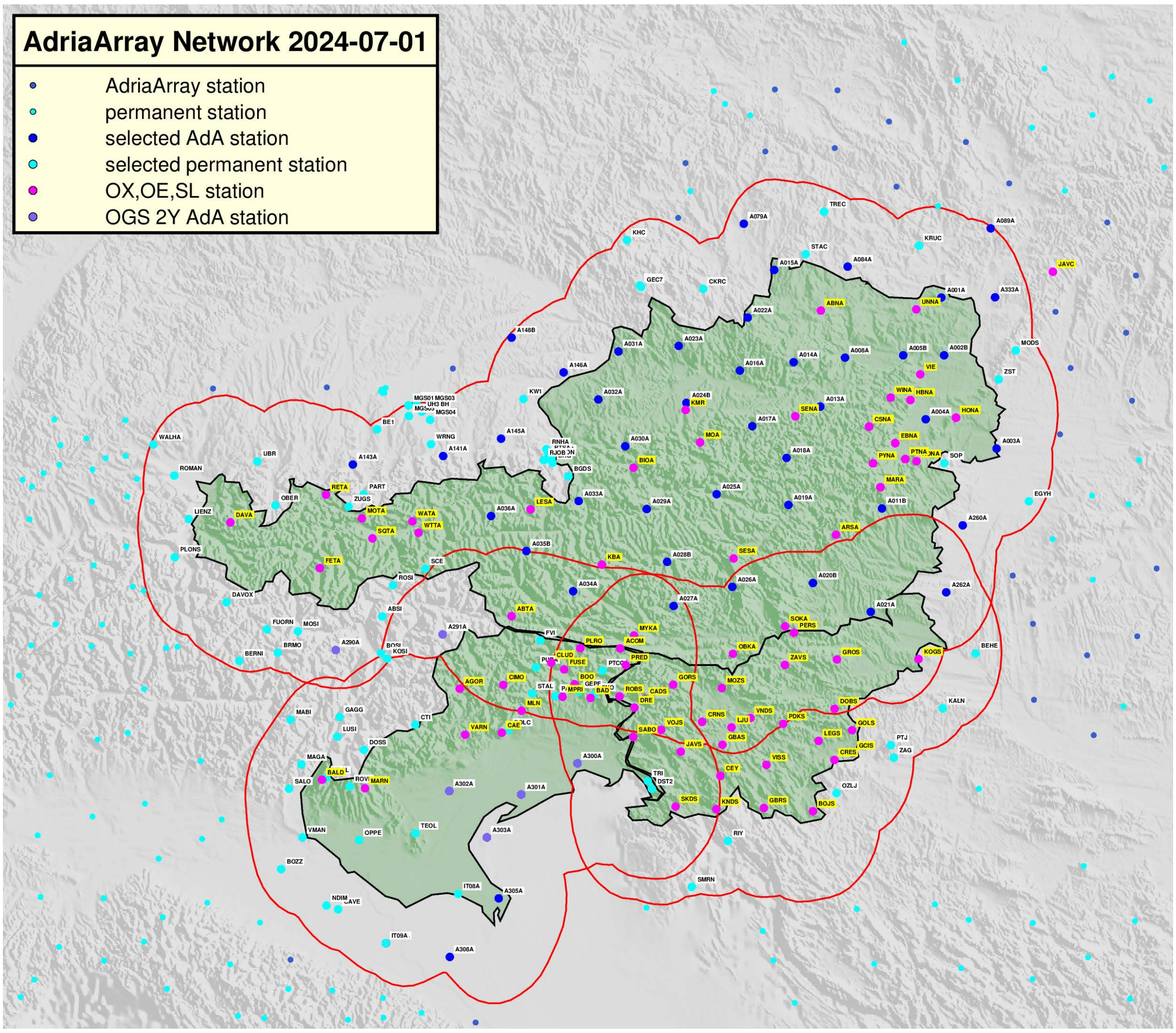

Figure 2. Map of the seismic stations used in the GOAT-CASE experiment: pink – permanent, light blue – additional permanent from other networks, dark blue – temporary additional AdriaArray stations, violet – OGS additional AdriaArray stations. The red lines define the area of the GOAT-CASE experiment, which is defined by the political borders plus the 50 km surrounding belt.

2. Seismic stations installations

2.1 Network geometry and infrastructural setting

As part of the AdriaArray project, OGS (Bragato et al., 2021) was commissioned to recolonise 6 sites of the former AlpArray project in north-eastern Italy: 2 in the Trentino-Alto Adige region, 3 in the Veneto region and 1 in the Friuli-Venezia Giulia region (Fig. 1).

Finding good sites to install a network of broadband seismic stations can be quite a challenge, especially in mountainous regions, but in our case, we were fortunate that our colleagues from ETHZ (Molinari et al., 2016) and INGV (Govoni et al., 2017) had already put considerable effort into selecting the final 6 sites: We would like to express our deepest gratitude to them.

The 6 OGS seismic stations can be divided into two spatially separated groups with different morphological and geological conditions: stations A290A and A291A are in the mountains of the Trentino-Alto Adige region, while stations A300A, A301A, A302A and A303A are in the Po Valley in the Veneto and Friuli Venezia Giulia regions.

2.2 Station design

A typical installation of an OGS seismic station for the AdriaArray project is shown in Fig. 3. The main components are the Nanometrics Centaur 6-channel data acquisition system (Nanometrics Centaur, 2024) coupled to the Nanometrics Trillium Compact (Nanometrics Trillium Compact, 2024) seismometer. The Trillium Compact is a broadband seismometer with a bandpass of up to 120 seconds. It is relatively small (especially in comparison to the Streckeisen STS-2 seismometer) and very easy to install: It only needs to be levelled and there is no mechanism to lock/unlock the mass. To ensure physical and thermal stability, the Trillium Compacts are installed on a marble base and covered with a plastic cover filled with polystyrene. If the installation is indoors, that is enough, whereas if the installation is outdoors, we bury the seismometer at least 0.5 metres deep.

The Nanometrics Centaur 6-channel data acquisition system proved to be a good choice in terms of reliability. It is capable of recording 6 channels simultaneously up to the 100 sps sampling rate of interest to us (and AdriaArray). It can record and store waveforms on its internal main memory and/or on removable media. It has a very precise

(a) (b) (c) (d) (e)

Figure 3. Components of an OGS seismic station for the AdriaArray project: (a) the Nanometrics Centaur acquisition system; (b) the mobile internet router with switches; (c) both integrated in a closed metal cabinet; (d) the Nanometrics Trillium Compact 120 sec broadband seismometer, installed on a marble plate; (e) the sensor covered with plastic thermal insulation.

(less than 10 milliseconds error) internal clock that is synchronised with the GPS and/or GALILEO GNS system. For the needs of OGS and AdriaArray, it is particularly important that it enables real-time data transmission by providing a standard SeedLink (SeedLink, 2008) server. To realise real-time data transmission, we use Teltonika's RUT955 industrial mobile routers, which exploit mobile internet technology. We build a VPN on top of it to increase security and to avoid problems caused by changing mobile IP addresses.

The electronic equipment of the stations also includes overvoltage protection, a battery that guarantees operation for around 1 week without mains power, power regulators and fuses.

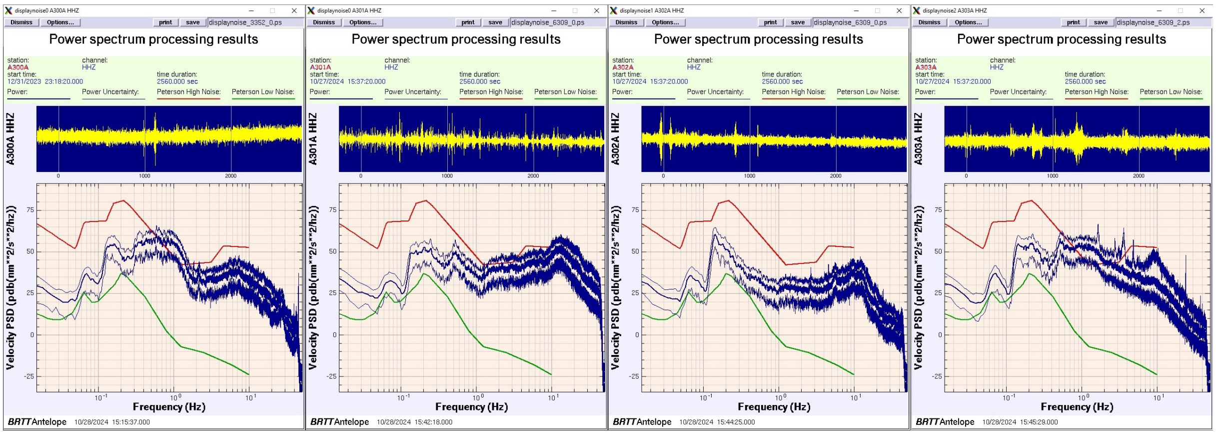

Figure 4. Power spectral density in velocity for the vertical channels of the 4 OGS seismic stations for the AdriaArray project.

Figure 4 shows the power spectral density in velocity for the vertical channels of the 4 OGS seismic stations for the AdriaArray project. It can be observed that the performances on the long-period (left) side of the spectra, are quite good and almost reaching the Peterson and Tilgner Low Noise Model (Peterson and Tilgner, 1985), while on the high-frequency (right) side of the spectra they reach the Peterson and Tilgner High Noise Model.

3. Data analysis and results

We begin with some of the motivations for the GOAT-CASE experiment. The additional sites with new seismic stations established as part of the AdriaArray project provide a good opportunity to virtually extend the seismic networks of the participant partners, at least for the duration of the project. It is expected that the best performing sites will be maintained beyond the end of the project: in this respect, we have had good experience with the seismic stations installed in the previous AlpArray project. OGS, GeoSphere Austria and ARSO have been exchanging real-time seismic data, both waveforms and parametric data, for many years, even before the formal establishment of the CE3R Network (Lenhardt et al., 2021). In general, real-time processing – when properly configured – is much simpler and less demanding than batch processing. OGS (Bragato et al., 2021) GeoSphere Austria and ARSO are the authoritative institutes for the publication of the reviewed seismic bulletins in their respective areas of responsibility. OGS, GeoSphere Austria and ARSO operate a relatively homogeneous system for the acquisition, exchange, analysis and archiving of real-time seismic data, using the Antelope software suite from Boulder Real Time Technologies as the centrepiece (Antelope, 2024). Among the Antelope routines, orb2orb enables fast and reliable exchange of waveforms, intermediate results and various processing steps between the partners. OGS, GeoSphere Austria and ARSO have little experience but great interest in AI-based processing of seismic data: the GOAT-CASE experiment is a good opportunity to test such algorithms in a real (and complex) seismic acquisition environment.

One of the challenges of the GOAT-CASE experiment is the correct setup of the detector and the associator used in Antelope: seismic noise level is not the same at permanent and temporary sites, as it tends to be higher with the latter. Strong motion seismic stations don't benefit from automatic onset detection in our seismic networks, apart from those operated by OGS in the Veneto region as part of the VenetOne project, which unfortunately are far too numerous to be mixed up with the rest of the seismic stations of the classic seismic networks. The management of the metadata describing the characteristics of the seismic stations seems to be a simple task, but experience shows that there are discrepancies and errors in the various seismic data centres that lead to incorrect analysis of the data. By performing the data analysis on the same seismic stations internally in the GOAT-CASE experiment, we hope to detect and correct such discrepancies if they exist. Our many years of experience with the Antelope software have also shown us that different servers with the same settings behave differently, contrary to expectations: not much, but sometimes enough to jeopardize the test results. Finally, we are aware that there may be discrepancies in naming the same things between our institutes: but again, we look forward to finding and fixing such discrepancies.

The opportunities offered by the GOAT-CASE experiment include the ability to refine processing at each institute by learning from experience, eliminating potentially redundant workflows and benefiting from new tools and/or routines developed for the experiment.

The goal of the GOAT-CASE experiment is to demonstrate the improvement of the seismic bulletins in the area when the additional seismic stations of the AdriaArray are added. To demonstrate this, we need to reprocess 3 years of data – which is a considerable amount of data – and define quality indicators such as azimuth gap and fault ellipse size.

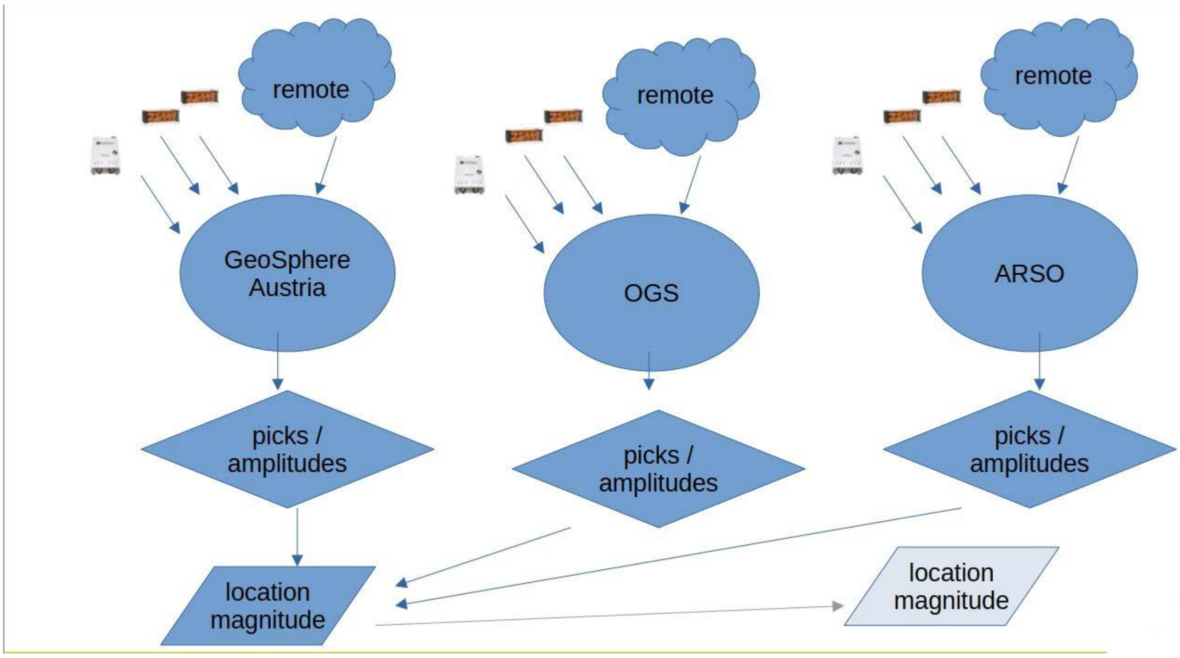

Figure 5. Schematic of the GOAT-CASE experiment analysis process: distributed and centralized.

Figure 5 shows the data analysis flow of the GOAT-CASE. The data acquisition and onset determination are divided between OGS, GeoSphere Austria and ARSO, while the central processing of the location determination and magnitude calculation as well as the comparison with the individual seismic bulletins is carried out centrally at GeoSphere Austria. Standard Antelope routines are used for the first steps, while new routines had to be developed for the comparison with the bulletins. The standard earthquake localization in Antelope is based on a grid search, which is very fast, but the locations must necessarily lie on the nodes of the grid used. To get an error ellipse, we post-processed each location with the genloc algorithm, which produces an error ellipse that we can use for comparison.

3.1 Results

Figure 6a shows a comparison between the automatic locations of the three institutes (GA, OGS and ARSO) and the manual locations of the three institutes (GA, OGS and ARSO) above a threshold of local magnitude M > 1.5 for the first two years of the experiment. Figure 6b shows a comparison between the automatic locations of the

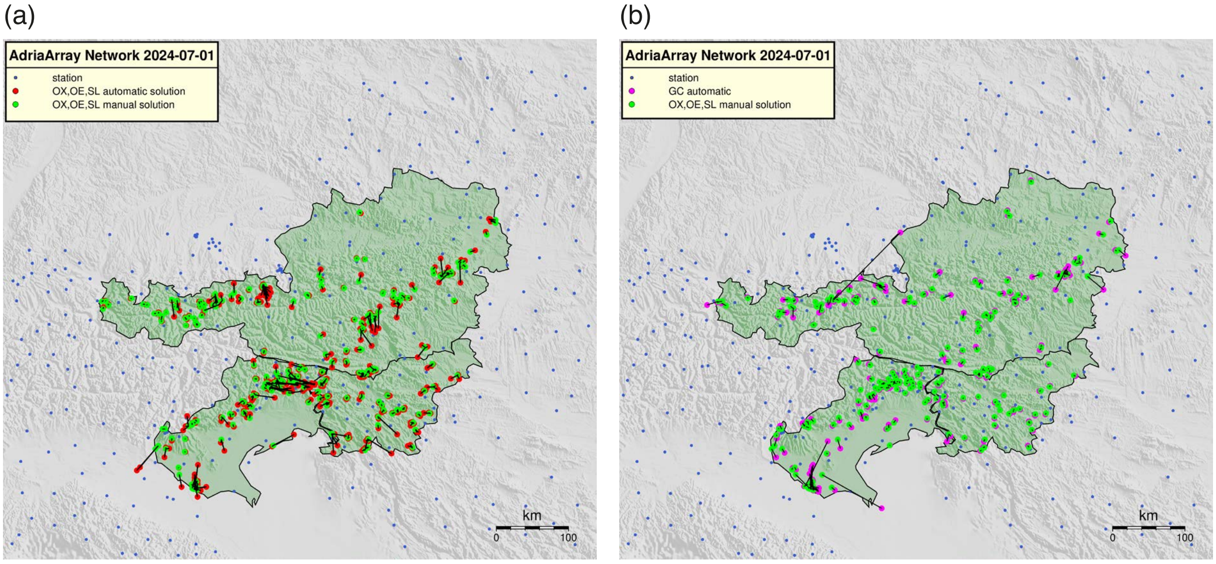

Figure 6. (a) For the individual institutions, comparison between automatic real-time locations (red dots) and manual locations of the individual institutions (green dots). (b) Comparison between GOAT-CASE earthquake locations (pink dots) and manual locations of the individual institutions (green dots).

GOAT-CASE (GC) experiment and the manual locations of the three institutes (GA, OGS and ARSO) above a threshold of local magnitude $M > 1.5$ for the first two years of the experiment. The blue dots are the seismic stations within the study area that were used for the experiment: for various reasons, not all seismic stations were usable during the first two years of the GC experiment. Manual locations (reference) are shown in green colour, automatic location in red colour and GOAT-CASE locations are shown in pink colour. Automatic and GOAT-CASE locations are connected to the corresponding manual locations with dark lines. Figure 6 and Table 1 indicate that the GOAT-CASE experiment worked very well. Disregarding the few outliers in Fig. 6b we conclude that GOAT-CASE procedure is performing better in locating the earthquakes in the selected area than the single institutes, which is reflected also in the median distances from the manual locations shown in Table 1. The average GOAT-CASE distance though is larger than the average of GeoSphere automatic, which is mostly attributed to the large error in location of an event in West Austria. In Fig. 6 we show only locations that are associated with manual locations: therefore, the sets of events on the left and right side differ slightly.

Table 1. Outcome of the GOAT-CASE experiment: distances in km from the manual locations.

	Number of events	Average distance from manual locations	Median distance from manual locations	Min distance from manual locations	Max distance from manual locations
ARSO automatic	117	8.80	3.52	0.37	37.64
OGS automatic	249	7.09	3.11	0.13	238.42
GA automatic	280	3.46	2.29	0.08	25.85
GOAT-CASE	336	4.48	2.24	0.21	131.48

In Fig. 7 we show the distributions of the differences between automatic and manual solutions for the three institutions and for the GOAT-CASE experiment. We see that most events located by automatic real-time systems of the participating institutions miss the reference locations by some km, which is also the case with the GOAT-CASE locations, but with fewer outliers. We attribute this to the larger number of onset detections used in GOAT-CASE procedure. According to the distribution of distances between manual and GC locations (Fig. 7, lower right), most GC locations are less than 10 km apart from reference. The group of events with location errors between 10 and 15 km are mostly stacked in distinct regions in SW OGS area, West Austria near Innsbruck and East Austria near Vienna, with the largest error in location exceeding 130 km.

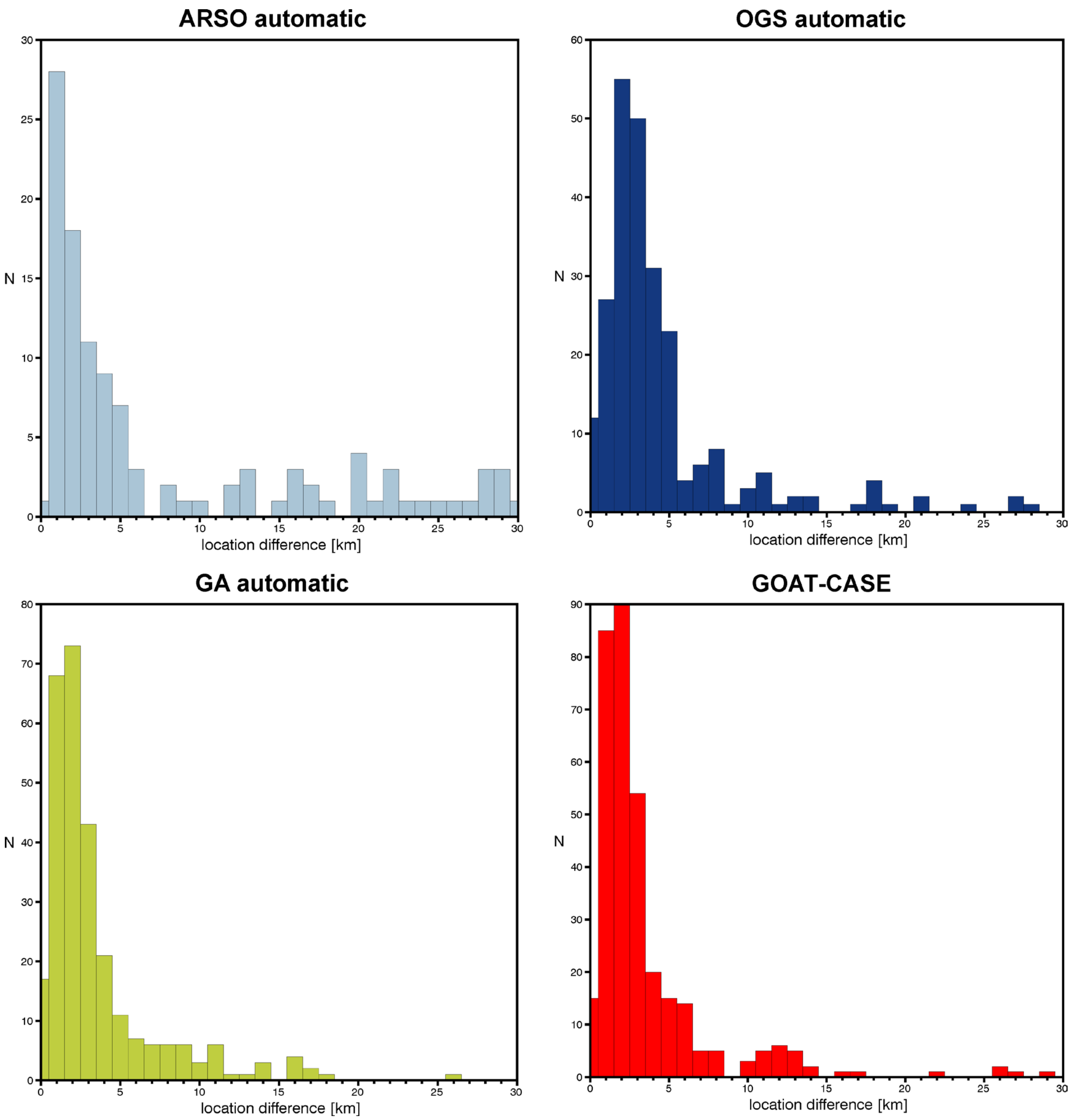

Figure 7. Distributions of distances between automatic and manual locations for the three participating institutions and for the GOAT-CASE experiment (lower right) in bins of 1 km.

4. Conclusions

The GOAT-CASE experiment proved to be very helpful in finding problems and highlighting differences in our routine seismic monitoring. For example, ARSO in Slovenia showed a lower magnitude threshold in its earthquake catalogues. Further on, the localization of events outside the GC area needs to be better tuned (better selection of stations, better tuning the grids, etc.). The GC experiment was performed on archive data for the first two years, while some tests clearly indicated that running it in near real time would significantly reduce the workload. GeoSphere Austria is routinely collecting locations in real time from other agencies, like INGV, ARSO and USGS: this improves its location capabilities and reliability. Exploiting the GOAT-CASE experiment, it seems appropriate that OGS and ARSO follow this procedure, at least for the earthquakes in the GOAT-CASE area.

All GOAT-CASE data will be made publicly available: this will facilitate further tests and comparisons within the AdriaArray project.

Data availability statement. Data available on request, contact authors.

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