

Data Quality Control of the Malta Seismic Network (2015-2024)

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Abstract

Malta lies in a seismically active region of the Central Mediterranean, where local and distant earthquakes pose a hazard to the local community. To address this, the Malta Seismic Network (MSN) was established, growing from three to eight stations over the past decade. This study reviews the performance and data quality of the MSN, assessing availability, noise levels, timing accuracy, and sensor orientation. Results show generally reliable operation, though a few individual stations faced challenges such as power shortages, equipment failures, and timing inconsistencies. The network has proven crucial during seismic crises and of benefit for geophysical investigations. Future developments aim to expand the station coverage and strengthen international collaborations, ensuring the MSN continues to advance earthquake monitoring and geophysical research in Malta and beyond.

Keywords: Seismology; Quality Control; Malta; Network

1. Introduction

Malta is located in a relatively stable part of the Pelagian Block in the Central Mediterranean, between Sicily and Libya, surrounded by extensional faulting that typically causes light-to-moderate earthquakes (Galea, 2007; Agius et al., 2020). The islands are occasionally also affected by more distant earthquakes from the Calabrian and the Hellenic Arc subduction zones (Galea, 2007). The main aim of the establishment of the Malta Seismic Network (MSN) was to improve the detection, location, and cataloguing of seismic events in the area (Agius and Galea, 2011; Agius et al., 2020) and provide critical data for assessing seismic risk, improving building codes, and enhancing public safety through early warning and rapid response systems. Moreover, high-resolution seismic observations contribute to advancing scientific understanding of the geodynamic processes shaping the central Mediterranean region. With an increasing population density and expanding infrastructure on the islands, the implementation of a robust seismic network on Malta is a vital investment in national resilience, ensuring that both scientific research and civil protection efforts are informed by reliable, real-time seismic information.

Since the establishment of the MSN 10 years ago (Agius et al., 2015), the network has seen an expansion from three to eight seismic stations across the Maltese islands (Galea et al., 2021) (Fig. 1). The network is operated by the Seismic Monitoring and Research Group (SMRG, <https://seismic.research.um.edu.mt>) within the Department of Geosciences, University of Malta (UM). The MSN is registered with the International Federation of Digital Seismograph Networks (FDSN) code ML (University of Malta, 2014). The network is integrated into the broader

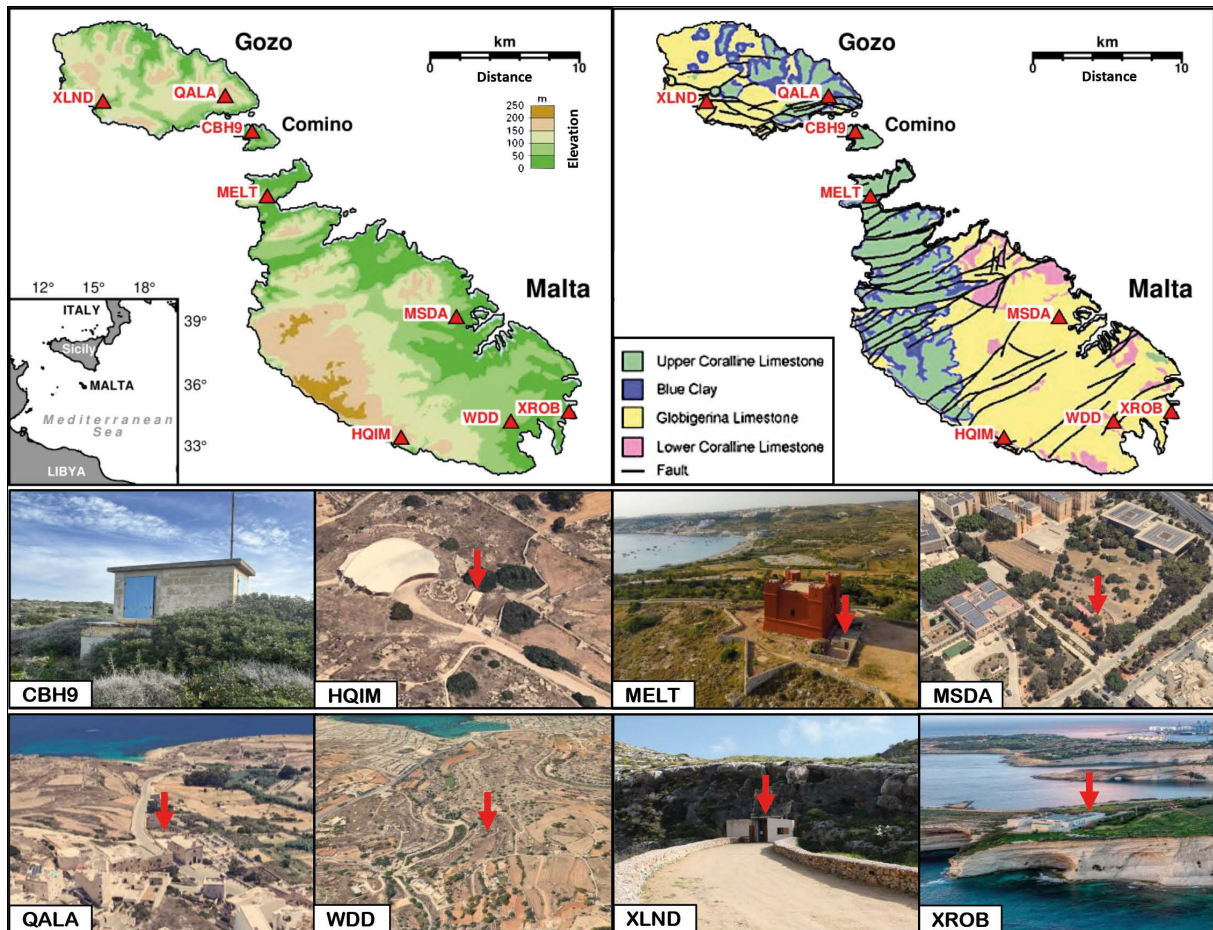


Figure 1. Stations of the Malta Seismic Network located across the three largest islands of the Maltese archipelago. Top left: Elevation map, with inset showing Malta’s location on a regional map. Top right: Simplified surface geology map of Malta. Bottom images show environmental settings of each site location (red arrow). Panoramic views are obtained from Google Earth.

Mediterranean monitoring frameworks by providing real-time access of three seismic stations through the European Integrated Data Archive (EIDA) and service infrastructure within ORFEUS datacentres (Strollo et al., 2021), thus strengthening regional cooperation and contributing to more effective hazard mitigation strategies. Data from station WDD, located in the south of Malta, has been available since 1995 as part of the MedNet network (FDSN code MN, Boschi et al., 1991), while stations MSDA and XLND, located at the University of Malta Msida campus and Xlendi (Gozo) respectively, have been made publicly available since October 2022. The data is also part of large continental-wide networks such as the Virtual European Broadband Seismograph Network (van Eck et al., 2004) and AdriaArray (Kolínský et al., 2025).

The primary challenge in operating a seismic network is maintaining continuous, high-quality data recording while ensuring consistency across all stations. This can be particularly difficult due to varying site conditions, including geological and environmental factors, accessibility constraints, unstable power supplies, unreliable internet connections, and equipment failures such as malfunctioning sensors, GPS units, or digitisers. As the network expands, the need for more robust backend systems and increased data storage grows. The processing of seismic data is not limited to local earthquake monitoring but can be used for seismic studies such as imaging structures and dynamics from a local scale (e.g., Laudi et al., 2023; Farrugia et al., 2024) to broader regional studies (e.g., Agius et al., 2022). Thus, it is important to acquire the highest quality data for different types of seismic studies and future investigations.

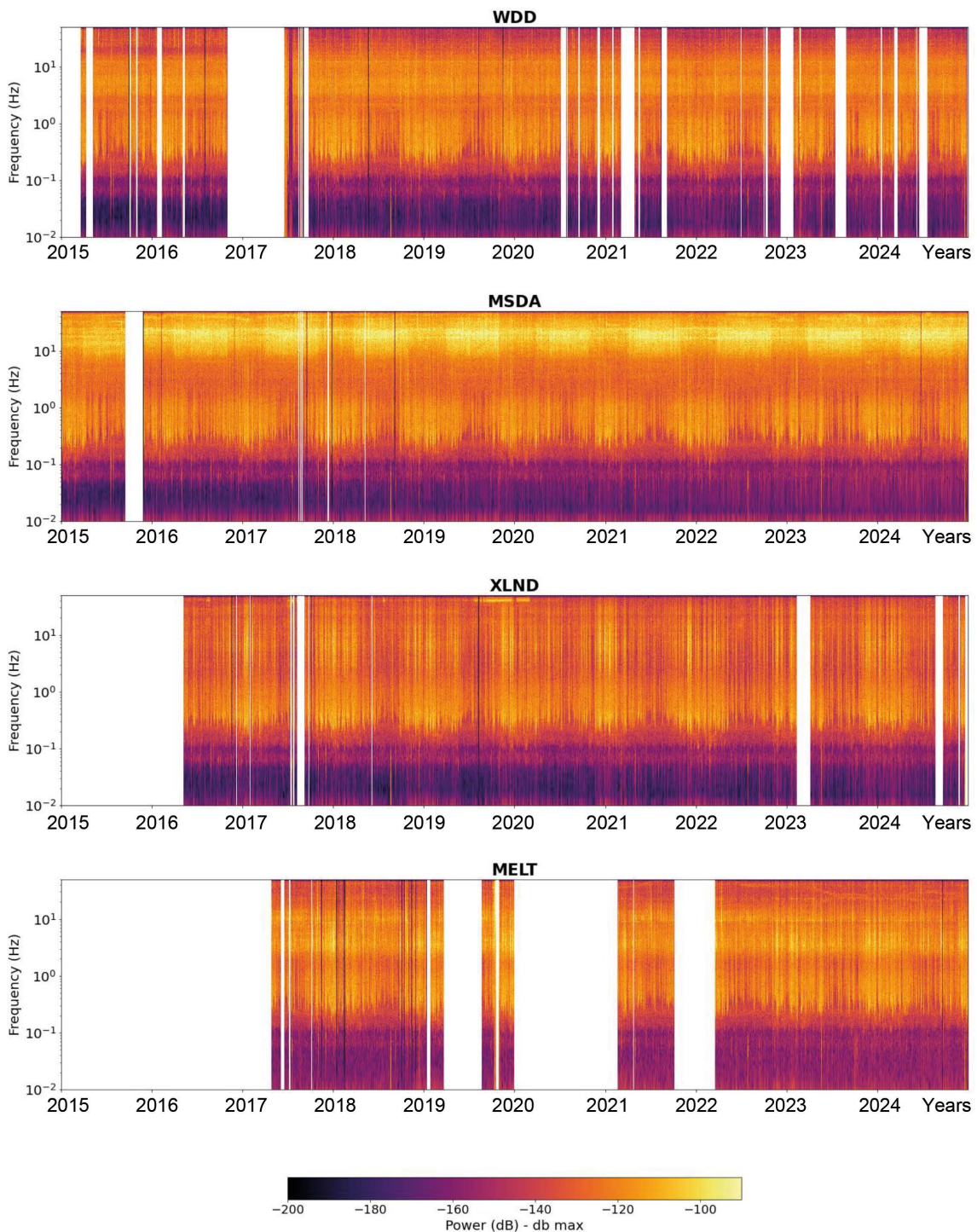
Here, we present a comprehensive review of the MSN’s data quality to assess the performance of each station. This analysis provides data users with a clearer understanding of data quality, enabling them to make necessary corrections if needed. Furthermore, by identifying the strengths and challenges of the MSN, this study contributes to the ongoing enhancement of Malta’s seismic monitoring capabilities and informs future plans for the network expansion.

2. Data processing

We process the data from MSN stations operating between 2015 and 2024 to look into data availability, spectral content, timing, and orientation. The data is in standard SEED format (Ahern et al., 2012) and processed using ObsPy (Beyreuther et al., 2010).

2.1 Spectral analysis

We perform daily spectral analyses using the Matplotlib Python library to process and visualise the data. In order to process the entire 10-year data, we took a time window of 5 minutes at 03:00 am each day. This time was chosen



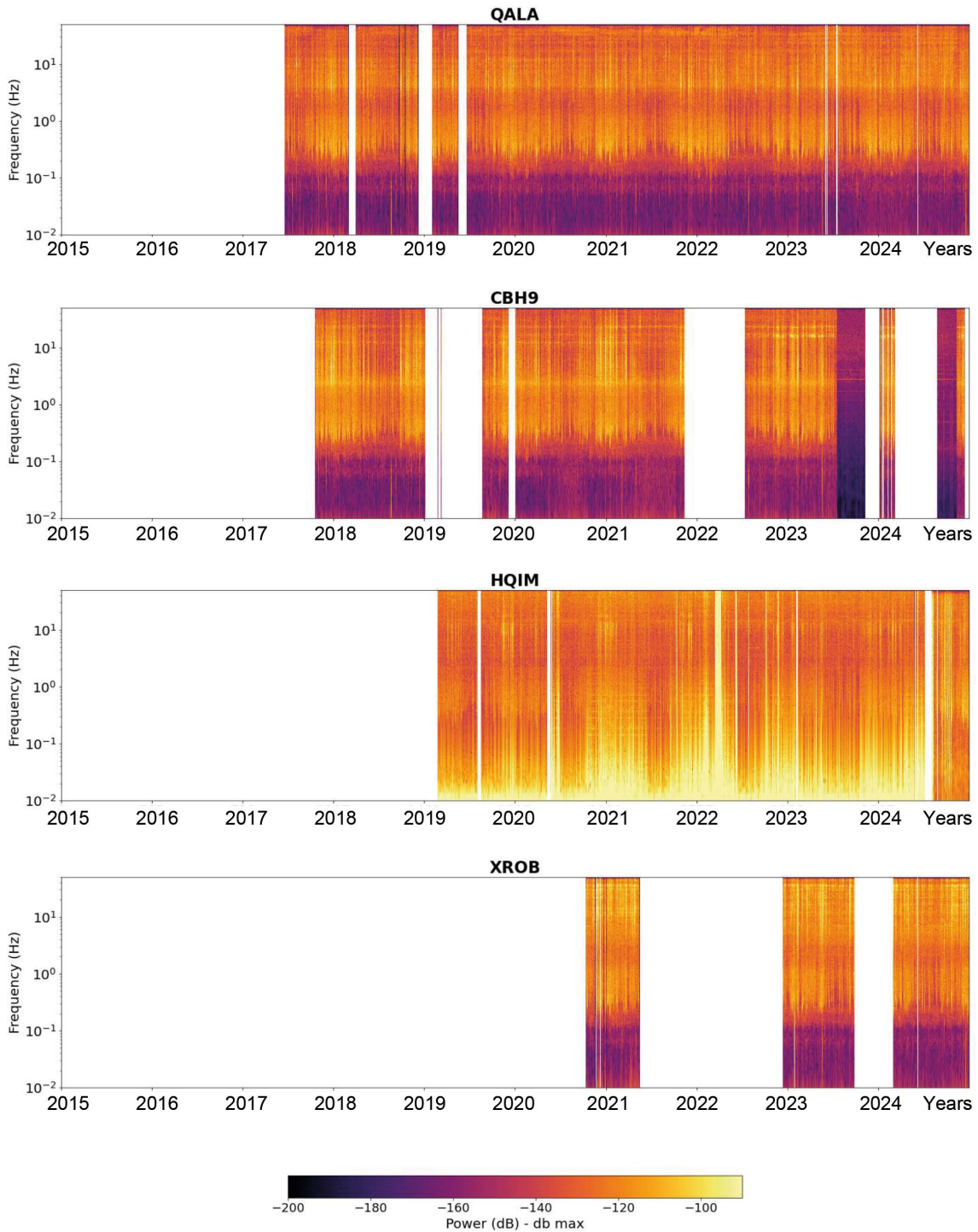
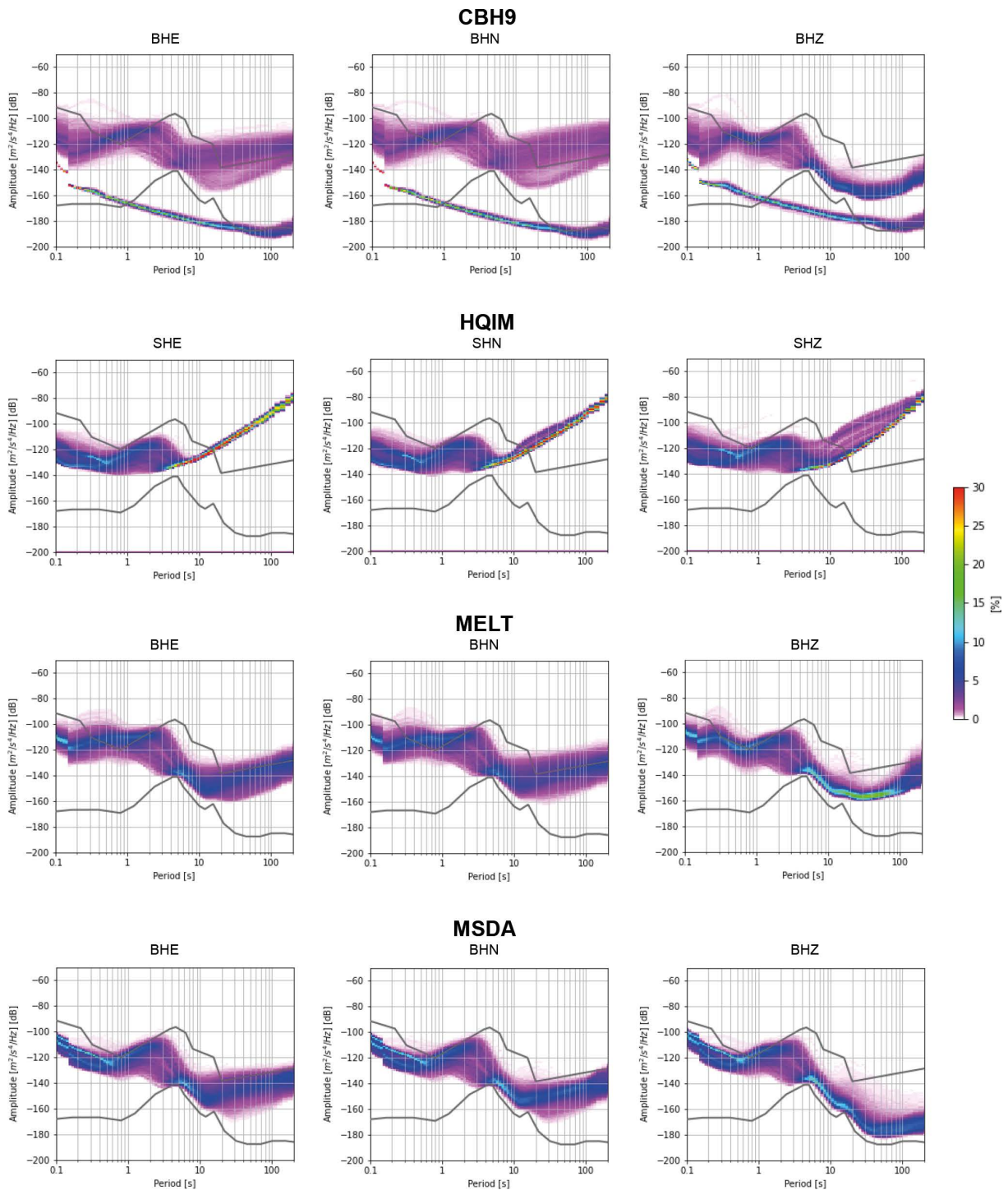


Figure 2. Data availability and spectrograms of the Malta Seismic Network. Gaps in the spectrograms show missing data. Stations are in the order of installation.

as it is most likely to have the lowest anthropogenic noise during the day. Any gaps were filled with zero values, data was detrended, 5% tapered on both sides, and the instrument response was removed to output acceleration. We compute the spectrogram of the vertical component of the HH channel for all stations except for HQIM, which has channel SH, all at 100 samples per second stream, splitting the data into a number of frequency-dependent points used in the Fast Fourier Transform (NFFT). Spectrograms are a good tool for rapidly assessing the change of a nonstationary signal’s frequency content over time. Figure 2 shows the spectrograms of the eight stations from MSN, sorted in chronological order as the stations were added to the network over the years, the first and latest being stations WDD and XROB respectively. Gaps in the data indicate no data availability.

2.2 Probabilistic power spectral density

Another way to assess the performance of a seismic station is to perform probabilistic power spectral densities (PPSD) (McNamara and Buland, 2004). Unlike spectral time series (Fig. 2), PPSDs show the probabilistic value of the amplitude for a set frequency within the waveform data (Fig. 3). PPSD graphs are a well-known method to assess the data quality of a seismic station because they give a good overview of the general behaviour of the amplitude-frequency characteristics of the ambient seismic noise (e.g., Petersen et al., 2019). The PPSD graphs are compared with low-noise (LNM) and high-noise models (HNM) (Peterson, 1993) and thus help establish if the station performance is within expected noise ranges. The PPSDs are calculated using the routine available in ObsPy. Here, we process that data for the year 2023, when all the stations were in operation, and thus all stations are likely to record the same earthquakes and similar ambient noise across the islands. We processed the three components,



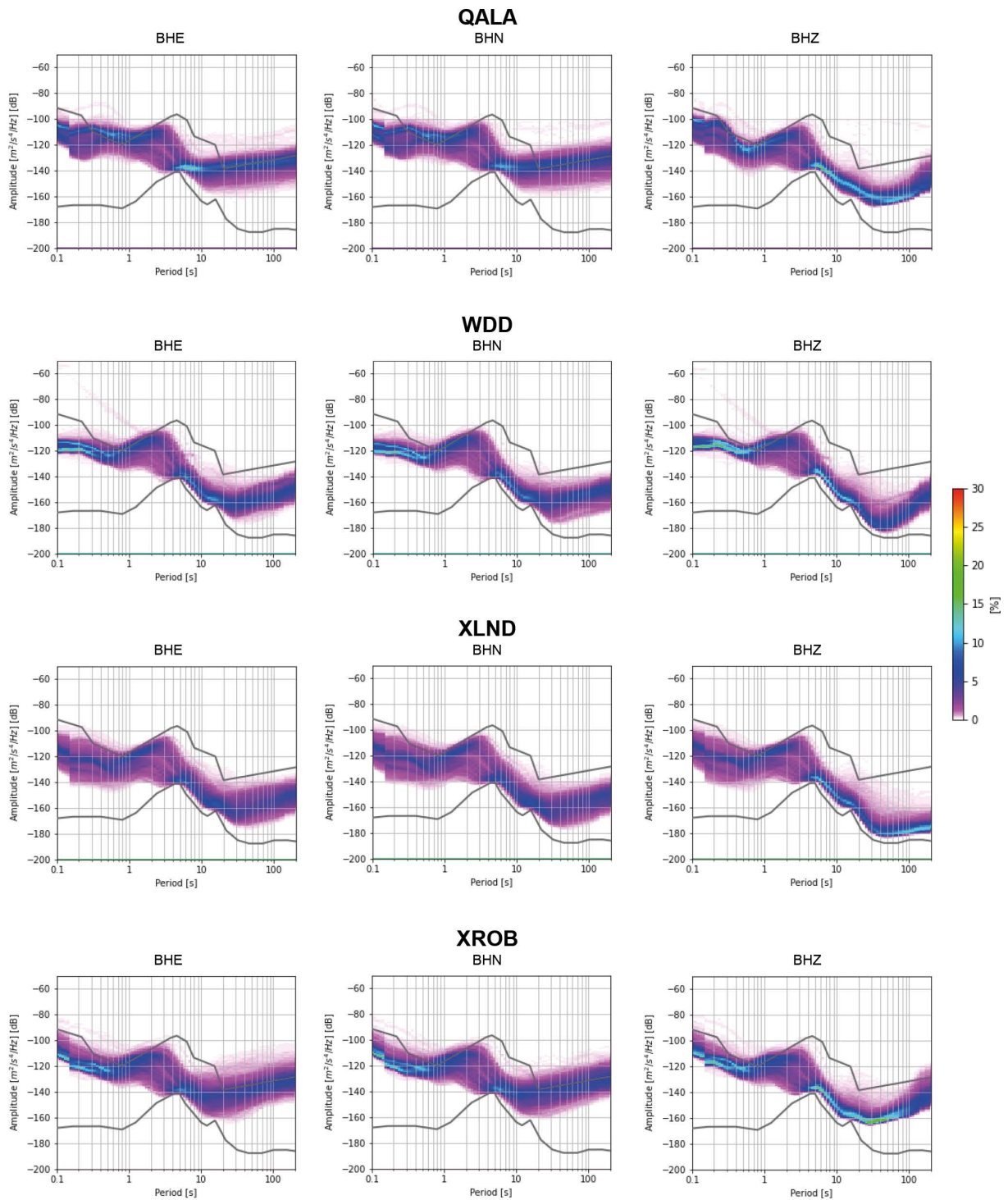


Figure 3. Seismic noise Probabilistic Power Spectral Densities (McNamara and Buland, 2004) for the year 2023, when all the stations were in operation. Left-to-right panels show the east, north and vertical components. Gray curves are the reference low-noise (LNM) and high-noise models (HNM) (Peterson, 1993).

Z, N and E, to compare the verticals with the horizontals. The latter are naturally expected to have higher noise levels. The BH and SH streams were used for the respective stations.

2.3 Timing consistency

Accurate timing is one of the most important parameters for a seismograph. It plays a crucial role in locating earthquakes, especially in small networks and on islands where precise localisation of nearby events is essential. A small error in timing can lead to significant mislocation of an earthquake, such as placing it offshore instead of onshore. To ensure timing consistency at each station, we analyse the arrival times of the *P* phase from regional and possibly more distant earthquakes. The *P*-wave travel-time residuals method is an effective, standard visual tool for identifying sudden jumps or linear drifts in a station's clock, which would manifest as a corresponding shift in the residual baseline. Each arrival is picked manually using earthquakes listed in the International Seismological Centre catalogue (ISC, 2025) that are located within a radius of 20 degrees from the station coordinates, have a maximum source depth of 40 kilometres and a minimum magnitude of 5. The manual picks are compared to theoretical arrivals based on the PREM model (Dziewonski and Anderson, 1981) and computed using TauP (Crotwell et al., 1999). The results are shown in Fig. 4.

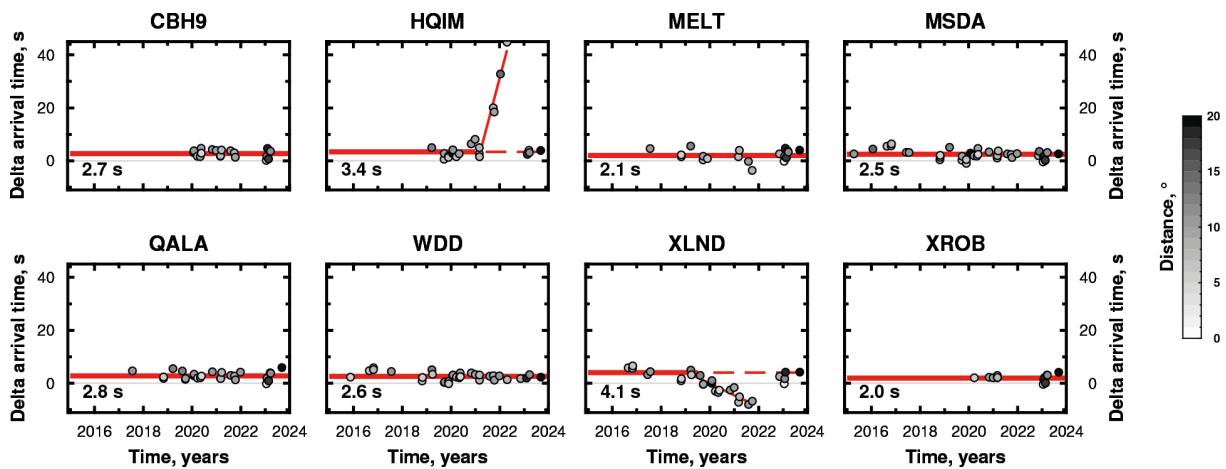


Figure 4. The arrival times of the *P* phase from regional and teleseismic earthquakes using data from the International Seismological Centre (ISC, 2025). Each arrival is picked manually using earthquakes that are located within a radius of 20° from the station coordinates, have a maximum source depth of 40 kilometres and a minimum magnitude of 5. Vertical axis shows the difference between the manual picks and theoretical arrivals based on the PREM model (Dziewonski and Anderson, 1981) and computed using TauP (Crotwell et al., 1999). Red line is the average value or linear trend. The earthquakes are plotted in time and colour-coded with epicentral distance.

2.4 Sensor orientation

Many seismic studies rely on the accurate orientation of vertical and horizontal components, including shear-wave splitting, surface waves, and receiver functions. Sensor orientation is typically set manually using a standard compass to align with true north. However, factors such as magnetic declination and technician accuracy can introduce errors. To verify alignment, the measured earthquake back azimuths derived from seismograms are compared with the theoretical back-azimuth derived from source and receiver coordinates. Following Galea et al. (2021), we analyse sensor orientation using data from local and regional earthquakes of magnitude 4.5 or greater and depths up to 40 km within a 20° epicentral distance, as listed in the ISC catalogue (2025). The waveforms are filtered, and one wavelength of the *P*-phase first arrival is selected. The earthquake back azimuth is determined from three-component wave polarisation (Magotra et al., 2002; Agius et al., 2018). This is compared with the theoretical back azimuth calculated from the station and epicentral coordinates to assess the sensor orientation (Fig. 5).

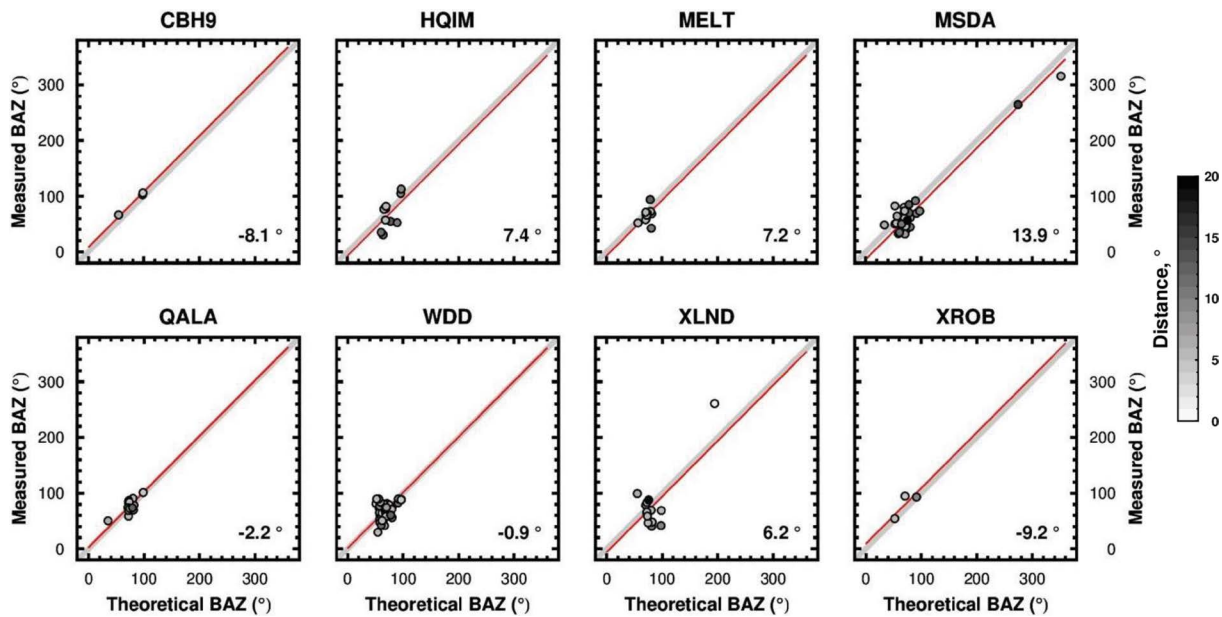


Figure 5. Sensor orientation measured from the wave polarization and compared to the theoretical back azimuth from station and epicentral coordinates. Earthquakes from the ISC catalogue between the years 2014–2024, with a magnitude >5.5 , a maximum depth of 40 km and within an epicentral distance of 20° are used. The waveforms are filtered, and 1 wavelength of the P phase is selected. The observed back azimuth is determined from 3-component wave polarization. Thick gray line is the 1-to-1 relationship between the measured and theoretical back azimuth. Red line is the average value.

3. Results

Data availability for the Malta Seismic Network varies from 59% for station XROB, to 99% for station HQIM (Table 1), with an average of 85% availability. Intermittent gaps, visible in Fig. 2, are primarily due to power problems or station maintenance.

The spectral time series in Fig. 2 show the overall station performance over time. In general, except for station HQIM, the stations show low power (in decibels) for the low frequency (long periods) and high energy in the higher frequencies (1–10 Hz). Seasonal summer–winter changes in the amplitude of frequencies between 0.1–1 Hz (1–10 seconds) are observed throughout the time series.

Station MSDA has high noise power at high frequencies (Fig. 2), probably because it is located at the UM campus close to roads with heavy traffic. Station HQIM is a short-period (10 s) seismometer at the time of study (recently replaced by a 60s instrument), thus, it performs poorly at long periods. Station CBH9 malfunctioned during the last months of 2023 and throughout 2024 during which the spectral signal can be seen to be flat (all purple). The effect on the spectral content during malfunctions can be better seen in the PSDs of Fig. 3 (CBH9), where the spectral curve does not follow the reference low and high-noise models (Peterson, 1993).

In the PPSD curves, all stations show a characteristic maximum at periods of 1–5 s, comparable to secondary microseismic noise in the Mediterranean (see, for example, Catania et al., 2025). For the shorter period band (<5 s) most curves fall within the LNM and HNM models, with the exception of stations CBH9 and MELT, and to a lesser extent QALA, whose horizontal-component curves exceed the high-noise model at periods of around 0.5–1.0 s. These three stations are the only ones that are installed on the topmost stratigraphic formation, Upper Coralline Limestone (Fig. 1, Table 1), which is underlain by a thick layer of clay. This type of geology always produces prominent Horizontal-to-Vertical Spectral Ratio (HVSr) peaks in this same period range throughout the Maltese islands (Farrugia et al., 2016). For longer periods (>5 s) these stations also exhibit horizontal component noise levels above the HNM, while the vertical components are markedly lower. Stations on bedrock (Globigerina Limestone on Lower Coralline Limestone) display better performance in all frequency bands (e.g., WDD and XLND).

Table 1. Technical specifications of the Malta Seismic Network stations.

Station Name	Lon °E	Lat. °N	Ele. m	Surface Geology	Sensor	Data Logger	Ins. Date yyyy-mm-dd	Data Trans.	Data Avail. %
CBH9	14.3314	36.0140	27	UCL	Trillium Compact	Centaur	2017-10-18	Cell	74
HQIM	14.4426	35.8277	129	GL	Geotiny (10 sec.) Geotiny (60 sec.)	Geobit	2019-02-19 2024-07-05	Cell	99
MELT	14.3427	35.9747	98	UCL	Trillium Compact	Centaur	2017-04-25	Cell	73
MSDA	14.4839	35.9012	48	GL	Trillium 120PA	Centaur	2014-12-19	LAN	98
QALA	14.3202	36.0349	91	UCL	Trillium Compact	Centaur	2017-06-15	LAN	96
WDD	14.5246	35.8375	15	GL	STS-2	Quanterra	1995-07-07	LAN	84
XLND	14.2200	36.0323	6	LCL	Trillium 120PA	Centaur	2016-05-04	LAN	96
XROB	14.5680	35.8434	26	GL	Trillium Compact	Centaur	2020-02-19	LAN	59

GL: Globigerina Limestone; UCL: Upper Coralline Limestone; LCL: Lower Coralline Limestone.

The timing accuracy of the digitizer was good with an average uncertainty of 0.1 μ s. Delay times from the predicted and observed *P* phase arrivals are in the range of 2.0-4.1 s for the stations respectively, and are in general stable throughout the 10 years of operation and consistent for earthquakes of regional and possibly larger distances. The method reveals clear timing problems occurring at stations HQIM (March 2021 to February 2023) and XLND (September 2019 to November 2022), with linear drift rates of approximately +96 and -12 milliseconds per day, respectively, during the affected months until the timing problem was resolved and the time delays returned to their normal values.

For the sensor orientation assessment, the available earthquake data set unfortunately provided a highly restricted range of azimuths. Most of the measurements were made for earthquakes originating from the east (40-100°), from the Hellenic subduction zone, Turkey and along the Alpide belt, whereas regions from the south and west of Malta are less seismically active. Nevertheless, for these earthquakes, many back azimuth measurements match closely the theoretical back azimuth values (<10°), indicating that sensor orientation is correct. Variations from the true back azimuth are to be expected due to polarization errors, earthquake location uncertainties, local and regional geological influences, and possibly due to ray path bending along subduction zones such as along the Hellenic or Calabrian slab.

4. Discussion

In general, the stations are kept in their original installation as described in Galea et al. (2021), and performed within their expected instrument sensitivity and within expected noise ranges for all the three components. All the stations have fixed power supply, with some having fixed broadband internet and others with mobile phone (cellular) data exchange (Table 1). Loss of data transmission is generally recovered automatically by SeisComP data acquisition system (Helmholtz Centre Potsdam GeoForschungsZentrums German Research Centre for Geosciences and gempa GmbH, 2008); short gaps in the data are mainly related to power outages, particularly following thunderstorms (WDD, MSDA, XLND, QALA, HQIM). Stations MELT and XROB suffered prolonged power cuts due to restoration works done to the sites housing the instruments, and station CBH9 is located on a remote island requiring additional logistics to visit the site. Moreover, station CBH9 had issues with

the digitizer towards the end of 2023 and again towards the end of 2024 after repairs failed. The malfunctions can be seen in the spectrograms (Figs. 2 and 3).

The broadband qualities of the seismic network are reflected in the variety of sensors used: STS-2, Trillium 120PA, Trillium Compact, and Geotiny (10, 60 seconds) (Table 1, Fig. 3). At long periods >40 seconds, sensor Trillium 120PA has the lowest noise levels in the range of -180 to -170 dB (station XLND and MSDA) up to 200 seconds, whereas sensor STS-2 has noise levels increasing from -175 to -150 dB for the same period ranges (WDD, Fig. 3). The Compact Trillium sensors have a minimum of -160 dB at about 20-50 seconds and increase gradually to -140 dB at 200 seconds (CBH9, MELT, QALA, XROB). The spectral performance limitation of station HQIM (Geotiny 10 seconds) is clearly visible with a cut-off at periods >5 seconds (Fig. 3). The sensor was replaced with a 60-second Geotiny broadband seismometer in July 2024. The improvement in the quality of the data and increase in a wider frequency range sensitivity can be seen in the spectrogram toward the last half of 2024, with lower noise levels for low frequencies (Fig. 2).

Timing difference between the theoretical time arrival of the *P* phase with the observed pick are expected, with variations due to ray paths propagating through lithospheric/mantle anomalies between the source and the receiver, hypocentral mislocations, etc. Topographical and geological variations at different stations of the MSN are only expected to contribute delay time differences in the order of 0.1 s or less (Randich, 2020). Problems with instrument timing were a result of malfunctions or problems with GPS signal reception that caused timing errors to increase over time. Although SeisComP does give information on the quality of the timekeeping, such timing issues are not always easy to identify in the early days and weeks of when the problem starts and are better analysed retroactively. Timing issues at XLND were related to a very long passive GPS cable (~50 meters) used to reach the surface above the station located inside an underground complex. The problem took long to resolve because no physical damage was observed on site and the cable had no prior problems. Following various tests and changes to the GPS antenna, the cable was replaced by taking a shorter route and surface exit. One possible reason for this timing issue could have been a result from a software update of the digitizer. In the case of station HQIM, the GPS antenna suffered damage during a storm and was eventually replaced. The timing drifts were previously observed in an unrelated study involving cross correlation of ambient seismic noise waveforms (Laudi et al., 2023), Such method provides high-resolution on the timing errors, however it depends on the stability of another station.

Despite the advancement made with the expanded seismic network to monitor local earthquakes, the challenge to detect and locate more distant offshore earthquakes, particularly towards the east, south-east to south of Malta remains. One major limitation is the station coverage with a very narrow azimuthal gap as shown in Fig. 6. Besides the MSN, reliable real-time seismic networks in the region are restricted to Sicily, southern Italy and the Pelagian islands; no data has been exchanged or was publicly available from Libya and Tunisia during the years of MSN. In particular, for micro-earthquakes (<M_L3.0) in the south-eastern quadrant around the islands, useful data is generally available only from the MSN, and often only from a few stations. Single-station epicentral

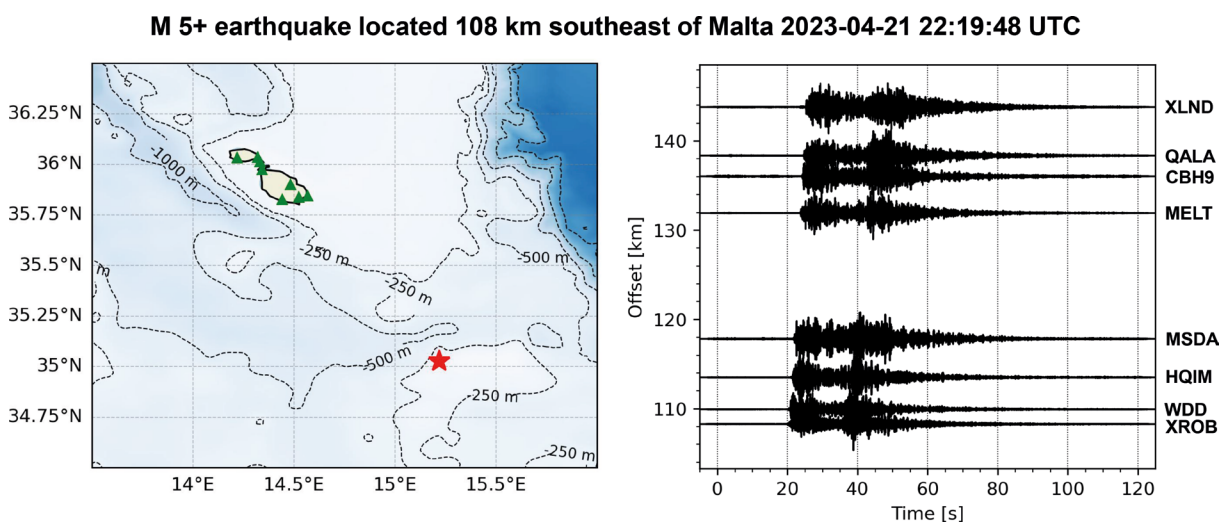


Figure 6. An example of earthquake seismograms recorded on the Malta Seismic Network. The earthquake occurred 108 km southeast of Malta at a magnitude of 5+ on 2023-04-21 22:19:48 UTC time (red star).

location has helped considerably to quantify and map such seismicity (Agius and Galea, 2011, Agius et al., 2020) but hypocentral parameters using this method suffer from a lack of precision. This situation can only be resolved with exchange of data from stations located on North Africa and/or the installation of ocean-bottom seismometers. A number of initiatives for collaboration with neighbouring North African countries and seismic networks over the years have been taken by the SMRG, including funded research project proposals and training of students, however the real-time exchange of data is still a goal to be achieved.

While the primary scope of the network remains that of monitoring local earthquakes in real-time, the data has been used for other studies such as to determine the exact time of collapse of the then popular Azure Window, (Galea et al., 2018), to explore the signature of a Medicane by combining seismic data together with satellites, radar, and marine buoys (Piroddi et al., 2021, Borzi et al., 2022), and to compare site amplifications using noise and earthquake data (Farrugia, et al., 2024). In another study the data was used to detect water level changes in the mean-sea-level groundwater aquifer below the islands (Laudi et al., 2023). Future studies will include an earthquake catalogue for this same period of operation, investigation of the shallow subsurface from quarry blasts and seismic tomography for the Maltese islands.

5. Concluding remarks

We have reviewed the performance and reliability of the Malta Seismic Network stations with regard to four main aspects: data availability, noise spectral levels, timing consistency and sensor orientation. As is to be expected, individual stations have occasionally presented instrumental or transmission problems, leading to loss of data, however it has never occurred for the whole network to be inoperative. The relatively small interstation spacing (less than 20 km) ensures that there are usually enough earthquake recordings to enable a reasonably good location of near and regional earthquakes, and adequate redundancy for global earthquake location. The data completeness over the monitoring period varies between 59-99%. Over this period, two stations encountered serious timing problems, clearly visible on a calibration graph, but these have been resolved. Sensor orientation was also observed to be satisfactory at all stations.

In terms of seismic noise level, the analysis reflects the general problems encountered by seismic networks on small islands, namely closeness to the sea and urban noise, particularly traffic. PPSD curves show horizontal component noise levels to exceed the vertical component level. In addition, there appears to be a geological site effect, where the horizontal component noise level at stations situated above a buried clay layer is enhanced in the 1-2 Hz band, and exceeds the HNM. Other stations perform satisfactorily at all frequency bands.

The development of the Malta Seismic Network since 2014 has produced a significant increase in both the quantity and quality of earthquake data and seismicity evaluation. It has also contributed significantly to public information and awareness, while facilitating the collaboration between the SMRG and civil authorities. For example, the MSN played a crucial role during the unusual seismic crisis between 2020-2023. Earthquakes struck a few kilometres offshore south of Malta (Galea et al., 2023), north of Gozo (22nd November, 2022, magnitude 4.5), followed by another long sequence consisting of hundreds of earthquakes located about 100-120 km south-southeast of Malta. Some of these earthquakes had magnitudes greater than 5 (Fig. 6) and were felt across the islands. The real-time system provided valuable information to the increasingly anxious population as daily earthquakes were felt for several weeks. The earthquake monitoring website (<https://seismic.research.um.edu.mt>) reached record hits of over 100,000.

While the Malta Seismic Network has faced challenges and limitations, ongoing improvements and future plans are expected to strengthen its performance, broaden its coverage, and expand its scientific and societal contributions. Additional stations are planned to expand the Malta Seismic Network. These include the installation of a seismic station in the north of Gozo, at the Ta' Giordian lighthouse, for better monitoring of the offshore seismicity there, a station in the center of Gozo at the University of Malta Xewkija Campus, and another station on the west coast of Malta (Fig. 7). This setup will improve the geometrical distribution of the stations across the Maltese islands. Plans are also underway to set up a Seismology in Schools program (e.g., Denton, 2008) with the distribution of Raspberry Shake sensors (Anthony et al., 2019) to post-secondary schools across Malta and Gozo (Fig. 7). From time to time, temporary experiments such as FASTMIT (Bozionelos et al., 2019) are also deployed, giving the opportunity to increment and enhance the network and perform detailed seismicity and geophysical studies. Other plans are to automate quality control with the automatic generation of plots like those presented here.

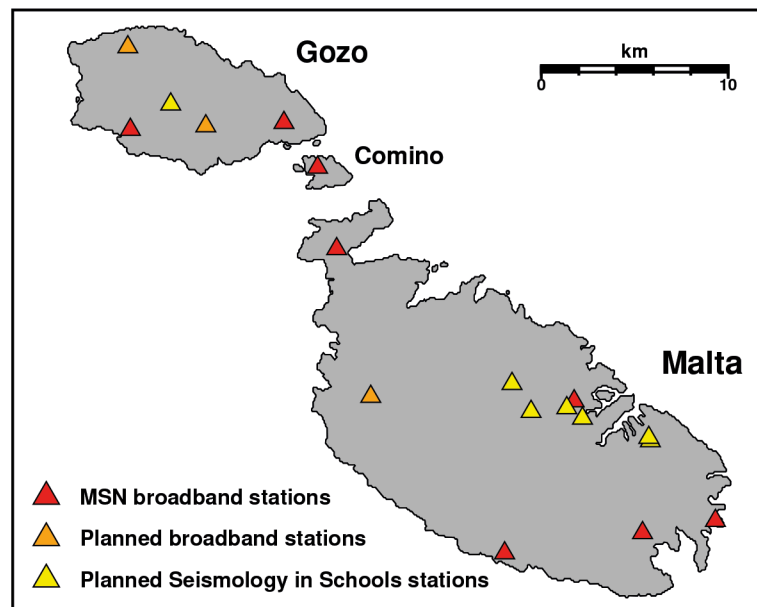


Figure 7. Planned expansion of the Malta Seismic Network. Red triangles are the current MSN broadband stations. Orange triangles are planned broadband stations. Yellow triangles are planned low-cost seismic stations for the “Seismology in School” program.

The advancement of the network will not only help the local community, but also the international seismological community with sharing of real-time data to the VEBSN (van Eck et al., 2004) and ongoing projects like AdriaArray (Kolínský et al., 2025) to study large scale geodynamics across the Mediterranean and beyond.

Data availability statement. Data of WDD, MSDA and XLND can be downloaded at: <https://webservices.ingv.it/fdsnws/dataselect/1/>. Data of other MSN stations is available on request.

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