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Research Note

Performance evaluation of Wied Dalam (WDD) seismic station in Malta

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Abstract. The continual operation of a permanent seismograph, now exceeding a couple of decades in some cases, naturally involves changes of hardware and software over time. Nonetheless, the long-term, consistent performance of the seismic station, and the good quality of its data, is very important for national seismic studies investigating the local seismicity, and also important for the international seismological community researching regional tectonics and deep Earth structures. Here we investigate the data availability and quality of the currently only seismic station on Malta (WDD) since its installation in 1995, and establish spectral patterns in the seismic data that may be influenced by diurnal variations, seasonal weather changes, and/or site-specific settings. The results are important for the future deployment of permanent seismic stations on the Maltese islands, and for the analysis of local seismic hazard and ground motion studies.

Keywords WDD station, quality control, seismic ambient noise, power spectral density, probability density function, site effect.

1 Introduction

The deployment of permanent seismic stations across the globe has been taking place for over a century. Seismographs have witnessed numerous changes in instrumentation, data recording and storage, as well as in data communication. Despite the rapid advancement in technology, cheaper equipment, and quicker installations, the proper installation of a seismic station with a good site selection and ongoing station maintenance remains critical for the long-term quality of the seismic data. Moreover, the usefulness of seismic data is greatly increased when 'background' seismic noise levels are low (McNamara and Buland, 2004). Such data is often used for seismic studies relating to regional and global seismicity and investigations of seismic sources and deep earth structures. Here we investigate the overall performance of the permanent station on the island of Malta, Central Mediterranean.

The University of Malta has operated various seismographs since the beginning of the 20th century, when seismographic instrumentation was in its early stages. A Milne-Shaw horizontal pendulum seismograph operated from around 1900 to the 1950's. In 1977 a vertical long-period Sprengnether seismograph with photographic recording was installed. This was replaced some years later by a three-component short period station with analogue paper recording. The seismograms from these instruments are still preserved by the Seismic Monitoring and Research Unit (SMRU) within the Physics Department at the University of Malta. At present the SMRU operates one permanent, broadband seismic station in Wied Dalam (WDD) in the southern part of the island, housed in a disused tunnel at a distance of about 900 metres from the coast (Figure 1). WDD seismic station is located on Lower Coralline limestone, the oldest of the four main geological formations outcropping on the Maltese archipelago. The geology of the Maltese islands is relatively young, with the oldest rock dating back only to the Tertiary period (Pedley et al., 1978; Mourik et al., 2011). The station was installed in June 1995, as part of the MedNet network,

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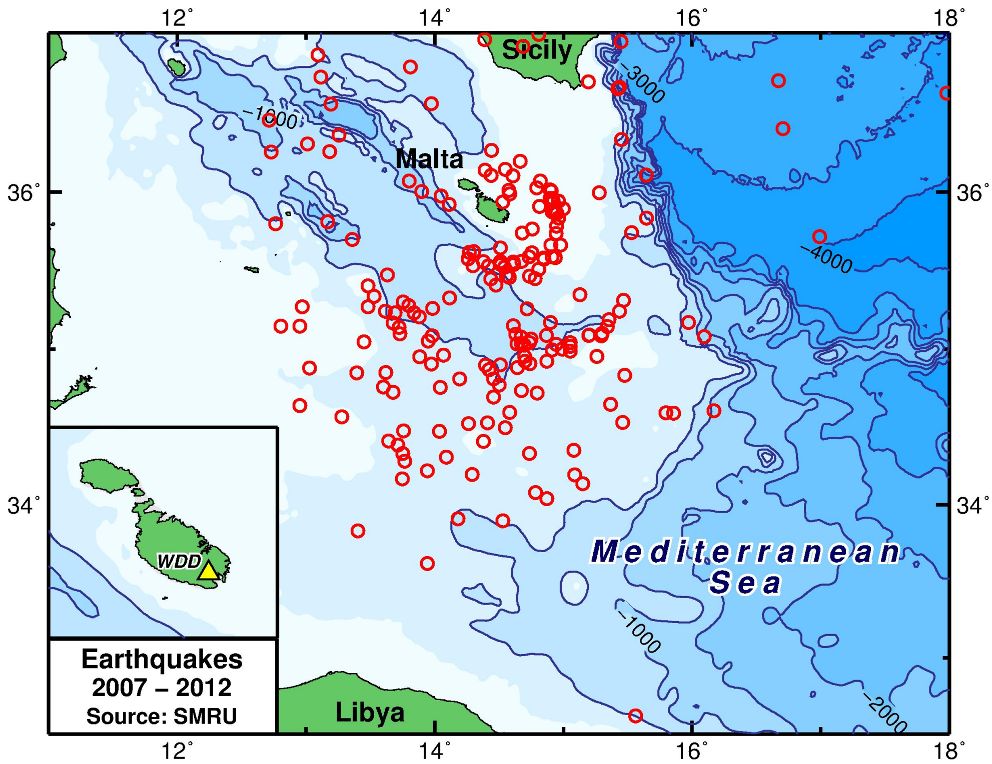

Figure 1: The seismicity around the Maltese islands. Red open circles are epicentres of earthquakes located for the time period 2007–2012. Data is from the online catalogue of the Seismic Monitoring and Research Unit, University of Malta http://seismic.research.um.edu.mt. Different shades of blue indicate the bathymetery in the region. Contour lines show specific depths in metres. Inset shows the location of the permanent broadband seismic station WDD on Malta (yellow triangle)

Figure 2: WDD seismic station. Left: The Quanterra Q680 data acquisition system. Right: The Streckeisen triaxial seismometer placed on a concrete platform.

managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome (Boschi and Morelli, 1994). The present instrumentation consists of a Streckeisen triaxial seismometer (STS-2) and a Quanterra Q680 data acquisition system (Figure 2) that transmits data in real-time to the SMRU at the Physics Department, via the SeedLink Internet protocol. This also enables real-time transmission to several European data centres. WDD also forms part of the Virtual European Broadband Seismic Network (VEBSN) managed by ORFEUS Data Centre in the Netherlands (van Eck et al., 2004).

The Maltese islands have been affected by a number of earthquakes in the historical past, the epicentre of these earthquakes being in the Sicily Channel (bordered by the Sicilian, Tunisian, and Libyan coastlines), in eastern Sicily, and as far away as the Hellenic arc. Some of these

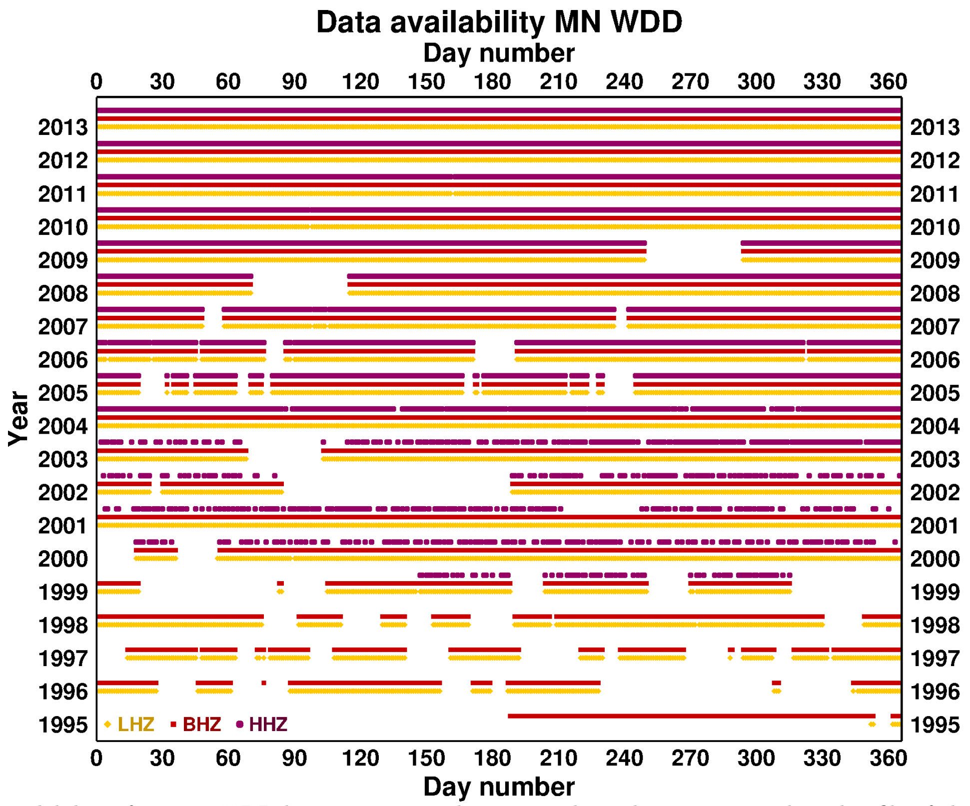

Figure 3: Data availability of station WDD between 1995 and 2013. Each mark represents a data day file of the respective vertical component: LHZ, BHZ, and HHZ.

earthquakes produced considerable damage to buildings (Galea, 2007). Since the station's installation, a significant database of earthquakes that have occurred close to the Maltese islands has been compiled. The seismicity for the period 2007–2012 is shown in Figure 1 and is thought to be mainly controlled by active faults in the Sicily Channel rift zone. The earthquakes shown in the figure were located using single-station polarisation analysis (Agius, 2007; Agius and Galea, 2011). This region is characterised by a moderate level of seismicity (Vannucci et al., 2004; D'Amico et al., 2013b) with magnitudes generally below 5. A study on this seismicity is important because it throws light on the activity and seismogenic potential of offshore fault systems. Many of these events, however, are too small to be detected by other European or North African stations, and therefore the presence of a sensitive seismograph on Malta is essential for producing a better picture of the seismicity.

In this study we investigate the data quality of the seismic station WDD and establish spectral patterns in the seismic data that may be influenced by diurnal variations, seasonal weather changes, and/or site-specific settings. The results will be important for the analysis of future installation of permanent seismic stations on the Maltese islands.

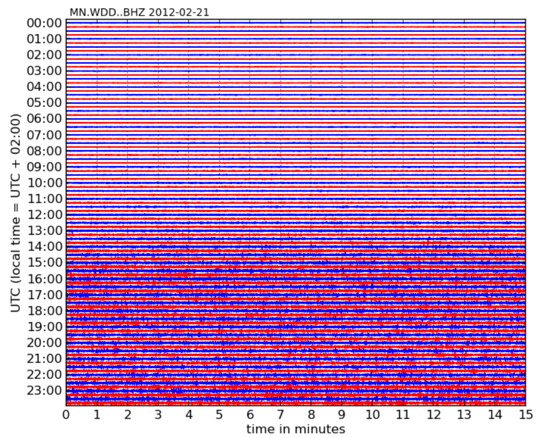

Figure 4: Varying amplitude of microseismic noise. The plot shows 24-hour seismic data of the vertical component (Z) at 20 samples per second (BH) for station WDD on 21st February 2012. Alternating blue and red traces represent 15 minutes of data.

2 Evaluating the seismic data quality

Two very important aspects of running and maintaining a seismic station is the data archiving and the regular analysis of its data quality. Digital seismic data of WDD station is available from international data centres such as ORFEUS and the Incorporated

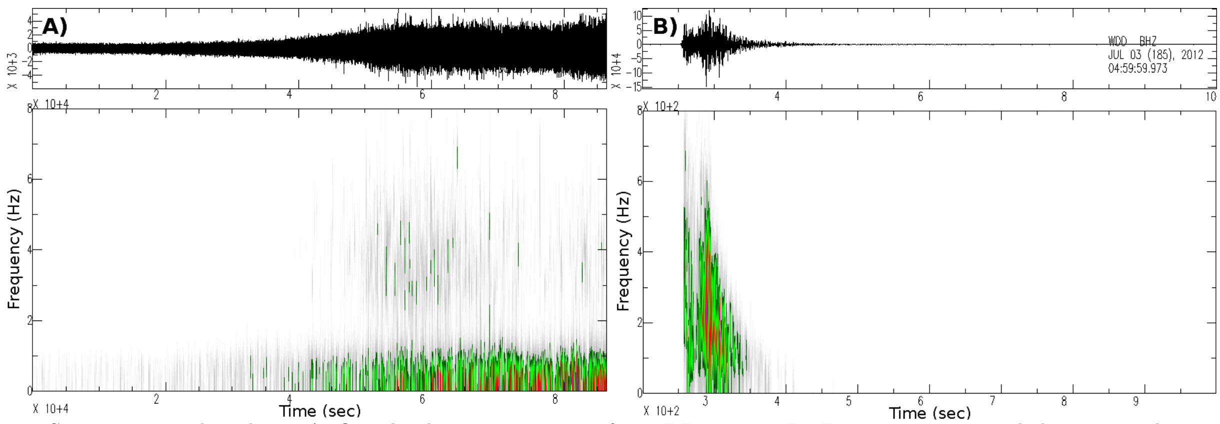

Figure 5: Seismic spectral analysis. A: One day long seismic trace for WDD station, BHZ component, recorded on 21st February 2012 (Figure 4). Below is the spectral analysis showing spectral power as a function of frequency and time. Red spots indicate higher energy. B: A seismic trace of a M 4.8 earthquake, 198 km south-east of Malta recorded at WDD, BHZ component, on 3rd July 2012, and the corresponding spectral analysis.

Research Institutions for Seismology (IRIS); a complete data set (since 1995) is available from the SMRU. The broadband seismic data is available in various channels HH, BH, LH, VH, and UH, with sampling frequency of 80, 20, 1, 0.1, and 0.01 samples per second, respectively. Figure 3 shows the data availability for the the vertical components LHZ, BHZ and HHZ. Continuous seismic data availability has improved over time, uninterrupted for the last years. Gaps in the data can either be from a station shut down due to maintenance, or electric/internet outage. In the earlier years, some loss of HH data is observed because this stream was the first to be erased automatically from the Quanterra hard disk.

Small diurnal variations in the seismic trace are typical and easily noticed visually on a 24-hour data plot such as Figure 4 for the 21st February 2012. The amplitude of the trace increases in the second half of the day. Such changes are usually weather related, as is the case on this particular day. On this date the islands experienced a severe rain storm that resulted in the dullest (lack of sun radiance due to thick clouds) day of the month with heavy rainfall of 24.2 mm ("February was the third coldest in almost a century" The Times, 2nd March 2012, p. 5., print). The increase in amplitude of the seismic trace is due to an increase in microseisms, background seismic noise generated by the storm. Because Malta is a small island, microseismic signals are dominated by the continuous swelling of the surrounding sea crashing onto the shore. These were amplified on the day of the storm.

Another way to inspect seismic data is by analysing the spectral content. Different sources of seismic signals, earthquake or otherwise, have a spectral signature. Figure 5 shows two examples of a spectral analysis, one showing the spectrogram of seismic ambient noise recorded throughout the day of the 21st February 2012 (same as Figure 4), and another spectrogram of a regional earthquake recorded on the 3rd July 2012 capturing a M 4.8 earthquake, 198 km south-east of Malta. The dominant frequencies for the ambient noise are between 0 and 1 Hz and are persistent throughout the day like a permanent hum. In the case of the earthquake signal the dominant frequencies are higher, in the range of 0 to 6 Hz. The seismogram of an earthquake has a different spectral and energetic content for the different arriving phases such as body waves and surface waves; hence the dominant frequencies are within a broad range. Eventually the energy decays with time, back to the background noise.

A powerful tool to evaluate the long-term performance of a broadband seismic station is the overview of the accumulative spectral content over a series of days, weeks, or months (Figure 6). This gives one the ability to examine artefacts related to station operation, episodic cultural noise (for example, day variations due to traffic) and seasonal weather changes — together they can form a baseline level of ambient noise of a certain site. Such an analysis is useful for characterising the current and past performance of a broadband sensor, for detecting operational problems, and for evaluating the overall quality of data of the station.

In this study we use the approach described by McNamara and Boaz (2006), which incorporates a probability density function (PDF) to display the distribution of seismic power spectral density (PSD). Figure 6 shows selected examples of PSD sampling the months of February and August, for the years 1996 and 2012. Each individual PSD curve represents a 30–minute segment of data. Most of the PSD curves follow a similar distribution of power spectra because most of the data contains background seismic noise, whereas the scattered curves

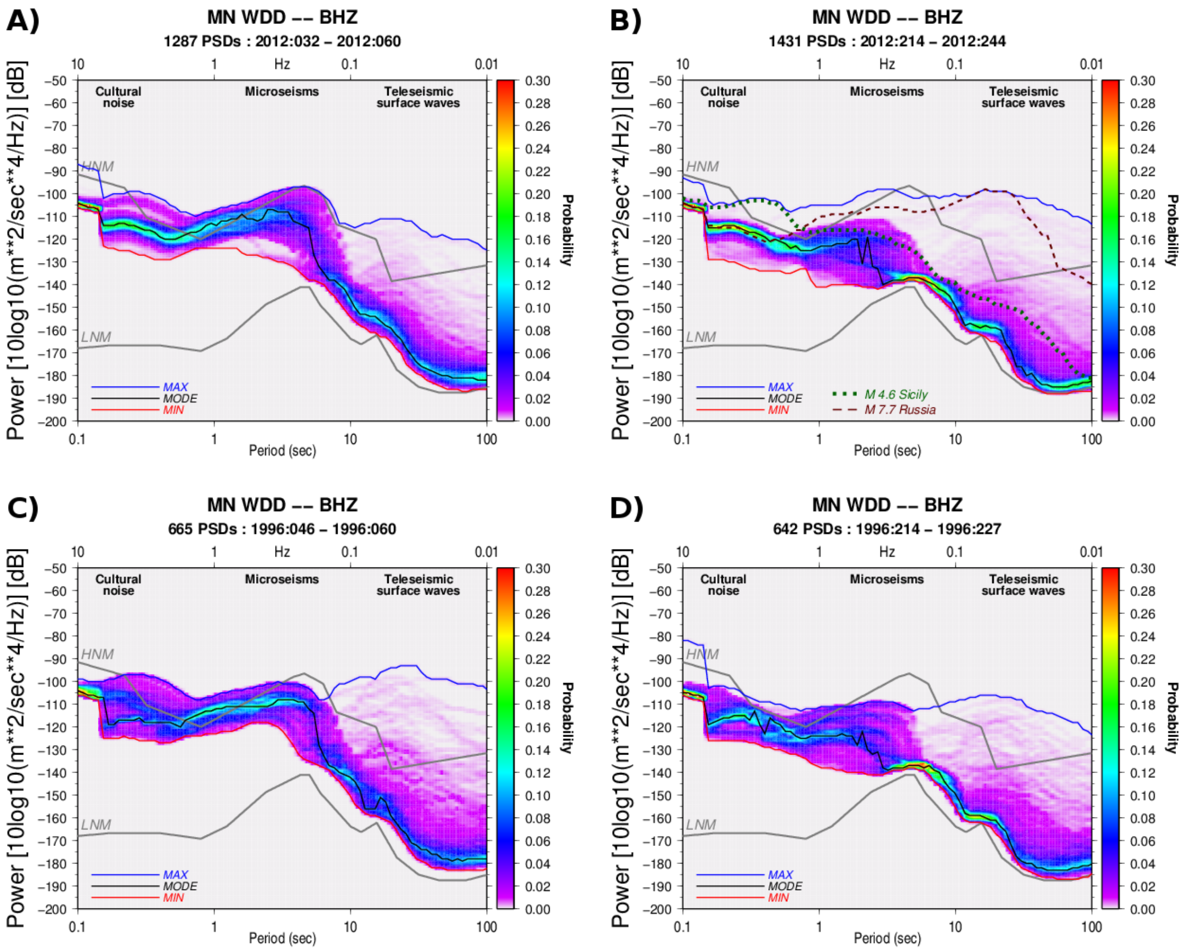

Figure 6: Seismic spectral analysis based on the calculation of Power Spectral Density (PSD) distribution using a Probability Density Function (PDF) (McNamara and Boaz, 2006). A: Noise analysis for the winter period using the seismic data of February 2012, day numbers 032–060. Grey curves: low noise model (LNM) and high noise model (HNM) (Peterson, 1993). Blue and red curves: maximum and minimum PSD for the data, respectively. Black curve: the highest probability mode. B: same as A, but for the summer period using the seismic data of August 2012, day numbers 214–244. Red, thin, dashed curve: the PSD for a teleseismic earthquake that occurred in Sea of Okhotsk, Russia on August 14th with a magnitude 7.7. Green, thick, dashed curve: the PSD for a regional earthquake that occurred in Sicily, Italy on August 28th with a magnitude 4.6. C and D: Same as A and B but for 1996. Less PSD curves are due to less data availability (Figure 3)

are of sparse earthquakes that occur over time. In Figure 6B, August 2012 plot, we show PSD examples of two earthquakes, a teleseismic and a regional event. The spectral content of the teleseismic event is dominant for periods longer than 1 second up to and exceeding 100 s, whereas for the regional earthquake the dominant spectra is for periods less than 1 second (> 1 Hz).

Ideally, background noise is of a low power order throughout the entire spectrum, but this is hardly ever the case; stations such as those close to the coast have an increased power level, particularly for short period waves (less than 10 seconds). Peterson (1993) has used the seismic data of a world-wide network of seismographs to establish a low noise model (LNM) and a high noise model (HNM) shown as grey curves in Figure 6. These models are used for comparison and serve as an indication of how a seismic station performs in terms of ambient seismic noise. During the month of February of 1996 and 2012, WDD has high power levels for periods between 0.2 and 10 seconds (0.1–5 Hz) (Figure 6 A and C). Although the highest probability mode only exceeds the HNM for periods close to 1 second (1 Hz), the broad range of high probability spectral distribution is considered excessive.

During the month of August (Figure 6 B and D), the power spectral distributions for the periods between 1 and 10 seconds (0.1–1 Hz) decrease substantially and are well within the low and high noise models. The amplitude contrast between February and August within the 1–10 second period band is assumed to be due to seasonal changes; very short-period spectra from cultural noise and long-period spectra from teleseismic events have a similar distribution in both months and are unaffected by weather changes. Note that the PSD for the

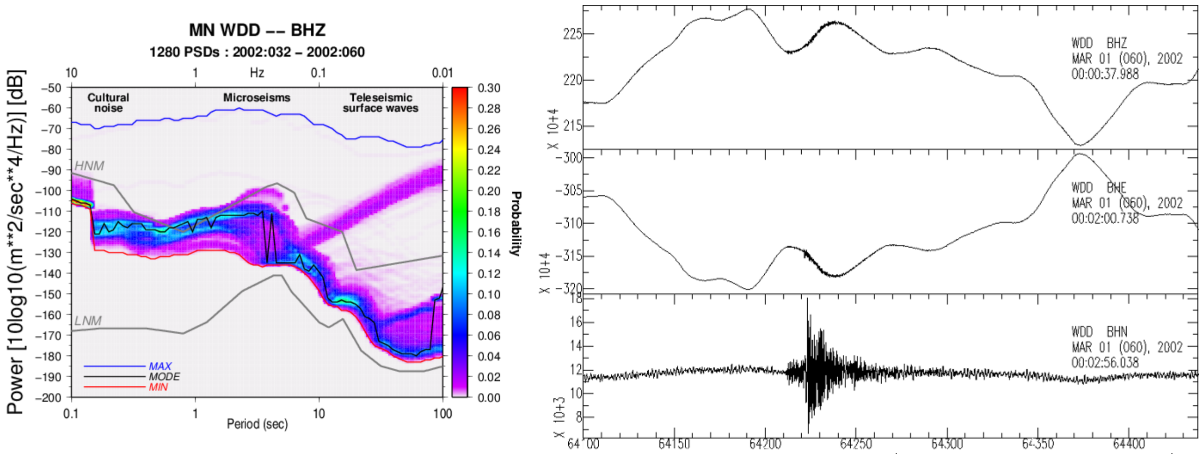

Figure 7: Example of poor seismic data quality. Left: The power spectral density distribution (McNamara and Boaz, 2006) for the BHZ component data for day numbers 032–060 of year 2002. Right: A BH, 3-component seismic trace of a local earthquake recorded during the same time period.

months of 1996 have less samples due to gaps in the data. Nevertheless, the very similar spectral patterns observed for the same months of 1996 and 2012 indicates that the conditions of the seismic station remained the same over the years.

3 Example of poor data quality

Figure 7 shows an example of poor seismic data quality in early 2002. Abnormal spectral patterns can be seen at the longer periods of the PSD for the BHZ component. The long period artefacts are also noticeable in the seismic trace of a local earthquake (Figure 7B). Components BHZ and BHE have a suspiciously long period, large amplitude signal inverted to one another whereas component BHN seems to be unaffected. Although the long period signal can be filtered out to 'save' the data for further processing such patterns are indicative of station operational problems. In such cases maintenance typically requires an on-site inspection, checking the instrument state-of-health for system warnings, and mass re-centering.

4 Station orientation

Various seismic studies, such as shear-wave splitting, depend on the station orientation, generally assumed to be correct (Ringler et al., 2013). Typically the station orientation is done manually during deployment by orienting the north-south station axes to point to the true north using a standard compass. One way to confirm the station's orientation is by locating earthquakes from three component (E, N, and Z) polarisation analysis and comparing the location with that published by international bulletins. This technique has been used by the SMRU to locate as many earthquakes in the Mediterranean region, particularly those occurring in southern Italy and Greece (Agius, 2007; Agius and Galea, 2011). The successful location of earthquakes, particularly those with a large signal-to-noise ratio, gives us confidence that the station orientation is correct, relative to the true north.

5 Seismic site response using seismic ambient noise and earthquake recordings

It is well established that earthquake ground shaking is not only a function of the earthquake magnitude and epicentral distance, but also of the site conditions. Seismic waves propagating close to the surface are strongly affected by the underlying near-surface structures such as soft layers in the sub-soil stratification, and by topographical features. Several studies show numerous examples of anomalous shaking amplification as a result of site effects (Borcherdt and Glassmoyer, 1994; Higashi and Sasatani, 2000; Aguirre and Irikura, 1997; Fukushima et al., 2000; Akinci et al., 2010; D'Amico et al., 2010; D'Amico et al., 2013a). Evaluating the site response of station WDD from local effects will help establish whether the PSD patterns for periods < 2 seconds (Figure 6) are site dependent. Furthermore, the spectral patterns of the site response can help in the site selection of future installations of permanent seismic stations on the islands, and can also be used for an accurate and proper calibration of seismic hazard evaluation and regional ground motion studies (D'Amico et al., 2012a; D'Amico et al., 2012b; Akinci et al., 2013).

In order to determine the site response of station WDD we select 16 local seismic events that have a good signal-to-noise ratio. The magnitude of the events are in the range of 2.5 to 4.3, with a travel path in the range of a few kilometres to about 100 km, and with a back-azimuth ranging between 30° and 250°. Data were processed for horizontal to vertical spectra ratio

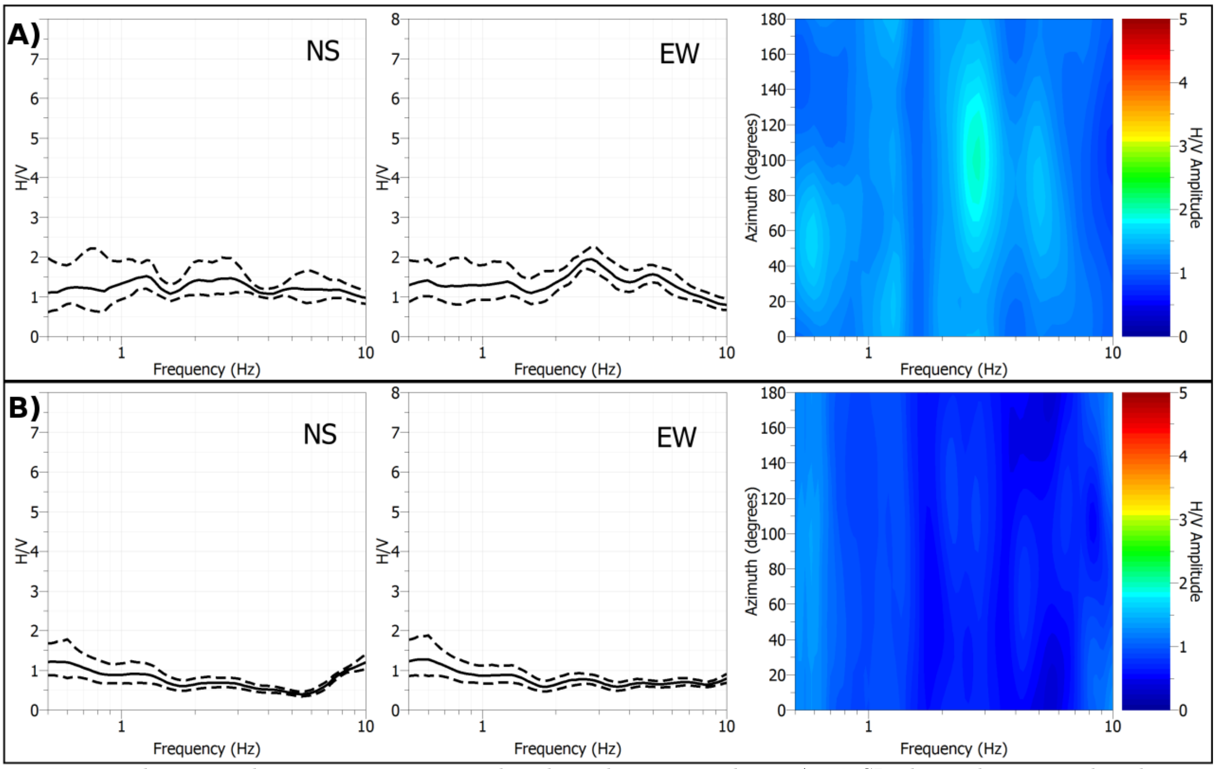

Figure 8: Horizontal to vertical spectra ratio using earthquake and noise recordings. A: HVSR obtained using earthquake recordings at WDD station. Left: Ratio of the north-south horizontal component with the vertical component (solid line). Dashed lines represent the confidence interval. Centre: Same as left, but ratio is of the east-west horizontal component with the vertical component. Right: H/V spectral energy with respect to frequency and azimuth (from north). B: same as A but for HVNSR obtained using noise recordings

(HVSR, Nakamura (1989)). The signals of the recorded earthquakes were base-line corrected, with the purpose of removing spurious offsets, and band-pass filtered in the range 0.08–20 Hz using a fourth order causal Butterworth filter. The analysis was performed considering time windows of 20 seconds, starting from S waves onset and using a 5% cosine-tapered window. The obtained Fourier spectra for each considered earthquake were smoothed using a proportional 20% triangular window. For each window the spectral ratio as a function of the frequency was computed, then the geometric mean was calculated We also performed analysis on a 40 minute ambient noise recording of station WDD. The data was processed using the horizontal to vertical noise spectral ratio (HVNSR) technique following the criteria suggested by SESAME project (Bard, 2004). The Fourier spectra were calculated in the frequency range 0.5–10.0 Hz and smoothed using a proportional 20% triangular window.

Figure 8 shows the obtained HVSR and HVNSR results using the north-south components and the east-west horizontal components separately. In both cases the H/V ratios at the site have a relatively flat behaviour and they do not show any significant peak. According to the SESAME (Bard, 2004) guidelines only the spectral ratio peaks having amplitude greater than two units can be considered significant. Therefore we can state that the WDD station has a flat rock response and it does not present any significant site effect due to the local geology. In Figure 8, the directional analysis is also presented. The amplitude is plotted with respect to azimuth and frequency for the averaged components. The noise analysis shows no directivity at all, whereas the earthquake data shows slight clustering at about 3 Hz signal around N100°E. No clear explanation can be given at this stage and further analysis on a larger data set is needed in order to explain this behaviour.

The flat H/V response of station WDD is attributed to the underlying Lower Coralline Limestone bedrock, the oldest of the geological formations outcropping on the Maltese archipelago. Other similar studies for areas in the northern parts of the islands that have outcrops of a younger geological formation show a different spectral pattern; the site response from temporary stations have a H/V peak amplitude within the frequency range of 1 and 5 Hz (Vella et al., 2013). Hence, station WDD and the site location itself can be used as a local reference, where the seismic data, unlike in other areas on the islands, is 'unaffected' by the underlying geology.

6 Concluding remarks

We conclude that WDD seismic station has a good performance history. The station has long-term (since 1995), broad-band seismic data availability. Spectral analysis of the data shows that the seismic power spectral density is within the global standard low and high noise model ranges (Peterson, 1993) for most frequencies. Noise levels are high for the frequency ranges of 0.1–5 Hz only during the winter months, due to weather storms. Seasonal variations in noise amplitude are consistent throughout the station's operational years and suggest a stable performance since installation. Analysis on the ambient seismic noise and earthquake data show WDD has a flat site response, indicating minimal effect from the station location. The stable geology at Wied Dalam and the high-quality, broad-band seismic instrument at WDD seismograph can serve as a local reference for calibration of future deployment of permanent seismic stations, as well as a reference for other seismic studies such as site spectral ratio techniques, seismic hazard evaluation and local ground motion studies of the Maltese islands.

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