Seismic noise characterisation at Gingin high optical power gravitational wave test facility

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Abstract.

A critical consideration in the design of next generation gravitational wave detectors is isolation from seismic vibrations that introduce various coherent and incoherent noises to the interferometers at different frequencies. We present the results of a detailed low-frequency ambient seismic noise characterization (0.1–10 Hz) at the Gingin High Optical Power Facility in Western Australia using a seismic array. The dominant seismic noise below 1 Hz is microseism (0.06–1 Hz), strongly correlated with swell and sea heights measured by nearby buoy stations. Above 1 Hz, the seismic spectrum is dominated by wind induced seismic noise with a diurnal variation that prevents characterizing the background anthropogenic noise sources based on their daily power variations. We use frequency-wavenumber (f-k) beamforming to distinguish between coherent and incoherent wind induced seismic noise. This allows the separation of some anthropogenic noise from wind induced noise based on the temporal variation of spatio-spectral properties. We show that the seismic coherency is reduced by wind induced seismic noise for wind speeds above 6 m/s. Furthermore, there are several spectral peaks between 4–9 Hz associated with the interaction of wind with a 40 m tall tower among which one at 4.2 Hz is strongest and coherent. By comparing our results with the properties of seismic noise at the advanced Virgo site, we demonstrate that while the secondary microseism noise level is two orders of magnitude higher in Gingin (0.2 Hz), the anthropogenic noise level is three orders of magnitude lower between 2 and 4 Hz due to the absence of nearby road traffic. It is also at least one order of magnitude lower between 4 and 10 Hz due to the sparse population in Gingin.

Keywords: ambient seismic noise, beamforming, gravitational wave detection

1. Introduction

One of the objectives of next generation gravitational wave (GW) detection is to extend the detector sensitivity to low frequencies down to 2 Hz [1]. A factor of 10 better
sensitivity than the current advanced ground-based detectors, enables aiming for a series of ambitious detection possibilities including inspiral and merger phases of compact binaries and intermediate mass black hole binaries [11, 12]. A significant instrumental challenge to achieve these goals is to isolate the detectors’ suspended test masses from vibrations induced by ambient seismic noise. State of the art techniques exploited in isolation systems are capable of suppressing seismic ground motion by 12 orders of magnitude above a few Hz [3]. However, challenges remain in improving the isolation systems for future detectors especially at low frequencies below 10 Hz. First, the sophisticated vibration isolation systems that enable detection of GWs above 10 Hz, have resonant frequencies around a few Hz [4]. This will be a major issue because ocean-earth coupled seismic wave energy (microseism) peaks between 0.1–1 Hz [5] which makes excess residual motion in these frequencies a common problem. Second, seismic disturbances change mass distribution in the Earth and induce unshieldable density fluctuations that affect the test masses [6, 7, 8]. This so-called Newtonian noise (NN) is predicted to be one of the limiting noise sources in third-generation detectors, such as the Einstein Telescope down to 2 Hz [1, 4, 9].

Seismic arrays have been widely proposed [4, 10, 11, 12] to actively assist the vibration isolation systems by cancelling ground motion [13]. The information obtained from a seismic array can be exploited by a feed-forward control system before the seismic vibration enters the system [14, 15]. Arrays can also be used to measure the ambient seismic wavefield allowing prediction and subtraction of NN [16, 12, 17, 18]. For an efficient isolation system, and for modeling the contribution of seismic noise to NN and its optimal subtraction, it is vital to classify seismic noise sources. Array analysis provides information on the seismic wave-types and its modes which helps determining the relative strength of the noise source and its directivity [19]. This helps to identify the effects of seismic noise on the interferometer [20, 21, 22]. In this paper we characterize seismic noise using both single station and array data analysis inside the High Optical Power Facility (HOPF) [23] near Gingin in Western Australia (WA). The results of seismic noise characterization study will support future developments in the facility.

In section 2, we begin with a general view on the properties of the ground vibrations in Gingin from 0.01 Hz to 20 Hz and compare them with those at the advanced Virgo (adVirgo) site in Italy [21]. After characterizing the three main seismic noise sources from 0.1–10 Hz i.e. microseism, wind induced and anthropogenic noise, we further analyze them separately. For this purpose, first in section 3, we characterize the primary and secondary microseism by comparing single station seismic data with oceanic wave data from two buoy stations in the Indian Ocean. Second, in section 4, after a brief review of beamforming [24] as an efficient array processing tool that separates the coherent and incoherent parts of the seismic noise [24], we characterize wind induced and anthropogenic noise by applying this method on array seismic data acquired in the site. In section 5, we present the dispersion profile extracted from surface waves that characterize the physical properties of the subsurface between 0.1 and 10 Hz. We also discuss the uncertainty of the beamforming measurements. In section 6, we present our
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Figure 1. Seismic array layout in the HOPF site on Google Earth image, Map Data ©2022 Google. 18 seismometers (s1–s18) are used in three sub-arrays of six nodes with similar logarithmic spacing as shown in the zoomed inset. The blue dot with the white cross shows the geometric center of the seismic array. An additional seismometer (s19) is deployed next to the triangular shaped leaning tower shown with the yellow triangle on its roof. Zadko telescope and GDC museum are located to the southeast of the tower. The inset on the top right of the figure shows the leaning tower and the Zadko telescope. The red dot on the roof of the Central-Station shows the location of an anemometer used in this study. Blue dots in the left bottom inset map show the locations of Jurien bay and Rottnest Island buoy stations in the Indian ocean which are 141 kms and 67 kms away from the seismic array, respectively.

major conclusions and discuss the implications on GW detection.
2. General properties of Gingin ambient seismic noise

Data used for this study were acquired during days 168–182 (July) of 2021 by an array of 19 broadband (T = 120 s) seismometers (3-component Nanometrics Trillium T120/PA), an anemometer (Intech WS3-WD-TB-CL) installed on the roof of the main laser room (Central-Station), and two buoy stations in the Indian ocean (Oceanographic Services, WA Department of Transport) which are shown in figure 1. HOPF site is located near Gingin, 71 km north of the Perth city centre in WA and 17 km east of the WA coast. There are three research lab buildings (the Central-Station, South End-Station and the East End-Station), housing two 80 m long suspended optical cavities. There is also a building for the Zadko telescope [25] as well as a public education centre, Gravity Discovery Centre (GDC) museum, and a 40 m tall leaning tower located northwest of the site which is shown by a yellow triangle in figure 1 (also shown in the top right inset).

HOPF is located in semi-arid bush land composed of shrubs and sparsely distributed trees. The nearest highway is 8 km away, and nearest town is 20 km away from the site with a population of only 900 (Australian Bureau of Statistics, 2021). In addition to the human activity during daytime inside the lab buildings, there are people working in or visiting the Zadko telescope and the GDC museum at days and nights including the weekends. There are a few farms sparsely located in the region. While the seismic environment at Gingin has many features common to other parts of the world, it has unique features in its spectrum that come from the local environment. To better clarify these features with a perspective on their relevance to GW detection, we compared the vertical and horizontal seismic probabilistic power spectral densities (PPSD) from a surface seismometer at the HOPF site with those of adVirgo site in Italy [26] during the same time between 20 June and 20 July 2019 (figure 2). Peterson’s new high- and low-noise models [27] are plotted for comparing the seismic noise levels with the global average.

The primary (0.06–0.1 Hz) and secondary (0.1–1 Hz) microseisms [5, 28, 29, 30] are highlighted with three peaks labeled as A, B and C in the vertical PPSD plot. Primary microseism (marked by A) is caused by the interaction of pressure fluctuations from infragravity ocean waves with ocean floor in the coastal areas [28, 29]. At some locations, there are two peaks associated with the secondary microseism. The low-frequency secondary microseism (0.1–0.3 Hz, marked by B) is made by standing waves with double frequencies as those of the primary microseism generated through the interaction of ocean swells with their reflections from the ocean floor [28, 31, 29, 32]. The third peak, referred to as high-frequency secondary microseism (0.3–1 Hz, marked by C), is caused by local sea waves generated by local sea wind [28]. At adVirgo it is believed to be caused by fluctuations in the wave heights in the Mediterranean sea [30]. The source of the primary and low-frequency secondary microseisms (A and B) is often considerably far from the coasts and they can create complex superposition of seismic body waves and surface waves [28, 33]. Although the primary and high-
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Figure 2. Power spectrum of (a) the vertical and (b) the horizontal seismic noise measured by a broadband seismometer on the surface at HOPF (blue) compared to those recorded at adVirgo (red) [26]. These measurements were made during the same month between 20 June and 20 July 2019 at the two sites. The solid line shows the mode and the 10th–90th percentile is represented as the band. Three peaks associated to the primary, low-frequency and high-frequency secondary microseisms are highlighted respectively as A, B and C on the vertical component. In both graphs the dashed gray lines show the Peterson’s new low and high noise models (LNM/HNM).

frequency secondary microseisms (A and C) have almost the same strength in the two sites, the low-frequency secondary microseism (B) is two orders of magnitude stronger in Gingin. At adVirgo, the microseism is generated by the northern Atlantic ocean, and at Gingin it comes from the Indian ocean. The storm systems, seasonal peaks, and coupling mechanisms are thus different for the two sites that explains the differences between their PPSDs.

In contrast to the microseisms, the Gingin seismic noise spectrum has lower power than that in adVirgo for the 1–10 Hz frequency band. One way to identify the reason for this and to characterize the noise sources above 1 Hz is to examine the spectrum over time. Therefore, we use spectrograms of the vertical and horizontal surface seismic data acquired during two weeks in July 2021 at location s12 (figure 3). The vertical component spectrogram shown in figure 3(a) better illustrates the underlying dominant seismic noise e.g. the microseism peaks around 0.08 Hz, 0.15 Hz and 0.6 Hz highlighted by A, B and C, respectively. An interesting feature is the similar temporal variation of the low-frequency secondary microseism (B) to that of the primary microseism (A) but with double frequencies. On the other hand, the horizontal component spectrogram (figure 3(b)) more clearly shows the daily power increase in the first half of the Julian days, equating to 8 am to 8 pm local time. In figure 3(b), we have overlaid wind speed measurements in black (the scale is on the right side of the figure).

It is clear that an increase in wind speed corresponds to an increase in the seismic
Figure 3. Spectrogram of (a) the vertical and (b) the horizontal component of seismometer s12 next to the East End-Station (figure 1). The data was recorded during days 168–182 of 2021. Each day in the figure starts at 8 am local time. Three peaks associated to the primary, low-frequency and high-frequency secondary microseism are highlighted respectively as A, B and C on the vertical component similar to those in figure 2(a). Scaled wind speeds (black) are overlaid on the horizontal component. Wind induced seismic noise is evident in the form of a diurnal variation of the power correlated with wind speeds across much of the spectrum especially below 0.1 Hz on the horizontal component.
noise power below 0.1 Hz and above 1 Hz. This is the wind induced seismic noise with a daytime periodicity that has dominated other seismic noise in several frequency bands in the background. The primary microseism peak around 0.08 Hz, marked by A in figure 3(a) is an example that can be distinguished from the wind induced seismic noise because it is better visible in the vertical component while it is partially masked in the horizontal component. In contrast, it is difficult to characterize anthropogenic noise above 2 Hz by a common daily variation in the seismic power due to the presence of wind induced seismic noise with a diurnal pattern at both components.

Comparing figures 2 and 3 with the observed daily seismic RMS changes associated with human activity in adVirgo [21], reveals the main reason for the differences between the two sites. Weaker anthropogenic noise is common in remote rural areas [34] like Gingin where other sources, like wind induced seismic noise, become more apparent. This explains the three orders of magnitude lower seismic noise power for HOPF in the 2–4 Hz frequency band than that for adVirgo (figures 2). The absence of highways in the vicinity of the HOPF means that seismic noise generated by local traffic is significantly lower than that at adVirgo in this frequency band [35]. Likewise, an order of magnitude lower power from 6 Hz to 10 Hz at HOPF compared to that at adVirgo is explained by sparser population nearby [21, 36].

In section 3, we use oceanic wave data to characterize the primary and secondary microseisms, and in section 4, we use beamforming and array seismic data to monitor the spatio-spectral properties of the seismic noise in the study area. This helps us to characterize the coherent wind induced seismic noise, as well as to characterize anthropogenic noise by separating it from incoherent wind induced seismic noise in the f-k domain.

3. Microseism

There are 19 seismometers in the array with minimum 0.5 m (s1–s2, s7–s8 and s13–s14) and maximum 540 m (s6–s19 and s13–s19) sensor separations (figure 1). Depending on the seismic velocity structure of the site, these values set a maximum and a minimum threshold respectively for the frequencies of the incident wavefield that can be reliably measured by the array [37, 38, 33]. The configuration of our seismic array has been originally designed to study low coherency of wind induced seismic noise in three distinct locations [39] and it cannot be used for beamforming analysis of microseism. Its aperture size (540 m) is far shorter than the wavelength of the microseism (∼ 30 km at 0.1 Hz) which leads to uncertain velocity measurements (discussed in section 5). Therefore, here we focus only on the single station seismic data.

Figure 4 shows the correlations between the seismic RMS peak ground velocity and the wave data measured at Jurien Bay and Rottnest Island buoy stations in the Indian ocean which are located 141 kms and 67 kms to the west of the seismic array, respectively. We used 15 minutes non-overlapping intervals of the band pass filtered vertical seismic data over the two weeks. Figure 4(a) and (b) show that the primary microseism (0.06–
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Figure 4. Temporal variations in the bandlimited RMS peak ground velocity (BLRMS PGV) computed using 15 minutes non-overlapping intervals for (a) primary microseism (0.06–0.1 Hz) which is correlated with swell wave heights except for the windy times with higher RMS peak ground velocities during days (each day starts at 8 am local time), (b) low-frequency secondary microseism (0.1–0.3 Hz) which is correlated with swell wave heights and (c) high-frequency secondary microseism (0.3–1 Hz) which is correlated with sea wave heights. The wave data were measured at Jurien Bay and Rottnest Island buoy stations in the Indian ocean, located 141 kms and 67 kms to the west of the seismic array, respectively.

0.1 Hz) and the low-frequency secondary microseism (0.1–0.3 Hz) are both correlated with swell wave heights and originate from the same source. The exception to this is the primary microseism with higher seismic RMS peak ground velocity during day times which is a local effect due to wind induced seismic noise (figure 3). We have previously observed that the wind induced seismic noise at this frequency band is incoherent [39]. Figure 4(c) shows the high-frequency secondary microseism (0.3–1 Hz) which is correlated with sea wave heights. The different temporal variations of the high frequency secondary microseism power is representative of a separate noise source (local sea waves hitting the WA shoreline) from that of the primary and low-frequency secondary microseisms (distant swell waves).

The correlation of the seismic data with two buoy stations more than 200 kms apart
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from one another shows that the microseismic wave energy mainly comes from the west. Increased swell heights on days 171, 172 and between days 179 and 182 (figures 4(a) and (b)) is suggestive of storms in the Indian ocean (distant source) which have increased the ocean-Earth coupled microseism energy. Such variations have been reported to be accompanied by seismic wave-type transition from body waves to surface waves and vice versa as it was explained by [33, 40, 32] for secondary microseism at 0.2 Hz. Surface waves associated with oceanic storms dominate the lower amplitude body waves, while in the absence of storms, body waves can be detected by lower amplitude and higher coherency. This results in an anti-correlation between the seismic noise power and seismic coherency which can be monitored along with the corresponding changes in the azimuths [41] and wave-speeds [33] using a seismic array with a configuration optimized for this purpose [42].

4. Monitoring seismic spatio-spectral properties by beamforming

The general idea of beamforming in seismology is to amplify the coherent portion of seismic wave energy and suppress the incoherent noise [43, 24, 44]. As an array processing method, it enables monitoring the temporal variation of the spatio-spectral properties of the seismic wavefield. This results in a useful separation between incoherent and coherent wind induced seismic noise and between incoherent wind induced seismic noise and coherent anthropogenic noise in HOPP. Applying beamforming to GW seismic noise site characterization for its efficiency in distinguishing between various noise sources and different wave-types based on their different coherency is gaining attention [22, 19, 33, 35].

We use frequency-wavenumber (f-k) beamforming [45] that maximizes the array beam power in the frequency domain. The frequency-domain signals of different sensors are phase delayed and stacked. This method assumes a 2D Earth model with spatial coordinate vector \( \mathbf{r} \) and a coherent plane wave traveling with horizontal velocity \( v \) (km/s), then it simultaneously calculates the azimuth \( \theta \) and slowness \( s = v^{-1} \) (s/km) of the seismic wavefield [46, 47]. The coherent portion of the seismic surface waves will be recorded at different locations \( \mathbf{r}_n \) of the array with corresponding travel times depending on the subsurface seismic velocity structure and the distances of the seismometers from the center of the array. The phase delays for all stations can be calculated in the form of a steering vector [44]

\[
\mathbf{a}(f, s) = e^{-2\pi i f s (\mathbf{r}_n - \mathbf{r}_0)},
\]

with

\[
s = (s \sin \theta, s \cos \theta)
\]

in which \( \mathbf{r}_n - \mathbf{r}_0 \) is the distance vector between \( n^{th} \) sensor and the reference sensor located at the center of the array \( \mathbf{r}_0 \). The azimuth (\( \theta \)) is measured clockwise from north and shows the directions from which the seismic wavefield arrived at the array. Then the
beam power associated with the azimuth and magnitude of \( s \) is calculated by applying the phase delays to the cross-spectral density of the Fourier transformed seismic traces \( X(f) \):

\[
P(f, s) = \frac{1}{L^2M^2} a^H(f, s)X(f)X^H(f)a(f, s),
\]

where \( L \) and \( M \) are respectively the window length and the number of the seismometers, and \( ^H \) denotes the Hermitian transpose. \( X(f)X^H(f) \) is the Hermitian cross spectral density matrix (CSDM) that stores all the auto-spectral densities in its diagonal terms and cross-spectral densities in its off-diagonal terms. By using a grid search that iterates over the slowness and azimuth, the beamformer (eq. (3)) estimates the power contributions from a variety of synthetic plane waves. The phase shifts generated by matching slowness and azimuth to those of the recorded plane wave stored in the CSDM will result in coherent phase stacking and maximum beam power at a certain frequency bin. By repeating this analysis over consecutive windows of the recorded seismic traces, temporal variations in the maximum beam power and the corresponding azimuths and slownesses are calculated. This provides additional information on the properties of the seismic wavefield.

Theoretically, the normalization factor \( \frac{1}{L^2M^2} \) in eq. (3) means that the beam power must be 1 for a signal that is perfectly coherent across the array. However, in practise, there is always contribution of incoherent noise from different azimuths that prevent the array to be ideally tuned on a specific noise source [42]. The higher the coherency, the beam power will be closer to 1 which can be used to infer the relative variations in the seismic coherency at a specific frequency band over time.

4.1. Wind induced seismic noise

Spatial and temporal fluctuations in the atmospheric pressure loads on the Earth’s surface, create local ground tilt [48, 49]. In a recent study in the HOPF [39] we showed that wind induced seismic noise affects the seismic coherency in two ways depending on its interaction with different surface objects at different frequencies. First, it is incoherent and masks the background coherent seismic noise during local daytime e.g. the primary microseism (0.06–0.1 Hz), etc. Second, when it excites resonant features in the landscape, it injects coherent seismic noise (several spectral lines between 4 to 9 Hz). Because of the spread of the wind induced seismic noise across the large portion of the seismic spectrum in the site, we have previously studied its low coherency via a dedicated coherence length analysis and discussed its implications for advanced GW detection [39]. We analyse this effect using beamforming in the next sub-section.

Investigation on the coherent version of the wind induced seismic noise in HOPF revealed that there are several wind-driven coherent spectral lines between 4–9 Hz. Figure 5 shows the beamforming results applied on the most coherent spectral line between 4.2–4.3 Hz. We band-pass filtered vertical component seismic data, and used 200 seconds long non-overlapping windows. Seismometer s19 next to the leaning tower
Figure 5. Beamforming results for vertical seismic noise data band-pass filtered between 4.2–4.3 Hz acquired during days 168–182 of 2021. (a) Variation of the beam power of which colors are used as the reference for the other measurements, (b) the absolute power of the reference seismometer in the center of the array which is compared against the wind speeds, (c) the azimuths and (d) the slownesses that resulted in the maximum beam powers. High beam powers (bright green and yellow) occur for wind speeds above 6 m/s and show the coherent wind induced seismic noise with convergent azimuth around 320 degree separated from the other features with lower coherency and absolute power (dark green and blue).

(Figure 1) was excluded from this analysis to guarantee enough source-array distance assumed for the beamforming algorithm regarding the leaning tower being a candidate source for the vibrations.

Figure 5(a) shows the array beam power \(P(f, s)\) in eq. (3)) along the azimuths that have maximized it. As it can be seen from the color-bar, the higher the beam power, the brighter the colors. Therefore, the colors of the other three sub-plots (figure 5(b)–(d)) are set based on their correspondent beam powers to help the reader follow the impact of the changes in the coherency of the wavefield on the other instantaneous measurements. Figure 5(b) shows the absolute power of the reference seismometer \(X_0(f)X_0^H(f)\) at the geometric center of the array. The absolute power of the rest of the seismometers
which have not been shown here are synchronised to that of the reference seismometer using the corresponding phase shifts. This in turn results in the synchronization of the beam power with the absolute power.

The magnitude of the absolute power is proportional to the window length. Here, we are only interested in its temporal variation and correlation with the wind speeds. Values with bright colour (bright green and yellow) in all of the plots show that the measurements made at the times with wind speeds above 6 m/s have high coherency (beam power). The coherent portion of the wavefield which is correlated with wind and has convergent azimuth values (bright colors clustered around 320 degree) is separated from the less coherent features (dark green and blue dots). The azimuth ($\theta$) in figures 5(c) shows the directions from which the seismic wavefield with maximum beam power (figure 5(a)) arrived at the array. The azimuth at the times with wind speeds above 6 m/s (320 degree) is in the north westerly direction consistent with the location of the tower (40 m tall) shown in figure 1. The slowness amplitudes ($s$) along these azimuths are represented in figures 5(d). These values are about 1.6 s/km i.e. wave speeds are about 625 m/s which is consistent with surface wave propagation at this frequency. Two other sources are present around 220 and 20 degrees with slowness values mainly between 2 and 2.5 s/km i.e. wave speeds between 400 and 500 m/s.

The spectrogram shown in figure 6 is calculated from the vertical seismic data measured by seismometer s19 next to the leaning tower. There are several spectral lines
between 4–9 Hz including one around 4.2 Hz. These lines do not exist in the spectrogram shown in figure 3 for seismometer s12 which is 400 m away from the tower. For wind speeds above 6 m/s, the power of these lines increases with wind speed and makes them the dominant feature in the spectrogram. This supports the beamforming results for the coherent wind induced seismic noise and determines the leaning tower with several wind-driven vibration modes as the source for this anomaly.

4.2. Anthropogenic noise

Single station seismic noise power (figure 3) shows that the seismic spectrum is dominated by wind induced seismic noise above 1 Hz. Monitoring the seismic spatio-spectral properties helps to gain more information about the background anthropogenic noise. Figure 7 shows the beamforming results for 2–4 Hz using 250 seconds long non-overlapping windows. Opposite to the coherent wind induced seismic noise (figure 5), there is an anti-correlation between the beam power and wind speeds higher than 6 m/s (dark blue values) which shows that wind induced seismic noise is incoherent at this frequency band. Overall, the beam power is constantly low (an average of 0.4) and the absolute power correlates with wind speed except for day 171 from 8 am to 6 pm local time (yellow), with 330 degree azimuths which could be due to a maintenance or a special event on the GDC museum which is open on weekends. A road at the north-west of the site can also be the candidate source. This shows that incoherent wind induced seismic noise is dominant except at times where the power and coherency of anthropogenic noise increase due to a temporary event.

The seismic PSD starts to increase from 3 Hz for the vertical and from 4.5 Hz for the horizontal component (figure 2) up to 10 Hz. Figures 5 to 7 show that the background seismic noise in this frequency band is dominated by incoherent wind induced seismic noise while there are also several coherent wind-driven spectral lines generated by the leaning tower. This means that several frequency bins between the spectral lines are required to separate between the effects of coherent and incoherent wind induced seismic noise on the anthropogenic noise for 4.3–10 Hz frequency band. Furthermore, because the array is not concentric, the short sensor separations in the array are in distinct locations in the three sub arrays (s1–s18 in figure 1). These factors, make it inefficient to use beamforming for monitoring the spatio-spectral properties of the anthropogenic noise at higher frequencies. Instead, in the next section, we provide a statistical perspective on the rest of the target frequency band.

5. Discussion

The slowness resolution of an array is controlled by its aperture size, sensor density and configuration [42, 44]. The f-k beamforming under the assumption of plane wave propagation, uses data independent weights (steering vector, eq. 11) for the seismic traces in the summation process. These weights are solely controlled by the geometry of
Figure 7. Beamforming results for vertical seismic noise data band-pass filtered between 2–4 Hz acquired during days 168–182 of 2021. (a) Variation of the beam power of which colors are used as the reference for the other measurements, (b) the absolute power of the reference seismometer in the center of the array which is compared against the wind speeds, (c) the azimuths and (d) the slownesses that resulted in the maximum beam powers. Low beam powers (dark blue) occur for wind speeds above 6 m/s and show the incoherent wind induced seismic noise with smeared azimuth and slowness values. A ten hours long coherent anthropogenic noise has sharply increased the beam power on day 171 from 8 am to 6 pm (yellow) local time with a narrow azimuth range pointing towards the north-west of the site (330 degree).

the array [43]. As a result of this and because the seismic wavefield is sparsely sampled in the space domain, the array’s capability to resolve slownesses in the f-k domain is directly subject to its geometry [38]. In section 3, we showed that the microseism mainly comes from the west of the array, and explained that we cannot use the current array to analyze the temporal variation in the directivity and wave speed of the microseism due to the limited aperture seize of the array.

In section 4, we presented the beamforming results in the frequency bands representative of particular anomalies in the study area. By monitoring the temporal variations in the power contributions from various azimuths and slownesses (spatio-
Figure 8. Histograms of (a) azimuth and (b) wave speed (dispersion plot) as a function of frequency for 0.1–10 Hz with 0.1 Hz frequency steps. The histograms are obtained from 79200 beamforming measurements made by the data from 19 seismometers acquired during days 172–182 of 2021.
spectral properties), we characterized the noise sources between 2 and 4.3 Hz. In order to provide an estimate on the uncertainty of those measurements and to extend the analysis statistically to lower and higher frequencies, in this section we calculate beamforming in the frequency band 0.1–10 Hz using finer frequency bins. Figure 8 shows the azimuth vs frequency and the wave speed vs frequency (dispersion plot) obtained from beamforming results using 0.1 Hz frequency bins for Julian days 172-182 of 2021. Each line in these plots is a histogram of the beamforming measurements at the frequency bin and the brighter colours mean higher histogram counts.

The histogram of azimuth vs frequency in figure 8(a) shows that the azimuths of the microseism ranges between $\sim 160$ and $\sim 280$ degrees and that the azimuthal uncertainty increases significantly below 0.6 Hz. On the other hand, the histograms of wave speed are multi-modal below 1.5 Hz with large standard deviations that increase towards 0.1 Hz. This happens because the wavefronts are so larger than the aperture of the array that they arrive at all of the stations almost simultaneously. This results in very large apparent wave speeds, hence very small slownesses below the slowness resolution of the array. The grid search finds high beam powers with quantized slowness values that in turn results in the multi-modal, uncertain and large wave speeds in the dispersion histograms below 1.5 Hz.

The beamforming results are reliable above 1.5 Hz. The seismic noise in the band between 1.5 and 5.5 Hz is multi-directional with no preferred direction. This could be the result of the local machinery, human and farm activities. Above 5.5 Hz, the noise mainly comes from north and north-west most likely due to the human activities in the Central-Station and GDC museum buildings inside the site, or a road at the north-west outside the site. The dispersion plot carries information about the geology of the study area beneath the array. This information is essential for modeling Newtonian Noise in gravitational wave detector sites [19, 16]. First it shows that the contribution of seismic surface waves on the surface seismic wavefield is dominant and that there are minimal complexity like reflections and refractions in the study area, as each of these features would appear as an additional curve in the dispersion plot. Besides the fundamental mode of the surface waves with the dominant counts (bright green), there may be higher modes with weaker contributions around 2 Hz, between 3 to 4 Hz and between 6.5 to 8.5 Hz which could not be clearly resolved due to the limited spatial resolution of the current array. The presence of such overtones at different frequencies could be suggestive of soft soil to hard rock transition at different depths [37, 19]. Detailed geological information (depth and shear wave velocity) can be derived from the inversion of the dispersion plot which is a non-unique problem.

6. Conclusions and future works

We presented the results of seismic noise site characterization for 0.1–10 Hz frequency band in HOPF gravitational research center in Gingin near WA using a seismic array composed of 19 seismometers. We first compared the general properties of seismic noise
with those at the adVirgo site in Italy. The secondary microseism between 0.1–0.3 Hz is about two orders of magnitude stronger in HOPF. Although we used simultaneous data from both sites (July 2019), it should be noted that this could be partly because at the HOPF site, the data acquisition was in the winter (southern hemisphere), while at adVirgo it was in the summer (northern hemisphere). The anthropogenic noise at HOPF is between one to three orders of magnitude weaker for 2–10 Hz compared to those at adVirgo. Together with the information obtained from the vertical and horizontal spectrograms, these features show that the HOPF site is located in a seismically rural area where wind induced seismic noise dominates the anthropogenic noise with a diurnal variation in the seismic noise power.

We further characterized the main seismic noise sources by analyzing the temporal variations in their spatio-spectral properties using single station and array analyses of the seismic data over two weeks in July 2021. We observed clear correlation between single station microseism noise power and swell and sea heights measured by two nearby buoy stations in the Indian ocean. We were able to use the temporal variations in the beam power of the seismic array, measured from beamforming, to distinguish between coherent and incoherent wind induced seismic noise. This helped us to find the most coherent vibration mode of the 40 m tall tower between 4.2 and 4.3 Hz among the other spectral lines present in the site from 4–9 Hz. Monitoring the incoherent version of the wind induced seismic noise in the 2–4 Hz frequency band demonstrated how it reduces coherency of anthropogenic noise for wind speeds above 6 m/s. We noticed that anthropogenic noise at this frequency band occasionally dominates the incoherent wind induced seismic noise with increased coherency and strength.

Finally, we estimated the histograms of azimuth and velocity as a function of frequency from 0.1–10 Hz with 0.1 Hz steps. We did this using the seismic data from 19 seismometers acquired during 10 days to discuss the potential of the array, the uncertainty of beamforming results using it, and the distribution of the noise sources in the study area. The velocity histogram showed that wave speeds estimates are uncertain below ∼1.5 Hz due to the limited aperture size of the array, but otherwise the dispersion plot is reliable. This analysis showed that surface waves mainly contribute to the ambient seismic noise wavefield while there are some evidence of overtones in few bands probably because of different layer’s stiffness at various depths. The azimuth histogram showed that the microseism come from the west (as expected), there is no preferred direction of the seismic field from 1.5 Hz to 5.5 Hz, and from 5.5 Hz to 10 Hz, the seismic waves mainly come from the north and northwest of the array most likely as a result of human activities within the site and or a nearby road outside the site.

The results of this research will be used to design a full scale test array for a gravitational wave detector site. The frequency dependant velocity and azimuth estimates will be used to optimize the configuration of a multi-grid seismic array. Our future plan is to deploy 40 three-component broadband seismometers that are connected to the main-station via WiFi. This will enable real-time low-frequency ambient seismic noise measurement for feed-forward control system research and developments. We
will also deploy an array of 20 three-component geophones inside the buildings, to better monitor higher frequency seismic waves near the optical cavities. Such an array will be easy to reconfigure, and will therefore allow for further array optimization studies. Borehole measurements and few active source seismic surveys are also planned to constrain the inversion of the dispersion plot or its updated version which is to be obtained via the optimum multi-grid seismic array in near future. This will provide more accurate geology information required for NN modeling.

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