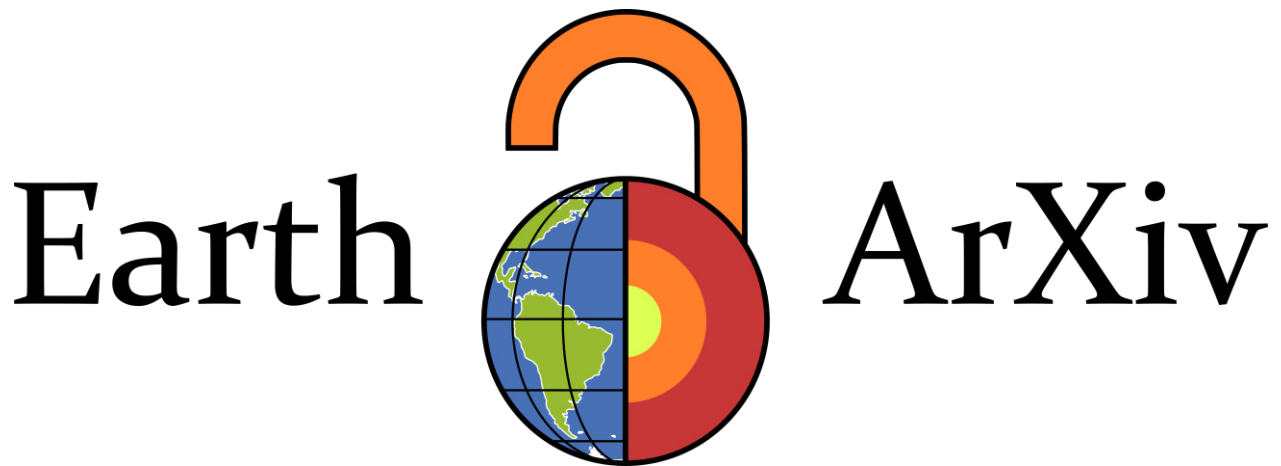




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Relationship between Meteorological Parameters and Temporal Variations of Microseismic Processes at the Belarusian Antarctic Research Station

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Abstract. This study involved an analysis of seismic data acquired in the surrounding area of the Belarusian Antarctic research station “Mount Vechernyaya” in February, 2023 to identify a possible relationship between the seismic noises and local meteorological parameters. Probability density functions of power spectral densities histograms were constructed using the ObsPy framework based on the source seismograms. Separate power spectral densities were also extracted for each time window for the more detailed analysis. In addition to the main peak of the secondary microseisms, some noticeable peaks can be identified in the range of 0.5-1.0 Hz on individual spectral power density graphs at certain time intervals. These peaks can be attributed to the so-called high-frequency microseisms that are often due to the coastal zone waves. The intensity of these peaks shows a significant correlation with the northward wind speed projection, with the correlation coefficient reaching its maximum at a time shift of 14 hours and can reach 0.51 for the horizontal components and 0.45 for the vertical component. The conducted polarization analysis shows the dominance of Rayleigh waves in the wave pattern of oscillations in the range of 0.5-1.0 Hz.

Keywords: Antarctica · Microseisms · High-frequency microseisms · Meteorology · Wind speed · Correlation · Power spectral density · Polarization analysis · Rayleigh wave.

1 Introduction

Traditionally, tectonic sources are of greatest importance in seismology along with controllable anthropogenic sources, primarily explosions, used in exploration seismology. Meanwhile, at any point on Earth, seismic signals are continuously observed in waveform records, caused by the interaction of the Earth’s surface with the hydrosphere, atmosphere and cryosphere [18], and usually having relatively small amplitudes. The existence of such signals, in particular, of seismic background noise, also known as microseisms, has been known since since

the beginning of the era of instrumental seismic observations, it was also then that the relationship between the intensity of seismic noise and such meteorological parameters as wind speed and baric tendency was first discovered [24]. However, the environmental seismology, which is using such signals, haven't received enough development until the recent time, when it became possible to conduct processing of large amount of continuous data, and cross-correlation methods have emerged that make it possible to obtain information about the mechanical properties of the media in which recorded microseismic vibrations propagate [18]. In addition, in recent years a number of publications have emerged, in which the usage of microseisms is proposed for the environmental monitoring, for example, sea storm activity and significant wave height estimation, or for sea ice monitoring in the conditions of Antarctica [7, 9, 8, 1].

In the context of microseismic noise research the Antarctica region is of specific interest, because low level of anthropogenic noise simplifies observations, and in March-April, when a sea ice cover is on its minimum and storm activity is high, microseisms can reach extremal high intensity [29, 12]. The Republic of Belarus is among the countries with its own seasonal Antarctic research stations. The Belarusian Antarctic research station, called Mount Vechernyaya, is situated in the eastern part of the Antarctic continent on Enderby Land, on the coast of the Cosmonaut Sea. Since 2023, the Belarusian Antarctic research station has been conducting seasonal seismological observations, primarily aimed at recording regional and local events, including those of cryoseismic origin. The observations have recorded and processed distant, regional, and local earthquakes, as well as microevents. The Belarusian Antarctic research station also includes a meteorological station, so its equipment allows studying the possible relationship between microseisms and local meteorological parameters.

2 Source data

In this study, data acquired in February 2023 near the Belarusian Antarctic research station were used to identify the main types of microseismic processes and analyze their temporal variations and potential relationships with meteorological parameters. The seismic data included three-component waveform recordings from a seismic station located in close proximity to the Antarctic station and consisting of a Delta-03M digitizer and two seismometer-velocimeters: a 1-second Lennartz LE-3Dlite sensor and a 20-second Lennartz LE-3D/20s sensor [19]. The sensors were installed at a bedrock outcrop in a natural shelter, a fissure in the rock covered with a tent to minimize wind interference. Since the primary interest in this study was microseismic noise of natural origin, and therefore primarily located in the frequency range below 1 Hz, data from a 20-second sensor was mainly used for further analysis. Data from a meteorological station located at the Belarusian Antarctic research station were also available for the entire observation period. These data included continuous measurements of meteorological parameters potentially associated with microseisms, such as wind speed and direction, atmospheric pressure at the station level, and air temperature.

3 Methodology

The standard method for characterizing microseismic noise levels is to calculate the power spectral density (PSD), which is typically expressed in units of acceleration [21, 2]. The power spectral density of seismic noise across the Earth’s surface can vary within a certain range, the upper and lower levels of which can be described using seismic noise models. The most commonly used are the new low-level and new high-level noise models (NLNM and NHNM) [21, 20, 25].

Using power spectral density to study microseisms raises the following problem: any seismic event – man-made interference or a tectonic earthquake – distorts and exceeds the intensity of the microseismic noise spectrum. This problem could be solved by identifying quiet intervals (with minimal amplitude) in waveform records, as is done, for example, when calculating HVSR [5]. However, microseisms form a quasi-stationary background noise with variations within hours and throughout the year. Therefore, manually identifying quiet intervals in continuous data over a period of several months is a very labor-intensive task. In this regard, in 2004, McNamara and Buland proposed an approach called the probability power spectral density (PPSD) or probability density function of the power spectral density (PDF PSD), which allows calculating the PSD for large volumes of continuous data [20]. The original continuous waveform record is divided into relatively long-time windows, typically one hour or more in duration, with an overlap of up to 50 percent. Then, for each time window, the power spectral density is calculated using the Welch method and significant amplitude smoothing is performed with a smoothing window width of one octave in frequency [20, 30]. The obtained spectral power densities for time windows are then divided into intervals by frequency and spectral amplitude, and a two-dimensional histogram is constructed using these values, showing the probability density distribution of the power spectral density for the continuous recording under study, with quasi-stationary microseismic noise dominating on the histogram over relatively unlikely seismic events [20].

Probability spectral power density histograms were obtained for all three components of the original seismograms for February 2023; calculations were performed using the ObsPy framework [6, 22, 17, 28]. In addition to the standard calculation parameters proposed in the original paper by McNamara and Buland, with a 50 percent time window overlap and an octave-wide amplitude smoothing window with a frequency resolution of 0.125 octaves, optimized parameters were also used [20]. The probability spectral power density method is most often used to estimate the overall noise level at seismic stations as one of the quality control indicators of seismic data [2]. In this application, the highly smoothed power spectral density curves, which are in good agreement with the shape of the NLNM and NHLM model curves, provide comprehensive information on the seismic noise level, and the relatively low frequency resolution of 0.125 octaves means fewer Fourier transform points and a faster calculation process. However, when using this method for detailed microseismic analysis, the low frequency resolution and significant amplitude smoothing make it impossible to distinguish between potential narrow spectral peaks of microseisms and, for

example, the fine structure of secondary microseismic peaks [2, 15]. Therefore, optimized parameters were selected for the PPSD calculations. These parameters included a time window overlap reduced to 33 percent to more accurately distinguish potential temporal variations, an amplitude smoothing window reduced to 0.1 octaves in frequency, and an increased frequency resolution of 0.0125 octaves. These parameters allow to obtain a spectral picture of the fine structure of microseismic peaks, while the spectra remain sufficiently smoothed for visual and numerical analysis.

Although the PPSD calculation does not require the identification of quiet sections of the record, culling out time windows containing earthquakes can be useful in analysis of time series containing power spectral density values to remove intensive short-term bursts in the power spectral density caused by a seismic event [2]. An algorithm for filtering out time windows containing recorded teleseismic events is described. This algorithm is based on the fact that surface waves from distant strong earthquakes ($M \geq 5$) form broad and intense spectral bursts at frequencies below 0.03 Hz [2, 4]. Since such events are relatively unlikely against a background of microseismic noise, a criterion can be introduced according to which a spectral curve lying 95 percent above the 80-th percentile of the probability density function of the power spectral density at frequencies below 0.03 Hz most likely represents the spectral curve of a teleseismic event and should be rejected [4]. Since seismic observations at the Belarusian Antarctic research station used a 20-second sensor with significant hardware noise at low frequencies, using such parameters for culling was impossible. However, strong earthquakes have a very characteristic spectral pattern in the frequency range from 0.05 to 0.1 Hz. Therefore, the implementation of the time window culling algorithm was tested. Rejection occurred if the spectral curve lay 70 percent above the 85-th percentile of the probability density function of the spectral power density in the range from 0.05 to 0.1 Hz.

4 Results and discussion

4.1 Power spectral densities calculation

After calculating the power spectral density with standard and optimized parameters histograms of the probability density function of the power spectral density, presented in figures 1a and 1b, were obtained. It can be seen that the shape of the power spectral density curves obtained with the parameters given in McNamara and Buland, 2004 [20] (figure 1b) closely resembles the shape of the curves of the NLNM and NHNM models. Meanwhile, calculating the probability density of the power spectra with a reduced amplitude smoothing window and increased frequency resolution reflects more features of the microseismic noise spectrum.

First of all, it is noticeable that the peak of secondary microseisms, located in the range from 0.1 to 0.4 Hz, can split into several separate spectral peaks [27]. For a short time, extremely high values of the spectral power density were also observed in this range, with a peak maximum of approximately 0.12 Hz. The

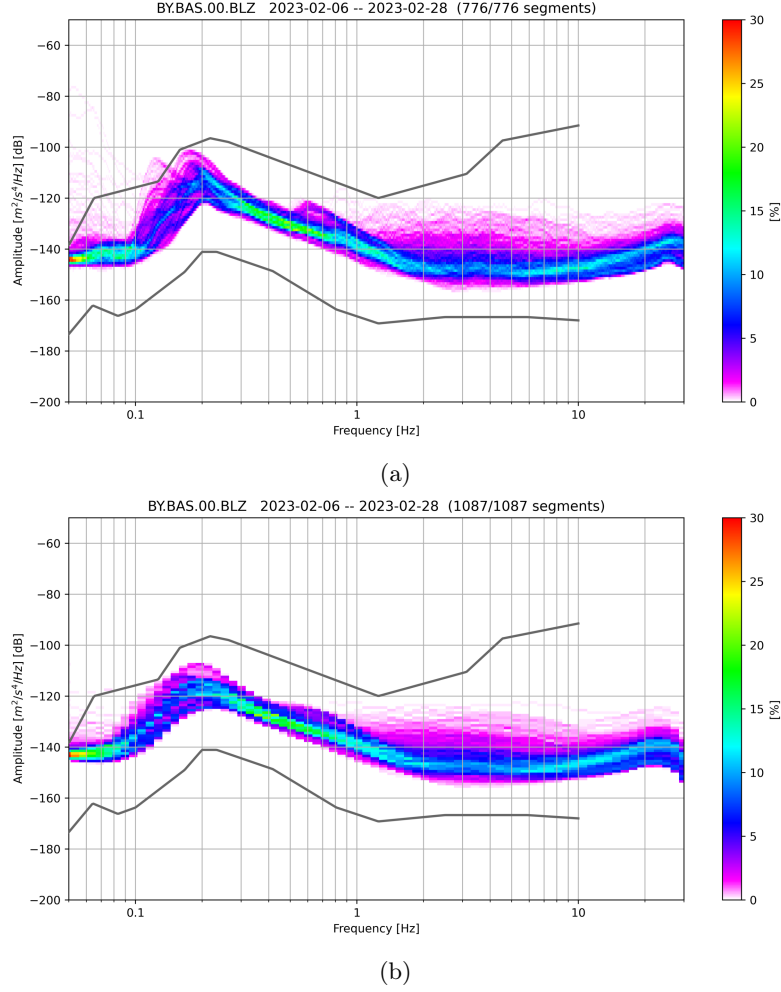


Fig. 1: (a) Histogram of the probability density function of the power spectral density obtained with the optimized calculation parameters. (b) Histogram of the probability density function of the power spectral density obtained with the calculation parameters according to McNamara and Buland, 2004 [20].

splitting of the secondary microseism peak is usually associated with the presence of several separate oceanic regions in which secondary microseisms are generated due to wave-wave interaction. Moreover, these regions can be significantly distant from each other and can even be located in different places in the water area [15, 27].

The peak of primary microseisms, located in the range of 0.05-0.07 Hz [27], is barely visible in the histograms. This is likely due to the fact that at frequencies below 0.03 Hz, the minimum level of the recorded microseismic signal (MLBN), defined as the first percentile of the spectral power density distribution, is due to the self-noise of the seismic sensor (figure 2), despite the fact that the sensor's amplitude-frequency response should be capable of recording the peak of primary microseisms [19].

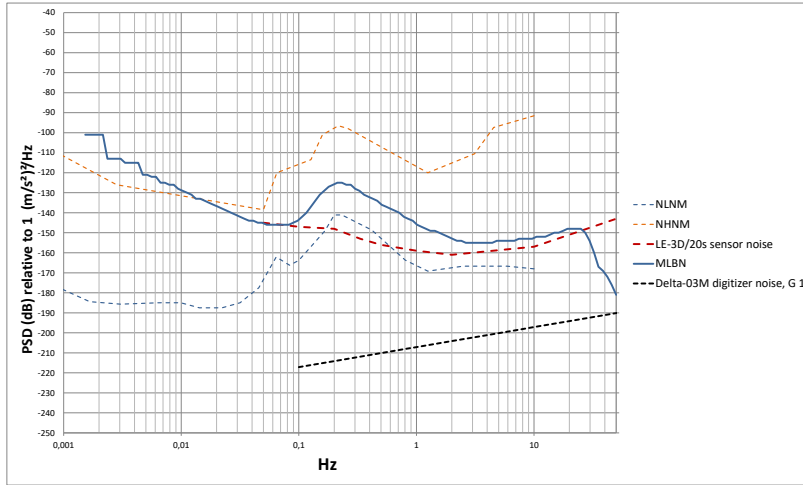


Fig. 2: The level of seismic sensor and digitizer self-noise, as well as the minimum level of background seismic noise (MLBN).

An attempt to filter out time windows containing strong earthquakes proved ineffective, as the 0.05 to 0.1 Hz range used for culling was too narrow and did not allow for reliable differentiation between teleseismic event waves and extremely intense primary microseisms. Since further analysis was conducted primarily in the high-frequency region above 0.35 Hz, the main source of spectral bursts in this region, which are undesirable for microseismic research, are body waves, which are not identified by this approach.

For a detailed analysis of the temporal variations of microseisms, individual graphs of the spectral power density for sequential hourly time windows were examined. The graphs show that the transition from one intense peak of secondary microseisms to another separated peak of lower intensity can occur within a single day, which may indicate the development of non-stationarity in the regions of secondary microseism generation (figures 3a, 3b). Moreover, at the end of the analysed period, pronounced peaks are observed in the spectra, which are localized quite accurately in the frequency range of 0.5-1.0 Hz (figures 3c, 3d). The large amplitude of the spectral peaks in the frequency range from 0.35 to 1.0 Hz gives reason to assume that they are caused by the occurrence of high-frequency microseisms [27, 31]. High-frequency microseisms are caused by the interference of sea waves at a relatively short distance from the shore and are usually correlated with the wind speed at the point of their recording [27, 31, 11]. The appearance of spectral peaks with similar intensity and frequency characteristics has been noted at seismic stations surrounding Lake Issyk-Kul [26]. Similar microseisms have been observed at Issyk-Kul during storms on the lake and are presumably caused by the formation of standing waves on the water during storm activity [26].

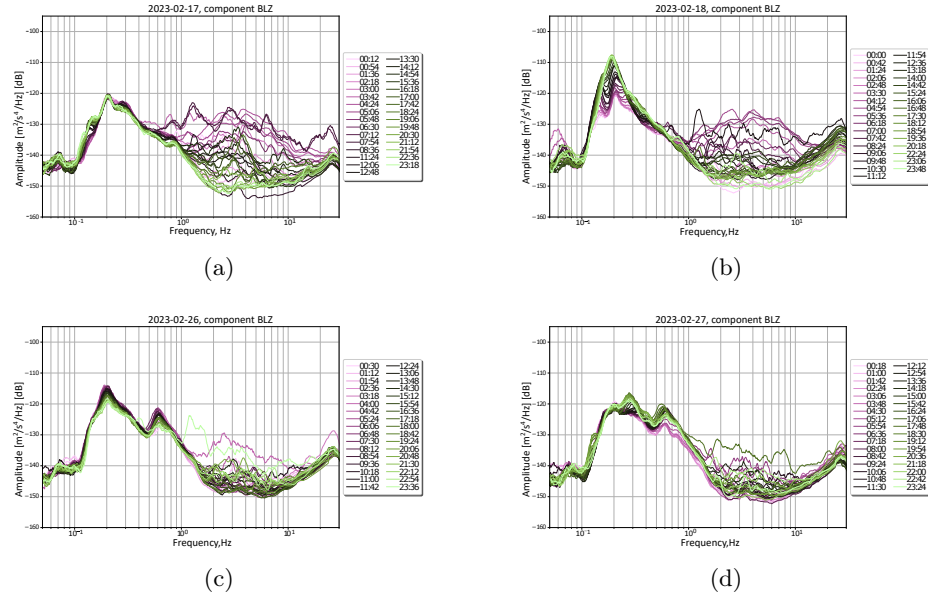
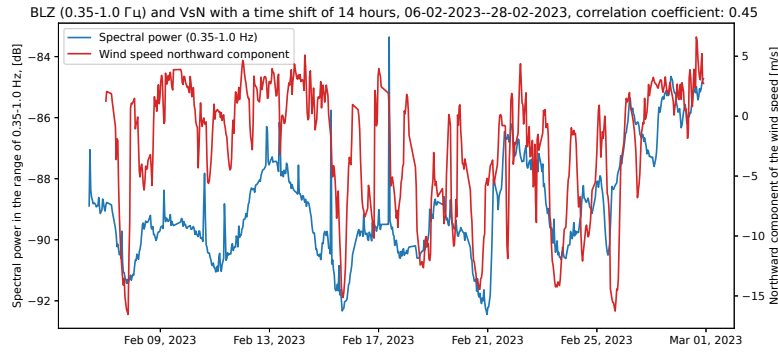
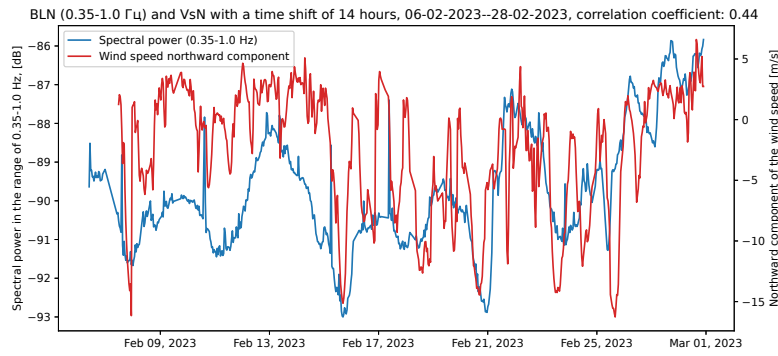


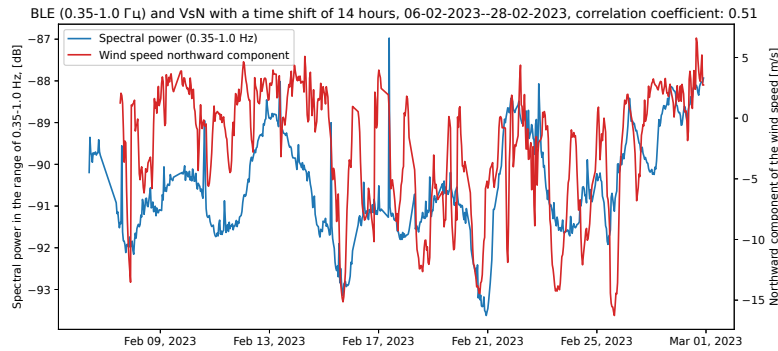
Fig. 3: Spectral curves of seismic noise for individual sequential time windows during the day.



(a)



(b)



(c)

Fig. 4: (a) Comparison of the integrated spectral intensity of the vertical component and the northward wind speed projection with a 14-hour shift. (b) Comparison of the integrated spectral intensity of the horizontal N-S component and the northward wind speed projection with a 14-hour shift. (c) Comparison of the integrated spectral intensity of the horizontal E-W component and the northward wind speed projection with a 14-hour shift.

Meteorological observations were conducted at the Belarusian Antarctic research station, and a possible relationship between local meteorological parameters and the intensity of high-frequency microseisms was investigated. Wind speed, atmospheric pressure, and temperature, averaged over the same time windows in which the spectral analysis was performed, were used for comparison. The intensity of high-frequency microseisms for all three components of the record was expressed as an integrated spectral power in the range of 0.35-1.0 Hz. The Pearson correlation coefficient was used to compare the degree of relationship between time series. The comparison revealed no correlation with air temperature (Pearson correlation coefficient of 0.06), as well as an insignificant negative correlation with atmospheric pressure (correlation coefficient of -0.28). Correlation with wind speed was also insignificant, with a correlation coefficient of 0.11. Such a low correlation coefficient may be due to the not taking wind direction into account. The observed peaks are presumably high-frequency microseisms, the source of which is the interference of waves on the water surface. In turn, large wind wave heights are achieved under the condition that the wind speed remains constant for a period of time, allowing the waves on the water surface to gain height [32]. This suggests that, to accurately compare wind speed with microseism intensity, wind direction must be taken into account, which can be achieved by calculating the northward projection of wind speed.

The correlation between the spectral power of microseisms and the projected wind speed is more significant: the correlation coefficient is 0.32 for the vertical component of oscillations and 0.34 for the horizontal component. To test for a possible time shift, which could potentially be caused by the time required for sufficiently high waves to develop on the water under the influence of wind and/or the time required for travelling waves to propagate to the region of their interference with waves coming from a different direction, a cross-correlation between the projected wind speed and the integrated spectral power of microseisms was calculated. The calculation results show that the maximum correlation is achieved with a time delay of approximately 14 hours, and the correlation coefficient reaches values of 0.45 for the vertical component and 0.51 for the horizontal E-W component (figures 4a, 4c). Furthermore, the time series graphs show a clear correspondence between the local minima of the wind speed projection and the integrated spectral power of microseisms.

4.2 Polarization analysis

A three-component polarization analysis was also performed on the analysed waveform records to estimate the azimuth of the potential source of the recorded secondary microseisms. Polarization analysis was performed using two methods: orthogonal distance regression for particle trajectories (ODR) [28] and eigenvalue decomposition of the covariance matrix [10]. In addition to the azimuth value, the orthogonal matrix decomposition method also yielded parameters for the degree of rectilinearity [23] and planarity of oscillations [13].

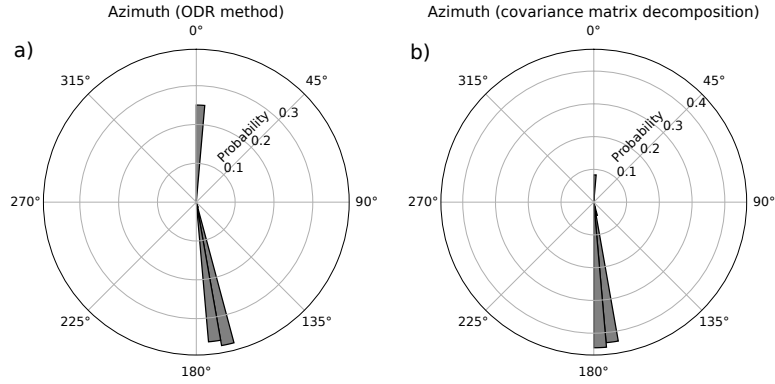


Fig. 5: (a) Estimation of the microseismic propagation azimuth in the 0.5–1.0 Hz range using the orthogonal distance regression method for particles motion. (b) Estimation of the microseismic propagation azimuth in the 0.5–1.0 Hz range using the covariance matrix decomposition method.

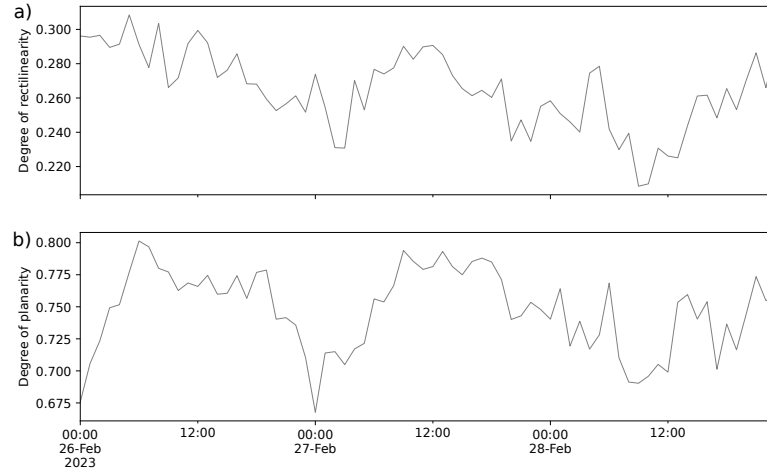


Fig. 6: (a) Change in the degree of rectilinearity of microseismic oscillations in the 0.5–1.0 Hz range over time. (b) Change in the degree of planarity of microseismic oscillations in the 0.5–1.0 Hz range over time.

The source material for both methods was continuous three-component records from February 26 to 28, 2023, when peaks of high-frequency secondary microseisms were observed and the frequency domain in the 0.5–1.0 Hz range was virtually free of seismic events. Polarization analysis was performed only in the

time domain for hourly windows over the course of all three days. The seismograms were pre-filtered in the 0.5 to 1.0 Hz range to remove the instrumental response. Calculations using both the ODR method and the covariance matrix decomposition revealed a predominant azimuth value of approximately 180 degrees, indicating that waves in this frequency range originated from the north, where the water surface is located relative to the microseismic recording site (figure 5). The resulting azimuth values of 0 degrees in this case can also be explained by the opposite uncertainty arising in the case of elliptical retrograde motion [16].

The rectilinearity values for the waves corresponding to the observed microseismic peak range from 0.20 to 0.30 (figure 6a), and the planarity value, which characterizes the motion of particles in one plane, ranges from 0.68 to 0.8 (figure 6b). This type of motion with low rectilinearity and high planarity is often characteristic of elliptical motion [14]. Combined with the possible uncertainty in determining the azimuth, these factors suggest that Rayleigh waves predominate in the observed high-frequency peaks. The publications showed that Rayleigh waves predominate in the wave pattern of secondary microseisms at distances of up to 2000 km [3].

5 Conclusions

At the Belarusian Antarctic research station, the spectral density curves of the microseismic background show intense peaks in the 0.5-1.0 Hz range. These peaks are high-frequency microseisms, caused by wave interaction in the waters during strong winds at a relatively short distance from the shore.

It should be noted that seismic noise in the 0.35-1.0 Hz range at the Belarusian Antarctic research station correlates quite well with the northward projection of local wind speed. With a time shift of 14 hours, the correlation coefficient reaches 0.45 for the vertical component of seismic vibrations and 0.51 for the horizontal component.

A polarization analysis shows that the seismic waves causing the high-frequency microseismic peak in the 0.5-1.0 Hz range propagate northward from the waters toward the recording seismic station. Moreover, the wave pattern of the oscillations is dominated by Rayleigh waves, which is typical of secondary microseisms caused by wave interference in offshore waters.

These facts, taken together, allow us to conclude that the appearance of intense peaks in the 0.5-1.0 Hz range on the spectral curves of seismic noise may be due to the wave-wave interaction of strong wind waves.

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