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IMMISSION DIRECTIVITY IN THE FREQUENCY DOMAIN

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ABSTRACT

The spatial domain has proven to be a crucial element in the measurement of environmental noise and allows for better identification and classification of noise sources. This paper presents spectral immission directivity, an extension of the concept of immission directivity into the frequency domain, which improves the spatial representation of noise at different frequencies. The proposed methodology combines spectral and spatial insights and provides a comprehensive view of the acoustic environment. Theoretical simulations were performed and validated by measurements in an anechoic chamber, confirming the reliability and precision of the approach. The integration of spectral immission directivity into existing noise measurement systems is seamless and requires no significant changes, and it improves their ability to localize and characterize noise sources. This advance reduces reliance on complex post-processing algorithms and promotes more efficient, accurate and cost-effective noise monitoring strategies. By enriching environmental noise assessments with spectral-spatial data, this research paves the way for innovative approaches to noise assessment and management.

Keywords: *Environmental noise measurements, Immission directivity, Sound source localization, Microphone array, Spatial filtering*

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1. INTRODUCTION

Noise pollution in urban areas is a significant but often overlooked environmental problem, largely due to inadequate measurement methods and impact assessments. Noise is defined as unwanted or disturbing sound and is constantly perceived by the auditory system, making it inherently intrusive. Urban areas, with their dense population and industrial activity, face particular challenges in managing noise levels. Apart from the effects on human health - which are associated with sleep disturbance, cardiovascular disease and cognitive impairment, noise pollution also has economic costs, such as healthcare expenditure, property devaluation and lost productivity. In addition, it disrupts ecosystems and affects biodiversity on land and in the sea [1-3]. Tackling noise pollution presents significant technical challenges, with the most effective strategy being to reduce noise pollution at the source itself. However, many noise sources, such as industrial plants, ports, railways, airports and construction sites, are constantly in operation and cannot be easily mitigated. The simultaneous activity of multiple sources makes accurate assessment difficult, as environmental noise is inherently dynamic and varies in time, frequency and space. Effective assessment requires sophisticated measurement and modeling techniques [4-6].

Noise propagation modeling, combined with sound power assessments, helps estimate individual contributions to overall noise levels. However, these models depend on extensive input data, including operating times, source geometries, and terrain characteristics, and are subject to uncertainties from variations in software tools and standards. Consequently, noise modeling primarily serves to extrapolate data from limited measurement points (MPs) to broader areas, a method supported by numerous studies [7-9]. Long-term measurements are crucial for accurate assessments, allowing the identification of dominant noise sources and enabling targeted reduction strategies.

However, manual post-processing, such as listening to recordings, is time-consuming and costly.

Recent advances in noise research have led to the development of the immission directivity (ID), a concept that can be seamlessly integrated into existing legally compliant noise measurement methods. By combining ID with standardized approaches, noise monitoring technologies can be further improved. ID is compatible with calibrated Type 1 noise level meters, ensuring traceability to SI units and enabling accurate assessments of environmental noise [10-12].

Using a small microphone array, ID identifies the most dominant noise source at each measurement integration time based on its location and direction relative to the MP. The inclusion of this spatial dimension in equivalent sound pressure level measurements has proven valuable in analyzing acoustic environments and distinguishing individual noise sources. Since traditional noise source identification is based on frequency analysis, combining spatial and spectral data is a logical next step. This paper presents Spectral Immission Directivity (SID), a novel approach that has emerged from our recent research and improves the analysis of environmental noise by incorporating spatial and frequency data. By mapping the directional distribution of different frequency components around the MP, SID improves the identification and classification of noise sources, especially in complex environments with multiple overlapping sources [13].

In addition to human-generated noise from traffic, industry and construction, SID can also be used to analyze biological sounds such as bird calls, insect activity and wildlife vocalizations, making it valuable for both urban and ecological studies. Its applications extend to urban planning, building design, traffic noise studies, public health research and biodiversity monitoring, supporting targeted noise mitigation strategies. In addition, SID can be seamlessly integrated into existing regulatory compliant methodologies and can serve as a key component in classification models and smart city monitoring networks.

To validate this approach, 16 hours of in-situ pilot measurements were conducted in a multi-source noise environment, demonstrating the ability of the SID's to distinguish and identify different noise sources and their contribution to the overall noise level. This study aims to use SID to transform the assessment of environmental noise, making it more accurate and effective.

2. METHODOLOGY

In this study, we performed in-situ measurements as a case study to evaluate the SID approach and analyze its performance in a real-world environment. We used a dedicated microphone array and the Delay, Subtract, and Sum (DSS) algorithm [12] to determine the direction of arrival (DOA) and spectral characteristics of the noise sources. Using SID, we identified the number of individual noise sources, analyzed their contribution to the overall noise level, examined their frequency characteristics, and determined the times at which they were present.

2.1 Equipment

The experimental setup for this research included specialized measuring devices and software tools for data acquisition. The Behringer UMC404HD ADC USB audio interface, which operates at a high sampling frequency of 192 kHz, was used to capture audio signals. A horizontal microphone array consisting of four Behringer ECM8000 measurement microphones arranged in a circle with a diameter of 27 mm was used. The DSS method was applied to the signals from the array. This configuration provided a computationally efficient system capable of capturing DOA over the frequency range of most environmental noise sources (100 Hz to 6300 Hz, in 1/3 octave bands) and operating with an integration time of 125 ms. The user interfaces and data acquisition programs were developed using LabVIEW 2023, while the processing of the measurement data and the generation of the figures was performed in MATLAB R2024a. This combination of hardware and software ensures accurate data acquisition and analysis.

2.2 Spectral immission directivity

ID, first introduced in 2018, is a ground-breaking concept in environmental acoustics that aims to address the challenges of understanding and quantifying the contributions of different noise sources to the overall noise level at a given MP. It captures both the spatial and temporal dynamics of noise and provides a detailed representation of how sound energy from different directions affects an acoustic environment. By incorporating both the direction of arrival (DOA) and the sound pressure level (SPL) of noise sources, ID serves as a valuable tool for analyzing complex soundscapes found in urban or industrial environments.

Building on the foundational principles of ID, a derived concept known as SID was developed. SID extends ID by integrating a 1/3-octave frequency analysis alongside the spatial distribution of noise sources around the MP. This extension enables a more comprehensive understanding of the acoustic environment and provides deeper insights into the frequency-specific contributions of the different noise sources. By combining spectral and spatial data, SID is a powerful tool for the assessment of environmental noise and contributes to the development of more effective noise mitigation strategies and the design of the urban soundscape.

To simplify the SID pattern, it can be reduced to a two-dimensional spatial problem by disregarding the elevation angle. This approach is feasible because environmental noise sources such as traffic, industrial plants and wind turbines are usually located at a certain distance from the MP, so that the propagating sound waves can be approximated as parallel to the ground. As a result, the A-weighted equivalent sound pressure level $L_{A,eq,T,fi}$ at a specific frequency can be defined by Eq. (1).

$$L_{A,eq,T,f_i} = 10 * \log\left[\frac{1}{T}\int_0^T\int_0^{2\pi} 10^{\frac{L_{p,A}(t,f_i,\varphi)}{10}} d\varphi dt\right] \quad (1)$$

Where $L_{p,A}(t,f_i,\varphi)$ stands for A-weighted instantaneous sound pressure level for the frequency f_i as a function of time t and direction φ. $L_{A,eq,T,fi}$ can be defined as the sum of a specific frequency of all noise sources that are present in the vicinity of the MP in the time interval T (from directions between 0 to 2π). To obtain the total A-weighted equivalent sound pressure level, we use the logarithmic summation of all $L_{A,eq,T,fi}$ for I number of frequency bands described with Eq. (2).

$$L_{A,eq,T} = 10 * \log \int_0^{f_I} 10^{\frac{L_{A,eq,T,f_i}}{10}} \quad (2)$$

At each point in time, the levels of the individual frequencies are assigned to a single direction — the most dominant — as the DSS algorithm only identifies the strongest source. By extending the measurement duration and sequentially activating different noise sources, unique ID patterns are generated for each frequency. The aggregation of these patterns forms the SID. As shown in the results section, analyzing the ID on a frequency basis helps significantly to identify the main noise sources, understand their contribution to the overall noise level and determine their spectral characteristics.

The frequency resolution can be chosen according to need. However, in this study, a 1/3-octave spectral analysis was chosen in line with standard practice to limit the amount of data and improve conceptual clarity. Regardless of whether a narrowband frequency analysis is used, the underlying method for calculating the SID remains unchanged.

In discrete form, Eq. (1) and Eq. (2) can be rewritten as Eq. (3) and Eq. (4), where N represents the measurement duration in terms of integration time count. I corresponds to the number of frequency bands, which was set to 19 in this study. The spatial resolution for DOA determination at the immission point was fixed at 6° on the horizontal plane, resulting in $M = 60$ observed angles.

$$L_{A,eq,T_N,f_i} = 10 * \log\left[\frac{1}{T_N}\sum_{n=1}^{N}\sum_{m=1}^{M} 10^{\frac{L_{p,A}(t_n,f_i,\varphi_m)}{10}}\right] \quad (3)$$

$$L_{A,eq,T_N} = 10 * \log \sum_{i=1}^{I} 10^{\frac{L_{A,eq,T_N,f_i}}{10}} \quad (4)$$

2.3 Measurement location

The MP was placed near a large cement plant, its stone quarry and an industrial area. The location of the main sources of noise can be seen in Fig. 1. Otherwise, there are several small villages in the vicinity of the MP where agriculture is practised.

Figure 1. MP and surrounding noise sources.

3. RESULTS

The in-situ measurements were carried out on a working day from 15:00 to 7:00. Fig. 2 shows the recorded data and the dynamics of the acoustic scene during the measurement. It can be clearly seen that the dominant direction (Fig. 2.b) was quite stationary during the night when the overall sound pressure level (Fig. 2.a) was lower. Spectrogram and spectrum (Fig. 2.c and Fig. 2.d) are also shown, which is a typical representation of noise measurement data. Even with only 16 hours of data, no direct conclusions about the noise sources can be drawn from Fig. 2. The data must be condensed to a level that is easier to interpret and clearer.

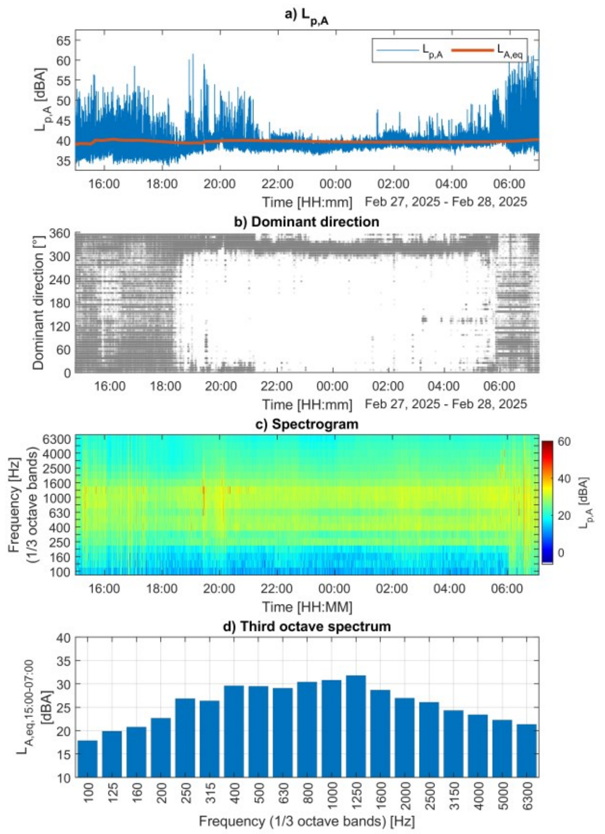

Figure 2. Noise measurement data.

To get a clearer picture of the contribution of the different noise sources around the MP, we use the ID pattern as shown in Fig. 3. The polar diagram shows how $L_{A,eq}$ is spatially distributed. We can notice that most of the sound energy comes from the southeast direction, but some other directions are also notable.

To get a better understanding of the different noise sources, Fig. 4 shows the comparison of the dominant direction distribution and the ID. It can be seen that the noise source in the southeast direction (approx. 330°) had a lower SPL at the MP than the noise sources in the directions 6°-30°, 72°-90°, 102°, 114° and 156°, as the contribution of the noise source in the southeast direction to the total $L_{A,eq}$ was not much higher compared to the other sources, although it was the most dominant noise source for most of the measurement.

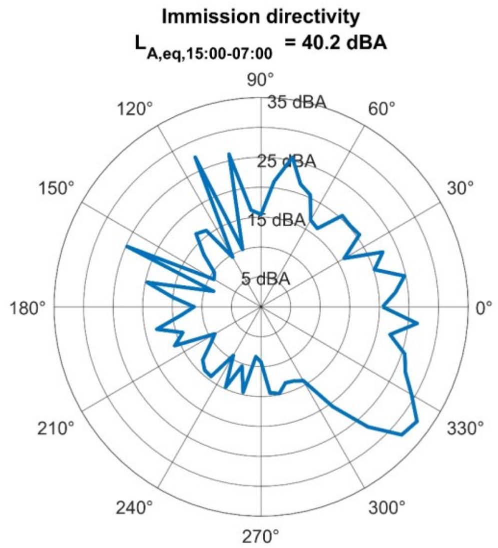

Figure 3. Imission directivity.

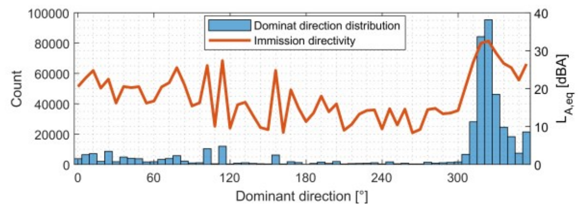

Figure 4. Dominant direction distribution around the MP.

Fig. 5 shows the SID of the measurement performed. The approximate spectrum and the dominant frequency bands of the main noise source are clearly recognisable. The sources in the directions 102°, 114° and 156° show a rather broadband spectrum, while the sources in the directions 72°-90° and 6°-30° show peaks in certain frequency bands.

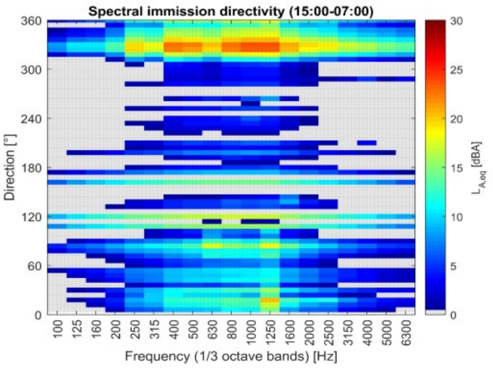

Figure 5. Spectral immission directivity.

To better represent the spatial-temporal dynamics of the acquired noise data, IDs for 1-hour intervals were calculated and can be seen in Fig. 6. A shift from a multiple noise source operation to a single noise source operation can clearly be observed as IDs between 15:00 and 19:00 display a more spatially even distribution of $L_{A,eq}$ around the MP and then a transition at 19:00 , when a noise source at 78° starts to dominate alongside the noise sources east of the MP. While some sources at 342°-24° are still present between 21:00 and 23:00, they completely stop operating thoughout the night. The dominance of this noise source ends at 5:00 when noise sources from other directions start to appear and by 7:00 they start to dominate.

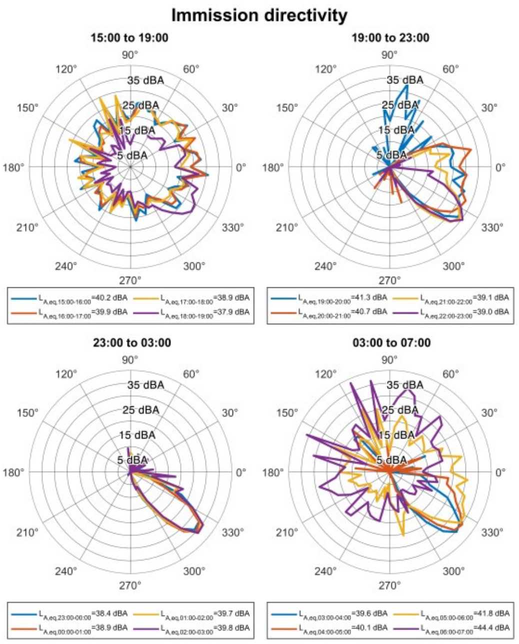

Figure 6. Hourly imission directivity.

SID allows us to examine 1-hour data in more detail by analysing the spatial-frequency content of the measurement. In Fig. 7, we can observe a noise source at 18° with a prominent peak at 1250 Hz in the frequency band from 15:00 to 17:00.

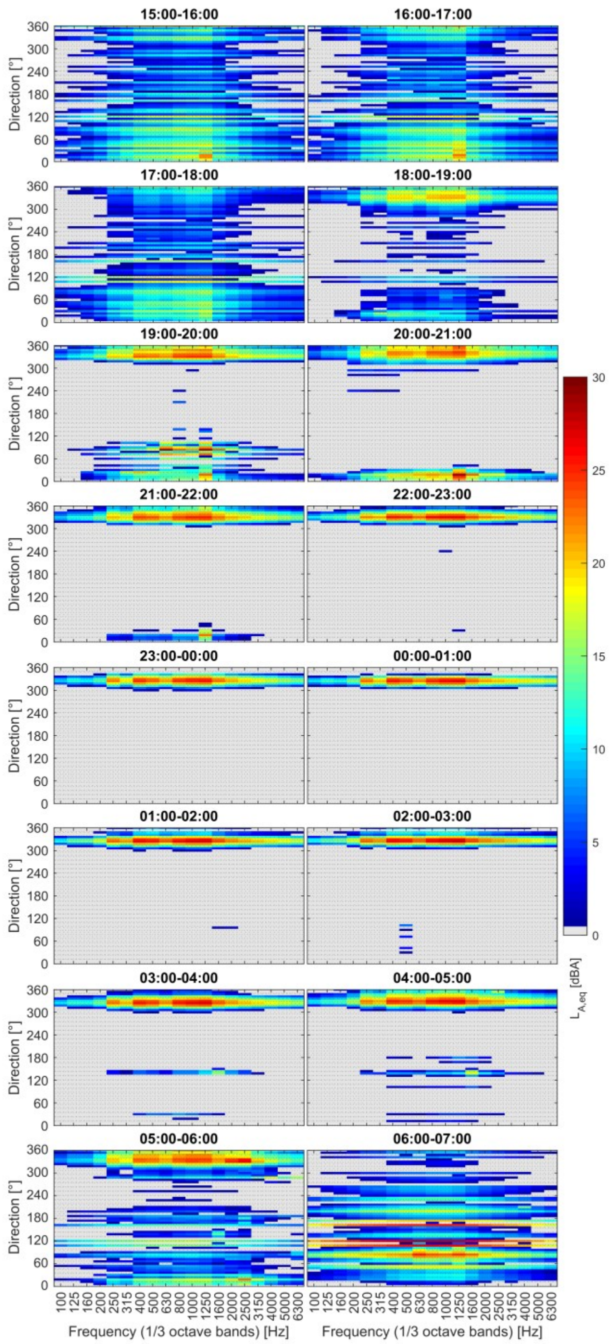

Figure 7. Hourly spectral imission directivity.

It is obvious that the operation of the source stopped between 17:00 and 19:00 and then continued until 22:00. Another noise source occurred between 19:00 and 20:00 with peaks at 630 Hz and 1250 Hz in a direction of about 78°. Looking at the data in the morning, especially between 6:00 and 7:00, noise with broadband frequency content and higher amplitudes can be observed in the directions of 102°, 114° and 156°.

If we filter the data spatially, we can calculate $L_{A,eq}$ of the 1/3-octave spectra for specific noise sources (their direction/location relative to the MP). Fig. 8 shows the results for six noise sources together with the total $L_{A,eq}$ (from 0° to 360°). It can be seen that the main noise source contributing the most to the total noise level is between 312° and 360°. The sources at 102°, 114° and 156° have broadband frequency components (influenced by the A-weighting) that could belong to an impulse noise source. The source at 6° - 30° had a peak in the frequency band of 1250 Hz, while the source at 72° - 90° had an additional peak in the frequency band of 630 Hz.

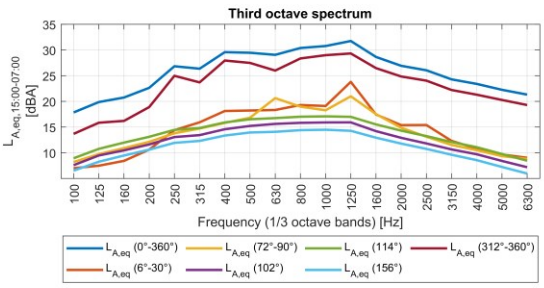

Figure 7. 1/3-octave spectrums of selected directions.

4. DISCUSSION

Pilot measurements were carried out on site to validate and evaluate the usability of the SID. Several noise sources were identified during the analysis, one of which accounts for the largest share of the total noise level. As shown in the ID polar diagram (Fig. 3), the industrial area proved to be the main noise source. A further analysis with the SID (Fig. 7) showed that the noise emissions from the industrial area have a broadband frequency spectrum that is most pronounced in the evening and at night (19:00–06:00).

In certain cases, certain frequency components can cause greater disturbance, especially when people are at home. This effect is more pronounced at lower frequencies, which are better able to penetrate into people's homes. In addition, it is widely recognized that tonal noise is a significant contributor to noise annoyance. The use of SID facilitates the rapid identification of such noise sources and increases the efficiency of noise monitoring and mitigation efforts.

One such noise source, presumably a heat exchanger, was detected between 19:00 and 20:00 at an angle of 78°. This source showed clear peaks at 630 Hz and 1250 Hz within the 1/3-octave frequency bands (Fig. 7). Another conspicuous noise source associated with stone quarry activities was detected in an 18° direction and occurred from 15:00 to 17:00 and again from 19:00 to 22:00. This source had strong tonal characteristics, as shown in Fig. 7.

In addition, three separate noise sources with broadband spectral characteristics were identified in the morning hours (06:00-07:00) in the directions 102°, 114° and 156°. These sources also appeared between 15:00 and 19:00. As these directions coincide with residential areas in nearby villages, it is plausible that these noise sources originate from human activities and may represent impulsive noise events.

These results highlight the effectiveness of SID in accurately identifying and characterizing complex noise environments, thereby supporting more targeted noise mitigation strategies.

5. CONCLUSION

The results of this study show the usefulness and efficiency of the SID for the measurement of environmental noise. A key advantage of SID is its ability to provide a comprehensive overview of the acoustic environment at a glance, allowing for quick identification of dominant noise sources without the need for extensive post-processing. In addition, SID offers flexibility in data analysis as measurements can be analyzed in real time or retrospectively, providing valuable insights for both immediate assessments and in-depth post-measurement evaluations. This capability significantly increases the efficiency of environmental noise assessments and facilitates targeted noise mitigation measures.

To further validate and extend the applicability of SID, future work will focus on conducting longer measurement campaigns in more diverse acoustic environments. This will include the investigation of biological sounds, which will provide additional insights into the effects of natural and anthropogenic noise sources. In addition, efforts will be made to expand the frequency range of the microphone array's frequency range will be extended to capture and analyze a wider range of noise sources. These planned improvements will increase the versatility of SID and make it a more robust tool for environmental and industrial noise monitoring.

6. ACKNOWLEDGMENTS

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