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Automatic detection of source direction and exclusion of irrelevant sounds in unattended noise monitoring systems

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ABSTRACT

A device featuring 8 MEMS microphones has been designed, which allows localizing dominant sound sources in 3D space by implementing techniques based on time difference of arrival. The device, also called Noise Compass, is intended to be used together with an outdoor measurement microphone in a noise monitoring terminal. By defining regions of interest in the vertical and horizontal planes in a monitoring and analysis system, non-relevant sounds can be automatically detected and excluded from the noise measurements. This article describes the direction detection mechanisms and shows two examples of system application: aircraft noise monitoring and a construction site with a road and railway nearby. Finally, other system applications are discussed.

1. INTRODUCTION

Noise pollution is a well-documented environmental challenge [1]. Many countries have legislation describing requirements for acceptable sound pressure levels as part of their environmental noise mitigation strategy. The requirements can be applicable to the summation of sound contributions from all noise sources present (for example, the sound level from external noise sources in front of a façade) or to single noise sources (for example, a landing platform or a construction site neighboring residential areas).

In the scenario of regulations applicable to single noise sources in complex urban soundscapes, the separation of relevant and irrelevant noise sources can be challenging. ISO 1996-2 [2], acknowledges this challenge when describing the selection of measurement site for environmental noise measurements, and includes guidance on how to determine residual sounds and unwanted events. As ISO 1996-2 instructs to remove all data including unwanted events or with too high residual sound before the evaluation of measurement results, efficient methods to identify irrelevant sounds are required when dealing with continuous long-term unsupervised noise monitoring and large amounts of data.

Current approaches to the identification of irrelevant sounds are the use of sound recording and playback, video cameras, and installations featuring several microphones used for sound source localization. Newer technologies are moving towards artificial intelligence (AI) for automatic classification of sounds.

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This paper presents a device within the category of multi-microphone devices, called Noise Compass. The device has 8 MEMS microphones that are used to localize dominant sound sources in 3D space, so that non-relevant sounds can be automatically detected by their location.

2. METHODS

The sound localization mechanism of Noise Compass is based on the time difference of arrival (TDOA) of the signals detected by the microphones mounted in the device. The use of TDOA for sound source localization is well described in the literature, but the basic theory is repeated here for completeness.

Consider two microphones j and i separated by a distance d, and a sound impinging with an unknow direction described by the vector $\mathbf{x}$. The TDOA or time lag τ_{ji} between the output signals from the microphones will be:

$$\tau_{ji} = -\frac{l}{c}, \quad (1)$$

where c is the speed of sound and l is the length determined by the delay in the sound reaching each microphone. The numerical value of τ_{ji} can be determined by cross-correlation of the microphone's actual output signals. By defining a vector $\mathbf{x}_{ji}$ between the microphones so that $|\mathbf{x}_{ji}| = d$, the length l can be expressed as:

$$l = |\mathbf{x}_{ji}| \cos \alpha, \quad (2)$$

where α is the angle between $\mathbf{x}$ and $\mathbf{x}_{ji}$. This angle can be found from the following equation:

$$\mathbf{x}_{ji} \bullet \mathbf{x} = |\mathbf{x}_{ji}||\mathbf{x}| \cos \alpha. \quad (3)$$

By defining $\mathbf{x} = [\cos \theta, \sin \theta]$ with $|\mathbf{x}| = 1$, it can be shown that:

$$x_{ji} \cos \theta + y_{ji} \sin \theta + c\tau_{ji} = 0, \quad (4)$$

which is the basic equation used by Noise Compass for the determination of direction. Equation 4 has only one unknown variable, θ, but it does not have a unique solution. To disambiguate θ, an overdetermined system of equations is established by introducing more sensors: Noise Compass features 8 microphones in total. By defining a matrix of 14 vectors and time lags (Equation 1) for the different combination of microphones, the system of equations is established. The best estimate of θ is then found by the method of least mean squares. This estimate will be equal to the direction of arrival of the dominant sound.

Figure 1 shows the placement of the 8 microphones in the body of the Noise Compass. By locating the microphones in two rows of alternating microphones, both elevation (vertical angle) and azimuth (horizontal angle) can be disambiguated. Noise Compass is designed as a supplement to conventional condenser measurement microphones that can be calibrated according to relevant standards. Noise measurements according to ISO 1996-2 cannot be performed by Noise Compass itself, but the device can determine the direction of the dominant impinging sound – information which in turn can increase the quality of the measurement.

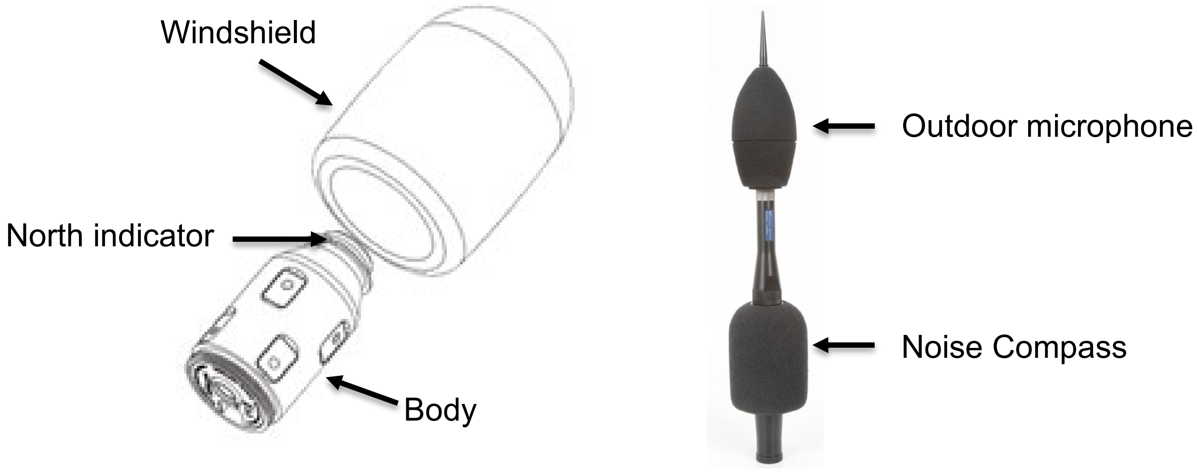

Figure 1 - Left: The 8 MEMS microphones are placed in the body of the Noise Compass, in two rows of 4 alternating microphones each. Right: The device is designed to be used as a supplement to conventional measurement microphones.

The nature of the correlation technique implies that the measured signals must be broadband, as is common with environmental noise. Pure-tone signals present an ambiguity which Noise Compass is not able to resolve accurately.

The default time resolution of the Noise Compass is 100 msec, which is a weighted average of the last 400 msec. The software used for data management may allow for coarser time resolutions.

3. LIMITATIONS

3.1 Competing sound sources

Noise Compass requires a software interface where the device can be set up and which is typically a part of the noise monitoring system. As Noise Compass identifies the direction of the dominant sound source, the system is not able to give meaningful results if several sounds of equal or similar sound pressure level are present simultaneously.

A quality indicator (QI) has been introduced to evaluate whether the resulting direction is associated to a dominant sound source, or if several sources of similar sound pressure levels are present in the soundscape. The QI value is the norm of the vector obtained by solving the overdetermined system described in the previous chapter.

QI = 1 is achieved when the location of a unique sound source has been identified, with negligible or non-existing sound from other directions. QI = 0 denotes sound coming from multiple directions, approaching a random incidence sound field. This implies that Noise Compass has limited usability indoors, a concept further discussed in chapter 5. The value of QI in real complex urban soundscapes, however, will always be between 0 and 1: different sound sources with different sound pressure levels contribute to the total level.

Figure 2 shows the case of QI = 0,4, where several sound sources contribute to the measured sound pressure level of $L_{Aeq,100ms}$ = 46,5 dB. Low QI values are typically associated to lower noise levels without a clear dominant source, like the case shown in the figure, but they can also take place if several sound sources emit higher sound pressure levels simultaneously. Figure 3, on the other hand, shows the case of a unique sound source dominating the sound measurement, with a calculated quality indicator QI = 0,9. In this case, sound from sound sources located at other directions is still present in the measurement, but the level of these sound sources is much lower compared to the level of the sound propagating in the identified direction.

Reflecting planes close to the Noise Compass will also provide mirror sources of incident sound and will affect the results.

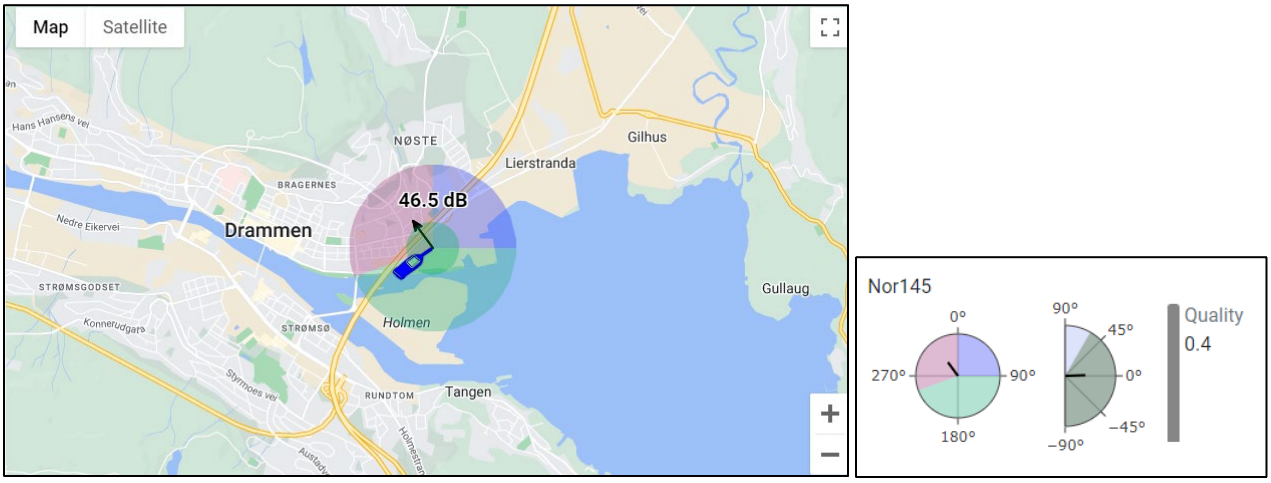

Figure 2 - Left: placement of the noise monitoring station, with measured sound pressure level (given as $L_{Aeq,100ms}$) and resulting direction of sound source. The length of the arrow indicates a low QI. Right: The calculated QI = 0,4 denotes that the identified directions, in azimuth and elevation, are affected by several noise sources with similar sound pressure levels.

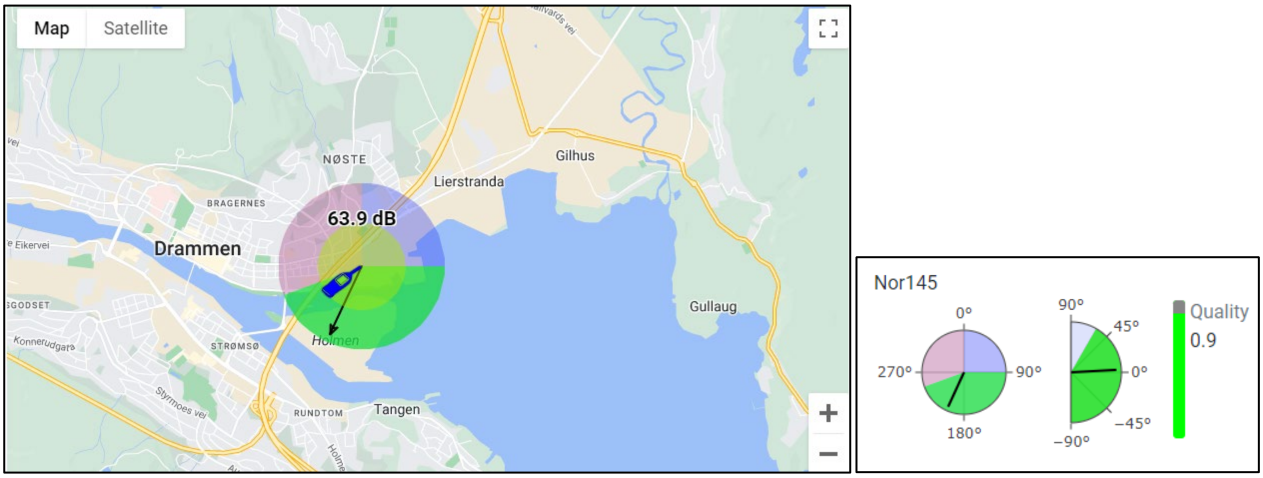

Figure 3 - Left: placement of the noise monitoring station, with measured sound pressure level (given as $L_{Aeq,100ms}$) and resulting direction of sound source. The length of the arrow indicates a high QI. Right: The calculated QI = 0,9 denotes that the identified directions, in azimuth and elevation, correspond to a dominating sound source with much higher sound pressure level than the other sources present.

3.2 Measurement error

Measurement accuracy is defined as the closeness of agreement between a measured quantity value and a true quantity value. A measurement is said to be more accurate when it offers a smaller measurement error.

The measurement error of 130 Noise Compass units has been measured in an idealized sound field. The measurement setup consists of a box with dimensions 59 cm x 59 cm x 59 cm, made of ½” plywood. The interior of the box is lined with 40 mm mineral wool. Additional mineral wool with thickness 100 mm is used to further minimize resonances inside the box. A turntable at the bottom of the box allows the Noise Compass unit under test to be mounted and rotated 360° in the horizontal plane. Broadband signals are delivered through 1” loudspeakers (flush mounted), a Focusrite Scarlett

18i8 audio interface and a Behringer Europower EPQ304 power amplifier. The Noise Compass is connected to a computer via LAN and the response is calculated with custom-made software.

The measurements were conducted on the horizontal plane, for 0º and 40º vertical incidence. Typical measurement errors, decomposed in a vertical component and a horizontal component, are shown in Figure 4.

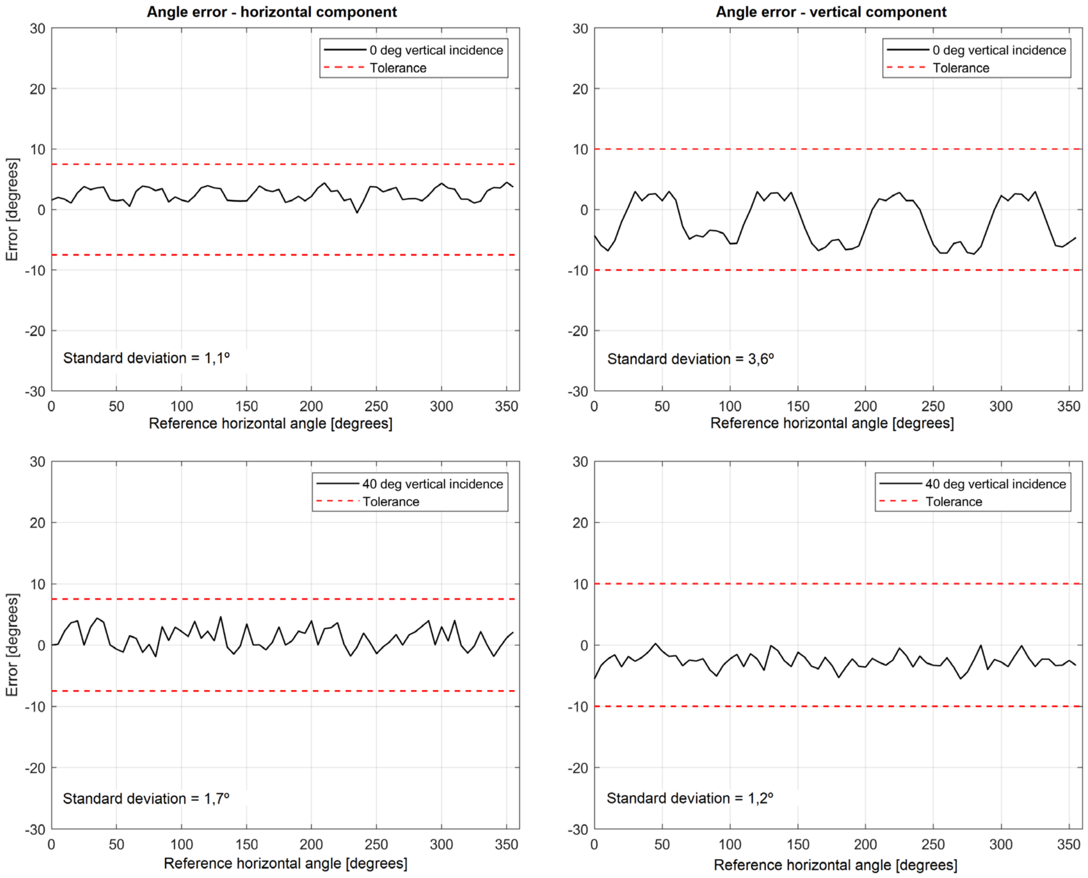

Figure 4 - Typical measurement error in the direction detection of a Noise Compass device.

The measurement error of 130 Noise Compass units was analyzed. The average standard deviation of the measured error components is shown in Table 1.

Table 1 – Average standard deviation of the measurement error for 0º and 40º incidence, in the horizontal plane, for 130 units. The standard deviations were computed separately for the horizontal and vertical components of the error.

Horizontal component (0º vertical incidence)	**Horizontal component (40º vertical incidence)**	**Vertical component (0º vertical incidence)**	**Vertical component (40º vertical incidence)**
1,5º	2º	3,5º	1,5º

The largest error component is found when localizing sound sources at 0º vertical incidence, since the reference point is located symmetrically between the two rows of microphones (see Figure 1). The error is then biased and follows the vertical direction of the closest microphone.

In all cases, the maximum error was found to be well within the following tolerances: ±7,5º for horizontal components and ±10º for vertical components. This error must be considered when defining monitoring zones.

4. CASE STUDIES

Two typical applications in complex urban soundscapes have been chosen as case studies: noise monitoring of a construction site and aircraft noise monitoring.

4.1 Noise monitoring of a construction site

An unattended noise monitoring station was placed in the construction site of the new Drammen Hospital in Norway [3]. The noise monitoring station consisted of a Norsonic sound level meter type Nor145 and a Noise Compass device. The equipment was connected to NorCloud, a cloud service for measurement management and data analysis delivered by Norsonic.

The construction site is located in a complex setting with neighboring industries, railway and motorway, with residential and commercial areas nearby. Figure 5 shows the disposition of the noise sources.

Figure 5 - Construction site in a complex urban soundscape. The construction site of the new Drammen Hospital is marked in red. Residential areas are located to the left side of the motorway.

The Norwegian guideline T-1442 [4] and its corresponding guide M-2061 [5] give spatial planning guidance to facilitate the prevention of health consequences due to environmental noise. Limits for construction site noise are given in these documents, see Table 2 for an example.

Table 2 – Example of noise limits from the Norwegian guideline T-1442. Recommended noise limits outdoors, for construction site activity with a duration longer than 6 months. The limits hold for sound pressure levels outside rooms for noise-sensitive use.

Type of building	**Day limit ($L_{pAeq12h}$ 07-19)**	**Evening limit ($L_{pAeq12h}$ 19-23) Sunday and public holiday limit ($L_{pAeq12h}$ 07-23)**	**Night limit (LpAeq12h 19-23)**
Residential, holiday homes, hospitals, nursing homes	60	55	45
Schools and kindergartens	55 (within work hours)		

Residential areas near the construction site of this case study are affected by several noise sources simultaneously. Evaluating the quality of the measurement data and documenting compliance with noise limits like those listed in Table 2 require an assessment of the contribution from the different noise sources.

NorCloud was used to define 4 different sectors in 3D space: Traffic, Industry and Construction Site were assigned to the areas covering the location of their corresponding noise sources, spanning elevation angles from 0º to 60º. The sector Aircraft was defined to gather noise contributions from sources located at elevation angles > 60º, see Figure 6 for the definition of the coordinate system. Figure 7 shows an illustration of the sectors.

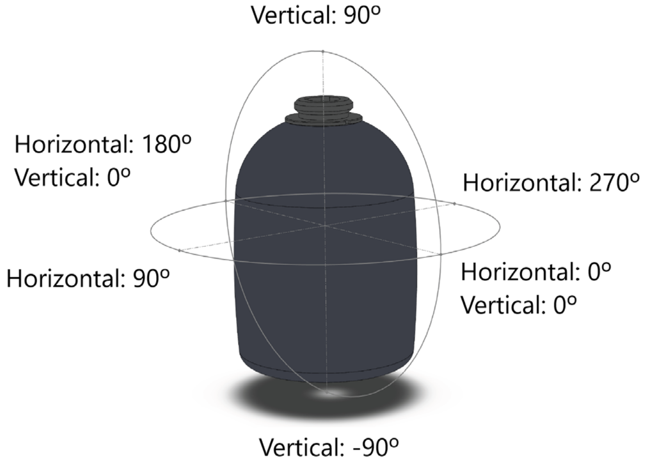

Figure 6 - Coordinate system used to define sectors in this case study.

Figure 7 - Noise Compass sectors defined with NorCloud. Traffic, Industry and Construction site span different horizontal angles within vertical angles 0º to 60º. The sector Aircraft spans elevation angles 60º to 90º, for all horizontal angles.

NorCloud was subsequently used to analyze the data collected with the Nor145 sound level meter, together with directional data obtained from the Noise Compass directional measurements. Figure 8,

Figure 9 and Figure 10 give an example of measurements done on the 12th May, 2022. Three different noise events are shown in the figures and illustrate how the dominant sound source can change also within short time windows.

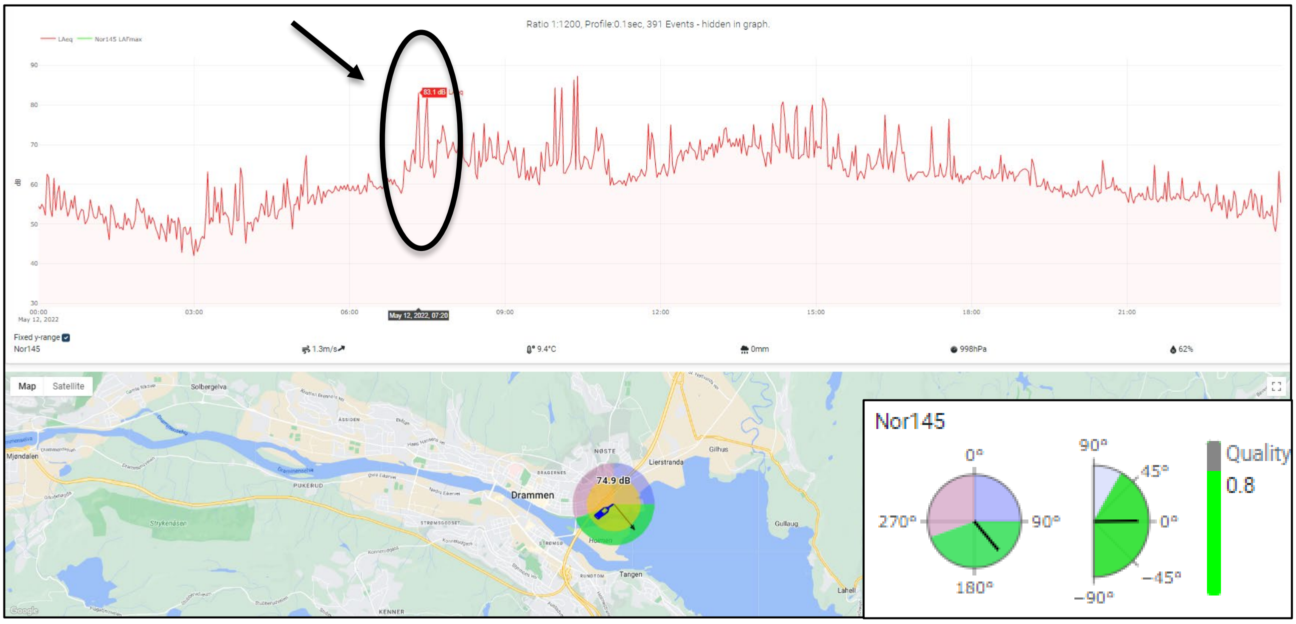

Figure 8 - Event registered on the 12th May, 2022, at 07:20. Noise Compass localized the dominant sound source in the Construction Site sector, with an equivalent noise level $L_{Aeq,100ms}$ = 74,9 dB. The graph at the bottom right shows the angles of incidence in the horizontal and vertical planes, and the calculated quality factor.

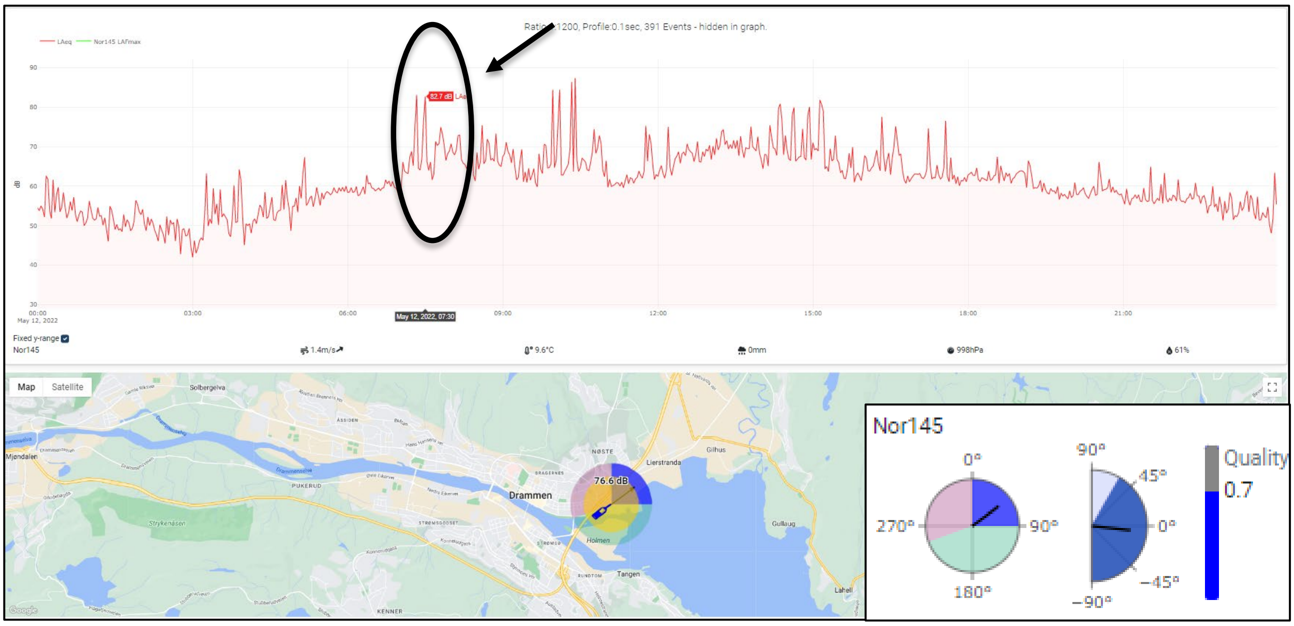

Figure 9 - Event registered on the 12th May, 2022, at 07:30. Noise Compass localized the dominant sound source in the Industry sector, with an equivalent noise level $L_{Aeq,100ms}$ = 76,6 dB. The graph at the bottom right shows the angles of incidence in the horizontal and vertical planes, and the calculated quality factor.

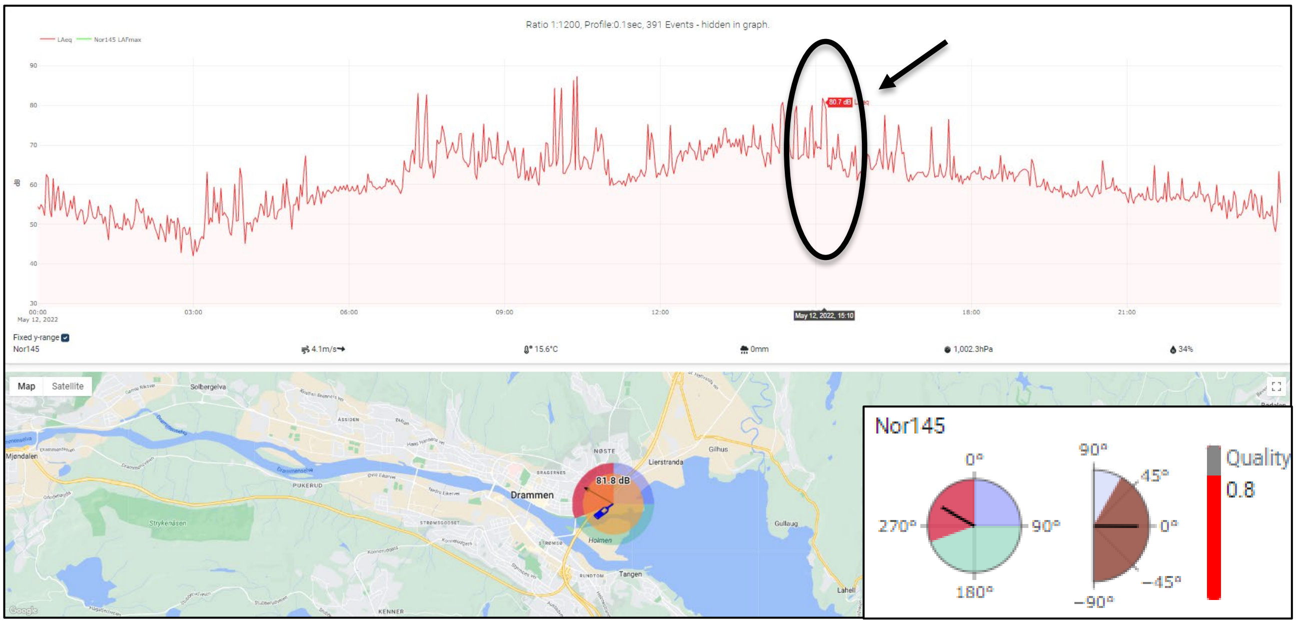

Figure 10 - Event registered on the 12th May, 2022, at 15:10. Noise Compass localized the dominant sound source in the Traffic sector, with an equivalent noise level $L_{Aeq,100ms}$ = 81,8 dB. The graph at the bottom right shows the angles of incidence in the horizontal and vertical planes, and the calculated quality factor.

Further possibilities for data processing like exclusion of non-relevant sounds and reporting of both directional data and noise quantities, are given by the measurement management system used. In the case of NorCloud, reports can be generated where the noise contribution from each sector is summarized. Table 3 shows an extract from such a report, for the date examined in this case study. Data between 6:00 in the morning and 19:00 in the evening is shown. In this case, the analysis shows that the highest sound pressure levels between hours 07 – 08 and 10 – 11 came from the Industry sector. These levels were clearly dominant with sound pressure levels > 3 dB to the noise contribution from the other sectors. Similarly, there were dominant contributions from the Traffic sector in the hours 14 – 16. Removing these non-relevant contributions yields more accurate noise measurements for the construction site.

Table 3 - Report from NorCloud for the 12th May, 2022, showing information about the different contributors to the total noise measurement. All sound pressure levels are given as L_{Aeq} over the time the sound was dominant. This time is given as a percentage.

Time	Road and railway	Industry	Construction Site	Unknown
06 - 07	72.6%, 59.9dB	0%, 63.3dB	1.6%, 64.6dB	25.8%, 58.6dB
07 - 08	5.6%, 67.2dB	6.4%, 80.7dB	36.8%, 74.3dB	51.1%, 68.1dB
08 - 09	11.1%, 72dB	4.7%, 71.8dB	35.3%, 70.5dB	48.9%, 66.1dB
09 - 10	2.6%, 66.8dB	9.1%, 77.5dB	39.9%, 72.5dB	48.5%, 64.2dB
10 - 11	17.5%, 65.6dB	6.4%, 84.2dB	26.6%, 80.2dB	49.6%, 67.1dB
11 - 12	37.9%, 67dB	3.5%, 72.6dB	8.4%, 66.4dB	50.2%, 62.5dB
12 - 13	36.2%, 66.1dB	2.4%, 70.3dB	10.9%, 72.8dB	50.5%, 67dB
13 - 14	18.8%, 71.5dB	3.7%, 71.7dB	25.9%, 72.7dB	51.6%, 68.9dB
14 - 15	52.5%, 75.8dB	1.7%, 72.9dB	6.3%, 70.4dB	39.4%, 71.1dB
15 - 16	39.8%, 74.7dB	1.4%, 70.3dB	9.2%, 71.7dB	49.6%, 67.2dB
16 - 17	19.5%, 65.7dB	1.7%, 74.4dB	17.1%, 70.7dB	61.6%, 67.8dB
17 - 18	36.9%, 67.6dB	4%, 72.8dB	4.4%, 66.4dB	54.7%, 63.4dB
18 - 19	34.6%, 63.5dB	0.1%, 65.7dB	11.8%, 64.7dB	53.5%, 61.9dB

4.2 Aircraft noise monitoring

Noise Compass is currently installed in several airports across Europe where aircraft noise is monitored by unattended monitoring terminals, see Figure 11 for a typical installation.

Figure 11 - Typical installation of Noise Compass in an unattended monitoring station.

These installations exploit the direction detection capabilities of Noise Compass to correlate noise events with a specific aircraft. By interfacing noise monitoring systems to flight schedules and radar information, high automatic correlation rates can be achieved.

Figure 12 is taken from the interface of the TRAVIS [6] system developed by the German company TopSonic. TRAVIS is intended as a community management solution where the public can openly access information on aircraft movements and noise levels around airports. Figure 12 shows the noise situation at the Berlin Brandenburg Airport in Germany, on the 1st May, 2023 around 13:00. The green and red circles indicate measured $L_{Aeq,1sec}$ values measured by unattended noise monitoring stations. Noise Compass has been installed in some of these stations.

In addition to correlating noise events with aircraft activity, Noise Compass can be used to further increase the data quality of aircraft noise measurements in the following ways:

- Identification of contaminated data. Non-relevant noise events can be identified by their location, a similar process to that presented in the case study of the construction site.
- Assessment of data plausibility. The match between the noise direction computed with Noise Compass and the expected flight track route can be evaluated.

Figure 12 - Screenshot from the publicly accessible TRAVIS software. The figure shows the aircraft activity at Berlin Brandenburg airport in Germany, with associated $L_{Aeq,1sec}$ levels measured by unattended noise monitoring stations. Noise Compass has been installed in some of these stations.

5. OTHER SYSTEM APPLICATIONS

Noise Compass is well suited for environmental noise monitoring of noise sources such as harbor noise, traffic noise (road, railway, aircraft) and noise from industrial sites, among others. Typically, these noise sources are part of complex urban soundscapes and bear similarities to the case studies presented in chapter 4.

The applicability of Noise Compass to indoors monitoring is, however, limited and performance degradation can be expected. When analyzing the contribution from the different directions, the device will also be analyzing reflections from the boundaries. Noise Compass is therefore better suited to rooms where reflections are significantly damped compared to the level of the noise emitting source, with a reverberant field of overall low level.

7. FURTHER WORK

Further work includes combining the possibilities of Noise Compass with AI algorithms for automatic classification of noise sources. Some of the possibilities this combination can unlock are disambiguating data samples with a low QI and automatic quality assurance of noise samples identified as relevant/irrelevant. Even though these activities can be performed with current recording and playback features present in many noise monitoring systems, AI algorithms for noise tagging can efficiently replace time-consuming manual processes.

6. CONCLUSION

We have presented a multi-microphone device featuring 8 MEMS microphones, which can be used to identify the direction of the dominant sound source in 3D space by using TDOA and cross-correlation techniques. We have shown the associated error in measurement and how the quality of the result can be evaluated. We have also presented case studies that show how the device can be effectively used for outdoors noise monitoring.

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