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A novel approach to port noise characterization using an acoustic camera

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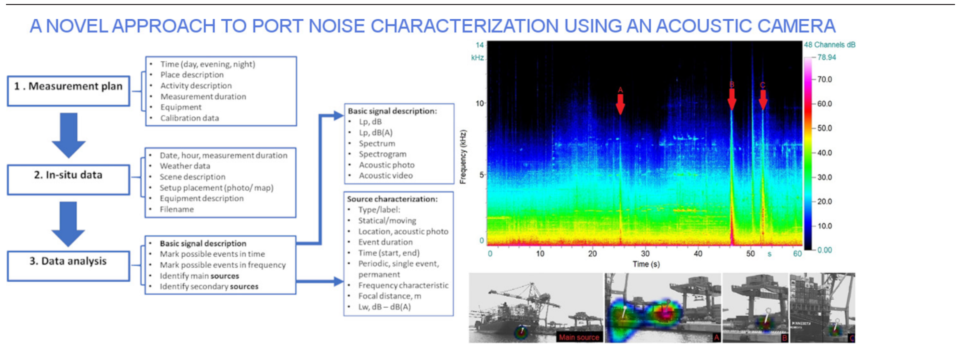
HIGHLIGHTS

- Acoustic camera application to port noise was investigated.
- A complex port environment with several different noise sources was studied.
- Data was processed using several advanced algorithms.
- Noise sources were identified and characterized.
- A SWOT analysis was developed.

GRAPHICAL ABSTRACT



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ABSTRACT

Acoustic cameras are powerful instruments combining an optical camera with a microphone array to obtain information about power and location of noise sources. The main aim of this study is to identify key points in the application of an acoustic camera to the characterization of port noise. An experimental campaign was carried out in the seaport of Genoa. Based on this experience, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was performed. The experimental results confirm the intrinsic complexity of the noise field in ports. Several noise sources were identified and can be categorized by their duration, intensity, location and spectral content; the analysis performed allows us to propose a basic framework for the innovative application of this technique to the port noise context. Acoustic cameras can be considered viable and useful tools to characterize and monitor port noise, following at least the minimum key points highlighted in the proposed framework.

1. Introduction

The Acoustic Camera (AC) concept has its roots in the pioneeristic work of Billingsley and Kinns dated 1976 in which the first microphone array was introduced (Billingsley and Kinns, 1976; Michel, 2006). From this early moment, an acceleration has been registered in the applications of both ACs and beamforming techniques in diverse fields such as automotive optimization, security, surveillance, and industrial machinery. As described in this study, outdoor acoustic implementations are limited to studies mainly on wind turbines, aircraft, and bypass road noise. The studies used an AC to both detect the main noise sources in a qualitative approach and to quantify noise levels (see e.g. Merino-Martinez et al., 2020; VanDercreek et al., 2021).

Port noise is a complex example of outdoor noise for two main reasons: first, the noise in ports involves multiple simultaneous noise sources, with a strong overlapping effect, and second, in most cases, it

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is impossible to go near these sources and apply classical techniques such as sound level meter measurements or acoustic intensity measurements in an accurate way (Di Bella and Remigi, 2013; Borelli et al., 2016). As a matter of fact, in a harbor many of the sources have very large dimensions and cannot be tested in a laboratory. Moreover, the operations of port terminals cannot be stopped during measures making it impossible to distinguish between the different contributions to the soundscape if many non-standard sophisticated techniques are not adopted. The inner complexity of the soundscape in a port is related to several work activities and sources simultaneously operating (both standing and moving) such as trains, heavy vehicles, ships, and industrial machines emitting sounds at different times for different periods and in different frequency bands. Furthermore, port noise characterization, monitoring and control are significant open problems related, among other relevant issues, to health, safety, and comfort of port workers and citizens living near the harbors (Borelli et al., 2019). Noise monitoring is traditionally performed by placing single omnidirectional calibrated microphones at various locations near or inside port areas. The sound amplitude estimated by the single microphones includes contributions from several environmental sources, and separating each specific contribution is a challenge: "*In a bustling environment, like a port, isolating a specific source and determining its relevance is a toilsome task*." (Bolognese et al., 2020). The AC approach based on mixing images and advanced sound analysis algorithms can be innovatively used to characterize harbor complex soundscape, contributing to the development of regulations and mitigation strategies. In this way, the well-established acoustic imaging technique is extended to a new application case, that is port noise, with relevant outcomes.

In this study, firstly the state of the art is presented, regarding an AC applied to outdoor noise. Secondly, the results obtained from an exploratory experimental campaign carried out in the port of Genoa (Italy) are shown. Thirdly, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis about the application of the AC to port noise characterization is carried out. Finally, a possible methodological framework for applying the AC in port noise studies is proposed.

2. State of the art: use of an acoustic camera for outdoor noise measurements

Source localization by an AC is done by acoustic beamforming techniques. A microphone array records the sound event of interest, and the differently delayed signals registered by every single microphone are analyzed applying mathematical algorithms to deduce the source position from the Direction of Arrival (DOA). The most common algorithm performs a Delay and Sum (DAS) of the signals, the differences in the arrival of the signal to every single microphone are used to calculate the path length differences thus locating the source in a spatial position in a given focal plane according to those delays. To accomplish this task, it is necessary to know the characteristics of the spatial distribution of the microphones in the array. Several acoustic beamforming algorithms are available, such as frequency domain beamforming (FDBF) and Delay and Sum (DAS) for time-domain analysis, both known as classical algorithms. Among advanced algorithms (see Merino-Martinez et al., 2019a, 2019b for a review of imaging methods using phased microphone arrays), there are a few widely used deconvolution methods, such as the deconvolution approach for the mapping of acoustic sources (DAMAS) and the CLEAN algorithm based on spatial coherence (CLEAN-SC) (Sijtsma et al., 2017) which removes artifacts in the noise source localization introduced by the specific geometry of the microphone array (Dougherty, 2008; Ramachandran et al., 2014; Gombots et al., 2021). Algorithms to improve acoustic image resolution are based on interpolation bilinear, bicubic, or sampling Kantorovich (SK) quasi-interpolation method, all of them recently compared by (Asdrubali et al., 2021), who found a better performance of SK to locate a source in a 3D space.

Some early perspectives of and challenges to the use of AC have been approached in recent years such as 3D sound mapping (Sarradj, 2012; Lima Pereira et al., 2021), a neuro-fuzzy algorithm for multi-dimensional data clustering to 3-Dimensional visualization (Popova et al., 2015), or the application to moving sources (Döbler and Heilmann, 2005), nearfield beamforming optimization (Erić, 2011), long term measurements, real-time analysis and directional hearing (Cerniglia, 2008), wind noise reduction (Zhao et al., 2018), and integration of sound maps for distributed sound sources (Brooks and Humphreys, 1999; Merino-Martinez et al., 2019b). Most of these challenges are still open, and AC optimization is in progress. Possible application scenarios of the AC have been proposed, including some outdoor applications such as noise barriers (Cerniglia, 2008), trains, airplanes (Heilmann et al., 2014), and ship noise modeling (Čurović et al., 2021). The relevant research studies that apply AC and acoustic beamforming to outdoor noise problems in the engineering field are summarized in Table 1; underwater and wildlife applications are not considered in the scope of this work.

As can be seen from the data reported in Table 1, outdoor noise measurements using an AC or a microphone array have been related mainly to the pass-by test of different vehicles such as cars, trains, and aircraft. Other applications include monitoring the impact of industrial plants in residential areas and wind turbine noise characterization. More recently, applications concerned the detection of drones or their use to identify noise sources (Herold et al., 2020). Most of the studies reported the use of an AC in the first step as a qualitative tool to locate noise sources by acoustic photos (AP) (Čurović et al., 2021; Bolognese et al., 2020; Fiebig and Dabrowski, 2020; gfai tech GmbH, 2019; Grubesa et al., 2019; Hoshiba et al., 2017; Di Bella et al., 2016; Kerscher et al., 2016; Ohata et al., 2014; Heilmann et al., 2014; Sasaki et al., 2011; Cerniglia, 2008; Schroeder, 2007; Brandes and Benson, 2007; Mellet et al., 2006; Döbler and Heilmann, 2005). Some authors have validated the sound pressure level measurements (L_p in dB(Z) and dB(A)) using a conventional sound level meter (Fiebig and Dabrowski, 2020; Lee et al., 2017; Kloow, 2009). On the other hand, it is common to use calibrated sources with known location, frequency, and level characteristics to validate experimental results (Asdrubali et al., 2021; Murovec et al., 2018; Hoshiba et al., 2017; Bradley et al., 2016; Ramachandran et al., 2014; Ohata et al., 2014; Fonseca et al., 2008; Brühl and Röder, 2000; Ernst, 2017).

Only two research items regarding the use of an AC in port noise were found (Bolognese et al., 2020) and (Čurović et al., 2021). The former presents an AP of a small ship in movement and reports qualitative information about onboard noise sources. The latter presents an AP of a ship and locates the main source at the exhaust of the ventilation system, and from this observation, considers ships as punctual sources in the model of port noise. Dealing with pass-by measurements, the Doppler effect should in principle be taken into account, but the sources in the harbor context are usually moving at very limited speeds and therefore corrections for Doppler effect are not needed as it is for example for aircraft measurements. Nevertheless, a lack of standardization was observed for pass-by measurements in different contexts (aircrafts, cars or ships), and mainly for outdoor noise measurements using an AC. In particular, the absence of measurement standards, recommendations, or a clear framework to use an AC in the port context is highlighted from this literature overview. From what above observed, it can be concluded that more research focused on applying AC in the study of port noise is needed.

To approach the application of AC measurements in port noise characterization, the authors performed a measurement campaign in the port of Genoa (Italy). The following sections describe the methodology, the analysis of data collected and present a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis to optimize the strategic planning of AC data collection.

Table 1
Use of an acoustic camera in outdoor noise problems.

Study/year	Outdoor noise problem	Measurement methodology	Validation/calibration	Setup	Hints
Asdrubali et al., 2021	Industrial noise source	Quantitative, artificial source position reconstruction	Prove source location	Planar mic array	Algorithm to calculate distances. Sampling Kantorovich (SK) interpolation algorithm performs better than bilinear or bicubic
Čurović et al., 2021	Noise emitted from a port	Qualitative, acoustic photo (AP)	NA	NA	The main noise source of a ship is located in the exhaust of ventilation systems. Ships can be considered as punctual sources
Bolognese et al., 2020	Port noise	Qualitative (AP)	NA	NA	Isolation of a sound source in a bustling area
Fiebig and Dabrowski, 2020	Noise Source Localization and Noise Reduction in Industrial Plant	Qualitative (AP, AV), spectrum (peak detection). Use a Sound level meter to determine L_w	Sound level meter 945A SVAN class 1	Bionic M-112 (CAE), 112 microphones; 10 Hz–24 kHz	Classify point, line, or area source.
gfai tech GmbH, 2019	Repeated wind noise (whistling) in a power plant	Qualitative (AP). Comparison of spectral characteristics and levels	NA	Star array 48; Ring array, Data Recorder mcdRec 721(gfai)	Locate source and measure the effectiveness of an intervention to mitigate noise
Grubesa et al., 2019	Localization of a drone (quadcopter)	Qualitative. Compares two DAS algorithms (freq. and time)	NA	16 channel, omnidirectional mics in a circular array	Possible use for noise monitoring in urban areas detecting unfamiliar sources
Moravec, 2019	Industrial plants	Measurements from different distances (250 to 300 m, 50 to 70 m,20 to 30 m), dominant frequency bands	NA	Star array 48 (gfai), 48 mics, diameter 3.7 m	Identify dominant sources, frequency characteristics possible interventions
Zhao et al., 2018	Wind noise reduction	Anechoic chamber test, quantitative	NA	Spherical array 64 microphones diameter 20 cm	Algorithm to eliminate noise from wind using spherical harmonics expansion
Murovec et al., 2018	Environmental noise in a residential area (sources: motorway, railway, and an industrial area)	Use directivity L_p (dB(A)) results to determine source contribution in time	Simulation/prove source directivity test, source (at 10 m)	Circular array 33 microphones, 1.2 m diameter, 100 Hz to 12 kHz	System for automatic noise source identification and classification
Benim et al., 2018	Wind turbine	SPL for 1/3 octave bands is compared with the measured values. Positioned according to DIN EN 61400-11/IEC 61400-11	Simulation: 3D URANS CFD calculations	Bionic M-112 (CAE), 112 MEMS-microphones; 10 Hz–24 kHz	Acoustic camera useful to study aeroacoustic optimization
Hoshiba et al., 2017	Unmanned aerial vehicles embed mic array design	Qualitative. MUSIC-based algorithm, whistle localization in an open area (tens of meters)	Prove source in a known position prove (whistle)	Compare two planar arrays 12 mics.	Water-resistance of the microphone array, efficiency in assembling, reliability of wireless communication, and sufficiency of visualization tools for operators
Lee et al., 2017	Equipment and processes on construction sites (six machines at four different subway construction sites)	Qualitative, Quantitative SPL - dB(A) & dB(C); 1 min duration. (15 m focal distance?)	Comparison of peak levels Leq with class 1 type level meter at a long distance	Acoustic camera Nor 848A; 256 mic, 1 m diameter; 20 Hz–20 kHz	Significant presence of low-frequency noise
Di Bella et al., 2016	Ship pass by	Qualitative, (AP)	NA	NA	Tugboat pass-by measurements for noise source localization. Water lapping can also be observed
Chelliah et al., 2016	Airport Noise Monitoring System	Quantitative, Measurements from a rooftop.	SPL calibration, laboratory test: Compared with a single mic, broadband source anechoic chamber.	Optimal microphone array (multiarm spiral), 24 microphones; delta = 0.72 m	Separate contribution of aircraft, optimizing parameters such as the size of the array, number of sensors in the array, and reconstruction distance.
Bradley et al., 2016	Wind turbines	Quantitative, Heights from 13 m above ground up to 36 m	Prove source at the turbine blade (Doppler and directivity)	Large 42 mic array (40 m scale)	Good quality of results
Kerscher et al., 2016	Wind turbine, a database for simulation of a wind farm	Qualitative (AP, AV), 100 m to 400 m. Spectral analysis	NA	Star array 48 microphones	It is possible to cancel the main source and find secondary sources.
Merino-Martinez et al., 2016; Merino-Martinez et al., 2014 Snellen et al., 2015	Aircraft noise Fly-over (landing)	115 fly-over measurements, spectrogram correction (Doppler and background noise). Quantitative: source SPL.	Simulation directivity array.	Spiral (diameter 1.7 m) 32 microphones, 45 Hz to 11,200 Hz	Large variability in noise levels for fly-overs of the same aircraft type
Ramachandran et al., 2014	Wind turbine	Quantitative, 50 m and 85 m away	Resolution: Prove source white noise	Compact microphone array (OptiNav 24) single-arm spiral	Advanced deconvolution methods. Reflection does not have a significant role
Ohata et al., 2014	Sound source detection in an outdoor environment using a quadrotor	Qualitative (AV-real-time), peak detection	Prove source at (1 m, 2 m, 3 m)	AscTech Pelican (16 channels)	Algorithm based on incremental MUSIC Generalized Singular Value Decomposition (iGSVD-MUSIC)

(continued on next page)

Table 1 (*continued*)

Study/year	Outdoor noise problem	Measurement methodology	Validation/calibration	Setup	Hints
Ballesteros et al., 2014	Bypass measurements (road traffic)	Fixed focus algorithm pass-by tests were performed at constant speed (ISO 362), 5 m 1.5 m height	Simulation/literature data	Optimized planar pseudo circular 84-microphone array diameter 4 m	Propose a methodology to use beamforming, sound pressure for each 1/3 frequency band
Heilmann et al., 2014	Pass-by train and airplane, stadium	Qualitative/perceived level dB (A)	–	Sphere 120 array, $r = 0.60$ m	Beamforming can work for 150 + m measurement and objects traveling at hundreds kmh
Sasaki et al., 2011	Omnidirectional mic array design and implementation (power substation)	Qualitative angular position of the source. Two positions, two orientations of the array 0\,90. Recording positions via GPS	Prove source, Indoor localization accuracy	32 channels	DSBF algorithm and optimum design of the array improves angular resolution in large outdoor ambient
Kloow, 2009	Wind turbine	Quantitative: sound power (laser distance meter) 10 positions. Spectral components. Qualitative	Sound meter level.	Star array 48	Recommendations to field measurements: logistical and acoustical
Navvab et al., 2009	Crowd noise measurements in a large stadium	Spectrum, spectrogram. Quantitative source and intensity.	Simulation	Spherical array AC, 120 mics	Acoustic camera data can be used in addition to simulations to assess complex noise scenarios
Fonseca et al., 2008	Pass-by cars	Quantitative, constant velocity 50 km/h	Prove source buzzer on the vehicle	Spiral 32 mic array 1.1 m	Moving source imaging methodology
Cerniglia, 2008	Noise barrier (effect of diffractor), industrial plant	Qualitative, third octave band photos	NA	Sphere 32 mic, 12 cameras	Omnidirectional array
Schroeder, 2007	Environmental noise (waste separation plant)	Qualitative AP (180 m)	NA	NA/AC	Long-distance acoustic photo
Brandes and Benson, 2007	Sound source imaging of low-flying airborne targets	Qualitative. focal distance 100 m approx. Frequency filters	Simulation for the optimization	32 microphones location optimized for 500 Hz	Can accurately detect small airplanes and bird migrations
Mellet et al., 2006	Acoustic source model during a pass-by (train)	Qualitative AP, third-octave band, Quantitative: source-level changes under velocity change	Experimental data single microphone	Two-dimensional star-shaped array 29 mics (200–4000 Hz)	Aeroacoustics and rolling sources identification on two-dimensional maps
Döbler and Heilmann, 2005	Acoustic pass-by, car	Qualitative	NA	gfai/NA	Synchronization between audio and video. Algorithm for pass-by that accounts for Doppler effect
Brühl and Röder, 2000	Acoustic source model during a pass-by (train)	Quantitative: source strength Fixed focal distance	Simulations/bypass with prove sources	Two mic-array vertical and horizontal (2 × 12 channels), d 30 cm	The Doppler frequency shift and amplitude augmentation of the sources are removed.

3. Methodology

3.1. Measurement setup

A total of 8 scenarios were measured in 3 different locations, during the daytime, with a gfai tech GmbH Star48 AC Pro microphone array (gfai tech GmbH, 2019). The use of the 48-channel data acquisition system mcdRec and a personal computer set up with NoiseImage Software for the acoustic analysis allowed acquisition, storage, and processing of the information. The signals were sampled at a rate of 48 kHz. The microphone array works in a frequency range from 66 Hz to 13 kHz. The array was calibrated by the manufacturer (Manthe et al., 2008). The resolution of the array was calculated for several focal distances using the half-power beamwidth (HPBW) criterion and is presented in Fig. 1. The minimum separation to distinguish two incoherent sources decreases when the frequency increases. However, it is necessary to clarify that the AC was designed to work with broadband signals and not with single-frequency sources (Grythe, 2015).

3.2. Operating procedure

During the measurement campaign, the AC was placed in view of the sources, at a distance ranging between 50 and 150 m, and the antenna was oriented so that it contained the entire sound field of interest. Therefore, the following measurement parameters were set: during the run, noise data were acquired for a container ship with a load capacity of 6350 TEU, gross tonnage (GT) 71787, deadweight (DWT) 72912 tons, 293 m long and maximum width of 40 m. During the measurements, the ship was discharging containers using a gantry crane

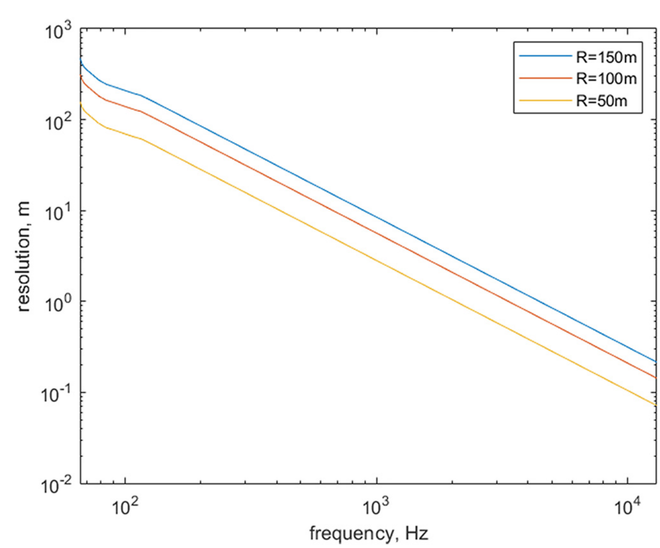


Fig. 1. Resolution of the Star48 AC Pro microphone array, using the HPBW criterion, as a function of frequency for several focal distances R.

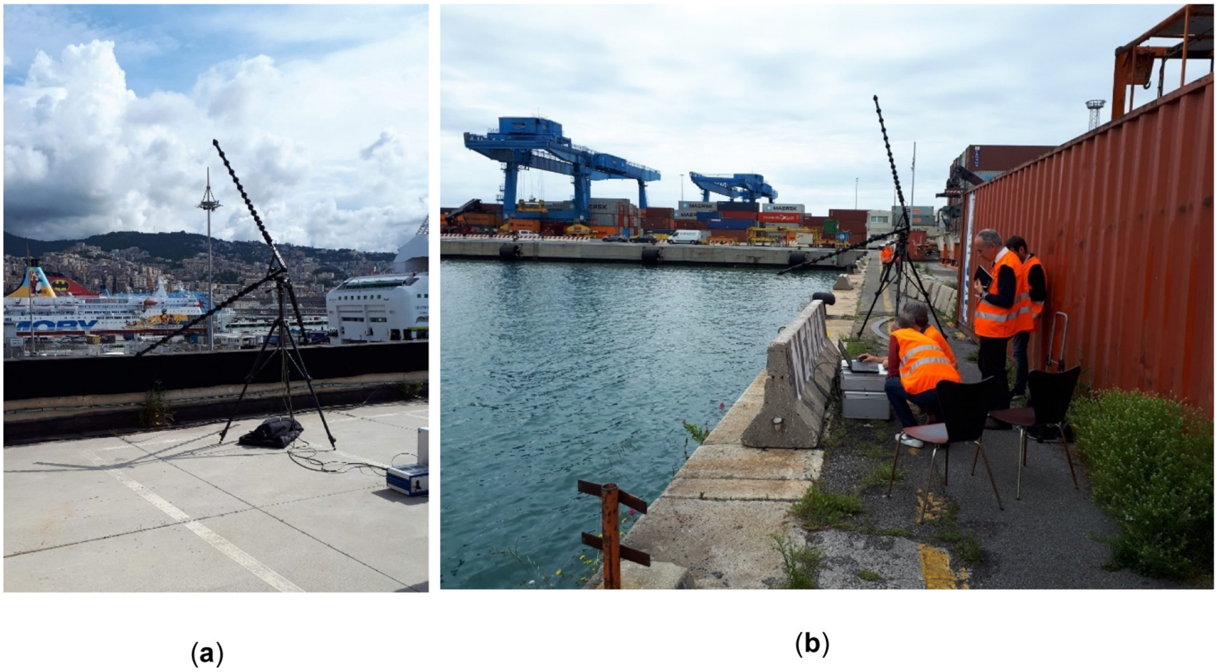


Fig. 2. Experimental setup for the test case measurements. (a) Microphone array; (b) University of Genoa AC-team.

(Figs. 2b and 3c). On the quay, the trucks loaded the containers and drove away. Other cranes were operating on the wharf during the measurements, while no other ship was berthed. As a second ship, a Ro-Pax vessel characterized by a 39139 GT, DWT 6875 tons, length of 214 m and maximum width of 27 m, was measured at berth. In this case another ship was berthed during the measurement Fig. 6b. The temperature was 20 °C, the relative humidity was 78.2%, while the wind speed remained below 2.5 m/s throughout the measurement duration.

3.3. Data-processing

The post-processing phase was carried out using gfai tech's NoiseImage software (gfai tech, 2021). At first, a general analysis was made, where AP and acoustic videos (AV) were produced for the entire records using beamforming algorithms. AP were generated taking a (time) portion of each signal group and the more prominent noise source was located in the image as a colormap. The procedure for acoustic videos was analogous, but a moving time window was used; this moving window is adjusted to resolve moving sources in the scene (typically, approximately 1 s was enough). In some cases, such as locating the main source of a berthed ship, no moving sources are registered, and the window size does not need to be adjusted. Then, a spectral analysis was carried out to identify relevant acoustic events, and, after identification, AP and AV were generated. Several advanced algorithms, available as options in the software, were used, in particular: *High Dynamic Range* (*HDR*), an iterative deconvolution technique that increases the dynamic of an acoustic photo and therefore facilitates the separation of sources through sidelobe-suppression (Döbler and Schröder, 2012); *RMS* (effective value), which is the common method to integrate an interval over a chosen time and create the image; *Max peak* which allowed to see the maximum values in the acoustic map whenever they occurred during the calculation interval; *Clean-SC*, an algorithm using spatial coherence to suppress the side lobes allowing a better identification of sources; and *Acoustic Eraser*, which enables the elimination or the isolation of sound sources by subtracting the reconstructed signal of the stronger source for all the microphone channels (Döbler and Schröder, 2010).

Finally, the received sound pressure levels L_p and the source power levels L_w were obtained for both broadband signals and acoustic events. To calculate those values, all the signals were analyzed using the direct level measurement (averaged for all the 48 mic recordings) and then applying an A-weighting filter. The calculation of L_w was made by setting the corresponding focal distance from the localized noise source, measured with a laser meter.

4. Results

The AC performed measurements evidenced and confirmed the complexity of the noise field in ports. Several sound sources were identified that could be categorized by duration, power level, location, and spectral content. The great capability of the AC resides in the possibility of studying the perceived sound level filtering portions of the three-dimensional parametric space composed of **space**, **time**, and **frequency** dimensions. Some examples will be shown of how these filtering options can be used to analyze measurements in a **spatial-based**, **time-based**, or **frequency-based analysis**.

The discharge operations of a large container ship were recorded, and some relevant results are presented to show how an AC works and how it can be applied in the port context. In the measurement campaign, the focal distances (R) were measured directly with a laser distance meter. The focal distance is a key variable to estimate correctly the sound power level L_w according to Eq. 1.

$$Lw = Lp + 20\log\left(R/R_0\right) + 10\,log\left(S/S_0\right) + A_{abs} \tag{1}$$

where L_p is the measured sound pressure level, R is the distance between the source and the AC, the reference distance $R_0 = 1m$, S/S_0 is equal to 4π for a monopole source and A_{abs} is the attenuation due to atmospheric absorption. The atmospheric attenuation is stronger for higher frequencies, however considering the broadband signal used to estimate the A-weighted sound power level, the overall correction due to atmospheric attenuation can be neglected for the considered distances in this experimental campaign.

The 48 delayed multiple signals obtained by the antenna are depicted in Fig. 3a. The signals are almost identical but delayed in time by the different

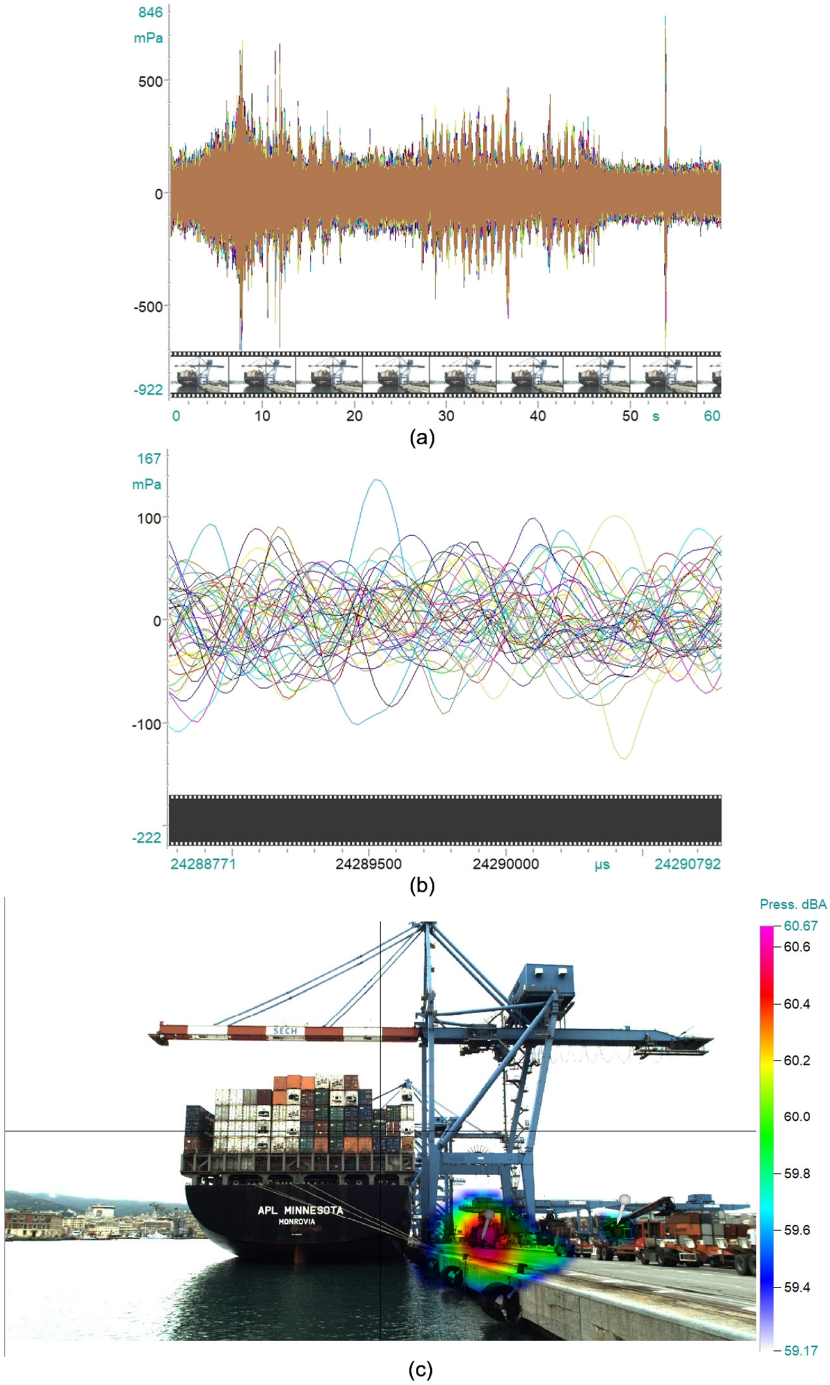


Fig. 3. Typical information obtained by the AC: (a) 48 audio signals on time basis scale: seconds; (b) 48 audio signals on time basis scale: microseconds; (c) AP of a ship in discharge operations (full frequency range 66 Hz to 13 kHz), the dynamic range has been adjusted, reducing it from a high value (10 dB) to a lower value that allows locating a single source in the image (1.5 dB in this case).

path lengths from the source to each microphone in the array. The Star48 AC Pro array was designed for environmental use and can be used in a mapping frequency range from 66 Hz to 13 kHz (however, every single microphone has a 20 Hz–20 kHz range). By applying the beamforming algorithms, it was possible to obtain APs and AVs of the port activities as shown in Fig. 3. A colormap indicating L_p (dB) is superimposed on the photo or video of the scene to identify the highest-level source position on an acoustic event generated by the drop of the crane load on the truck. This measurement gives an $L_p = 60.8$ dB(A), with an approximate focal distance of 122 m, which means by Eq. (1) $L_w = 113.5$ dB(A).

4.1. Spatial-based analysis

The spatial-based analysis not only refers to the colormap over the photo but includes a geometric study of the acoustic signals based on the beamforming algorithms. In particular, the beamforming analysis can be performed by deleting, using the "acoustic eraser" (Döbler and Schröder, 2010), some specific sources from an AP to assess information regarding secondary sources. In this way, a certain portion of space is excluded from the analysis, together with the sources there located. Fig. 4 presents an example of how this analysis can detect the

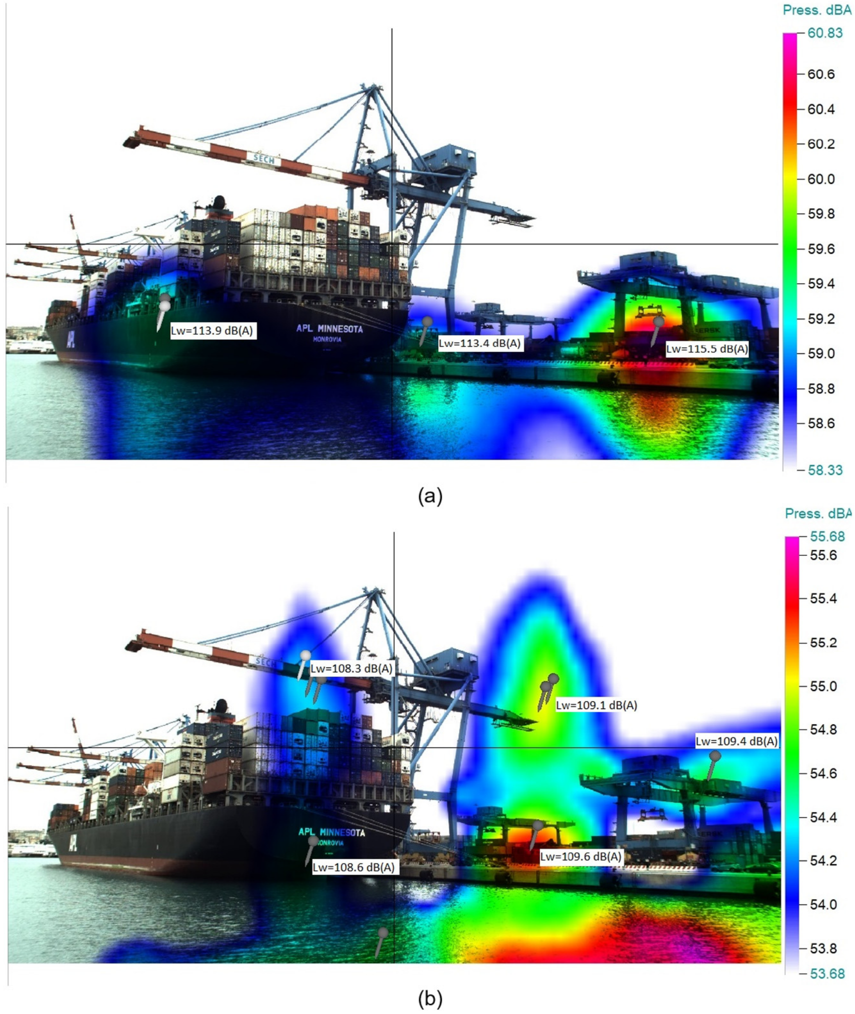


Fig. 4. Spatial-based analysis to obtain information about primary and secondary sources (full frequency range 66 Hz to 13 kHz): (a) main sources: machinery operation at the vessel, truck loading, truck loading by small tower crane; (b) secondary sources after excluding the main sources identified in the first AP: motor, tower crane, small tower crane, truck caravan.

secondary noise sources (Fig. 4b) after excluding the main source (Fig. 4a). Both pictures were obtained from the same run, and similar information regarding all the sources possibly contributing to the sound field could be gleaned. Of course, the visual analysis of every source can be post-processed, including the data concerning emitted noise, that is, spectra over time, SPL and SPW time histories, sonograms, etc.

4.2. Time-based analysis

Results from the time-based analysis are presented in Fig. 5. This figure shows several APs localizing main and secondary sources, as well as related sound levels (L_p and L_w). As can be seen, many sources generate significant levels at the measurement point, explaining the noise soundscape in the port and the neighborhood. Using a focal distance of 143 m, the source strength is determined with sound power level values (L_w) exceeding 100 dB(A). Some of the sources are permanent for the entire measurement period such as engine noise, and others are single events that take place in a single time but represent some peaks in the signal (that can be detected from the spectrogram), such as the gantry crane loading a truck with the related impact noise. Some of the sources are static, but others, such as the truck caravan, are in movement during the operations.

The results shown in Figs. 4 and 5 are not trivial. When measuring noise emissions in ports, two of the main problems that are commonly encountered are due to source overlapping and large distance from the emitting sources. Source overlapping hinders the identification of the specific contribution coming from each acoustic source. A large distance from the emitting sources, e.g. the engine of a gantry crane or the vents of a ship, makes the measurement inaccurate. The AC tackles simultaneously these two problems. It was possible to distinguish the contribution from every single source emitting within the sound field even if the equipment was far from the noise source. Moreover, as shown in Fig. 4, a specific source in the harbor (a crane, a truck, a ship funnel, etc.) was selected from the video and its emissions followed over time, then another one was selected and so on, obtaining the spectral time history for each one. The same was done by selecting the time interval in which a certain event occurs, as for Fig. 5. In this way, through the beamforming technique, the masking effect coming from the overlapping of the different sources in harbors was overcome.

4.3. Frequency-based analysis

The spectral (or frequency-based) analysis gives information about some other noise sources and characteristics. In particular, strong tonal components are identified analyzing the spectrogram, where a few tonal components occur in different lapses. After filtering each of the two peaks in the spectrum of a given lapse, it was possible to identify a secondary source at the top of the large gantry crane system (1488 to

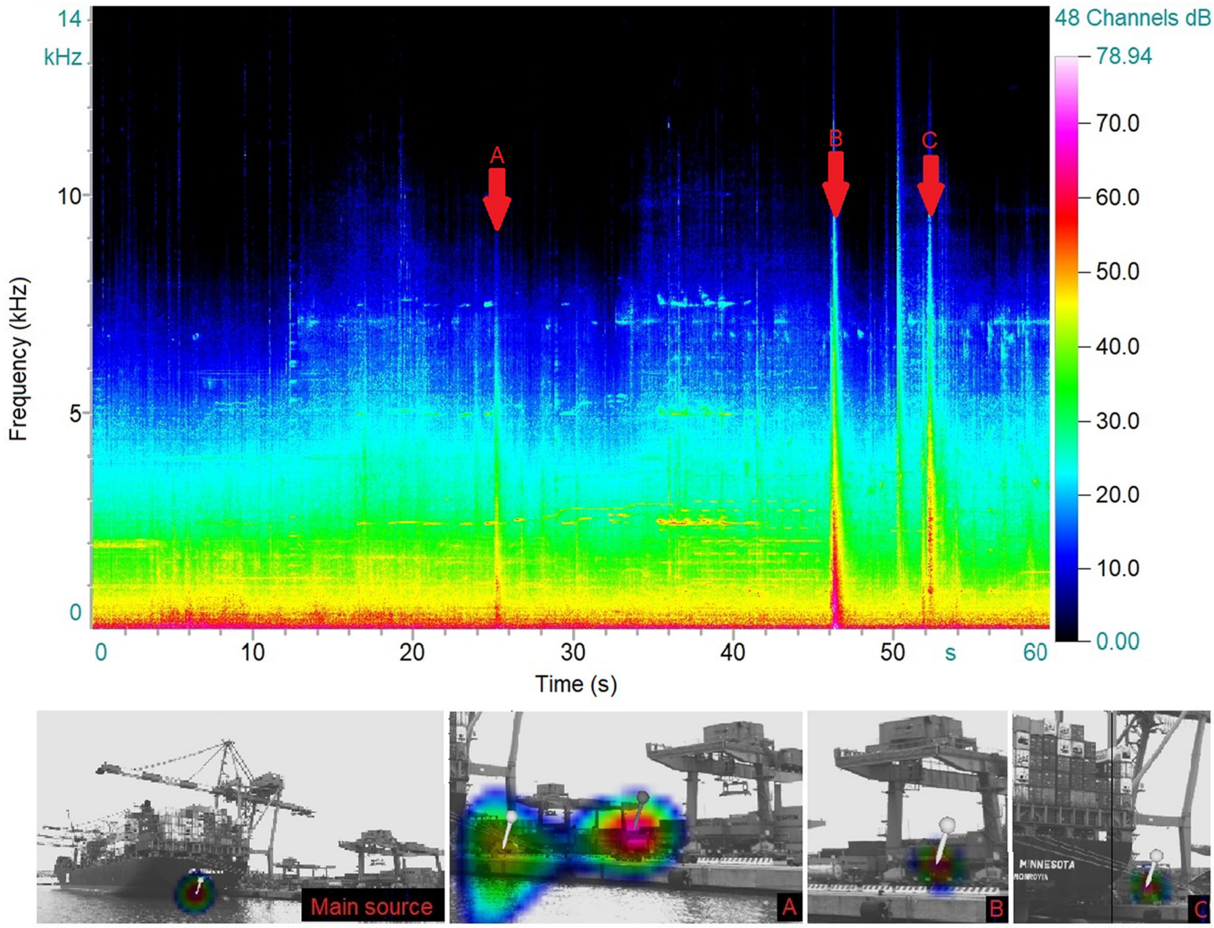


Fig. 5. Time-based analysis: some APs obtained in loading/discharge activities using the spectrogram to detect time events (full frequency range 66 Hz to 13 kHz). **Main source**: Motor; L_w = 108.7 dB(A). **Event A**: truck caravan arriving at the vessel; L_w = 115.8 dB(A). **Event B**: small gantry crane (impact); L_w = 129.4 dB(A). **Event C**: L_w = 122.4 dB(A).

1570 Hz) and a source in the small gantry crane (2789 to 2988 Hz). The results are depicted in Fig. 6. In Fig. 6a the narrowband crane spectrum shows a few peaks in the range from 3000 Hz to 4000 Hz, possibly generated by the movement of the crane trolley. Fig. 6b shows the spectrum of a ship in the dock, with the characteristics of an internal combustion engine, with a large energy distribution for the low frequencies. In comparison, the crane spectrum is less unbalanced in the low frequencies.

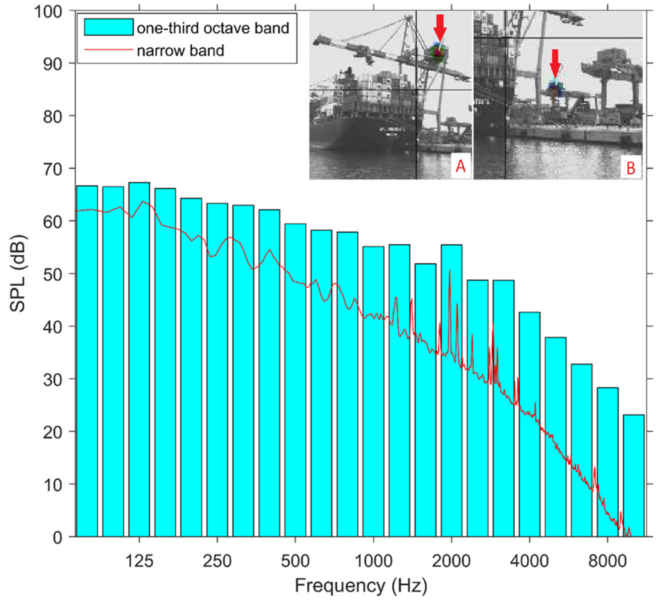
From the information collected, it is possible to identify the sources with a higher and a lower (but still relevant) sound level. Hence, through their characterization, signals that exceed the law threshold levels are detected and possible strategies for noise mitigation can be developed. The results reported here are based on brief recording periods; the analysis could easily be extended, prolonging the recording time, and multiplying the measurement positions, until a complete description of the sound field generated inside a port during usual work activities is reached. An overall noise mapping identifying each of the sources emitting in the harbor could be obtained by employing an AC, providing the ideal basis for any port noise acoustic planning and mitigation action.

5. Discussion

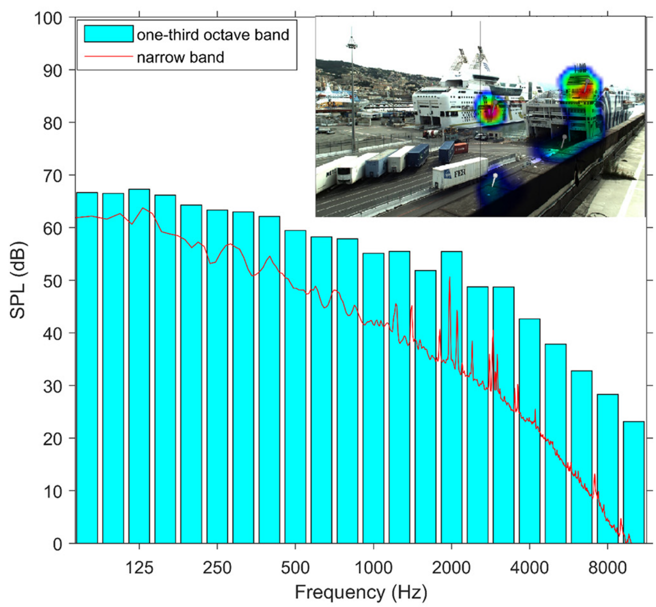
5.1. SWOT analysis

The SWOT (Strengths, Weakness, Opportunities, and Threats) analysis is useful for fields requiring strategic planning. Strengths and Weaknesses are considered internal factors (in our case, factors directly related to the AC). Meanwhile Opportunities and Threats are related to external factors, i.e., the port environment (Valentin, 2001; Gürel, 2017). Interesting features were identified after the measurement campaign, and the corresponding SWOT analysis is presented in Table 2. This matrix resumes some aspects to be considered in the optimization of the measurement methodology. The internal factors (Strengths and Weaknesses) are linked directly to the AC, highlighting the characteristics providing advantages over other measurement techniques. On the other hand, the external factors (Opportunities and Threats) are characteristics that represent elements in the environment that may be beneficia or cause troubles for the measurement process. The factors identified are classified as either *acoustical* or *logistical* factors to make the analysis clearer.

Considering the positive factors, i.e., Strengths and Opportunities, it is evident that an AC gives advantages and represents a viable technique to be applied in port noise surveys. From an acoustical point of view, a port is an outdoor and complex noise scenario with characteristics suitable to an AC due to source dimensions, location, and overlap. An AC can identify several noise sources in a harbor and estimates their position and sound levels. Besides, if necessary, the results can be validated with a Sound Level Meter, the standard instrument usually prescribed in regulations. At a logistical level, an AC setup is suitable for implementation in the port environment thanks to an easy transportation (access to several harbor locations by car), the opportunity to perform measurements far from port operations, and an easy setting to start a new run. It must be remembered that port noise characterization



(a)



(b)

Fig. 6. Frequency-based analysis was performed to obtain information about primary and secondary sources. In each figure the frequency spectrum of the signal is presented, with an AP isolating the applied frequency filter. (a) tonal noise: large gantry crane system (1488 to 1570 Hz) and small gantry crane (2789 to 2988 Hz). (b) near passenger vessel-main exhaust, L_w = 115.1 dB(A), secondary passenger vessel-ventilation system L_w = 109.9 dB(A).

and monitoring are difficult issues to address with traditional techniques. Considering that a standard general procedure for port noise assessment is still to be designed and that guidelines to use an AC in this context do not exist currently, the preparation of a methodological framework aimed at port noise mapping based on AC technology is to be pursued.

The main limitations emerge from the analysis of the negative aspects (Weaknesses and Threats). From an acoustical point of view, the main problem is the accurate evaluation of the focal distance to calculate the Sound Power Level L_w. This problem can be overcome in several ways such as:

1. Using a laser meter tool for precision measurements.
2. Marking a few signs on the ground to be used as references to estimate focal distance by triangulation (Asdrubali et al., 2021).
3. Using GPS measurements and map information.
4. Using geometric algorithms to extract the distance directly from the photograms.

Moreover, a great challenge is the design of a measurement plan able to account for the great variability of port activities involving source mobility, periods (day, evening, night), seasonality, and the randomness of operations (and operators). In this sense, coordination with port authorities and private stakeholders is necessary to implement the planned AC measurements. It is an option to split the measurements into two categories: aimed at characterizing a particular source or with the scope of portraying a wide soundscape. In any case, it cannot be ignored that the human skills required for in-situ measurements and post-processing (as well as the high cost of the equipment) represent barriers for a rapid and large-scale use of the beamforming technique in port noise characterization and monitoring.

5.2. Proposed measurement framework

The analysis performed allows to propose a basic framework for applying the beamforming technique to the new context of ship port noise. The proposed framework is resumed in Fig. 7. The framework is subdivided into three main steps to be taken successively: 1. Measurement plan design, 2. In-situ data collection, and 3. Data analysis workflow.

The **measurement plan** must consider all the key aspects to perform an effective monitoring campaign. The plan includes the definition of **Activity description**: main objective (single source or soundscape, characterization), **time**: the measurement period (random sample or schedule by operation conditions or daytime frame). **Place definition**: the sample points must be placed in the port considering a complete view of the scene (for monitoring or soundscape characterization), and if a single source must be characterized, measurements from different distances are advisable (Moravec, 2019). **Measurement duration**: must be enough to identify not only background noise but also single events. Equipment to use during the measurement and calibration **data** (certificate number, date).

In situ data is a set of collected measurement information during each measurement (additional to the AC register) that could be of importance in the analysis, such as **date**, **time** and **measurement duration**, **weather data** (temperature, relative humidity, wind direction and speed), a brief **scene description** (that can be seen at the photogram), information around the **setup placement** (could be a photo and a GPS location data), **equipment description** to establish any possible changes from the setup proposed in the measurement plan, and the related **filename** corresponding to the stored data taken by the AC.

Finally, a minimal framework is proposed to attempt a **data analysis** that gives precise information around the collected measurements and that must be completed after the measurements (post-processing). The first step is to make a **basic signal description**. From the whole signal, extract the global indicators L_p (dB and dB(A)), spectrum, spectrogram, AP and AV. The second step consists of analyzing the signal and the AV to **identify possible events in time**, in the same way using the spectrum and spectrogram to identify the **possible events in frequency**. The final step proceeds to the **source identification and characterization** for each identified event. The source characterization could be done including a **label** or basic description of the source, **type** (moving, static), spatial **location** at the scene using an AP, **time location**

Table 2
Matrix of the SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis for the application of an acoustic camera to port noise characterization.

Internal	Strengths	Weaknesses
AC	Characteristics that give advantages over other measurement techniques	Characteristics that give disadvantages compared to other measurement techniques
Acoustical	The AC can identify noise sources and estimate position and sound levels. The AC can be applied to dynamic or stationary noise sources. The AC has advanced post-processing analysis tools for spectral or broadband analysis. The results from the AC can be validated with traditional measurements by a Sound Level Meter.	The AC needs additional measurements to determine L_w (focal distances). The AC must be placed transversal to the plane of the moving source for a pass-by measurement, and some sources could move with complex trajectories during the recording. Absence of real-time analysis for the information collected.
Logistical	The AC is plug-and-play and needs a short time to start a new run The AC is transportable The AC performs measurements far from port operations (safe location) The AC reduces the time of the measurements if compared with a sound level meter.	The AC is an expensive setup. The AC requires specialized operators currently difficult to find. The AC requires at least two operators for running. The AC needs a car to be moved. The AC is not waterproof and requires equipment protection. The AC requires a large storage capacity for long term measurements
Environmental	**Opportunities**	**Threats**
Port	External elements in the environment that give benefits	External elements in the environment that could cause problems
Acoustical	The *port* is an outdoor and complex noise scenario. The noise sources in the harbor have characteristics, such as dimension, location, and overlap, suitable for AC measurement. Port noise characterization and monitoring are open relevant problems that are difficult to assess with traditional techniques. There is not yet a standard procedure to assess port noise measurement.	Visual recognition of the objects in a AP/AV of the *port* is a complex task. The design of a measurement plan considering the great variability of the port activities involving sources' mobility, periods (day, evening, night), seasonality, the randomness of operations (and operators) is challenging due to the complexity of this scenario. Wind and climatic events affecting the noise measurements
Logistical	Port noise characterization, monitoring, and control to pursue not only comfort but also safety. In a port, many of the locations are accessible by car. Generally, the dimensions of ports are large enough to place the AC and obtain a wide view of the activities.	In a port, many public authorities and private stakeholders act simultaneously, with a tangled responsibility framework. In a port, some measurement positions expose the setup to unexpected unfavorable weather conditions. In a port, some locations cannot give an electrical power supply.

(permanent, event duration, periodic), the **frequency characteristic** using a spectrogram, and finally the **focal distance** and related Source Power Level L_w.

This proposal contains minimal elements as a recommendation to begin a path towards effective port noise measurement campaigns and can be improved, including additional elements coming from other experiences and surveys.

6. Conclusions

This study assesses the applicability of AC measurements to port noise characterization. The results of an exploratory campaign in the Port of Genoa confirm the effectiveness of the novel application of well-established acoustic imaging technique to harbor noise: several analyses were performed, such as spatial-based analysis (to detect secondary sources), time-based analysis (to detect acoustic events), and frequency-based analysis (to detect some issues as tonal noise). A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was implemented considering the outcome from the pilot measurement campaign and the literature review.

The first measurements showed that large-diameter long-range acoustic cameras are a viable and useful tool to characterize and monitor different port noise sources. Therefore, this measurement technique enables a direct and effective comprehension of the acoustic phenomena occurring inside the port over time, which no other current equipment can achieve.

However, due to the complexity of such an environment, a set of key points was highlighted to avoid the most common problems that could arise during the survey. Furthermore, a framework to accomplish an effective outdoor noise measurement campaign using an acoustic camera was proposed and could be considered as a pre-normative requirement while standards on the topic are still pending.

Future work developments include extensive experimental campaigns in EU harbors, aiming to draw a classification procedure for port noise sources and carefully assess the AC accuracy when measuring in a large outdoor space with several sources emitting. Different ship operations (underway, maneuvering, and at wharf) are also to be explored, to have a more detailed and informed framework.

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CRediT authorship contribution statement

All the authors equally contributed to this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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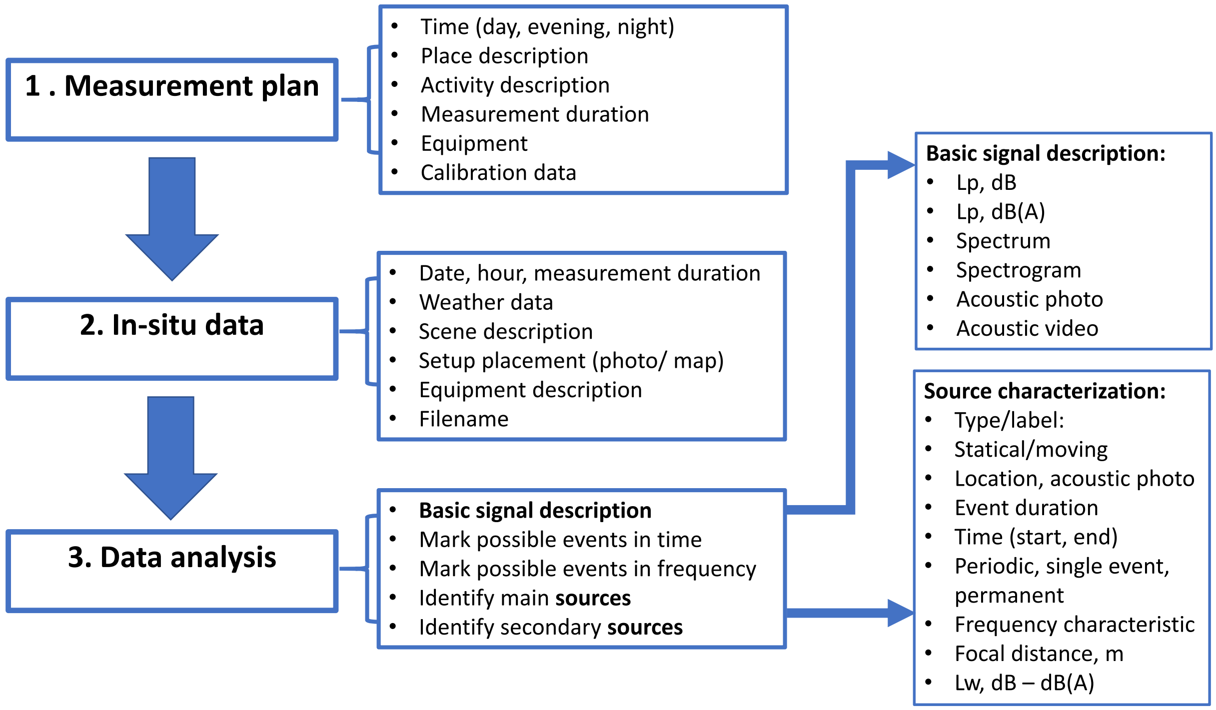

Fig. 7. Proposed measurement framework to use an AC in port noise characterization.

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