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Introduction to the Acoustic Camera

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Noise, or unwanted sound, has been proven to have a negative effect on human health. It is in the best interests of companies and industries to design the quietest product possible, and to make use of unexpected noises as a means of identifying problems with the final product. These situations require the source of noise emissions to be located.

An acoustic camera system utilizes beamforming to identify regions of high sound pressure level on an optical image. The aim of this thesis is to introduce the acoustic camera and its capabilities to other students, by way of documenting my experiences working with the acoustic camera system possessed by Metropolia University of Applied Sciences.

Measurements conducted in various situations confirmed the camera's ability to locate sound sources. Several shortcomings within the camera setup that led to reduced efficiency in the operation of the camera were recognized, and better measurement practices may lead to improved results. The thesis focuses on the creation of acoustic images; more advanced data analysis options are beyond the scope of this paper.

Keywords	acoustic camera, acoustic photo, noise, NoiseImage, sound

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1 Introduction

Sound is the result of pressure variations, or oscillations, in an elastic medium (e.g., air, water, solids), generated by a vibrating surface, or turbulent fluid flow (Hansen, 2001, p. 23). By nature, sound is everywhere on Earth, as the movement of living things and other objects generates vibrations that propagate through the air. The ability to perceive sounds, as found in humans and other animals, is called hearing.

Noise is defined as “unwanted sound”. As such, whether a sound is considered normal or unwanted depends on the listener and the situation. For instance, a loud, consistent revving engine sound is to be expected at a motorcycle racetrack but unwelcome outside of an office building. For many products, especially electronic devices, an unexpected noise can be indicative of faults that require troubleshooting. Noise is often unavoidable; as technology advances and products become progressively more powerful, their higher energy requirements usually result in an increase in noise emission, and a compromise between noise level and performance must be reached during the design phase. Additionally, the subjective nature of noise means that a noise does not have to be “loud” to be found disruptive. In any case, excessive exposure to noise has been demonstrated to cause and contribute to a variety of health problems in humans, ranging from psychological stress to hearing damage (Berglund, et al., 1999). The mitigation of noise is thus of great interest to many industries, and in many cases, identifying the source of noise is an important first step in that process.

An acoustic camera is a device designed to locate sound sources. Unlike a sound level meter, which can measure the volume of a noise but not identify where that noise is emitted from, an acoustic camera can achieve the latter through a technique called beamforming. The result is an “acoustic photo”, in which sounds are visualized and their sources can be located.

An acoustic camera system is in possession of Metropolia University of Applied Sciences and is currently located at its Myyrmäki campus. However, as acoustics is not a specialized field at Metropolia, there is no obvious starting point and no expert that students can refer to in person when it comes to using the acoustic camera for measurements and creation of acoustic photos. In writing this thesis, my aim is to provide that starting point

for scientific-minded students at Metropolia, and hopefully to all beginners in general, by way of documenting relevant knowledge and experiences with the camera system.

2 Background Theory

2.1 Sound pressure level

Sound pressure is the oscillations in pressure above and below the ambient atmospheric pressure when a sound wave propagates in air. The amplitude of this deviation is expressed in Pascal (Pa) (Hansen, 2001, pp. 23-24).

Humans can perceive sound pressures in the range of 20×10^{-6} Pa to approximately 200 Pa. Such a large range would be considered impractical for daily usage; thus, a logarithmic measure called **sound pressure level** is preferred instead. The sound pressure level is measured in decibels (dB) and is defined by the following equation (Möser, 2009, pp. 5-6):

$$\boldsymbol{L_p = 20 \log_{10}\left(\frac{p}{p_0}\right),}$$

where L_p is the sound pressure level, p is the root mean square sound pressure, and p_0 is the reference sound pressure. In air, which is where most measurements take place, the reference sound pressure is commonly given as $p0 = 20\,\mu Pa$.

Some notable sound pressure levels are listed below:

- 0 dB: defined as the lower hearing threshold in humans
- 40 dB: quiet conversation, average home noise
- 60 dB: normal conversation
- 80 dB: busy street
- 110 dB: live rock music
- 130-150 dB: threshold of pain

2.2 Sound frequency

In the context of sound waves, **frequency** is defined as the number of pressure variation cycles per second and is expressed in Hertz (Hz) (Hansen, 2001, p. 24). It informs the

perception of pitch in human; a high frequency sound wave will be perceived as sounding "higher" than one of a lower frequency.

The range of human hearing is commonly given as 20 to 20,000 Hz, though there is considerable variation between individuals. Moreover, the human ear is not equally sensitive to all frequencies, i.e. at the same sound pressure level, a 2000 Hz tone will be perceived as louder than one at 200 Hz.

In real life, a noise is usually composed of different frequencies.

2.3 Frequency weighting

As noted above, humans do not perceive all sound frequencies in the same way. Thus, when measuring the sound level, **frequency weighting** can be applied to ensure the meter reading is the same as what humans perceive (NoiseMeters Inc., n.d.). Several weighting curves are depicted in Figure 1.

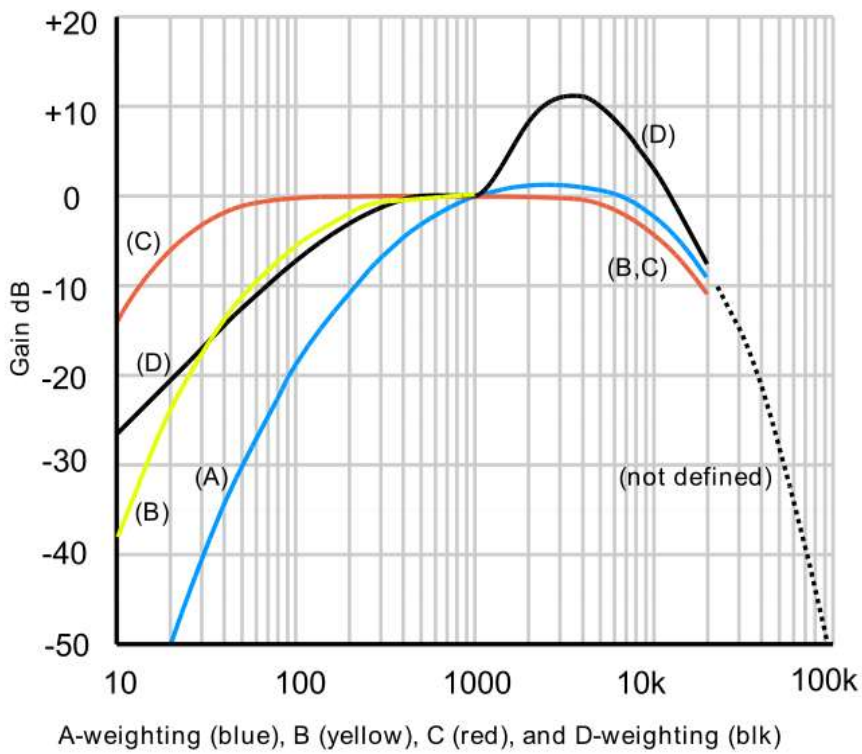

Figure 1. A-, B-, C- and D-weightings across the frequency range 10 Hz – 20 kHz.

The three most common weighting curves are:

- A-weighting: Expressed in dB(A), an A-weighted frequency conforms to a notional human hearing response. The most common weighting that is used in noise measurement, A-weighting is defined in the sound level meter standards (IEC 60651, IEC 60804, IEC 61672, ANSI S1.4) and is mandated to be incorporated into all sound level meters (Pulsar Instruments, n.d.) (NoiseMeters Inc., n.d.).
- C-weighting: Expressed in dB(C), a C-weighted frequency corresponds to the flatter hearing response at higher levels (100 dB and above). Many sound level meters include C-weighting, and it is also described in IEC 61672 (Pulsar Instruments, n.d.) (NoiseMeters Inc., n.d.).
- Z-weighting: Expressed in dB(Z), Z-weighting is a flat frequency response of 8Hz to 20kHz (±1.5dB), i.e. actual noise that is made with no weighting at all for the human ear (Pulsar Instruments, n.d.).

B- and D-weighting curves, as seen in Figure 1, are no longer considered to be standard and are not commonly used in the present time.

2.4 Beamforming

It is known that waves of the same frequency, when travelling in the same direction, will interfere with each other. Interference can be destructive, i.e. when these waves are out of phase and cancel each other out, or constructive, i.e. when they are in phase and their amplitudes add up. Such a constructive interference pattern can be thought of as a “beam” pattern.

Beamforming, also known as spatial filtering, is a signal processing technique used to transmit or receive radio or sound waves in a directional signal (McNeil, 2018).

- When transmitting, multiple identical signals is sent out at slightly different times, creating a pattern of constructive and destructive interference. Utilizing this, the signal can be directed preferentially at desired targets.
- When receiving, a range of sensors receive the signal at different delays, then combined such that the expected pattern of radiation is preferentially received.

In the case of microphone arrays, sound requires different amounts of time to reach individual microphones. By calculating the time differences between a sound event and

the received signal for each microphone, direction and strength of sound sources are determined. The calculated sound pressure is then mapped on the optical picture of the measurement object. (gfai tech, n.d.)

3 Acoustic Camera

The acoustic camera is a product of gfai tech GmbH, a subsidiary of the Society for the Advancement of Applied Computer Science (GFaI e.V.) Based in Berlin, Germany, gfai tech introduced the first “commercially viable” acoustic camera system to the market in 2001 (gfai tech, n.d.).The acoustic camera hardware comprises of several parts, which facilitate easier transport and storage of the whole system. The system is c

3.1 Microphone array

For different measurement requirements, there are varying array types and sizes available for microphone arrangements. All arrays come with an integrated fixed-focus camera and a tripod. (gfai tech, n.d.)

The microphone array model Ring48_75C, pictured in Figure 2, features 48 microphone channels. Each individual microphone may be equipped with a foam cover that serves as protection from wind and dust. At the center of the ring array is the Logitech C600 camera, which can record video at a maximum resolution of 640x480 at 30 frames per second. For connection with the data recorder, two data cables are provided.

Additional specifications:

- Diameter: 75 cm
- Weight: 1.8 kg

Figure 2. Camera array affixed to a tripod.

- Maximum sound pressure level: 130 dB(A)
- Operating environment: 0-40°C, 0-80% relative humidity
- Ingress protection rating: IP20
- Optimal measurement distance: 0.5 to 10 m. During testing, measurements have been made at ranges up to 25 m without obvious problem.

3.2 Data recorder

The data recorder was developed especially for use with the acoustic camera and is capable of a high sampling rate with a high number of channels at the same time. (gfai tech, n.d.) Specifically, the data recorder converts analog signals captured by the microphone array into digital form, which in turn is transferred to a computer for analysis.

The data recorder model mcdRec_721C is shown in Figure 3.

Figure 3. mcdRec_721C data recorder, front view.

Additional information:

- Dimensions: 42 x 31 x 20 cm
- Weight: 10 kg
- Operating environment: 0-45°C, 0-80% relative humidity
- Ingress protection rating: IP20

3.3 NoiseImage software

NoiseImage is a proprietary software program developed by gfai tech for use with their acoustic camera system. The program provides a graphical user interface for “acquisition, as well as for analysis and evaluation” of acoustic data (gfai tech, n.d.). Version 4.9.1 of NoiseImage for Microsoft Windows is included with the system at Metropolia.

Most of the features in NoiseImage require a hardware license key to run. Without a license, the user is restricted to opening previously saved NoiseImage projects and files in view-only mode.

4 Instructions for Operation of Acoustic Camera

In this chapter, instructions for using the acoustic camera, and more specifically for the creation of acoustic photos, are included. For more advanced use of the NoiseImage software, additional instructions may be found in the included digital manual. (GFaI, 2017)

4.1 Assembly

For the system found at Metropolia, the acoustic camera components are housed in three storage cases, while the tripod is kept in a canvas bag. The USB license dongle is kept separately, and access must be granted by a supervisor. Considering the need for mobility, a laptop computer is used for control of the system in most cases.

To assemble the acoustic camera system, follow the following steps:

1. Take the components out of the cases. Foam covers may be applied to the array microphones.
2. Attach the microphone array to a tripod and adjust to the appropriate height and angle.
3. Connect the data recorder to a power source.
4. Connect the data recorder to the array using cables labelled “1” and “2”. Make sure the cables are plugged into their corresponding sockets.
5. Connect the camera to the computer via USB.

6. Connect the data recorder to the computer with an Ethernet cable.
7. Plug the USB license dongle into the computer and open the NoiseImage program.

4.2 Recording

In NoiseImage, click the Recording button. After the connection between the computer and the recorder is established, the Recorder Control panel and Live Preview windows will appear. An instance of the recording interface is shown in Figure 4. It should be noted that this layout is user customizable; the default layout may appear different from the example shown here.

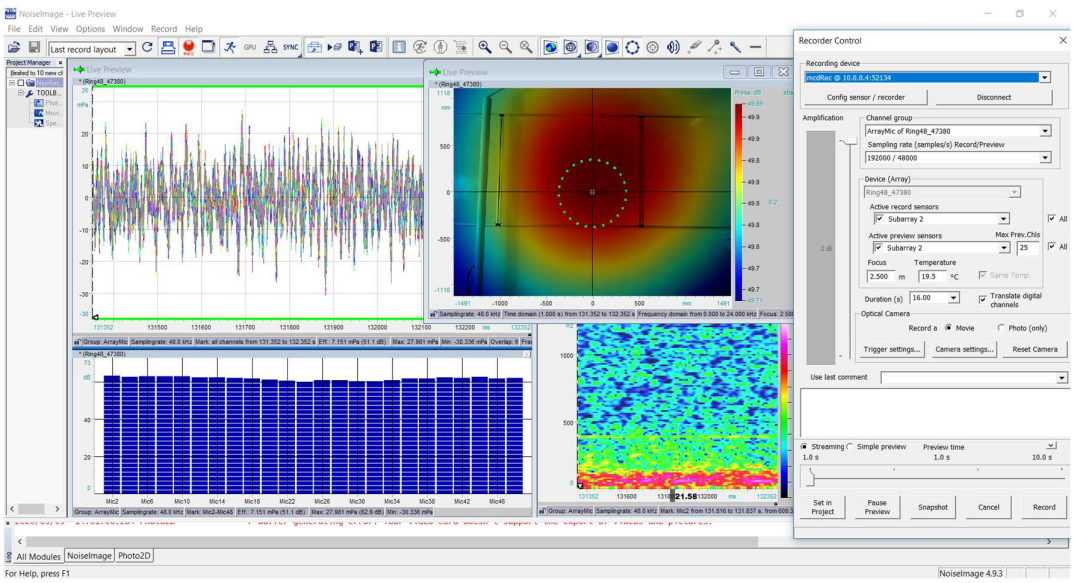

Figure 4. NoiseImage user interface for recording.

1. Check the Live Preview windows to confirm that the microphones and camera are functional. Sample time for the preview can be selected in the Recorder Control panel.
2. Enter parameters e.g. temperature, focus (distance from object to camera lens), and recording duration. Set the camera to capture either video (movie) or a single still (photo only).
3. Set a trigger by clicking on “Trigger settings”. Pre-trigger allows recording to begin *before* the trigger is activated by a set amount of time. In cases when recording

is to be triggered in reaction to a sound occurrence, the pre-trigger would cover for the reaction time and ensures the occurrence is recorded.

4. Click Record, then Trigger when appropriate. Data is captured by the microphone array and the camera, synchronized, and transferred to the data recorder.
5. Upon completion of recording, the data is transferred to the computer. Close the Recorder Control panel.

4.3 Sound analysis

The data is displayed in a Channel View window. The audio can be played back by clicking the Play button on the toolbar, or Options > Play.

A-weighting should be applied before any analysis work. This can be done via the right-click menu, as seen in Figure 5.

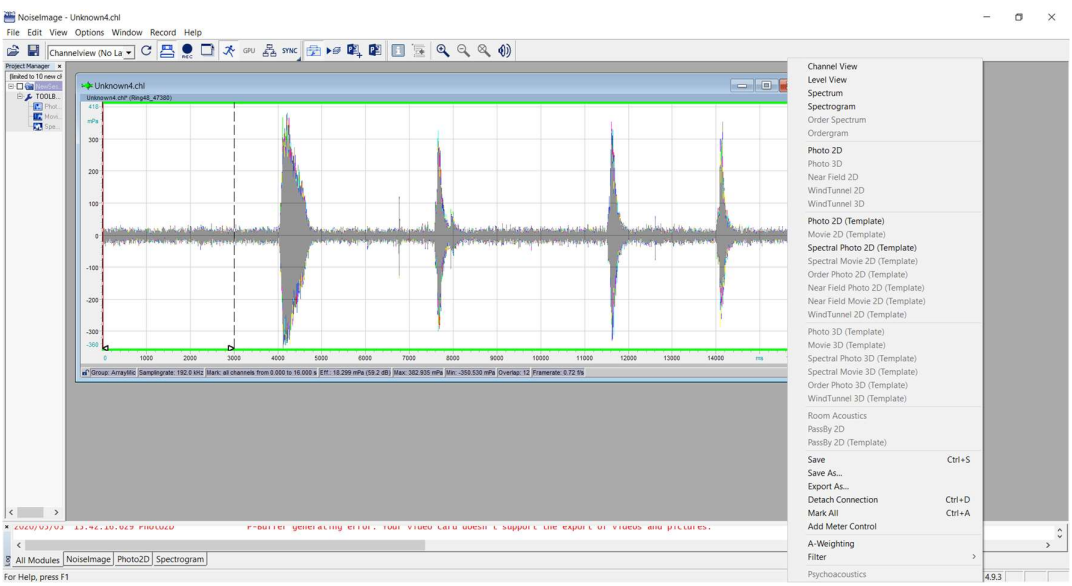

Figure 5. Right click menu showing available templates and actions.

In an acoustic photo, the optical image serves as a reference layer, onto which the calculated acoustic map is superimposed. To generate an acoustic photo from a selected section of the data, select “Photo 2D (Template)”. If no section is specified, the full data range will be used for calculation. A larger selection necessitates longer processing time. In general, analysis of acoustic data requires a significant amount of processing power; no other task should be carried out while analysis is ongoing.

Once calculated, the result is displayed in a new window, as shown in Figure 6.

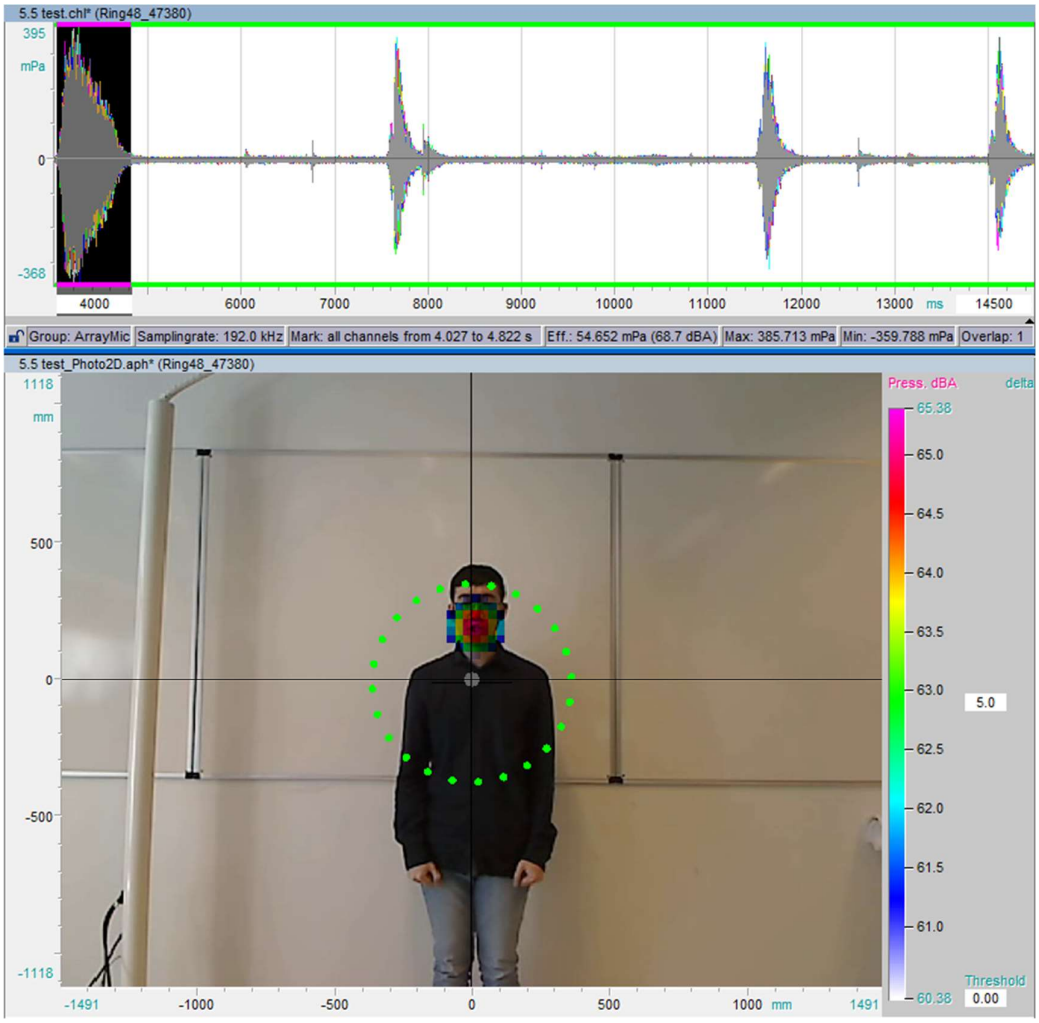

Figure 6. Acoustic photo showing identified source of sound.

On an acoustic map, sound pressure levels are represented as colors, with corresponding values shown in the color scale on the right. The scale can be changed between the following display modes:

- Absolute (abs): automatic scaling
- Relative (rel): scaling based on current image segment
- Difference (delta): the maximum value is determined by current segment; the difference between maximum and minimum is set manually.
- Manual (man): maximum and minimum values are entered manually

Similarly, the measurement unit can be switched between dB (logarithmic) or Pa (linear).

From this view, the user may select a different portion of channel data to recalculate the acoustic map. If real time mode is enabled, recalculation starts immediately with a new selection.

At any given point, data currently in view can be saved in NoiseImage-specific formats or exported into standard formats for other programs e.g. audio (.wav), photo (.jpg, .png), or video (.avi).

5 Field Tests

5.1 Käpylä apartment

An apartment in the Käpylä neighborhood of Helsinki were made available for our testing of the acoustic camera system. The apartment is situated at the ground floor and faces the road of Koskelantie. Measurements were taken in the bedroom with the camera facing the window; the aim was to see the difference in noise level between when the window is open and when it is closed.

When the window was closed (Figure 7), noise level was stable throughout with a maximum of approximately 28.5 dB(A).

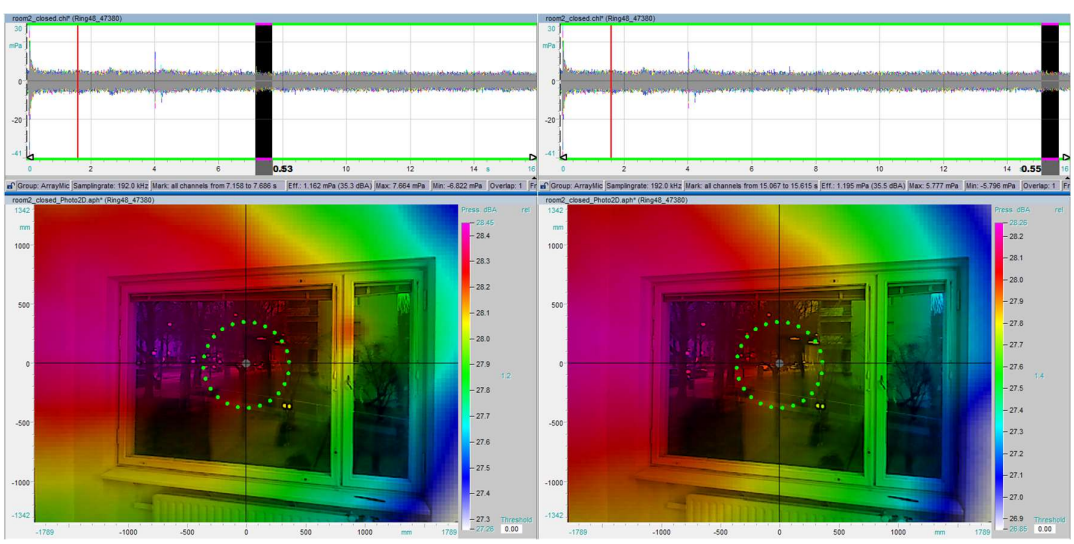

Figure 7. Acoustic photos of bedroom window, closed.

As expected, the highest noise levels can be identified as coming from the road, where a steady number of cars were passing by. Notably, the acoustic map lines up well with the boundary of the road that can be seen or otherwise inferred from the photo.

When the window was open, the noise level increased significantly, reaching a momentary maximum of 45.77 dB(A) in a 12-second interval. The open window provided a point of entry for sounds coming from outside, which is easily identified in the acoustic photos (Figure 8).

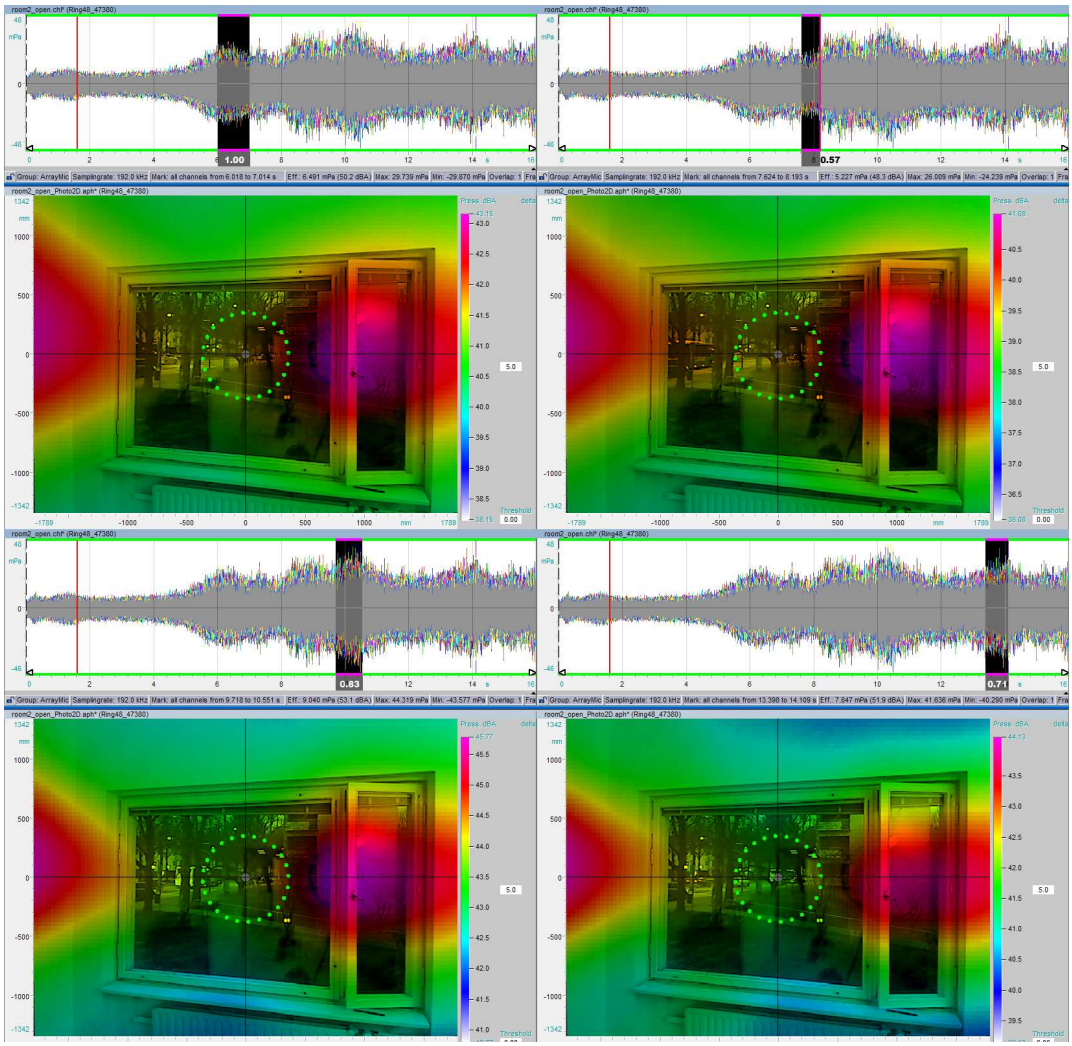

Figure 8. Acoustic photos of bedroom window, open.

The waveform of the recorded data displays some notable variation in sound levels over time. Given the fact that sounds coming from the road are inherently unpredictable, we decided not to investigate further.

The photos above also show a second spot of high sound level to the left of the frame. Based on observations of the scene, this can be explained not as a distinct source of sound behind the wall, but as an echo in the room. Since the window was only partly open, sounds entered the room at an acute angle. As such, the sound waves travelling in this path concentrated towards a smaller area of the wall and reflected from the surface, resulting in a reflection, or echo, that is identifiable on the acoustic map.

Before ceasing work for the day, we moved the camera to the sidewalk outside the apartment and made an informal measurement of sounds coming from the road. In such a situation where there are moving sound sources, i.e. cars, the result would be best represented through a series of time-synchronized photos, i.e. a video. The option to generate an acoustic movie in NoiseImage was not available, therefore multiple acoustic photos were calculated so that the change in position over time of sound sources can be discerned. These photos are included in Appendix 1.

5.2 Metropolia automotive workshop

When identifying problems with a vehicle, an auto mechanic may opt to keep the engine running and listen for unusual noises that might be indicative of the problems. In cases where vehicles must be run indoors, it is necessary that there is an exhaust extraction system to capture and remove the harmful exhaust fumes produced by the internal combustion engine. However, such a system becomes a second source of noise when running, which might interfere with the noises coming from the vehicle. A situation of this description happened in the automotive workshop at Metropolia's Myyrmäki campus, which provided an opportunity to demonstrate some of the capabilities of the camera to a group of students.

For all measurements, the camera was situated six meters away from the car. First, noise levels emitted by only the car engine were measured, as shown in Figure 9. To keep the amount of exhaust gas to a minimum, the recording duration was limited to 3 seconds for every measurement that followed.

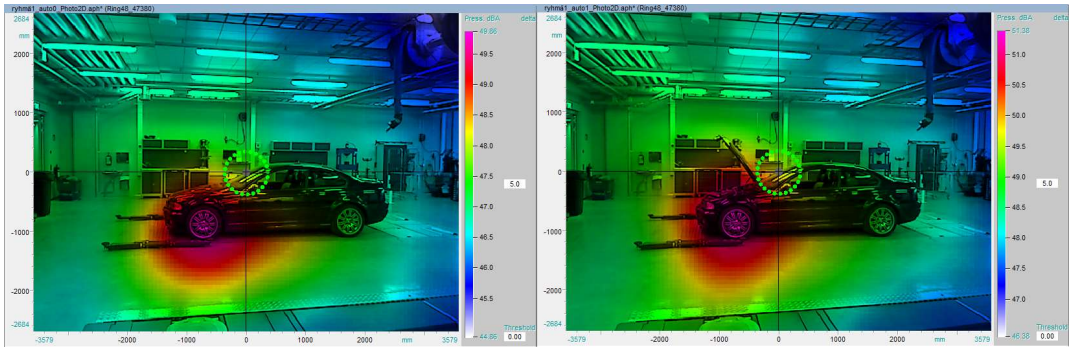

Figure 9. Acoustic photos of car engine.

When the hood of the car was open, engine noise could exit more freely upwards. This is reflected in the acoustic photo, where the localized area of highest sound level is slightly more spread out at the top. Overall levels increased by approximately 1.5 dB(A); this difference was not obviously perceived by the listeners behind the camera.

Next, the hose of the extraction system was attached to the exhaust pipe of the car. Initially, only the extraction system was running (Figure 10).

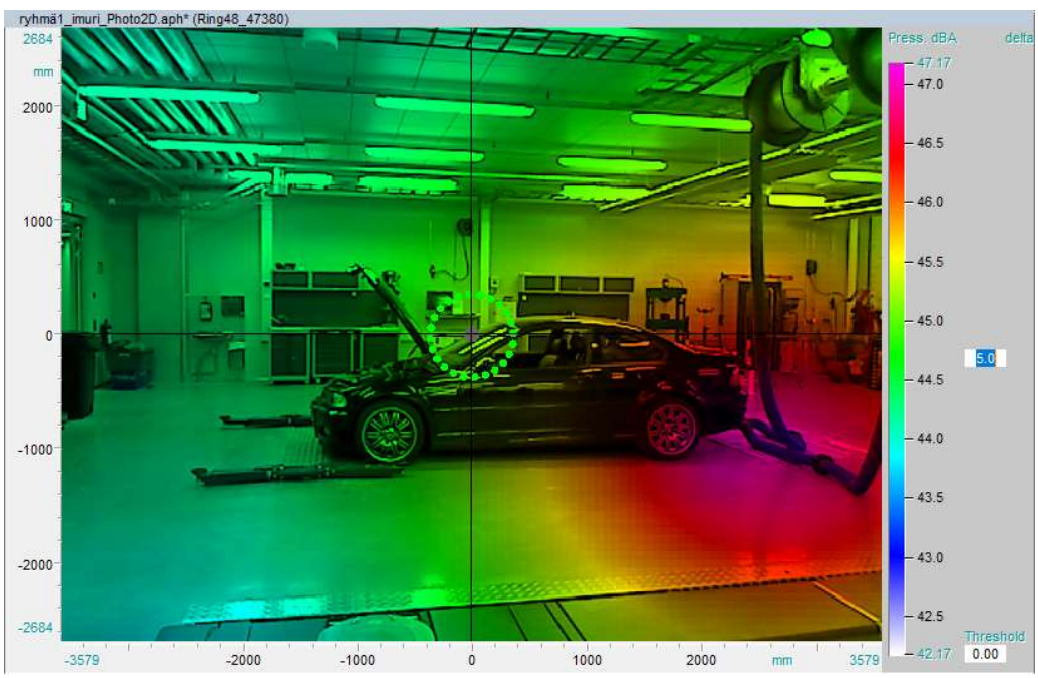

Figure 10. Acoustic photo of exhaust extraction system.

Noise emitted from the vacuum can easily be defined in the acoustic photo. The maximum noise level was measured at 47.17 dB(A), which is 4.21 dB(A) lower than that

emitted by the car engine alone, and the decrease in loudness could be perceived immediately.

Following this, the car engine was restarted and running alongside the extraction system, as captured in Figure 11.

Figure 11. Acoustic photo of car engine and exhaust extraction system running simultaneously.

While the vacuum noise is much less identifiable here than in Figure 10, its effect on the surroundings becomes apparent upon examination. Compared to photos shown in Figure 9, noise levels towards the right half of the frame have increased, which indicates the presence of the second source of sound.

The maximum noise level was measured at 51.88 dB(A) coming from the engine, which is 0.5 dB(A) higher than when the engine was running individually. According to the rules for calculating combined sound levels (Federal Highway Administration, 2017), this increase corresponds somewhat to the 4.21 dB(A) difference measured between the two sources of sound.

Since the engine noise was of greater interest, the possibility of removing or reducing the vacuum noise during data analysis was briefly explored. By looking at the frequency spectra of the noises, it was determined that both types of noise showed similarities in

terms of the frequencies emitted, which greatly reduced the likelihood of satisfactory separation of the two noises. In any case, separation was not attempted due to our lack of experience with the process. The relevant spectra are included in Appendix 2.

For the final part of the demonstration, an acoustic photo was taken from underneath the car chassis (Figure 12).

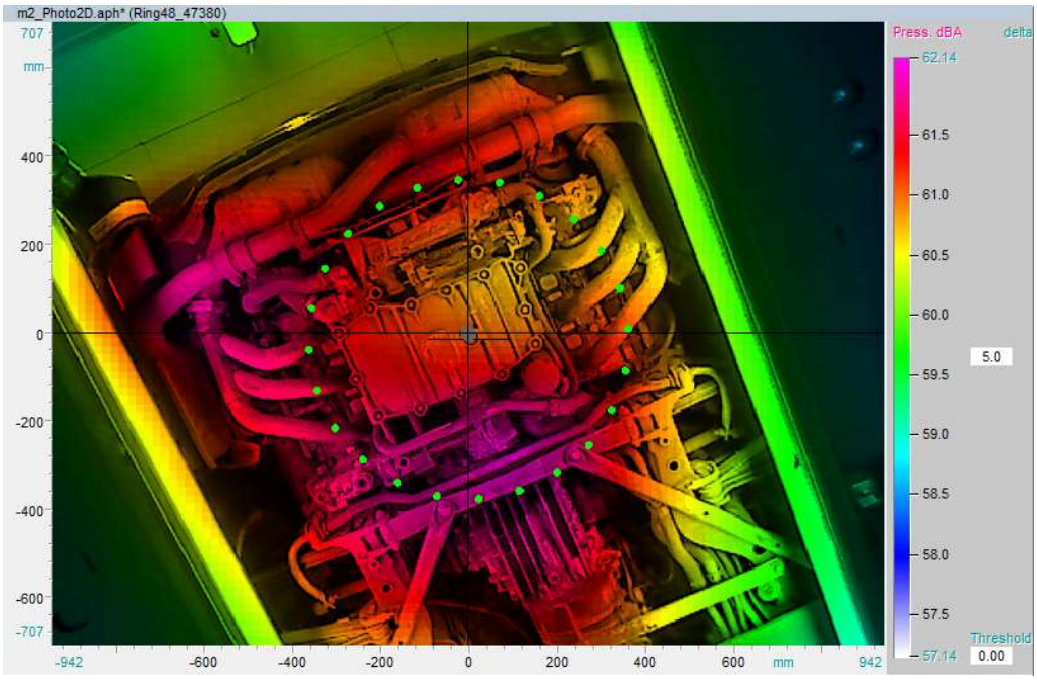

Figure 12. Acoustic photo of car chassis.

While this photo identifies certain parts of the car that emit more noise than others overall, little information about the parts themselves could be derived from this perspective.

5.3 Hernematala demolition site

The Circular Economy Aspects of Construction in Municipalities project, better known by its Finnish acronym RANTA, was a project implemented from November 2016 to January 2019 in Finland. RANTA was introduced with the purpose of enhancing circular economy aspects in building demolition, namely the recycling and reuse of materials from demolished buildings. The project was coordinated by Green Net Finland and featured participation from the City of Helsinki and Metropolia University of Applied Sciences, among others (Green Net Finland, n.d.).

The Hernematala demolition site in Helsinki was used as a case study in the RANTA project (City of Helsinki, 2019). To produce raw materials from demolition waste at the site, the concrete must be crushed. The quality of the materials, i.e. suitability for reuse, may differ depending on the crushing method. During the project, it was determined that a mobile crusher produced superior results compared to those of a bucket crusher, both in terms of quality and volume of the crushed concrete. However, noise levels produced by a mobile crusher were also higher, which might lead to problems in obtaining an environmental permit for its operation. Since a permit could be obtained more easily for the slower but less noisy bucket crusher, it is considered the safer option.

Metropolia was contacted for the noise evaluation of the two machines at Hernematala in September of 2018. For much of the session, the acoustic camera system was situated on an elevated platform approximately fifteen meters away from the machines, which were positioned near each other.

First, a measurement of the background noise was taken (Figure 13).

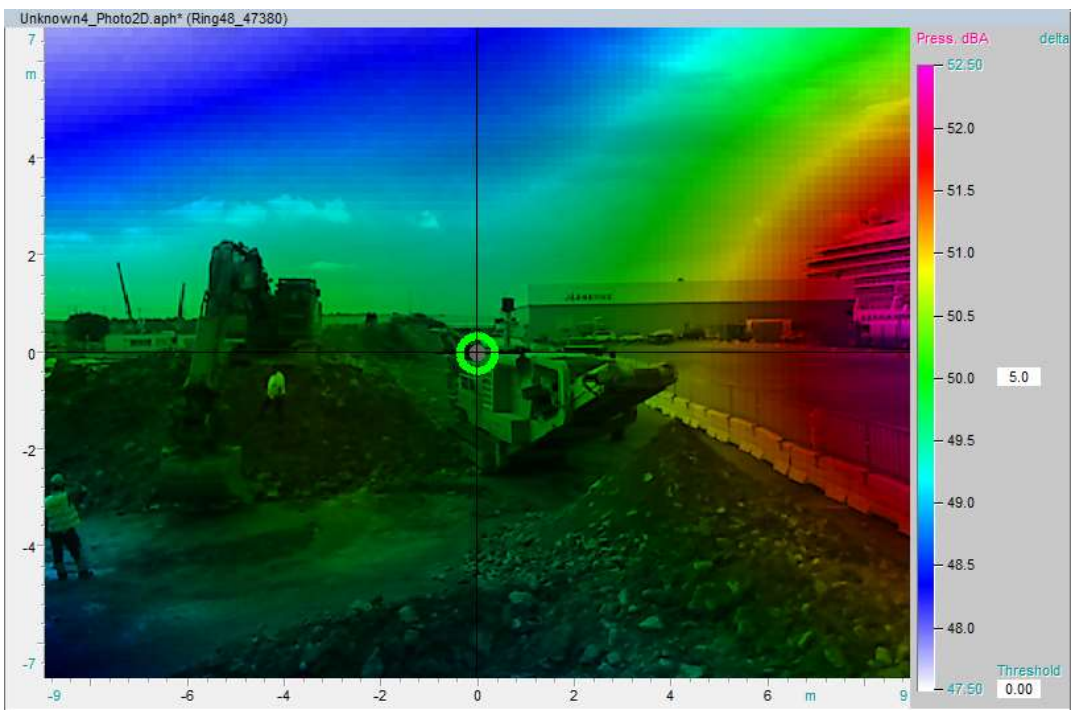

Figure 13. Acoustic photo of background noise at construction site.

The demolition site is located close to a port. During this period, most of the background noise came from the direction of the cruise ship docked at the pier, which can be seen in the photo. The maximum noise level is 52.50 dB(A), which is expected given the surroundings.

Measurements of each individual crusher took place next. For the measurement shown in Figure 14, the maximum noise level from the mobile crusher is approximately 78 dB(A). Noise appeared to originate from the center of the machine's body and spread quite evenly in all directions.

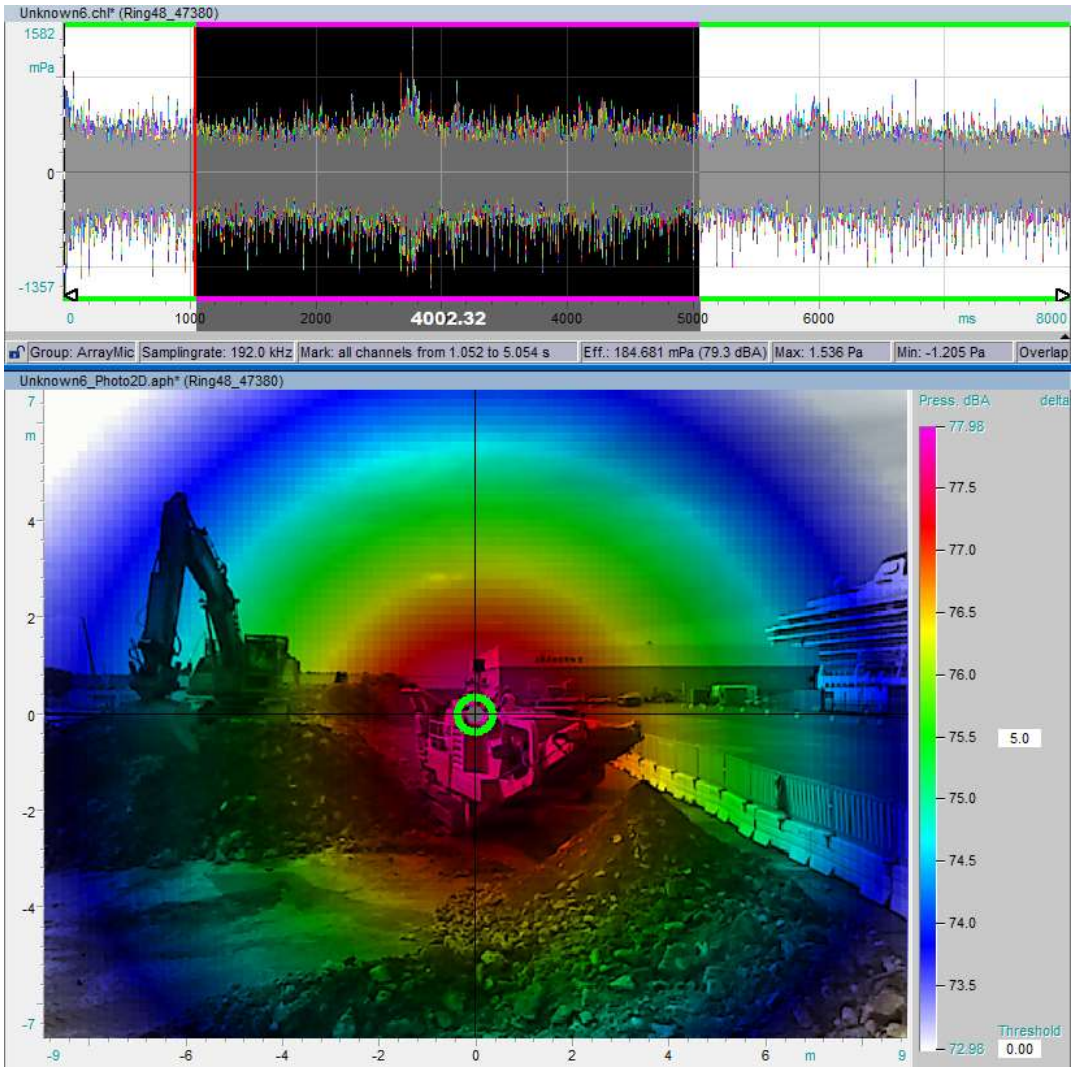

Figure 14. Acoustic photo of mobile crusher.

It can be seen in Figure 15 that the loudest noises came from the bucket part of the machine, where the crushing of materials took place. The bucket crusher was noted to run more slowly, and therefore more quietly, than the mobile crusher; the maximum noise level measured here is 74.1 dB(A).

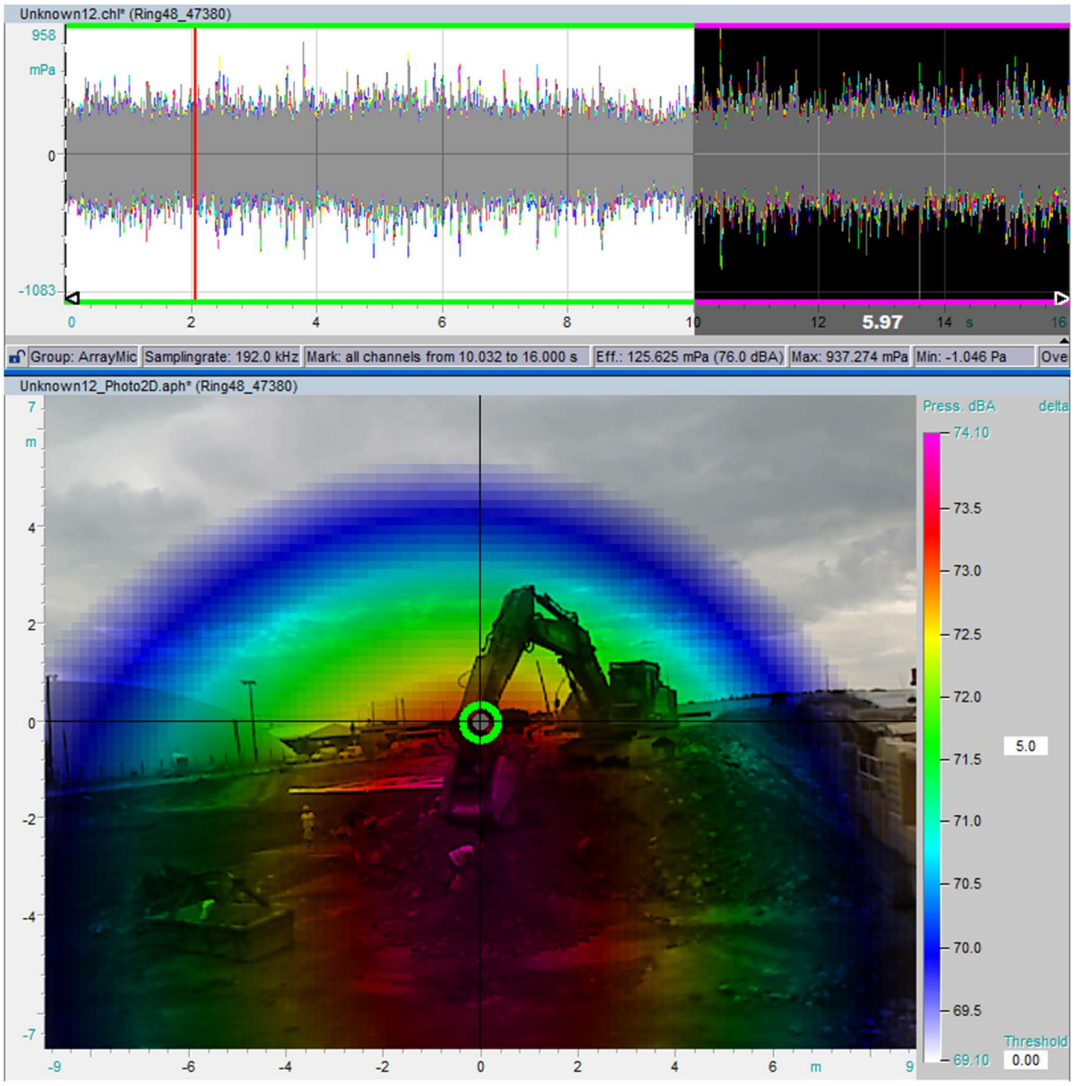

Figure 15. Acoustic photo of bucket crusher.

As displayed in both Figures 14 and 15, the waveforms peak regularly, indicating the rates at which the concrete is crushed. At times, noise level would increase sharply; these fluctuations are inherent in the crushing process, as the concrete varies in size and composition. Additional noise is also generated when the crushed concrete is unloaded onto the ground and accumulates.

A measurement of both crushers running concurrently was taken next. As seen in Figure 16, overall noise levels increased as expected.

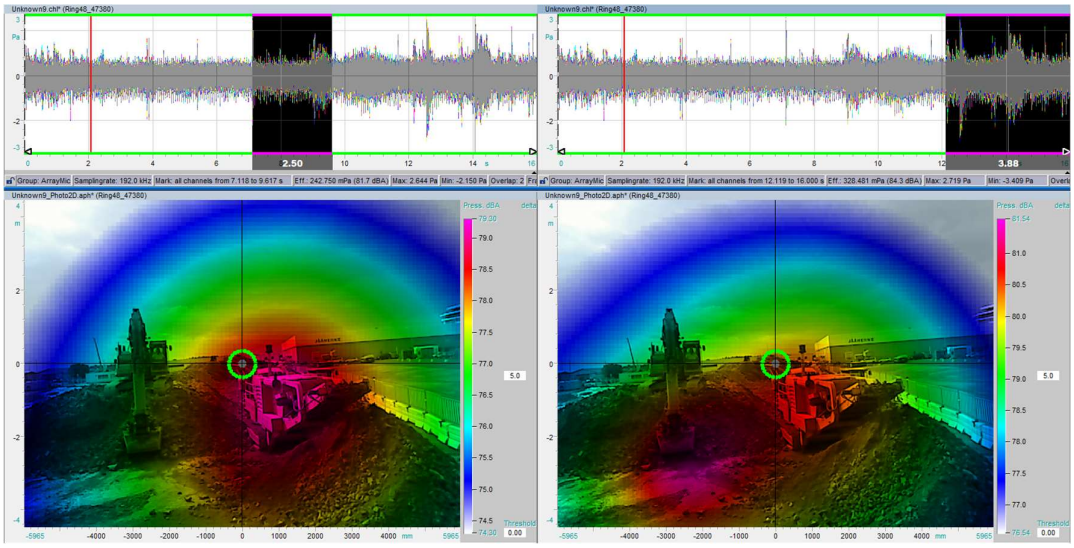

Figure 16. Acoustic photos of crushers running simultaneously.

As the noises peaked and combined unpredictably, each machine would produce the loudest measured noise level at different times. demonstrates that, while the mobile crusher remained consistently louder at 79-80.5 dB(A), the bucket crusher generated the loudest occurrence measured at 81.54 dB(A).

Afterwards, a measurement of the mobile crusher was taken from outside the construction site, approximately 15 meters away from the machine. The result is shown in Figure 17.

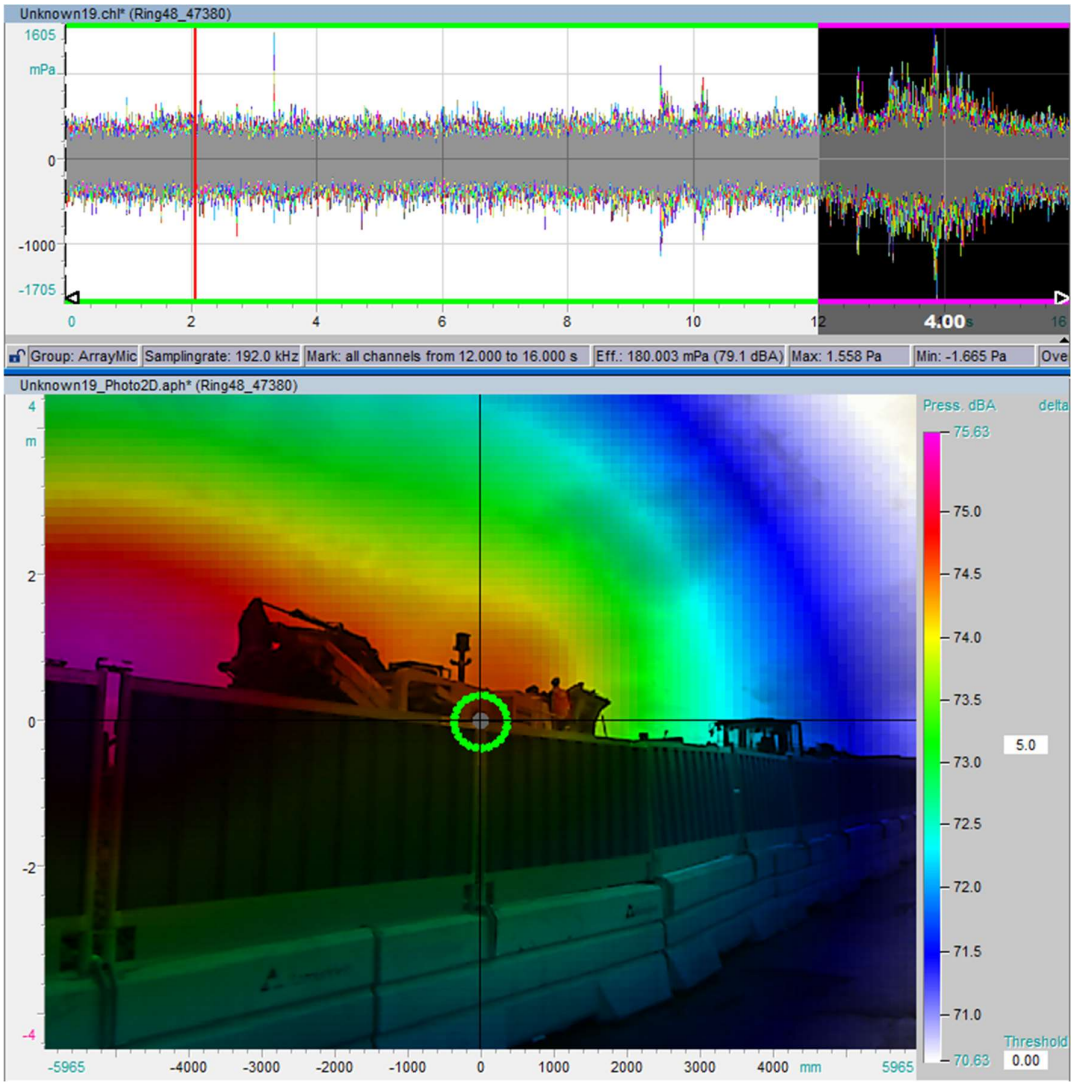

Figure 17. Acoustic photo of mobile crusher from behind the fence.

The maximum reading here is 75.63 dB(A), a decrease from previous results. This can be explained by the presence of two things that served as noise barriers from this vantage point: the fence and the pile of crushed concrete. It can be inferred that, as more of the concrete is crushed and gathered into a bigger pile, even more noise could be absorbed over time. This may lead to better noise mitigation measures, as materials found and generated on-site could potentially be positioned around the machinery in a way that utilizes their soundproofing properties to the fullest.

6 Discussion and Conclusions

It should be recognized that the acoustic camera is primarily designed for identifying sound sources. While the camera system can measure sound levels, it should be used in conjunction with, and not in place of, a dedicated sound level meter.

The acoustic camera's ability to locate the sources of noise has been confirmed through measurements. As shown in the above examples, the camera had the most success with stationary sources, as well as in situations where the sounds of interest were sufficiently louder than ambient noise. The acoustic camera license acquired by Metropolia did not include access to the Acoustic Movie function in NoiseImage; that capability would have extended the range of applications for the camera, particularly in cases of moving objects.

NoiseImage is custom software designed by gfai tech specifically for use with their own products. Consequently, NoiseImage is not especially user-friendly, and beginners may encounter difficulties while learning to use the program. For instance, actions in NoiseImage are typically performed with the cursor with few keyboard shortcuts available, therefore increasing the time required to perform each action. To improve productivity, use of a computer mouse is recommended over a trackpad.

Given that the computer is an integral part of the acoustic camera assembly, the performance of the Dell Latitude 7480 laptop provided by Metropolia proved to be unsatisfactory. Slow data analysis was a frequent occurrence, and the export of videos in NoiseImage was not supported due to the lack of a discrete video card. Laptops in the "mobile workstation" category, despite being larger and heavier in general, possess superior processing and graphics capabilities, and would be more appropriate for use with the acoustic camera while still meeting the requirement for portability.

The Hernematala case provided some valuable insight regarding the operation of the acoustic camera in an outdoor environment. At the demolition site, access to a power outlet was not available, therefore a portable generator was an absolute necessity. Furthermore, work had to be halted on two separate occasions due to rainy weather. As indicated by its IP20 rating, the camera system is not protected against dust and water

ingress. In such a situation, the setup should be disassembled and moved under water-proof cover as quickly as possible. Metropolia has since made plans to develop portable shelter and power source for the acoustic camera system.

As stated in the introduction, this thesis is intended to serve as a guide for beginners looking to make measurements with the acoustic camera. Therefore, much of the focus of the paper is on the recording process as well as the creation of acoustic photos. More advanced data analysis should be possible, thanks to the many options available in NoiseImage that were insufficiently explored during the writing of this paper. Similarly, due to the limited amount of time and opportunity for taking measurements, it is highly likely that the procedure detailed in this paper can be improved upon and even formalized in the future.

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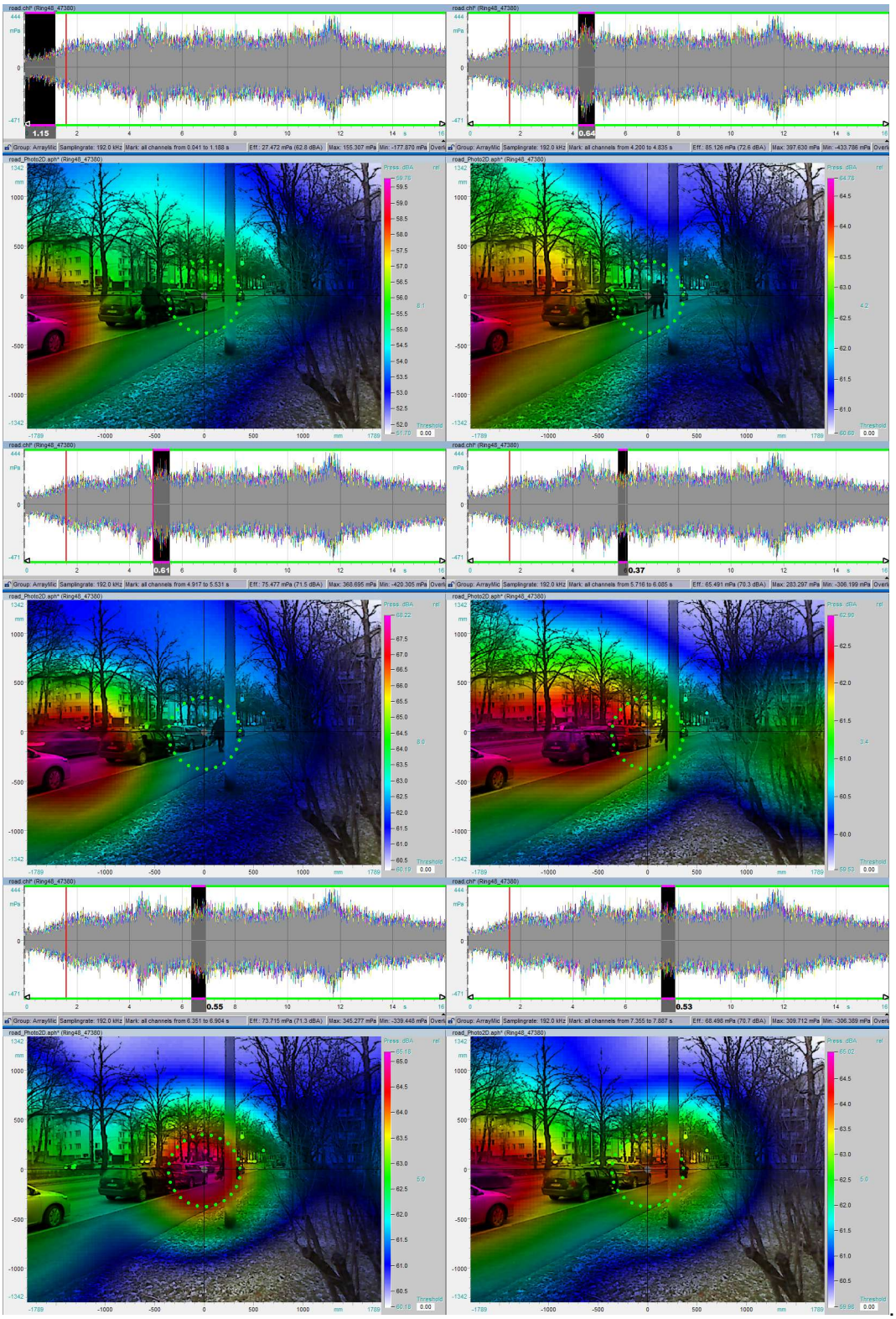
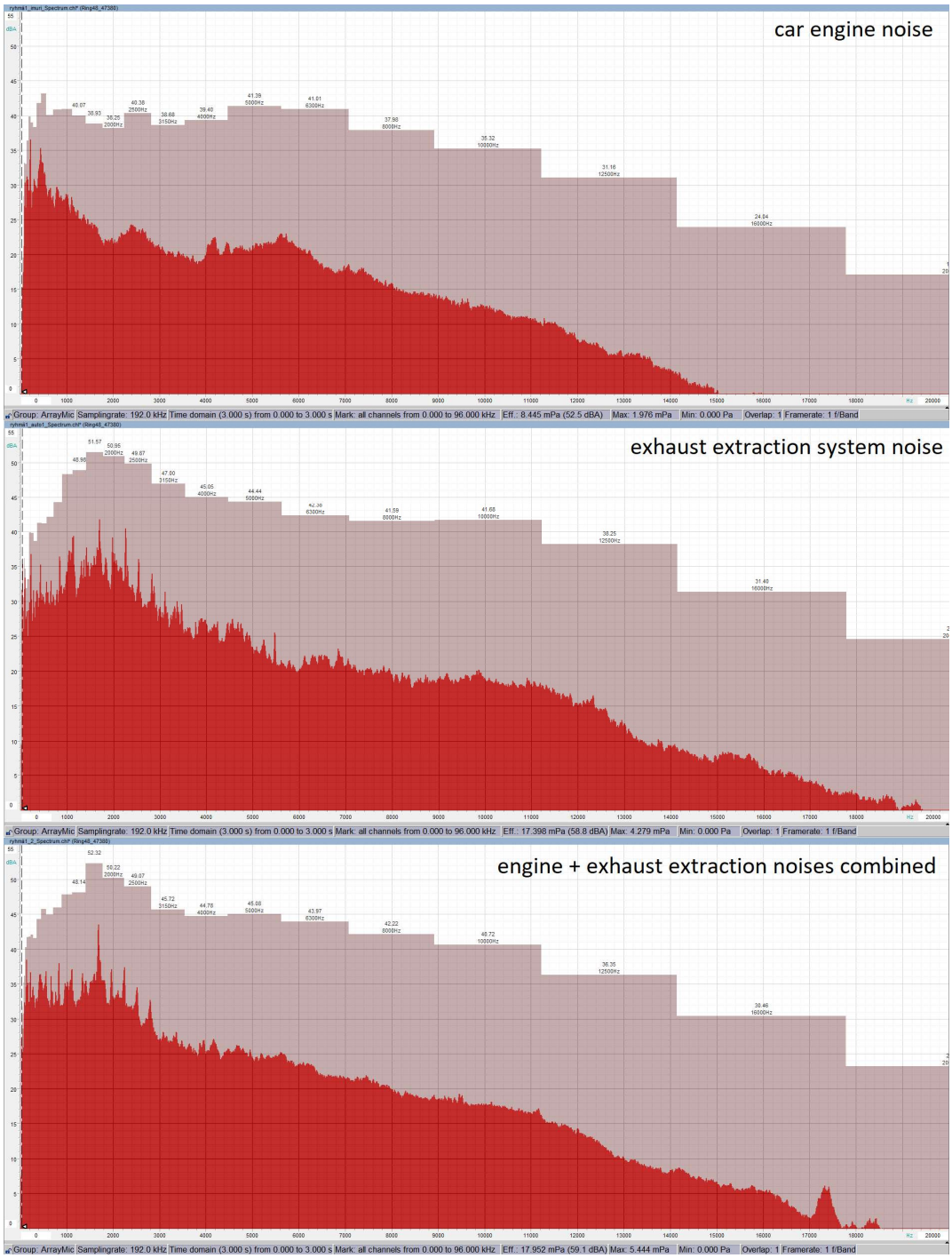
Appendix 1. Acoustic photos of passing cars



Appendix 2. Frequency spectra of noises