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Ranking Industrial Noise Sources with Noise Mapping and Beamforming Techniques

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Abstract

Noise is one of the environmental aspects where it seems more difficult to guarantee full compliance with legal limits, especially in complex industrial plants with a multitude of noise sources. Very often tonal characteristics are present, which may lead to tonal penalty according to noise regulations. This paper describes the application of noise mapping combined with acoustic camera beamforming techniques, to identify, localize and rank industrial noise sources, including those with strong tonal content, showing how this combined use can help in the development of effective noise reduction plans for industrial plants. Starting from the development of an acoustic model, based on ISO 9613 and including all relevant noise sources, a validation process is applied which includes acoustic camera measurements at receivers in the far field from the sources, typically close to sensitive locations, such as neighbouring houses. Practical examples are presented and discussed.

Keywords: beamforming, noise source localization, noise mapping, noise action plan, industrial noise control.

1 Introduction

Environmental noise assessments around industrial sites are generally performed by means of short or long-term measurements around the site, and near sensitive receivers, such as dwellings, where compliance with legal limits must be verified. Typically, legal limits related to noise nuisance in the vicinity of a factory (or other noisy activity), can be established in terms of the difference between the background noise (factory off) and the total noise (factory on), accounting also to specific noise characteristics such as tonality and impulsivity and, in some cases, low-frequency content. When legal limits are exceeded, the factory is required to take actions to reduce its noise emissions.

Noise abatement measures can be very costly and, therefore, should be carefully studied, so that the right noise sources are selected to act upon, and the right noise control actions are taken. Failing to do this normally leads to a company spending a lot of money, which can easily amount to several tens or hundreds of thousands of euros and end up still not complying with the legal criteria. This is especially true in complex industrial plants, with a multitude of noise sources, where it is not really possible to find out which are the most important sources just “by feeling”, and, also, one cannot switch on and off each individual source to measure their separate contributions to the total noise observed near a neighbour. So, to correctly identify and rank the noise sources, and establish a realistic noise control action plan, advanced modelling and/or measuring techniques must be called in.

The development of computer modelling techniques that simulate the acoustic emission and propagation, enables one, in our days, to model with good accuracy and reasonably fast, the most complex scenarios of noise generation and propagation [1]. The results are normally presented in the form of coloured noise maps, each colour corresponding to a given interval of noise levels, typically in steps of 5 dB. Above all, such a model, if correctly developed, enables one to rank noise sources, extract the individual contributions of each noise source to any given receiver, update the information whenever changes are introduced in the factory, and establish detailed noise control action plans with predictable results. Difference maps can also be extracted from such a model, in order to depict before vs. after maps, total noise vs. background noise maps, or scenario 1 – scenario 2 maps, etc. By ranking the sources and predicting the practical outcome of any scenario, one can effectively optimize the investment in noise control actions.

Having said this, the development of an accurate acoustic model of a factory that can be effectively used to establish a successful environmental noise action plan is not that easy. Getting the correct input data is, as in any model, the most critical part of the job: the “garbage in, garbage out” expression fully applies here [2]. In practice, the sound power of each source is estimated, from sound pressure measurements close to the source, and eventually later adjusted, following a validation process, to tune the model and make it as close as possible to reality. It is worth saying that we are, of course, mainly interested in the accuracy of the model for the correct calculation of the source’s contributions at the relevant receivers, such as houses nearby the factory, so the validation process should have this in mind.

There are situations, however, where a model validation process by sound pressure level measurements is not enough to be sure about the results or, in other cases, where we want to perform a first check to confirm which are the more relevant areas of the factory to include in the model. In other situations, one may have difficulties identifying the origin of a specific frequency tone which leads to a legal penalty or, maybe, have doubts about the influence of the directivity of some source upon its contribution at a certain receiver, or simply can’t reach a source to measure it (e.g., a factory stack). These are all situations where it can be very useful to make use of adequate acoustic camera beamforming techniques.

This paper summarizes the methodologies involved and presents several practical examples, from various types of industries, where application of noise mapping combined with acoustic camera beamforming techniques have been used to identify, locate and rank industrial noise sources, showing how this combined use can help in the development of effective noise reduction plans for industrial plants.

2 General methodologies applied

2.1 Noise mapping and action plans for industrial plants

For the development of an industrial noise map it is necessary to model all the variables involved in the complex environmental problem that is noise, so that the computational prediction obtained from the physical model of sound propagation can be as accurate as possible.

The next paragraphs describe in more detail the information needed for the production of an accurate and reliable acoustic model.

- Software: The software used for the preparation of noise maps is CadnaA. For the industrial sources the program is set to follow the international standard recommended for industrial noise, i.e., ISO

9613-2: "Acoustics - Attenuation of sound propagation outdoors, Part 2: General method of calculation.
- Topography: In preparing a noise map, information is needed on the land altimetry, including contour lines and spot elevations. From this information, the digital terrain model is built and used as the basis for the simulation.
- Map Area: The map area is the area defined as the surrounding area outside the industrial plant. It is chosen so as it can consider the influence from the plant on residential surrounding areas.
- Data on buildings and other construction elements: The buildings belonging to the factory, all the surrounding residential and industrial buildings, as well as some objects of interest such as walls and embankments, which act as "noise barriers" in the sound propagation outdoors, must be identified and introduced into the model.
- Noise source characterization: Field work is done to identify all the main noise sources from the plant, and assessment of the sound power emitted from each identified source. A noise source database is created with technical information needed for the modelling of each source. The sound pressure levels, L_p, measured close to each source are subsequently converted into sound power levels, L_w, taking into account the corrections applied to the type of source and type of sound propagation.
- Validation/Calibration of the model: a correct acoustic model is strongly dependent on the quality of input data. To reduce the uncertainties associated with the estimation of the sound power levels of sources, obtained from near-field sound level measurements, an extensive validation/calibration process is implemented after all the input data is introduced in the model and a first map calculation is done. The validation of the acoustic model is made by comparing the sound pressure levels measured in the field with the calculated values at the same points, taking into account the actual operating conditions of the plant during those field measurements. The process includes “source validation”, where short-term measurements are made under the direct influence of only a small number of sources and compared with the results of the model at the same points, and “model validation”, where noise measurements are performed for longer periods in the far field of all plant noise sources for a final validation of the model as a whole.

From the model, it is then possible to identify, characterize and rank all the relevant noise sources based on its acoustical influence at relevant receiving points around the Plant. Typically, these are located at the property limits of the Plant and/or at sensitive receivers (such as houses), at given locations.

After comparing predicted noise levels at relevant receivers with established criteria and having identified and ranked the sources according to their individual contributions to the overall noise levels at those receivers, it is then possible to propose required noise reductions for each source, as necessary to comply with noise limits, preferably with a reasonable safety margin in order to account for the uncertainties of both measurements and calculations.

In this way, the risk of future complaints from neighbours, or of non-compliance with legal limits, can be highly reduced. Moreover, the noise map and the associated information delivered with it, can become an important noise management tool for the HSE team of the Plant.

2.2 Acoustic Camera beamforming technique

The Acoustic Camera is a measurement tool which in general uses Delay and Sum Beamforming. This technology calculates the actual sound scene into a visual sound map, which consists of a superposition of different sound sources. The basic principle relies on the accurate calculation of the specific runtime delays of acoustic sound emissions radiating from several sources to the individual microphones of an array [3]. The simplest approach is the straightforward calculation of a delay-and-sum Beamforming function in the time domain. The reconstructed time function at every location x is calculated as [4]:

$$\hat{f}(\mathbf{x},t)=\frac{1}{M}\sum_{i=1}^{M} w_i f_i(t-\Delta_i). \tag{1}$$

Where t denotes time, M is the number of microphones in the sensor array, and w_i are optional spatial shading weights acting similar to the windowing coefficients applied before performing time signal spectral transforms to reduce leakage and smearing effects. Delay-and-sum Beamforming function in the time domain is also illustrated in Figure 1 below for an easy example using two point sources situated in front of a microphone array with 4 channels.

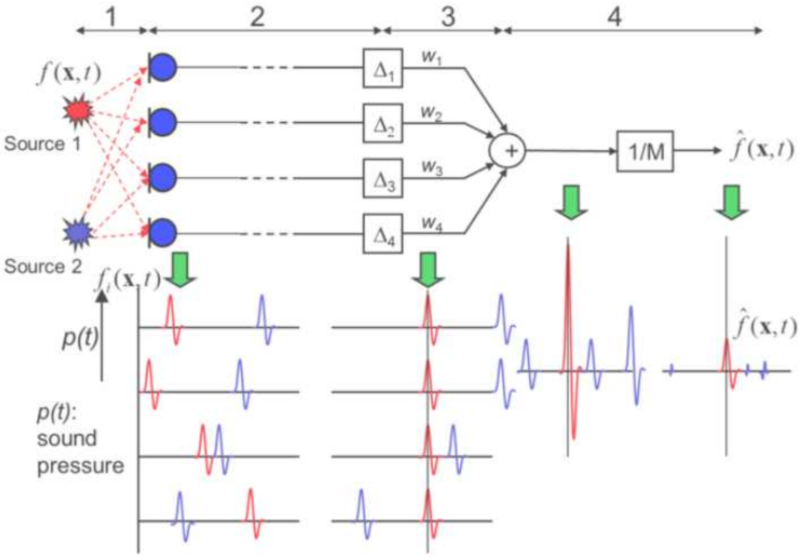


Figure 1 – Principle of time domain Beamforming [5].

The Delay-And-Sum-Beamformer in frequency domain is based on a similar principle as in time domain. The block diagram in Figure 2 illustrates the same easy example, using two point sources.

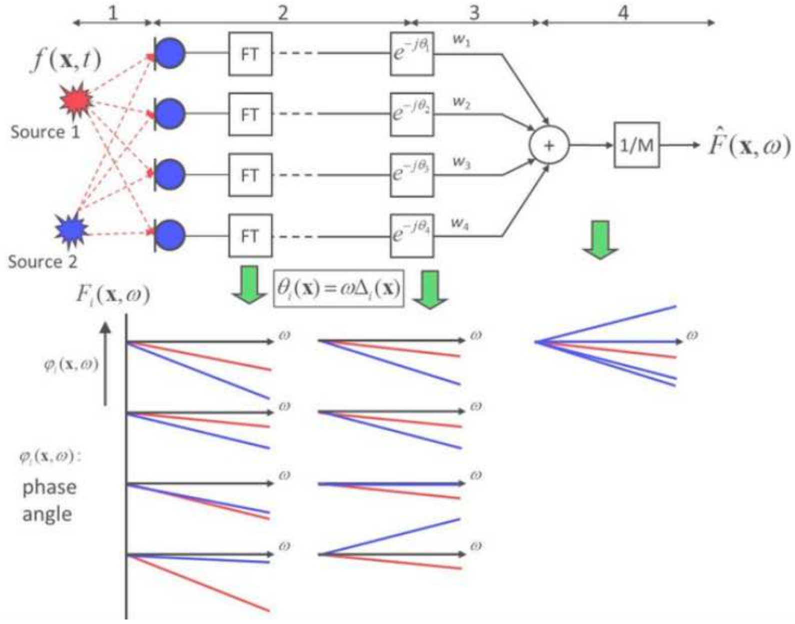


Figure 2 – Principle of frequency domain Beamforming [5].

The Beamforming system used in the examples below is the Acoustic Camera from GFAI Tech, in the configuration recommended for outdoor industrial noise studies, including (see figure below):

- The Array Star48 | AC pro: 48 microphones, 3,4 m diameter, recommended frequency range: 100 Hz – 13kHz, recommended distance range: 7 to 500 m;
- Data Recorder mcdRec 721: 48 mic channels, sampling rate from 48 kHz to 192 kHz for each analog channel and up to 6MS/s;
- Software NoiseImage: acquisition, evaluation and storage of data, acoustic images and movies.

Figure 3 – Acoustic camera system used in the projects described below.

3 Practical examples of application

3.1 Fertilizer Manufacturing Plant

This Fertilizer Manufacturing plant, in existence since the mid-1950s, is an important unit for the production of chemical fertilizers for agriculture and has been progressively altered in order to respond to market needs. The facilities in question are covered by the environmental licensing procedure under the IPPC (Integrated Pollution Prevention and Control). Noise monitoring carried out for the renovation of the environmental permit, showed the existence of significant sound levels at a residential area to the west of the factory, with the two major noise sources: the factory itself and a national road, set between the factory and the sensitive area. Given this situation and considering the concept of co-responsibility defined by the Portuguese Environment Agency (APA), it was found that the contribution in terms of noise from each of these sources was about 50 %.

In order to reduce the co-responsibility of the factory, the company decided to develop a noise map and action plan. For that purpose, an acoustic model was created, which included nearly 200 noise sources, each one of which was measured in close-field, and the model was validated by measurements at 52 validation points, within the industrial site limits, and 5 validation points near sensitive receivers. Next figure shows an example of the field work.

Figure 4 – Example of close field measurement of two noisy chimneys (left) and nearby validation points, in the direction of the residential area.

The national road was also included in the model, as the major background noise source, so that co-responsibility of both noise sources could be calculated. A 3D view of the total noise map (factory + road) for the night indicator Ln is shown in the figure below.

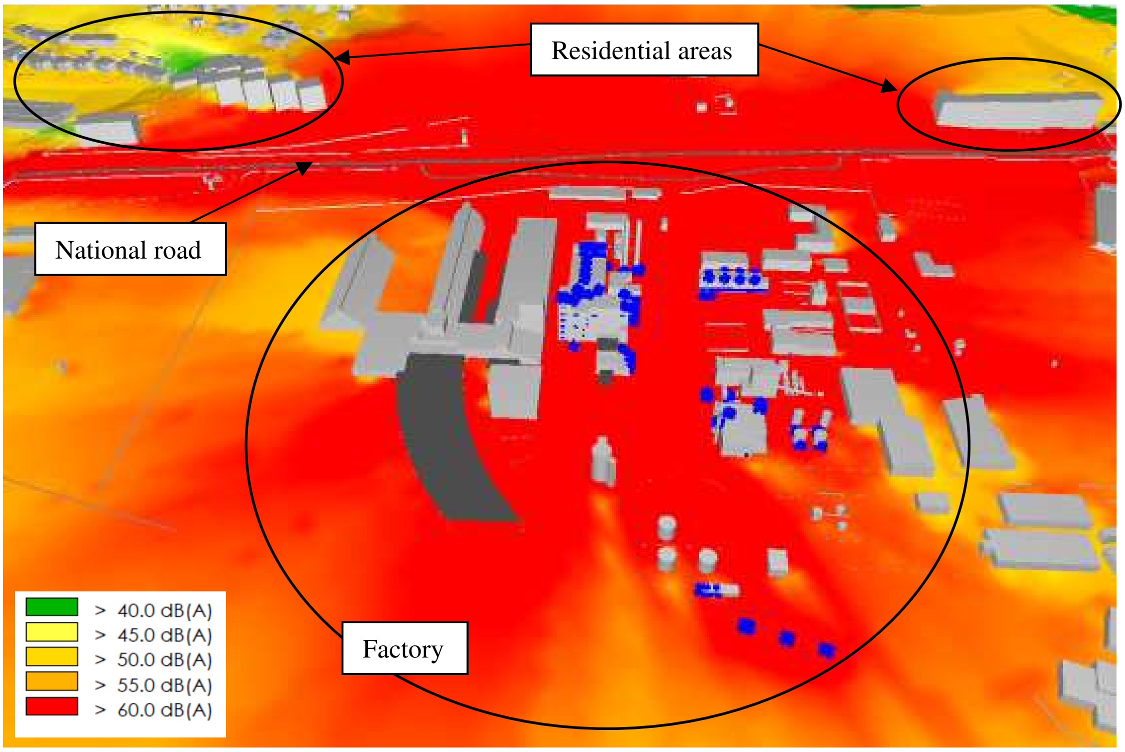


Figure 5 – 3D view of the L_n noise map, including both the factory and the national road.

The goal for the action plan was set in terms of L_{den} and L_n of the specific noise (SN) contribution near the residential areas as: $L_{den(SN)} < 62$ dB(A); $L_{n\ (SN)} < 52$ dB(A). Note that the legal limits applicable to the residential area, according to the municipal master plan, are 65/55 dB(A) respectively for L_{den}/L_n, which means the defined goal corresponds to the specific noise being at least 3 dB(A) below the limits. This allows a margin to accommodate the background noise contribution, namely from the national road, i.e.: a noise quota of 50% for each (specific and background noises).

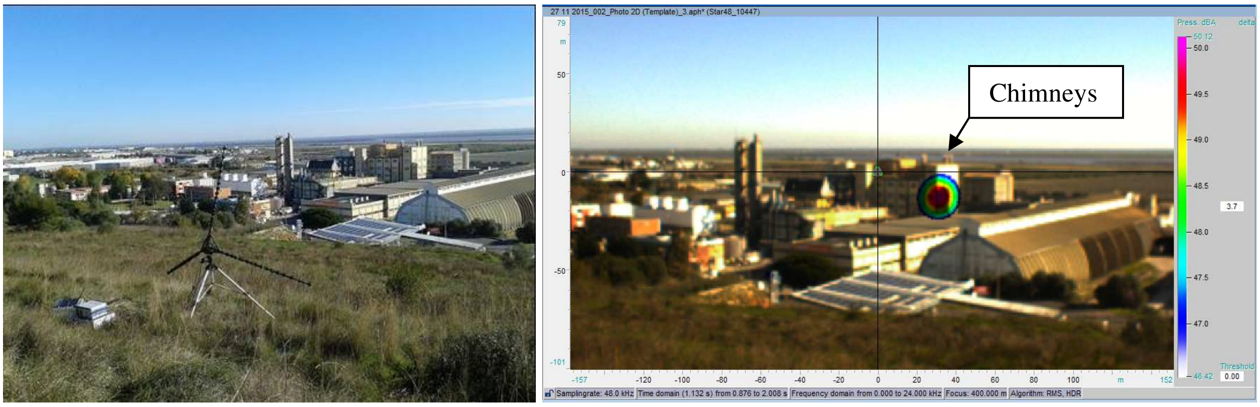
The action plan was divided in 3 phases, as summarized in the table below:

Table 1 – Action plan summary

Phase	Description	Estimated cost [€]
1	Intervention in a large air-cooled condenser, the top ranked noise source, consisting in the replacement of fans, reducers, motors and frequency variators.	250.000
2	Introduction of silencers in 5 chimneys on the terrace of the Fertilizer building.	100.000
3	Intervention at the level of windows and openings, namely on the façades of the Milling building.	50.000

After completion of phase 1, new noise measurements were taken, both near the condenser and at validation points, to check the results obtained, concluding that they were according to the predicted by the model: between 10 and 12 dB(A) noise reduction in the emission of the air-cooled condenser and a 4 to 5 dB(A) specific noise reduction at the residential areas, down to 54 dB(A) for L_n. However, before proceeding to phase 2, it was necessary to carry out additional engineering studies, including CFD (computer fluid dynamics) calculations, for the optimisation of the silencers – this was needed because there were limits to the maximum height of the chimneys, due to a nearby airfield, and limits due to chimneys air intakes for monitoring gas emissions.

At this point, it was also decided to cross-check the results of the model, by means of acoustic camera / beam forming tests in the propagation path between the chimneys and the more exposed residential area. A first test was performed close to the residential area, at about 400 m distance from the fertilizer production building and the noisy chimneys, in order to confirm that the air-cooled condenser was no longer a problem and that the second more important sources were the chimneys, as predicted from the model. Next figure shows the position of the acoustic camera and the main results obtained, for the global noise in dB(A).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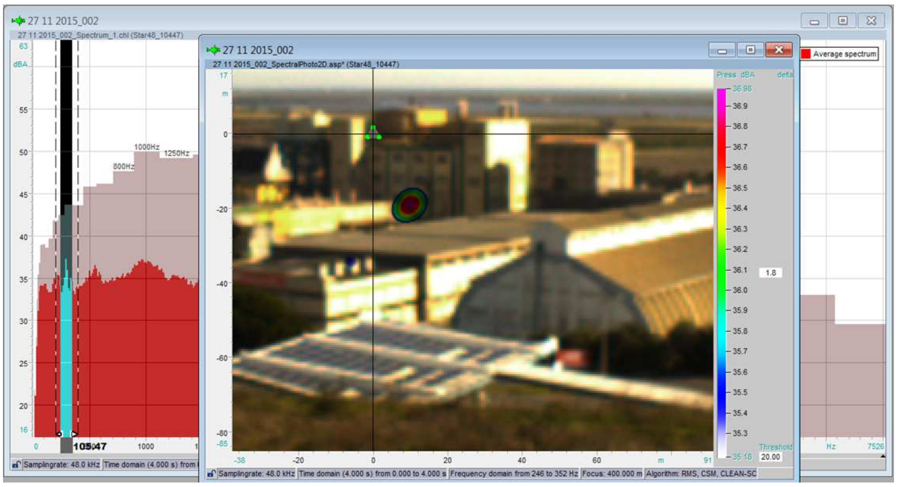
Samplingrate: 48.0 kHz | Time domain (1.132 s) from 0.876 to 2.008 s | Frequency domain from 0.000 to 24.000 kHz | Focus: 400.000 m | Algorithm: RMS, HDR

Figure 6 – First beam forming tests, at 400 m distance from the noise sources.

Note that for such a large distance, unless there is no wind, it is very possible that some refraction occurs along the propagation path and that, therefore, the angle-of-arrival slightly deviates from the direction of the source. Whereas this is generally negligeable for the horizontal direction, this is not the case for the vertical direction: the apparent source will appear higher than the real source, in case of downwind propagation, and lower, in case of upwind propagation [6]. As shown inf the figure above, a vertical down deviation of about 10 m was found between the noise focus which appears in the acoustic camera imaging and the noisier chimneys position. Analysis of the wind data for the time of measurement showed a slight upwind condition occurred, so that a deviation of about 1,4 degrees in the vertical direction of sound propagation, along the 400 m propagation path, is plausible, which matches the 10 m vertical error: arcsen(10/400) = 1,4° .

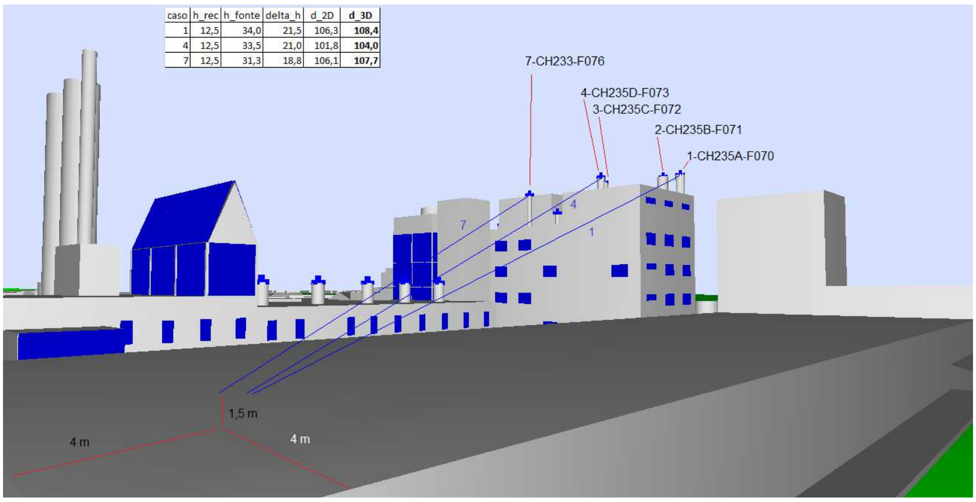
Searching through the spectrum of the recorded signal, it was also found the origin of a tone in the 1/3rd octave band of 315 Hz: one of the 5 chimneys, installed to the left and at a lower height than the two noisiest ones, as can be seen in the figure below, accounting for the vertical shift down of about 10 m. Note that this chimney was in fact the only noise source in the building with a tone in this frequency band, in the near-field measurements. The fact that it is detected in the acoustic camera at 400 m distance is very relevant, as it can generate a tonal penalty according to the regulations.



Samplingrate: 48.0 kHz | Time domain (4.000 s) from 0.000 to 4.000 s | Frequency domain from 246 to 352 Hz | Focus: 400.000 m | Algorithm: RMS, CSM, CLEAN-SC

Figure 7 – Identification of the origin of a 315 Hz tone.

To confirm the results, a second beamforming test was conducted, where the acoustic camera was installed closer to the sources, at the roof of a nearby warehouse within the factory site, at an approximate distance of 100 m to the sources, as shown in the figure below.



caso	h_rec	h_fonte	delta_h	d_2D	d_3D
1	12,5	34,0	21,5	106,3	**108,4**
4	12,5	33,5	21,0	101,8	**104,0**
7	12,5	31,3	18,8	106,1	**107,7**

Figure 8 – Geometry of the second beamforming test, shown in the acoustic model.

This second test was performed on a different day, with almost no wind, and the results were quite clear, definitely showing the prevalence of the noisy chimneys as the top ranked noise sources in the direction of the sensitive receivers, as exemplified in the figure below.

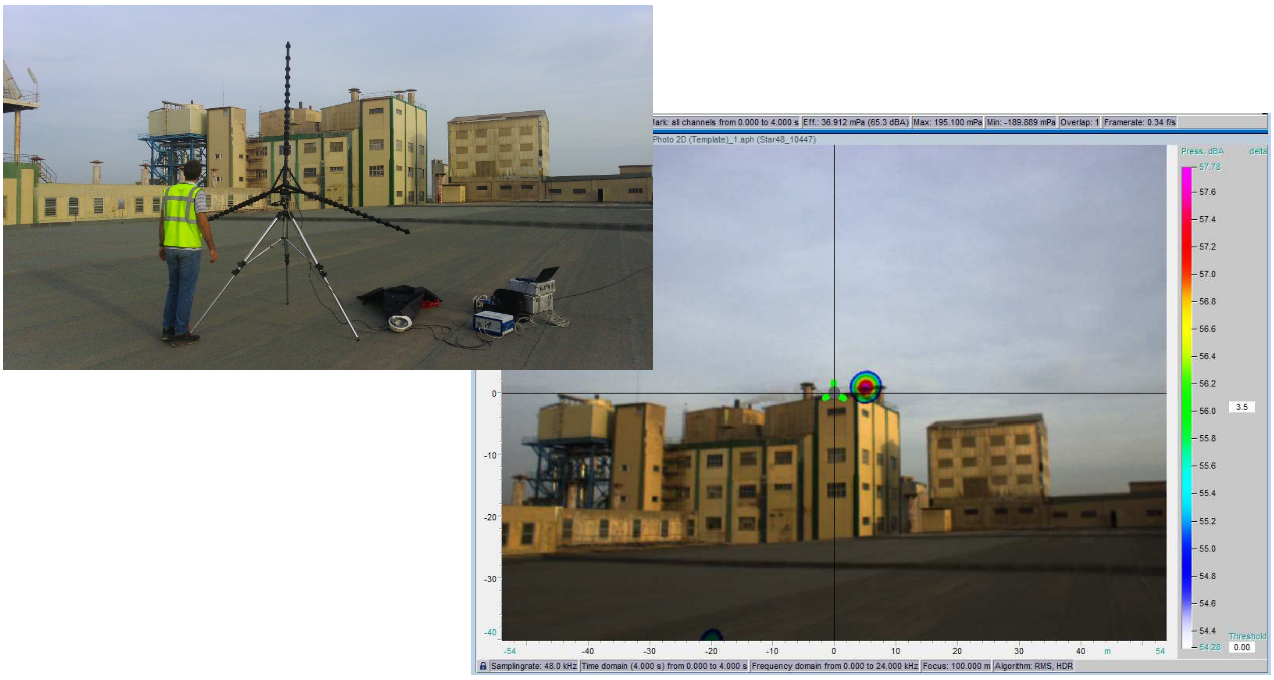


Figure 9 – Second beamforming tests, at 100 m from the noise sources.

The results of the beamforming tests were crucial in this project, to confirm the need for noise reduction measures in the chimneys and for the company to decide to go forward to the 2nd phase of the action plan investment. In the end, the company decided to change the fertilizer production process, deactivating the ventilation systems which included the noisy chimneys – an alternative and even more effective noise control action (eliminate the noise sources !).

3.2 Other examples

Next figures illustrate several other examples of application of beamforming techniques for the identification and quantification of noise sources in industrial facilities.

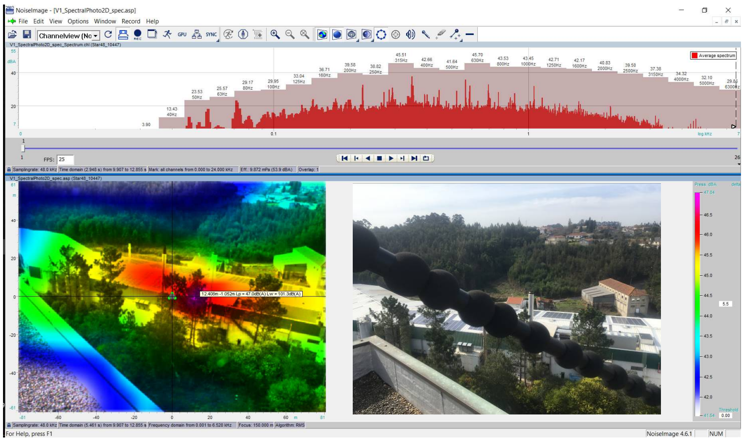


Figure 10 – Identification of the noisiest areas of a corrugated cardboard packaging factory.

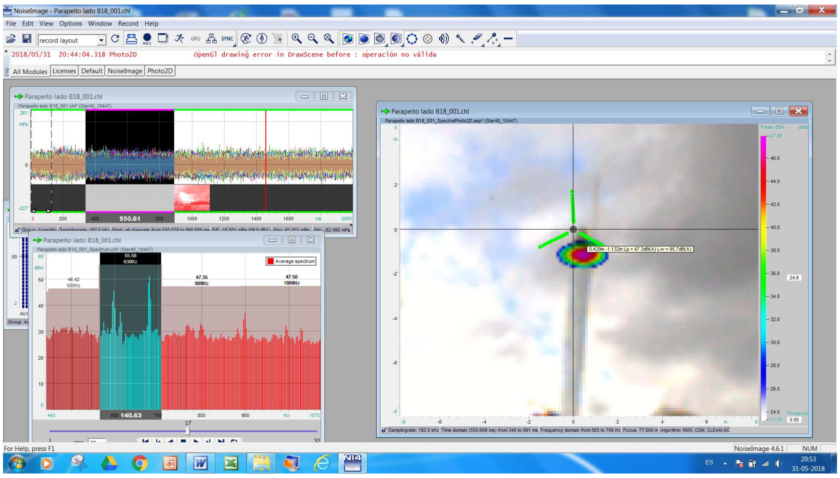


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Figure 11 – Testing the emission of a 630 Hz tone from an industrial stack, in a pharmaceutical plant.

4 Conclusions

The application of noise mapping combined with acoustic camera beamforming techniques, is a very powerful tool to identify, localize and rank industrial noise sources. The synergy and complementarity between the two techniques certainly contribute to improve the accuracy of the noise data obtained, which is the basis for effective noise reduction plans for industrial plants. Our and others experience [7], shows that, although it takes a large amount of work and state-of-the-art technology to produce reliable industrial acoustic models, it is worth the effort, as it definitely helps achieving the best possible results in noise abatement programs for a given investment. Cross-checking results of noise mapping models with those obtained from beamforming measurements, do represent an important added value for the predictability of the outcome of noise reduction projects, reducing the inherent risks associated for the company.

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