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USE OF THE BEAMFORMING TECHNIQUE TO CREATE PSYCHOACOUSTIC MAPS INSIDE AN AUTOMOTIVE VEHICLE

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Abstract. *The presence of unwanted sound sources inside a vehicle can be a sign of a malfunctioning system and it can, also, cause acoustic nuisance both occupants of the car and outsiders to it. The first step to eliminate a source is locating it. This paper use the beamforming algorithm, with a two-dimensional circular array, for mapping the location of the sound sources inside an automotive vehicle. On top of these maps it is proposed a technique for creation of maps of psychoacoustic parameters such as loudness and sharpness, to measure the level of disturbance to the human auditory system produced by these sources.*

Keywords: *beamforming, psychoacoustic, vehicular noise*

1. INTRODUCTION

In acoustics, noise is any unwanted sound, either interfere with the communication, or cause discomfort or health problems. Inside automotive vehicles, noises can cause distractions and can lead to accidents, besides being indications of malfunction of some mechanism.

The noise source identification of an equipment and the determination of its cause are the first step to eliminate it, guaranteeing the well-being of people around and the proper operation of the equipment. Knowing what mechanisms and components are generally noisier, allows the manufacturer to reformulate the project, focusing on a quieter model. But it is not always possible to identify the location of such discomfort without the use of special equipment.

In this paper, a brief review of the beamforming technique is provided, and then is proposed a technique to create psychoacoustics maps using the parameters loudness, sharpness and roughness through integration in critical bands as showed in Fastl (1982). This is possible through information obtained by the beamforming technique. A circular microphone array with twelve sensors is used to create these maps inside an automotive vehicle. This psychoacoustic beamforming enables concentrate the effort to locate the most uncomfortable noise sources which is not necessarily the one with higher acoustic power.

2. BEAMFORMING

The beamforming is a spatial filter technique that uses microphones arrays, where is possible to control the sensitivity to the incidence of sound waves in a certain direction or point in space, i. e., allowing the sound sources identification by this technique.

In nature, several animal species, including humans, use a primitive form of this technique to locate certain sound sources, through one ear on each side of the head for example. However, the first artificial acoustic array was created only during the First World War. For more details, see Johnson *et al* (1993).

Each sensor in the array occupies a different position in space, then it has a different time signals that are a function of the distance between the sensor and the sound source. To drive the array for certain direction in space, where you want to search the source, the algorithm apply different time delays in each signal in order to amplify the signal coming from that direction. So when the arrangement is directed to an area where there is a sound source, all signals will be in phase, therefore will have a much stronger response than if the array had analyzed a region with no source. In this paper, it is assumed the plane wave model for the beamforming algorithm.

2.1 Time Domain

Modeling a plane wave travelling in the direction $\vec{s}$, the sound pressure p will be a function of the position $\vec{x}$ and time t, i. e.

$$p(\vec{x},t) = f(\vec{x}\cdot\vec{s} - c_0 t) \tag{1}$$

where c_0 is the speed of sound. For each microphone *m*, where m= 1, 2, …, M, the sound pressure will be only time-dependent:

$$p_m(t) = \bar{f}(t) \tag{2}$$

where the top bar is used for distinguish the function f in eq. 1.

The beamforming response b(t) is given by the sum of the M signals delayed to each other:

$$b(t) = \frac{1}{M}\sum_{m=1}^{M} p_m(t - \Delta_m) \tag{3}$$

The symbol Δ_m represents the delay of the sensor *m* compared with the reference point in the array. For plane waves, the delay is given by:

$$\Delta_m = \frac{\overrightarrow{x_m} \cdot \vec{s}}{c} \tag{4}$$

where $\overrightarrow{x_m}$ is the position of the microphone *m* (**Figure 1**) . The result is normalized by the factor 1/M. When selecting adequate delays, the signal from the focused region is amplified while the signal from the other regions is diminished.

If the spherical waves model were assumed, it would be necessary to use a weigh factor for each microphone signal to correct the decay of the amplitude.

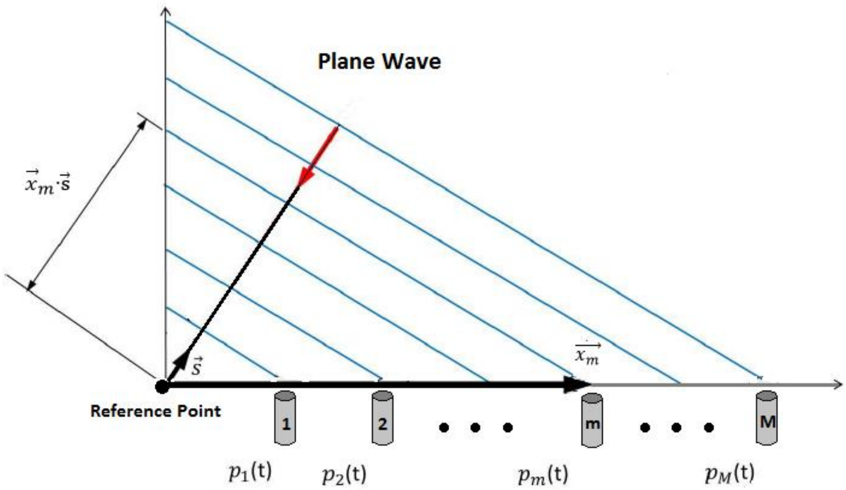


Figure 1 – The spatial beamforming technique representation

2.2 Frequency Domain

If the time history is not important, the algorithm can be made in the frequency domain. This way allows the use of techniques that reduces the sidelobes level and the reflection effects, besides others improvements.

In the frequency domain, the beamforming equation is given by:

$$B(\omega) = \frac{1}{M}\sum_{m=1}^{M} P_m(\omega) e^{-i\omega\Delta_m} \tag{5}$$

where B(ω) and P_m are the b(t) and $p_m(t)$ Fourier transforms, respectively.

For more details of the improvement techniques of the frequency domain see Santos (2013).

2.3 Acoustic Maps Constructions

After processed signals from a grid of directions the information obtained can projected on a plan to create acoustic maps. In this case, each pixel of the map corresponds to a direction in space analyzed by the algorithm as illustrated in Figure **2**.

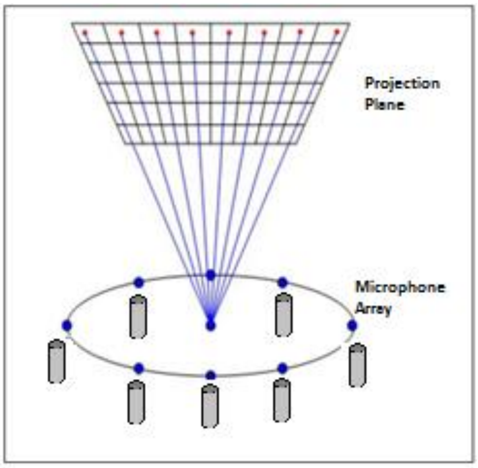


Figure 2 - Creation scheme of acoustic maps

3. PSYCHOACOUSTICS AND PSYCHOACOUSTICS MAPS

Sound waves with same intensity but with different frequencies are not interpreted the same way by the human auditory system, because they activate different auditory sensations. Psychoacoustics models were created to measure these sensations, like loudness, sharpness, roughness etc.

Loudness is the model that measure the psychological correlate of physical strength. In this paper, sone will be the unit used to measure loudness.

Sharpness is a weighted loudness, where higher pitches have higher weights. The unit used to measure sharpness is the acum.

Roughness is the model that describes the human perception of fast temporal variations of sounds. This parameter is measured in asper.

For more details on these parameters, see Fastl (1982).

The psychoacoustics maps can be created from the beamforming information. After applying the frequency domain algorithm, the time dependence can be rebuilt for each pixel in the original map. With these signal, the magnitude of the psychoacoustics parameters can be calculated for each pixel in the map, i. e., for each direction applied in the beamforming stage (Figure 3). To calculate in specific frequencies bands, the specific parameters at critical band rate can be integrated desired band.

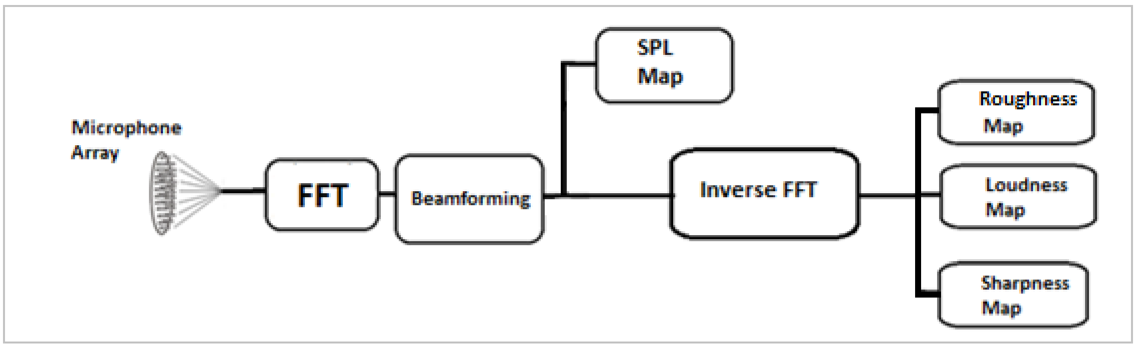


Figure 3 - Creation scheme of psychoacoustic maps

4. PSYCHOACOUSTICS MAPS INSIDE THE AUTOMOTIVE VEHICLE

The technique propose in the section 3 was tested in three different stages for build three psychoacoustics maps: loudness map, sharpness map and roughness map, besides the SPL map. A two-dimensional circular array, radius 120 mm, with twelve microphones (Figure 4) was used. The array properties can be seen in Tab. 1, for the calculation reference see Christensen *et al* (2004). Above the upper frequency limit, the spatial aliasing occurs.

Figure 4 - Two-dimensional circular array

Table 1 – Array properties

Resolution @ 1m, 1400Hz, θ=30°	Maximum Sidelobe Level	Frequency Range
1,7º	7,8 dB	1400 to 3500 Hz

For the measurements inside the vehicle, ¼" BSWA microphones, model MPA416, were chosen. For data acquisition, NI 9234 boards were used. Also from NI, the software LabVIEW were used for control the acquisition and for process the incoming data. The psychoacoustics parameters calculation were made by the closed *virtual instruments* from LabVIEW.

The measurements had the sample rate fixed in 25600 Hz, averaging 150 blocks, each having 2560 samples.

The array was positioned in the passenger seat backrest (Figure 5), and its inclination was modified for each case.

Figure 5 - Array positioned in the passenger seat

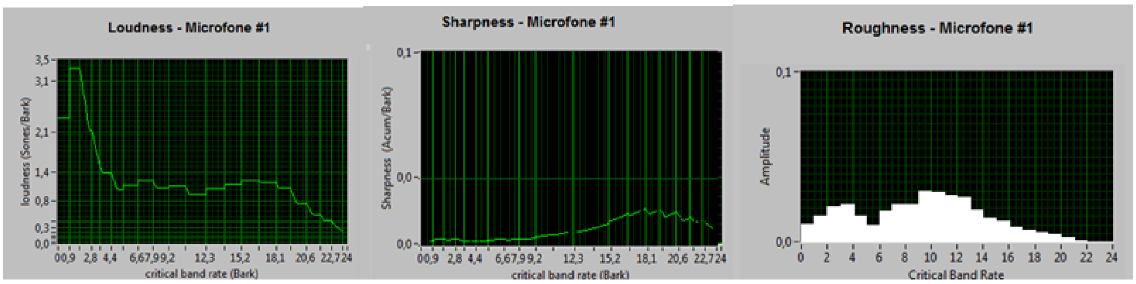
Three different cases were analyzed:

- Ventilation air outlet
- Ventilation air outlet while windshield wipers were running
- Moving vehicle on a bumpy road with the driver window open

For each case, it were plotted the specific loudness, sharpness and roughness for the first microphone, and it were created loudness and sharpness maps centered in some third-octave bands and roughness map in the octave band centered in the 2000 Hz.

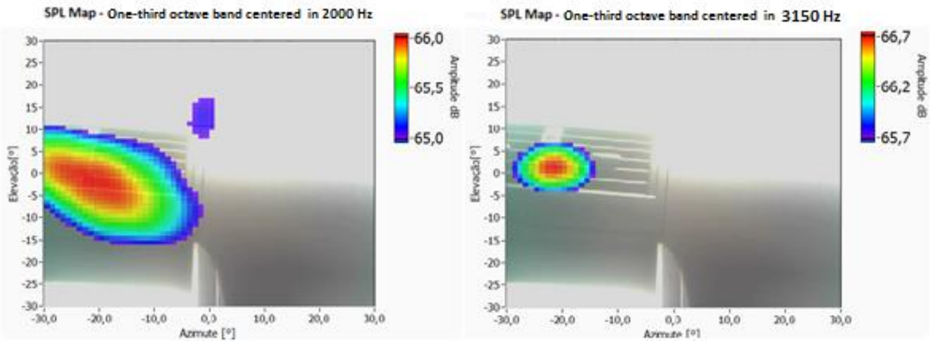
4.1 Ventilation Air Outlet

Figure 6 shows the specific psychoacoustics parameters measures by the microphone #1, it can be noticed that the acoustic energy is concentrated in the lower frequencies, nevertheless it was possible build all the acoustics maps. The SPL maps (Figure 7) shows that there is, as expect, a sound source coincident with the ventilation air outlet. In this case, the loudness maps (Figure 8), the sharpness maps (Figure 9) and the roughness map (Figure 10) are extremely consistent with the SPL map, which suggests that the sensations measure by this parameters match with acoustic power in this case.



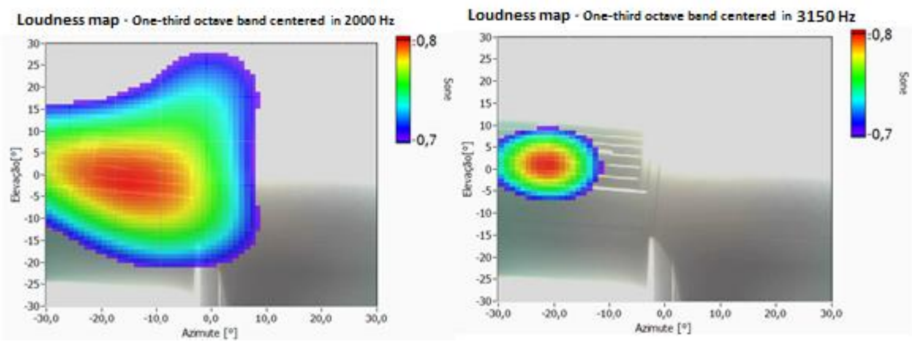
(a) (b) (c)

Figure 6 – (a) Specific loudness (b) specific sharpness (c) specific roughness



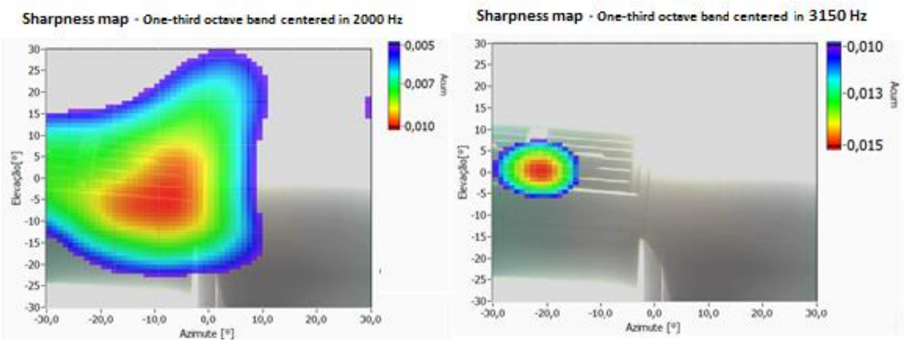
(a) (b)

Figure 7- SPL maps centered in one-third octave band (a) 2000 Hz (b) 3150 Hz



(a) (b)

Figure 8 - Loudness maps centered in one-third octave band (a) 2000 Hz (b) 3150 Hz



(a) (b)

Figure 9 - SPL maps centered in one-third octave band (a) 2000 Hz (b) 3150 Hz

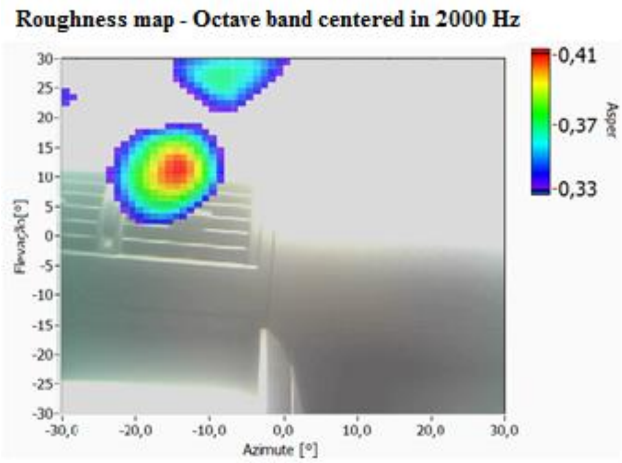
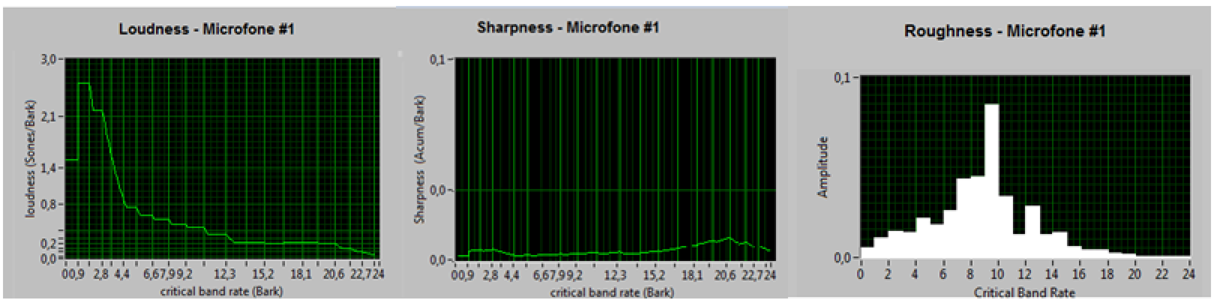


Figure 10 – Roughness map centered in octave band 2000 Hz

4.2 Ventilation air outlet while windshield wipers were running

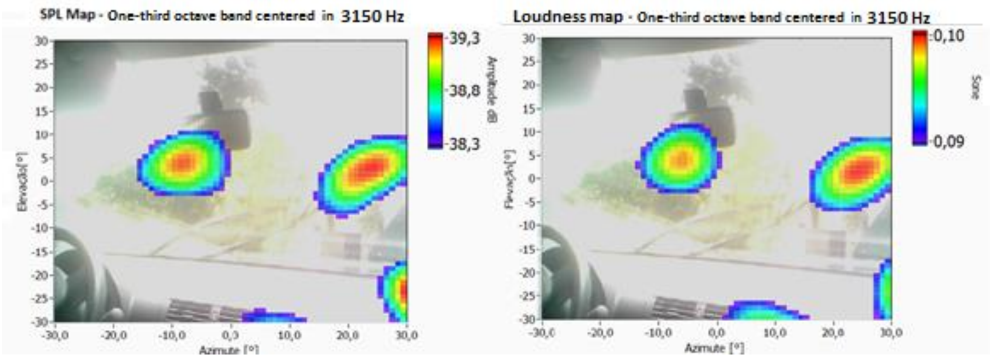
Again, in this case, the acoustic energy is concentrated in the lower frequencies, as shown in

Figure 11. The SPL map (Figure 12a) and the loudness map (Figure 12b) are consistent and suggesting the sound source locating the ventilation air outlet and the windshield wipers. While the sharpness map (Figure 13a) shows only the ventilation air outlet, which suggest that the psychoacoustics sensation measure by the sharpness is not consistent with the acoustic power in this case. The same can be concluded for the roughness map (Figure 13b).



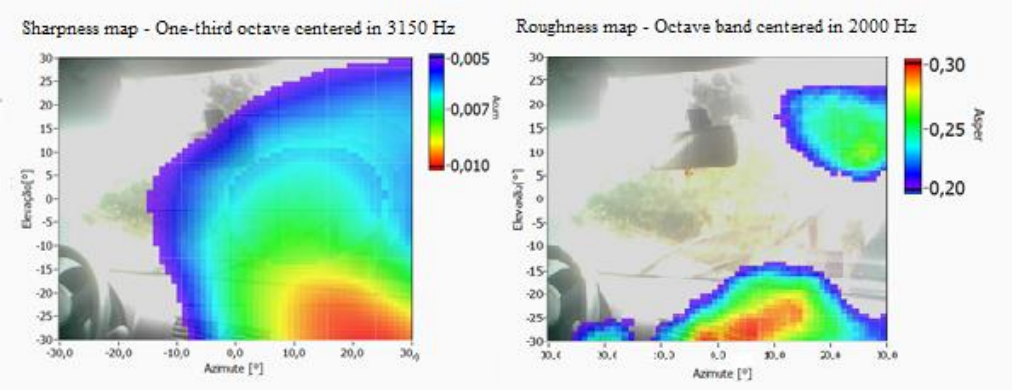
(a) (b) (c)

Figure 11 - (a) Specific loudness (b) specific sharpness (c) specific roughness



(a) (b)

Figure 12 – (a) SPL map centered in 3150 Hz (b) Loudness map centered in 3150 Hz

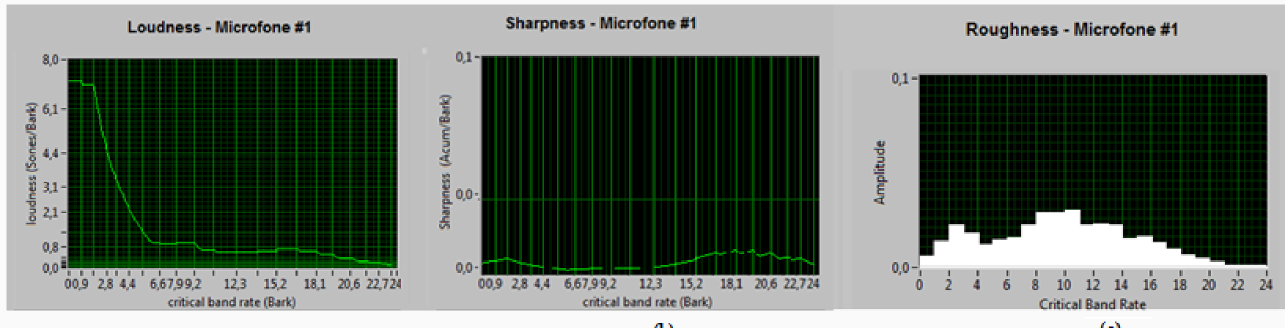


(a) (b)

Figure 13 - (a) Sharpness map centered in 3150 Hz (b) Roughness map centered in 2000 Hz

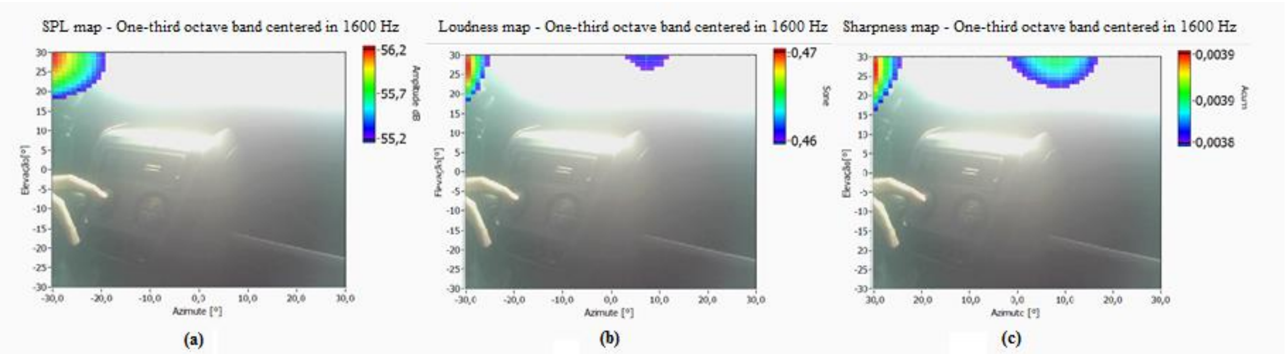
4.3 Moving vehicle on a bumpy road with the driver window open

In this last case, the acoustic energy distribution is no different than the previously cases, as can be seen in Figure 14. The SPL, loudness and sharpness map (Figure 15) are consistent to each other, and suggesting the open window and windshield as sound source, but the roughness map (Figure 16) suggest the vehicle floor as the roughness source.



(a) (b) (c)

Figure 14 - (a) Specific loudness (b) specific sharpness (c) specific roughness



(a) (b) (c)

Figure 15 - (a) SPL map centered in 1600 Hz (b) Loudness map centered in 1600 Hz (c) Sharpness map centered in 1600 Hz

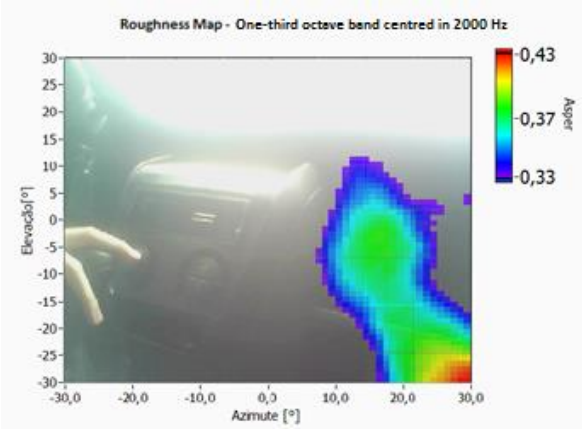


Figure 16 - Roughness map centered in octave band 2000 Hz

5. CONCLUSIONS

This paper shows that it is possible to create sound sources location maps from the beamforming information using psychoacoustics. The results shows that this technique is valid even for small energies in the measured frequency band, although the frequency range is limited by the array geometry. With the proper array, the results can be interpreted as nuisance maps that show the sources that cause greater discomfort, and its use may contribute for designing projects not only quieter but also less irritating.

6. REFERENCES

Christensen J.J., Hald, J. *Technical Review: Beamforming No. 1*, Brüel&Kjær Sound&Vibration Measurement A/S, Nærum, Denmark (2004)

Fastl, H, Zwicker, E.; *Psychoacoustics, Facts and Models*; Springer Verlag; New York (1982)

Johnson, D. H., Dudgeon D. E., *Array Signal Processing*, Prentice Hall, Englewood Cliffs, NJ, USA (1993).

Santos, L., *Comparação de Métodos de Otimização da Identificação de Fontes Sonoras Por Beamforming*, Master of Science Thesis, Mechanical Engineering Program, Universidade Federal do Rio de Janeiro - COPPE, Rio de Janeiro, Brazil (2013)

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