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Experimental analysis of spatial properties of the sound field inside a car employing a spherical microphone array

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Introduction

- The experimental evaluation of the sound field inside a car is usually performed employing microphone systems having very limited capability of detecting the direction-of-arrival of wavefronts

- binaural microphones, but this revealed to be useful only for subsequent binaural listening tests

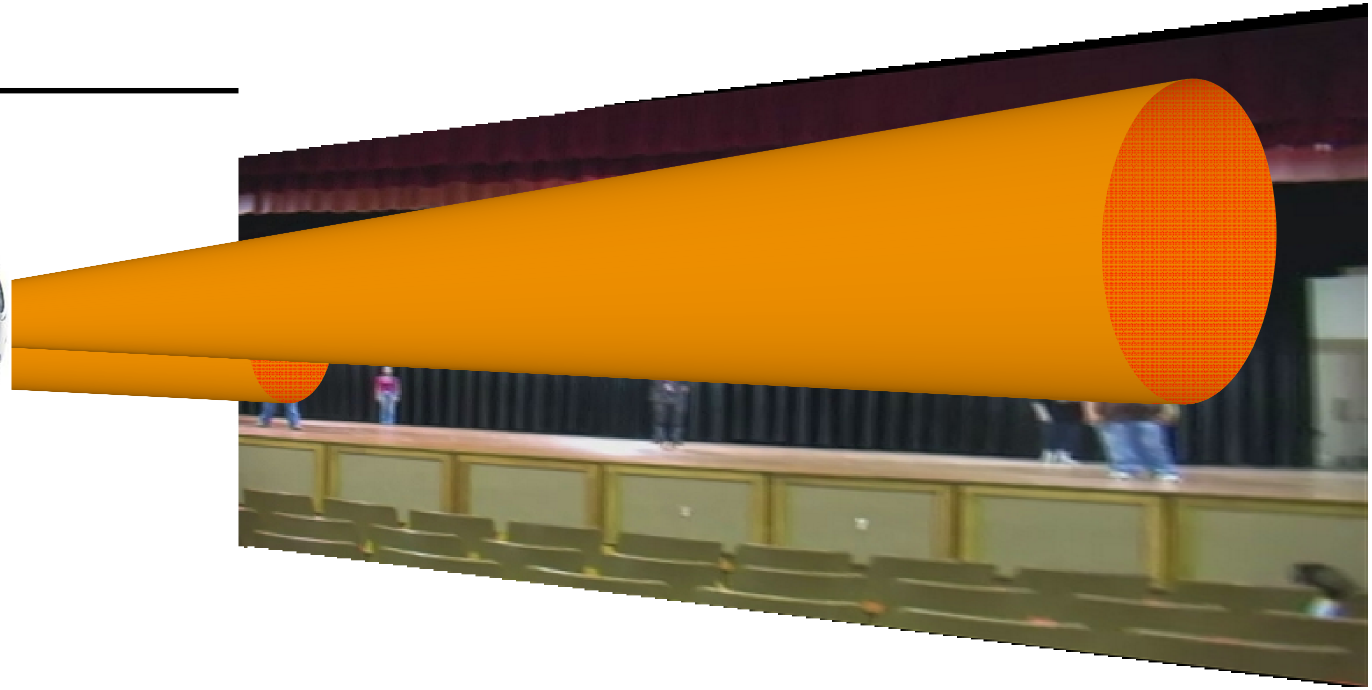
- low-order microphone arrays have been employed inside cars (i.e., Soundfield microphones), but their spatial resolution revealed to be insufficient

Introduction

- Recently, high-order spherical microphone arrays have been developed

- It revealed a successful both for music and speech recording, and for analyzing the spatial properties of the sound field inside concert halls and theatres (or outdoors).
- "virtual microphone" methodology allows listening to the sound arriving from a very narrow cone around a selected direction

Vitrual microphones



We synthesized highly directive virtual microphones starting from 32 omnidirectional ones

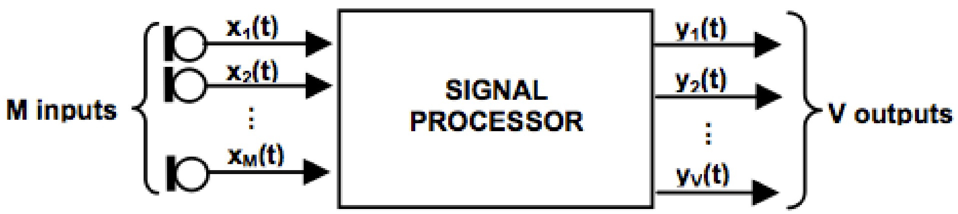
The microphone array

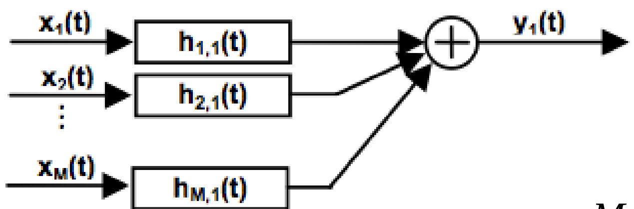
Eigenmike® by mhAcoustics

- 32 high quality capsules
- Pre-amplifiers and A/D converters packed inside the sphere
- All the signals are delivered to the audio interface through a digital CAT-6 cable
- The audio interface is an EMIB Firewire interface based on TCAT DICE chip:
  - supported by any OS
  - 8 digital output(ADAT) + 2 analogue output
  - Wordclock
- The pre-amplifier gain control is operated by MIDI control

The signal processing

The idea → Synthesis of 32 directive virtual microphones in the direction of the capsules employing a set of digital filters





M = 32 signals coming from the capsules

V = 32 signals yielding the desired virtual microphones

Bank of M x V FIR filters

$$y_v(t) = \sum_{m=1}^{M} x_m(t) * h_{m.v}(t)$$

Output signal of V mic.

Input signal from the m-capsule

Matrix of filters

Traditional design of the filters

The processing filters h_{mv} are usually computed following one of several, complex mathematical theories, based on the solution of the wave equation (often under certain simplifications), and assuming that the microphones are ideal and identical

In some implementations, the signal of each microphone is processed through a digital filter for compensating its deviation, at the expense of heavier computational load

Novel approach

No theory is assumed: the set of h_{mv} filters are derived directly from a set of impulse response measurements, designed according to a least-squares principle.

outputs of the microphone array are maximally close to the prescribed ideal responses

This method also inherently corrects for transducer deviations and acoustical artefacts (shielding, diffractions, reflections, etc.)

Virtualizing software

<u>Matlab script</u>

•Inputs:

- ✓ 2048 samples of each IR
- ✓ The number of virtual microphones
- ✓ Directivity of each virtual microphone
- ✓ Azimuth and elevation of each virtual microphone

IRs Matrix inversion

Output: FIR filters matrix

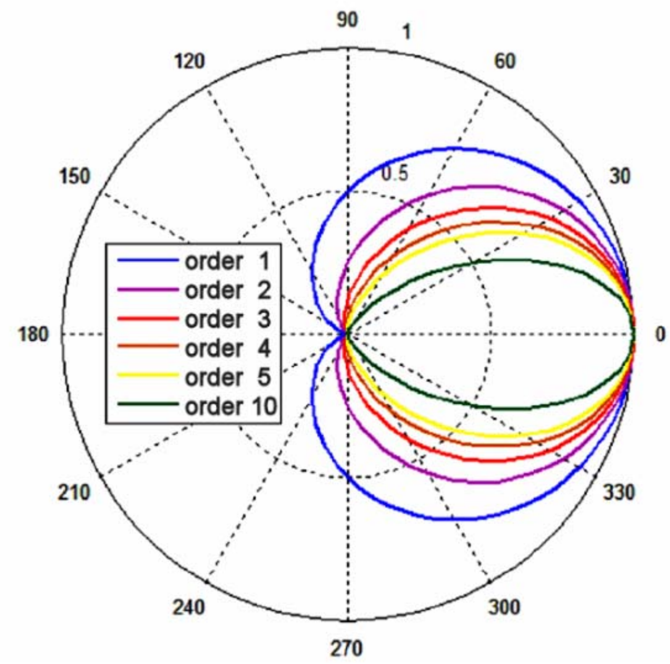
FIRs matrix ⊗ **Capsules' signals** = **Virtual mics**

Virtual microphones synthesized for this research:

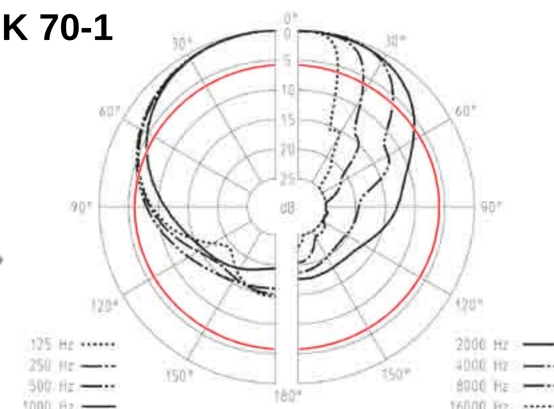
32 4^{th} order and 64 7^{th} order CARDIOIDS

Virtual mikes polar pattern

- Polar pattern of obtained virtual microphones are similar to the ones of a directive real microphone
- In this experiment we used 4° to 7° order cadioids to avoide rear/lateral lobes
- Due to technical problems during real microphones characterization these measures are valid in the bands from 125 Hz to 8 kHz

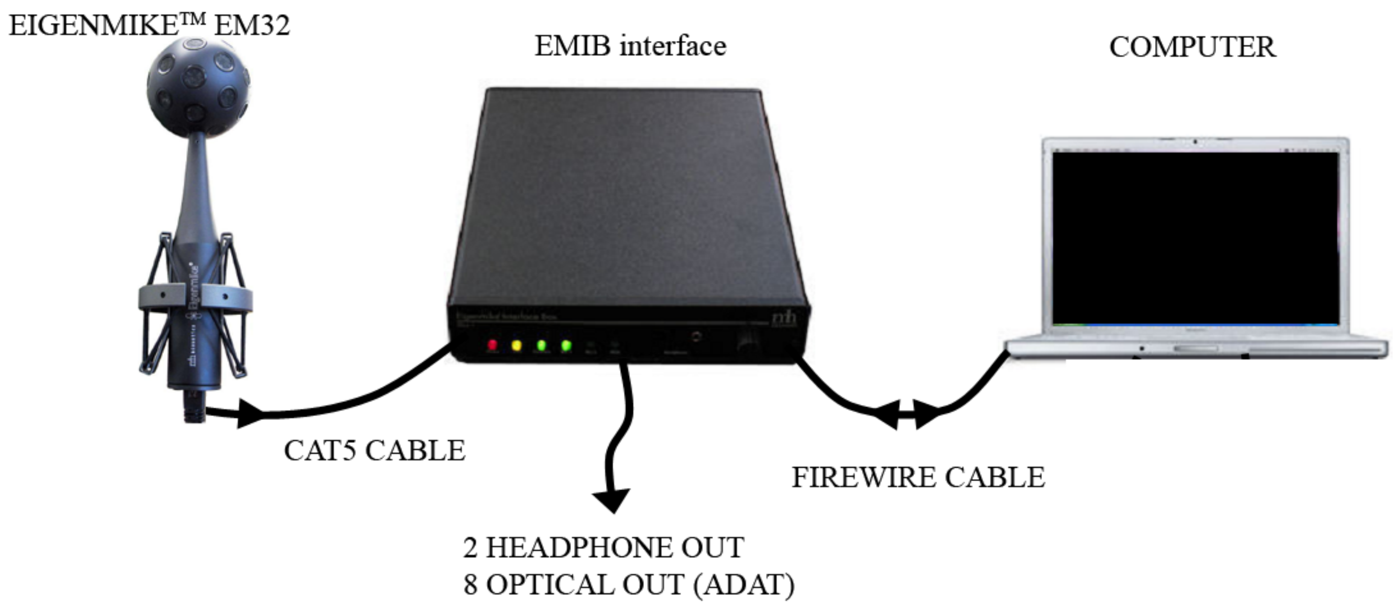


Sennheiser MK 70-1



Measurement system

- Eigenmike array, EMIB soundcard, PC



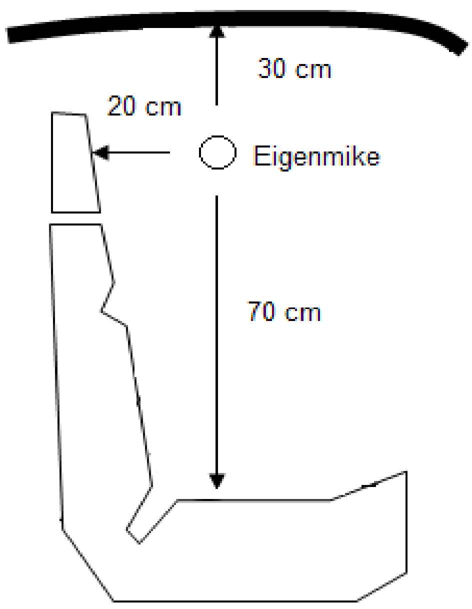
The car subject to measure

- The car involved in the experiment was a FIAT Scudo, a space wagon

- Lot of space to place instrumentation

Microphone placement

- The microphone array was placed in the front seat as shown below



Type of measure

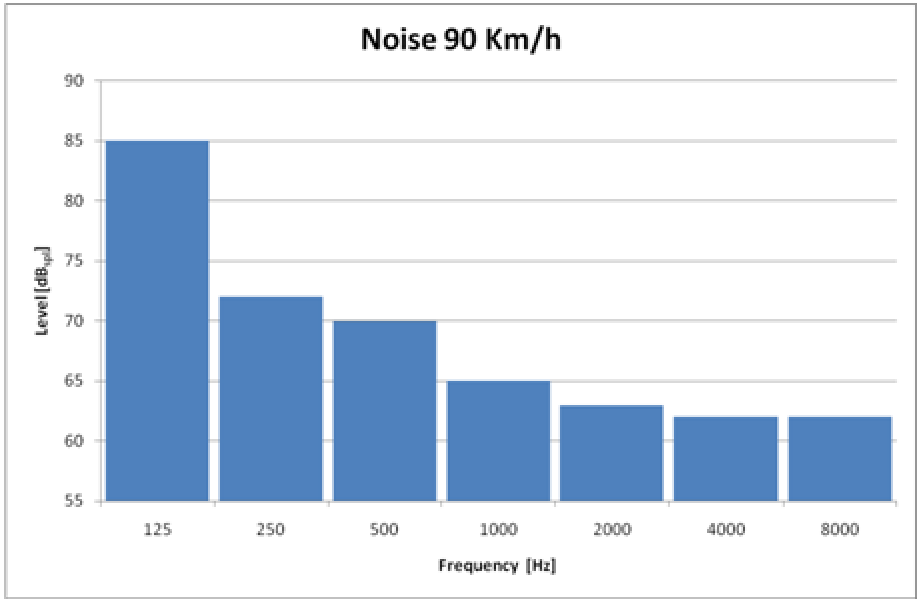
- The first type of measure was background noise measurements
- We recorded the noise at different speed and gear on 3 types of roads

	Speed	Gear	Road type
Test 1	50 Km/h	2	State highway
Test 2	50 Km/h	3	State highway
Test 3	90 Km/h	3	Ring road
Test 4	90 Km/h	4	Ring road
Test 5	110 Km/h	5	Highway

- We compute 32 virtual 4° order cardioids to cover the sphere surface

Background noise spectrum

- Octave band spectrum of background noise



- Similar spectrum for other speeds and gears

Panoramic image

- Panoramic image of the car cockpit

- 360° x 180° image mapping the whole solid angle
- Obtained joining some smaller photos

Interpolating values on the borders

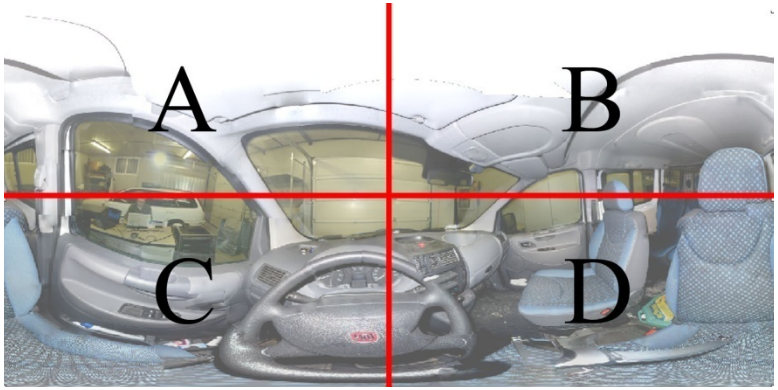
- Problem interpolating values

  on the borders: no virtual microphone on the borders

- Find the solution thinking the image is some way like an unwarpped world map

Interpolating values on the borders

- Solution: round the original image with mirrored versions thinking that it represent a sphere

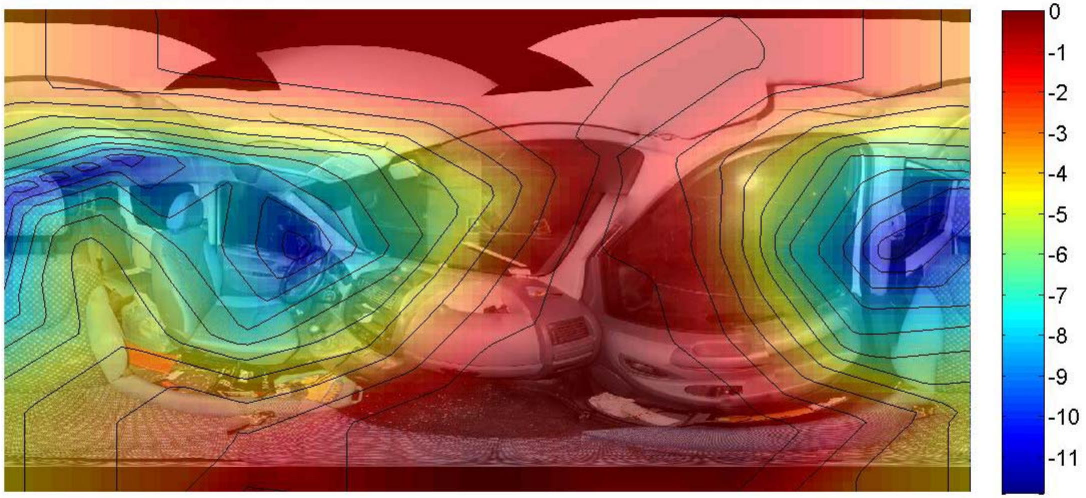


- Interpolation arrangement

D	C	D	C	D	C
B	A	B	A	B	A
A	B	**A**	**B**	A	B
C	D	**C**	**D**	C	D
D	C	D	C	D	C
B	A	B	A	B	A

Noise SPL maps

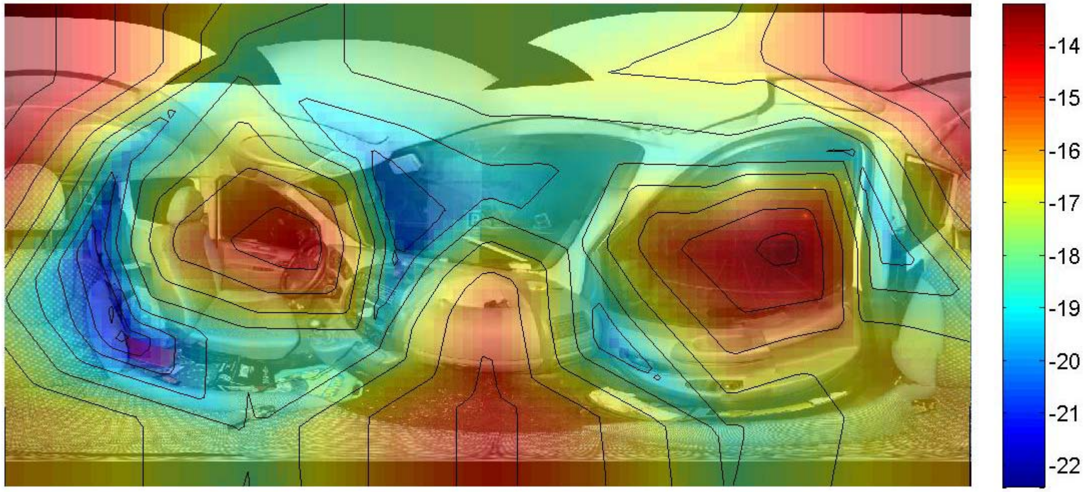
- false-color maps of the average SPL of the background noise recorded inside the car cabin
- cabin noise @ 90 km/h, gear 3, 125 Hz



- Noise source: car frame

Noise SPL maps

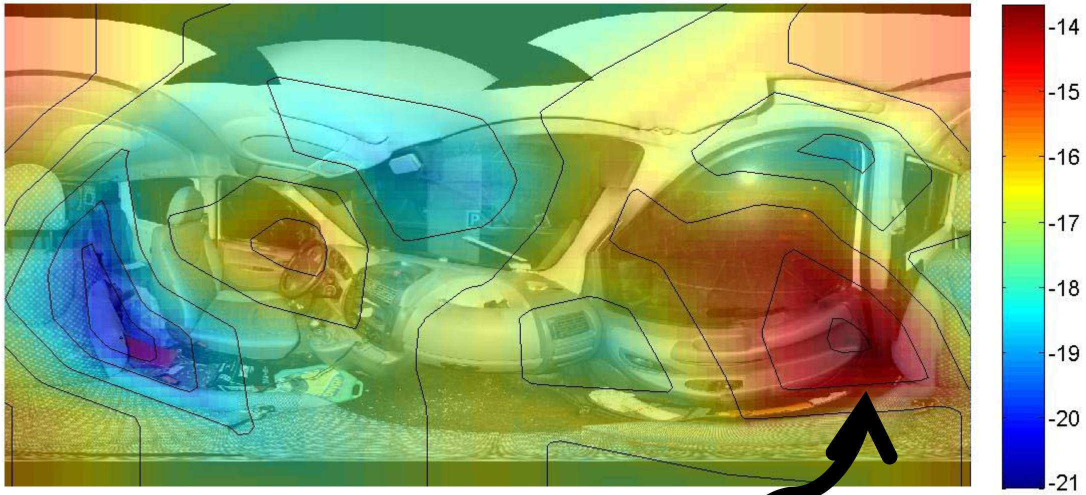
- noise @ 90 km/h, gear 4, 500 Hz



- Sources: floor and side windows

Noise SPL maps

- cabin noise @ 110 km/h, gear 5, 500 Hz



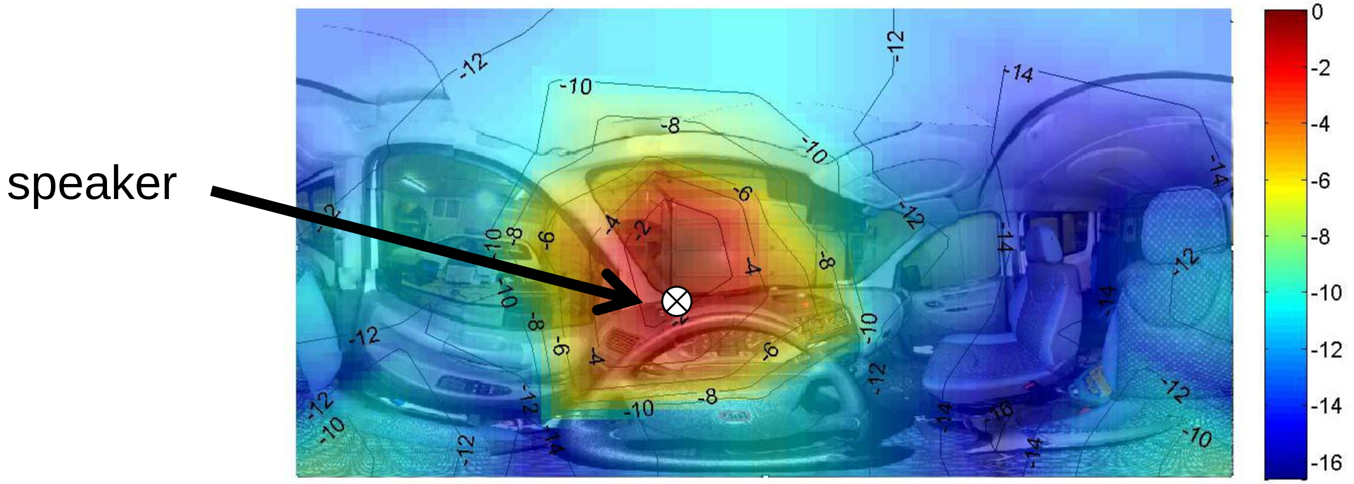
- Sources: leakage from the door

Measuring the speker system

- Sound system made of 6 speakers:
  - 2 front woofers (inside the car doors)
  - 2 front tweeters (near the windshield)
  - 2 rear woofers (inside the car walls)
- Speaker feeded with an Exponential Sine Sweep to obtain 32 recorded signals
- The 32 recorded sweeps we obtained 32 IR by deconvolution
- The 32 IR were virtualized into 64 vitual IR using a 7° order cadioids

Speaker sound maps

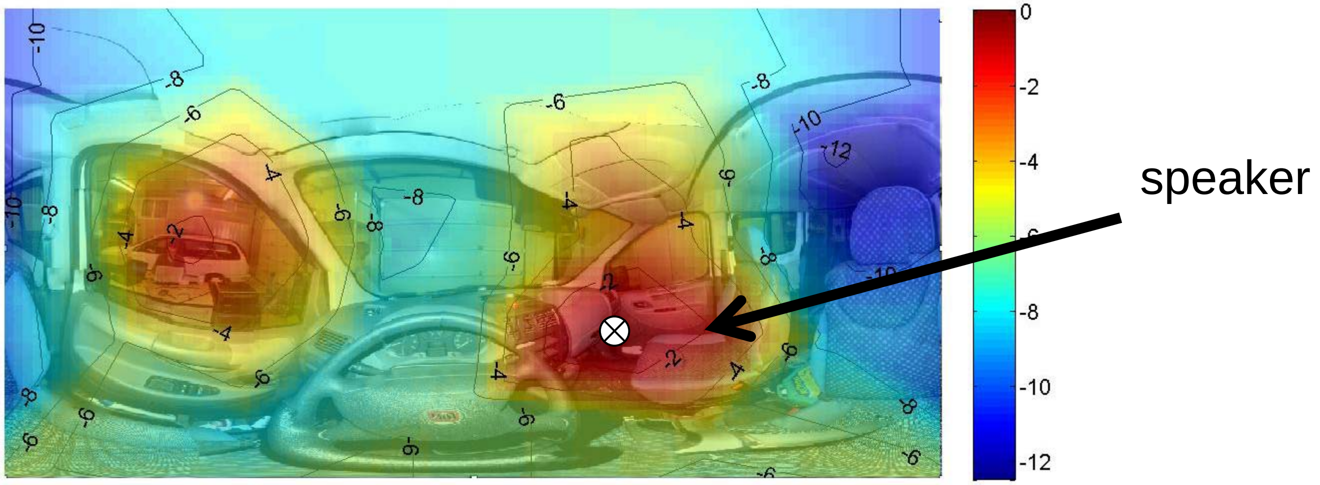
- Front Left Tweeter @ 2000 Hz



- Primary reflection on the windshield, the virtual source is shifted up

Speaker sound maps

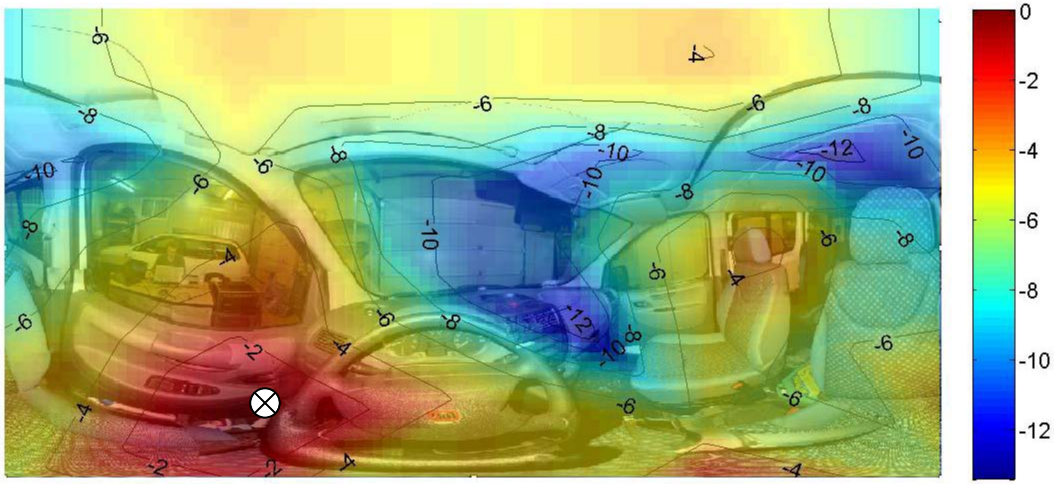
- Front Right Woofer @ 4000 Hz



- Reflection on the left side window and ceiling

Speaker sound maps

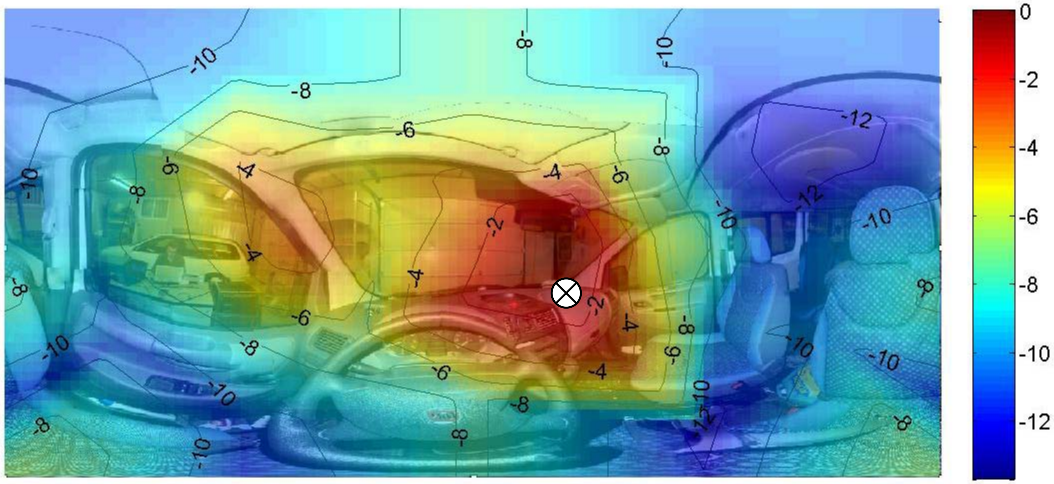
- Front Left Woofer @ 125 Hz



- Weak reflections from the ceiling and opposite wall

Speaker sound maps

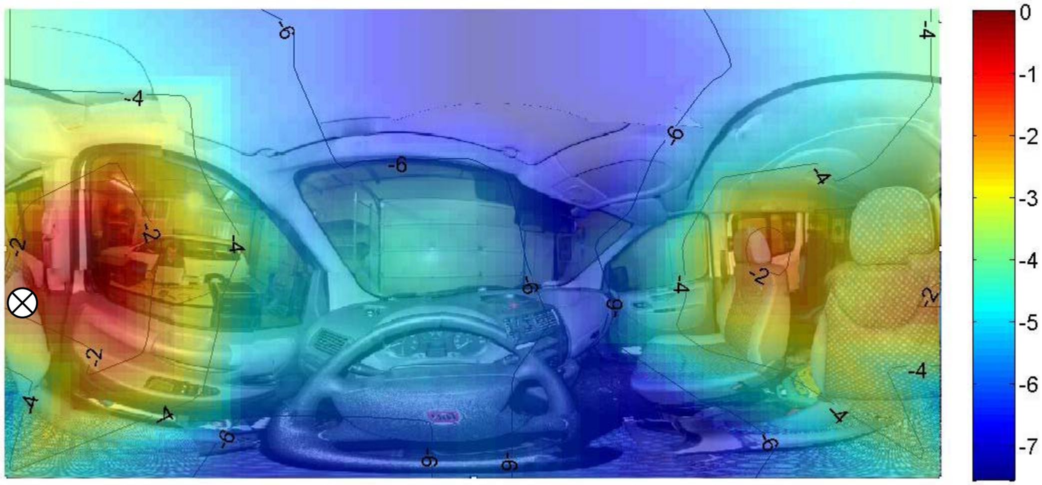
- Front Right Tweeter @ 2000 Hz



- Reflections coming from the opposite side (side window and frame)

Speaker sound maps

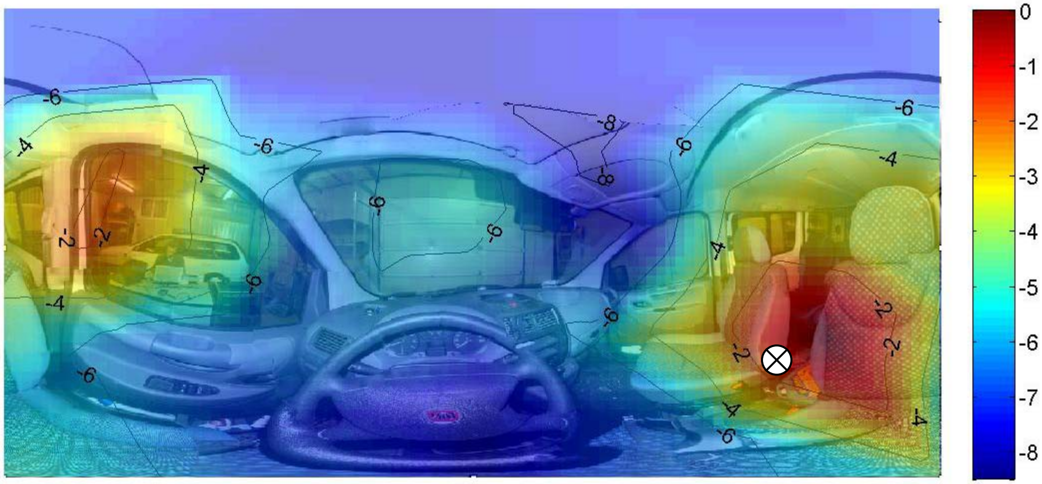
- Rear Left Woofer @4000 Hz



- Direct wave propagates through seat and the wall
- Reflection from the right wall

Speaker sound maps

- Rear Right Woofer @2000 Hz



- Direct wave propagates beetween the seat
- Reflection on the left side

Analyzing wave propagation

- A graphic tool was developed in matlab to a sliding window analysis over time
- Collecting the image it is possible to build a video and so distinguish the reflected wave during an impulse response measurement
- We choose an FFT window size of 256 samples, overlapped of half window

The post processing software

MATLAB script

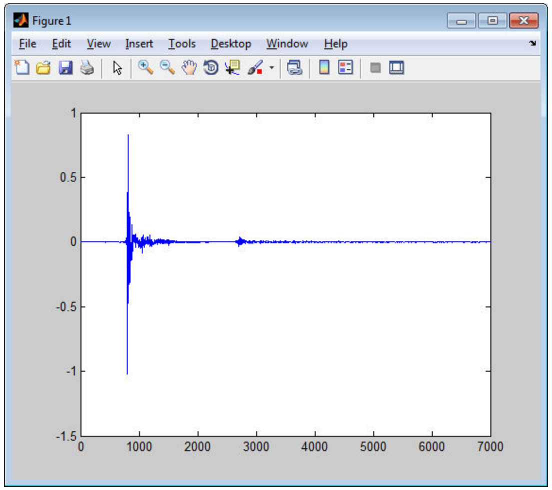
Polar plot of the sound levels in the horizontal plane

Mesh map of the levels on a 360° x180° picture of the room

Dynamic plots

<u>1st step</u>

Import of WAV files containing the IRs obtained from the 32 virtual microphones

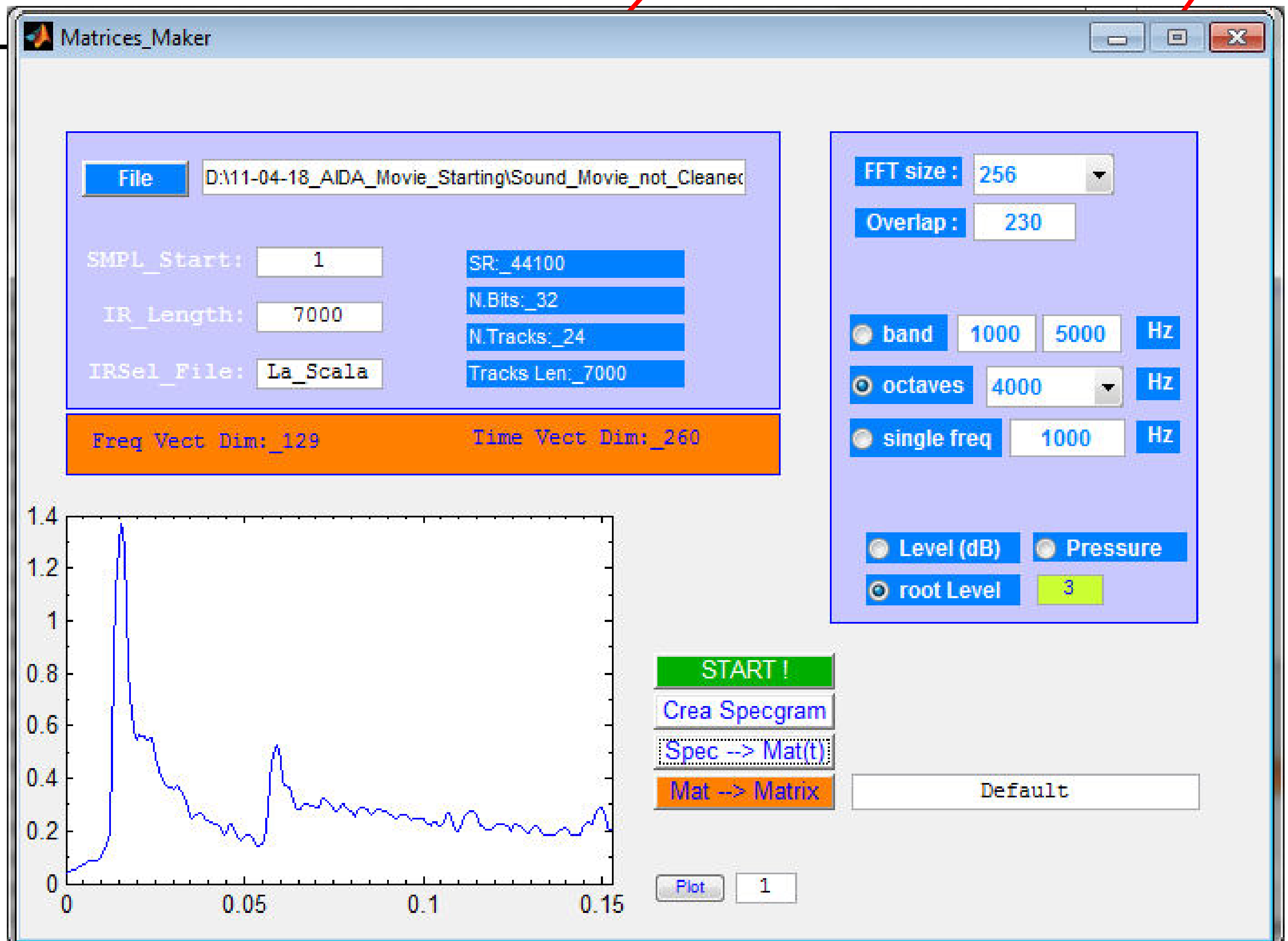


2nd step

FFT processing

Impulse Response length

Frequency bands of analysis



Pressure

Level (dB)

Root 2

Root 3

The results

The probe is not calibrated with an absolute level: every point of measure has its own level normalization and colour scale.

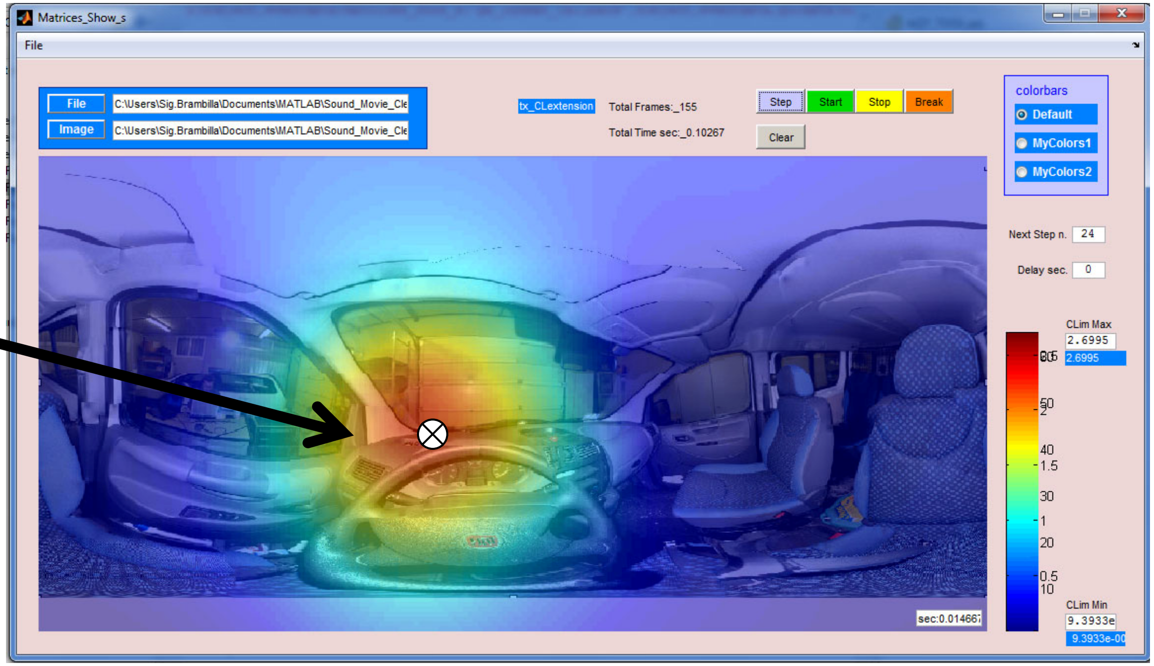
NEVERLESS

Growing the distance between source and receiver the lobe of the reflections becomes more relevant in comparison with the direct sound.

Speaker sound propagation map

- SPL video frame of front left tweeter @4000 Hz, t = 14.6 ms

speaker

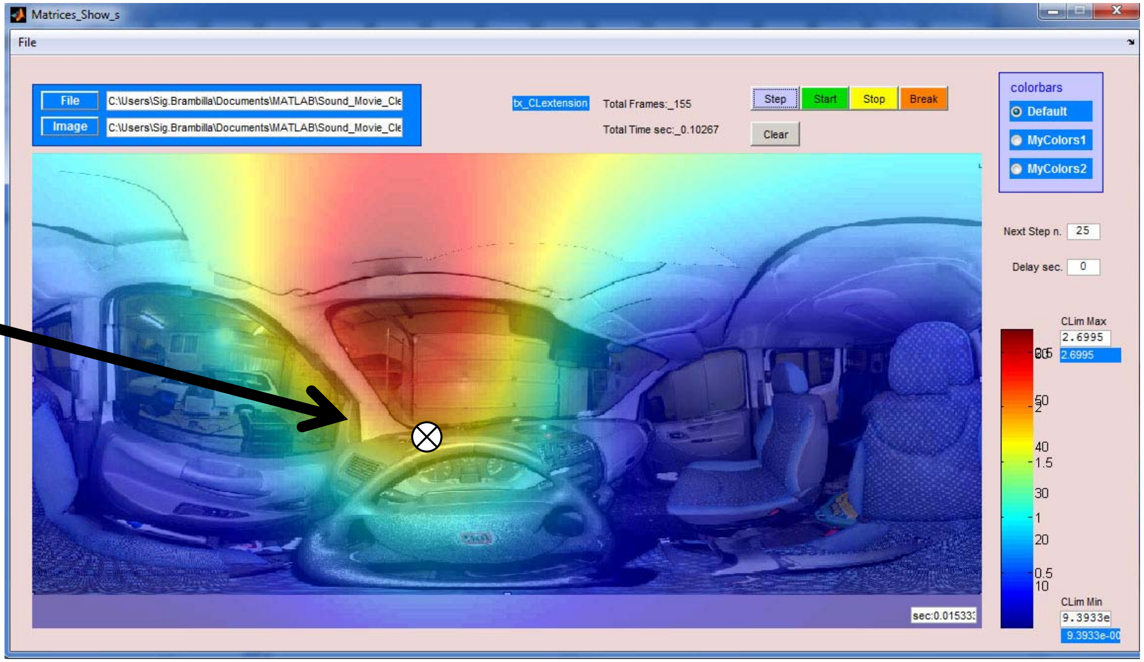


- Direct sound from the speaker

Speaker sound propagation map

- SPL video frame of front left tweeter @4000 Hz, t = 15.3 ms

speaker

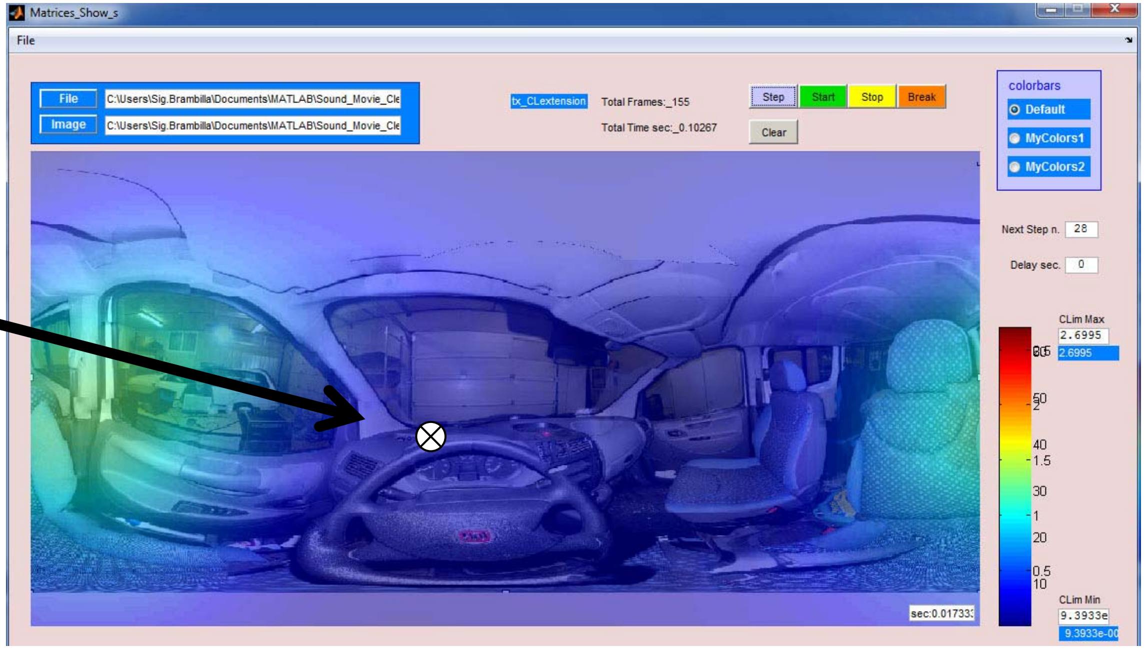


- Early reflection from the windshield/ceiling

Speaker sound propagation map

- SPL video frame of front left tweeter @4000 Hz, t = 17.3 ms

speaker



- Reflection from the car frame/side window

Conclusions

- The use of Eigenmike coupled with virtual microphones methodology allowed to inspect the sound field inside a car’s cabin with higher spatial resolution compared with low-order microphone arrays.
- The false-color maps obtained during noise measurements provided consistent results with these hypotheses:
  - low frequencies components of noise are mainly due to chassis vibrations;
  - at high frequencies the doors/windows leakage become noticeable

Conclusion

- Analysis of the IRs provided useful information about the way the wave field moves inside the car.
- False-color maps always revealed the source of the stimulus and its primary reflections
- The video created by the time-depended analysis provided an intuitive way to inspect the paths of the wave field too

Developments

- Combined use with loudspeaker array to perform listening test about sound spatialization
- Overcome the limitations currently posed by the binaural technology which was employed till now for subjective assessment of both the "background noise quality" and the "sound system quality".