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Published Version:
Guidorzi P., Pompoli F., Bonfiglio P., Garai M. (2020). A newly developed low-cost 3D acoustic positioning system: Description and application in a reverberation room. APPLIED ACOUSTICS, 160, 1-6 [10.1016/j.apacoust.2019.107127].

Availability:
This version is available at: https://hdl.handle.net/11585/706409 since: 2024-09-05

Published:
DOI: http://doi.org/10.1016/j.apacoust.2019.107127

A newly developed low-cost 3D acoustic positioning system: description and application in a reverberant room

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Summary

A newly developed low-cost 3D acoustic positioning system is used to measure the sound field inside a reverberation room. The measurement system requires a personal computer, a standard multi-channel sound card and very few external components such as 4 small amplified loudspeakers (used only for the 3D positioning system) placed at known fixed positions and a microphone, used as probe for both the positioning and the sound field measurements. A dodecahedron is used to excite the reverberant room with an MLS signal. The measurement is performed moving the microphone inside the reverberation room and measuring, point by point, the local impulse response, in order to analyze the room modes and possibly compute a spatially localized reverberation time. The results of the measurements are compared with a FEM model of the sound field inside the reverberation room.

PACS no. 43.55.Mc, 43.58.-e

1. Introduction

In many cases it may be useful to associate an acoustic measurement with the position in the three-dimensional space of the microphone. Examples of applications are room acoustics measurements [1,2], measurements on road noise barriers according to the EN 1793-5 [3,4], where it is useful to know quickly the position of the microphones, or noise measurements around an industrial machine. The system proposed in the present work allows to obtain the position in the three-dimensional space of a microphone, relative to a small loudspeaker grid, used as origin of the geometric reference system and to associate one or more data to each measurement position [5]. This measurement system differs from existing systems based on other physical principles (laser, GPS, infrared, etc. ...) in being at the same time sufficiently precise for research or work purposes but also very economical since the hardware components cost a few tens of euros (excluding computer, sound card and microphone, which every researcher or acoustic technician already owns).

2. Principle of measurement

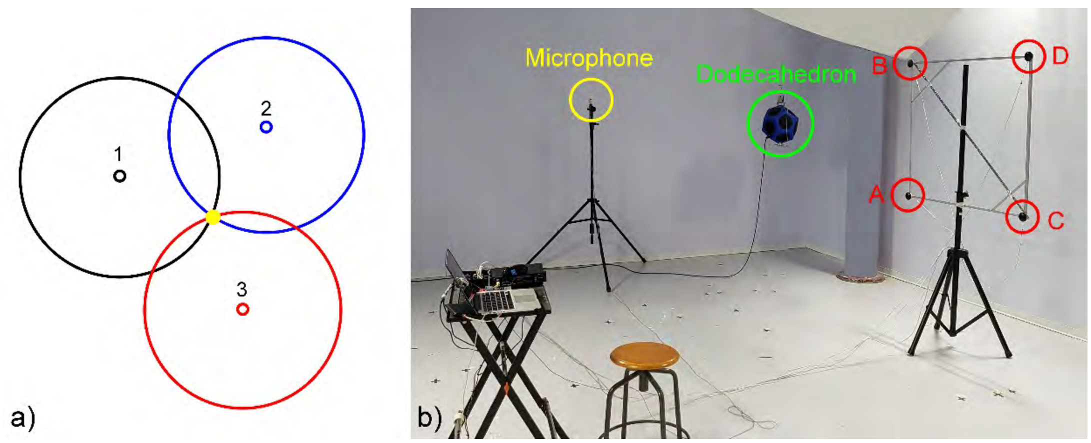

Figure 1. a) Trilateration on a two-dimensional plane. b) Measurement setup: microphone (in the yellow circle); auxiliary sound source (green circle); 4 loudspeakers grid (red circles).

The determination of the position in the three-dimensional space of a target, in principle, is reduced to the measurement of its distance from some other known points, and it is similar in principle, but simpler, to the determination of the position with the GPS system [6,7,8]. In a 2D plane, to find the position of an unknown position point it is required to know the distance from 3 known points, as shown in Figure 1 a); in 3D space it is necessary to know the distance from 4 points to have a unique solution. The presented system measures, using acoustic waves, the distances between a single microphone and 4 loudspeakers, positioned on a grid of known dimensions and position, which fixes the origin of the reference system, as shown in Figure 1 b).

Assuming that:

- the target (microphone) is positioned at an unknown position at coordinates (x, y, z)
- the 4 loudspeakers are positioned respectively at known positions, at coordinates (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3) and (x_4, y_4, z_4)
- the known distances, hypothetically measured without error using acoustic waves, between the loudspeakers and the microphone (radius of the respective spheres) are respectively r_1, r_2, r_3 and r_4

the equations that describe the system are:

$$
\begin{aligned}
(x-x_1)^2+(y-y_1)^2+(z-z_1)^2&=r_1^2\\
(x-x_2)^2+(y-y_2)^2+(z-z_2)^2&=r_2^2\\
(x-x_3)^2+(y-y_3)^2+(z-z_3)^2&=r_3^2\\
(x-x_4)^2+(y-y_4)^2+(z-z_4)^2&=r_4^2
\end{aligned} \qquad \text{(Eq. 1)}
$$

The system of equations (Eq. 1) is solved by taking 3 spheres (and 3 equations) at a time, to simplify the problem computationally, obtaining 2 possible solutions of which only one is right. The procedure is applied for all 4 possible combinations of 4 spheres taken 3 at a time, following the method described in [9,10]. Examining the 4 pairs of solutions found, the solution that appears in all 4 pairs is the real position of the target.

Each loudspeaker emits a different MLS signal, orthogonal to the others 3, so the 4 signals can be identified even if played simultaneously. The microphone captures the sum of the 4 MLS signals and the software reconstructs the 4 corresponding impulse responses by means of cross-correlation between the 4 respective MLS signals and the signal received from the microphone, performed efficiently and quickly thanks to the Fast Hadamard Transform (FHT) [11,12,13]. From the first peak of each of the impulse responses, the arrival times of the sound from the 4 loudspeakers to the microphone are determined. See for example Figure 2 a), where the 4 peaks are marked A, B, C and D. From the 4 arrival times, computed the 4 distances between the microphone and the 4 loudspeakers (considering the air temperature dependency of the sound speed), the distances loudspeakers-microphone r_1, r_2, r_3 and r_4 are determined and consequently the position in the space of the microphone is found by three-dimensional trilateration calculations. A fifth MLS signal can be played from another source such as a dodecahedron, superimposed to the 4 MLS signals used for the 3D localization, with different purposes: for example, to excite a closed space and perform the measurement of the room impulse response at different points [14,15]. The 5 MLS signals do not interfere with each other, apart from a slight residual noise, visible in Figure 2 a), before the first peaks (marked with blue arrows), negligible in most cases. In Figure 2 a) is also shown the fifth impulse response measured from the MLS played by a dodecahedron, marked “EXT”.

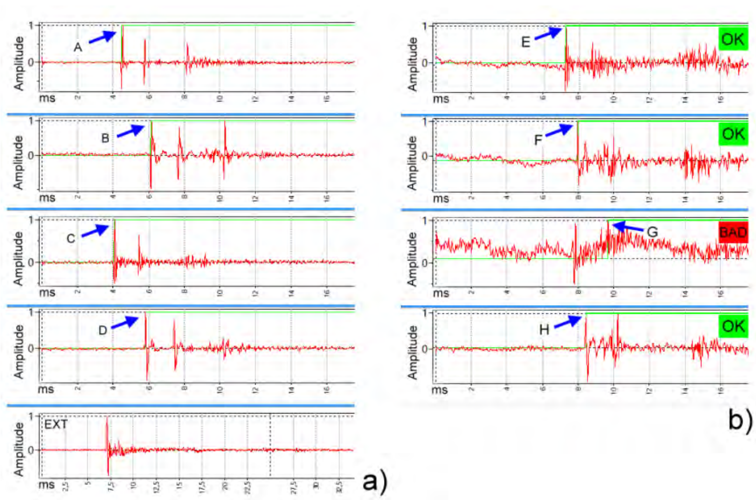

Figure 2. a) Impulse responses from the 4 loudspeakers for localization (A, B, C and D) and additional impulse response of the room (EXT). b) Example of bad measurement of the impulse responses from the 4 loudspeakers for localization purposes.

If a higher Signal to Noise Ratio for the “EXT” impulse response measurement is required, it is possible to divide the measurement of each point into two successive steps, at the expense of an increase in measurement time. In the first step, the positioning measurement is done; in a second step, the room impulse response measurement in that position is done, using also different signals types, such as the Exponential Swept Sine. In the case of movement of the microphone by mistake during measurement or the presence of excessive background noise, the reconstructed impulse responses will not be sufficiently clean for the correct detection of distances, as shown in Figure 2 b). The measurement software will automatically discard them based on signal to noise ratio calculations. During test measurements near very noisy industrial machines, it was observed that with the loudspeakers used in this work, the positioning system gives correct results in presence of background noise up to about 110 dB SPL.

3. The measurement system

The measurement system consists of a hardware part and a software part and allows real-time measurements in 3D space. The hardware, visible in Figure 1 b) and in Figure 3, includes a personal computer, a standard multi-channel soundcard, the grid and support on which the 4 loudspeakers are mounted, 4 power amplifiers, a single microphone (used for both position detection and acoustic measurement) and the necessary cables. Two stereo power amplifiers are used to drive the 4 small no-brand loudspeakers (tweeter) on the grid. The software deals with the generation of MLS signals, the measurement of impulse responses, trilateration calculations and the management of measured points.

Figure 3. Measurement system. PC and amplifiers.

3.1 Measurement accuracy

The factors that most affect the accuracy of the position detected, excluding measurement errors, are:
- size and geometry of the loudspeaker grid;
- frequency response of loudspeakers and microphone;
- sample rate of the measurement system;
- distance of the microphone from the grid;
- air temperature;

The measurement of the distance of the microphone from a single loudspeaker is calculated multiplying the time delay of the first peak of the impulse response (flight time of the sound wave) with the speed of sound, considered as a function of the air temperature. Not considering advanced processing such as oversampling, the discrete interval between two samples on the time axis provides the resolution in terms of measured distance. Using a sample rate of 44.1 kHz the time between 2 samples is 0.01041667 ms, so that the distance resolution is around 7.8 mm, considering 343 m/s as sound speed; using a 96 kHz sample rate, the distance resolution is around 3.6 mm. The mentioned theoretical spatial resolutions are relative to a single distance measurement; in this application the 4 distances between the microphone and the 4 loudspeakers on the grid are processed by the trilateration algorithm in order to determine the 3D position in the space, so the actual resolution and accuracy of the measurement are not easy to calculate. Statistical measurements were performed using a square 1 m x 1 m grid on which the 4 loudspeakers were mounted (Figure 1 b)) and with different combinations of soundcard sample rates and distances of the microphone from the center of the grid. It has been found that the useful area covered by the 3D positioning system with a grid of this size extends for at least 10 meters in every spatial direction. It is expected that by increasing the grid size the covered area can be increased. The results of a series of measurements carried out by placing the microphone at the two ends of a rigid meter, using a sampling frequency of 96 kHz are shown as an example in Figure 4 a) and b).

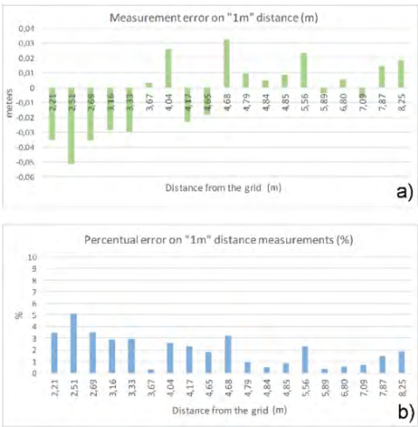

Figure 4. a) Measurement error on 1 m distance (96 kHz sample rate). b) Percentual error on measurements (96 kHz sample rate)

Observing in Figure 4 a) the measurement error relative to the nominal value of 1 m, as a function of the microphone-grid distance, it can be seen that the error increases approaching the speaker grid, probably due to a deformation of the shape of the impulse response. From a distance of about 3 or 4 meters, the absolute error is generally less than 3 cm. Figure 4 b) shows the corresponding percentage errors with respect to the average value measured (1.004 m). The mean error over all distances, at the sample rate of 96 kHz, is less than 2%, with a standard deviation of about 2.34 cm. Repeating similar measurements, with the same boundary conditions, at the sample rate of 44.1 kHz, a percentage error of about 3.5% is obtained. These results suggest that by increasing the sampling frequency (for example at 192 kHz) or by oversampling the data in the time domain, the precision can be further increased.

4. Application example

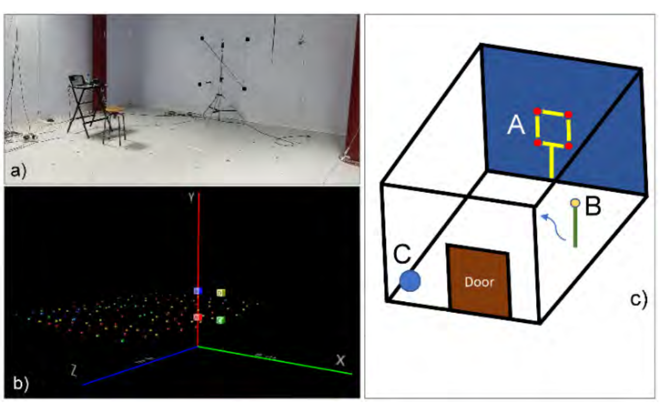

Figure 5. a) Measuring inside the reverberation room; b) points measured with the 3D positioning system. c) Measurement configuration: A: loudspeaker grid; B: microphone on the stand; C: dodecahedron

A series of measurements were carried out in the reverberation room of the University of Ferrara. The room has a volume of about 252 m^3, the area of the floor is around 50 m^2, the side walls are of different lengths between 6.42 m and 8.53 m, the heights in different points of the room are between 4.26 m and 6.02 m. There are four curved diffusers (area = 4.35 m^2) hanging from the ceiling. The 3D positioning system was used to sample the sound field inside the room in 109 points. All measurements were performed at a fixed height of 2 meters from the ground, placing the microphone on a stand, moved manually to cover the entire area of the room. The distance between the different measurement points was approximately 0.5 m; no particular care was taken for an exact positioning of the individual measurement points, since the exact position was calculated by the 3D positioning system and associated with each corresponding acoustic measurement. The geometrical "step" of nearly 0.5 m between sampled points was chosen because the wavelength at the frequencies analyzed in this study is less than 100 Hz. Considering the Nyquist spatial theorem, the maximum frequency that can be analyzed with this geometrical step is $f_{upper} = c/2s = 343$ Hz where c is the velocity of sound (m/s) and s is the (approximate) measurement step (m) [1,2]. Together with the 4 MLS signals emitted by the 4 small loudspeakers on the grid for determining the position of the microphone, a fifth MLS signal, different from the other 4, was emitted by a dodecahedron placed inside the reverberation room (shown in Figure 1 b), in a different position). For each measurement point, the "local" impulse response of the chamber was measured, using the MLS signal emitted by the dodecahedron. MLS signals of order 18 (2^{18}-1 = 262143 samples), orthogonal to each other, with a time length of about 6 seconds at a sample rate of 44.1 kHz, were used for both the dodecahedron and the 4 loudspeakers on the grid. The room has reverberation times of less than 6 seconds above 315 Hz and a maximum of 7 seconds at a frequency of 100 Hz. The time length of the MLS signal of about 6 seconds has been chosen as a compromise, due to the large number of measurements to perform. In fact, the small speakers of the grid are high-pass filtered above 1600 Hz so their impulse responses (including the room reverberation) are certainly shorter than 6 s. The impulse responses from the dodecahedron signal, for frequencies lower than 315 Hz, will present a very slight "contamination" from the tail of the measured impulse response, at the beginning of the time axis, due to the MLS measurement cyclical properties [12,13,14]. Preliminary experiments within the reverberation room have proven that this contribution is negligible for the type of analysis performed. The grid with the 4 loudspeakers has been placed in the middle of the back wall of the room, as shown in Figure 5 a). At the foot of the line joining the two left speakers, A and B, as shown in Figure 5 b), is the origin of the three-dimensional Cartesian reference system. The entrance door of the room is on the wall opposite to the one where the loudspeaker grid was positioned. The dodecahedron (C in Figure 5 c)) was placed near a corner of the room, at the left of the entrance door. The 109 measurements were made covering the whole area of the reverberation room, detecting for each point the position in space and the impulse response of the chamber. The dodecahedron was left in a fixed position. For this study only measurements at a fixed height of 2 m have been taken.

4.1 Spectral analysis

A "cloud" of georeferenced points was measured, each of which is associated with an impulse response measured at that point, as shown in Figure 5 b). The FFT of the impulse responses was then performed. In Figure 6 an overview of the spectral content of the measured points can be observed; each row represents a measurement point (in measurement chronological order), each column is a single discrete frequency, from 20 Hz to 100 Hz, in steps of 0.67 Hz. The color scale indicates the levels in dB and goes from the bottom (blue color) upwards (red) with a range of about 50 dB. The presence of vertical red lines allows highlighting specific frequencies at which there are modal resonances in many points of the room.

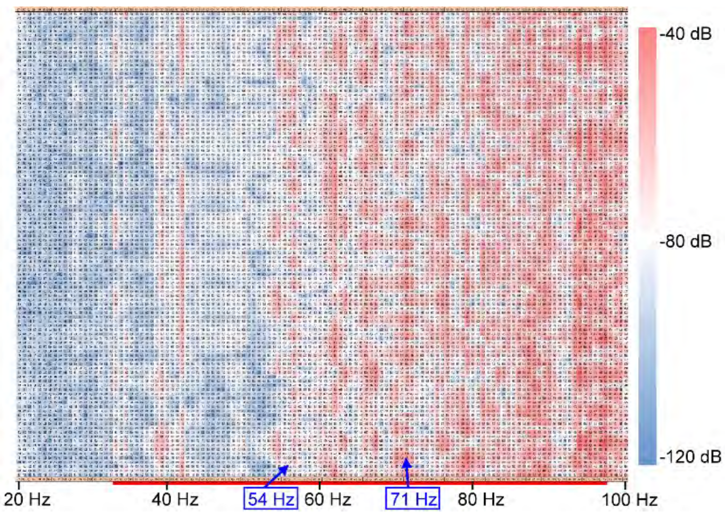

Figure 6. “Fingerprint” of the reverberation room, measured at 2 m height; the columns corresponding to 54 Hz and 71 Hz are highlighted

4.2 Modal analysis

The spectra corresponding to each measurement point were associated with their position in space. All the measurements were made at a height of 2 m and the projected results on a 2D plane, which represents the reverberation room seen from above, have been analyzed. Spectrum values, at a single frequency and at each measurement point, were spatially interpolated to obtain a color map as shown in Figure 7, were the red color means high sound levels and the blue color low sound levels. The upper side of the projected map is the wall in the middle of which was placed the grid with the 4 speakers, origin of the reference system, as shown in Figure 5. As an example, the study of the sound field at two resonance frequencies, 54 Hz and 71 Hz, clearly visible in the room "Fingerprint" in Figure 6, is shown below. The map shown in Figure 7 a) represents the sound field distribution in the reverberation room at the height of 2 m, computed from the FFT of the georeferenced Impulse Responses, at the frequency of 54.5 Hz. The areas colored in green or blue represent "holes" in the sound field due to destructive interference of stationary waves. The amplitude range of the plot in Figure 7 a) is around 38 dB. Figure 7 b) shows the result of FEM modeling of the reverberation room, at a height of 2 m and for a frequency of 54 Hz, calculated considering the sound source at the same point where it was kept in the measurement shown in Figure 7 a). FEM modeling was performed with the Comsol Multiphysics software; the three-dimensional geometry of the reverberant room was imported into the model; the air volume inside the room was discretized with a mesh of tetrahedral elements for a maximum simulation frequency of 560 Hz (higher frequency of the 500 Hz one-third octave band). Figure 7 c) shows a map similar to that shown in Figure 7 a), calculated at the frequency of 71.3 Hz from the FFT of the georeferenced impulse responses. Figure 7 d) shows the result of the FEM modeling at a frequency of 71 Hz, similar to the map obtained from 3D measurements shown in Figure 7 c). Both examples, for the frequency of 54 Hz and 71 Hz, show a good agreement between the map from actual measurements and that from the FEM model at the corresponding frequencies. The maps obtained from the measurements have a spatial resolution worse than the corresponding maps obtained from the FEM model, due to the limited number of measurement points (109 in this study). This aspect can be improved by increasing the number of measured points. The FEM model is more precise, but it can take a long time to be fine-tuned. Moreover, it can be difficult to simulate complex environments such as a recording studio or a listening room with complex geometries and unknown characteristics.

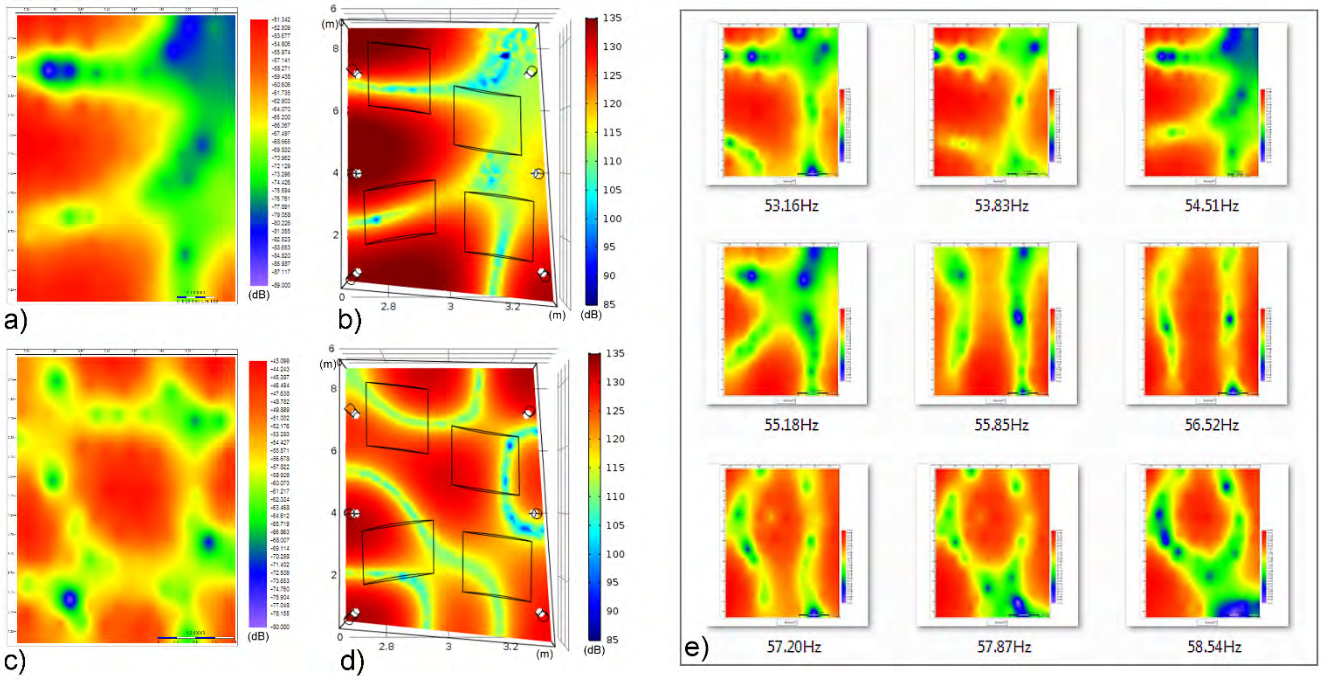

Figure 7. a) Map of sound levels obtained from the FFT of the measured impulse responses at 54.5 Hz and a height of 2 m. b) Map of sound levels obtained from the FEM model of the reverberation room at 54 Hz and a height of 2 m. c) Map of sound levels obtained from the FFT of the measured impulse responses at 71.3 Hz and a height of 2 m. d) Map of sound levels obtained from the FEM model of the reverberation room at 71 Hz and a height of 2 m e) Example of normalized level maps from 53.16 Hz to 58.54 Hz

Figure 7 e) shows, as an example, some maps computed from the FFT of the measured impulse responses at other adjacent frequencies, from 53.16 Hz to 58.54 Hz, calculated in the same way as described above. All the maps shown in Figure 7 e) are normalized to better highlight modal resonances. From each impulse response measured at 109 points, it is also possible to calculate a decay curve by applying Schroeder's backward integration and consequently maps of reverberation time at any point in the room can be obtained.

5. Conclusions

A new three-dimensional positioning system was presented and an example of application in a reverberation room was shown. The positioning method allows the location of a point in space through acoustic waves, associating it with the measurement of a georeferenced impulse response, and has proven precise enough to make reliable measurements and to discover and help solve problems related to the local acoustic field in a closed environment. The proposed method can be used to analyze the acoustic field in complex environments, such as a recording studio, where the creation of an FEM model would be difficult, and identify its modal distribution. Unlike other positioning systems, in the method presented the position sensor (microphone) is also used to make the acoustic measurement itself, ensuring maximum accuracy in positioning.

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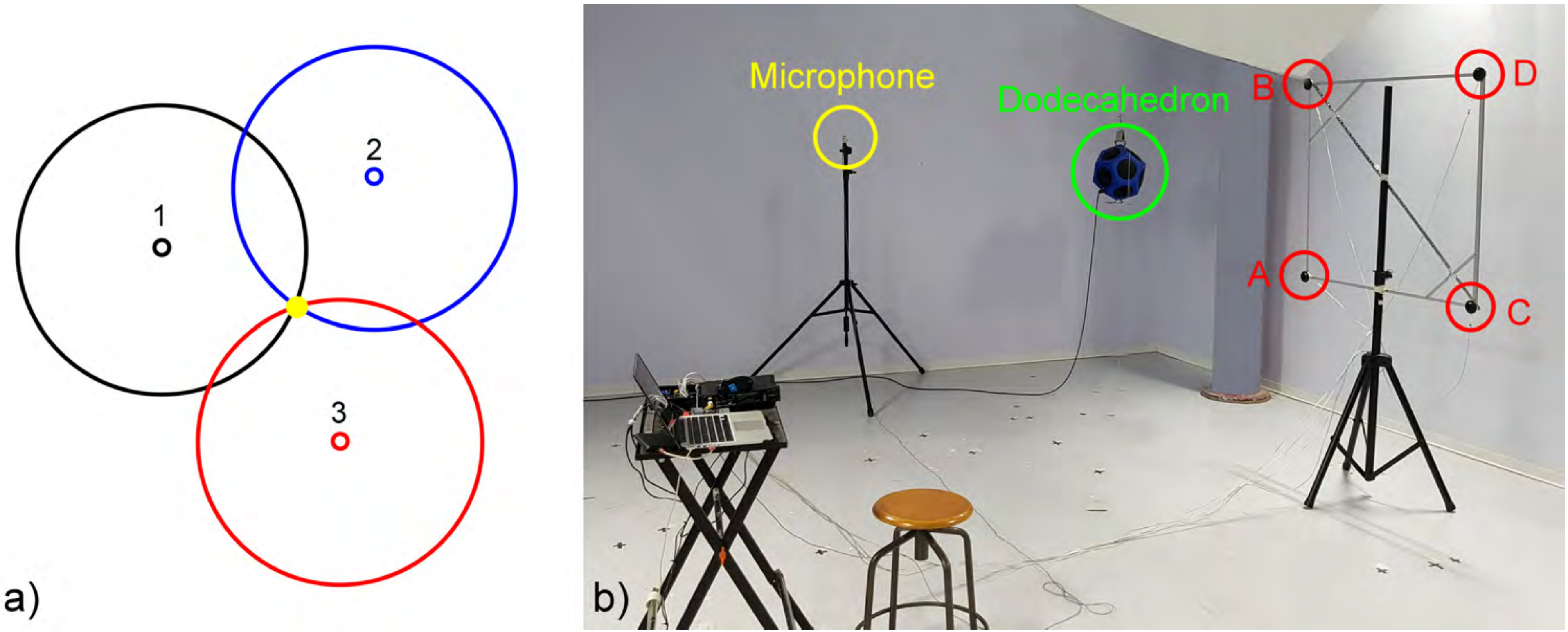
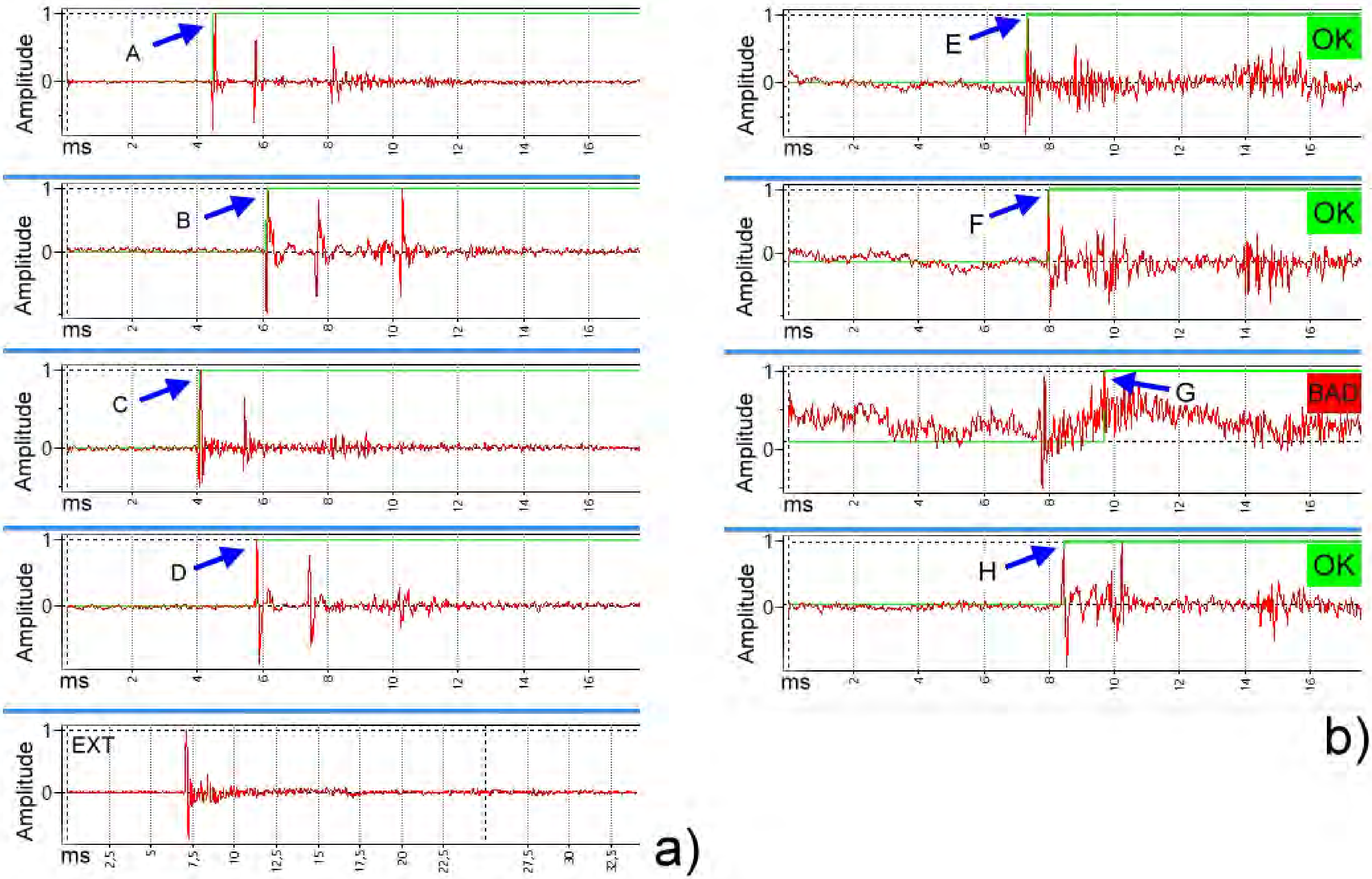

1
2
3
a)
Microphone
Dodecahedron
B
D
A
C
b)



A
B
C
D
EXT
E
F
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H
OK
OK
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Amplitude
ms
a)
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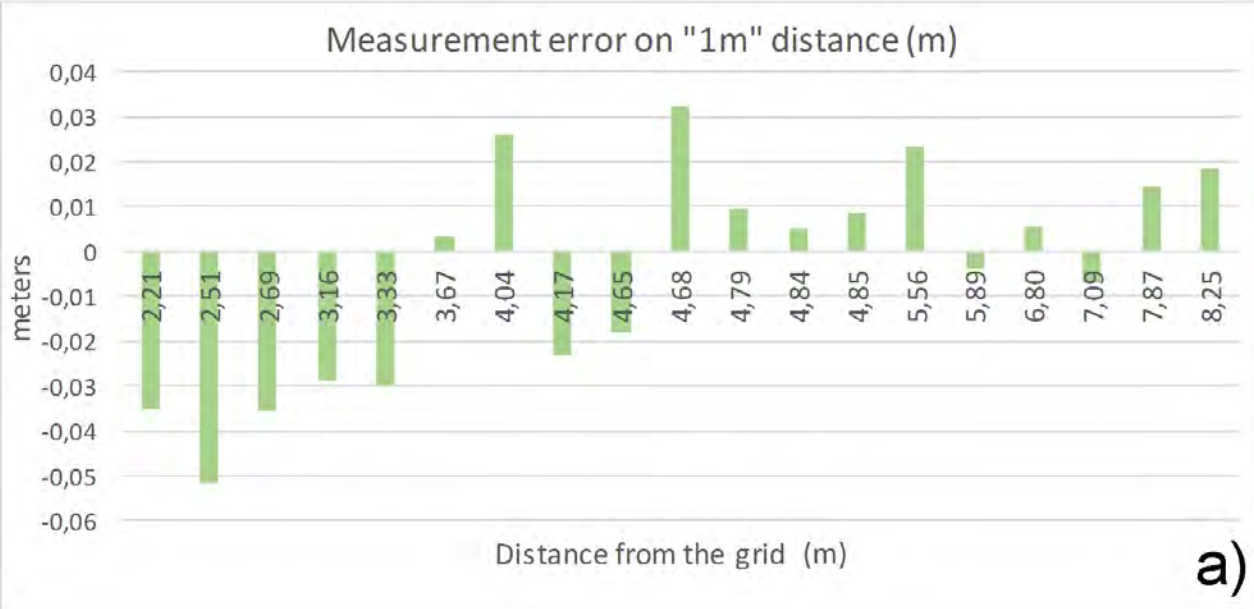
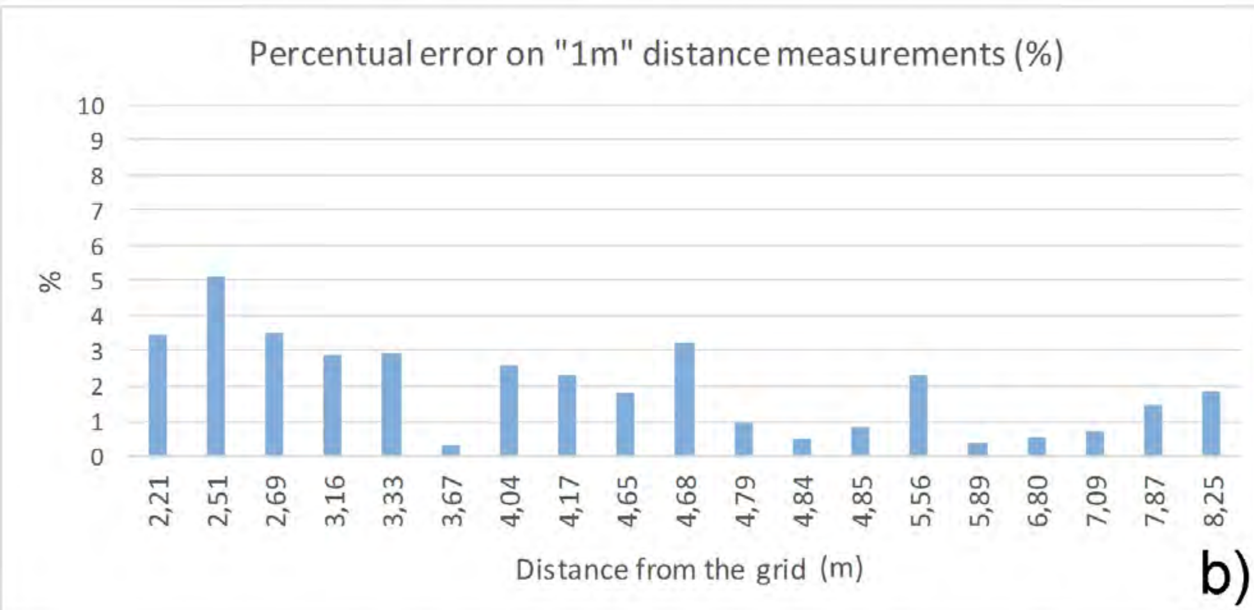
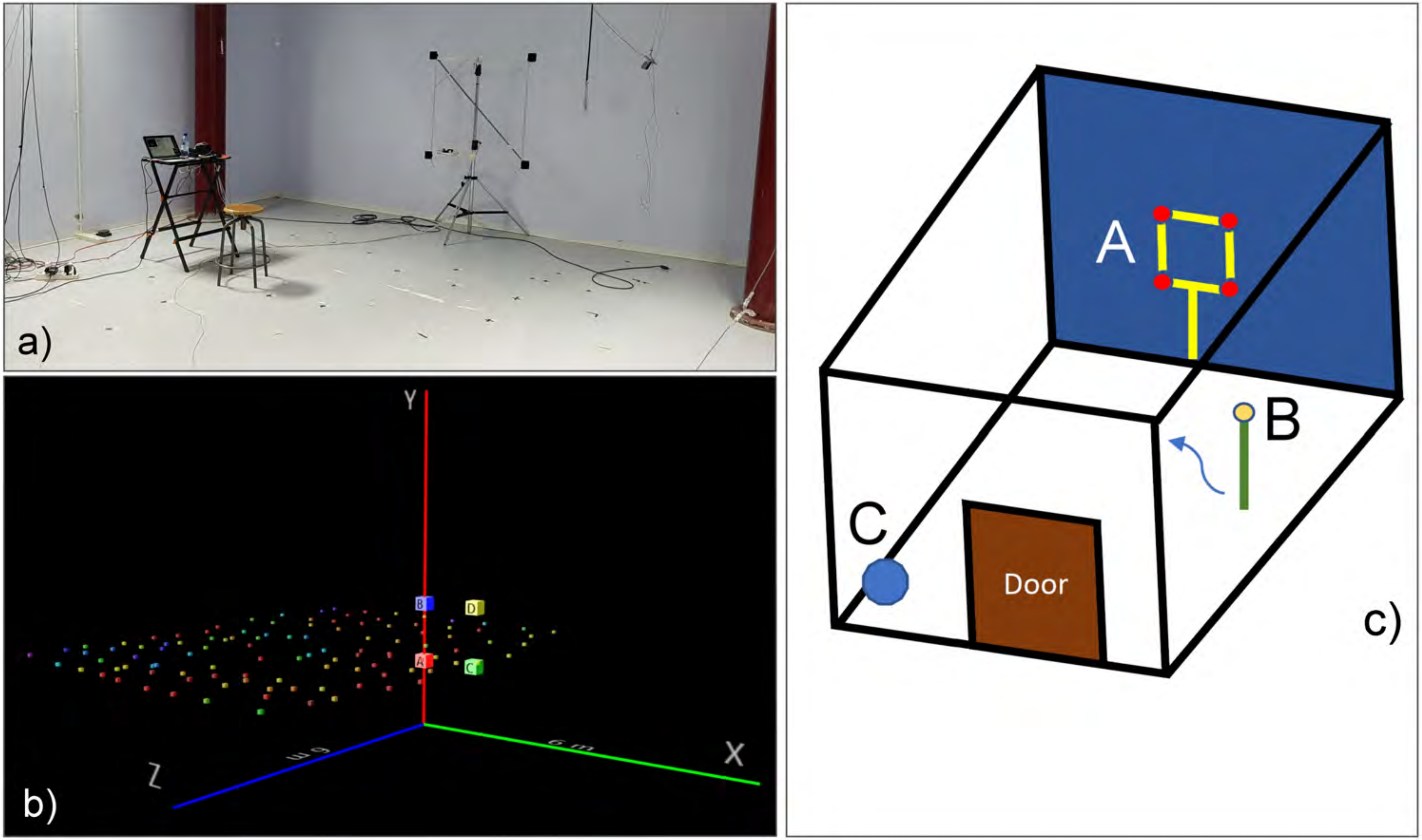
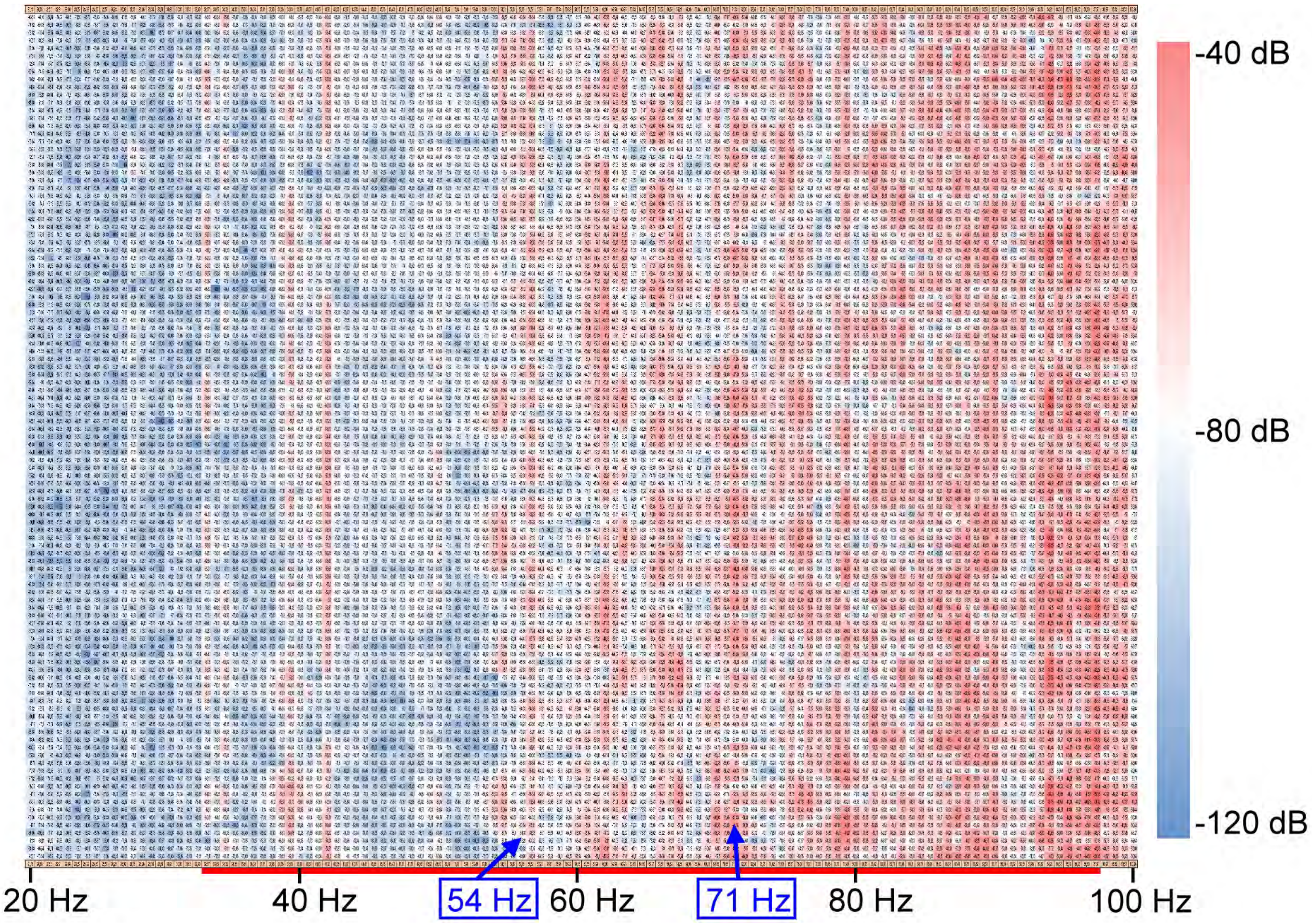
3D APS - Audio Positioning System - (c) 2017 by Paolo Guidorzi
Impulse Responses - Geotagging channels
Microsoft

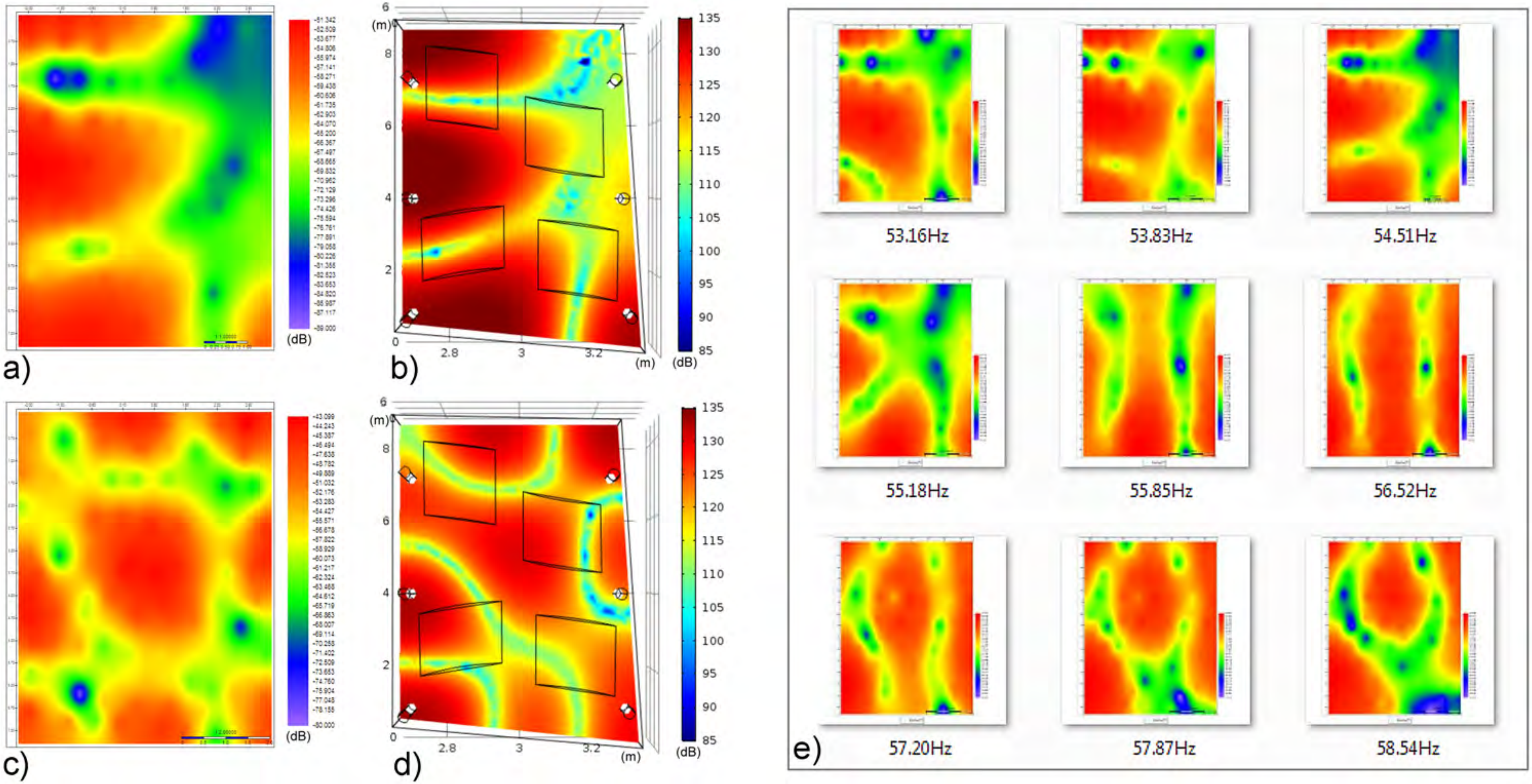

Measurement error on "1m" distance (m)
meters
0,04
0,03
0,02
0,01
0
-0,01
-0,02
-0,03
-0,04
-0,05
-0,06
2,21
2,51
2,69
3,16
3,33
3,67
4,04
4,17
4,65
4,68
4,79
4,84
4,85
5,56
5,89
6,80
7,09
7,87
8,25
Distance from the grid (m)
a)


Percentual error on "1m" distance measurements (%)
%
10
9
8
7
6
5
4
3
2
1
0
2,21
2,51
2,69
3,16
3,33
3,67
4,04
4,17
4,65
4,68
4,79
4,84
4,85
5,56
5,89
6,80
7,09
7,87
8,25
Distance from the grid (m)
b)


a)
Y
B
D
A
C
6 m
6 m
Z
X
b)
A
B
C
Door
c)



-40 dB
-80 dB
-120 dB
20 Hz
40 Hz
54 Hz
60 Hz
71 Hz
80 Hz
100 Hz



a)
(dB)
b)
6
(m)
8
6
4
2
0
2.8
3
3.2
(m)
135
130
125
120
115
110
105
100
95
90
85
(dB)
c)
(dB)
d)
6
(m)
8
6
4
2
0
2.8
3
3.2
(m)
135
130
125
120
115
110
105
100
95
90
85
(dB)
e)
53.16Hz
53.83Hz
54.51Hz
55.18Hz
55.85Hz
56.52Hz
57.20Hz
57.87Hz
58.54Hz