

# Passive Indoor-Localization using Echoes of Ultrasound Signals

Fabian Hoeflinger<sup>1\*</sup>, Addythia Saphala<sup>2</sup>, Dominik Jan Schott<sup>2</sup>, Leonhard Michael Reindl<sup>2</sup>,  
Christian Schindelbauer<sup>3</sup>

<sup>1</sup> Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, Freiburg, Germany;

<sup>2</sup> Department of Microsystems Engineering, University of Freiburg, Freiburg, Germany;

<sup>3</sup> Department of Computer Science, University of Freiburg, Freiburg, Germany;

\* Correspondence: fabian.hoeflinger@emi.fraunhofer.de;

## Abstract

*In this paper, we present our novel indoor-localization system. The system uses only short inaudible acoustic signals to locate acoustically passive objects in a room. Moving objects can be detected as well as resting objects. The localization device consists of a transmitter (speaker) and a multi-channel receiver with up to eight receivers (microphones). The total time-of-flight path from the speaker to the microphones is the round-trip-time of the signal from the speaker to the reflecting object and back to the microphones. Therefore, a localization algorithm is used to translate the timing into object coordinates. By using a simple approach of direct intersection, the 3D-coordinates of the reflecting surface of the target can be derived. In an experiment, we demonstrate the functionality of this approach.*

**Key Words** – indoor-localization, embedded system, signal processing, acoustic signals, passive localization, time-of-flight.

## 1 Introduction

Localization of persons or objects inside a room in inner space can serve multiple functions such as security, energy conservation, and occupancy detection [1][2][3]. In this work, a device for detecting changes inside indoor environments via inaudible acoustic echolocation is realized. The localization is done without any kind of active sender, markers or tags on the object or person. The approach exploits the change in acoustic impedance between objects and environment. After transmitting an acoustic signal from the sensor module's speaker, an array of microphones that has been arranged in the module around the speaker record the returning echoes to determine the location of the reflecting object. The exact position of the speaker and microphones relative to each other is known. Hence, the location of the objects can then be derived by using the phased array approach and calculating the time of arrival of the echoes [4].

## 2 State of the Art

There are various method of presence detection with acoustic signals in air. The most commonly used being active detection by attaching transmitters to the objects or passive detection by capturing echo distances as one-dimensional vectors with a single-transducer ultrasound distance sensor.

One of the most common ultrasonic sensors that can be used for presence detection available right now is a simple ping sensor e.g. *HC-SR04* and *Maxbotix LV-MaxSonar* sensor series. This type of sensor measures the time of flight from reflected acoustic signal and time of transmission. These sensors generally have a very high directivity and narrow field of view. To utilize these sensors as presence detector, strategic placement and static area of detection are required [5][6]. Furthermore multiple sensors are required to cover a large area and visible installation within reach e.g. on the desk or chair can be inconvenient. To avoid cross-interference between multiple sensors due to transmission from a sensor transmitter to a receiver on a different sensor, a transmission slot allocation is required additionally [7]. In [12], Zhou et. al. present another system for indoor localization. They combine inertial measurements and ultrasound distance measurements for infrastructure-free indoor continuous tracking of a speaker.

A different system that provides multi-dimensional indoor-localization via (active) ultrasound tag or smartphone tracking has been developed by Telocate. A transmitting tag is attached to objects of interest and monitored by a sensor array mounted on the ceiling. The location of the tag is then derived centrally from the time delay between the received signals [8]. We have also shown in the past, that the approach works underwater as well [9].

In comparison, the device developed in this work is able to derive the location of the target without an active tracking tag. The novelty of using omnidirectional transmitter and a microphone array enables the device to perceive the direction of echoes to localize the target. This

is especially difficult for indoor operation in a small room since the walls, floor, ceiling and clutter inside the room cause considerable interfering echoes.

### 3 Methods

Echolocation, such as the method used by bats to locate their prey, is a phenomenon where the reflected sound waves are used to determine the location of objects or surfaces which reflect the sound waves due to a change in acoustic impedance. This concept has been extensively used for various investigations in the physics and engineering fields, such as sound navigation and ranging (SONAR) [10]. For bats, the incoming reflected wave's direction can be resolved due to complex signal processing in the bat's ears and brain. While the echolocation system of bats is not completely understood, one of the more obvious aspects is the backscattered signals' difference of arrival in time between left and right ear, which can be used to calculate the incoming sound wave direction [11]. The figure below shows the transmit time  $t_0$ , the time reflected sound wave arrived in one ear  $t_1$  and in the other ear  $t_2$ . The difference between  $t_1$  and  $t_2$  can be used to derive the angle of arrival, and the difference of both of them to  $t_0$  can be used to calculate the range.

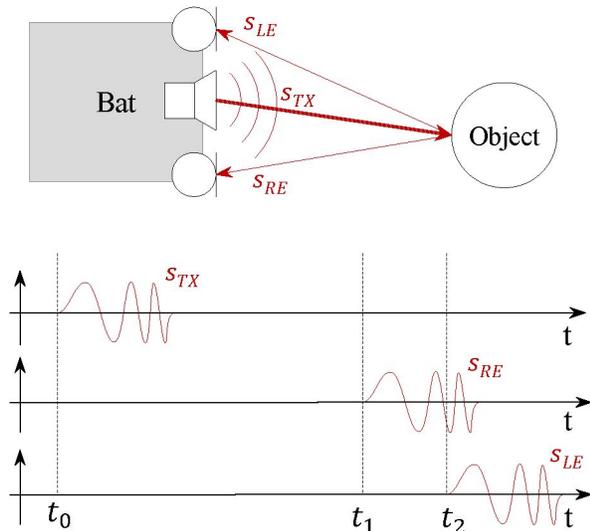


Fig. 1. Timing of signal propagation.

To obtain three-dimensional coordinates with static arrangement, a four elements microphone array is used. This array records the incoming echo wave with different time of arrival, depending on the incoming signal direction.

## 4 Development

### 4.1 Hardware

The system consists of a single acoustic transmitter, a multi-channel receiver, a power distribution board and a central computer to analyze the recorded signals. Four microphones are placed equidistantly around the speaker and connected to the receiver board. The set-up is shown in Fig. 2, as it is used for the experiment reported below. The power board and central computer are not shown in this work.

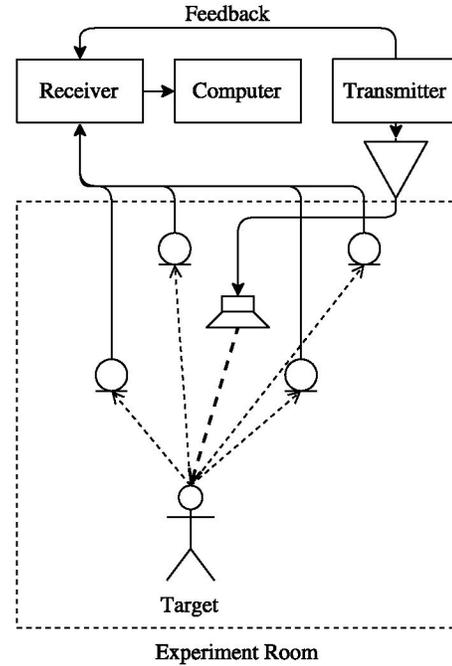


Fig. 2. Schematic representation of the system.

The transmitter unit uses a *Teensy 3.6* single-core embedded processing unit with the complementary Audio Shield connected to a single commercial off-the-shelf (COTS) speaker with the external standard audio amplifier *Visaton Amp 2.2 LN*.

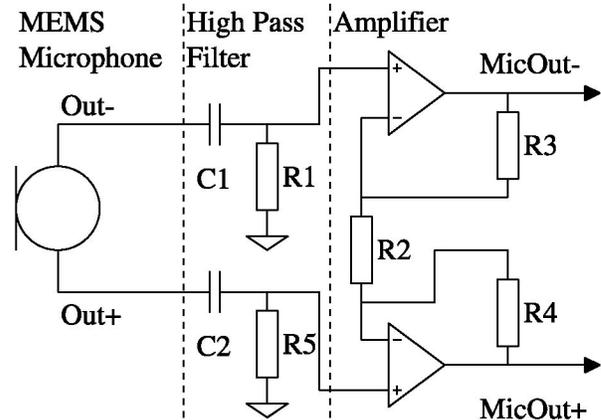


Fig. 3. Schematic of microphone input circuit.

The microphone units consist of the MEMS microphone *ICS-40720* and a pre-amplifier with high pass filter and instrumentation amplifier with op-amp *OPA 1652*, as shown in Fig. 4. The microphone units are designed to have balanced signal outputs. Each microphone is mounted on a separate circuit board, see Fig. 4, to enable variations in placement for different receiver configurations in the future.



Fig. 4. MEMS Microphone of the Microphone-Array.

The receiver is an eight channel analog-to-digital converter (ADC) connected to a microcontroller. The analog input signal went through differential amplifier and active filters before digitalization. The ADC used in the receiver is a *Texas Instruments ADS8588s*, with simultaneous sampling, 16-bit resolution and implements the successive approximation method. With the same sample and hold trigger for all channels simultaneously, the sampled signal is considered to be coherent.

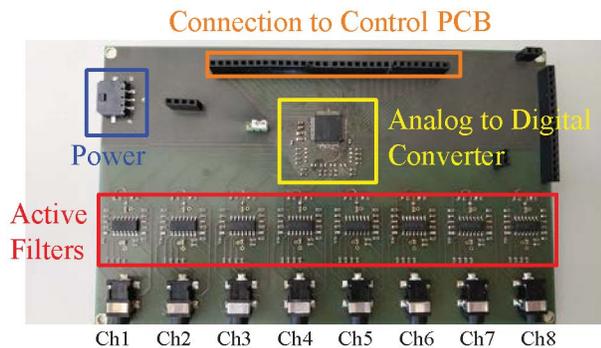


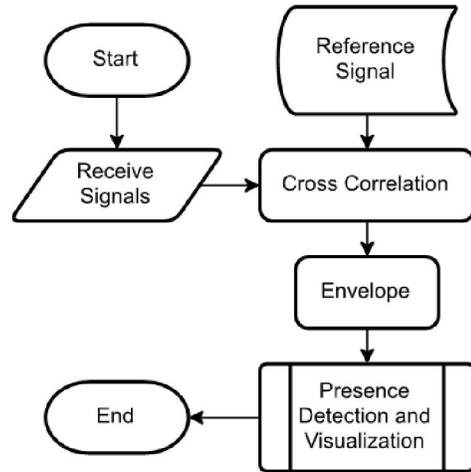
Fig. 5. Receiver hardware.

In the working configuration, only four channels are used for inputs from microphone array and one channel is used for direct feedback from the transmitter. The recording of ultrasonic echoes is triggered by external interrupt from the transmitter; a single period of recorded

signal henceforth is referred to as a frame. The frame is recorded and then sent for further signal processing.

## 4.2 Digital Signal Processing

As discussed above, the frame consist of a four channel input from microphones and a feedback channel to mitigate play-back jitter. We calculate the cross-correlation of the feedback channel against our known reference signal to obtain the time of transmission. The cross correlation result from the four microphone channels indicate the time-of-arrival of the echoes to the respective microphones. In the following, we refer to the timing of transmission as  $t_0$ , all other channels timings are regarded relative to the prior  $t_0$ . The resultant signal is referred to as echo profile. An example of such echo profiles is shown below in Fig. 7. To reduce the interference from surrounding objects, floors and walls, the empty room echo profile is used to extract the impulse response of the object from the room's echo profile. Matrices containing the relation between space coordinates and the distance to each microphone and speaker are used to translate the timing into coordinates, assuming constant speed of sound. The total time of flight path from the speaker to the microphones is the addition of the time of flight from the speaker to the target and the time of flight from the target to the microphones.



## 5 Experiment

### 5.1 Set-Up

In the experiment, a static object mimicking a person's head, as they are sitting at an office desk is used as a target. The hard smooth surface of the object is intentional for the sake of usability and to remove unintended movements from our measurements at this early stage. In the setup shown in the Fig. 6, the expected echo from the target is recorded by the microphone array. The distance between the microphones is small compared to the distance between "Device" and "Target", contrary to the schematically depiction in Fig. 2.

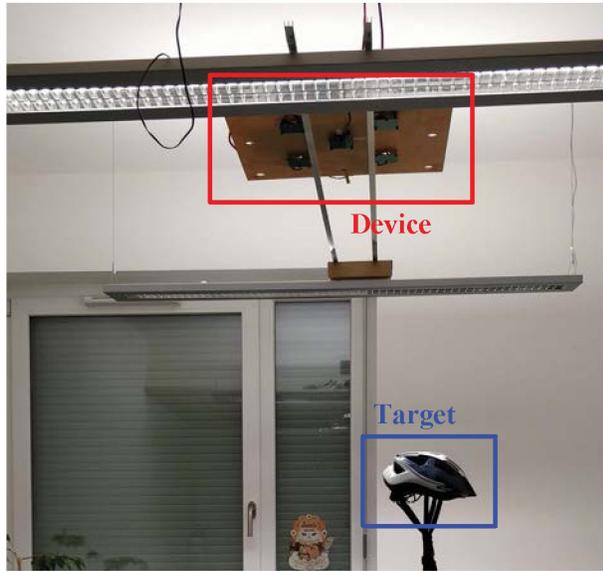


Fig. 6. Target and localization device.

## 5.2 Results

An exemplary cross-correlation result from one of the microphone channels is shown in Fig. 7 a-c for different room situations. At first the experimental area is set to a default state and all persons removed from the room. Initially a baseline is recorded for this empty room, that shows strong echoes from walls, ceiling, floor, desks and other perpendicular hard surfaces (see Fig. 7a). Consecutively, our “Target” is placed at different positions in the room and a recording taken (see Fig. 7b). The additional reflective object adds another echo to the room response albeit with an amplitude lower than the strong wall reflections, due to the limited perpendicular area visible to the sensor. By regarding the difference, we can extract the change introduced by the “Target”, as shown around the time around 6 ms in Fig. 7c. This approach returns a peak of about 30 dB amplitude under this ideal conditions. For larger distances and softer objects a considerable decrease of amplitude is to be expected.

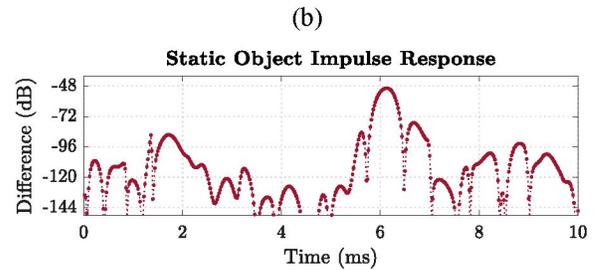
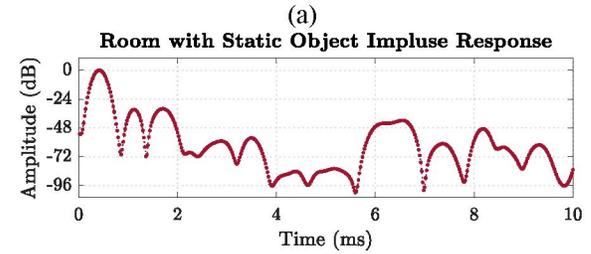
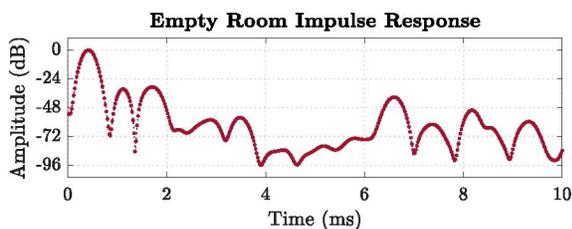
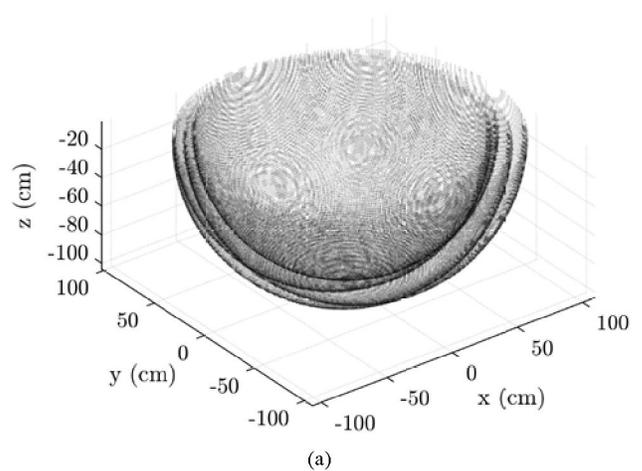


Fig. 7. Impulse response in different scenarios.

From a single microphone, a semi spherical shape which indicates the distance of the surface as seen from the microphone can be generated. By simple AND operation of the matrix from all channels, the semi spherical shapes intersection can be derived, which indicates the location of the reflecting surface of the target. In Fig. 8, OR operation is also shown to present the semispherical shape from all microphones. The result of AND operation is an array of coordinates, therefore the point of reflection can be derived as the mean point of the coordinates, with consideration to the orientation of the surface normal.



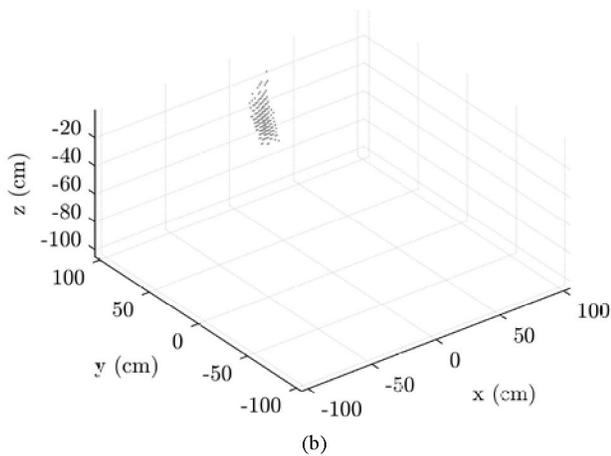


Fig. 8. Semispherical shape from all microphones and the result of calculation.

From a single microphone, a semi spherical shape which indicates the distance of the surface as seen from the microphone can be generated. By simple AND operation of the matrix from all channels, the semi spherical shapes intersection can be derived, which indicates the location of the reflecting surface of the target. In Fig. 8, OR operation is also shown to present the semispherical shape from all microphones. The result of AND operation is an array of coordinates, therefore the point of reflection can be derived as the mean point of the coordinates, with consideration to the orientation of the surface normal.

The total distances travelled by the signal from the speaker to each microphone are shown in the Table 2. Compared to the distance measured by laser distance sensor as our reference measurements in Table 1, the errors are shown in Table 3, with mean of absolute error of 0.105 m.

Table 1 Reference Measurements

Distance(m)	Ch.1	Ch.2	Ch.3	Ch.4
Position 1	2.146	2.179	2.022	1.991
Position 2	2.049	2.047	2.349	2.222
Position 3	2.187	2.285	2.349	2.256
Position 4	2.339	2.220	2.198	2.317

Table 2 Signal Travel Distances

Distance(m)	Ch.1	Ch.2	Ch.3	Ch.4
Position 1	2.081	2.061	1.932	1.857
Position 2	1.966	1.945	2.115	2.169
Position 3	2.318	2.359	2.555	2.393
Position 4	2.352	2.264	2.291	2.413

Table 3 Distance Errors

Distance(m)	Ch.1	Ch.2	Ch.3	Ch.4
Position 1	-0.065	-0.119	-0.09	-0.134
Position 2	-0.083	-0.102	-0.234	-0.053
Position 3	0.131	0.074	0.206	0.137
Position 4	0.013	0.044	0.093	0.096

While the derived location from direct intersection coordinates, the reference coordinate and the position error are shown in table below. Keep in mind that the derived position coordinates are influenced by various factors such as the shape of the target, the distance of the reflecting surface (surface of the helmet) from the center coordinate of the target, and the difference due to the curvature of direct intersection method. The mean of absolute error of the position is 0.178 m.

Table 4 Reference Position

Position (m)	X	Y	Z
Position 1	0.180	0.802	-0.645
Position 2	-0.027	-0.928	-0.575
Position 3	0.586	-0.408	-0.999
Position 4	-0.730	0.135	-0.977

Table 5 Direct Intersection Results

Position (m)	X	Y	Z
Position 1	0.146	0.893	-0.405
Position 2	-0.172	-0.936	-0.304
Position 3	0.618	-0.81	-0.626
Position 4	-0.601	-0.253	-0.956

Table 6 Position Error

Position (m)	X	Y	Z
Position 1	0.034	-0.091	-0.24
Position 2	0.145	0.008	-0.271
Position 3	-0.032	0.402	0.373
Position 4	-0.129	0.388	-0.021

## 6 Conclusion and Outlook

In this work, a device for passive indoor localization is presented. The echoes are detected by cross correlating received signals with reference signals. Feedback signal is used to provide the time of transmission. The echo profile of the room in empty state can be used as baseline reference to extract the time of arrival of the echo from the target. By using simplistic approach of direct intersection, the coordinates of the reflecting surface of the target can be derived. The direct intersection method requires precise calibration and reasonable normal surface. Other methods to visualize or calculate the target location coordinates could be developed to enhance the detection ability of the device. As an example, a line for future work would be to couple our approach with a probabilistic occupancy map such as e.g. presented in [13]. Further adjustment of the ultrasound signal could improve the device performance as well. The self-calibration and determination of what is to be considered an empty room is subject to further investigation in the future.

## 7 Acknowledgment

This work was supported by the Fraunhofer Gesellschaft and the state of Baden-Württemberg in the Framework of the MERLIN project.

## 8 References

- [1] S. Soumya, M. Chavali, S. Gupta, and N. Rao, "Internet of things based home automation system," in *Proc. Information Communication Technology (RTEICT) 2016 IEEE Int. Conf. Recent Trends in Electronics*, pp. 848–850, May 2016.
- [2] H. N. Saha, N. Saha, R. Ghosh, and S. Roychoudhury, "Recent trends in implementation of internet of things — a review," in *Proc. Electronics and Mobile Communication Conf 2016 IEEE 7th Annual Information Technology (IEMCON)*, pp. 1–6, Oct. 2016.
- [3] D. Caicedo and A. Pandharipande, "Distributed ultrasonic zoned presence sensing system," *IEEE Sensors Journal*, vol. 14, pp. 234–243, Jan. 2014.
- [4] J. C. Chen, K. Yao, and R. E. Hudson, "Acoustic source localization and beamforming: Theory and practice," *EURASIP Journal on Advances in Signal Processing*, vol. 2003, p. 926837, Mar 2003.
- [5] ITead Studio, *Ultrasonic ranging module: HC-SR04*, Nov. 2010. Rev. 2.
- [6] "LV-MaxSonar R-EZTM Series High Performance Sonar Range Finder MB1000, MB1010, MB1020, MB1030, MB1040 data sheet."
- [7] D. Caicedo and A. Pandharipande, "Transmission slot allocation and synchronization protocol for ultrasonic sensor systems," in *Proc. Sensing and Control (ICNSC) 2013 10th IEEE International conference on Networking*, pp. 288–293, Apr. 2013.
- [8] F. Höflinger et al., "Acoustic Self-calibrating System for Indoor Smartphone Tracking (ASSIST)," *2012 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Sydney, NSW, 2012, pp. 1–9. doi: 10.1109/IPIN.2012.6418877
- [9] D. J. Schott, M. Faisal, F. Hoeflinger, L. M. Reindl, J. B. Andreu and C. Schindelbauer, "Underwater localization utilizing a modified acoustic indoor tracking system," *2017 IEEE 7th International Conference on Underwater System Technology: Theory and Applications (USYS)*, Kuala Lumpur, 2017, pp. 1-5. doi: 10.1109/USYS.2017.8309451
- [10] J. Patel and G. Panchal, "An iot-based portable smart meeting space with real-time room occupancy," in *Intelligent Communication and Computational Technologies (Y.-C. Hu, S. Tiwari, K. K. Mishra, and M. C. Trivedi, eds.)*, (Singapore), pp. 35–42, Springer Singapore, 2018.
- [11] H. N. Saha, A. Mandal, and A. Sinha, "Recent trends in the internet of things," in *Proc. IEEE 7th Annual Computing and Communication Workshop and Conf. (CCWC)*, pp. 1–4, Jan. 2017.
- [12] Zhou, Bing, et al. "BatTracker: high precision infrastructure-free mobile device tracking in indoor environments." *Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems*. ACM, 2017.
- [13] Hornung, A., Wurm, K. M., Bennewitz, M., Stachniss, C., & Burgard, W. "OctoMap: An efficient probabilistic 3D mapping framework based on octrees". *Autonomous robots*, 34(3), 189-206, 2013
- [14] Ens, Alexander, et al. "Acoustic self-calibrating system for indoor smart phone tracking." *International Journal of Navigation and Observation* 2015, 2015.