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Experimental Calibration for Electronic Beamforming with Sensor Arrays

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1. Introduction

A sensor array system with N channels is assumed to have the same characteristics for each channel, which are composed of a sensor and an amplification system. In beamforming applications, the gain and phase of each channel are key elements in the synthesis of the beampattern (van Veen & Buckley, 1988). On the other hand, the position of the sensors in the array and the orientation of the axis/plane where the array is placed are also important for an accurate calculation of the weight vector.

In real implementation, specific parameters of each channel show a large deviation from their relative values. These errors exist due to small tolerances in sensor specifications or in the components in the amplification system, or even due to deviations in the position of the array sensors. These deviations, in the relative gain and phase of each channel, can produce errors in the pointing direction, as well as an increment in the sidelobe levels. These errors deteriorate the system performance (Barton, 2005), (Godara, 2004), (Naidu, 2001).

Usually, each channel's behaviour is unknown with enough accuracy and it can vary in time. Therefore, it is necessary to implement auto-calibration, which allows to cancel or to compensate the differences between each channel of the system (Skolnik, 2001). There are many analytic models, which are based on arrays with a large number of sensors (Barton, 2005), (Godara, 2004), (Swindlehurst, 1996), (Quazi, 1982), that allow to establish a relation, in a statistical sense, between the phase and gain errors of each sensor and the deviations in the radiation/reception pattern of the beamformer (particularly on the pointing angle, the main beam width or the sidelobe level). However, the errors with arrays with a small number of sensors do not fulfil those previous analytic models. Therefore, it is necessary to carry out detailed analysis of the degradations that are caused by these errors.

2. System description

A detection and position measurement system has been designed. The hardware of the proposed system is formed by:

- A PC with a Pentium processor, with one Innovative Integration M6713 card, which includes a C6713 DSP. M6713 hosts an Omnibus SD16 module, which provides 16 channels of 18 bit, 48 kHz sigma-delta A/D and D/A converters.
- A transmission (Tx) uniform linear array (ULA) formed by 8 amplifiers, each one with 2 channels, and 15 tweeters.
- A reception (Rx) ULA formed by 2 multi-channel preamplifiers, each with 8 channels, and 15 studio microphones.

Fig. 2-1 shows the acoustic transmission and reception arrays.

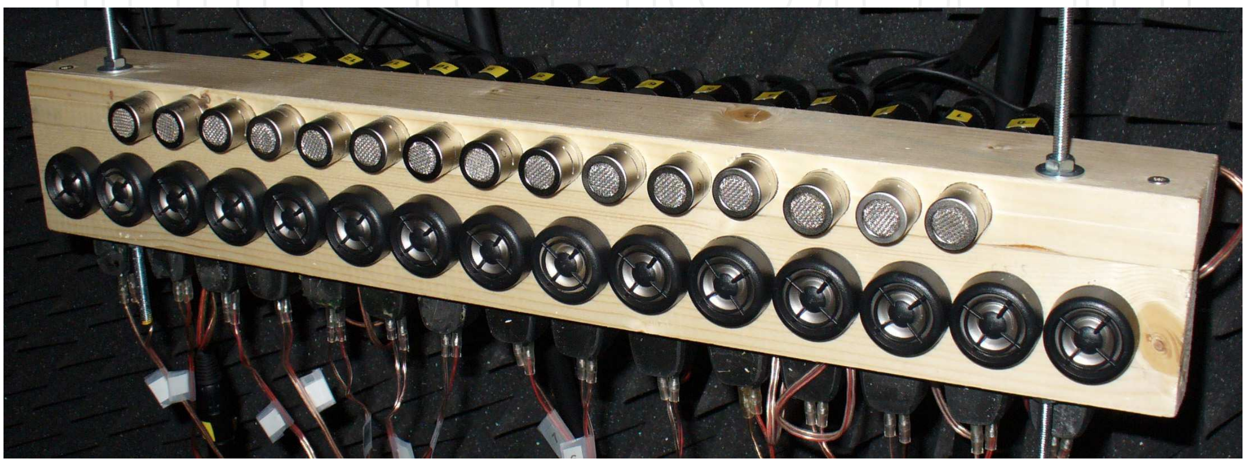

Fig. 2.1. Transmission (below) and reception (above) arrays

As the system uses low cost components, the calibration data of these components are not available. Therefore, it is important to know the dispersion of the characteristics of these components. An anechoic chamber has been built to do tests. Inside this chamber, the Tx and Rx arrays are located at one of the sides of the chamber. A Tx sensor and a Rx sensor, which have been taken as reference, are located at the opposite side, at a distance of 4.2 m. The hardware implements a narrow band system that detects the existence and also the position of targets in different environments, on the basis of multi-function radars (Barton, 2005), (Sabatini & Tarantino, 1994), (Billeter, 1989). Electronic beams are implemented, using beamforming techniques (Naidu, 2001), (Van Veen & Buckley, 1988), from the in-phase and quadrature signals of each channel. Fig. 2-2 shows the employed signal processing algorithm.

The main blocks are described as follows:

- Transmitter: The Tx beamforming block generates a signal for a steering angle for each sensor. The signal frequency is 7 kHz. The Tx phase and gain compensation block compensates the gain and phase of each sensor and channel of the transmitter.
- Receiver: A band pass filter with a frequency range from 6 kHz to 8 kHz. The I+Q demodulator block obtains the in-phase and quadrature components of the signals. The Rx phase and gain compensation block compensates the gain and phase of each sensor and channel in the receiver. The Rx beamforming block processes the signals received for each sensor to form a beam at a specific steering angle. The matched filter block applies an optimal filter to maximize the signal-to-noise ratio (SNR).

This calibration method employs a reference sensor located opposite to the array on a perpendicular axis to the plane of the array (broadside). Two types of calibration are defined:

- Calibration of the Tx array, using a reference microphone
- Calibration of the Rx array, using a reference loudspeaker (tweeter).

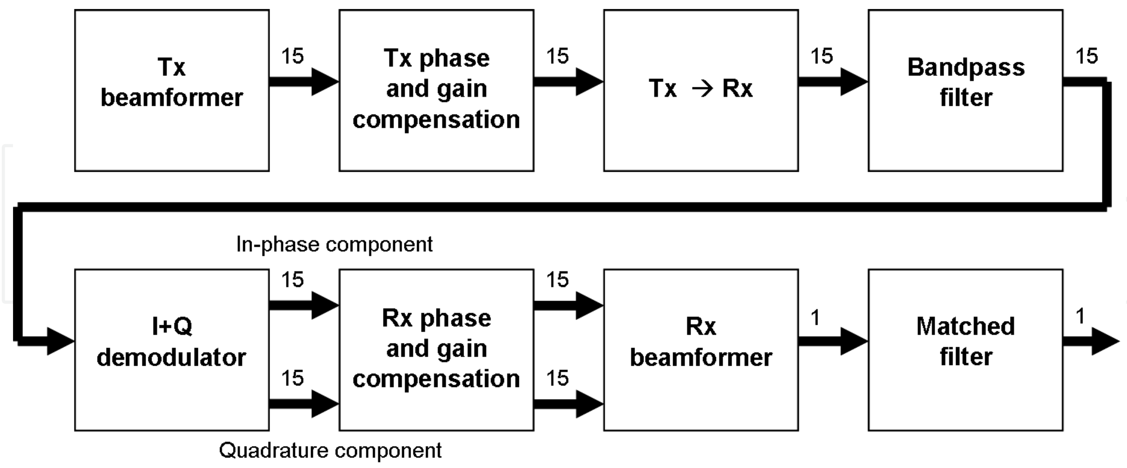

Fig. 2.2. Signal processing algorithm

The calibration system is based on the hypothesis of working with spherical waves, because the acoustic system is used under near field conditions. Since spherical waves are assumed, signals that are transmitted/received between the sensors of the array and the reference sensors arrive with different gains and phases. These gains and phases are taken into account in calibration. As the position of the reference sensor is known, the theoretical amplitudes and phases of the signal of each channel can be calculated, and then compared with real data, extracting the information to carry out the phase and gain compensation.

3. Transmitter array calibration

A sinusoidal pulse of 7 kHz and 5 ms width is used with a reference microphone located at 4.2 m range and 0º from the array perpendicular angle. Pulse signals are transmitted sequentially by each loudspeaker of the transmission array. Then, they are received in the reference microphone and, finally, are processed together. Experimental signals received at loudspeakers number 0, 3 and 13 are presented in Fig. 3-1.

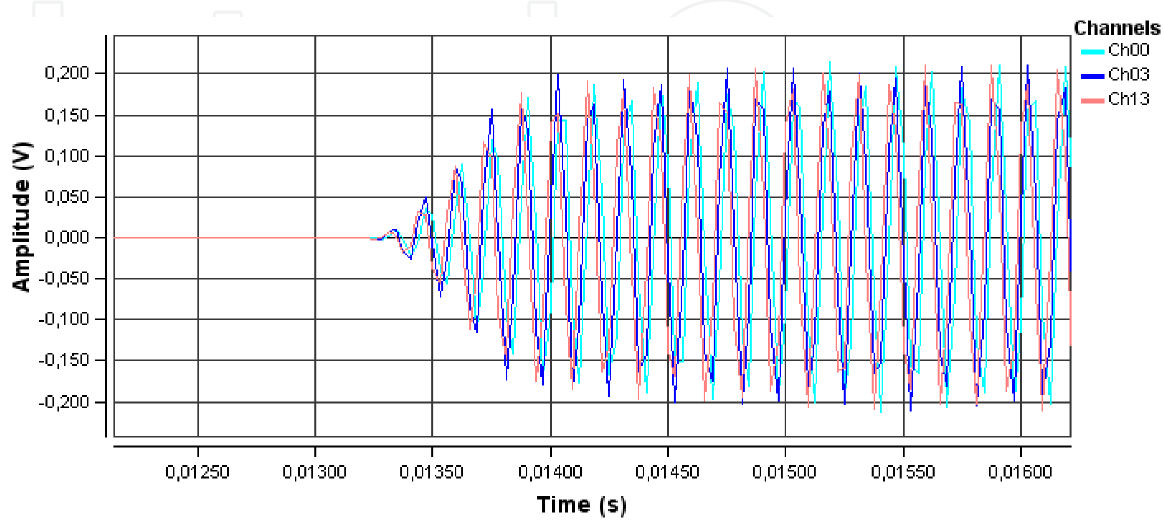

Fig. 3.1. Received signals from the Tx array

Module and phase values of the signals can be obtained using the described processing algorithm. Module values are showed in Fig. 3-2.

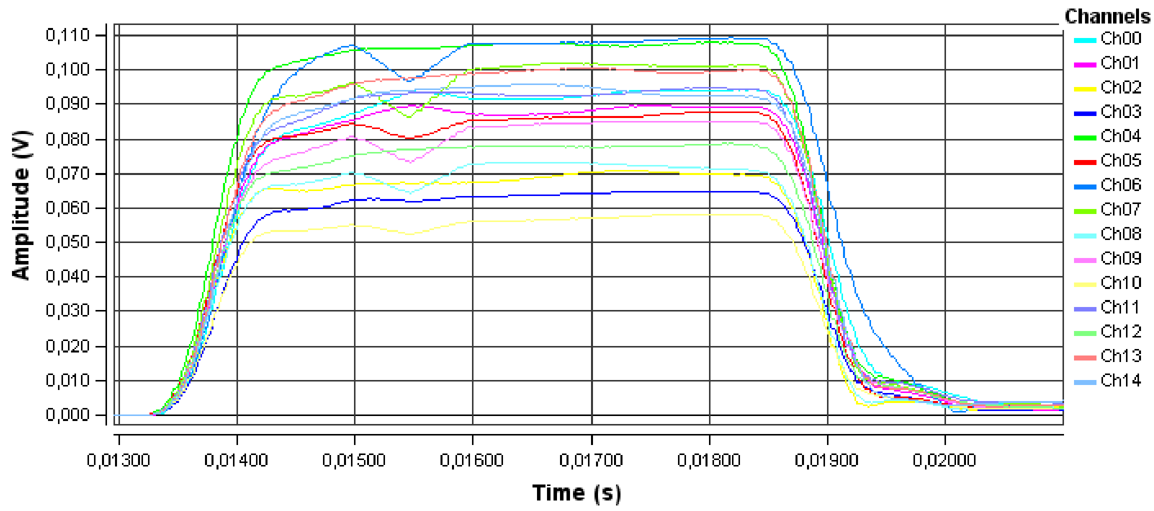

Fig. 3.2. Tx module values

The average of the module is calculated for the pulse length. Relative gains are obtained by normalising the module averages of each channel with respect to channel 0. They are showed in Table 3-1.

0	1	2	3	4	5	6	7
1.00	0.95	0.74	0.69	1.16	0.92	1.15	1.06

8	9	10	11	12	13	14
0.77	0.89	0.61	1.01	0.84	1.07	1.02

Table 3.1. Tx relative gains

In the same way, phase values of each sensor are obtained, using channel 0 as reference. They are showed in Fig. 3-3.

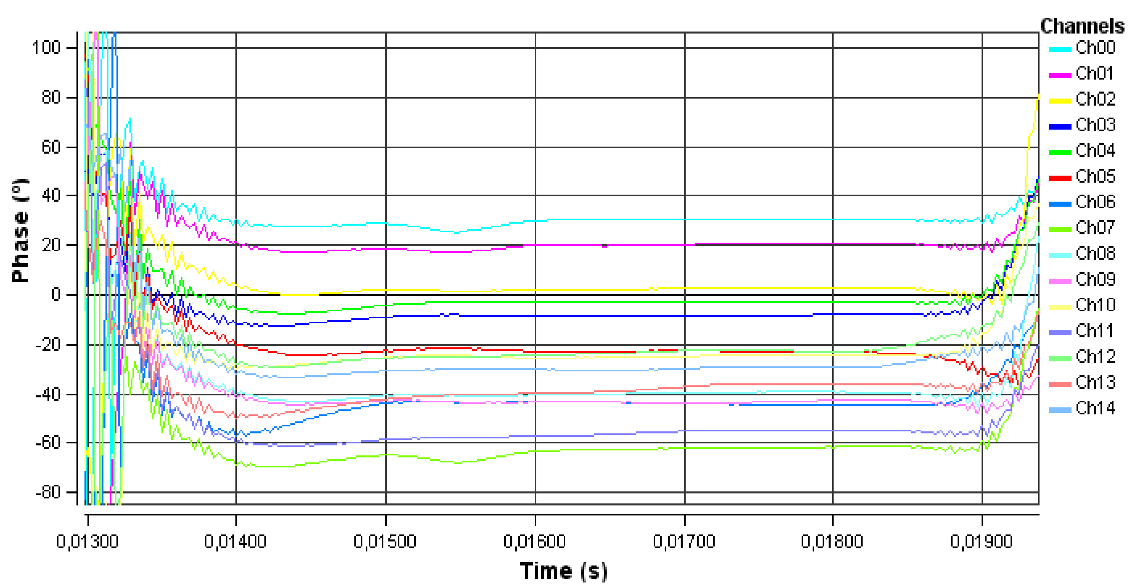

Fig. 3.3. Tx phase values

The average of the phase for each channel is calculated for the pulse length, and relative phases are obtained. They are shown in Table 3-2.

0	1	2	3	4	5	6	7
-49.0	-45.8	-52.3	-53.9	-41.5	-56.1	-74.2	-92.6

8	9	10	11	12	13	14
-70.5	-76.8	-63.3	-101.6	-78.0	-103.8	-108.4

Table 3.2. Tx relative phases (º)

The beampattern is calculated by steering the array from -90º to 90º, using classical beamforming techniques, and obtaining the maximum value from the matched filter output. Fig. 3-4 shows the obtained beampattern when the relative gains and phases of the sensors are not compensated. Fig. 3-5 shows the beampattern with relative gain and phase compensations before the beamforming is applied.

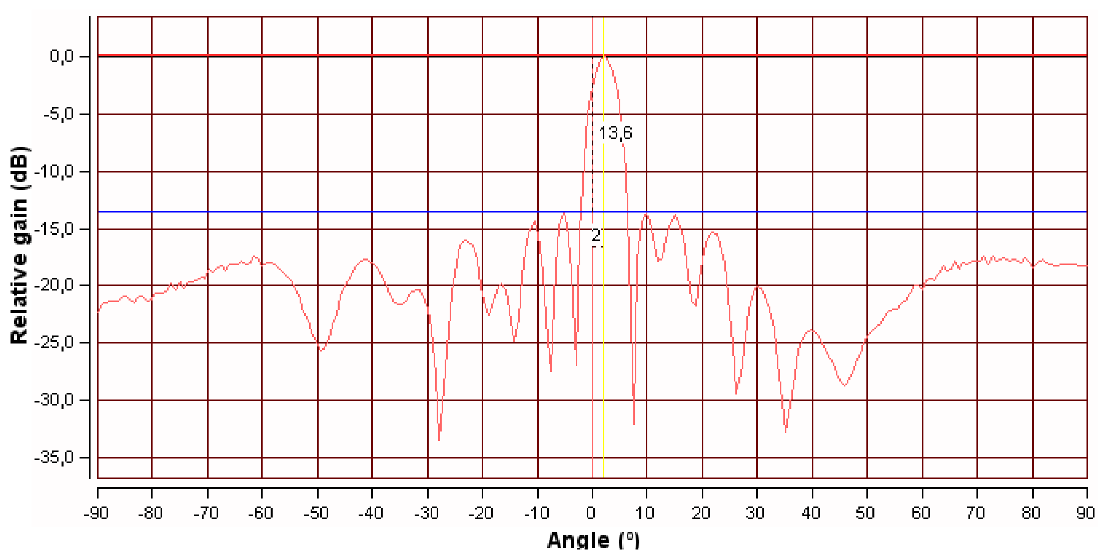

Fig. 3.4. Tx beampattern without compensation

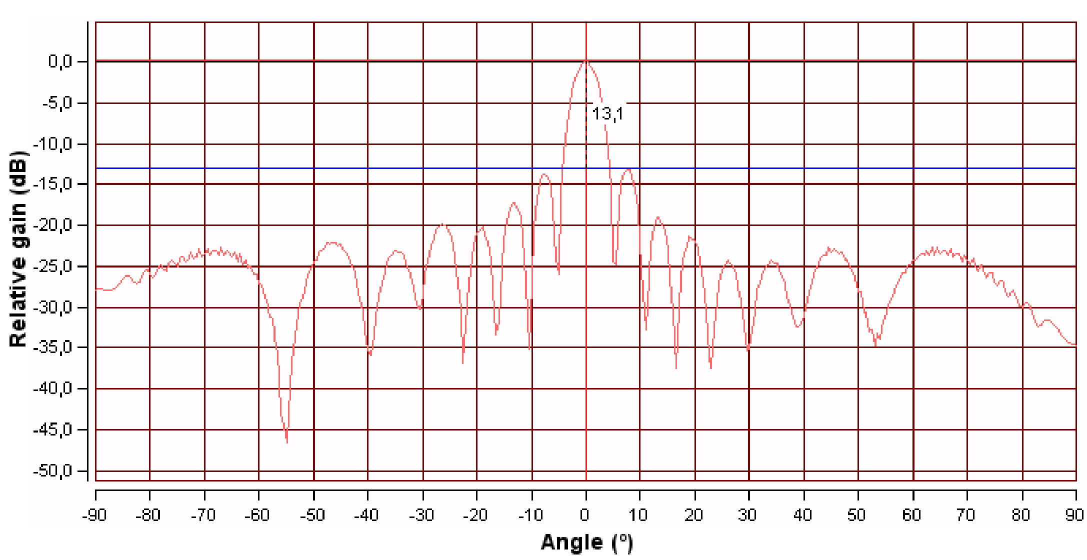

Fig. 3.5. Tx beampattern with compensation for 0º

Parameters obtained with and without gain and phase compensations are shown in Table 3-3.

	Without compensation	With compensation
Aiming error	2º	0º
Sidelobe level	13.6dB	13.1dB

Table 3.3. Tx beampattern parameters

To analyse if the calibrations of relative module and phase were independent of the steering angle, the system has been calibrated with the data obtained with the reference microphone placed at 0º, but with the reference microphone positioned now at -15º (with the same range). The obtained beampattern is presented in Fig. 3-6, where it is shown that the relative phase of the sensors of the Tx array under test does not depend on the steering angle. Therefore, the calibration in one angle is enough.

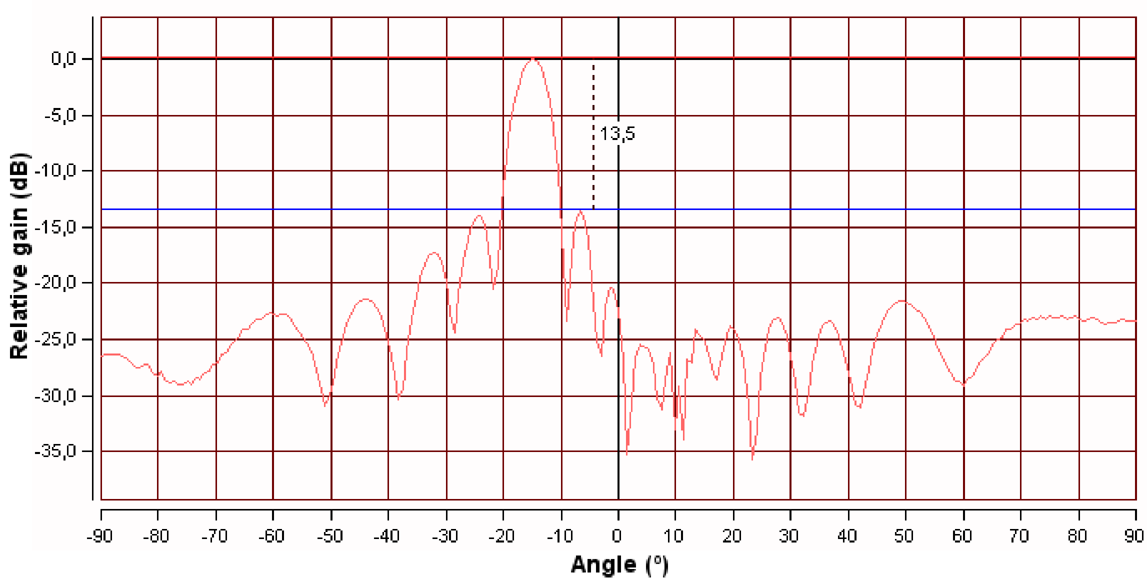

Fig. 3.6. Tx beampattern pointing to -15º with compensation for 0º

4. Receiver array calibration

A sinusoidal pulse of 7 kHz and 5 ms width is used with a reference loudspeaker located at 4.2 m range and 0º from the axis normal to the array. Also, in this case, spherical waves are assumed. A pulse signal is transmitted by the reference loudspeaker, and immediately, the signals received in the microphone array are recorded. The module and phase of the received signals can be obtained by means of the processing algorithm. The obtained module values are shown in Fig. 4-1.

Relative gains are obtained by means of the amplitude normalisation of each channel regarding channel 0. These relative gains are shown in Table 4-1. In the same way, phase values are obtained, using channel 0 as reference. These phases are shown in Fig. 4-2. The average of the phase of each channel is calculated for the pulse length. Relative phase values are obtained and shown in Table 4-2.

The beam-pattern is calculated by steering the array from -90º to 90º, using the classic beam-forming techniques, and obtaining the maximum value from the matched filter output. Fig. 4-3 shows the beam-pattern when the relative gain and phase of the sensors are not compensated. Fig. 4-4 shows the corresponding beampattern when relative gain and phase compensation is employed. The parameter values obtained with and without gain and phase compensation are shown in Table 4-3.

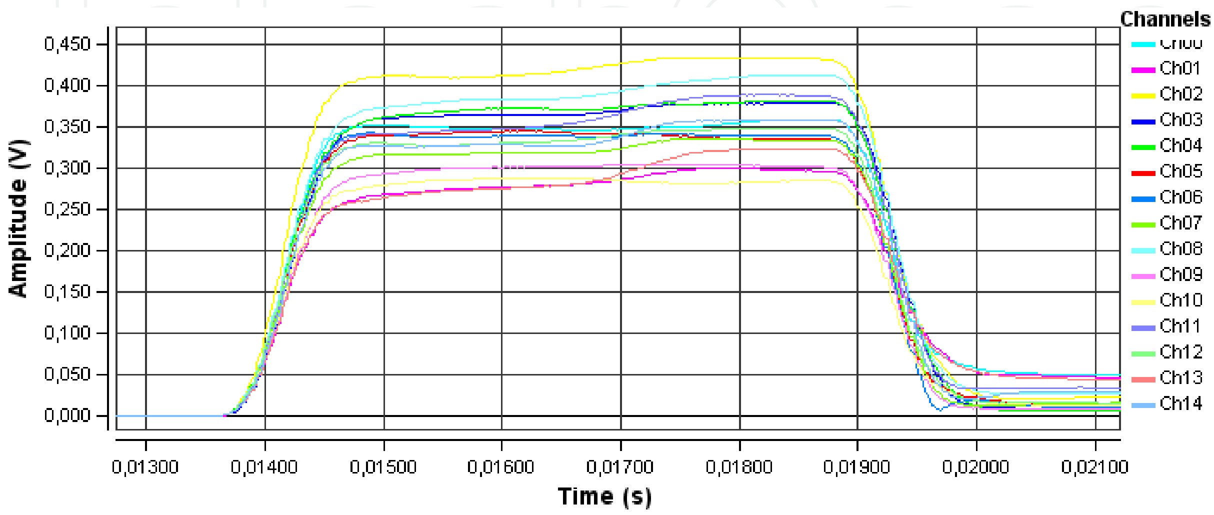

Fig. 4.1. Rx module values

0	1	2	3	4	5	6	7
1.00	0.82	1.21	1.06	1.07	0.97	0.97	0.93

8	9	10	11	12	13	14
1.13	0.86	0.81	1.05	0.97	0.84	0.97

Table 4.1. Rx relative gains

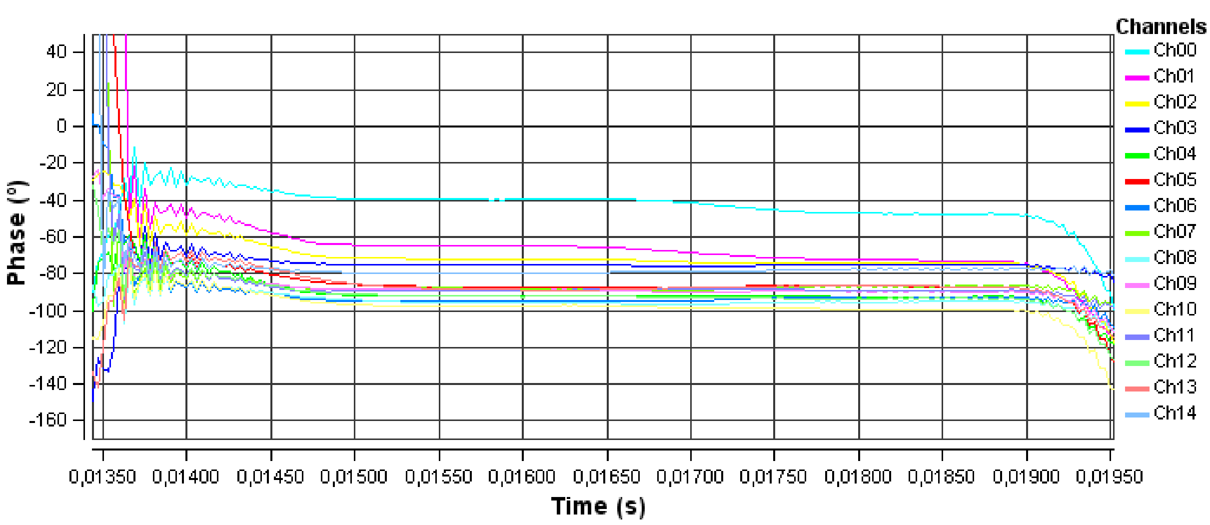

Fig. 4.2. Rx phase values

0	1	2	3	4	5	6	7
-29.6	-47.5	-45.6	-42.3	-54.8	-46.7	-52.1	-45.1

8	9	10	11	12	13	14
-53.7	-49.0	-60.9	-55.6	-65.2	-66.7	-65.6

Table 4.2. Rx relative phases (º)

	Without compensation	With compensation
Aiming error	2º	0º
Sidelobe level	12.6dB	13.2dB

Table 4.3. Rx beampattern parameters

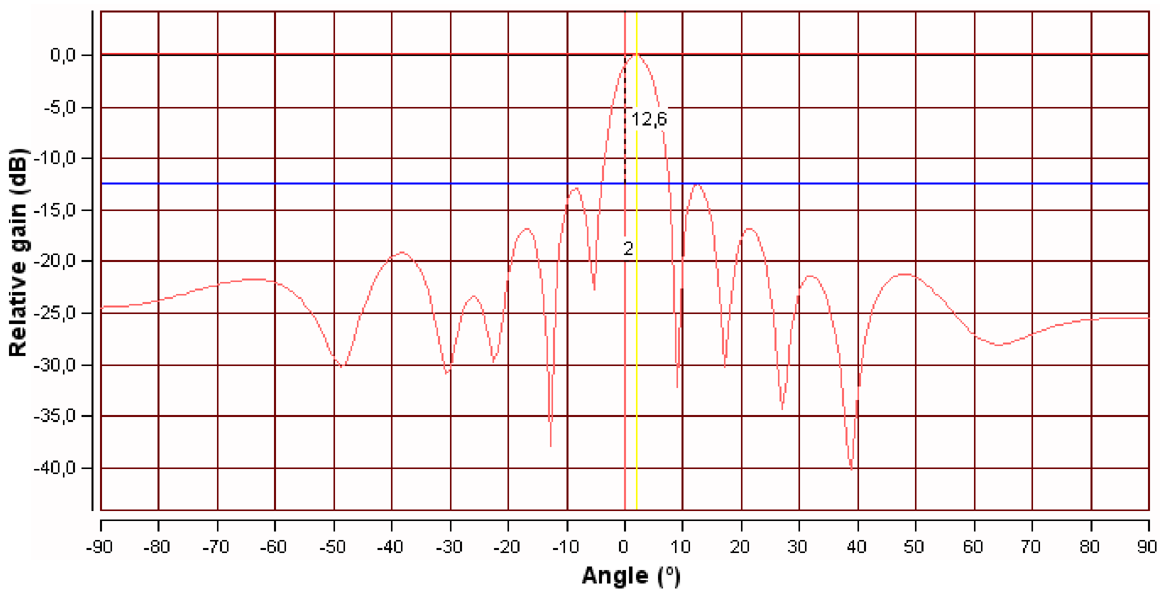

Fig. 4.3. Rx beampattern without compensation

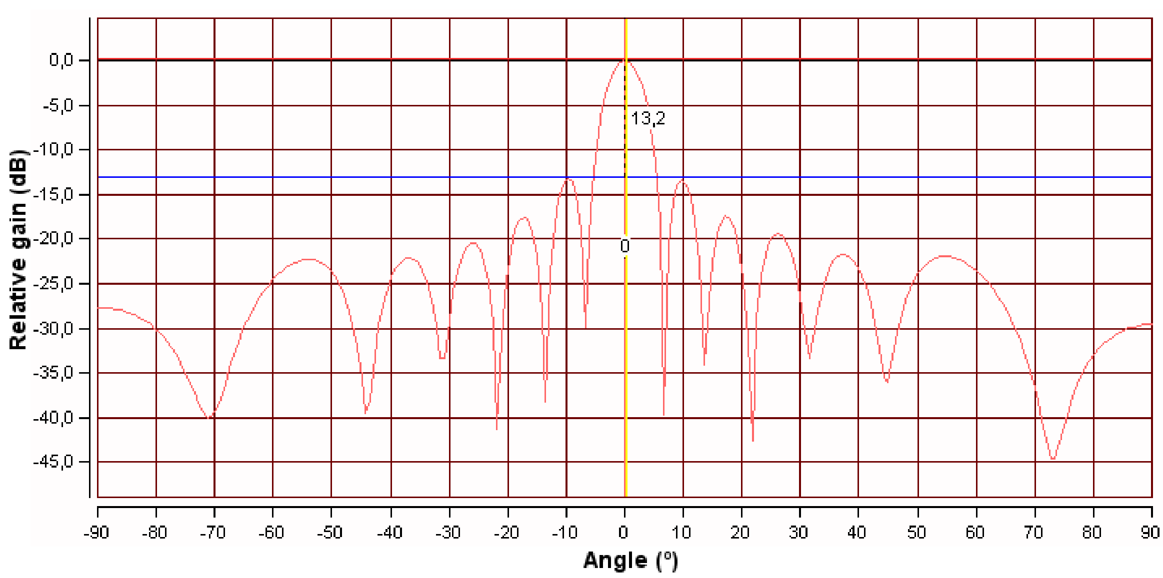

Fig. 4.4. Rx beampattern with compensation for 0º

Using the calibration data obtained with the loudspeaker pointing to with the reference loudspeaker placed now at -15º (in the same range), the independence of module and phase calibrations from the steering angle is analysed. The beampattern obtained is shown in Fig. 4-5. It shows that relative phases of the Rx sensors do not depend on the steering angle. Therefore, calibrating in one angle is enough.

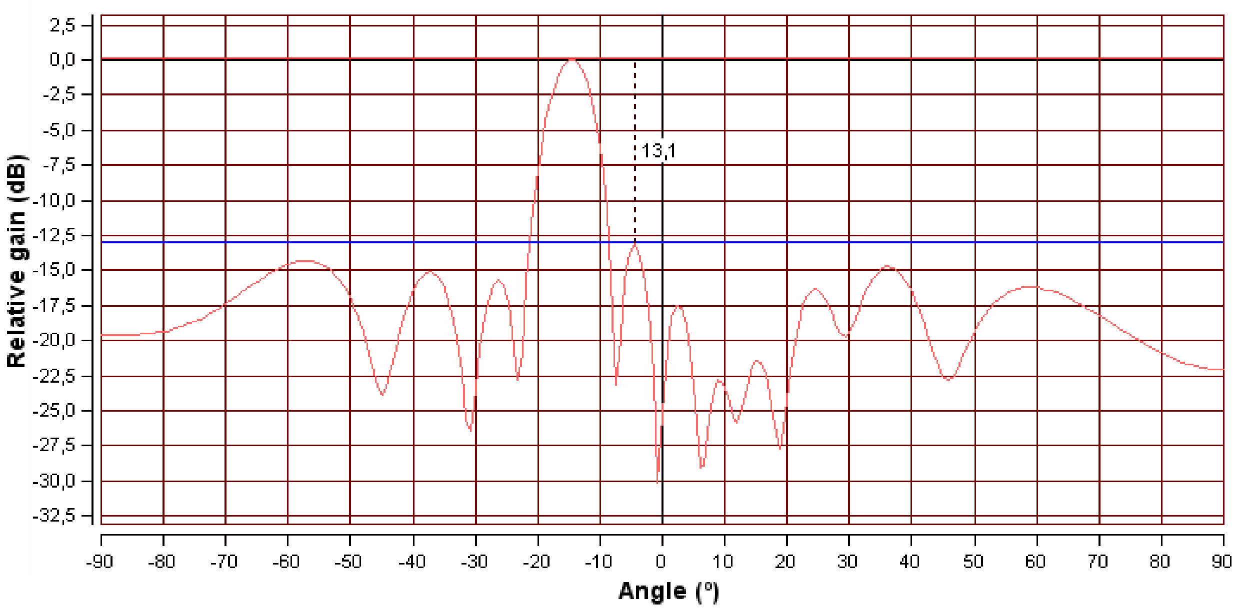

Fig. 4.5. Rx beampattern receiving at -15º with 0º compensation

5. Verification of calibration independence from steering angle

To check the independence of the phase and gain calibrations from the steering angle, these calibration methods have been proved in the same radar system, but with different transmitter and receiver arrays. In this case, the acoustic transmitter array is composed of 8 tweeters, while the acoustic reception array is composed of 8 electret condenser microphones. Fig. 5-1 shows the acoustic Tx and Rx arrays employed for verification of the calibration independence from the steering angle.

Fig. 5.1. Transmission (above) and reception (below)

5.1 Transmitter array calibration

Actually, the applied calibration method is exactly the same as shown in Section 3. It applies the same reference microphone, located opposite to the Rx array on a perpendicular axis to its plane (broadside). The only difference is that in this case, a sinusoidal pulse of 6 kHz and 0.5 ms width is used, and the band-pass filter employed has a frequency range from 5 kHz to 7 kHz. Normalising the amplitude of each channel, regarding to channel 0, the relative gains are obtained and presented on Table 5-1.

0	1	2	3	4	5	6	7
1.00	0.58	0.68	0.77	0.82	0.79	0.45	1.02

Table 5.1. Tx relative gains

The average of the phase for each channel is calculated over the pulse length, and the following relative phase table is obtained.

0	1	2	3	4	5	6	7
0.00	33.3	12.2	15.	50.6	44.2	34.8	55.9

Table 5.2. Tx relative phase

The beampattern is calculated by steering the array from -90º to 90º. Fig. 5-2 shows the beampattern when the relative gain and phase of the sensors are not compensated. Fig. 5-3 shows the corresponding beampattern when relative gain and phase compensation is employed. The parameter values obtained with and without gain and phase compensations are shown in Table 5-3.

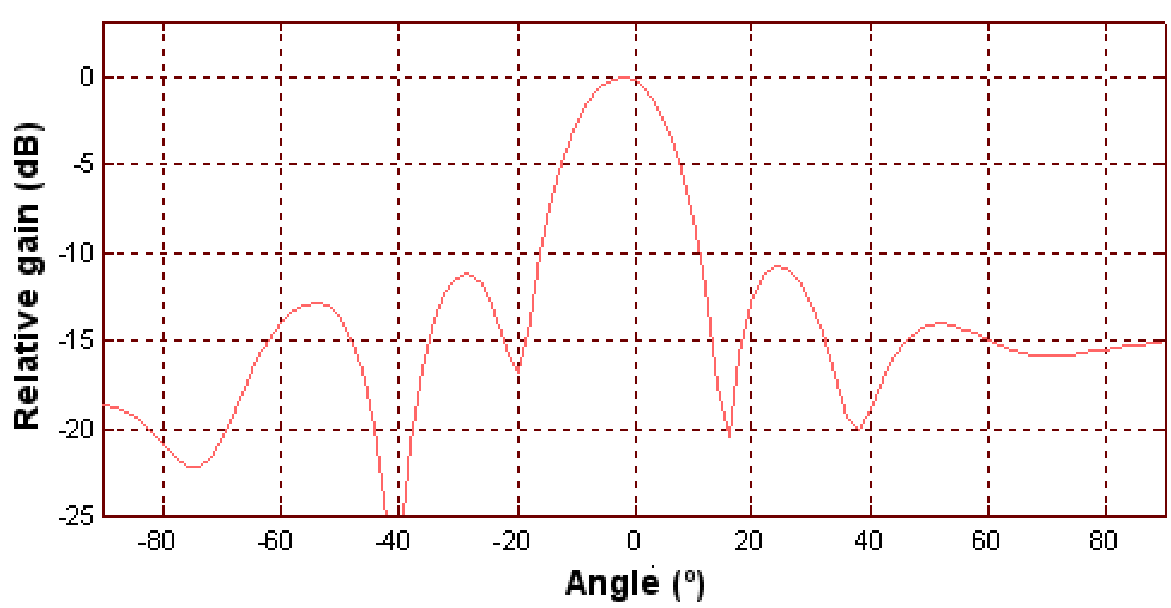

Fig. 5.2. Tx 0º beampattern without compensation

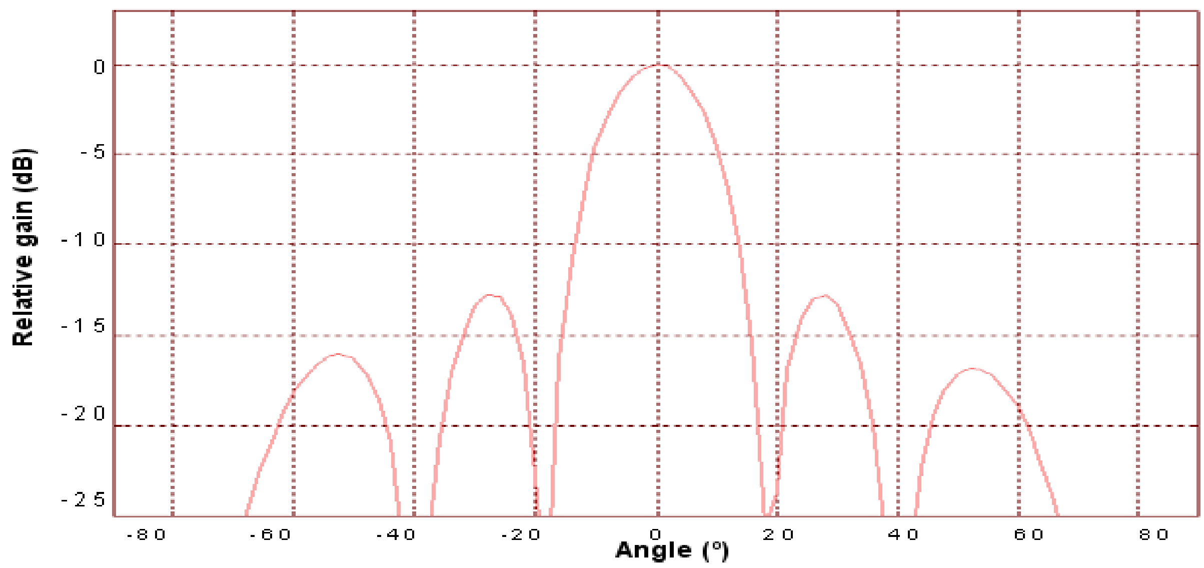

Fig. 5.3. Tx 0 º beampattern with compensation

	Without compensation	With compensation
Aiming error	2º	0º
Sidelobe level	10.8dB	12.75dB

Table 5.3. Tx beampattern parameters

Using the calibration with a 0º reference microphone and the reference microphone placed now at -15º (in the same range), the beampattern obtained is presented in Fig. 5-4.

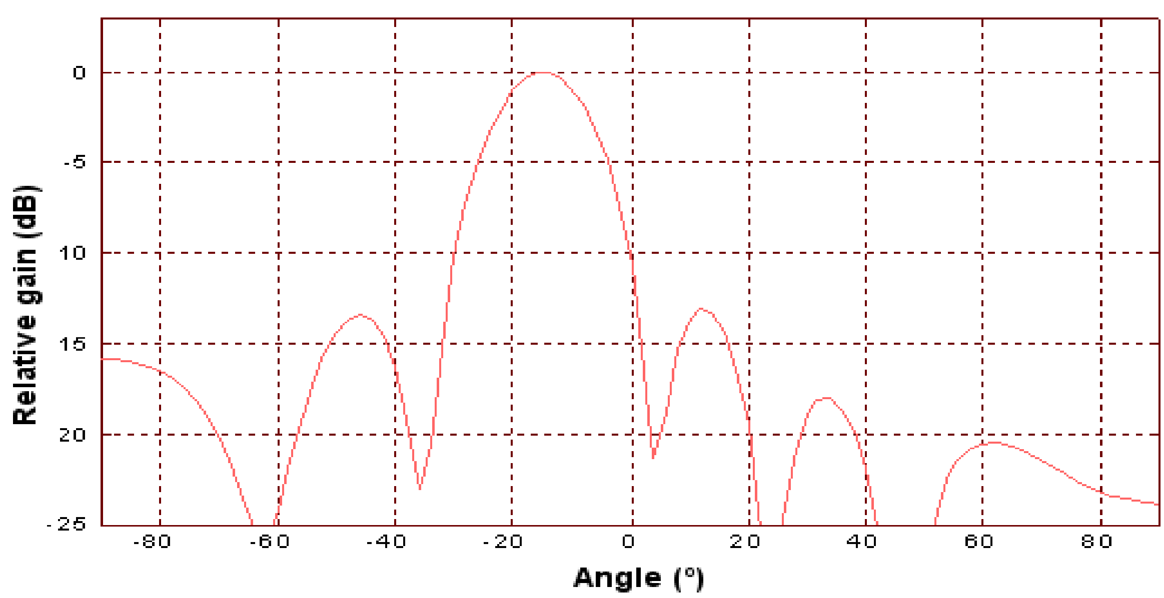

Fig. 5.4. Tx (-15) º beampattern with 0º compensation

As shown in Section 4, the relative phases of the sensors of the Tx array do not depend on the steering angle. Therefore, calibrating the Tx array for a single angle is enough.

5.2 Receiver array calibration

In this case, a sinusoidal pulse of 6 kHz and 0.5 ms width is used with a reference loudspeaker. Normalising the amplitude of each channel, regarding to channel 0, relative gains are obtained, which are presented on Table 5-4.

0	1	2	3	4	5	6	7
1.00	0.86	0.59	0.98	0.92	0.65	1.12	1.09

Table 5.4. Rx relative gains

The average of the phase for each channel is calculated over pulse length, and the following relative phase table is obtained.

0	1	2	3	4	5	6	7
0.00º	33.3º	12.2º	15.0º	50.6º	44.2º	34.8º	55.9º

Table 5.5. Rx relative phases

Also in this case, the beampattern is calculated by steering the array from -90º to 90º, using classical beamforming techniques, and obtaining the maximum value from the matched filter output. Fig. 5-5 shows the beampattern when the relative gain and phase of the sensors are not compensated. Fig. 5-6 shows the corresponding beampattern when relative gain and phase compensation is employed. The parameter values that have been obtained with and without gain and phase compensations are shown in Table 5-6.

	Without compensation	With compensation
Aiming error	-2º	0º
Sidelobe level	7.8dB	12.75dB

Table 5.6. Rx beampattern parameters

As the aim of this section is to analyse the calibration independence from the steering angle, the system has been calibrated with the data obtained with the reference tweeter placed at 0º, but with the reference tweeter placed at -15º (with the same range). The obtained beampattern is showed in Fig. 5-7. It shows that the relative phases of the microphones that compose the Rx array under test depend on the steering angle. For this Rx array, the behaviour of the relative phases of its microphones is different. In this case, it is very important to calibrate the Rx array for each steering angle.

To solve this problem, a new module and phase calibration has been made for pre-compensation of the theoretical phase for a -15º angle, and obtaining relative phase averages and gains, which are showed on Table 5-7. With these new values, the beampattern is recalculated and showed in Fig. 5-8. Therefore, in this case, for the Rx array, it is necessary to calibrate each steering angle used.

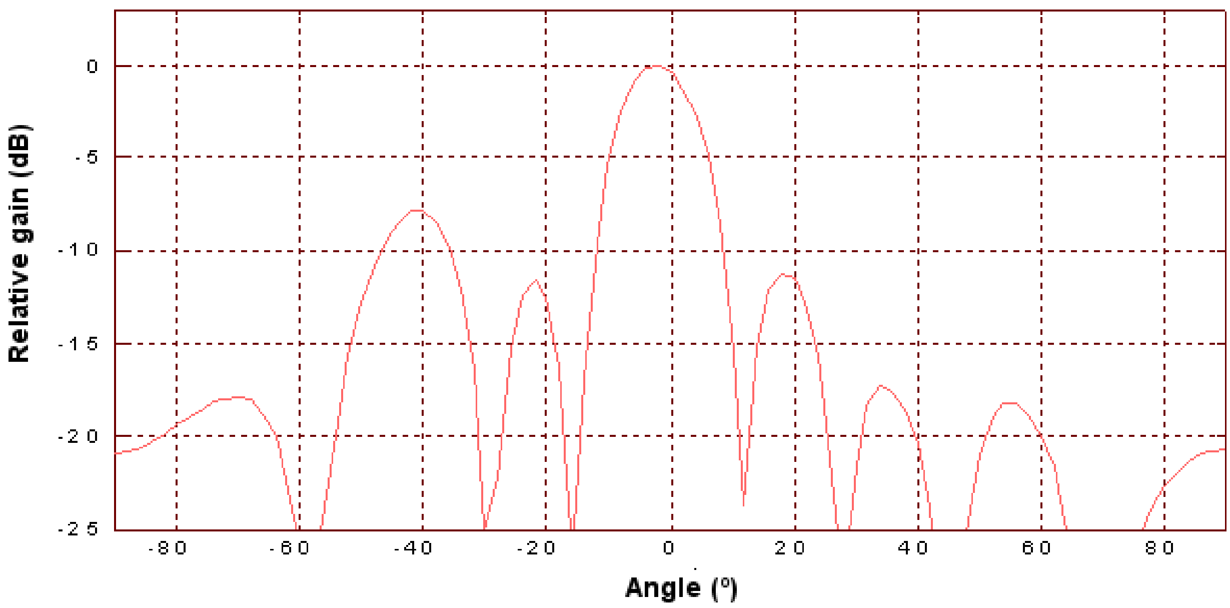

Fig. 5.5. Rx beampattern without compensation

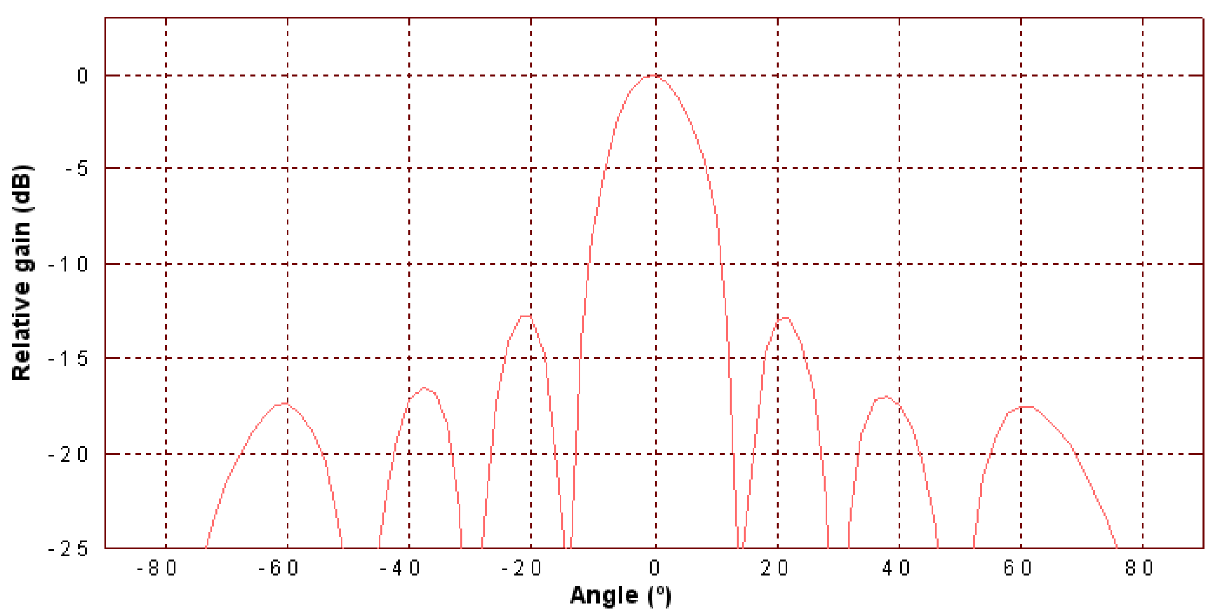

Fig. 5.6. Rx 0 º beampattern with compensation for 0º

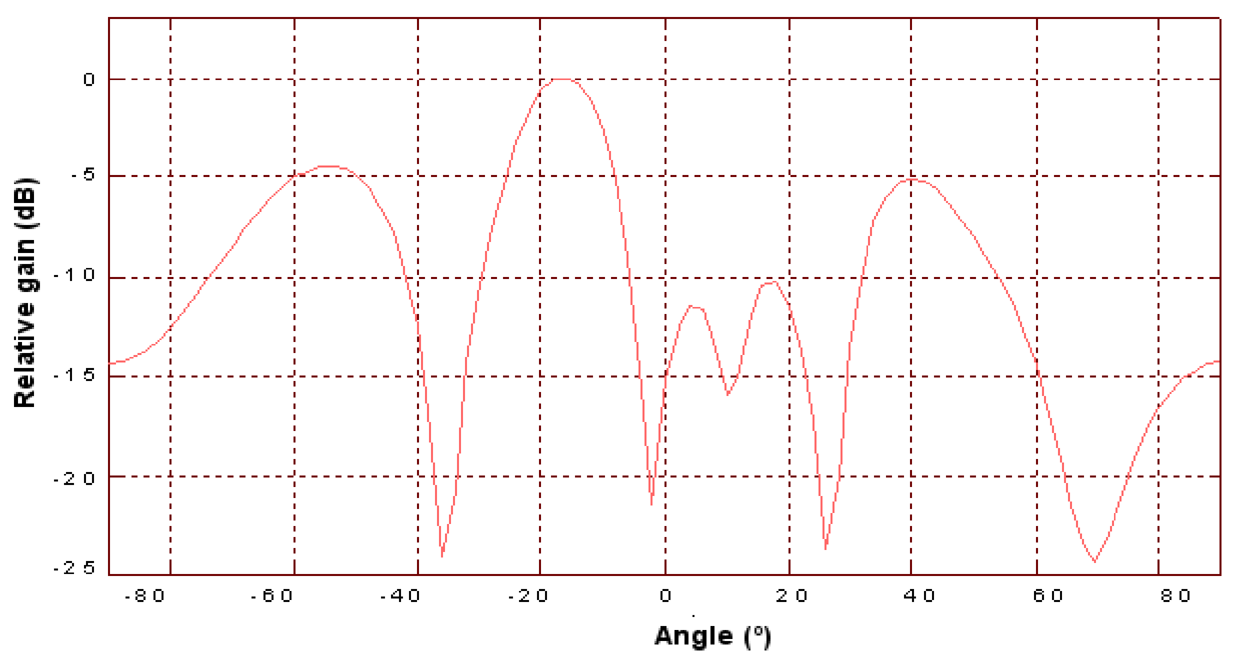

Fig. 5.7. Rx (-15°) beampattern with compensation for 0°

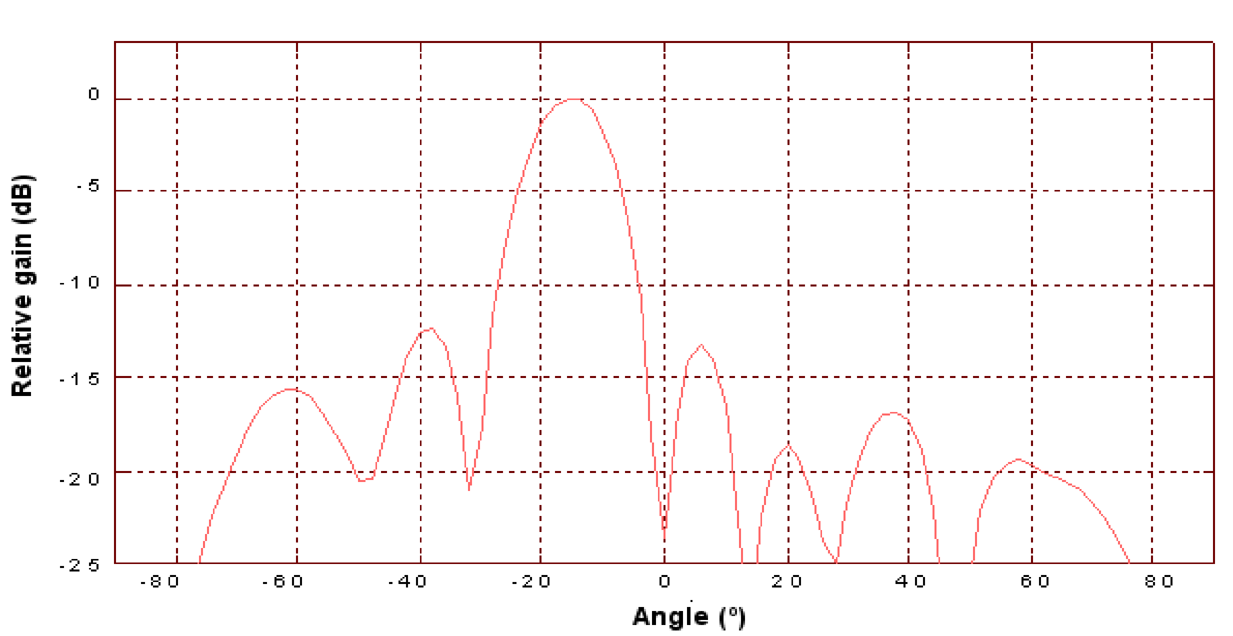

Fig. 5.8. Rx (-15) ° beampattern with compensation for (-15) °

	0	1	2	3	4	5	6	7
Amplitudes	1.00	0.86	0.59	0.98	0.92	0.65	1.12	1.09
Phases	0.00^{o}	42^{o}	87^{o}	-8^{o}	-277^{o}	-267^{o}	-42^{o}	-312^{o}

Table 5.7. Relative phases and gains

6. Conclusions

In this chapter, a method to calibrate sensor arrays to be employed as part of narrow band acoustic radars is shown. The proposed method allows obtaining compensation values, for both gain and phase, and for each sensor. Therefore, the obtained beampatterns improve considerably regarding to those without calibration. Beampatterns obtained with calibration approach the theoretical ones.

This work has shown that the independence of the relative phases of the sensors of the transmission and reception arrays from the steering angle depends on the particular arrays that are employed in the radar system. In other cases, the relative phases do not vary with the steering angle. In this case, a calibration in a unique angle is enough to obtain a good array performance; in some other cases, the calibration values depend on the steering angle, and a calibration for each steering angle used must be done.

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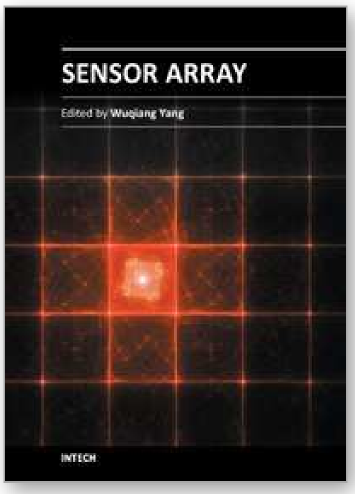

Sensor Array

Edited by Prof. Wuqiang Yang

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Sensor arrays are used to overcome the limitation of simple and/or individual conventional sensors. Obviously, it is more complicated to deal with some issues related to sensor arrays, e.g. signal processing, than those conventional sensors. Some of the issues are addressed in this book, with emphasis on signal processing, calibration and some advanced applications, e.g. how to place sensors as an array for accurate measurement, how to calibrate a sensor array by experiment, how to use a sensor array to track non-stationary targets efficiently and effectively, how to use an ultrasonic sensor array for shape recognition and position measurement, how to use sensor arrays to detect chemical agents, and applications of gas sensor arrays, including e-nose. This book should be useful for those who would like to learn the recent developments in sensor arrays, in particular for engineers, academics and postgraduate students studying instrumentation and measurement.

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