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The uncertainty in standardised sound power measurements: complying with ISO 17025

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1 INTRODUCTION

In the context of "testing laboratory" one of the most important aspect to deal with is the measurement result. Whenever decisions are based on measurement results, it is important to have some indication of the quality of the results. In every area concerning with noise measurement many standards are available but without an expression of uncertainty, it is impossible to judge whether two results are in compliance or not.

ISO/IEC 17025 is an international standard related with the competence of calibration and testing laboratories. It contains the requirements that testing and calibration laboratories have to meet if they wish to demonstrate that they operate to a quality system, are technically competent and are able to generate technically valid results. ISO/IEC 17025 deals specifically with the requirements for the competence of laboratories performing testing and calibration and for the reporting of the results, which may or may not contain opinions and interpretations of the results. The standard requires appropriate methods of analysis to be used for estimating uncertainty of measurement.

In this point of view, for a testing laboratory performing sound power measurement according to specific ISO standards and European Directives, the measurement of uncertainties is the most important factor to deal with.

Sound power level measurement, according to ISO 3744:1994 , performed with a limited number of microphones distributed over a surface enveloping a source is affected by a certain systematic error and a related standard deviation. Making a comparison of measurement carried out with different microphone arrays is difficult because results are affected by systematic errors and standard deviation that are peculiarities of the number of microphones disposed on the surface, their spatial position and the complexity of the sound field. A statistical approach could give an overview of the difference between sound power level evaluated with different microphone arrays and an evaluation of errors that afflict this kind of measurement. Despite the classical approach that tend to follow the ISO GUM this thesis present a different point of view of the problem related to the comparison of result obtained from different microphone arrays.

2 ISO/IEC 17025 and uncertainty

2.1 Introduction

Testing laboratories that would demonstrate they operate a management system, they are technically competent and that their results are technically valid, have to meet the requirements given by ISO 17025:2005 [3]. This standard is made on the basis of years of extensive experience in the implementation of the ISO/IEC Guide 25 [2] and EN 45001 [1] that have been replaced several years ago. As shown in Annex A of the ISO 17025:2005 this has been made on the basis of ISO 9001 (the first edition was based on ISO 9001:1994 [7] and the second and current edition has been based on ISO 9001:2000 [8]). The main differences between these two standards are due to more accuracy in evaluating the measurement uncertainty, demonstrate the technical competence in running testing or calibration procedures, demonstrate and ensure the competence of the personnel, ensure the measurement traceability and assure the quality of test and calibration results. Considering that ISO 17025 is more restrictive than ISO 9001 and considering that all the requirements given in ISO 9001 are covered by ISO 17025, laboratories that operate in accordance with ISO 17025 also operate in accordance with ISO 9001. On the other side laboratories that operate according to ISO 9001 do not operate in accordance to ISO 17025 because ISO 9001 do not demonstrate by itself the competence of the laboratory to produce technically and valid data and results.

As written in Chapter 1 of ISO 17025, it specifies the general requirements for the competence to carry out tests related to standard methods, non-standard methods and laboratory-developed methods. It is applicable to all organizations performing tests and it is for use by laboratories in developing their system for quality, administration and technical operations.

2.2 *Uncertainty concept*

According to the "International vocabulary of basic and general terms in metrology" [6], uncertainty of measurement is a parameter, associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand.

Knowledge of the uncertainty of measurement of testing results is fundamentally important for laboratories especially when they have to demonstrate the measurement accuracy and when results have to be compared with other coming from different laboratories. A measurement result with no information on its uncertainty is a result that it is not comparable at all. More over if the measurement conditions and the measurement method are not under control the measurement will be not valid or not good enough. Competent laboratories have to know the performance of their testing method and its associated uncertainty. What is really interesting is that the uncertainty is not related with a measurement instrument but a more precise uncertainty related with a testing method where many factors are involved from environment conditions to operators and instrumentations. Usually evaluating uncertainties seems to be simply when the testing method is standardised but sometimes standards shown discrepancy and errors and evaluating they uncertainty is difficult. This aspect will be investigated in chapter 4.

As introduced by ILAC document "according to ISO/IEC 17025, testing laboratories must report uncertainty estimates where specified by the method, where required by the client and/or where the interpretation of the result could be compromised by a lack of knowledge of the uncertainty. This should at least be the case where testing results have to be compared to other testing results or other numerical values, such as specifications. In any case laboratories should know the uncertainty associated with a measurement whether it is reported or not." [5]

In general, a measurement or a measurement method has imperfections that give rise to an error in the measurement result that is, usually formed by two components:

- random component that is imperfection due to unpredictable or stochastic variations of influence quantities. The effects of such variations are cause of variations in repeated observations of the measurand and for this reason it is not possible to get a compensation for this error in the measurement result. It is possible to reduced the influence of this error on the measurement just increasing the number of observations of the measurand. In a theoretical view increasing the number of observations, random error will tend to get zero value;
- systematic component that is an imperfection of the measurement due to a systematic component distinguishing on each observation of the measurand. As for the random component, systematic component can not be eliminated. The real difference is due to the fact that this error component can be quantified and corrected using correction factors or correction values. It is assumed that, after the correction, the expected value of the error coming from systematic effect is zero.

After this distinction in imperfections of the measurement it is very important distinguish the meaning of "error" and "uncertainty" where the first is the systematic component and the second is the random component. In the ISO GUM [4] the term "error" is defined as the difference between an individual result and the true value of the measurand and it is a single value. By the definition the value of a known error can be applied as a correction to the result. While "uncertainty" is correlated with lacks of knowledge of the value of the measurand and, furthermore, a complete knowledge requires an infinite amount of information.

The ISO GUM also define some sources of error that have influence of the final result:

- non-representative sampling;

- inadequately known of effects of environmental conditions or imperfect measurements of these;
- technical skills of personal involved in measurement;
- finite instrument resolution or discrimination threshold;
- approximation and assumptions incorporated in the measurement method procedure;
- variation in repeated observations of the measurand under apparently identical conditions.

In the ISO GUM uncertainties have been divided into two general groups based on their method of evaluation. The first has been named "Type A" and have been included calculations of uncertainty contributions from a series of repeated observations using statistical method. The second group has been named "Type B" and have been included all the other method that differ from "Type A". Every component of uncertainty are evaluated using appropriate method and each of those components is expressed as a "standard deviation" that is the "standard uncertainty". The standard uncertainty of a measurement result, when that result is obtained from the values of a number of other quantities, is termed "combined standard uncertainty" and denoted by u_c. As defined by ISO GUM, it is the estimated standard deviation associated with the result and is equal to the positive square root of the combined variance obtained from all variance and covariance components, however evaluated, using what is termed in this Guide the law of propagation of uncertainty. Each uncertainty component, defined from the standard uncertainty of each uncertainty source, are combined in order to produce an overall value of uncertainty that covers all that sources, the "combined standard uncertainty" u_c. Finally an "expanded uncertainty" U is obtained by multiplying the combined standard uncertainty by a coverage factor k. The intended purpose of U is to provide an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

The coverage factor is based on the level of confidence required for the purpose o the measurement. This factor is usually in the range of values from 2 to 3 that correspond to a particular level of confidence from 95 to 99 percent. The level of confidence is the level is the percentage of probability in which it is possible to find the real value.

The result of a measurement is then conveniently expressed as $Y = y \pm U$, which is interpreted to mean that the best estimate of the value attributable to the measurand Y is y, and that $y - U$ to $y + U$ is an interval that may be expected to encompass a large fraction of the distribution of value that could reasonably be attributed to Y. Such an interval is also expressed as $y - U \leq Y \leq y + U$.

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3 SOUND POWER LEVEL: STANDARDS AND DIRECTIVES

3.1 ISO 3744:1994

This Standard, which is part of the ISO 3740 series, specify methods for determining the sound power levels of machines, equipment and their sub-assemblies under essentially free field conditions near one or more reflecting planes (indoors or outdoors). As specified in ISO 3744:1994 [1] has been developed a method for determining the sound pressure levels on a measurement surface enveloping the source, and for calculating the sound power levels produced by the source. The sound power level is evaluated from the sound pressure level measurements because of the premise that the sound power of the source is directly proportional to the mean square sound pressure averaged over time and space

The value of the sound power level of a source determined according to the procedure given in this Standard is different from the true value because of some considerations. Measurement uncertainty associated with this measurement method is aroused from several factors which affect the results, some associated with the environmental conditions in the measurement laboratory and others with the experimental techniques. The measurement uncertainty depends on the standard deviation of reproducibility as presented in the standard and on a degree of confidence that is desired. The standard deviations, shown in ISO 3744, are associated with the test condition and procedures defined in it and not with the noise source itself. These values arise in part from variations between measurement laboratories, changes in atmospherics condition, outdoors environment, the acoustical properties of the reflecting plane, background noise, and the type and calibration of instrumentation. They are also due to variations in experimental techniques, including the size and shape of the measurement surface, number and location of microphone positions, sound source location, integration times, and determination of environmental corrections, if any. Moreover this standard deviation include the uncertainty associated with repeated measurement on the same conditions (standard deviation of repeatability) that is, usually, much smaller than the uncertainty associated with the inter-laboratory variability.

The accuracy used in this standard is of “grade 2” and, in it, have been defined some specifications:

- criterion for suitability of test environment, $K_2 \leq 2$ dB, that is a correction term that take into account the influence of reflected or absorbed sound on the surface sound pressure level. This value is 0 in case of a real free field with no sound absorption or sound reflection at all;
- limitation for background noise, $\Delta L \geq 6$ dB (if possible, exceeding 15 dB) and $K_1 \leq 1.3$ dB, that is the difference between the sound pressure level of the source under test and the sound pressure level without any sources on;
- precision of method for determining L_{WA} expressed as standard deviation of reproducibility, $\sigma_R \leq 1.5$ dB.

In the standard have been specified several requirements that are necessary in order to meet the purpose of the measurement conditions. First of all the test environment shall be free from reflecting objects other than a reflecting plane so that the source radiates into a free field over a reflecting plane. The source shall be enveloped by an hypothetical reference box or an hemisphere and the microphone shall be positioned on this surface. The surface of the hypothetical hemisphere has a surface of area given by the equation $S = 2\pi r^2$. The instrumentation system, as specified in the standard, shall meet the requirements for a type 1 instrument specified in IEC 651 or, in the case of integrating-averaging sound level meters, the requirements for a type 1 instrument specified in IEC 804. The filters used shall meet the requirements of IEC 225. All the adverse atmospheric conditions having effect on the microphones shall be avoid in order to reduce any possible errors in the measurement procedure.

The number of microphones used for the testing procedure have been defined with specific table and diagrams. For the measurement, the Standard required a minimum number of 9 microphone positions up to 20, equal distributed over the surface and so with equal areas of the measurement surface, but a reduction of these number positions is allowed in according with a preliminary investigation regarding noise emitted by families of machineries, when their pressure levels do not deviate more than 0.5 dB from those determined from measurement over a the compete set of microphone positions. Finally the microphone shall always be oriented in such a way that the angle of incidence of the sound waves is that for which the microphone is calibrated.

A spatial disposition of the microphones over the hypothetical surface is shown in Figure 1, Figure 2 and Figure 3 while their microphone coordinates are presented in Table 1. In this table have been presented all the 20 microphone positions for a complete hemisphere.

Microphone position	$\frac{x}{r}$	$\frac{y}{r}$	$\frac{z}{r}$
1	-0.99	0	0.15
2	0.50	-0.86	0.15
3	0.50	0.86	0.15
4	-0.45	0.77	045
5	-0.45	-0.77	0.45
6	0.89	0	0.45
7	-0.33	0.57	0.75
8	-0.66	0	0.75
9	0.33	-0.57	0.75
10	0	0	1.0
11	0.99	0	0.15
12	-0.50	0.86	0.15
13	-0.50	-0.86	0.15
14	0.45	-0.77	0.45
15	0.45	0.77	0.45
16	-0.89	0	0.45
17	-0.33	-0.57	0.75
18	0.66	0	0.75
19	-0.33	0.57	0.75
20	0	0	1.0

Table 1 - Coordinates of key microphone positions (1-10) and additional microphone positions (11-20)

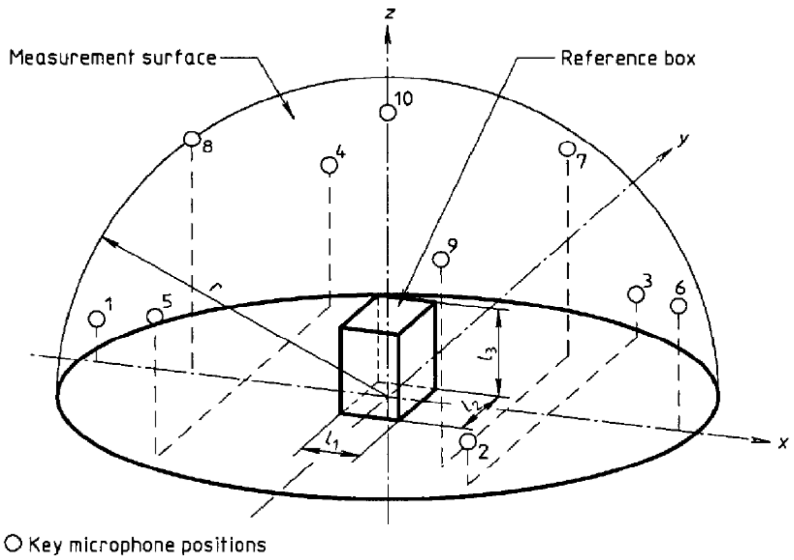

Figure 1 - Microphone array on the hemisphere - Key microphone positions

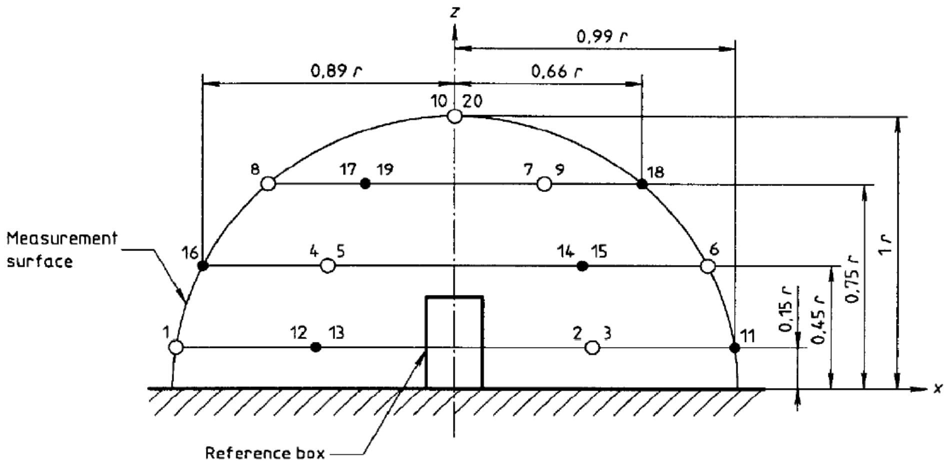

Figure 2 - Microphone array on the hemisphere - lateral view

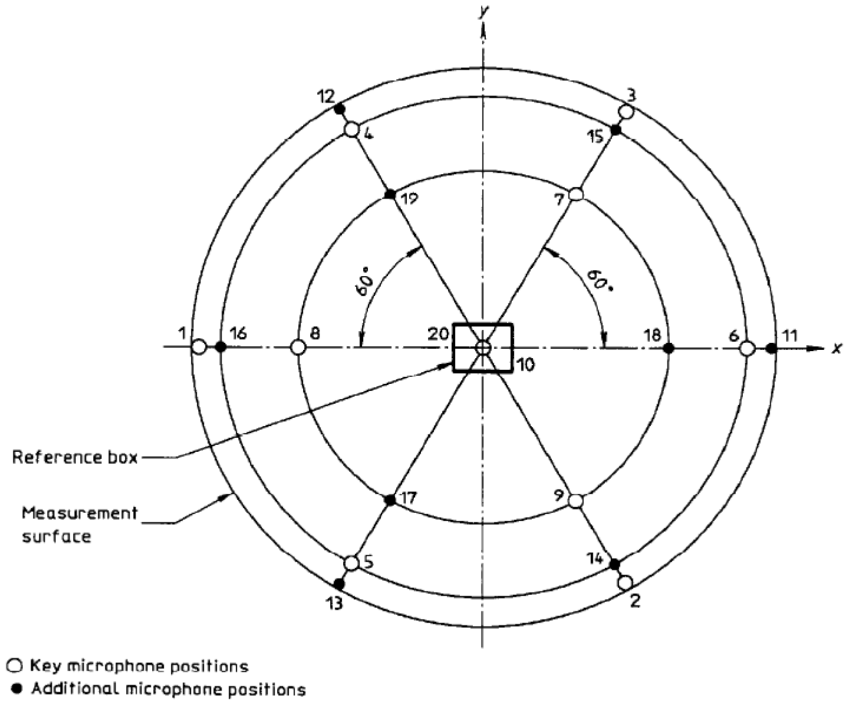

Figure 3 - Microphone array on the hemisphere - top view

The complete calculation for the sound power level evaluated using the ISO 3744 is listed as presented in the Standard.

3.1.1 Calculation of sound pressure level and sound power level

For the A-weighted sound pressure level or the level in each frequency band of interest, the Standard required to calculate an average sound pressure level over the measurement surface using the equation 3.1:

$$\overline{L_p^i} = 10\log_{10}\left[\frac{1}{N}\sum_{i=1}^{N}10^{0.1L_{pi}^i}\right]dB$$

3.1

Where:

$\overline{L_p^i}$ is the sound pressure level averaged over the measurement surface, in decibels, with the source under test in operation;

L_{pi}^i is the sound pressure level at the i^{th} microphone position, in decibel;

N is the number of microphone positions.

If A-weighted sound pressure levels are calculated from frequency band pressure levels, the standard required that equation 3.2 shall be used.

$$L_{pA} = 10\log_{10}\left[\sum_{j}10^{0.1(L_{pj}+A_i)}\right]dB$$

3.2

Where:

L_{pj} is the frequency band pressure level, in decibel, in band *j*;

A_j is the A-weighting value at the centre frequency of band *j*, as given in Table 2.

Octave-band centre frequencies	One-third-octave band centre frequencies	A-weighting values A_j
63	50 63 80	-30.2 -26.2 -22.5
125	100 125 160	-19.1 -16.1 -13.4
250	200 250 315	-10.9 -8.6 -6.6
500	400 500 630	-4.8 -3.2 -1.9
1000	800 1000 1250	-0.8 0 0.6
2000	1600 2000 2500	1.0 1.2 1.3
4000	3150 4000 5000	1.2 1.0 0.5
8000	6300 8000 10000	-0.1 -1.1 -2.5

Table 2 - A-weighting values, A_j

3.1.2 Correction for background noise

As defined the correction K_1 (A-weighted or in frequency bands) is given by:

$$K_1 = -10\log_{10}(1-10^{-0.1\Delta L})\ \text{dB} \tag{3.3}$$

Where:

$$\Delta L = \overline{L_p^i} - \overline{L_p^{ii}} \tag{3.4}$$

and

$$\overline{L_p^{ii}} = 10\log_{10}\left[\frac{1}{N}\sum_{i=1}^{N}10^{0.1L_{pi}^{ii}}\right]dB \tag{3.5}$$

Where:

$\overline{L_p^i}$ is the sound pressure level averaged over the measurement surface, in decibels, with the source under test in operation;

$\overline{L_p^{ii}}$ is the sound pressure level of the background noise averaged over the measurement surface, in decibels;

N is the number of microphone positions.

If ΔL > 15 dB, no correction is made, while ΔL is between 6 dB and 15 dB the correction factor shall be evaluated. If the 6 dB criterion is not satisfied , the accuracy of the results is reduced.

3.1.3 *Correction for the test environment*

For open test sites which consists of a hard, flat ground surface, such as asphalt or concrete, and with no sound-reflecting objects within a distance from the source equal to three times the greatest distance from the source centre to the lower measurement points, it is assumed that the environmental correction K_2 is less than or equal to 0,5 dB and is, therefore, negligible.

3.1.4 *Calculation of surface sound pressure*

The surface sound pressure level is defined as the sound pressure level averaged over the measurement surface and the correction factors K_1 and K_2.

$$\overline{L_{pf}} = \overline{L_p^i} - K_1 - K_2 \qquad \textbf{3.6}$$

3.1.5 *Calculation of sound power level*

The sound power level, L_W, shall be calculated as:

$$L_W = \overline{L_{pf}^{i}} + 10\log_{10}\left(\frac{S}{S_0}\right) \text{dB}$$

3.7

Where:

S is the area of the measurement surface, in square metres;

S_0 = 1 m²

3.1.6 *Directivity index*

It is a measure of the extent to which a source radiates sound predominantly in one direction. On each microphone position shall be evaluated as:

$$DI_i = L_{pi}^{*} - \overline{L_p^{*}}$$

3.8

Where:

L_{pi}^{*} is the sound pressure level at microphone position *i*, corrected for background noise;

$\overline{L_p^{*}}$ is the sound pressure level averaged over the measurement surface, corrected for the background noise.

3.2 *Directive 2000/14/EC*

2000/14/EC Directive [3] is the European Directive that is focused on the noise emission of machineries used outdoor. Each Member State have to guarantee that each machine, included in this directive, is complying with the given requirements in order to compare the noise emission all over the Member State. This Directive is based on the principles and concepts on a new approach to technical harmonization and standards. For this purpose the manufacturer or his authorised representative shall measure the sound power level of the equipment and give the indication of the guaranteed sound power level to the equipment and ensure that the equipment is accompanied by an EC declaration of conformity in order to certify thereby that the equipment is in conformity with the provisions of this Directive.

The aim of this Directive is to harmonise the laws of the Member States relating to noise emission standards, conformity assessment procedures, marking, technical documentation and collection of data concerning the noise emission in the environment of equipment for use outdoors. "Equipment for use outdoors" means all machinery defined in Article 1 of Directive 98/37/EC [4] that is intended to be used in the open air and which contributes to the environmental noise exposure.

This directive is based on the measurement of the sound power level according to ISO 3744:1995 and 3746:1995 [2] but several discrepancies are highlighted:

- Measurement uncertainty: as defined in the Directive, the measurement uncertainties are not taken into account in the framework of conformity assessment procedures in the design phase;
- Calculation of surface sound pressure level: Attach III of the Directive define that the surface sound pressure level shall be determined at least three times. If at least two of the determined values do not differ by more than 1 dB, further measurements will not be necessary. Otherwise the measurements shall be continued until two values differing by no more than 1 dB are obtained. The A-weighted surface sound pressure level to be used for calculating the sound power level is the arithmetic mean of the two highest values that do not differ by more than 1 dB;
- Additional microphone positions on the hemispherical measurement surface (EN ISO 3744:1995). The most difference between the measurement method given by ISO 3744 and

Directive 21000/14/EC is due to the additional information to clauses 7.2.1 and 7.2.2 of ISO 3744:1995. The Directive define that a set of 12 microphones on the hemispherical measurement surface may be used. The number (12) of microphones may be reduced to six, but the microphone positions 2, 4, 6, 8, 10 and 12 following the requirements of clause 7.4.2 of ISO 3744:1995 have to be used in any case. Generally the arrangement with six microphone positions on a hemispherical measurement surface has to be used. If there are other specifications laid down in a noise test code in this Directive for a specific equipment, these specifications shall be used. The location of these 12 microphone positions distributed on the surface of a hemisphere of radius *r* are listed in the form of Cartesian coordinates in the Table 3. The radius *r* of the hemisphere shall be equal to or greater than twice the largest dimension of the reference parallelepiped. The radius of the hemisphere shall be rounded to the nearest higher of the following values: 4, 10, 16 m. In Figure 4 is shown the spatial disposition of the microphone array.

Microphone position	$\frac{x}{r}$	$\frac{y}{r}$	z
1	1	0	1.5 m
2	0.7	0.7	1.5 m
3	0	1	1.5 m
4	-0.7	0.7	1.5 m
5	-1	0	1.5 m
6	-0.7	-0.7	1.5 m
7	0	-1	1.5 m
8	0.7	-0.7	1.5 m
9	0.65	0.27	0.71 *r*
10	-0.27	0.65	0.71 *r*
11	-0.65	-0.27	0.71 *r*
12	0.27	-0.65	0.71 *r*

Table 3 - Coordinates of the 12 microphone positions – Directive 2000/14/EC

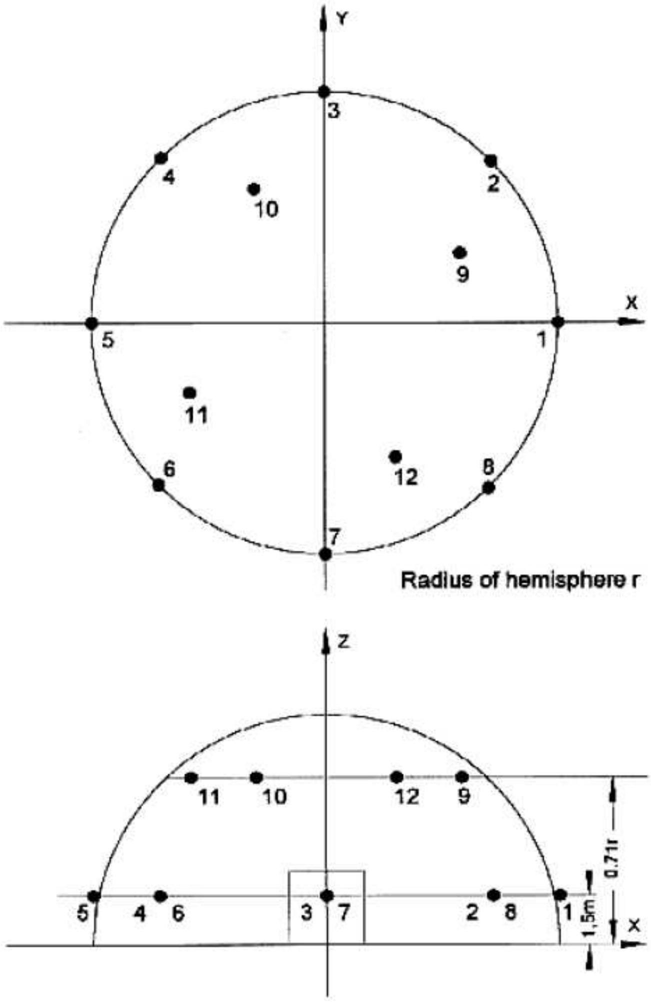

Figure 4 - Microphone array on the hemisphere - Directive 2000/14/EC

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4 STANDARDISED SOUND POWER DETERMINATION: SYSTEMATIC ERROR AND STANDARD DEVIATION

4.1 Introduction

Sound power level measurement, according to ISO 3744:1994 [2], performed with a limited number of microphones distributed over a surface enveloping a source is affected by a certain systematic error and a related standard deviation. Comparing measurement carried out with different microphone arrays is difficult because systematic errors and standard deviation are peculiarities of the number of microphones disposed on the surface, of their spatial position and of the complexity of the sound field. A statistical approach could give an overview of the difference between sound power level evaluated with different microphone arrays and an evaluation of errors that afflict this kind of measurement.

Uncertainty related to determination of sound power levels, using sound pressure method, could be difficult to figure out but at the same time it is an important aspect to deal with. Some sources of uncertainties are easy to evaluate but some of they are difficult to manage with. As presented by Loyau T. [7] until now these uncertainties have been obtained experimentally by using inter-laboratory measurement, but they are generally overestimated because it has been obtained a value that is the same for every acoustic sources even if measured using different microphone arrays. This approach tend to rise the total uncertainty to higher values because sound power levels measured in different environmental conditions, with different operators, with different instrumentations and different facilities are used to get an uncertainty value that has to cover all the situations, but measurement using different microphone arrays are affected by different systematic error and standard deviation. While systematic error could be adjusted, standard deviation is an estimation of the "scattering" of measurement results in the form of measurement uncertainty.

A new approach of calculation of systematic error and its uncertainty has been studied in order to define a specific error and uncertainty for a given acoustic source that could be described using descriptors as the maximum Directivity Index and the microphone array used for the test.

The purpose is to shown differences between measurement carried out according to the ISO 3744:1994 with a microphone array composed by 10, 19 and 29 positions on a hemispherical surface enveloping the noise source and a microphone array composed by 6 and 12 microphone positions, on the same hemispherical surface, as described in the 2000/14/EC Directive.

4.2 Noise source

For a theoretical model a noise source has been reproduced using mathematical equation and, for this purpose, a model has been developed in order to evaluate the sound power level generate from noise sources made by two point sources acting with coherent interaction with different amplitude and phase and that have been evaluated in many different setup (presented in this chapter) with several methods in the frequency range from 50 to 10.000 Hz in 1/3 octave bands. Moreover all the data has been A-weighted. The two point sources have been driven emitting pure tones, the various frequency contribution, given by each source, have been weighted in agreement with pink noise simulating a more realistic sound field and to do that the complex pressure has been multiplied by a factor:

$$Factor = \frac{1}{\omega * \sqrt{\omega}} \qquad \textbf{4.1}$$

The choice of two point sources has been done cause of the simplicity to deal with mathematical equation and because any source that change its volume as a function of time may be approximated by a monopole source at frequencies where it is small compared with the wavelength. Furthermore the sources can act with the same or different phase in order to realize simply and complex sound field. The two sources have been placed above the reflecting floor with a minimum height of 0.2 meter to a maximum of 1.4 meter and have been moved, independently, around the hemisphere centre between -1 to 1 meter in x and y directions, in order to generate a huge number of sound sources with different directivity index.

4.3 Mathematical models

Many simulations have been evaluated and compared checking any possible mistake in the model definition. For this purpose several different method have been used to evaluate the total sound power of a noise source and the data obtained with these methods have been compared.

The evaluation have been done using methods listed below:

- Reference system: Sound power level radiated by a single monopole;
- Coherent reference system: Sound power level radiated by two monopoles acting with coherent interaction;
- Incoherent reference system: Sound power level radiated by two monopoles acting with incoherent interaction;
- True intensity on an box surface and on a hemisphere, using the relation between sound power and the sound intensity;
- Sound intensity in far field on a hemisphere;
- Sound power according ISO 3744:1994.

All the mathematical models used to evaluate the data have been validated on many sources setup. Different amplitude and phase have been checked and the system has been validated on the basis of these results.

4.3.1 Reference system

All the simulated data have been referred to the sound power level emitted by a monopole evaluated under free field condition and affected by the ground reflection [6].

$$P_{a\_reference} = \frac{\rho c k^2 |Q|^2}{8\pi}\left(1+\frac{\sin 2kh}{2kh}\right)$$

4.2

Where h is the distance from the ground.

Equation 4.2 gets the sound power radiated by a monopole, obtained by integration of the sound intensity over a spherical surface. Some other considerations must be done with this equation with reference to the used methods. To get the sound power radiated by two monopoles, that act with incoherent interaction, a simply sum of the two sound power radiated by each source has been done:

$$P_{a\_reference} = \left(\frac{\rho c k^2 |Q_A|^2}{8\pi}\left(1+\frac{\sin 2kh_A}{2kh_A}\right)\right) + \left(\frac{\rho c k^2 |Q_B|^2}{8\pi}\left(1+\frac{\sin 2kh_B}{2kh_B}\right)\right)$$

4.3

Q_A and Q_B are the volume velocities of the two sources A and B, and h_A and h_B are the respective distances from the ground. This evaluation is simple because the two sources do not act on each other and the resulting sound power is given by the sum of the sound power of the two sources.

More complicated is the equation for the sound power radiated by two monopoles that act with coherent interaction. In this case correlated sources affect each other and each monopole is affected by the presence of another monopole that emits sound at the same frequency. In this case the radiated sound power is given by [9]:

$$P_{a\_reference}A = \frac{\rho c k^2 |Q_A|^2}{8\pi}\left(1 + real\left\{\frac{Q_B}{Q_A}\frac{je^{-jkr_{AB}}}{kr_{AB}} + \frac{Q_{A^1}}{Q_A}\frac{je^{-jkr_{AA^1}}}{kr_{AA^1}} + \frac{Q_{B^1}}{Q_A}\frac{je^{-jkr_{AB^1}}}{kr_{AB^1}}\right\}\right)$$

4.4

$$P_{a\_reference}B = \frac{\rho c k^2 |Q_B|^2}{8\pi}\left(1 + real\left\{\frac{Q_A}{Q_B}\frac{je^{-jkr_{BA}}}{kr_{BA}} + \frac{Q_{B^1}}{Q_B}\frac{je^{-jkr_{BB^1}}}{kr_{BB^1}} + \frac{Q_{A^1}}{Q_B}\frac{je^{-jkr_{BA^1}}}{kr_{BA^1}}\right\}\right)$$

4.5

$$P_{a\_reference} = P_{a\_reference}A + P_{a\_reference}B$$

4.6

Where Q_{A^1} and Q_{B^1} are the volume velocities of the two image sources A and B and r_{AB}, r_{AA^1}, r_{AB^1}, r_{BA}, r_{BB^1} and r_{BA^1} are the distances between the sources (see Figure 5).

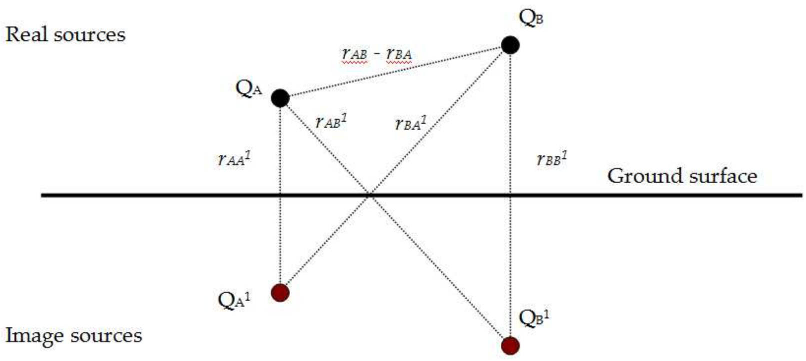

Figure 5 - Coherent source system

Finally the sound pressure level for each method has been defined by:

$$L_W = 10\log_{10}\left(\frac{P_{a\_reference}}{P_{ref}}\right)\text{dB}$$

4.7

Where P_{ref} is reference sound power ($1*10^{12}$ W).

4.3.2 True sound intensity on a box surface

Another method to evaluate the sound power is related to the measurement of the Intensity over a surface with a box shape enveloping the sources [5]. The integral over any surface, totally enclosing the source, of the scalar product of the sound intensity vector and the associated elemental area vector provides a measure of the sound power radiated directly into the air by all sources located within the enclosing surface. This measurement is based on discrete-point sampling of the intensity field normal to the measurement surface as defined in ISO 9614:1993 [1]. The precision of measurement of the normal component of sound intensity at a position is sensitive to the difference between the local sound pressure level and the local normal sound intensity level. A large difference may occur when the intensity vector at a measurement position is directed at a large angle (approaching 90°) to the local normal to the measurement surface. In order to avoid this source of error the model provide to create a box surface enveloping the source (or both the sources) that is 1 metre bigger than the biggest distance between the two sources.

For each single source and on each discrete point has been evaluated pressure and the normal component of the particle velocity taking into account the reflection effect of the ground [10]:

$$\hat{p}(r) = \frac{j\omega\rho Q e^{-jkR_{dir}}}{4\pi R_{dir}} \left(1 + \frac{R_{dir}}{R_{ref}} Q_r e^{-jk(R_{ref}-R_{dir})} \right)$$

4.8

Where R_{dir} is the distance between the source and the receiver position, R_{ref} is the distance between the imaginary source and the receiver position and Q_r is the “spherical reflection factor” [3]:

$$Q_r = R(\theta) + (1 - R(\theta))(1 - jd\sqrt{\pi}erfc(jd)e^{-d^2})$$

4.9

Where:

$$d = \frac{1-j}{2}\sqrt{fR_{ref}}\left(\cos\theta + \frac{\rho c}{Zs}\right)$$

4.10

$$erfc(z) = \frac{2}{\sqrt{\pi}}\int_{\pi}^{\infty} e^{-t^2}dt$$

4.11

$$Zs = \left(1 + 9.08\left(\frac{1000f}{\sigma}\right)^{-0.75} - j11.9\left(\frac{1000f}{\sigma}\right)^{-0.73}\right)\rho c$$

4.12

Equation 4.12 defines the ground impedance and this is a simple, empirical, single parameter model of the characteristic impedance of porous materials developed by Delany and Bazley [4].

$$R(\theta) = \frac{\frac{Zs}{\rho c}\cos\theta - 1}{\frac{Zs}{\rho c}\cos\theta + 1}$$

4.13

Where θ is the angle that the reflected wave has on the ground surface (see Figure 6).

For the purpose of this thesis the Flow Resistivity σ has been set to a really high value (10^20) in order to simulate a ground floor made by concrete for each equation used for the simulation.

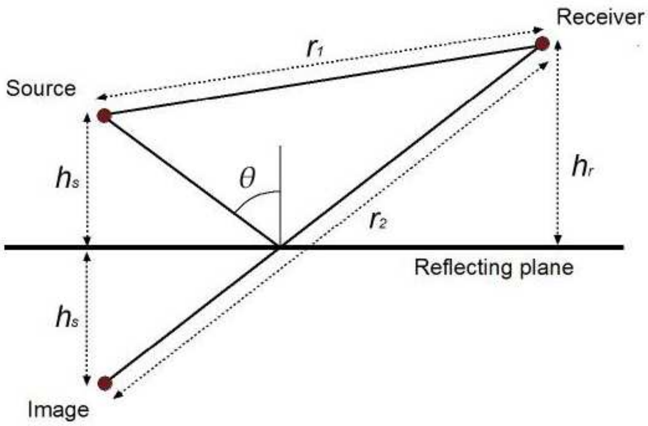

Figure 6 - Source and receiver over a reflecting surface

The radial component of particle velocity has been evaluate by:

$$\hat{u}_r(r) = \frac{\hat{p}(r)}{\rho c}\left(1 + \frac{1}{jkr}\right)$$

4.14

And its normal component:

$$\hat{u}_{norm}(r) = \hat{u}_r(r)\cos\vartheta$$

4.15

Where ϑ is the normalization angle as shown in Figure 7

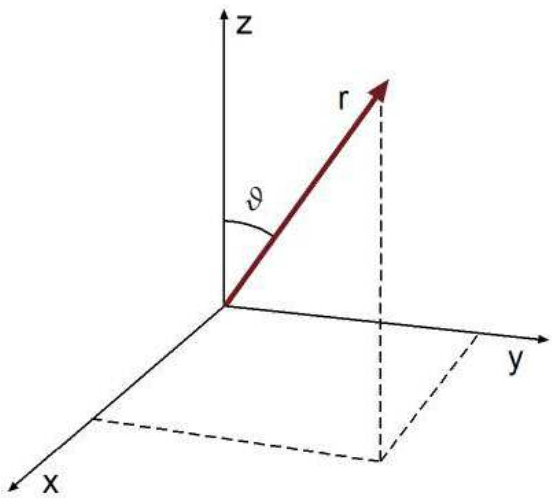

Figure 7 - Coordinate system

Finally the sound intensity has been evaluated by:

$$I_{norm}(r) = \frac{1}{2}\mathrm{Re}\{\hat{p}(r)\hat{u}^*_{norm}(r)\}$$

4.16

In the case of two incoherent sources, the total sound power is given summing up the two sound intensity, on each point of measure on the same surface area enveloping both the sources. Integrating the given data, over the surface, has been got the sound intensity level. The sound power level has been evaluated making use of the equations:

$$L_I = 10\log_{10}\frac{|I|}{I_{ref}} \text{ dB}$$

4.17

$$L_W = L_I + 10\log_{10}\left(\frac{S}{S_0}\right) \text{ dB}$$

4.18

Where I_{ref} is the reference sound intensity (1*10^{-12} W*m^{-2}), S is the area of the surface enveloping the sources and S_0 is the reference area (1 m^2) .

The last explanation is related to the coherent model. In this case the equation that describe the model is:

$$I_{norm}(r) = \frac{1}{2}\mathrm{Re}\left\{[\hat{p}_A(r) + \hat{p}_B(r)][\hat{u}_{Anorm}(r) + \hat{u}_{Bnorm}(r)]^*\right\}$$

4.19

Where $\hat{p}_A(r)$ and $\hat{u}_{Anorm}(r)$ are complex pressure and normal component of the particle velocity for source A, $\hat{p}_B(r)$ and $\hat{u}_{Bnorm}(r)$ are complex pressure and normal component of the particle velocity for source B. The sound power level has been evaluated making use of equation 4.17 and 4.18.

The difference between coherent and incoherent sources is that with two incoherent sources the total sound power is the sum of energy generated in the field by each source, while for coherent sources the sound field of the two sources act one on each other and the total sound power is given summing complex pressure and complex particle velocity before of the evaluation of the sound intensity level. This explanation is valid for each method used in this model to get the sound power level.

4.3.3 True sound intensity on a hemisphere

This method has been developed to evaluate the sound power level with the same equations described in paragraph 4.3.2. In this method pressure and particle velocity have been evaluated over the microphone positions given by the ISO standard and by the European Directive over a hemispherical surface.

4.3.4 Sound intensity in far field on a hemisphere

In a plane progressive wave the sound pressure and the particle velocity are in phase (φ=0) and related by the characteristic impedance of the medium as represented by equation:

$$\hat{p}(r) = \rho c \hat{u}_r(r)$$

4.20

In a simple spherical sound field we have the following relation between the sound pressure and the particle velocity:

$$\hat{u}_r = \frac{\hat{p}}{\rho c}\left(1 + \frac{1}{jkr}\right)$$

4.21

In far field

$$\left(1+\frac{1}{jkr}\right)\Rightarrow 0$$

4.22

It is apparent that the component of the particle velocity in phase with the sound pressure is $\frac{\hat{p}}{\rho c}$ just as in a plane propagating wave, which explains why the sound intensity equals:

$$I_r = \frac{p_{rms}^2}{\rho c}$$

4.23

In this case the sound intensity is simply related to the mean square sound pressure which can be measured with a single microphone.

$$\frac{|\hat{p}|^2}{2} = p_{rms}^2$$

4.24

Equation 4.23 is also valid in the simple spherical sound field generated by a monopole source in free space, irrespective of the distance to the source. However, in the general case the sound intensity is not simply related to the sound pressure, and both the sound pressure and the particle velocity must be measured simultaneously and their instantaneous product time-averaged.

On the basis of these equations the sound intensity level has been evaluated on each microphone position, defined by ISO standard and European Directive, over the hemispherical surface.

4.3.5 Sound power according to ISO 3744:1994

This method is based according to the ISO 3744:1994 where the computation of the sound power level from the sound pressure level measurements is based on the premise that the sound power output of the source is directly proportional to the mean square sound pressure averaged over time and space. As specified in the standard the value of the sound power level of a source, determined according to the procedure given in it, is likely to differ from the true value. This difference will be explained in paragraph 5.2.1. For the sound pressure level, in each frequency band of interest, the Standard required to calculate an average sound pressure level over the measurement surface:

$$\overline{L_p^i} = 10\log_{10}\left[\frac{1}{N}\sum_{i=1}^{N}10^{0.1L_{pi}^i}\right]\text{dB}$$

4.25

Where:

$\overline{L_p^i}$ is the sound pressure level averaged over the measurement surface, in decibel, with the source under test in operation, L_{pi}^i is the sound pressure level at the i^{th} microphone position, in decibel and N is the number of microphone positions.

And finally the sound power level has been calculated by:

$$L_W = \overline{L_{pf}^i} + 10\log_{10}\left(\frac{S}{S_0}\right)\text{dB}$$

4.26

Where:

S is the area of the measurement surface (in square metres) and S_0 is the reference area (1 m^2).

The pressure evaluated in each microphone position has been evaluated as described in paragraph 4.3.2.

4.4 Maximum Directivity Index

The maximum Directivity Index (max DI) is the maximum value measured over a given microphone array. Max DI is taken as a descriptor of the complexity of a sound field generated by a source and from Loyau's paper [8]"… knowing the max DI of a source, it could be possible to determine, a priori, the uncertainty on the A-weighted sound power level."

$$\max DI = \max DI_i \tag{4.27}$$

Where DI_i is the Directivity Index measured at microphone position i.

$$DI_i = L^*_{pi} - \overline{L^*_p} \tag{4.28}$$

Where L^*_{pi} is the sound pressure level at microphone position i and $\overline{L^*_p}$ is the sound pressure level averaged over the measurement surface. The DI is a measure of the extent to which a source (or more) radiates sound predominantly in one direction and it as been evaluated as defined by the ISO 3744:1994 in "Annex E" . It is only an additional information that is not compulsory for the result.

The maximum Directivity Index has been used to define and classify the complexity of the sound field generated by the source and evaluated by a specific microphone array. In fact, for each microphone array, the max DI for the same source is different because of the sampling position of the microphones of the sound field.

4.5 *Bibliography*

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5 VALIDATION OF THE RESULTS

5.1 Introduction

Several sources setup have been tested. Different source space positions and different source volume velocities have been compared over a spherical surface with a radius of 16 meters with all the methods presented in paragraph 4.3. This comparison have been done to find out differences and/or good agreement with results from different mathematical equation checking any possible inconsistency.

Results from 8 source setup (as an example of the thousand evaluated source setup) are presented below (from Figure 8 to Figure 15). In every picture has been presented results in function of the temperature from 0 to 40 Celsius degrees. More over have been presented result for each single source and for the interaction of the two point sources. Differences up to 1.5 dB are observable and explanation of these differences are explained in the next paragraphs.

In function of these results it is possible to assert that all the equations used have been well designed to simulate the evaluation of the Sound Power emitted by the two sound sources.

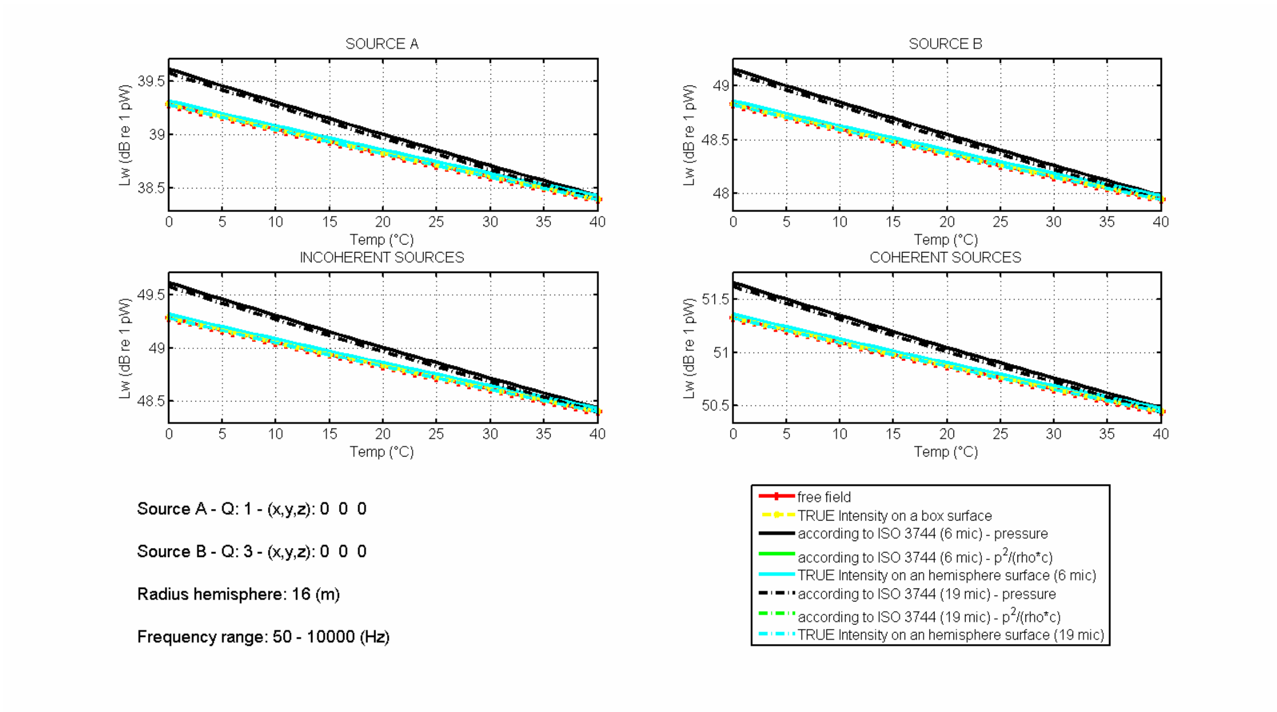

Figure 8 - sources set up 01

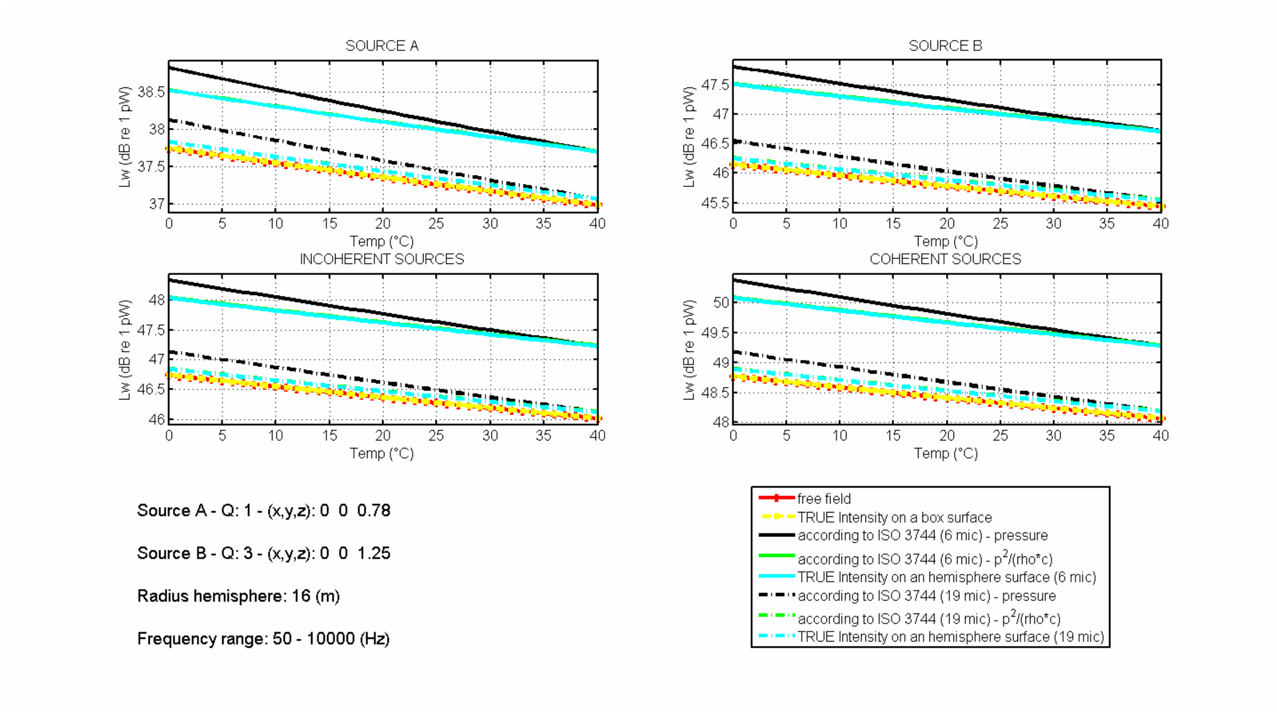

Figure 9 - sources set up 02

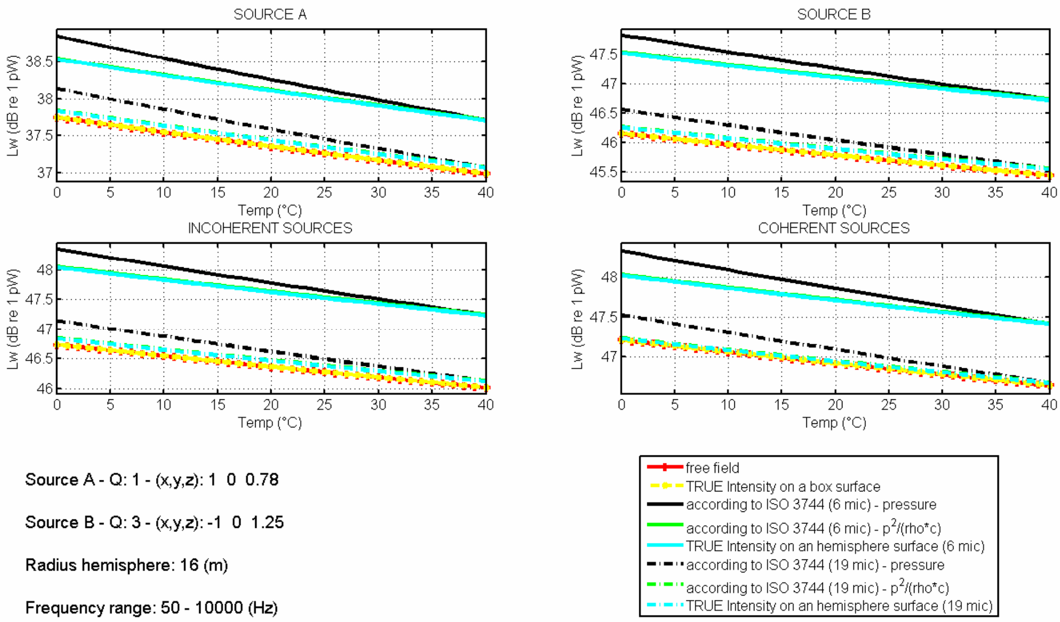

Figure 10 - sources set up 03

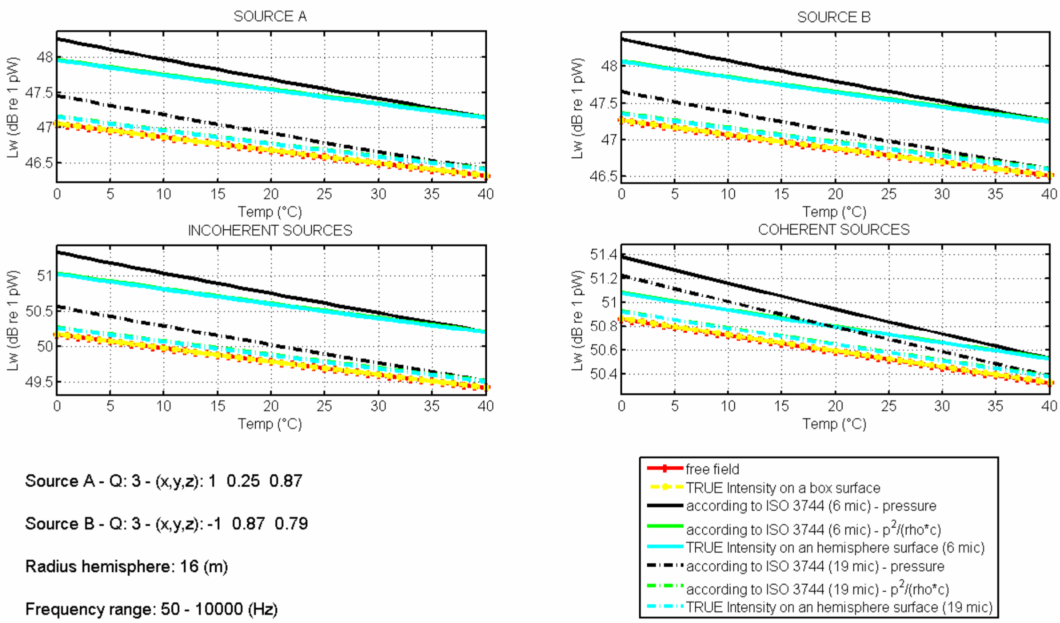

Figure 11 - sources set up 04

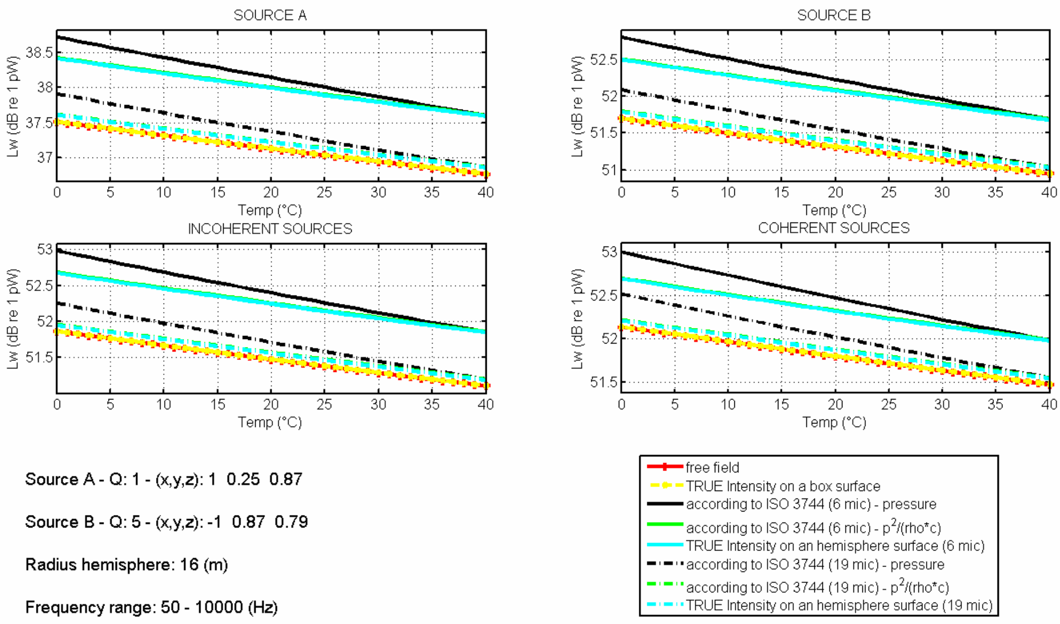

Figure 12 - sources set up 05

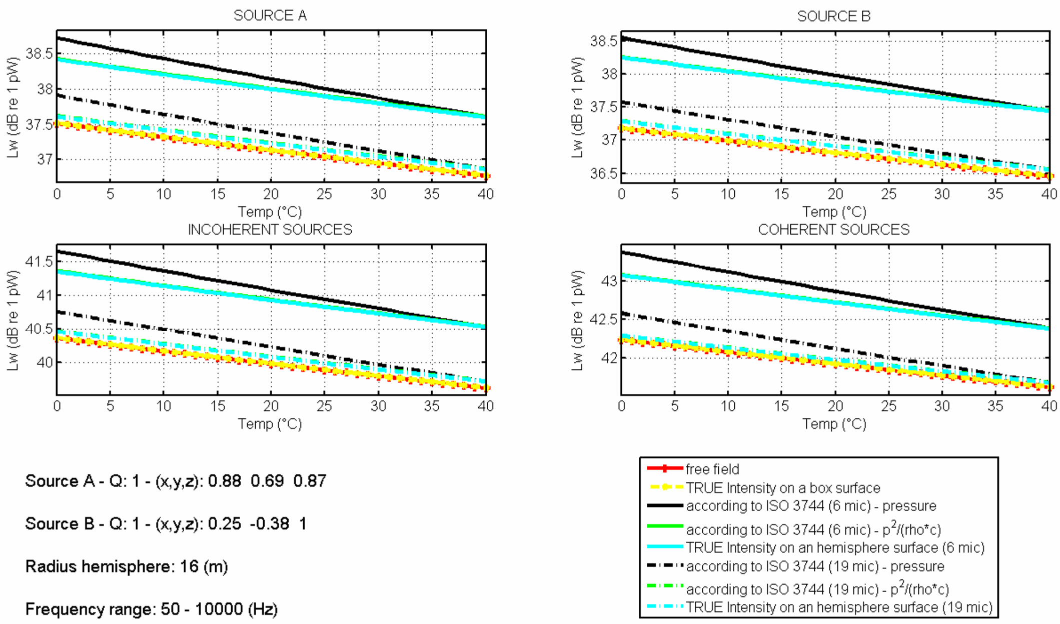

Figure 13 - sources set up 06

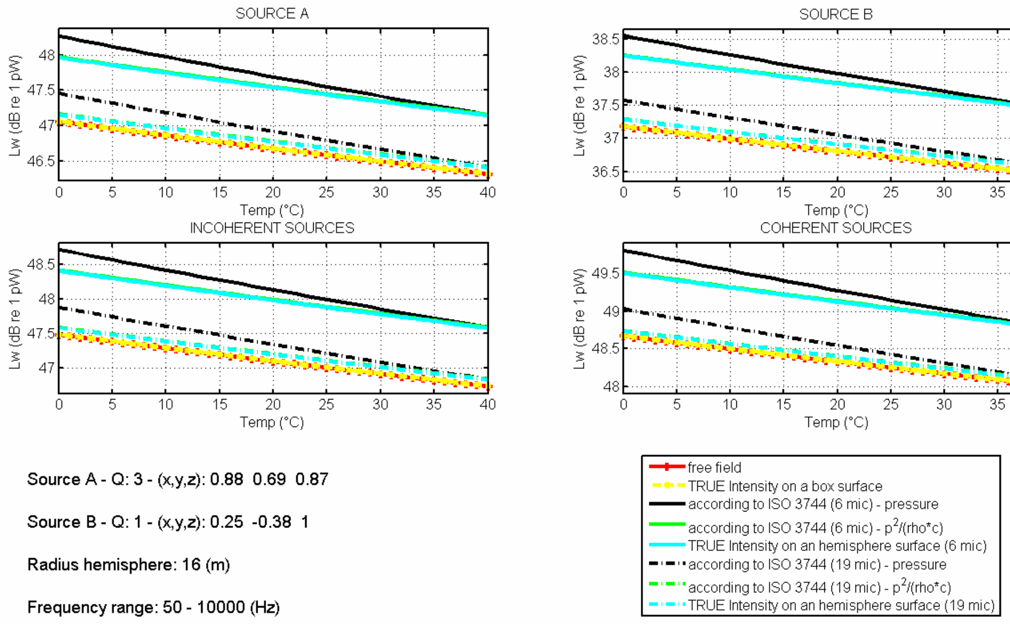

Figure 14 - sources set up 07

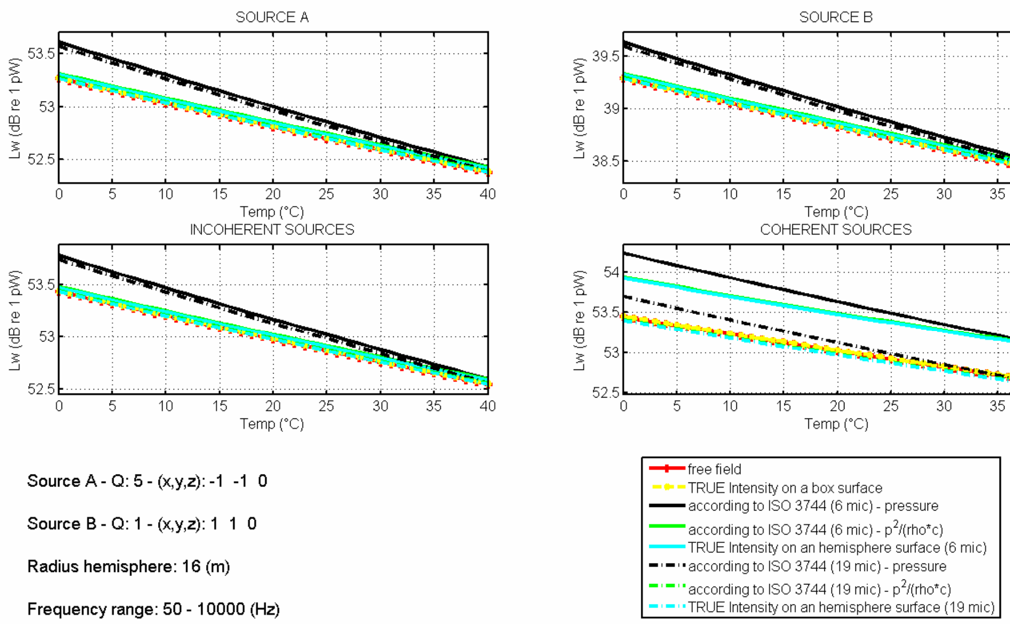

Figure 15 - sources set up 08

5.2 *Significant results*

5.2.1 *Limitations of the Standard*

In ISO 3744:1994, the computation of sound power level from sound pressure level measurements is based on the premise that the sound power output of the source is directly proportional to the mean square sound pressure averaged over time and space ($L_p=L_I$) even thought this is an approximation to the real sound power level. The Standard assumes the sound pressure level as the sound intensity level, but these values have little difference.

$$L_p = 10\log_{10}\left(\frac{p^2}{p_{ref}^{\;2}}\right)\text{dB}$$

5.1

$$L_I = 10\log_{10}\left(\frac{p^2/\rho c}{I_{ref}}\right)\text{dB}$$

5.2

Where I_{ref} is $1*10^{-12}$ $W*m^{-2}$.

These two equations are "almost" valid only if the pressure is measured in far field when the relation between sound pressure and particle velocity is approximated as shown in equations:

$$\hat{u}_r = \frac{\hat{p}}{\rho c}$$

5.3

Errors due to the approximation under exact free field condition have been studied in Hubner's paper [1]. Partial errors have been defined: "near field errors" that is the ratio of the true sound power over the approximated sound power; "finity error" due to the influence of a limited number of microphones (sound pressure values); "actual measurement error" that is due to the fluctuations caused by instruments, observers, meteorological condition, etc. .

Approximation given by "near field errors" is based on the relation between the ratio of $p_{ref}^{\;2} / I_{ref}$ and ρc:

$$\frac{p_{ref}^{\;2}}{I_{ref}} = 400 \tag{5.4}$$

In Figure 16 has been shown systemic errors affecting the ISO method. These data have been obtained for three different static pressure conditions and a temperature range from 0 to 40 °C.

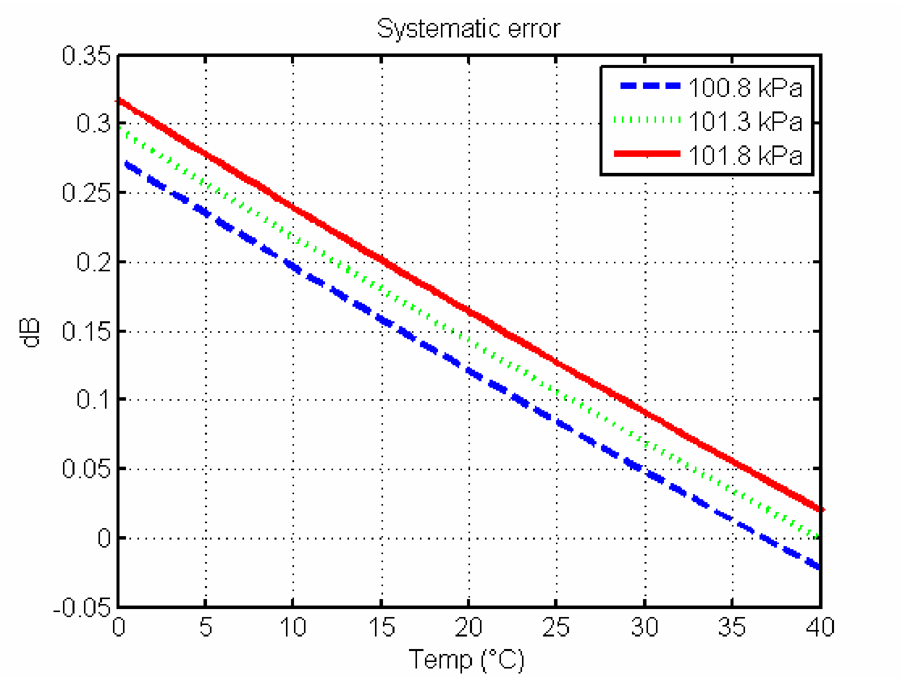

Figure 16 – systematic error for approximation.

Equation 5.5 shown how this error has been evaluated.

$$err = 10\log_{10}\left(\frac{\rho c}{p_{ref}^{\,2}/I_{ref}}\right)\text{dB}$$

5.5

5.2.2 *Microphone array*

The microphone array density has high influence on the valued “max DI” but, high microphones density in microphone arrays, as presented in standard and directive, is not directly related with a right evaluation of the value. For this explanation all the evaluated data has been compared with values got from a microphone array made with 1000 microphones randomly distributed over the hemispherical surface that could well represent the “true” max DI or the best estimation of the true max DI.

As shown in Table 4, the max DI values obtained for each microphone array from several different sources setup have been presented. As defined by directive and standard, microphone arrays have been tested to find out correlations between max DI value and microphone density but, as shown, the value change in no simply way. No simply relation has been observed between max DI and microphone density for microphone arrays as defined in this paper because of the low number of microphones. Obviously, increasing the total number of microphones distributed all over the hemispherical surface the max DI value will be better evaluated as shown in the case over 1000 microphones but, a comparison between microphone arrays made with a low number of microphones shown real difference in results. Results presented in Table 4 shown poor efficiency in the right max DI evaluation for some microphone distributions and 10 microphone array seems to better evaluate the max DI than 12 microphone array. This behavior is due to the fact that the sound field is not well sampled and well represented by some particular microphone distributions that are made by microphone positions set on the same plane. While ISO gives coordinates that permit to distribute microphones over the surface at various height, EC Directive define some microphones positions set with a fixed height, that is 1.5 meter above the reflecting plane (obviously in different points symmetrically distributed around the circumference of the hemisphere) and so these microphones are placed on the same plane. The height of these microphones are not related with the radius as for the other microphone coordinates that are defined in function of the radius, these have a fixed height. Distribution of microphones defined by the ISO standard are completely different and microphones are distributed on different planes that permit a best sampling of the sound field.

A better explanation is given studying a simply model. A point source with its image source has been evaluated in function of its height from the ground. In Figure 17 has been shown the differences of the evaluated sound power level over a specific microphone array and the reference sound power level. The noise source has been set up with a fixed volume velocity and only one parameter has been changed. The height of the source has been moved from 0.0 to 1.0 meter in fixed step of 0.02 meter.

While in Figure 18 have been presented results of the sound power level evaluated.

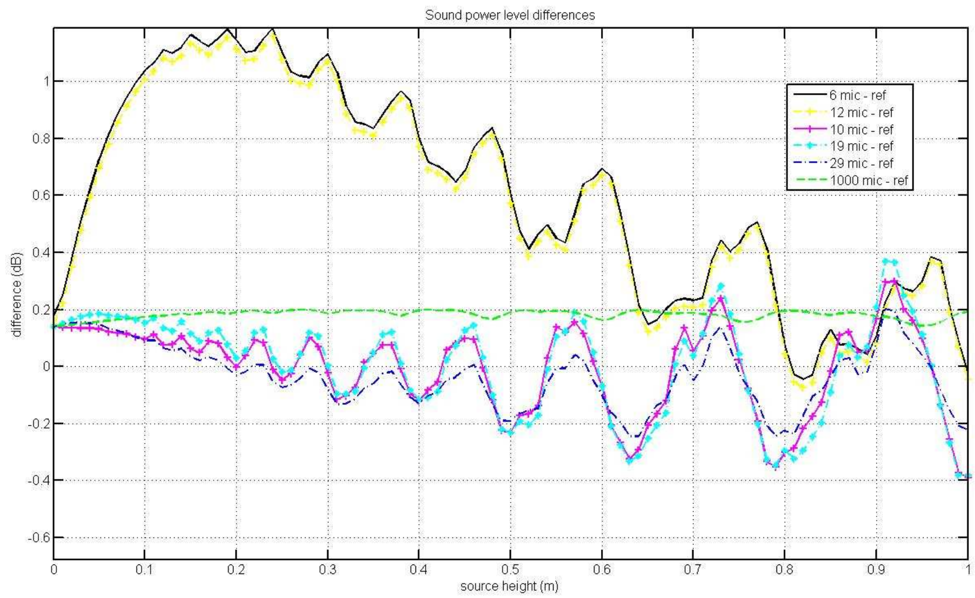

Figure 17 – sound power level differences between evaluated value over a specific microphone array and the reference value – in function of source height.

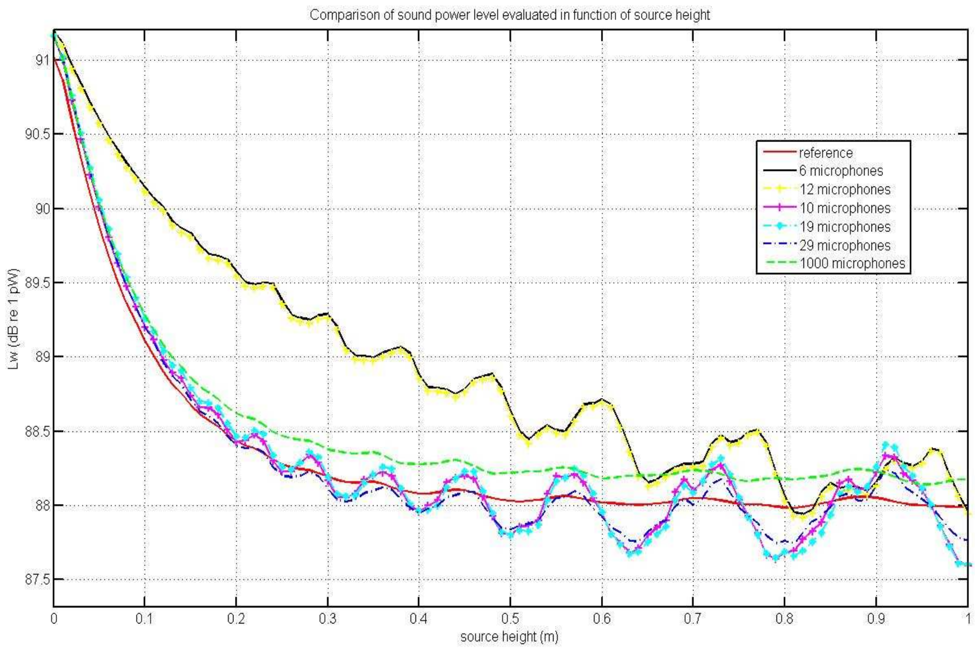

Figure 18 - Comparison of sound power level evaluated in function of source height

Some explanation are necessary. For the 1000 microphones the first difference with the reference value is due to the "near field error approximation" as presented in Sec. 5.2.1. Then it is interesting observing the differences from the microphone arrays as described in

2000/14/EC (6 and 12 mic) and in ISO 3744 (10, 19 and 29 mic). Sound power level evaluated over a microphone array as described by 200/14/EC shown larger variations due to the spatial disposition of the microphones. As a matter of fact, a microphone array as defined by ISO 3744 gives a better evaluation of the sound power level with a low variation. In addition in Figure 19 has been shown the complexity of the generated sound field, evaluated using the max DI over a microphone array made by 1000 microphones, and in comparison have been shown the max DI values evaluated over the microphone array made by a low number of microphones.

These results are in agreement with what it was expecting. 6 and 12 microphones give the worst result in the sound power estimation, therefore a good statistical approach could be helpful to reduce discrepancies between values evaluated over different microphone arrays.

In Table 4 have been presented results from 9 random source set up as an example of differences of sound power level evaluated each from a different equation given by Standard, Directive and 1000 microphones randomly distributed over the hemispherical surface.

SOUND POWER LEVEL	**Source setup 1**	**Source setup 2**	**Source setup 3**	**Source setup 4**	**Source setup 5**	**Source setup 6**	**Source setup 7**	**Source setup 8**	**Source setup 9**
Reference	91.3239	89.7875	90.2359	88.259	83.9645	85.3796	91.3035	89.7791	90.2383
6 mics	90.2185	89.8388	90.6600	89.0184	84.3906	85.766	92.1470	90.4787	90.5060
12 mics	91.3925	90.1165	90.6578	88.5211	84.199	85.5569	91.9004	90.3265	90.5738
10 mics	91.0096	89.8143	90.1211	88.0289	83.6434	85.176	91.0507	89.7870	90.1749
19 mics	91.0266	89.8585	90.0964	88.0472	83.634	85.2237	91.1313	89.7814	90.2285
29 mics	90.9375	89.5751	90.1677	88.1296	83.8129	85.1469	91.0282	89.7004	90.0553
1000 mics	91.4930	89.9942	90.396	88.4605	84.1392	85.596	91.3457	89.8894	90.4655
DIFFERENCE between sound power level measured over a specific microphone array and the reference value									
6 mics	-1.1055	0.0513	0.4241	0.7594	0.4261	0.3864	0.8435	0.6996	0.2678
12 mics	0.0685	0.3290	0.4219	0.2621	0.2345	0.1773	0.5969	0.5474	0.3356
10 mics	-0.3143	0.0268	-0.1148	-0.2301	-0.3210	-0.2037	-0.2528	0.0079	-0.0634
19 mics	-0.2973	0.0710	-0.1395	-0.2118	-0.3304	-0.1560	-0.1722	0.0023	-0.0098
29 mics	-0.3864	-0.2124	-0.0682	-0.1293	-0.1516	-0.2327	-0.2753	-0.0787	-0.1829
1000 mics	0.1691	0.2066	0.1601	0.2015	0.1747	0.2164	0.0422	0.1103	0.2272
MAX DIRECTIVITY INDEX									
6 mics	2.1171	1.1776	1.0945	1.2081	1.157	0.9163	0.5058	1.4851	1.6583
12 mics	1.2416	0.8996	1.0967	1.7054	1.3486	1.1255	0.8672	1.6373	2.1334
10 mics	1.5642	1.3732	1.0518	0.978	1.1699	1.1399	0.7948	1.1360	0.6604
19 mics	1.5473	1.3290	1.0764	0.9597	1.1793	1.0922	1.0826	1.2065	1.2012
29 mics	1.5287	1.6124	1.2788	0.8772	1.0661	1.3995	1.2509	1.2874	1.3744
1000 mics	3.7491	3.9356	4.244	3.5692	4.028	4.1227	4.0024	4.2475	4.4214

Table 4 – max DI and sound power level differences

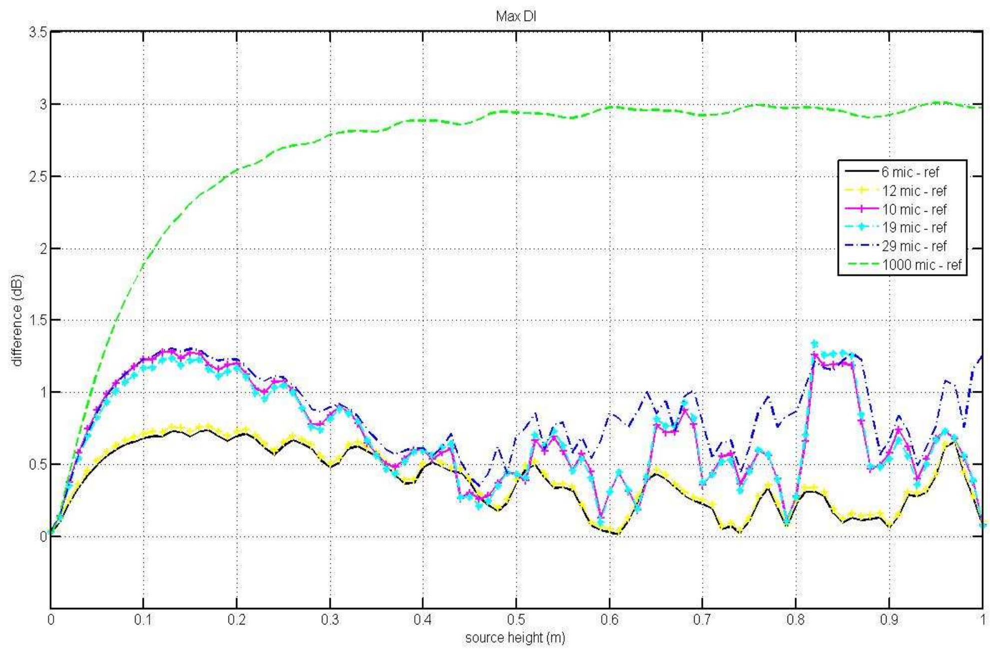

Figure 19 – max DI evaluated value over a specific microphone arrays – in function of source height.

Several sources setup have been evaluated with all the method presented in paragraph 4.3 and some sound power level data are presented for microphones array made by 19 and 6 microphone positions. Their results shown deviation between the true value (reference method) and the measured value. In the most simply case, where the sources have been setup on the origin of the hemispherical coordinate system (Figure 8), the only difference is due to the deviation caused by the standard approximation (see paragraph 5.2.1). Increasing distance and altitude of the two sources, deviation of the sound power level increase or decrease in function of the distribution of the sampling microphones over the hemispherical surface. The 6 microphone positions shown almost everywhere an over estimation of the sound power level while generally the 19 microphone positions shown an under estimation of it (from Figure 8 to Figure 15).

Some other results have been analyzed in order to get more information on the mesh density over the hemisphere surface. As shown in Figure 21, increasing the density of the microphones up to 1000 microphone positions randomly distributed on the hemisphere surface, a fine mesh does not affect the result and almost the same result is given from a microphone mesh more poor as 10, 19 or 29 microphones. These data have been obtained by the real ISO standard method (equation 4.26) on each microphone positions. More over have been evaluated a microphone array composed by 12 microphones, the whole configuration defined by 2000/14/EC, and by 1000 microphones randomly distributed. A microphone array made by 100 microphones have been got making use of φ and θ angle, with a uniform distribution of φ angle and a distribution that follow a *sin* function for θ angle (see Figure 20).

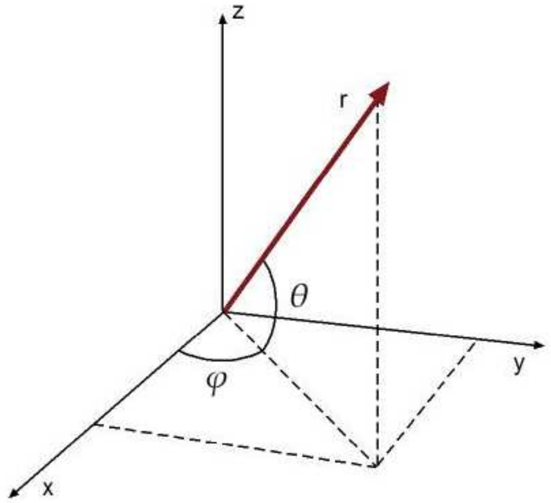

Figure 20 - Spherical coordinate system

The data obtained by a microphone array with 6 and 12 positions, as defined by the European Directive 2000/14/EC, shown an over estimation with a similar standard deviation, while the data obtained by the two microphone array (19 and 29 microphone positions) defined by the ISO standard shown a more accurate result as shown for a microphone array made by 100 microphones (see Figure 21).

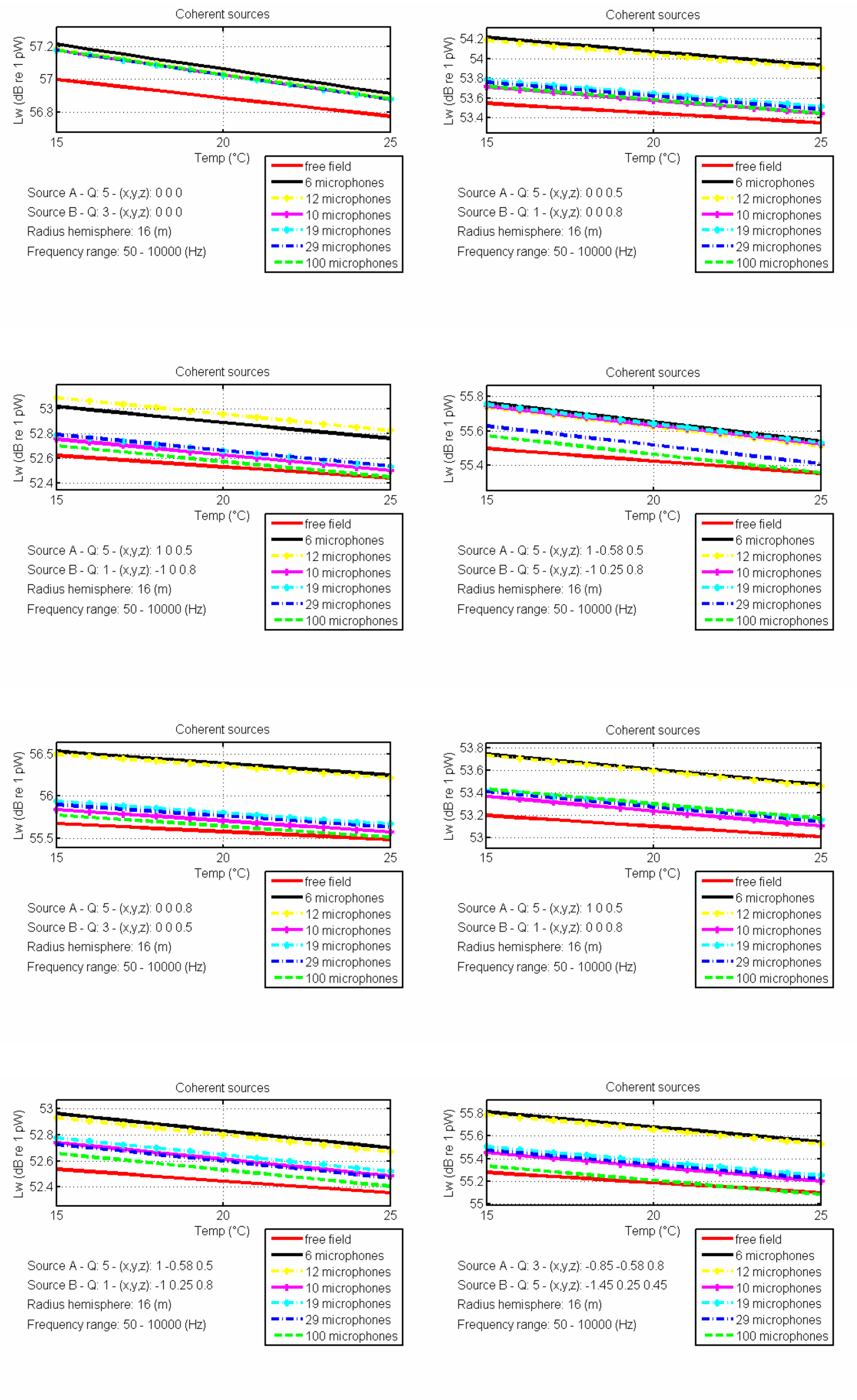

Figure 21 - Comparison of different mesh density over a hemispherical surface

5.2.3 Microphones' density on a box surface

The effect of the microphones' density on results got over a box surface enveloping the source has been analyzed. Source directivity does not affect the sound power level evaluated over the box surface because on its the microphone positions are well distributed on each surface enveloping the sources. In Figure 22 has been shown the difference between several mesh density on a box surface in order to shown the little deviation caused by the mesh density. The model used for the simulation has been set with 100 points for each surface and the grid mesh is so fine to get a very good agreement between the evaluated data and the reference sound power level estimated in free field condition.

The theoretical box surface have been done according to ISO 3744:1994 [1].

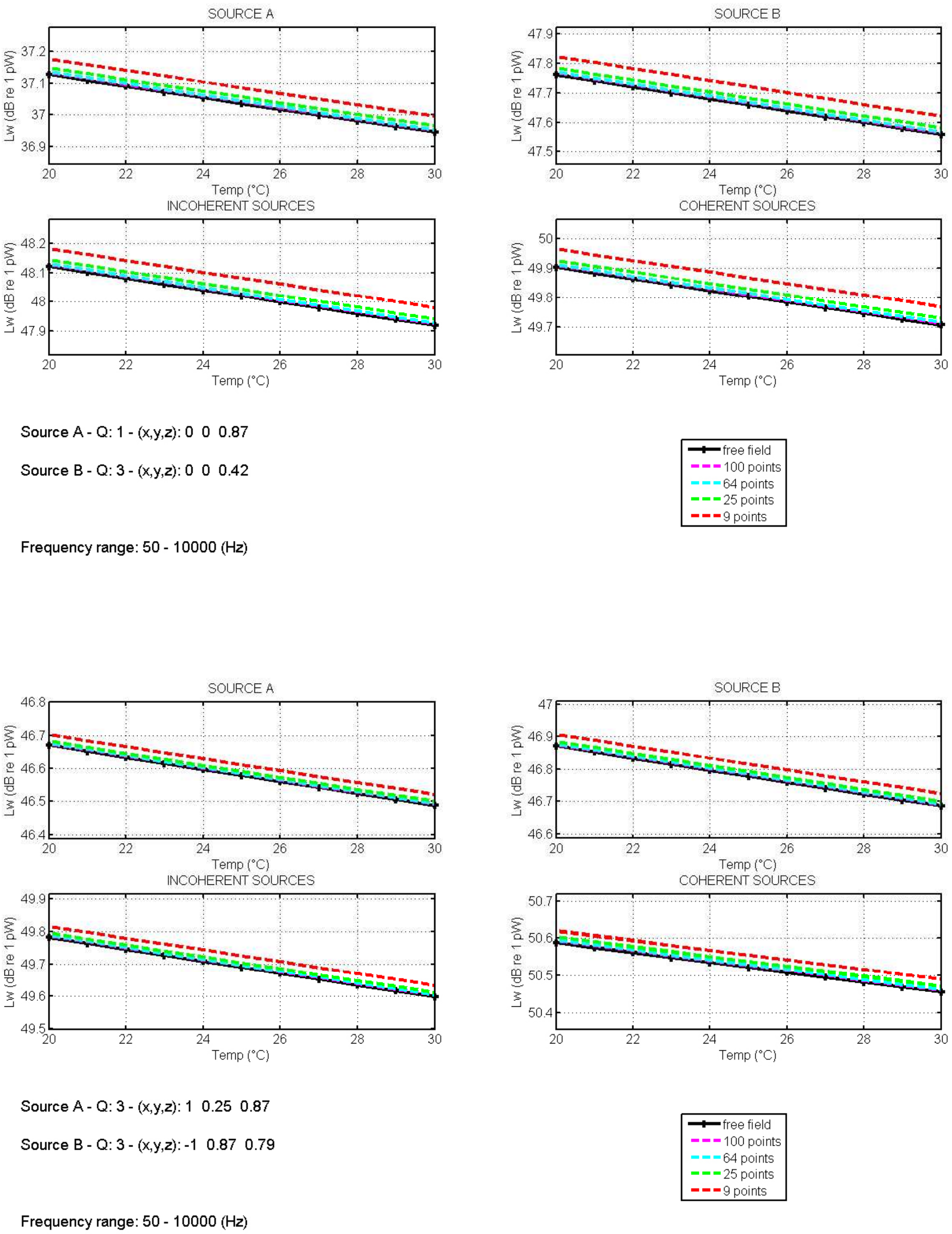

Figure 22 - Effect of mesh density of a box surface enveloping the sources

5.2.4 Directivity index

The Directivity Index describes the spatial noise radiation of the source over the microphone positions and the max DI describes the complexity of the sound field generated by a source. From Figure 23 to Figure 25 are shown Directivity Index data from 3 examples of sources setup.

The last case seem to be the worst case because of the distribution of the microphones over the surface but this is not completely true. Obviously, increasing the number of microphone positions over the surface the final result will be more precise, even thought a little number of microphone positions could be good enough in order to get a final result with a good approximation or with a low standard deviation. In this case the most important cause of deviation is related with the microphone distribution over the surface and also related with the complexity of the sound field. As shown in Figure 21, the microphone array composed by 10 microphones shown a better results than the microphone array composed by 12 microphones. This difference seems to be related with a better sampling position of the sound field generated by the sources.

As shown in Figure 23, Figure 24 and Figure 25 several source set up have been evaluated in order to achieve information concerning the source directivity. Directivity Index (equation 3.8) over different microphones array has been evaluated in order to observe changing in the sound field generated by the same source over the hemispherical surface.

This index is the difference between the average sound pressure over the hemispherical surface and the pressure measured at the microphone position. Obviously each microphone array, for the same sound filed, have a different DI because of the different sampling position on the hemispherical surface and because of the complexity of the sound field on the surface. With a microphone array made with a little number of microphones it is possible to observe that the DI measured is far from the other, especially if DI is measured over a huge number of microphone positions, as for example 500 as shown in Figure 23, Figure 24 and Figure 25.

The same source gets a different DI value for each microphone array. For this reason a DI value has to include the specification of the total number of microphones and their position on the hemisphere surface.

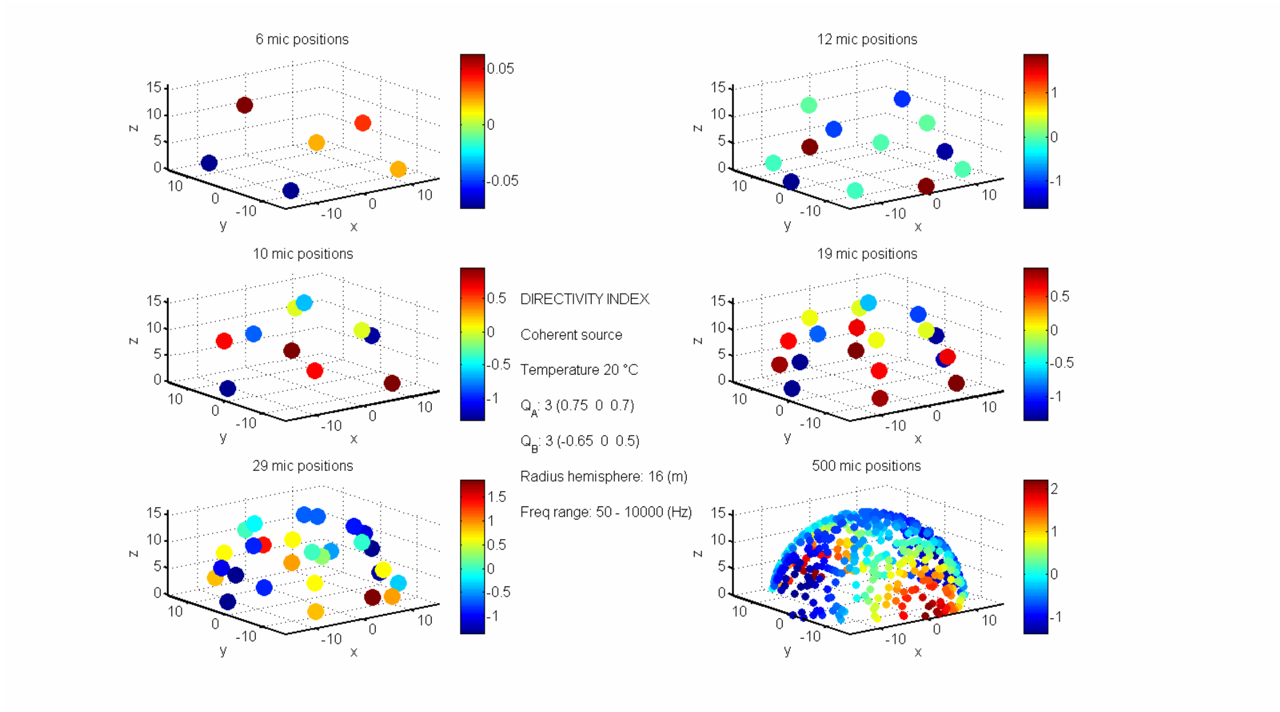

Figure 23 - Directivity Index over several microphone array on a hemispherical surface at 20 °C

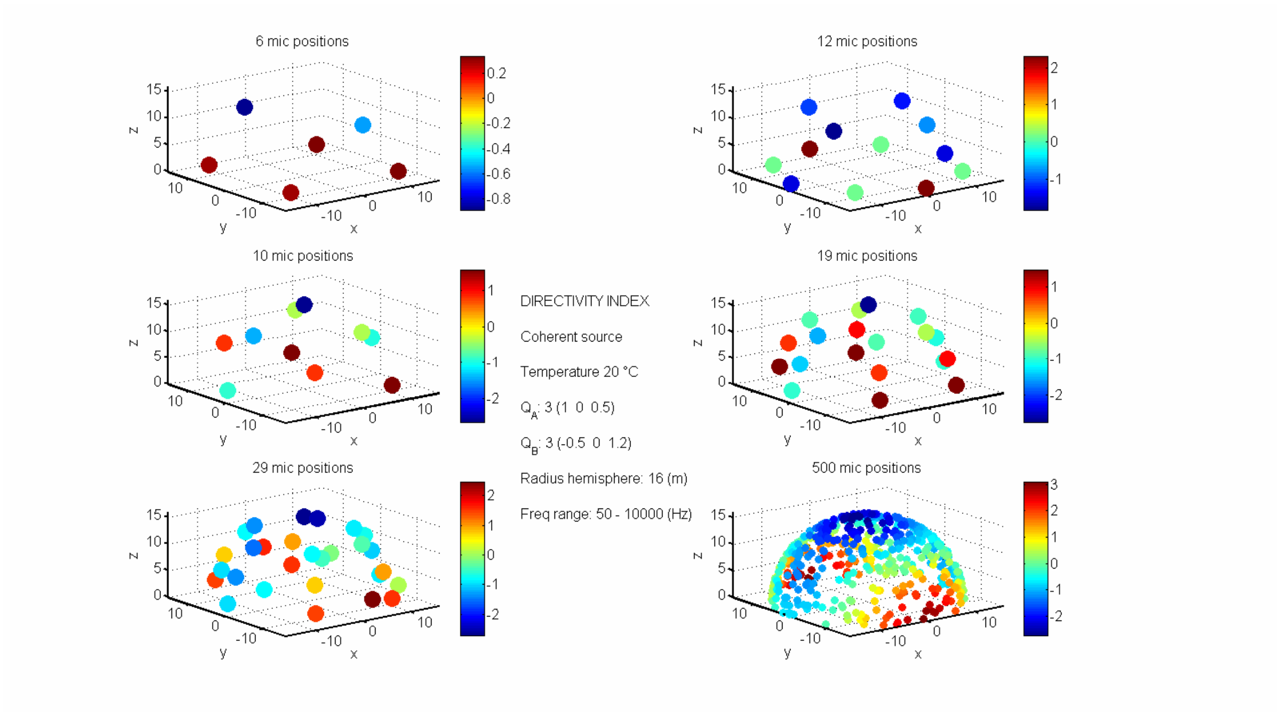

Figure 24 - Directivity Index over several microphone array on a hemispherical surface at 20 °C

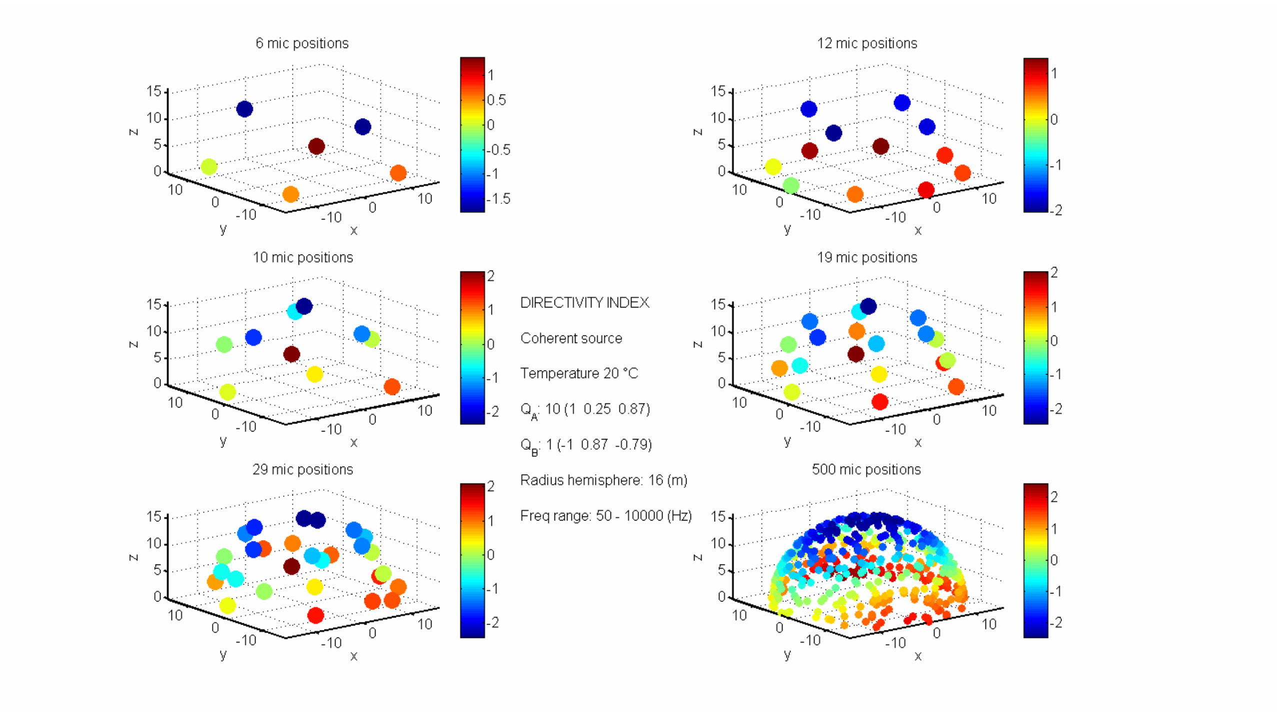

Figure 25 - Directivity Index over several microphone array on a hemispherical surface at 20 °C

5.2.5 *"True Intensity" and "Intensity in far field"*

Deviation between sound power level measured with the "True Intensity" (paragraphs 4.3.2 and 4.3.3) and "Intensity in far field" (paragraph 4.3.4) over a hemispherical surface is due to the normal component of the particle velocity.

These differences are shown in diagrams from Figure 8 to Figure 15. Both the methods with 19 and 6 microphone positions are affected by this deviation:

- Light blue and green dash dot lines for comparison between "True Intensity" and "Intensity in far field" over 19 microphone positions;
- Light blue and green solid lines for comparison between "True Intensity" and "Intensity in far field" over 6 microphone positions.

5.3 Bibliography

[1] Acoustics – Determination of sound power levels of noise sources using sound pressure – Engineering method in an essentially free field over a reflecting surface, ISO 3744:1994, International Organization for Standardization;

[2] Hubner G., Analysis of errors in measuring machine noise under free-field conditions, J. Acoust. Soc. Am. 53, 4 (1973).

6 STATISTICAL EVALUATION

6.1 Introduction

This thesis presents result from statistical errors evaluation of sound power levels determination using several microphone arrays as described according to International Standard ISO 3744:1994 and European Directive 2000/14/EC and, with respect to Loyau's paper [2], the statistical data, made by different sources setup, has been extended to cover a wide range of different sources described by maximum Directivity Index up to 4 dB. For a more complicated sound field, with a maximum Directivity Index higher than 4 dB, it is necessary to get sound sources generate by more than 2 point sources.

In particular, the testing surface was made according to ISO 3744:1994 with a microphone array of 12 positions on the hemispherical surface and with the possibility to reduce this number to 6 following the requirements of clause 7.42 of ISO 3744:1994. As reported in 2000/14/EC Directive, Part A, paragraph 5: "generally the arrangement with 6 microphone positions on a hemispherical measurement surface has to be used".

ISO 3744:1994 "annex B", table B.1 defined microphone arrays made by 10, 20 and 30 but on this simulation have been used 10, 19 and 29 microphone positions. The 10 microphones array is so defined by the standard, the 19 microphone array comes from the table B.1 mentioned above without 1 microphone because as defined in the standard, microphone position 10 and 20 are overlapped and for this reason only 1 microphone has been set in that position. The 29 microphone array comes from the previous table B.1 (for 20 microphones without the overlapped position) plus the microphone positions set in table B.2 that are additional microphone positions for source that emits discrete tones.

6.2 Statistical results

As defined by *Guide to the expression of uncertainty in measurement* [1], Type A uncertainty is uncertainty evaluated by the statistical analysis of series of data. In most case, the best available estimate of the expected value of a quantity is the arithmetic mean or average of several observations obtained under the same conditions of measurement. This average is characterized by a variability given by the experimental standard deviation of the measured value. Moreover an error could affect the measured value, because of imperfect measurement, inadequate determination of the corrections of the systematic effects and incomplete knowledge of certain physical phenomena. Systematic errors could be corrected while uncertainties could not be corrected but could be only estimated.

Statistical results shown in this chapter give us many information about systematic errors and uncertainty related on different microphone arrays and related with the complexity of the source under test. Each microphone array has a different systematic error and different standard deviation. Furthermore each source has a different sound field and a different Directivity Index that describe its complexity. High max DI means source with a complex sound field and a source described by high max DI becomes more complicated in order to be evaluated. This source descriptor could be used to identify the systematic error that afflict the measured value and its standard deviation describe the spread of the “real value” around the measured value.

The statistical data has been evaluated to obtain information about the method error and uncertainty. The data has been split up to show contribution in the systematic error and standard deviation given by:

- incorrect placement of the source in the centre of the hemisphere;
- microphone array;

- atmospheric temperature;
- max Directivity Index of the source under test.

All the statistical data presented in this chapter has been evaluated taking into account the max DI of the sources. As shown in Figure 26, results are related to the mean difference, that is the systematic error, (Eqn. 6.1) between the sound power level evaluated with the reference system equation (Par. 4.3.1) and the sound power level evaluated over a specific microphone array as defined in directive and standard.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{6.1}$$

$$x_i = SPLarr_i - SPLref_i \tag{6.2}$$

Where *SPLarr* in the sound power level of the *i*-source under test evaluated as defined in Par. 4.3.5 for each microphone array, *SPLref* is the reference sound power level of the *i*-source under test evaluate as defined in Par. 4.3.1 and *n* is the number of the evaluated sources.

Standard deviations (Eqn. 6.3), maximum and minimum values have been calculated on the previous mean difference.

$$std = \left(\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2\right)^{1/2} \tag{6.3}$$

The data has been divided to present the systematic errors and the associated standard deviation introduced by each microphone array and they are displayed in diagram where limits in y-axis (± 1.5 dB) are the standard deviation given in table 1, paragraph 1.4 on ISO 3744:1994.

From Table 21 to Table 25 it has been shown values evaluated at different temperature and all data has been divided into classes defined by the max DI in step of 1 dB from 0 to 4 dB, from Figure 27 to Figure 40 has been shown this data in a graphical layout with a graphical representation of the spreading of difference value related to the max DI. With these results is possible to evaluate the systematic errors that afflict the measurement method related to a specific microphone array and its standard deviation in order to compare sound power level of sources measured using different microphone arrays. Groups arranged in max DI classes have been evaluated to split the huge number of sources that have been analyzed and to check for any possible differences. All the evaluated data have been presented in groups divided by temperature, microphone array and max DI value, see paragraphs 8.1 and 8.2.

A microphone array made by 6 or 12 microphones have a high systematic error due to the uncertainty given by the disposition of the microphones on the hemisphere surface, while a microphone array made by 10, 19 or 29 microphones have a systemic error kept down due to the better distribution over the surface and also a better evaluation of the DI of the source. Comparing the microphone array presented in this paper, high microphones density is not directly related with better result. Obviously increasing the density a better result has to be expected but as shown from Table 21 to Table 25 a microphone array made by 12 microphones has a systematic error higher than systematic error given by 10 microphones. The reason is due to the distribution of these microphones over the hemispherical surface. In fact, when they are well distributed, as the microphone array made by 10 microphones, a low microphones density could give a result with a low systematic error. The same is not true evaluating the standard deviation. A microphone array made by 10 microphones shown a standard deviation higher than 12 microphones. An explanation could be given taking into account paragraph 8.2. In this case the same sources configuration has been moved around the hemisphere centre and its sound power level has been evaluated. In the general case, increasing the number of microphone positions the max DI of the sound source will be higher (see Table 20). The same sound source present different max DI value in function of the microphone array used in the evaluation.

Microphone arrays defined by the ISO 3744:1994 shown, in general, low systematic errors and low standard deviations that are smaller and smaller increasing the microphone density from 10 to 29, while microphone arrays as defined by Directive 2000/14/EC tend to over estimate the real value and the systematic error seems to be higher with high max DI value.

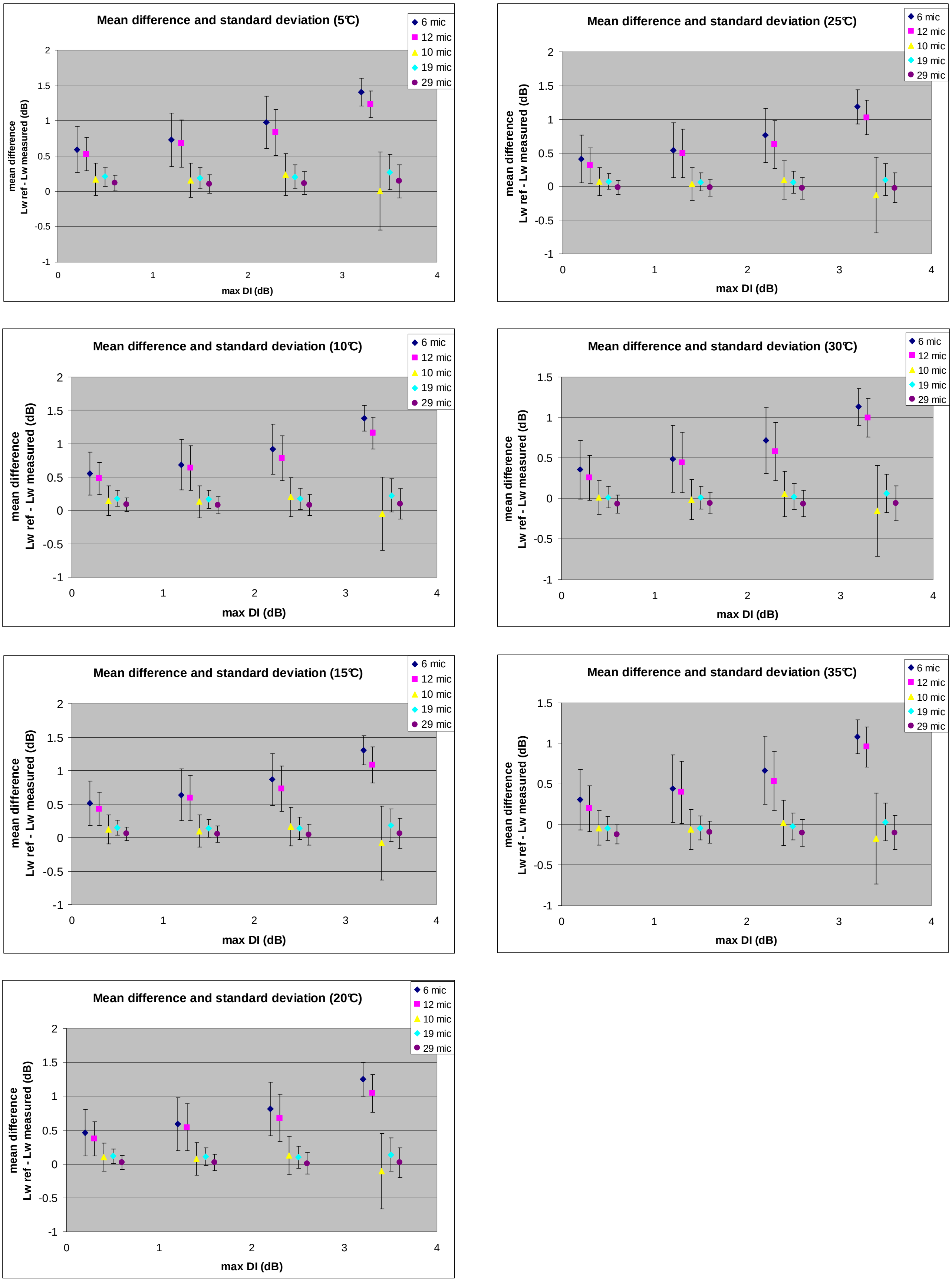

Figure 26 – systematic errors and standard deviation referred to a specific microphone array in function of the temperature.

6.3 Bibliography

[1] Guide to the expression of uncertainty in measurement, GUM, International Standard for Standardization, Geneva, Switzerland, (1995);

[2] Loyau T., Determination of sound power levels using sound pressure: The uncertainties related with the measurement surface and the number of microphones, Noise Control Eng. J. 55 , 1 (2007).

7 CONCLUSIONS

7.1 *A new formula*

A general equation (Eqn. 7.1) should be developed to minimize systematic errors given by the used method and to obtain a better uncertainty estimation related to the description of the source under test and related with the chosen method. Obviously this method uncertainty has to sum with other type of uncertainties linked with this test method: reproducibility uncertainty [2]-[3] and instrumental uncertainties [1]. The statistical approach presented in this chapter allow to reduce the uncertainty. This is possible because this approach gives values of systematic errors that permit to reduce the total uncertainty related with different microphone arrays in different atmospheric conditions and taking into account errors due to the right positioning of the source in the centre of the hemisphere. A new formula that take into account errors presented above could be defined as:

$$L'_W = L_W + K_1 + K_2 - SE \qquad \textbf{7.1}$$

Where:

L_W sound power level calculated by Eqn. 4.26;

K_1 correction for background noise (ISO 3744:1994);

K_2 correction for the test environment (ISO 3744:1994);

SE systematic error given by the developed model. This value is related to the microphone array, atmospheric temperature and max DI.

Its uncertainty is given by standard deviation of the systematic error (SE). The value of SE could be found from Table 21 to Table 25 in Appendix B, in function of the atmospheric temperature and in function of the max DI value of the tested source.

7.2 *Conclusions*

Uncertainty is one of the most relevant problem related with measurement in general and laboratories that perform testing activity have to guarantee measurement quality and results. Another important aspect is related to the comparison of measurement carried out in different laboratories and in particular using different equipment setup. Sometime Standard or Directive are not so helpful and discrepancy could occur. In the latter case we need to have information about such measurement and errors introduced in the result. The object of this article was to find a way to compare sound power value measured with different microphone array but based on the same procedure. The uncertainty studied has no relation with the dimensions or the shape of the source but it was related with a parameter that describe its sound field.

Microphone arrays as defined by directive 2000/14/EC shown high systematic errors and high standard deviations. Data obtained using this directive are generally affected by overestimation of the real sound power level while microphone arrays as defined by standard ISO 3744:1994 shown lowest systematic errors and a low standard deviation range. Anyway all the sound power levels evaluated over a wide range of max DI are affected by uncertainty that is within the estimated value of the standard deviation determined in accordance with the standard.

In conclusion if the measured value over a specific microphone array is corrected by the specific systematic error, as presented in this paper, its standard deviation would be less than the estimated standard deviation given by the standard. All the evaluated standard deviation values are within 0.5 dB while the general standard deviation given by ISO 3744:1994 is 1.5 dB. Moreover data from different microphone arrays could be compared with a good agreement because they are corrected by the systematic error that affect the measurement.

Forasmuch as the measurement uncertainty depends on the standard deviation and on the degree of confidence that is desired, for a normal distribution of sound power levels there is 95% of confidence that the true value of the sound power level of a source lies within the range:

- ± 3 dB (in any case) applying the standard deviation given by ISO 3744:1994;
- ± 0.5 (in the worst case) applying the correction of the systematic error given by the statistical approach present in this thesis.

7.3 Bibliography

[1] Caligiuri L.M., The evaluation of uncertainty in environmental acoustic measurement according to the ISO "Guide", Noise Control Eng. J. 55 , 1 (2007);

[2] Carletti E., Towards a harmonized procedure for the declaration of sound power levels within Directive 2000/14/EC, Noise Control Eng. J. 55 , 1 (2007);

[3] Carletti E., Inter-laboratory test for the assessment of reproducibility uncertainties on the sound power levels of earth-moving machines, Euronoise 2006, Finland.

8 APPENDIX A – STATISTICAL RESULTS

8.1 *multi temperature and different source setup*

	6 diff	6 DI	12 diff	12 DI	10 diff	10 DI	19 diff	19 DI	29 diff	29DI
mean	0.7010	1.2260	0.6800	1.4990	0.1652	1.3007	0.1939	1.5108	0.1086	1.6430
standard deviation	0.3735	0.5113	0.3299	0.5086	0.2457	0.4565	0.1504	0.4857	0.1368	0.4793
max	2.4332	3.1334	2.1097	3.4311	1.3637	3.8963	1.3278	3.6644	0.9881	3.7392
min	-0.5382	0.0398	-0.4597	0.2028	-1.1615	0.2009	-1.1015	0.3152	-0.7527	0.4485

Table 5 – temperature 5°C – 63000 sources setup

	mics	DI<1	1<DI<2	2<DI<3	3<DI<4
systematic error	6	***0.5946***	***0.7313***	***0.9777***	***1.4076***
standard deviation		0.3238	0.3786	0.3678	0.2
number of source pos.		23751	33835	5398	16
systematic error	12	***0.5284***	***0.6778***	***0.8363***	***1.2319***
standard deviation		0.2368	0.3322	0.3252	0.1906
number of source pos.		10995	41156	10684	165
systematic error	10	***0.1673***	***0.1559***	***0.2368***	***0.006***
standard deviation		0.2305	0.2421	0.2958	0.5515
number of source pos.		17288	40571	5027	114
systematic error	19	***0.2086***	***0.1878***	***0.2073***	***0.2706***
standard deviation		0.1386	0.1472	0.167	0.2509
number of source pos.		8242	44841	9581	336
systematic error	29	***0.1194***	***0.1057***	***0.1149***	***0.1425***
standard deviation		0.1106	0.1299	0.1594	0.2329
number of source pos.		3417	46327	12648	608

Table 6 - temperature 5°C – statistical data refered to max DI values

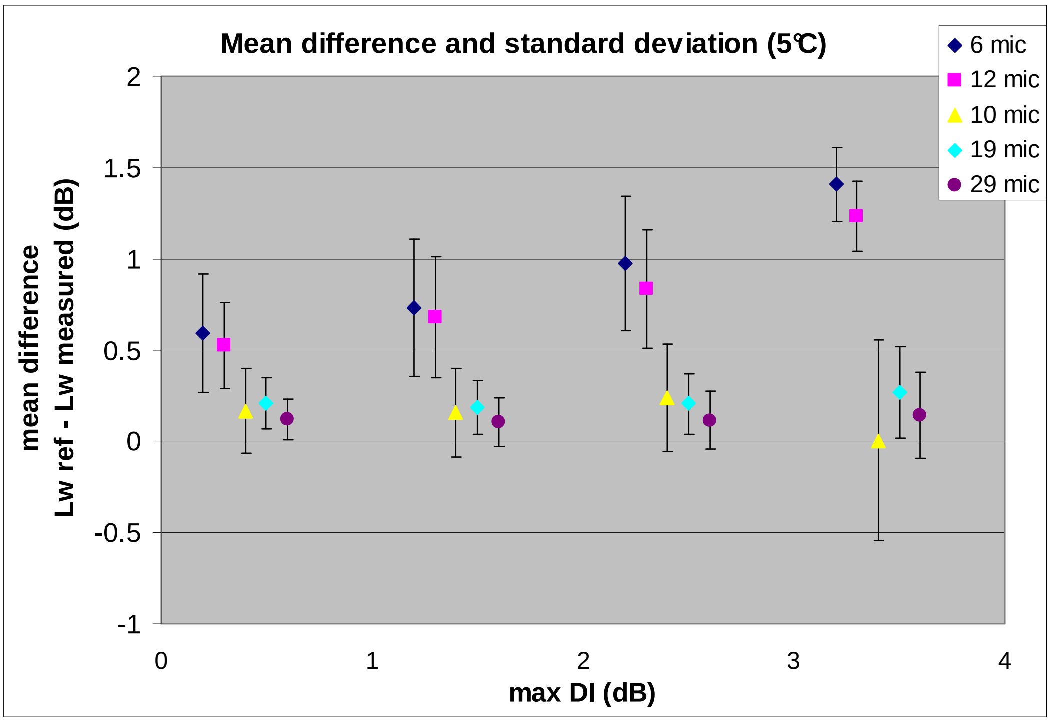

Figure 27 - temperature 5°C – systematic error and standard deviation

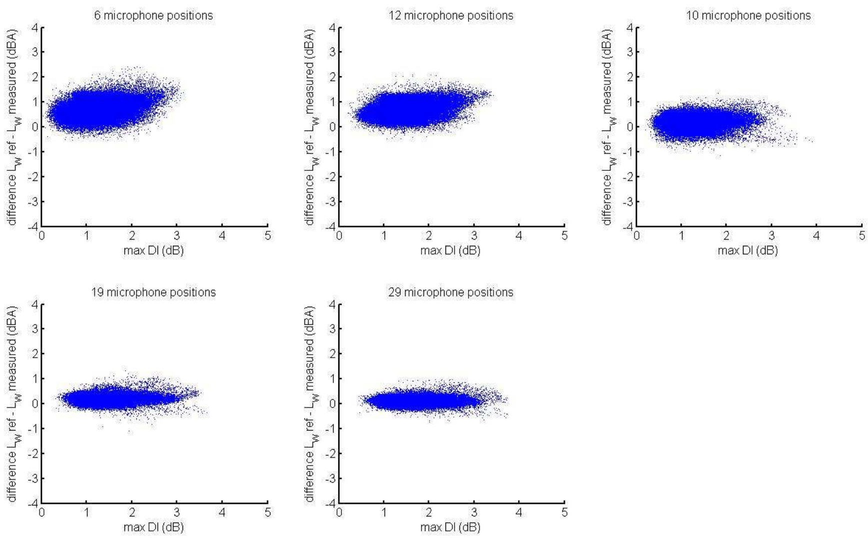

Figure 28 - temperature 5°C – Spreading of difference value related with the max DI

	6 diff	6 DI	12 diff	12 DI	10 diff	10 DI	19 diff	19 DI	29 diff	29DI
mean	0.6582	1.2409	0.6366	1.5122	0.1402	1.3022	0.1700	1.5200	0.0805	1.6521
standard deviation	0.3753	0.5120	0.3331	0.5114	0.2405	0.4619	0.1396	0.4874	0.1335	0.4809
max	2.3869	3.1474	2.0704	3.4464	1.3429	3.9185	1.3373	3.6748	0.9815	3.7425
min	-0.5834	0.0776	-0.4924	0.1873	-1.1692	0.1349	-1.0872	0.3403	-0.7657	0.4292

Table 7 – temperature 10°C – 63000 sources setup

	mics	DI<1	1<DI<2	2<DI<3	3<DI<4
systematic error	6	***0.553***	***0.6849***	***0.919***	***1.3818***
standard deviation		0.3249	0.3806	0.3759	0.1926
number of source pos.		22950	34327	5708	15
systematic error	12	***0.4798***	***0.6356***	***0.7817***	***1.1591***
standard deviation		0.2377	0.3347	0.3333	0.2428
number of source pos.		10645	41009	11169	177
systematic error	10	***0.1459***	***0.1306***	***0.2007***	***-0.0475***
standard deviation		0.2217	0.2382	0.2908	0.5517
number of source pos.		17520	40216	5142	122
systematic error	19	***0.181***	***0.1668***	***0.174***	***0.2241***
standard deviation		0.1206	0.1353	0.1644	0.2496
number of source pos.		7892	44848	9903	357
systematic error	29	***0.0879***	***0.0796***	***0.0808***	***0.0991***
standard deviation		0.1013	0.1258	0.1585	0.2273
number of source pos.		3313	46111	12926	650

Table 8 - temperature 10°C – statistical data refered to max DI values

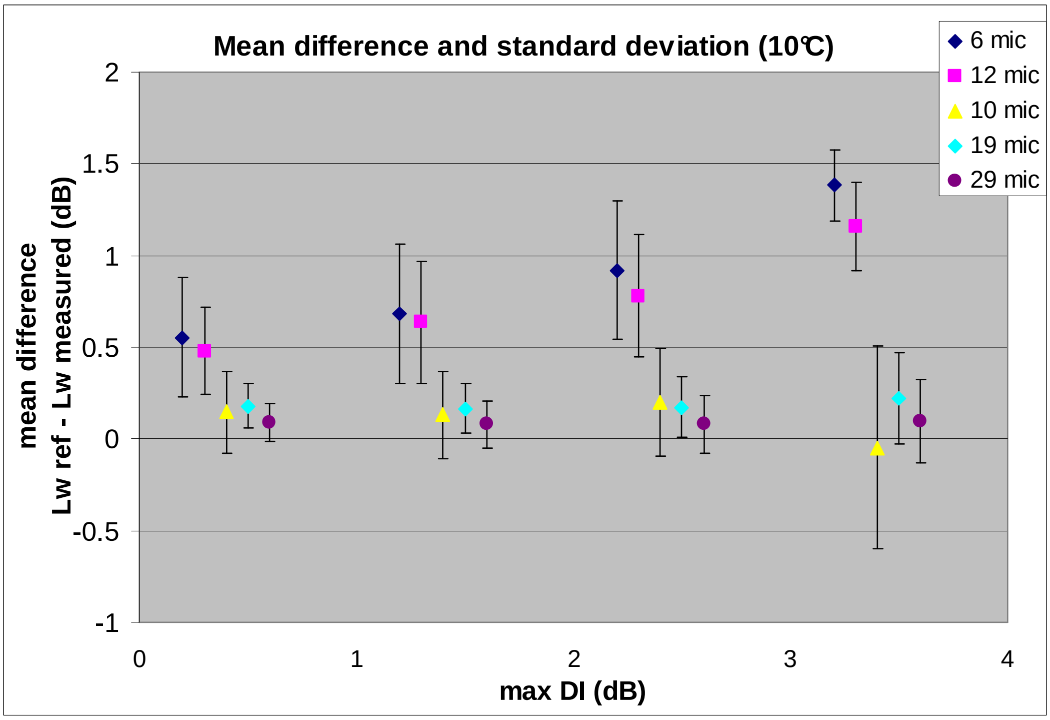

Figure 29 - temperature 10°C – systematic error and standard deviation

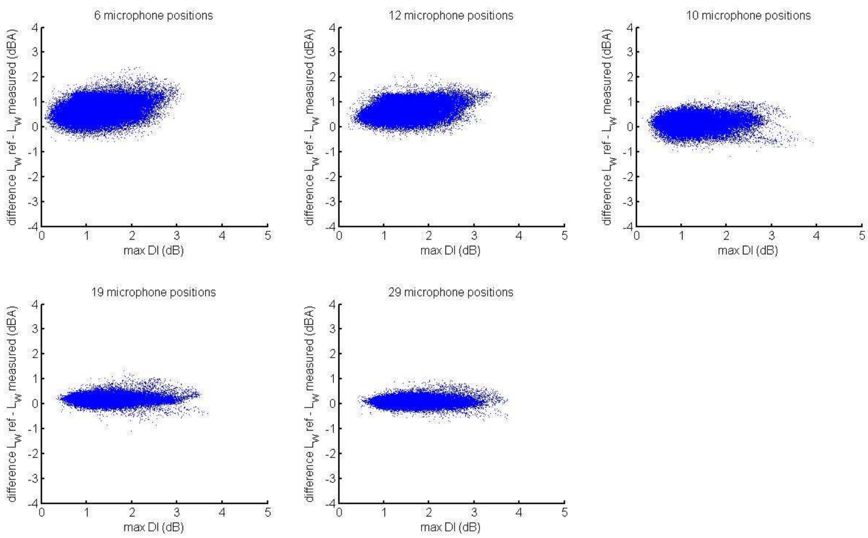

Figure 30 - temperature 10°C – Spreading of difference value related with the max DI

	6 diff	6 DI	12 diff	12 DI	10 diff	10 DI	19 diff	19 DI	29 diff	29DI
mean	0.6137	1.2560	0.5917	1.5264	0.1110	1.3057	0.1398	1.5309	0.0509	1.6635
standard deviation	0.3810	0.5124	0.3397	0.5123	0.2393	0.4650	0.1344	0.4905	0.1313	0.4811
max	2.3477	3.1473	2.0319	3.4506	1.2961	3.9337	1.3166	3.6816	0.9622	3.7714
min	-0.6684	0.0617	-0.5592	0.1741	-1.0826	0.2379	-1.0306	0.3079	-0.7569	0.3841

Table 9 – temperature 15°C – 63000 sources setup

	mics	DI<1	1<DI<2	2<DI<3	3<DI<4
systematic error	6	***0.5104***	***0.636***	***0.8661***	***1.3007***
standard deviation		0.3312	0.386	0.3845	0.2178
number of source pos.		22157	34871	5958	14
systematic error	12	***0.43***	***0.59***	***0.73***	***1.09***
standard deviation		0.25	0.34	0.34	0.27
number of source pos.		10114	41069	11626	191
systematic error	10	***0.1228***	***0.0996***	***0.1626***	***-0.0798***
standard deviation		0.2161	0.2388	0.2885	0.5523
number of source pos.		17396	40195	5287	122
systematic error	19	***0.1499***	***0.138***	***0.1383***	***0.1791***
standard deviation		0.1114	0.1291	0.1637	0.244
number of source pos.		7767	44696	10155	382
systematic error	29	***0.0594***	***0.0516***	***0.0458***	***0.0595***
standard deviation		0.0992	0.1226	0.158	0.2233
number of source pos.		3072	46057	13198	673

Table 10 - temperature 15°C – statistical data refered to max DI values

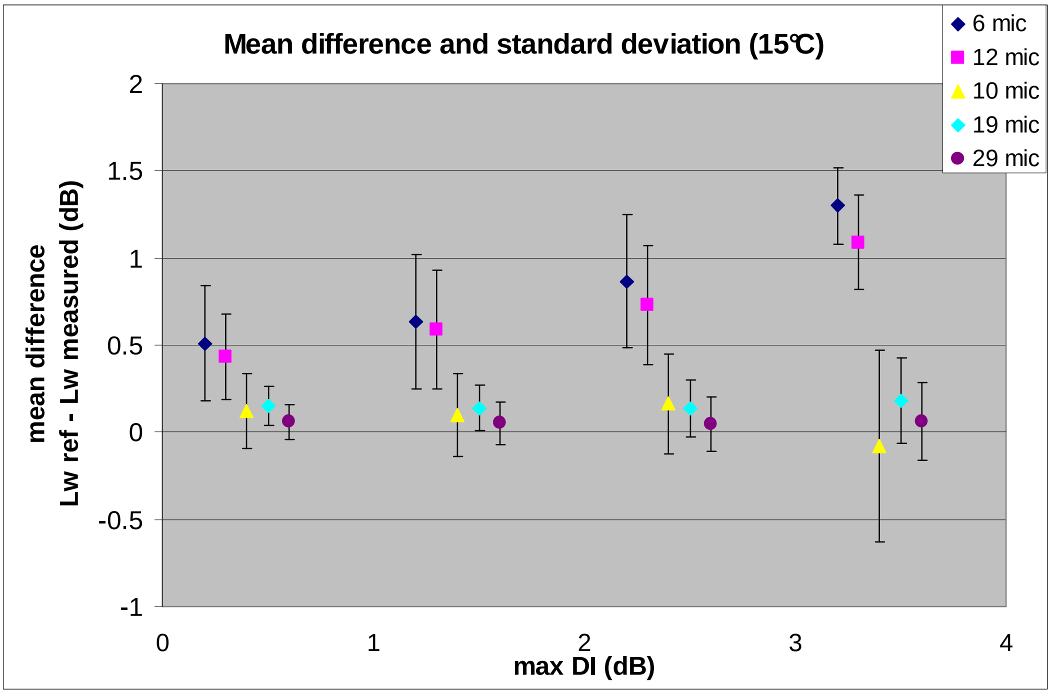

Figure 31 - temperature 15°C – systematic error and standard deviation

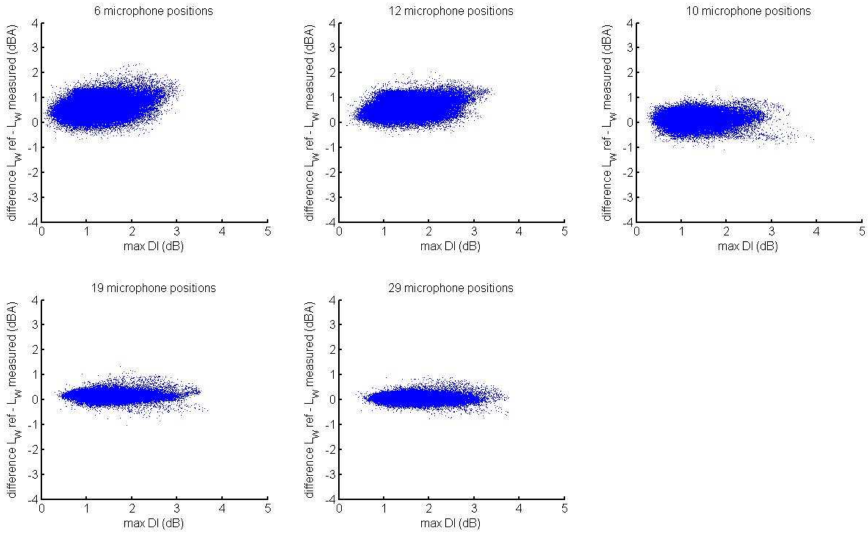

Figure 32 - temperature 15°C – Spreading of difference value related with the max DI

	6 diff	6 DI	12 diff	12 DI	10 diff	10 DI	19 diff	19 DI	29 diff	29DI
mean	0.5664	1.2704	0.5444	1.5409	0.0845	1.3094	0.1068	1.5422	0.0189	1.6720
standard deviation	0.3902	0.5131	0.3491	0.5125	0.2383	0.4647	0.1334	0.4927	0.1313	0.4833
max	2.2967	3.1467	1.9943	3.4395	1.2550	3.9414	1.2771	3.6853	0.8976	3.8034
min	-0.7628	0.0714	-0.5993	0.1029	-1.0467	0.1929	-1.0294	0.3308	-0.7903	0.4285

Table 11 – temperature 20°C – 63000 sources setup

	mics	DI<1	1<DI<2	2<DI<3	3<DI<4
systematic error	6	***0.4598***	***0.5873***	***0.8146***	***1.2495***
standard deviation		0.3422	0.3935	0.3936	0.2482
number of source pos.		21503	35270	6209	18
systematic error	12	***0.373***	***0.5426***	***0.6776***	***1.0418***
standard deviation		0.2551	0.3495	0.3485	0.2768
number of source pos.		9540	41148	12119	193
systematic error	10	***0.1024***	***0.0716***	***0.1283***	***-0.1093***
standard deviation		0.2082	0.2406	0.2851	0.5588
number of source pos.		17429	40095	5350	126
systematic error	19	***0.1144***	***0.1062***	***0.103***	***0.138***
standard deviation		0.1099	0.1278	0.1626	0.2425
number of source pos.		7521	44601	10479	399
systematic error	29	***0.0219***	***0.0213***	***0.0099***	***0.0205***
standard deviation		0.1004	0.1219	0.1586	0.2209
number of source pos.		3070	45672	13549	709

Table 12 - temperature 20°C – statistical data refered to max DI values

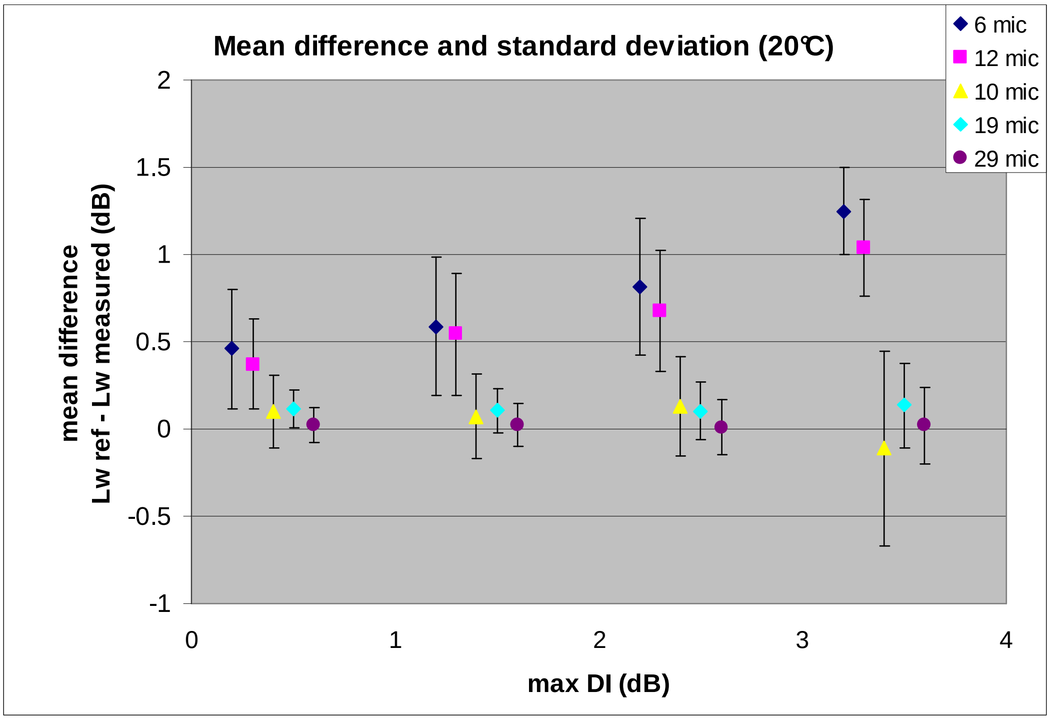

Figure 33 - temperature 20°C – systematic error and standard deviation

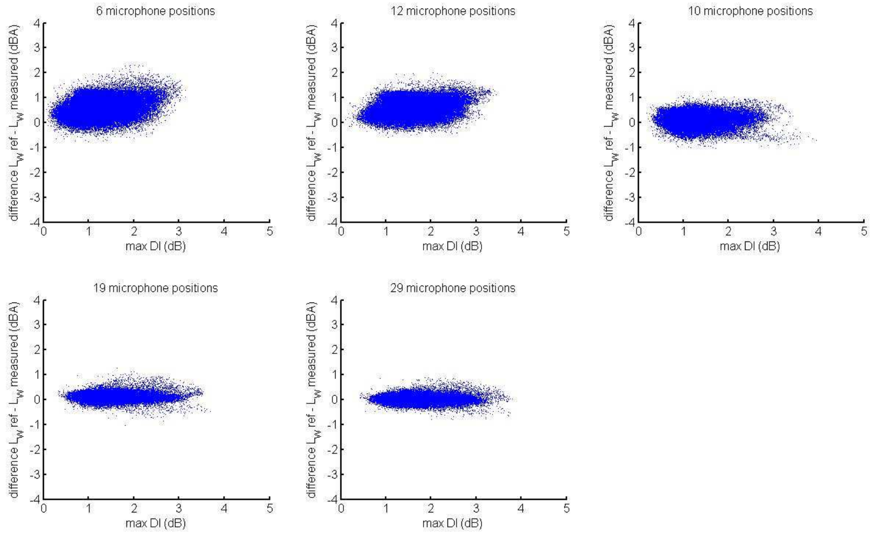

Figure 34 - temperature 20°C – Spreading of difference value related with the max DI

	6 diff	6 DI	12 diff	12 DI	10 diff	10 DI	19 diff	19 DI	29 diff	29DI
mean	0.5180	1.2836	0.4961	1.5548	0.0495	1.3158	0.0656	1.5550	-0.0182	1.6775
standard deviation	0.4008	0.5145	0.3598	0.5132	0.2399	0.4659	0.1386	0.4957	0.1345	0.4887
max	2.2965	3.1883	1.9575	3.4339	1.2192	3.9419	1.2430	3.6864	0.9079	3.8265
min	-0.8576	0.0647	-0.5843	0.0964	-1.0588	0.1617	-1.0425	0.3609	-0.8249	0.4615

Table 13 – temperature 25°C – 63000 sources setup

	mics	DI<1	1<DI<2	2<DI<3	3<DI<4
systematic error	6	***0.4074***	***0.5378***	***0.7627***	***1.1834***
standard deviation		0.3532	0.4033	0.403	0.2522
number of source pos.		20851	35646	6485	18
systematic error	12	***0.3128***	***0.4935***	***0.6288***	***1.0244***
standard deviation		0.2642	0.3603	0.355	0.2561
number of source pos.		9088	41120	12598	194
systematic error	10	***0.0695***	***0.0351***	***0.0962***	***-0.1245***
standard deviation		0.2072	0.2429	0.2835	0.5635
number of source pos.		17071	40276	5523	130
systematic error	19	***0.0749***	***0.0639***	***0.0652***	***0.1009***
standard deviation		0.1177	0.1338	0.1628	0.2396
number of source pos.		7267	44348	10975	410
systematic error	29	***-0.0166***	***-0.0156***	***-0.0267***	***-0.0209***
standard deviation		0.1023	0.1256	0.1601	0.2195
number of source pos.		3056	45282	13920	742

Table 14 - temperature 25°C – statistical data refered to max DI values

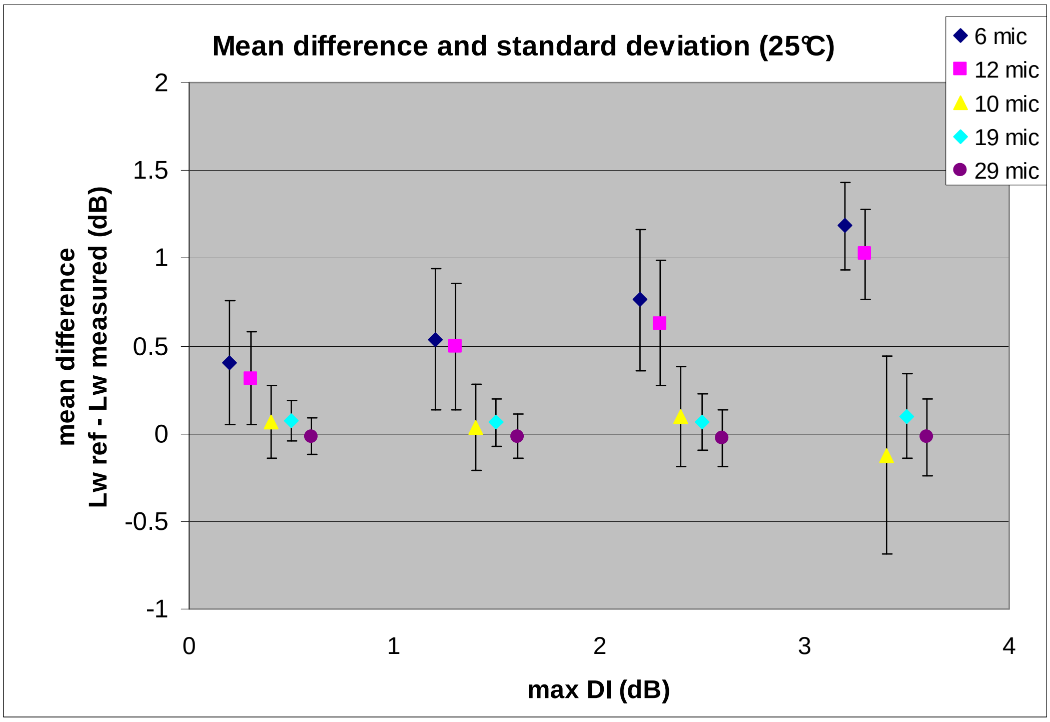

Figure 35 - temperature 25°C – systematic error and standard deviation

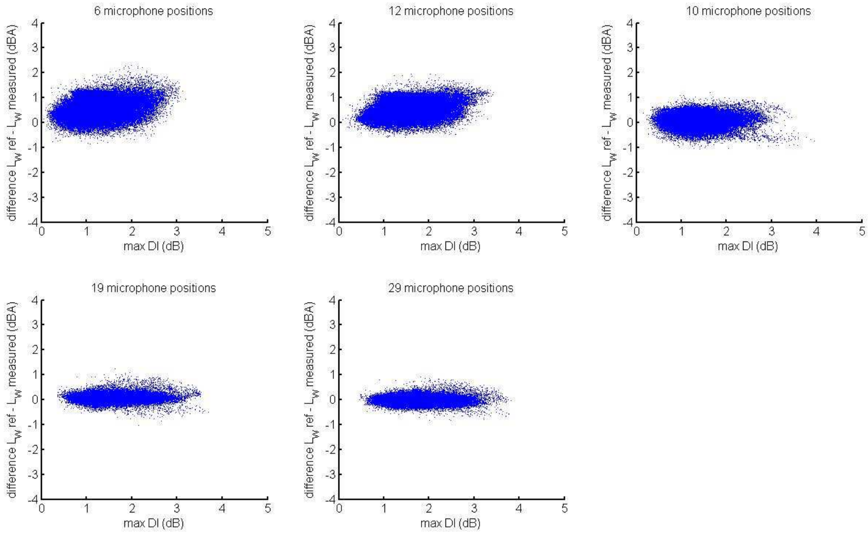

Figure 36 - temperature 25°C – Spreading of difference value related with the max DI

	6 diff	6 DI	12 diff	12 DI	10 diff	10 DI	19 diff	19 DI	29 diff	29DI
mean	0.4710	1.2961	0.4484	1.5679	-0.0003	1.3248	0.0140	1.5670	-0.0592	1.6802
standard deviation	0.4110	0.5156	0.3707	0.5143	0.2428	0.4715	0.1457	0.5023	0.1387	0.4973
max	2.2999	3.2223	1.9213	3.4489	1.1922	3.9362	1.2197	3.6856	0.8775	3.8345
min	-0.9203	0.0866	-0.6954	0.1412	-1.0795	0.1415	-1.0124	0.3352	-0.8567	0.4505

Table 15 – temperature 30°C – 63000 sources setup

	mics	DI<1	1<DI<2	2<DI<3	3<DI<4
systematic error	6	***0.3546***	***0.49***	***0.7171***	***1.1315***
standard deviation		0.3656	0.4113	0.4113	0.2274
number of source pos.		20249	35983	6751	17
systematic error	12	***0.2538***	***0.4447***	***0.5817***	***0.9983***
standard deviation		0.2753	0.3713	0.3615	0.2383
number of source pos.		8695	41056	13054	195
systematic error	10	***0.0138***	***-0.0144***	***0.0587***	***-0.1507***
standard deviation		0.2081	0.2469	0.2805	0.5623
number of source pos.		16868	40133	5866	133
systematic error	19	***0.0151***	***0.0112***	***0.0218***	***0.0631***
standard deviation		0.134	0.1416	0.162	0.235
number of source pos.		7235	43699	11632	434
systematic error	29	***-0.0683***	***-0.0568***	***-0.0646***	***-0.0589***
standard deviation		0.1098	0.1308	0.1609	0.2168
number of source pos.		3444	44434	14345	777

Table 16 - temperature 30°C – statistical data refered to max DI values

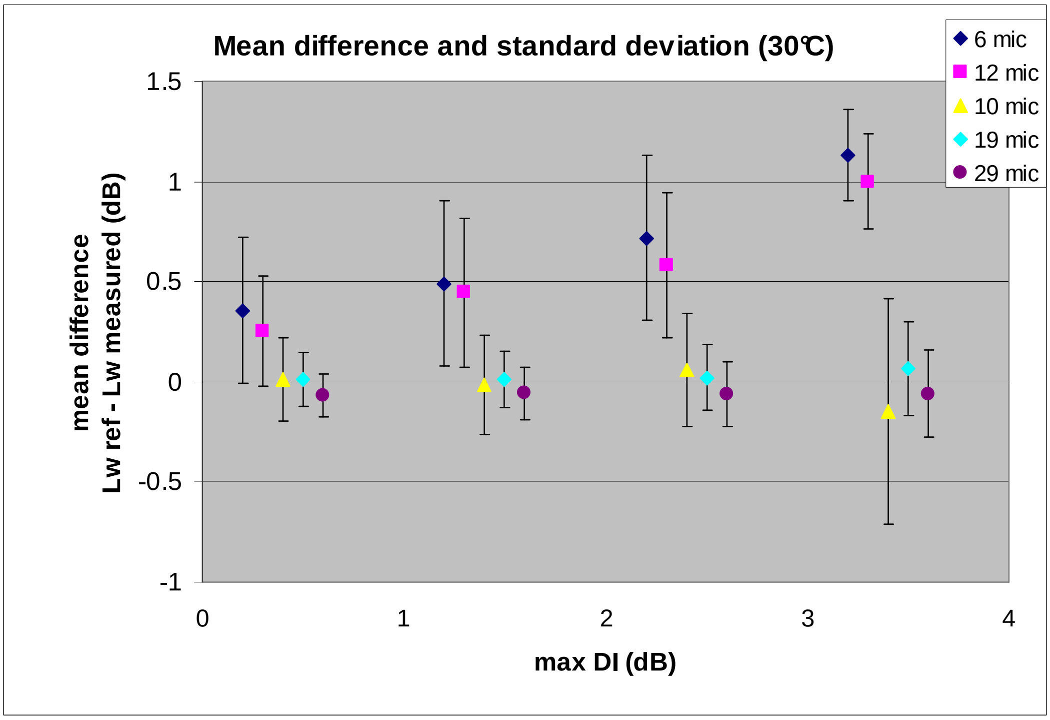

Figure 37 - temperature 30°C – systematic error and standard deviation

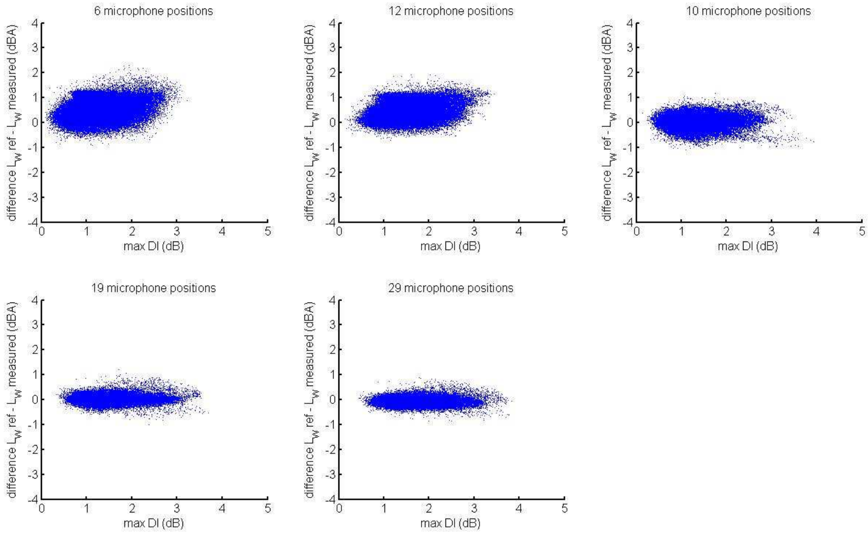

Figure 38 - temperature 30°C – Spreading of difference value related with the max DI

	6 diff	6 DI	12 diff	12 DI	10 diff	10 DI	19 diff	19 DI	29 diff	29DI
mean	0.4266	1.3090	0.4026	1.5813	-0.0485	1.3334	-0.0380	1.5773	-0.0990	1.6861
standard deviation	0.4189	0.5166	0.3803	0.5151	0.2467	0.4770	0.1534	0.5077	0.1428	0.5021
max	2.3061	3.2418	1.8855	3.4555	1.1857	3.9259	1.1943	3.6835	0.8442	3.8268
min	-0.9645	0.0889	-0.7946	0.1213	-1.0877	0.1909	-1.0353	0.3347	-0.8863	0.4292

Table 17 – temperature 35°C – 63000 sources setup

	mics	DI<1	1<DI<2	2<DI<3	3<DI<4
systematic error	6	***0.5946***	***0.7313***	***0.9777***	***1.4076***
standard deviation		0.3238	0.3786	0.3678	0.2
number of source pos.		23751	33835	5398	16
systematic error	12	***0.5284***	***0.6778***	***0.8363***	***1.2319***
standard deviation		0.2368	0.3322	0.3252	0.1906
number of source pos.		10995	41156	10684	165
systematic error	10	***0.1673***	***0.1559***	***0.2368***	***0.006***
standard deviation		0.2305	0.2421	0.2958	0.5515
number of source pos.		17288	40571	5027	114
systematic error	19	***0.2086***	***0.1878***	***0.2073***	***0.2706***
standard deviation		0.1386	0.1472	0.167	0.2509
number of source pos.		8242	44841	9581	336
systematic error	29	***0.1194***	***0.1057***	***0.1149***	***0.1425***
standard deviation		0.1106	0.1299	0.1594	0.2329
number of source pos.		3417	46327	12648	608

Table 18 - temperature 35°C – statistical data refered to max DI values

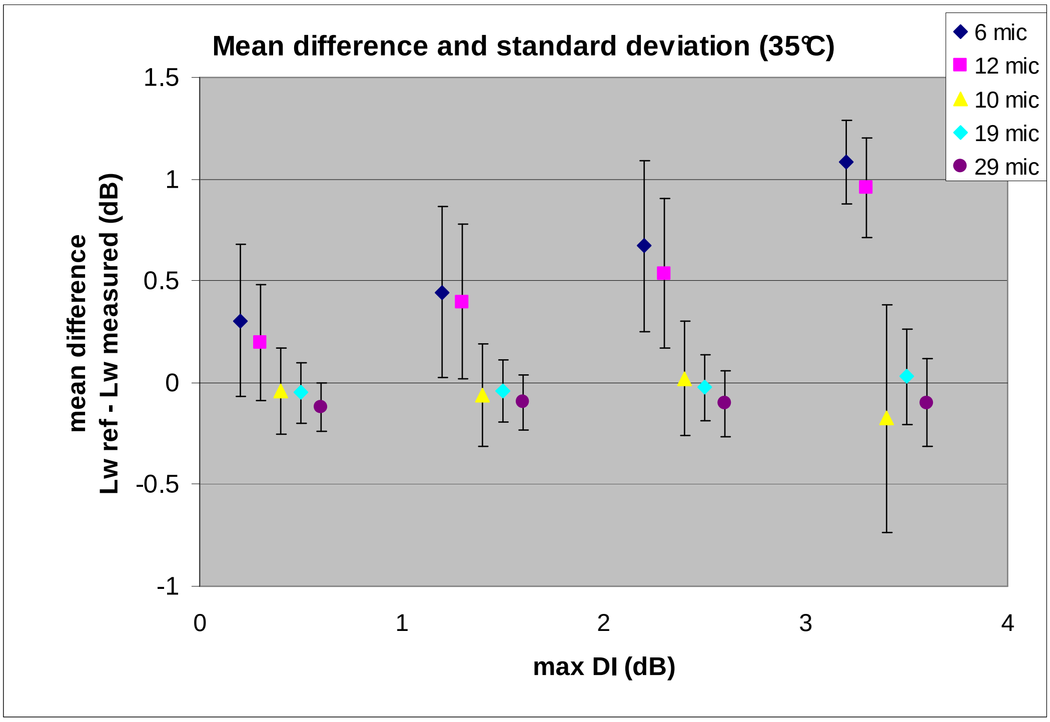

Figure 39 - temperature 35°C – systematic error and standard deviation

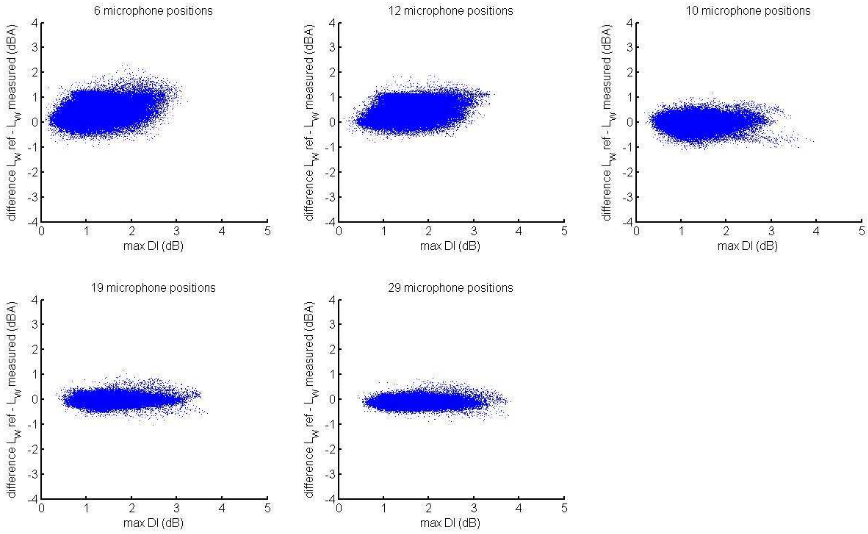

Figure 40 - temperature 35°C – Spreading of difference value related with the max DI

8.2 *Single temperature (20°C) and the same source moved closed to the centre of the hemisphere*

	6 diff	6 DI	12 diff	12 DI	10 diff	10 DI	19 diff	19 DI	29 diff	29DI
mean	0.7010	1.2260	0.6800	1.4990	0.1652	1.3007	0.1939	1.5108	0.1086	1.6430
standard deviation	0.3735	0.5113	0.3299	0.5086	0.2457	0.4565	0.1504	0.4857	0.1368	0.4793
max	2.4332	3.1334	2.1097	3.4311	1.3637	3.8963	1.3278	3.6644	0.9881	3.7392
min	-0.5382	0.0398	-0.4597	0.2028	-1.1615	0.2009	-1.1015	0.3152	-0.7527	0.4485

Table 19 – temperature 20°C – 26492 sources setup

	mics	DI<1	1<DI<2	2<DI<3	3<DI<4
systematic error	6	*0.1449*	*0.1067*	*0.455*	*0*
standard deviation		0.0907	0.203	0.2375	0
number of source pos.		6933	16931	2628	0
systematic error	12	*-0.0409*	*0.0767*	*0.1423*	*0*
standard deviation		0.0949	0.1651	0.1399	0
number of source pos.		1615	17817	7060	0
systematic error	10	*-0.0412*	*0.0353*	*0.3021*	*0.416*
standard deviation		0.0939	0.1041	0.1319	0.0286
number of source pos.		618	13954	11674	246
systematic error	19	*0*	*-0.124*	*0.12*	*0.3026*
standard deviation		0	0.0853	0.133	0.0887
number of source pos.		0	11894	13877	721
systematic error	29	*0*	*-0.1678*	*0.0899*	*0.0752*
standard deviation		0	0.1088	0.2292	0.1618
number of source pos.		0	8118	15946	2428

Table 20 - temperature 20°C – statistical data refered to DI values

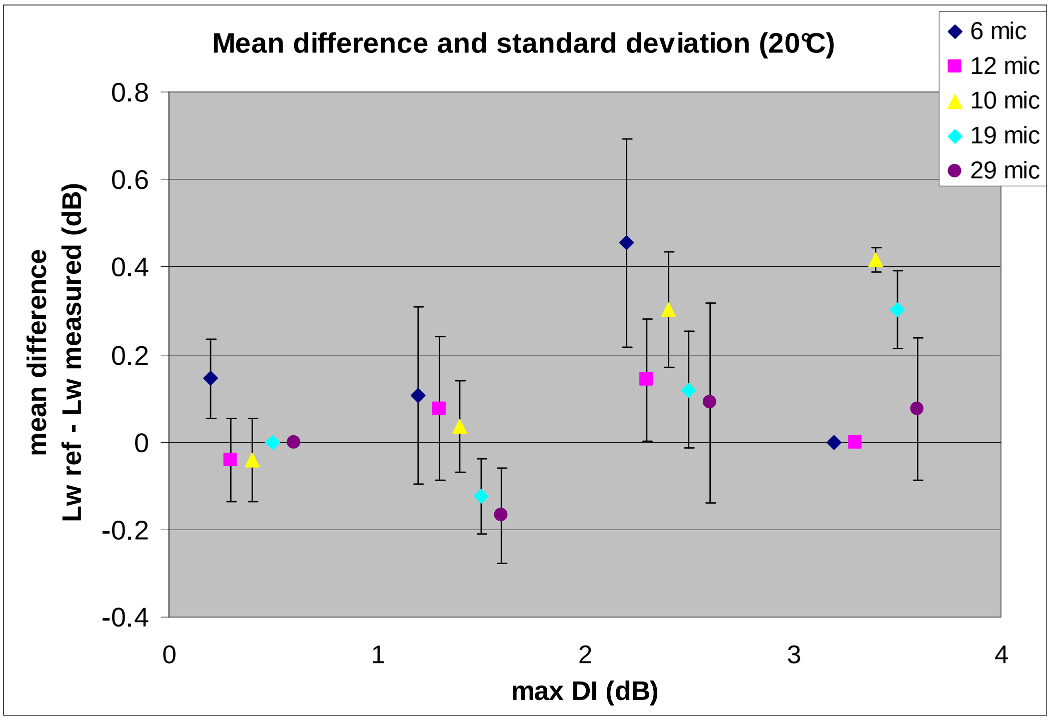

Figure 41 - temperature 20°C – systematic error and standard deviation

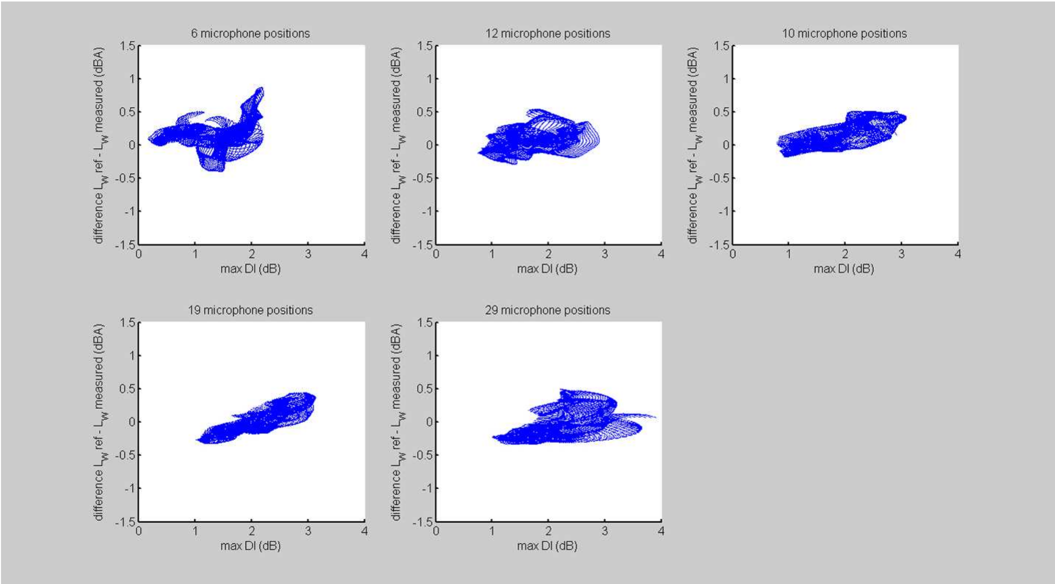

Figure 42 - temperature 20°C – Spreading of difference value related with the max DI

9 APPENDIX B – SYSTEMATIC ERROR AND STANDARD DEVIATION

In this appendix are shown values of systematic errors and standard deviations evaluated over different microphone arrays in function of the temperature. Furthermore the presented data have been divided in classes in function of the evaluated max DI value.

9.1 6 microphones array

	TEMP (°C)	MAX DIRECTIVITY INDEX (dB)			
		maxDI<1	**1<maxDI<2**	**2<maxDI<3**	**3<maxDI<4**
systematic error	5	***0.5946***	***0.7313***	***0.9777***	***1.4076***
standard deviation		0.3238	0.3786	0.3678	0.2
number of sources setup		23751	33835	5398	16
systematic error	10	***0.553***	***0.6849***	***0.919***	***1.3818***
standard deviation		0.3249	0.3806	0.3759	0.1926
number of source positions		22950	34327	5708	15
systematic error	15	***0.5104***	***0.636***	***0.8661***	***1.3007***
standard deviation		0.3312	0.386	0.3845	0.2178
number of source positions		22157	34871	5958	14
systematic error	20	***0.4598***	***0.5873***	***0.8146***	***1.2495***
standard deviation		0.3422	0.3935	0.3936	0.2482
number of source positions		21503	35270	6209	18
systematic error	25	***0.4074***	***0.5378***	***0.7627***	***1.1834***
standard deviation		0.3532	0.4033	0.403	0.2522
number of source positions		20851	35646	6485	18
systematic error	30	***0.3546***	***0.49***	***0.7171***	***1.1315***
standard deviation		0.3656	0.4113	0.4113	0.2274
number of source positions		20249	35983	6751	17
systematic error	35	***0.3056***	***0.4451***	***0.6702***	***1.0834***
standard deviation		0.3746	0.4182	0.4172	0.2072
number of source positions		19759	36203	7020	18

Table 21 – statistical result for a 6 microphones array in function of the max DI

9.2 12 microphones array

	TEMP (°C)	MAX DIRECTIVITY INDEX (dB)			
		maxDI<1	**1<maxDI<2**	**2<maxDI<3**	**3<maxDI<4**
systematic error	5	***0.5284***	***0.6778***	***0.8363***	***1.2319***
standard deviation		0.2368	0.3322	0.3252	0.1906
number of sources setup		10995	41156	10684	165
systematic error	10	***0.4798***	***0.6356***	***0.7817***	***1.1591***
standard deviation		0.2377	0.3347	0.3333	0.2428
number of source positions		10645	41009	11169	177
systematic error	15	***0.43***	***0.59***	***0.73***	***1.09***
standard deviation		0.25	0.34	0.34	0.27
number of source positions		10114	41069	11626	191
systematic error	20	***0.373***	***0.5426***	***0.6776***	***1.0418***
standard deviation		0.2551	0.3495	0.3485	0.2768
number of source positions		9540	41148	12119	193
systematic error	25	***0.3128***	***0.4935***	***0.6288***	***1.0244***
standard deviation		0.2642	0.3603	0.355	0.2561
number of source positions		9088	41120	12598	194
systematic error	30	***0.2538***	***0.4447***	***0.5817***	***0.9983***
standard deviation		0.2753	0.3713	0.3615	0.2383
number of source positions		8695	41056	13054	195
systematic error	35	***0.1982***	***0.3975***	***0.5358***	***0.9586***
standard deviation		0.2844	0.3815	0.3665	0.2469
number of source positions		8308	40971	13523	198

Table 22 – statistical result for a 12 microphones array in function of the max DI

9.3 10 microphones array

	TEMP (°C)	MAX DIRECTIVITY INDEX (dB)			
		maxDI<1	**1<maxDI<2**	**2<maxDI<3**	**3<maxDI<4**
systematic error	5	***0.1673***	***0.1559***	***0.2368***	***0.006***
standard deviation		0.2305	0.2421	0.2958	0.5515
number of sources setup		17288	40571	5027	114
systematic error	10	***0.1459***	***0.1306***	***0.2007***	***-0.0475***
standard deviation		0.2217	0.2382	0.2908	0.5517
number of source positions		17520	40216	5142	122
systematic error	15	***0.1228***	***0.0996***	***0.1626***	***-0.0798***
standard deviation		0.2161	0.2388	0.2885	0.5523
number of source positions		17396	40195	5287	122
systematic error	20	***0.1024***	***0.0716***	***0.1283***	***-0.1093***
standard deviation		0.2082	0.2406	0.2851	0.5588
number of source positions		17429	40095	5350	126
systematic error	25	***0.0695***	***0.0351***	***0.0962***	***-0.1245***
standard deviation		0.2072	0.2429	0.2835	0.5635
number of source positions		17071	40276	5523	130
systematic error	30	***0.0138***	***-0.0144***	***0.0587***	***-0.1507***
standard deviation		0.2081	0.2469	0.2805	0.5623
number of source positions		16868	40133	5866	133
systematic error	35	***-0.0411***	***-0.0617***	***0.0202***	***-0.1745***
standard deviation		0.2134	0.2505	0.2797	0.5598
number of source positions		16665	40063	6137	135

Table 23 – statistical result for a 10 microphones array in function of the max DI

9.4 19 microphones array

	TEMP (°C)	MAX DIRECTIVITY INDEX (dB)			
		maxDI<1	**1<maxDI<2**	**2<maxDI<3**	**3<maxDI<4**
systematic error	5	***0.2086***	***0.1878***	***0.2073***	***0.2706***
standard deviation		0.1386	0.1472	0.167	0.2509
number of sources setup		8242	44841	9581	336
systematic error	10	***0.181***	***0.1668***	***0.174***	***0.2241***
standard deviation		0.1206	0.1353	0.1644	0.2496
number of source positions		7892	44848	9903	357
systematic error	15	***0.1499***	***0.138***	***0.1383***	***0.1791***
standard deviation		0.1114	0.1291	0.1637	0.244
number of source positions		7767	44696	10155	382
systematic error	20	***0.1144***	***0.1062***	***0.103***	***0.138***
standard deviation		0.1099	0.1278	0.1626	0.2425
number of source positions		7521	44601	10479	399
systematic error	25	***0.0749***	***0.0639***	***0.0652***	***0.1009***
standard deviation		0.1177	0.1338	0.1628	0.2396
number of source positions		7267	44348	10975	410
systematic error	30	***0.0151***	***0.0112***	***0.0218***	***0.0631***
standard deviation		0.134	0.1416	0.162	0.235
number of source positions		7235	43699	11632	434
systematic error	35	***-0.048***	***-0.0412***	***-0.023***	***0.0291***
standard deviation		0.149	0.15	0.1628	0.2322
number of source positions		7188	43314	12046	452

Table 24 – statistical result for a 19 microphones array in function of the max DI

9.5 29 microphones array

	TEMP (°C)	MAX DIRECTIVITY INDEX (dB)			
		maxDI<1	**1<maxDI<2**	**2<maxDI<3**	**3<maxDI<4**
systematic error	5	***0.1194***	***0.1057***	***0.1149***	***0.1425***
standard deviation		0.1106	0.1299	0.1594	0.2329
number of sources setup		3417	46327	12648	608
systematic error	10	***0.0879***	***0.0796***	***0.0808***	***0.0991***
standard deviation		0.1013	0.1258	0.1585	0.2273
number of source positions		3313	46111	12926	650
systematic error	15	***0.0594***	***0.0516***	***0.0458***	***0.0595***
standard deviation		0.0992	0.1226	0.158	0.2233
number of source positions		3072	46057	13198	673
systematic error	20	***0.0219***	***0.0213***	***0.0099***	***0.0205***
standard deviation		0.1004	0.1219	0.1586	0.2209
number of source positions		3070	45672	13549	709
systematic error	25	***-0.0166***	***-0.0156***	***-0.0267***	***-0.0209***
standard deviation		0.1023	0.1256	0.1601	0.2195
number of source positions		3056	45282	13920	742
systematic error	30	***-0.0683***	***-0.0568***	***-0.0646***	***-0.0589***
standard deviation		0.1098	0.1308	0.1609	0.2168
number of source positions		3444	44434	14345	777
systematic error	35	***-0.1202***	***-0.0961***	***-0.1028***	***-0.0988***
standard deviation		0.1177	0.1356	0.1627	0.2144
number of source positions		3473	44027	14697	803

Table 25 – statistical result for a 29 microphones array in function of the max DI

10 APPENDIX C – MATLAB CODE

10.1 Statistical main code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Theoretical model - Uncertainty in ISO 3744
% STATISTICAL DATA
% Cadriano's case
% A-weighted
% sources emit pink noise
% speed of evaluation - 12000 source position per hour
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% profile on

close all
clear all

% costants
stat_pres=101300;                   % Pa
cost_R=287;                         % J/(kg*K)
T=25:5:25;                           % temperature (°C)
si=10^20;                           % flow resistivity
W_ref=1e-12;                        % W/m^2
Pa_ref=1e-12;                       % W
p_ref=2e-5;                         % Pa
f=load('freq.txt');                 % frequecy
Aw=load('Aw_50_10000.txt');         % frequecy

fmax=max(f);
fmin=min(f);

% surface dimension
radius=16;                          % hemisphere radius in m

source set up
val_Q_1=[17 35 42 39 48];
val_Q_2=[17 51];

for qq=1:length(val_Q_1)
    phi_1(qq)=2*pi*rand;
    Q_A(qq)=val_Q_1(qq)*exp(j*phi_1(qq));         % source A - volume velocity
end

for qqq=1:length(val_Q_2)
    phi_2(qqq)=2*pi*rand;
    Q2_A(qqq)=val_Q_2(qqq)*exp(j*phi_2(qqq));     % source B - volume velocity
end

Q=[Q_A];
Q2=[Q2_A];

rx=-0.7:0.112:0.1;        % X coordinate - value expressed in m - source 1
```

```
ry=-0.8:0.153:0.8;         % Y coordinate - value expressed in m - source 1
rz=0.2:0.245:1.2;         % height from the ground - value expressed in m -
source 1

rx2=-1.011:0.368:0.5;         % X coordinate - value expressed in m - source 2
ry2=-0.2:0.1095:0.5;         % Y coordinate - value expressed in m - source 2
rz2=0.2:0.35:1;       % height from the ground - value expressed in m - source 2

number_sources_positions=length(Q)*length(Q2)*length(rx)*length(ry)*length(rz)*l
ength(rx2)*length(ry2)*length(rz2)
number_of_interaction=length(Q)*length(Q2)*length(rx)*length(ry)*length(rz)*leng
th(rx2)*length(ry2)*length(rz2)*length(T)

%%
surface_ISO=2*pi*radius^2;              % as defined in the ISO 3744

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% hemisphere's coordinates
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

x6=load('x6_2000-14.txt');
y6=load('y6_2000-14.txt');
z6=load('z6_2000-14.txt');
X6=x6.*radius;
Y6=y6.*radius;
Z6=zeros(length(z6),1);
for zz=1:length(z6)
    if z6(zz)==0
        Z6(zz)=1.5;
    else
        Z6(zz)=z6(zz)*radius;
    end
end

x12=load('x12_2000-14.txt');
y12=load('y12_2000-14.txt');
z12=load('z12_2000-14.txt');
X12=x12.*radius;
Y12=y12.*radius;
Z12=zeros(length(z12),1);
for z=1:length(z12)
    if z12(z)==0
        Z12(z)=1.5;
    else
        Z12(z)=z12(z)*radius;
    end
end

x10=load('x10.txt');
y10=load('y10.txt');
z10=load('z10.txt');
X10=x10.*radius;
Y10=y10.*radius;
Z10=z10.*radius;

x19=load('x20.txt');
y19=load('y20.txt');
z19=load('z20.txt');
X19=x19.*radius;
Y19=y19.*radius;
```

```
Z19=z19.*radius;

x29=load('x29.txt');
y29=load('y29.txt');
z29=load('z29.txt');
X29=x29.*radius;
Y29=y29.*radius;
Z29=z29.*radius;

%%
ISO_surf=(10*log10(surface_ISO));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% BODY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for a0=1:length(T)

    c(a0)=20.05*sqrt(273.15+T(a0));
    rho(a0)=(stat_pres)/(cost_R*(273.15+T(a0)));

    for i=1:length(f)
        w(a0,i)=2*pi*f(i);
        k(a0,i)=w(a0,i)/c(a0);

        % pink noise
        fac(a0,i)=w(a0,i)*(w(a0,i)^(1/2));        % source 1 - factor used to
get a more realistic spectra with high emission in low frequencies instead of
high frequencies
        fac2(a0,i)=w(a0,i)*(w(a0,i)^(1/2));
    end

    for a1=1:length(Q)
        for a2=1:length(Q2)
            for a3=1:length(rx)
                for a4=1:length(ry)
                    for a5=1:length(rz)
                        for a6=1:length(rx2)
                            for a7=1:length(ry2)
                                for a8=1:length(rz2)

                                    rx_A(a0,a1,a2,a3,a4,a5,a6,a7,a8)=abs(rx(a3)-
rx2(a6));
                                    ry_A(a0,a1,a2,a3,a4,a5,a6,a7,a8)=abs(ry(a4)-
ry2(a7));

r1(a0,a1,a2,a3,a4,a5,a6,a7,a8)=sqrt(sqrt((rx_A(a0,a1,a2,a3,a4,a5,a6,a7,a8)^2)+(r
y_A(a0,a1,a2,a3,a4,a5,a6,a7,a8)^2))+(rz(a5)-rz2(a8))^2);
                                    r2(a0,a1,a2,a3,a4,a5,a6,a7,a8)=rz(a5)*2;
                                    r3(a0,a1,a2,a3,a4,a5,a6,a7,a8)=rz2(a8)*2;

r4(a0,a1,a2,a3,a4,a5,a6,a7,a8)=sqrt(sqrt((rx_A(a0,a1,a2,a3,a4,a5,a6,a7,a8)^2)+(r
y_A(a0,a1,a2,a3,a4,a5,a6,a7,a8)^2))+(rz(a5)+rz2(a8))^2);

                                    for i=1:length(f)
                                        % REFERENCE COHERENT
                                        if r1(a0,a1,a2,a3,a4,a5,a6,a7,a8)==0
                                            if r2(a0,a1,a2,a3,a4,a5,a6,a7,a8)==0
```

```
cohe_P1{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i)=(((rho(a0)*c(a0)*(k(a0,i)^2)*((abs(Q(a1)+
Q2(a2)))^2))/(8*pi*fac(a0,i)^2))*2);

cohe_P2{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i)=0;
                                            else

cohe_P1{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i)=((rho(a0)*c(a0)*(k(a0,i)^2)*((abs(Q(a1)+Q
2(a2)))^2))/(8*pi*fac(a0,i)^2))*(1+(sin(2*k(a0,i)*rz(a5)))/(2*k(a0,i)*rz(a5)));

cohe_P2{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i)=0;
                                            end
                                        else
                                            if r2(a0,a1,a2,a3,a4,a5,a6,a7,a8)==0

cohe_P1{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i)=(((rho(a0)*c(a0)*(k(a0,i)^2)*((abs(Q(a1))
)^2))/(8*pi*fac(a0,i)^2))*2)*(1+real((Q2(a2)/Q(a1))*((j*exp(-
j*k(a0,i)*r1(a0,a1,a2,a3,a4,a5,a6,a7,a8)))/(k(a0,i)*r1(a0,a1,a2,a3,a4,a5,a6,a7,a
8)))));
                                            else

cohe_P1{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i)=((rho(a0)*c(a0)*(k(a0,i)^2)*((abs(Q(a1)))
^2))/(8*pi*fac(a0,i)^2))*(1+real(((Q2(a2)/Q(a1))*((j*exp(-
j*k(a0,i)*r1(a0,a1,a2,a3,a4,a5,a6,a7,a8)))/(k(a0,i)*r1(a0,a1,a2,a3,a4,a5,a6,a7,a
8))))+((Q(a1)/Q(a1))*((j*exp(-
j*k(a0,i)*r2(a0,a1,a2,a3,a4,a5,a6,a7,a8)))/(k(a0,i)*r2(a0,a1,a2,a3,a4,a5,a6,a7,a
8))))+((Q2(a2)/Q(a1))*((j*exp(-
j*k(a0,i)*r4(a0,a1,a2,a3,a4,a5,a6,a7,a8)))/(k(a0,i)*r4(a0,a1,a2,a3,a4,a5,a6,a7,a
8))))));
                                            end
                                            if r3(a0,a1,a2,a3,a4,a5,a6,a7,a8)==0

cohe_P2{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i)=(((rho(a0)*c(a0)*(k(a0,i)^2)*((abs(Q2(a2)
))^2))/(8*pi*fac2(a0,i)^2))*2)*(1+real((Q(a1)/Q2(a2))*((j*exp(-
j*k(a0,i)*r1(a0,a1,a2,a3,a4,a5,a6,a7,a8)))/(k(a0,i)*r1(a0,a1,a2,a3,a4,a5,a6,a7,a
8)))));
                                            else

cohe_P2{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i)=((rho(a0)*c(a0)*(k(a0,i)^2)*((abs(Q2(a2))
)^2))/(8*pi*fac2(a0,i)^2))*(1+real(((Q(a1)/Q2(a2))*((j*exp(-
j*k(a0,i)*r1(a0,a1,a2,a3,a4,a5,a6,a7,a8)))/(k(a0,i)*r1(a0,a1,a2,a3,a4,a5,a6,a7,a
8))))+((Q2(a2)/Q2(a2))*((j*exp(-
j*k(a0,i)*r3(a0,a1,a2,a3,a4,a5,a6,a7,a8)))/(k(a0,i)*r3(a0,a1,a2,a3,a4,a5,a6,a7,a
8))))+((Q(a1)/Q2(a2))*((j*exp(-
j*k(a0,i)*r4(a0,a1,a2,a3,a4,a5,a6,a7,a8)))/(k(a0,i)*r4(a0,a1,a2,a3,a4,a5,a6,a7,a
8))))));
                                            end
                                        end


cohe_REF_f{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i)=(cohe_P1{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i
)+cohe_P2{a0,a1,a2,a3,a4,a5,a6,a7,a8}(i))*(10^(Aw(i)/10));
                                    end

                                    % 2000/14 - 6 microphones

cohe6=sources_coherent_5(rx(a3),ry(a4),rz(a5),rho(a0),Q(a1),si,f(:),fac(a0,:),rx
2(a6),ry2(a7),rz2(a8),Q2(a2),fac2(a0,:),p_ref,X6(:),Y6(:),Z6(:),w(a0,:),k(a0,:),
Aw(:));
                                    % 2000/14 - 12 microphones
```

```
cohe12=sources_coherent_5(rx(a3),ry(a4),rz(a5),rho(a0),Q(a1),si,f(:),fac(a0,:),r
x2(a6),ry2(a7),rz2(a8),Q2(a2),fac2(a0,:),p_ref,X12(:),Y12(:),Z12(:),w(a0,:),k(a0
,:),Aw(:));
                                    % ISO 3744 - 10 microphones

cohe10=sources_coherent_5(rx(a3),ry(a4),rz(a5),rho(a0),Q(a1),si,f(:),fac(a0,:),r
x2(a6),ry2(a7),rz2(a8),Q2(a2),fac2(a0,:),p_ref,X10(:),Y10(:),Z10(:),w(a0,:),k(a0
,:),Aw(:));
                                    % ISO 3744 - 19 microphones

cohe19=sources_coherent_5(rx(a3),ry(a4),rz(a5),rho(a0),Q(a1),si,f(:),fac(a0,:),r
x2(a6),ry2(a7),rz2(a8),Q2(a2),fac2(a0,:),p_ref,X19(:),Y19(:),Z19(:),w(a0,:),k(a0
,:),Aw(:));
                                    % ISO 3744 - 29 microphones

cohe29=sources_coherent_5(rx(a3),ry(a4),rz(a5),rho(a0),Q(a1),si,f(:),fac(a0,:),r
x2(a6),ry2(a7),rz2(a8),Q2(a2),fac2(a0,:),p_ref,X29(:),Y29(:),Z29(:),w(a0,:),k(a0
,:),Aw(:));

                                    % coherent sources

cohe_tot_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8}=sum(sum(cohe_REF_f{a0,a1,a2,a3,a4,a5,a6
,a7,a8}(:)));

cohe_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8}=10*log10(cohe_tot_REF{a0,a1,a2,a3,a4,a5,a6,
a7,a8}/Pa_ref);


cohe_ISO_6{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe6(1,1)+ISO_surf;

cohe_ISO_12{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe12(1,1)+ISO_surf;

cohe_ISO_10{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe10(1,1)+ISO_surf;

cohe_ISO_19{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe19(1,1)+ISO_surf;

cohe_ISO_29{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe29(1,1)+ISO_surf;


diff_6_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe_ISO_6{a0,a1,a2,a3,a4,a5,a6,a7,a8}-
cohe_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8};

diff_12_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe_ISO_12{a0,a1,a2,a3,a4,a5,a6,a7,a8}-
cohe_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8};

diff_10_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe_ISO_10{a0,a1,a2,a3,a4,a5,a6,a7,a8}-
cohe_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8};

diff_19_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe_ISO_19{a0,a1,a2,a3,a4,a5,a6,a7,a8}-
cohe_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8};

diff_29_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe_ISO_29{a0,a1,a2,a3,a4,a5,a6,a7,a8}-
cohe_REF{a0,a1,a2,a3,a4,a5,a6,a7,a8};

                                    % directivity

DI6max{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe6(1,2);

DI12max{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe12(1,2);
```

```
DI10max{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe10(1,2);

DI19max{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe19(1,2);

DI29max{a0,a1,a2,a3,a4,a5,a6,a7,a8}=cohe29(1,2);

                                    coord{a0,a1,a2,a3,a4,a5,a6,a7,a8}=[Q(a1);
Q2(a2); rx(a3); ry(a4); rz(a5); rx2(a6); ry2(a7); rz2(a8)];

                                    clear cohe6
                                    clear cohe12
                                    clear cohe10
                                    clear cohe19
                                    clear cohe29
                                end
                            end
                        end
                    end
                end
            end
        end
    end

COORD=[coord{a0,:,:,:,:,:,:,:,:}];

diff_6=[diff_6_REF{a0,:,:,:,:,:,:,:,:}];
diff_12=[diff_12_REF{a0,:,:,:,:,:,:,:,:}];
diff_10=[diff_10_REF{a0,:,:,:,:,:,:,:,:}];
diff_19=[diff_19_REF{a0,:,:,:,:,:,:,:,:}];
diff_29=[diff_29_REF{a0,:,:,:,:,:,:,:,:}];

mean_diff_6=mean(diff_6);
mean_diff_12=mean(diff_12);
mean_diff_10=mean(diff_10);
mean_diff_19=mean(diff_19);
mean_diff_29=mean(diff_29);

std_diff_6=std(diff_6);
std_diff_12=std(diff_12);
std_diff_10=std(diff_10);
std_diff_19=std(diff_19);
std_diff_29=std(diff_29);

max_diff_6=max(diff_6);
max_diff_12=max(diff_12);
max_diff_10=max(diff_10);
max_diff_19=max(diff_19);
max_diff_29=max(diff_29);

min_diff_6=min(diff_6);
min_diff_12=min(diff_12);
min_diff_10=min(diff_10);
min_diff_19=min(diff_19);
min_diff_29=min(diff_29);

DI6m=[DI6max{a0,:,:,:,:,:,:,:,:}];
mean_DI6m=mean(DI6m);
std_DI6m=std(DI6m);
max_DI6m=max(DI6m);
```

```
min_DI6m=min(DI6m);

DI12m=[DI12max{a0,:,:,:,:,:,:,:,:}];
mean_DI12m=mean(DI12m);
std_DI12m=std(DI12m);
max_DI12m=max(DI12m);
min_DI12m=min(DI12m);

DI10m=[DI10max{a0,:,:,:,:,:,:,:,:}];
mean_DI10m=mean(DI10m);
std_DI10m=std(DI10m);
max_DI10m=max(DI10m);
min_DI10m=min(DI10m);

DI19m=[DI19max{a0,:,:,:,:,:,:,:,:}];
mean_DI19m=mean(DI19m);
std_DI19m=std(DI19m);
max_DI19m=max(DI19m);
min_DI19m=min(DI19m);

DI29m=[DI29max{a0,:,:,:,:,:,:,:,:}];
mean_DI29m=mean(DI29m);
std_DI29m=std(DI29m);
max_DI29m=max(DI29m);
min_DI29m=min(DI29m);

MTX=[cohe_REF{a0,:,:,:,:,:,:,:,:}; cohe_ISO_6{a0,:,:,:,:,:,:,:,:};
cohe_ISO_12{a0,:,:,:,:,:,:,:,:}; cohe_ISO_10{a0,:,:,:,:,:,:,:,:};
cohe_ISO_19{a0,:,:,:,:,:,:,:,:}; cohe_ISO_29{a0,:,:,:,:,:,:,:,:}; diff_6;
diff_12; diff_10; diff_19; diff_29; DI6m; DI12m; DI10m; DI19m; DI29m];
MTX1{a0}=[COORD; MTX];

STAT{a0}=[mean_diff_6 mean_DI6m mean_diff_12 mean_DI12m mean_diff_10 mean_DI10m
mean_diff_19 mean_DI19m mean_diff_29 mean_DI29m; std_diff_6 std_DI6m std_diff_12
std_DI12m std_diff_10 std_DI10m std_diff_19 std_DI19m std_diff_29 std_DI29m;
max_diff_6 max_DI6m max_diff_12 max_DI12m max_diff_10 max_DI10m max_diff_19
max_DI19m max_diff_29 max_DI29m; min_diff_6 min_DI6m min_diff_12 min_DI12m
min_diff_10 min_DI10m min_diff_19 min_DI19m min_diff_29 min_DI29m];

clear COORD
clear MTX
clear diff_6
clear mean_diff_6
clear std_diff_6
clear max_diff_6
clear min_diff_6
clear DI6m
clear mean_DI6m
clear std_DI6m
clear max_DI6m
clear min_DI6m
clear diff_12
clear mean_diff_12
clear std_diff_12
clear max_diff_12
clear min_diff_12
clear DI12m
clear mean_DI12m
clear std_DI12m
clear max_DI12m
```

```
clear min_DI12m
clear diff_10
clear mean_diff_10
clear std_diff_10
clear max_diff_10
clear min_diff_10
clear DI10m
clear mean_DI10m
clear std_DI10m
clear max_DI10m
clear min_DI10m
clear diff_19
clear mean_diff_19
clear std_diff_19
clear max_diff_19
clear min_diff_19
clear DI19m
clear mean_DI19m
clear std_DI19m
clear max_DI19m
clear min_DI19m
clear diff_29
clear mean_diff_29
clear std_diff_29
clear max_diff_29
clear min_diff_29
clear DI29m
clear mean_DI29m
clear std_DI29m
clear max_DI29m
clear min_DI29m

end

save matrice_T MTX1
save statistica_T STAT

% profile viewer
```

10.2 Source coherent 5

```
function
result=sources_coherent_5(rx,ry,rz,rho,Q,si,f,fac,rx2,ry2,rz2,Q2,fac2,p_ref,X_mi
c,Y_mic,Z_mic,w,k,Aw)

for i=1:length(X_mic)
    for ii=1:length(f)

p_mic1_f(ii)=pressure_microphone_6(rx,ry,rz,X_mic(i),Y_mic(i),Z_mic(i),rho,Q,si,
f(ii),w(ii),k(ii),fac(ii));

p_mic2_f(ii)=pressure_microphone_6(rx2,ry2,rz2,X_mic(i),Y_mic(i),Z_mic(i),rho,Q2
,si,f(ii),w(ii),k(ii),fac2(ii));
        p_mic_f(ii)=p_mic1_f(ii)+p_mic2_f(ii);
        p_mic_f_rms(ii)=((((abs(p_mic_f(ii)))^2)/2)*(10^(Aw(ii)/10)));
    end
    p_mic(i)=sum(sum(p_mic_f_rms));
    p(i)=sqrt(p_mic(i));
    spl_mic(i)=10*log10((p(i)^2)/(p_ref^2));
    pp(i)=10^(0.1*spl_mic(i));
    clear p_mic_f
    clear p_mic_f1
    clear p_mic_f2
    clear p_mic_f_rms
end

p_mic_avg=(sum(sum(pp)))/(length(X_mic));
spl_avg=10*log10(p_mic_avg);

for i=1:length(X_mic)
    DI(i)=spl_mic(i)-spl_avg;
end

maxDI=max(DI(:));

result=[spl_avg maxDI];
```

10.3 Pressure mic 6

```
function
p_mic=pressure_microphone_6(source_X,source_Y,source_Z,mic_X,mic_Y,mic_Z,rho,Q,s
i,f,w,k,fac)

reale_X=mic_X-source_X;
reale_Y=mic_Y-source_Y;
dis=((reale_X^2)+(reale_Y^2))^(1/2);

mic_H_reale=(mic_Z)-(source_Z);
dir_dis=((dis^2)+(mic_H_reale^2))^(1/2);

spher_fac=sphere_factor_3(source_Z,mic_Z,dis,si,f,k);

p_mic=((j*w*rho*Q*exp(j*(-k*dir_dis)))/(4*pi*dir_dis*fac))*spher_fac;
```

10.4 *Sphere factor 3*

```
function sphere_fac=sphere_factor_3(hs,hr,d,si,f,k)

R1=sqrt(d^2+(hs-hr)^2);
R2=sqrt(d^2+(hs+hr)^2);
dR=(R2-R1);

% Q for the coherent part of the field (including roughness)
Qc=calc_q(R2,hs+hr,si,k,f);

p2=exp(i.*k*R2)/R2.*Qc;
p1=exp(i.*k*R1)/R1;

sphere_fac=conj(1+p2./p1);

function Q=calc_q(R2,hshr,it,k,f)
costeta=hshr/R2;
if it>=1e10 % If impedance=hard, set Q=1
  Q=ones(size(k));
else
  beta=1./imp(it,f);
  % plane wave reflection coefficient
  Rteta=(costeta-beta)./(costeta+beta);
  w=(1+i)/2.*sqrt(k*R2).*(beta+costeta);
  Fw=zeros(1,length(k));
  for j=1:length(k)
    Fw(j)=1+i*sqrt(pi)*w(j)*wfunc2(w(j));
  end
  Q=Rteta+(1-Rteta).*Fw;
end


function w=wfunc2(z)
% function w=wfunc2(z) calculates exp(-z^2)*erfc(-iz)
% from Chien & Soroka, JSV 69, no2, 1980.
x=real(z);
y=imag(z);
h=0.8; % kan minskas för att öka beräkningsnoggrannheten
if (x>6 || y>6)
  w=i*z*(0.5124242/(z^2-0.2752551)+0.05176536/(z^2-2.724745));
else
  if (x>3.9 || y>3)
    w=i*z*(0.4613135/(z^2-0.1901635)+0.09999216/(z^2-
1.7844927)+0.002883894/(z^2-5.5253437));
  else
    C1=exp(-2*y*pi/h)-cos(2*pi*x/h);
    D1=sin(2*x*pi/h);
    P2=2*exp(-(x^2+2*y*pi/h-y^2))*((cos(2*x*y)*C1-sin(2*x*y)*D1)/(C1^2+D1^2));
    Q2=2*exp(-(x^2+2*y*pi/h-y^2))*((cos(2*x*y)*D1+sin(2*x*y)*C1)/(C1^2+D1^2));
    for n=1:5
      H2(n)=2*y*h/pi*(exp(-n^2*h^2)*(y^2+x^2+n^2*h^2))/((y^2-
x^2+n^2*h^2)^2+4*y^2*x^2);
      K2(n)=2*x*h/pi*(exp(-n^2*h^2)*(y^2+x^2-n^2*h^2))/((y^2-
x^2+n^2*h^2)^2+4*y^2*x^2);
```

```
    end
    H=h*y/pi/(y^2+x^2)+H2(1)+H2(2)+H2(3)+H2(4)+H2(5);% Där är ett pi för mycket
i nämnaren i artikeln!
    K=h*x/pi/(y^2+x^2)+K2(1)+K2(2)+K2(3)+K2(4)+K2(5);
    if y<pi/h
      H=H+P2;
      K=K-Q2;
    elseif y==pi/h
      H=H+P2/2;
      K=K-Q2/2;
    else
      H=H;
      K=K;
    end
    w=H+i*K;
  end
end

function z=imp(si,f)
% imp calculates the impedance according to Delany and Bazley
% si= ground flow resistivity
% f= frequency (array)
z=1+9.08*(1000*f/si).^(-0.75)+i*11.9*(1000*f/si).^(-0.73);
```