Free-Field Microphone Calibration Comparison: Time-Selective Technique and Reciprocity

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ABSTRACT

Advances in technology have reflexes in many fields of human knowledge. Metrology is not an exception. The calibration of microphones in free-field conditions were for many years a hard task that was almost exclusive for national metrology institutes. The reason for that was the necessity of very costly and complex facilities to produce a free-field condition, specifically, an anechoic chamber. Advances in signal processing lead to the Time-Selective Technique development, which allowed to emulate free-field conditions by means of digital filtering wave reflections. That opened the door for secondary laboratories to implement free-field calibration at a considerably lower cost. But how reliable are those calibrations? Could it be that a regular acoustic laboratory could play the role of an anechoic chamber? To answer those questions, a comparison will be made between the calibration of a laboratory standard microphone proceeded by the classic free-field reciprocity method - performed by the Brazilian national metrology institute at its anechoic chamber - and by a time-selective technique free-field secondary calibration - performed by an accredited secondary laboratory of the Brazilian calibration network (RBC) - therefore assessing the reliability of this last method in real conditions.

Keywords: Microphone, Free-Field, Calibration, IEC 61094-8, IEC 61094-3
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1. INTRODUCTION

The world of acoustic measurements mostly hinges on a single component, small and fragile, namely, the microphone. A reliable and expensive acoustic measuring system attached to a poor microphone would profit nothing to grasp the real physical phenomenon nor to express it. For that reason, microphone testing and calibration is an issue that have had a special attention by the metrological community, as seen in the many parts of the IEC 61094 series, each one carefully looking to one aspect of how one can have a reliable manufacturing guideline and an accurate periodic test for microphones.

Among many measuring applications that a microphone could have, one of the most common is its usage on conditions that are best approach by a free-field approximation. The reliability of those measures, as expected, is guaranteed by the microphone calibration on this same sound field, as parts 3 and 8 of IEC 61094 series covers. Nevertheless, an issue comes up regarding calibration, once testing a microphone in real free-field conditions was, for many years, only possible by means of an anechoic chamber, a facility that is really complex and expensive to implement. For that reason, free-field calibration was almost exclusively offered by primary metrology institutes, while secondary laboratories had calibration setups just for pressure-field condition calibrations. Because of that, the most common method to assure free-field measurements, even today, is to calibrate a given microphone on pressure-field conditions, using a comparison coupler or an electrostatic actuator, and after that, to add a correction data provided by the manufacturer to the obtained pressure-field response. The correction data should also consider which pressure-field method is being used and be customized to it, as responses for each method are knew not to be the same.

The main problem with this practice is that, even with a customized correction data for each pressure field method, those are, at best, good average corrections considering microphones in brand new condition. Effects of time and wear on the microphone membrane are not considered for determining those corrections, nor are effects of deformations on the microphone grid, when the grid itself is considered at all. It means that, when a free-field microphone is calibrated by a pressure-field method and then this response is corrected to free-field, what the final users have in their hands is not the actual free-field response of their microphone.

This situation is being changed with advancements in signal processing. As every change in technology, specially referring to metrology, it generally first affects scholars and academic studies, usually involving universities and national metrology institutes, and just after being well consolidated it spreads to secondary laboratories, to the public and market, eventually allowing final users to have access to this. In this specific scenario the Time-Selective Technique (TST) is found. This technique is known for a while and have been used for reciprocity calibrations since roughly the early 2000', but its use by secondary laboratories is not common practice yet. It is slowly entering, mainly because of its still complicated implementation and the lack of any market customized calibration setup using it. Considering national metrology institutes, TST was applied as a complement to the traditional anechoic room facility, as recommended on conclusions of international comparison reports, as Euramet. On the other hand, for secondary laboratories, anechoic chambers are not economically viable, so, TST have to be stretched to provide results in environments that are not anechoic, although they are expected to be carefully set for this purpose, especially regarding room dimensions and source positioning.

The question that is raised is quite simple: are those results reliable? Are secondary laboratories using TST on a non-anechoic environment capable of reach values and results that are compatible to the ones obtained by national metrology institutes using a classical anechoic chamber reciprocity method? The result of this work expects to convincingly address this question, answering on the basis of real results of a microphone calibration on both conditions and standardized values.

2. FREE-FIELD CALIBRATION

2.1 Primary metrology institutes

Primary metrology institutes (PMI) are institutions that are on the top of metrology pyramids at a given context, and in general there is only one for each country, as PTB on Germany, NMI on Australia, NIST on the USA and Inmetro on Brazil. Those laboratories generally pursue primary methods and the lowest uncertainty possible for those methods as well, so much so that secondary laboratories of their contexts could also reach lower uncertainties when using their traceability.

Regarding microphones, seeking primary method means to seek the reciprocity method. Narrowing the scope to free-field microphones, it means to apply IEC 61094-3, which is possible mainly by means of an anechoic chamber. Considering the high cost involved in constructing this facility and the complexity of its implementation, this was possible for PMI because of government resources and highly specialized scholars that usually work at them. This method basically uses classical reciprocity technique at an anechoic room to determine the microphones sensitivity for a given frequency range.

The quest for lower uncertainties and for better compatibility on calibration results between PMIs lead to some comparisons that showed fragilities when this free-field method was used as base to the closely related case that include sound level meter free-field testing on anechoic rooms and their corrections in the context of IEC 62585. Two reports were of paramount importance to evidence that, namely, Euromet Project 394, and later on, Euramet Project 1056, concluding that for a future comparison aiming more stable results it was suggested that laboratories would proceed with the "use of a technique to reduce the effect of reflections even in anechoic rooms." Naturally this advice would be suitable for sole microphone calibrations as well.

These reports showed that even the complex and costly anechoic facility would profit on using modern digital filtering techniques. One of those is the Time-Selective Technique (TST), that commonly by means of swept sines and time windowing could clean up imperfections caused by eventual reflections. For that reason, most of world reference PMIs on acoustics and microphone calibrations use some kind of technique to enhance its already reliable method, leading to low uncertainties and compatible results.

2.2 Secondary laboratories

While PMIs are the references at a given context, the secondary laboratories are the contact point to final metrological service consumers. An accreditation organism is responsible to ensure that those laboratories have, for each service in its scope, traceability and adequate instrumentation, competent staff and a proper quality system, according to the guidelines of IEC 17025.

The reality in those laboratories is directly influenced by market share, costs and demands on service. They could be part of an organization that uses their services for themselves (first part laboratory); a laboratory that is also manufacturer or seller of the equipment they calibrate (second part laboratory); or an independent laboratory that provides calibration services for others and do not manufactures or sells equipment (third part laboratory). Quite obviously, although they are supposed to have passion for their work, those laboratories should also be economically profitable and self-sustainable. For that reason, over-costly or lengthy methods are avoided by all means.

Considering what was previously said about the anechoic chamber complexity and cost it is expected that secondary laboratories, in general, would not provide that service. Nevertheless, free-field measures are very common, and demand for free-field calibrations is a reality in virtually every acoustic metrological context. A solution for that, allowed by standards as IEC 61672-3, is to calibrate microphones at pressure-field (whereas real or simulated) and to apply suitable correction data to those results. That permission explains this practice by secondary laboratories, as previously mentioned. This is the most common practice today for secondary microphone and sound level meter calibrations, once all of the pressure-field method instrumentation and implementation are much simpler, faster and more affordable than an anechoic room.

2.3 An actual free-field response

Basically, secondary laboratories adopt one (or more) of three pressure-field methods: comparison coupler, electrostatic actuator or multi-frequency sound level calibrator. Each one of those produces a certain frequency response, that, although intended to be pressure-field, are not the same. For that reason, laboratories should apply suitable correction data, and manufacturers are expected to provide them as well, which unfortunately, is not always the case.

Nevertheless, even in the case that customized suitable correction data are applied to the pressure-field response, the result obtained is not the actual microphone's free-field response, but, at best, an adequate approximation of this. This is truth because manufacturers base their correction data on average responses for a given microphone model, and those responses are mainly from brand new microphones. Hence, effects of time and wear, deformations on the microphone grid and relaxation of its membrane are not, and probably could not, be considered. This can be seen on Table 1, where it is shown the difference between mean pressure-field frequency responses of new and used microphones of the same model, based on more than 20 microphone samples.

Table 1: Time and Wear effects on microphone's frequency response

Frequency [Hz]	Used – New [dB]
31,5	0,28
63	0,13
125	0,08
250	0,09
500	0,07
1000	0,00
2000	0,04
4000	0,19
5000	0,23
6300	0,39
8000	0,67
10000	1,02

It is clear by these differences that corrections based on new microphone samples will not be sufficient to determine the free-field frequency response of a used microphone of that same model. Relying on that can produce errors greater than 1 dB, depending on the case. Microphones that are on the work ground, being used sometimes at a daily basis on environments that are rough and hostile, usually are the same microphones that a secondary laboratory is expected to calibrate. For that reason, correction data added to a pressure-field response are not the best approach to determine their free-field frequency response. Moreover, concerning sound level meter's tolerances, this practice could lead to opposite conformity declarations, as showed by the authors elsewhere [4].

Considering that issue, in the Brazilian context, some research started to be made, trying to implement the same technological advances that were being used as a fine tuning at PMIs, but expanding it for environments that were not anechoic. The idea seemed promising, as it would be possible to determine the actual free-field frequency response of a single microphone at a considerably lower cost. In other words, each microphone with all of the singular effects of aging and harsh use on them would be actually considered and reflected on their calibration, leading to a much more accurate result. The question that was raised is a fair one, as stated on the introduction, how reliable could those results be? Could a secondary laboratory at a non-anechoic environment reach results compatible to those of PMIs using cutting-edge technology?

3. RESULTS

3.1 Method

The best way for attesting the reliability of the calibration results is comparing the proponent to the stablished reference. In the case of free-field microphone calibrations, it means to compare results obtained by an accredited secondary laboratory to the results of the reference PMI. In the Brazilian context, Inmetro plays that role of metrological reference nationwide, and its electroacoustic laboratory, Laeta, is responsible for microphone calibrations. On the other hand, Total Safety is a company that has an accredited calibration laboratory, Calilab, an independent third-part accredited laboratory, member of the Brazilian Calibration Network (RBC). The results of a calibration performed by those two will be compared.

Normalized Error is one of the most common statistical methods for comparing compatibility of measurement results, therefore, it was the chosen method for comparing those results. Normalized Error (NE) can be obtained through Equation 1:

$$NE = \frac{|R_a - R_b|}{\sqrt{\left({U_a}^2 + {U_b}^2\right)}} \qquad \text{Equation 1}$$

where *R* are the results and *U* the uncertainties from two given laboratories, *a* and *b*, all expressed in the same unit. NE values ranging from zero to one, excluding it, are considered compatible, while values greater than one denote non-compatible results.

A reference microphone Brüel & Kjær 4180, serial number 2488297, was chosen for its proven stability. The microphone was first calibrated at Calilab (secondary laboratory), by means of a TST at their facilities, that, although carefully prepared for this purpose, it is not anechoic. The results of this calibration were reported in a calibration certificate that was registered at a notary's office to publicly attest its date. Later on, this same microphone was sent to Laeta (PMI), for a free-field reciprocity calibration, at an anechoic room and also using TST as a method for enhancing the calibration performance. The results of this last were also expressed at a calibration certificate. Once Inmetro is a Federal Institution, their calibration certificate, including its date, already have legal public faith.

The frequency range chosen was based on two factors, first, the secondary laboratory accredited scope, that limited its range to 20 kHz, and second, the frequency where results for different sound fields begin to diverge. Results bellow 1 kHz are known to be roughly the same independent of the sound field. In other words, calibration results using a free-field set up or a pressure-field method would be virtually the same. Therefore, a calibration on this range from 1 kHz to 20 kHz would optimize the free-field frequency response differences on the audible range could and its analysis.

3.2 Calibration comparison

Figure 1 shows the sensitivity frequency response of the microphone calibrated by means of TST at a non-anechoic facility by a secondary laboratory (Calilab - Total Safety), with an adequate accreditation scope for those tests, and by means of TST at an anechoic room by a primary metrology institute (Laeta - Inmetro).

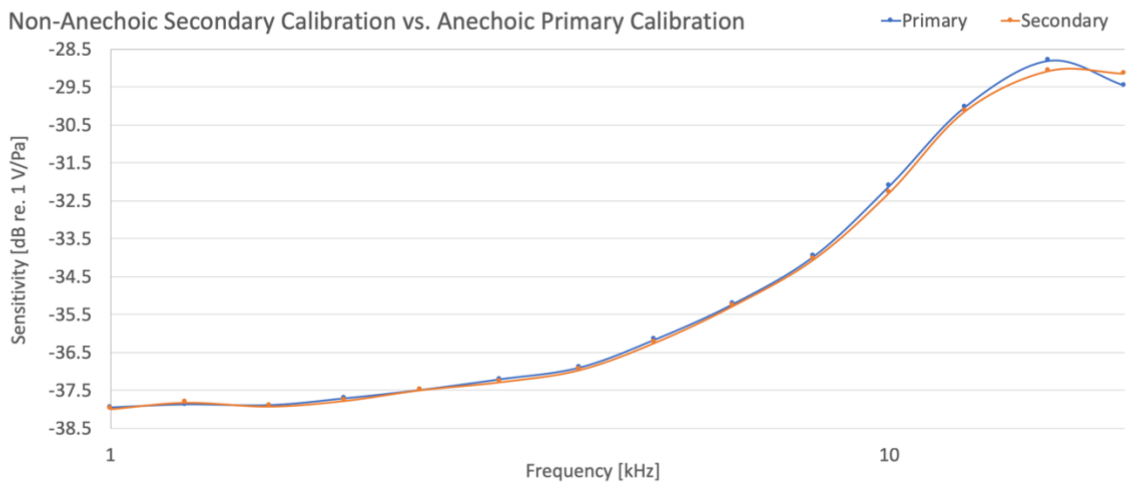

Figure 1: Calibration results obtained at anechoic chamber method by a PMI (Laeta – Inmetro) and TST at a regular secondary laboratory facility (Calilab – Total Safety)

The comparison between results obtained by the primary laboratory using the classic anechoic chamber reciprocity method and the results obtained by the secondary laboratory by means of time-selective technique comparison at a regular laboratory facility can be found on Table 2. The source documents of those results are the calibration certificate number 0225/2018 from March 09th, 2018, issued by Laeta (Inmetro) and calibration certificate number RBC10-10229-375 from January 03rd, 2018, issued by Calilab (Total Safety). The certificate issued by the secondary laboratory was registered at a notary's office on January 09th, 2018, to publicly attest the issuing date.

As mentioned before, the comparison method chosen to infer compatibility in-between results was Normalized Error, where NE below 1,00 results, excluding it, are taken as an indicator that the values are compatible. It means that if values of NE showed on Table 2 do not exceed 1,00, both methods can be considered compatible.

Table 2: Comparison using Normalized Error (NE) between results obtained by classic anechoic chamber (Laeta) and TST regular facility (Calilab)

Frequency [kHz]	Sensitivity Laeta [dB]	Uncertainty Laeta [dB]	Sensitivity Calilab [dB]	Uncertainty Calilab [dB]	NE
1	-37,96	0,14	-37,99	0,20	0,12
1,25	-37,88	0,13	-37,82	0,20	0,25
1,6	-37,90	0,13	-37,92	0,20	0,08
2	-37,72	0,13	-37,77	0,24	0,18
2,5	-37,50	0,13	-37,49	0,24	0,04
3,16	-37,22	0,12	-37,28	0,24	0,22
4	-36,91	0,11	-36,96	0,24	0,19
5	-36,17	0,11	-36,24	0,31	0,21
6,3	-35,23	0,13	-35,27	0,31	0,12
8	-33,97	0,14	-34,04	0,31	0,21
10	-32,11	0,15	-32,28	0,43	0,37
12,5	-30,03	0,19	-30,14	0,47	0,22
16	-28,81	0,20	-29,08	0,39	0,62
20	-29,46	0,20	-29,15	0,39	0,71

NE results indicate that, even without an anechoic chamber, it would be still possible to perform free-field microphone calibration achieving reliable result. Another factor that should be considered is that, while Laeta is placed at Xerém, a city on the state of Rio de Janeiro, virtually on sea level (27 m), Calilab is located at São Caetano do Sul, a city on the state of São Paulo, 770 m higher than sea level. The reported results from Calilab were normalized to sea level, as expected, and in these conditions, showed on Table 2, absolute sensitivity was compatible. Besides, free-field reciprocity by a PMI has a considerably lower uncertainty than any other method, showing the solidity of the proponent method by comparing it in a tougher condition.

This first test is a good indicator of a compatibility for secondary calibration in the Brazilian context. For reliability enhancing purposes, another comparison was sough as second witness. It was important that this further test would include data from other parts of the world, so much so potential circular arguments would be avoided. It is good to notice that on the first test, Inmetro was the traceability source for Calilab’s reference microphone, but it also provided reference data for comparison. This requirement was met by elaborating a way to compare to the own IEC 61094-7, that informs a typical pressure-field to free-field correction for Brüel & Kjær 4180.

A comparison between this well stablished correction and one based on results obtained by means of this secondary free-field calibration could strengthen its validity. For this purpose, a pressure-field reliable calibration is also necessary. The same microphone used on the former comparison was also calibrated by means of pressure-field reciprocity method by Inmetro in the same occasion, resulting on calibration certificate number DIMCI 0099/2018 from January 25th, 2018. The difference between the results from Calilab's secondary free-field calibration using TST and pressure-field reciprocity calibration resulted on a correction estimation. Table 3 shows a comparison from this correction data based on Calilab's results and the one stablished by IEC 61094-7.

Table 3: Comparison between 4180 (S/N 2488297) free-field correction based on TST at a regular facility (Calilab) and the one stated on IEC 61094-7

Frequency [kHz]	Correction to FF Calilab [dB]	Correction to FF IEC 61094-7 [dB]	Difference [dB]	NE
1	-0,01	0,08	-0,09	0,42
1,25	0,16	0,12	0,04	0,19
1,6	0,05	0,19	-0,14	0,65
2	0,19	0,28	-0,09	0,35
2,5	0,45	0,42	0,03	0,10
3,16	0,63	0,66	-0,03	0,12
4	0,90	1,03	-0,13	0,48
5	1,54	1,56	-0,02	0,07
6,3	2,39	2,39	0,00	0,01
8	3,45	3,62	-0,17	0,47
10	5,00	5,13	-0,13	0,24
12,5	6,98	6,92	0,06	0,10
16	8,24	8,57	-0,33	0,70
20	9,43	9,04	0,39	0,89

The difference between corrections was lower than Calilab's uncertainty for secondary free-field microphone calibration for every single frequency. Comparison based on NE also showed compatibility for the whole frequency range. This shows that even a correction data, based on many measurements and having more uncertainties associated are clearly compatible to results well stablished reported by an international standard. Therefore, the proponent free-field calibration results seem solid and reliable.

4. CONCLUSIONS

Comparison results clearly shows that using TST for signal manipulation of results obtained even at a non-anechoic facility can be reliable. This is further attested considering that calibrations at secondary laboratories are normally expected to have greater uncertainties when compared to PMI.

One of the practical results of this is that, besides the enhanced reliability that regular costumers of metrological services will have on their microphone calibrations, standards can begin to count on the fact that an actual free-field response is something feasible even to secondary laboratories. Hence, this method can also be mentioned as preferable on standards that requires some kind of free-field testing, as sound level meter standards.

On the other hand, even without the main obstacle to a free-field calibration putted aside, that is, the anechoic room, the complexity to implement adequate TST is still great, and the instrumentation for that is not available as a common commercial calibration setup. It is still easier and more affordable to set a pressure-field calibration method. The time length of this free-field method could be compared to a comparison coupler calibration, but it still takes more time than electrostatic actuator or multi-frequency sound level calibrator.

Concluding, despite its complexity, the results of this method are much more reliable for the final user than the common correction data solution. It is expected that, in a near future, every standard would put this as preferable and more secondary laboratories could supply their metrological community with this asset.

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