AN INTERLABORATORY COMPARISON PROGRAMME ON ELF MEASUREMENTS PERFORMED IN GREECE

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Abstract
The scope of this paper is the description of an interlaboratory comparison programme for extremely low frequency (ELF) electromagnetic fields (EMF) measurements performed at the High Voltage Laboratory of the National Technical University of Athens. The programme was organised in two stages in an exposure environment similar to that of electric power lines and in general 50 Hz devices. The four accredited participating laboratories from Greece, measured in the first stage the electric field produced by a transmission line supplied by 5, 10, 15 and 20 kV. The magnetic field produced by a middle voltage cable carrying 250, 500, 750 and 1000 A was measured in the second stage. All measurements were taken both in band pass and broadband mode, setting the laboratories field sensors at fixed positions and distances from the experimental layouts. The results for all measurement scenarios were analysed statistically with a robust algorithm in order to estimate the reference average values and standard deviations and calculate the z-scores for the performance evaluation of the laboratories. The purpose of this interlaboratory comparison programme was to demonstrate the technical competence of the participating laboratories, as well as to survey their continuing performance and improve their quality of measurements.

Introduction
The standard ISO/IEC 17025 [1] requires participation in an “inter-laboratory comparison program” (ILC) for every accredited test laboratory that should cover all measurements and tests that lie within its scope of accreditation. Participation in inter-laboratory comparisons offers many benefits for laboratories and is a prerequisite for demonstrating traceability, proficiency and quality assurance and proving their technical competence. According to ISO/IEC Guide 43 [2,3], ILCs involve organization, performance and evaluation of calibration/tests on the same or similar calibration/test items by two or more laboratories in accordance with predetermined conditions. There are many types of ILCs [3,8]. In their policy, all accreditation and other relevant bodies require participation in ILC programs [8,9,10]. However, in EMF measurements, result comparison programs have to be applied.
In a results comparison program, all participants measure the same EMF source, usually in normal work conditions [6,7]. In this paper, the authors present the results and analysis of inter-laboratory comparisons performed by accredited laboratories in two different cases. The ILC program described in this paper has been set up to comply with the requirement of ISO/IEC 17025 [1] and covers the two types of measurement (electric and magnetic field) which are described in IEC 61786 [4].

Participants
In this interlaboratory comparison procedure four accredited laboratories (with five groups) have participated:
- Non Ionizing Radiation Office – Greek Atomic Energy Commission (with two groups) (Accredited by the Hellenic Accreditation System S.A. (ESYD), Certificate Number 117-2)
- FASMETRICS LTD (Accredited by the Hellenic Accreditation System S.A. (ESYD), Certificate Number 323)
- High Voltage Laboratory, National Technical University of Athens (Accredited by the Hellenic Accreditation System S.A. (ESYD), Certificate Number 490)
- EMC HELLAS (Accredited by the Hellenic Accreditation System S.A. (ESYD), Certificate Number 552)

The participants have been randomly named as laboratories 1-5. Each group knows its number but it does not know the numbers of the other groups.

Interlaboratory Comparison Scheme

In ISO/IEC Guide 43-2 [3], one can find a few ILC schemes; however, in EMF measurements, "result comparison programmes" are usually applied [6,7]. In result comparison programmes, all participants measure the same EMF source under the same working conditions. The purpose of the comparison presented in this paper, is to evaluate the technical performance of the participating laboratories according to the relevant standards and recommendations that are referenced in the end of this paper.

The comparative measurements programme were carried out in two steps at the High Voltage Laboratory of NTUA in accordance with the requirements of the standard IEC 61786 [4] for the measurement of low frequency electric and magnetic fields and the relevant policy of the Hellenic Accreditation System S.A. (ESYD) for the participation of laboratories in proficiency testing schemes [9].

- During the first phase of the test, the electric field created by a high-voltage transmission line was measured. A setup with a scale transmission line supplied with 5, 10, 15 and 20 kV was properly formed at the High Voltage Laboratory of NTUA. A testing transformer with transformation ratio of 110V/55kV was used for the production of the high voltage. Between the low voltage network, by which the transformer was powered and the primary side of the transformer a suitable stabilizer was placed, in order to prevent fluctuations in the network voltage from passing into the produced voltage, as well as a variac for changing the level of the produced high voltage. The measurement of the high voltage level was carried out on the low voltage side (U_1) with an appropriate calibrated voltmeter. The five measurement groups recorded at each voltage level the electric field at a height of ~ 1,8m at a specific distance from the transmission line with a sensor connected via optical fiber with a fieldmeter. The sensor was placed at a distance of ~ 10m from the fieldmeter so that the measurements would not be affected by the presence of the operators. The experimental layout is displayed in Figure 1.

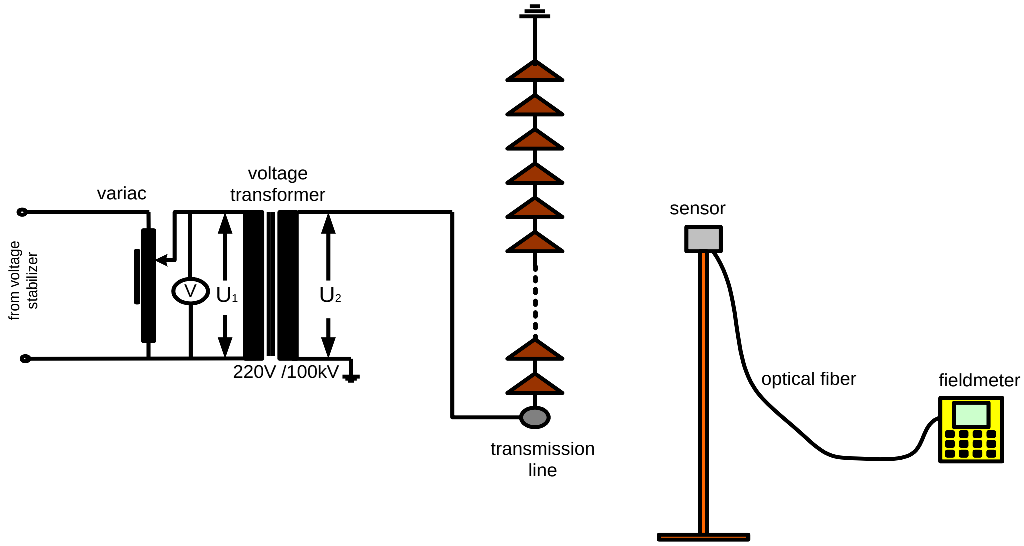

Figure 1: Test setup for the measurement of Electric Field (E)

- During the second phase of the test, the magnetic field generated by a cable carrying 250, 500, 750 and 1000 A was measured. The cable was connected to the secondary side of a current transformer (0-6000A), which provided the required value of the current. The transformer was supplied by the low voltage network through an autotransformer, which enabled varying the level of the produced current. At the beginning of each cycle of measurements the current of the cable (I_2) was measured with a suitable calibrated clamp meter. For each current value, the five measurement groups recorded the magnetic field in a particular place at a height of ~ 1,7m again with a sensor and a fieldmeter. This time the sensor was connected to the fieldmeter either directly or via optical fiber, depending on the type of the fieldmeter. Unlike the electric field, the magnetic field is not affected by the presence of the operator. The experimental layout is displayed in Figure 2.

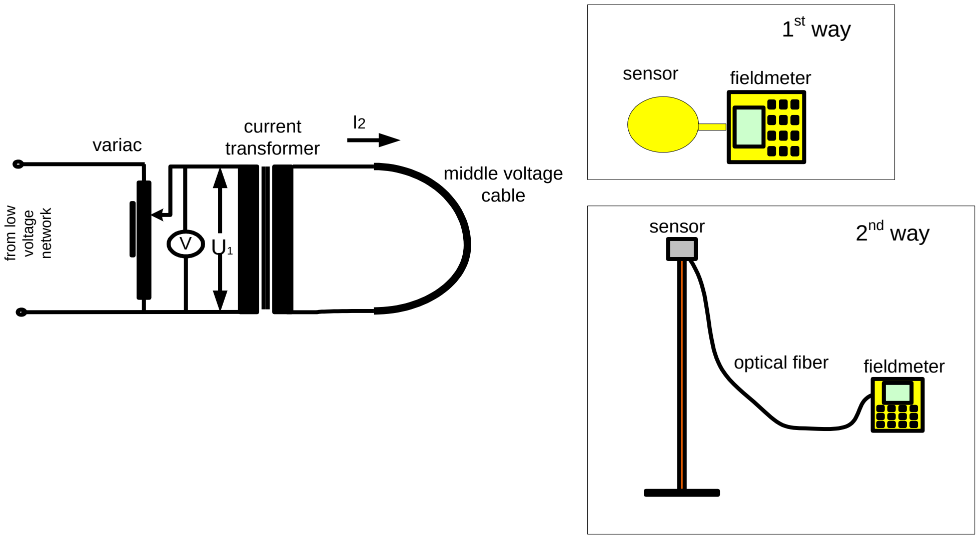

Figure 2: Test setup for the measurement of Magnetic Field (B)
1st way: the sensor is directly connected to the fieldmeter
2nd: the sensor is connected to the fieldmeter via an optical fiber

Results

The participating teams used different types of measuring equipment. Specifically, the following meters were used: NARDA/EFA-300 (3 groups), NARDA/EFA-3 (1 group) and PMM/8053 (1 group). The equipment was calibrated in the laboratories of: NARDA Germany (3 groups), SEIBEDORF Austria (1 group) and PMM (now NARDA Italy) (1 group).

The participants in the comparative measurements delivered two types of results: measurements across the entire frequency range of the fieldmeters (broadband measurements) and measurements in a narrow band around the fundamental frequency of 50Hz (band pass measurements).

Each participating laboratory submitted the measured values of electric field strength (E) in V/m for each voltage level and its uncertainty in %. These values are presented in Table 1 for band pass measurements and Table 2 for broadband measurements. Also, each participating laboratory submitted the measurements values of magnetic field (B) in μT for each current level and its expanded uncertainty in %. The submitted measurement values are presented in Table 3 for band pass measurements and Table 4 for broadband measurements.

Laboratory	**1**	**2**	**3**	**4**	**5**
5kV	256,358	260,223	257,936	264,29	261,343
10kV	508,353	498,425	502,484	517,84	512,759
15kV	756,559	752,285	762,110	781,72	762,036
20kV	1028,989	1008,050	1018,430	1031,75	1030,584
Uncertainty	**8,8**	**7,02**	**5,3**	**16,16**	**3,47**

Table 1: Band pass measurements for E [V/m]

Laboratory	**1**	**2**	**3**	**4**	**5**
5kV	257,850	261,188	257,951	264,00	261,710
10kV	514,437	497,752	502,204	519,89	513,023
15kV	769,188	752,046	763,845	781,67	763,313
20kV	1034,270	1004,910	1020,820	1033,53	1031,025
Uncertainty	**9,9**	**7,02**	**5,3**	**16,16**	**3,47**

Table 2: Broad band measurements for E [V/m]

Laboratory	**1**	**2**	**3**	**4**	**5**
250A	3,641	3,4290	3,3248	3,49	3,579
500A	7,421	7,0239	6,9535	7,07	7,476
750A	10,48	10,1204	10,0810	10,11	10,622
1000A	14,61	14,0572	13,9370	14,05	14,848
Uncertainty	**4,8**	**5,29**	**5,3**	**15,9**	**5,78**

Table 3: Band pass measurements for B [μT]

Laboratory	1	2	3	4	5
250A	3,696	3,4687	3,3454	3,45	3,619
500A	7,587	7,0356	6,9587	7,06	7,462
750A	10,75	10,0824	10,0750	10,13	10,625
1000A	14,88	14,0800	13,9320	14,07	14,824
Uncertainty	**6,7**	**5,29**	**5,3**	**15,9**	**5,78**

Table 4: Broad band measurements for B [μT]

Z-scores

The proposed algorithm (ISO 13528, Annex C Algorithm A) [5], produces robust values of the mean and standard deviation of the data used. The most common estimate of the average value is the median, the middle value of ordered series of results. The median of the absolute deviations of all measurements from their median is used in order to estimate the standard deviation. This value is known as median absolute deviation (MAD) and to make it equivalent to the standard deviation of the normal distribution it must be multiplied by 1.483 (MADe). A key element of the method is that it does not specify a single value for the estimator, but a set of values and the algorithm is performed iteratively. For a set of p measurements x_1, x_2, ..., x_p (optionally placed in ascending order) the procedure is as follows:

- Step 1: Calculate initial values for x^* (robust average) and s^* (robust standard deviation) as
  x^* = median of x_i (i = 1, 2, …, p)
  s^* = 1.483 median of $|x_i - x^*|$ (i = 1, 2, …, p)
- Step 2: Calculate $\delta = 1.5s^*$
- Step 3: For each x_i (i = 1, 2, …, p), calculate the new x_i^*

$$x_i^* = \begin{cases} x^* - \delta, & x_i < x^* - \delta \\ x^* + \delta, & x_i > x^* + \delta \\ x_i, & x^* - \delta \le x_i \le x^* + \delta \end{cases} \qquad (1)$$

- Step 4: Calculate the new values of x^* and s^* from:

$$x^* = \frac{1}{p}\sum_{i=1}^{p} x_i^* \qquad (2)$$

$$s^* = 1.134\sqrt{\frac{1}{p-1}\sum_{i=1}^{p}(x_i^* - x^*)^2} \qquad (3)$$

- Steps 2, 3 and 4 are iterative until the process converges. Convergence may be assumed when there is no change from one iteration to the next in the third significant figure of the robust standard deviation and of equivalent figure in the robust average.

The following classification of the result of a participating laboratory [5,6,7]:

- $|z| \le 2$: satisfactory result
- $2 < |z| < 3$: area considered to give "warning signal",
- $|z| > 3$: area considered to give "action signal".

At each stage of the experiment (E / B measurement), the z scores of the five participating teams are calculated for each voltage/current level and for all measurement modes provided by the laboratories (broadband/band pass). For the overall assessment of the laboratories, because of the small number of participants and individual test levels, a summary bar graph is chosen as a presentation method. The z scores of all laboratories for each level of voltage/current are shown in figures 3-6 for each measurand (E/B) and each form of measurement (broadband/band pass).

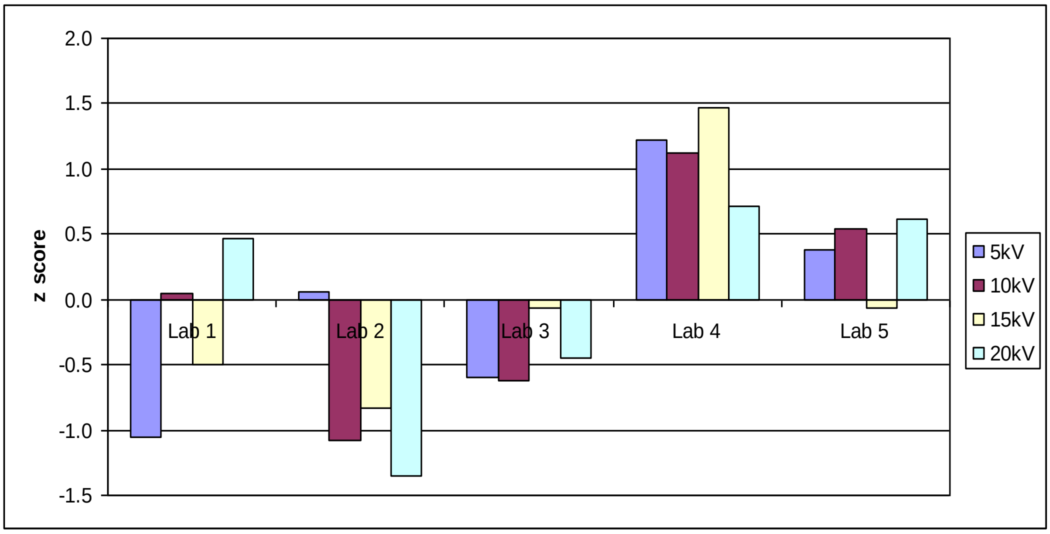

Figure 3: Z-scores for band pass measurement of Electric Field (E)

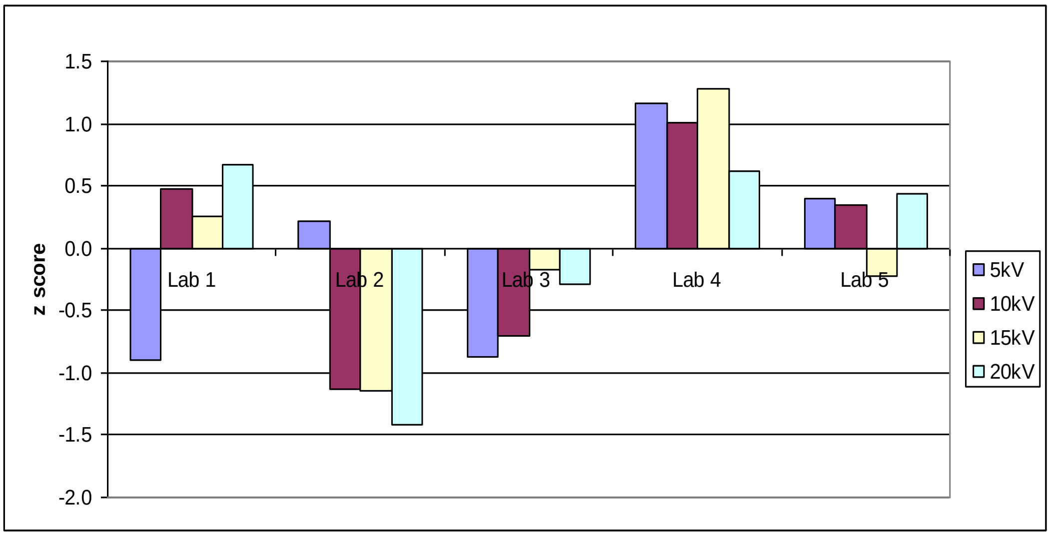

Figure 4: Z-scores for broadband measurement of Electric Field (E)

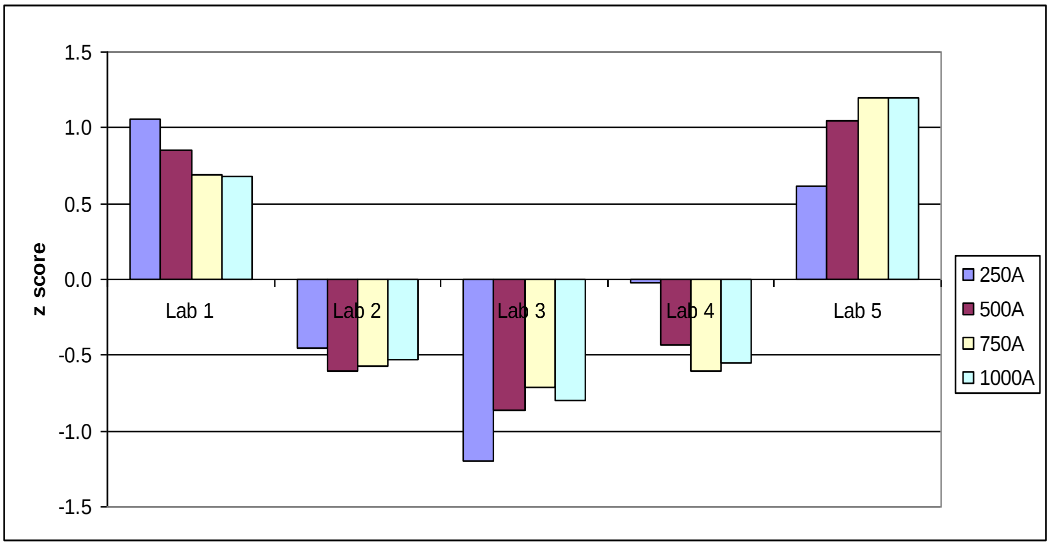

Figure 5: Z-scores for band pass measurements of Magnetic Field (B)

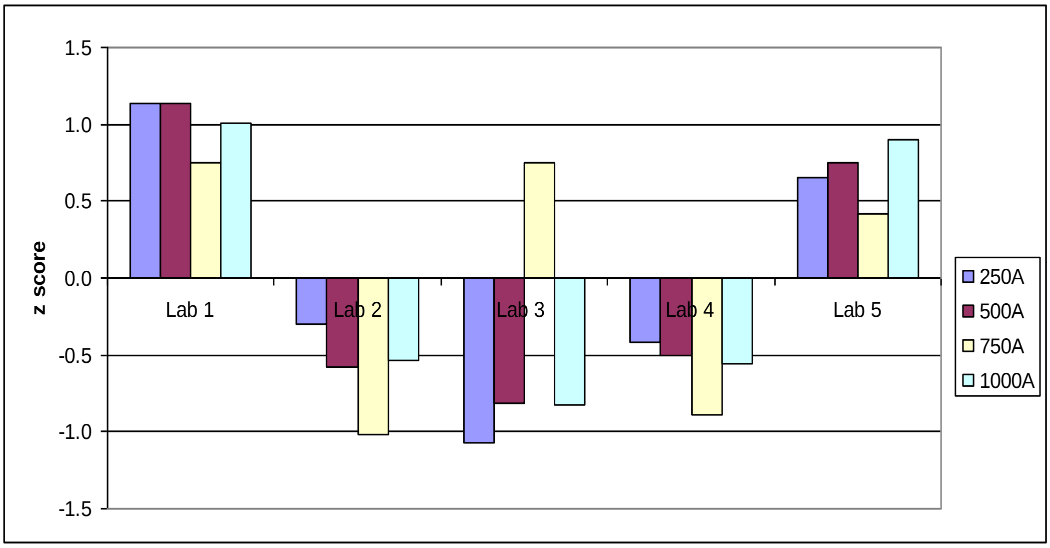

Figure 6: Z-scores for broadband measurements of Magnetic Field (B)

Discussion

The results of the measurements, their assessment and some hints for improvement of similar measurements in the near future are presented in this paper. Based on the calculations of the z scores and their depiction in bar charts, the evaluation of the performance of the participating laboratories can be determined as:

- The comparison of the estimates x * and s * for the average value μ and the standard deviation σ between the individual test levels shows an obvious dependence of the standard deviation from the mean. Specifically, the higher the average value of the measurements of E / B, i.e. the higher the level of voltage / current, the higher the standard deviation of the measurements. Placing sizes x * and s * in a chart, it is clear that the function connecting them is linear. In each case the equation is derived through linear regression, as illustrated in figures 7 and 8.

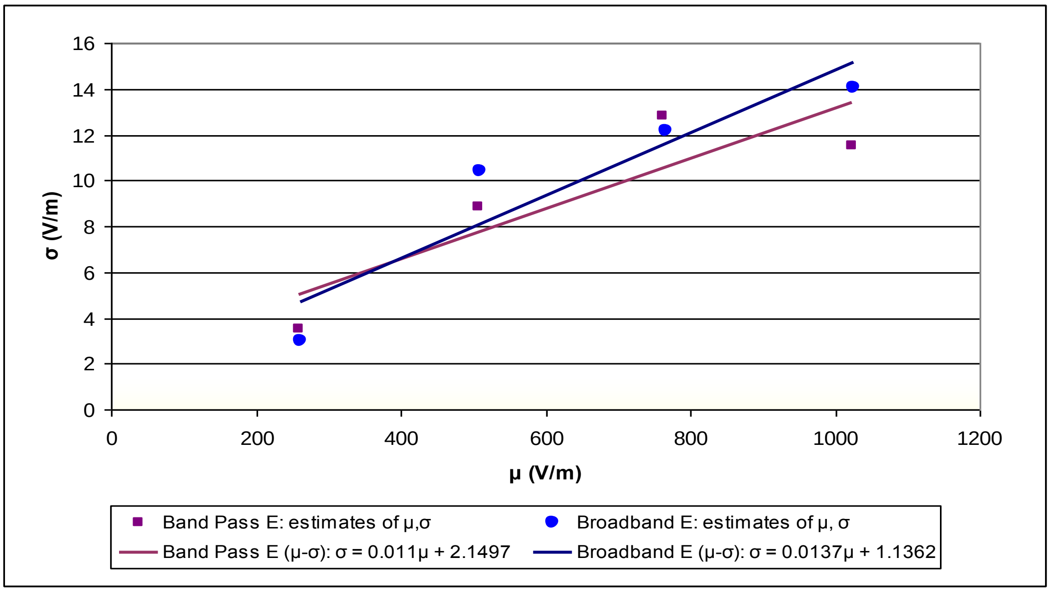

Figure 7: Variation (μ-σ) for the measurements of Electric Field (E)

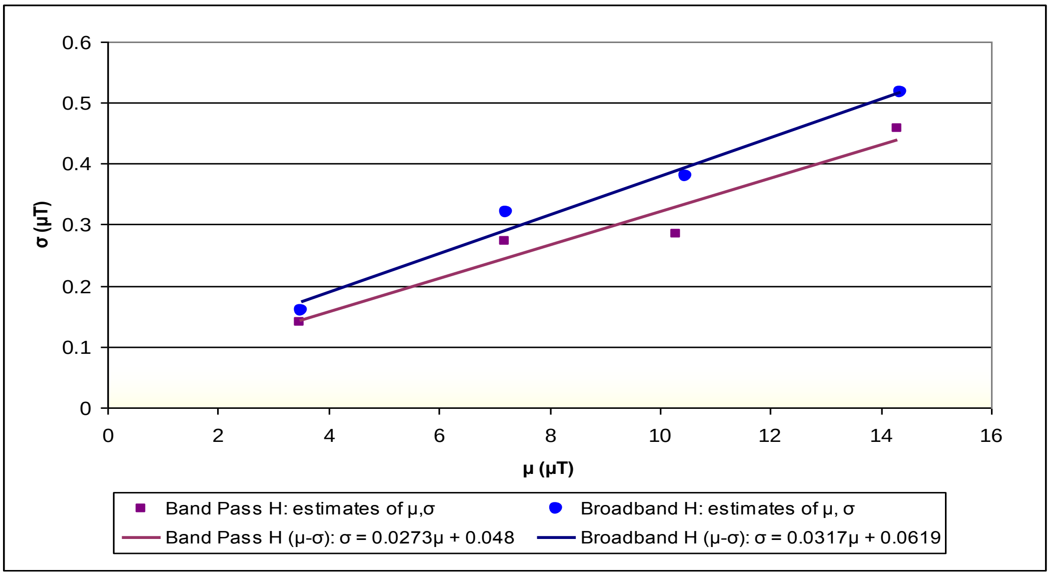

Figure 8: Variation (μ-σ) for the measurements of Magnetic Field (B)

- From the above charts, the following conclusions can be drawn: In all cases the relationship between μ and σ is in the form σ = a + bμ. The lines for the magnetic field have a bigger slope ($b_H > b_E$) for both broadband and band pass measurements, while broadband lines have a bigger slope than the band pass lines for both the electric and the magnetic field measurements ($b_{broadband} > b_{band\ pass}$).
- In statistical terms, the identification of these lines is complicated by the fact that the values x * and s * are estimates of the mean value μ and the standard deviation σ and thus subject to an error. However, according to the standard ISO 5725-2 [11], the errors in the estimated standard deviation prevail, because the slope of the line is usually small (around 0.1 or less) and errors in estimating the average value have small effect. The lines obtained have indeed very small slope (approximately 10^{-2}), while the applied robust algorithm introduces a small bias in the estimates of μ and σ.
- It is also interesting to note that, while generally zero mean does not necessarily lead to zero standard deviation, because the value μ=0 can be formed by mutually balancing measurements, in this case the measurands are fields. This means that in order to achieve μ=0, all laboratories must have measured zero field, resulting in σ=0. However, the lines have α ≠ 0.
- As far as the magnitude of the fields recorded by the laboratories is concerned, several band pass measurements which were slightly higher than the corresponding broadband ones, were found. This is theoretically impossible for measurements performed under identical conditions. Although this phenomenon did not affect the z scores, it indicates either imperfections of the measurement method of the laboratories or mainly the instability of the voltage/current which leads in practice to the production of different fields during the band pass and the broadband measurements (this is expected in the measurements of the magnetic field, where there was instability of the current, due to the absence of a voltage stabilizer). Only in the measurements of laboratory 1 this kind of discrepancy was not found.
- The order in which the laboratories performed their measurements affects the results, because of the unstable produced fields. Finally, it should be noted that the instruments used by the laboratories do not have the same frequency range, a fact that definitely could be the cause of differences found mainly in the broadband measurements.

Conclusions

This paper deals with the implementation of comparative measurements of extremely low frequency electromagnetic fields. The lack of available proficiency testing programs on that field, organized either by national or by international bodies, as well as the requirement of ESYD for accredited laboratories to participate in proficiency testing programs at least every four years, led us to the attainment of the proficiency testing scheme presented in this paper. The results for all measurement scenarios were analysed statistically with a robust algorithm in order to estimate the reference average values and standard deviations and calculate the z-scores for the performance evaluation of the laboratories. Based on the calculations of the z scores and their depiction in bar charts, the evaluation of the performance of the participating laboratories can be determined as:

- The performance of all laboratories is satisfactory, because no laboratory has been rated with a |z|>2.
- From Figures 3-6, it can be assumed that laboratories have shown more consistent behaviour when

measuring the magnetic field. In the measurements of the magnetic field, only laboratory 2 shows an alternation in the sign of its z scores for the broadband results. In the measurements of the electric field only laboratories 3 and 4 receive z scores with the same sign for all voltage levels. Laboratories 2 and 5 display changes in the signs of their z scores, but these are the same for broadband and band pass results. The largest inconsistency is found in the results of laboratory 1, which shows different sign-variations in the band pass measurements compared to those in the broadband measurements.

- At this point, the following must be clarified: The z scores of a well-behaving laboratory are in general expected to show a small variation around zero. Repetitive z scores with the same sign are indications of the behaviour of the instrument (such as its frequency response) or of a systemic factor of the measurement method (such as the calibration parameters of the instrument). If these z scores are above the threshold (|z|>2), it can be said that this is a systematic error (bias) caused by the instrument. In this experiment there have been no |z|>2, so the image of z scores with the same sign is not perceived as bias. On the contrary, it is positively evaluated as a consistent execution of the measurement method unaffected by the individual test levels.

Acknowledgments

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