COOMET Pilot Comparison 473/RU-a/09:

Comparison of hydrophone calibrations in the frequency range 250 Hz to 200 kHz

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Abstract: A description is given of the COOMET project 473/RU-a/09: a pilot comparison of hydrophone calibrations at frequencies from 250 Hz to 200 kHz between Hangzhou Applied Acoustics Research Institute (HAARI, China) **-** pilot laboratory - and Russian National Research Institute for Physicotechnical and Radio Engineering Measurements (VNIIFTRI, Designated Institute of Russia of the CIPM MRA). Two standard hydrophones, B&K 8104 and TC 4033, were calibrated and compared to assess the current state of hydrophone calibration of HAARI (China) and Russia. Three different calibration methods were applied: a vibrating column method, a free-field reciprocity method and a comparison method. The standard facilities of each laboratory were used, and three different sound fields were applied: pressure field, free-field, and reverberant field. The maximum deviation of the sensitivities of two hydrophones between the participants' results was 0.36 dB.

Key words: metrology; comparison; calibration; hydrophone; facility.

1. Introduction

In order to assess the current state of hydrophone calibrations, to test the consistency of the calibration results obtained in free-field, pressure field and reverberant water tank, and with the aim to investigate the possibility to extend free-field calibrations of hydrophones to a lower frequency range, a pilot comparison of hydrophone calibrations in the frequency range 250 Hz to 200 kHz between the Russian National Research Institute for Physicotechnical and Radio Engineering Measurements (VNIIFTRI, Designated Institute of Russia of the CIPM MRA[1]) and Hangzhou Applied Acoustics Research Institute (HAARI, China), registered as COOMET project 473/RU/09. The comparison was carried out during the periods 28 September to 7 October 2009 at VNIIFTRI and 14 June to 23 June, 2010 at HAARI [1]. The HAARI, main laboratory of underwater acoustics calibrations in China, acted as the pilot laboratory on the behalf of the National Institute of Metrology (NIM, China) in this comparison.

The comparison was proposed during the meeting of IEC/TC87 held in Seoul (Republic of Korea) in May 2009 and was approved by the COOMET Secretariat on 14 August 2009 as a bilateral comparison starting 14 August 2009 and ending 30 November 2010 where HAARI was designated as pilot laboratory. New measurement methods developed at the VNIIFTRI were included in this comparison to avoid correlations and eventually reveal systematic effects.

Two hydrophones, B&K 8104 and TC 4033 provided by HAARI, were used as standard hydrophones in the comparison. This report describes the standard hydrophones, the calibration methods and standard facilities of HAARI and VNIIFTRI that were used in the comparison. The calibration results and an analysis are also presented.

2. Standard hydrophones used for comparison

Two hydrophones were chosen for the comparison: one B&K 8104 hydrophone manufactured by Brüel & Kjær A/S in Denmark where its sensitive element has a stack of four piezoelectric ceramic ring elements of diameter 12 mm, and one TC 4033 hydrophone manufactured by Reson A/S in Denmark, where its sensitive element has a piezoelectric ceramic sphere with diameter 20 mm. Information on the devices used for the calibration are listed in Table 1 along with the frequency ranges over which the calibrations were undertaken. Each participant calibrated both hydrophones at about 20 discrete frequency points.

The two types of hydrophones were chosen as they are used on a routinely basis as standard measuring hydrophones at HAARI. Results from HAARI on the long term stability of TC 4033 hydrophone collected over five years from 2005 to 2009 for which the water temperature was varying between 13 °C and 24 °C, are listed in Table 2. The mean of the standard deviation in the frequency range 1 kHz to 200 kHz is 0.25 dB, showing that TC 4033

[1] International Committee for Weights and Measures – Mutual Recognition Arrangement
http://www.bipm.org/en/cipm-mra/

hydrophone is remarkably stable. The B&K 8104 showed a larger temperature dependence in the frequency range 10 kHz to 150 kHz and was less stable [2]. The results are complex, depending strongly on the acoustic frequency, and indicate a nonlinear dependence on temperature. Although the frequency range is lower in the comparison reported here than in [2], the B&K 8104 hydrophone shown to be stable also in the low frequency region.

Table 1. Information on the two standard hydrophones used in the comparison.

Hydrophone type	Manufacturer	Frequency range (kHz)	Nominal sensitivity at 250 Hz (dB, *re*:1V/μPa)	Integral cable length (m)	Nominal capacitance (nF)
8104	Brüel & Kjær A/S	0.25 - 1	–205	10	7.8
4033	Reson A/S	0.8 - 200	–203	10	7.8

Table 2. Long term stability information of the TC4033 hydrophone.

Frequency (kHz)	Overall mean (dB, *re*:1V/μPa)	Maximum deviation (dB)	Minimum deviation (dB)	Standard deviation (dB)
1	− 202.04	0.24	− 0.16	0.18
2	− 202.12	0.12	− 0.18	0.13
4	− 202.26	0.26	− 0.34	0.23
8	− 202.36	0.36	− 0.24	0.25
10	− 202.58	0.38	− 0.22	0.25
20	− 203.96	0.26	− 0.44	0.29
25	− 204.72	0.42	− 0.28	0.27
40	− 205.78	0.28	− 0.22	0.22
50	− 205.74	0.24	− 0.16	0.15
80	− 203.70	0.60	− 0.30	0.37
100	− 198.20	0.40	− 0.40	0.29
160	− 214.80	0.40	− 0.20	0.23
200	− 220.52	0.42	− 0.68	0.44

3. Calibration methods and their standard facilities

3.1. Calibration methods and their standard facilities used in HAARI

3.1.1 Vibrating column method and its standard facility

The vibrating column method was used for calibrations in the frequency range 250 Hz to 1 kHz. This method uses an open column of liquid at low frequencies for which the wavelength is larger than the height of the column. Hence, the hydrophone can be calibrated in a simple way [3]. Figure 1 shows the schematic diagram of the standard facility using the vibrating column method. The pressure sensitivity of the B&K 8104 hydrophone was measured using this facility. During the comparison, the head of B&K8104 hydrophone was immersed in a column of water, and the hydrophone was fixed by a bracket through its cable, vertically suspended close to the central axis of the column. A continuous sinusoidal signal was transmitted, and the vibrating open column was used as the calibration sound field. Its expanded uncertainty (k = 2) for hydrophone calibrations is estimated to 0.6 dB [3] (cf. Appendix).

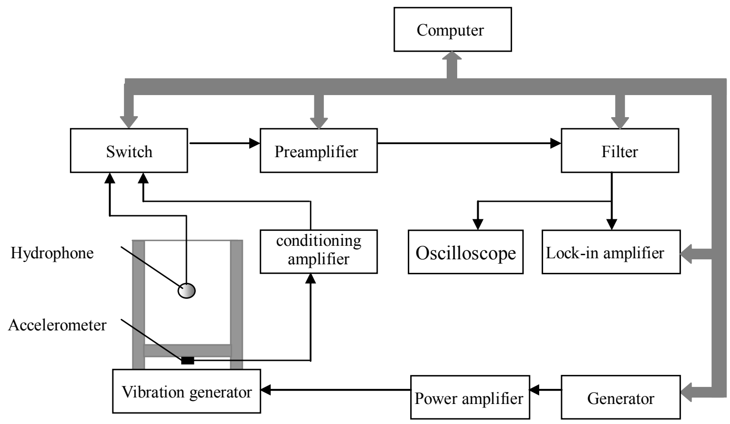

Figure 1. Schematic diagram of the standard facility using the vibrating column method.

3.1.2 Free-field reciprocity method and its standard facility

The free-field reciprocity method was used for calibrations in the frequency range 800 Hz to 200 kHz. For this method, three transducers are employed of which at least one is reciprocal. Two of the transducers are placed in water in free-field conditions, where one of them is used as projector and the second as receiver (hydrophone). With three pairs, three independent electrical transfer impedances are obtained. From these quantities, the free-field sensitivity of the hydrophone can be determined [3]. Figure 2 shows the schematic diagram of the standard facility using the free-field reciprocity method. The free-field sensitivity of TC 4033 hydrophone was measured using this facility. During the comparison, a projector and hydrophone pair was mounted onto a π-shaped calibration framework, through their free-flooding carbon fiber poles. A tone-burst signal was transmitted, and an anechoic water tank (50 m long; 15 m wide; 10 m deep) was used as the calibration sound field. Its expanded uncertainty (k = 2) [4] for hydrophone calibrations is estimated to 0.7 dB at frequencies below 100 kHz, and 0.9 dB in the frequency range 100 kHz to 200 kHz (cf. Appendix).

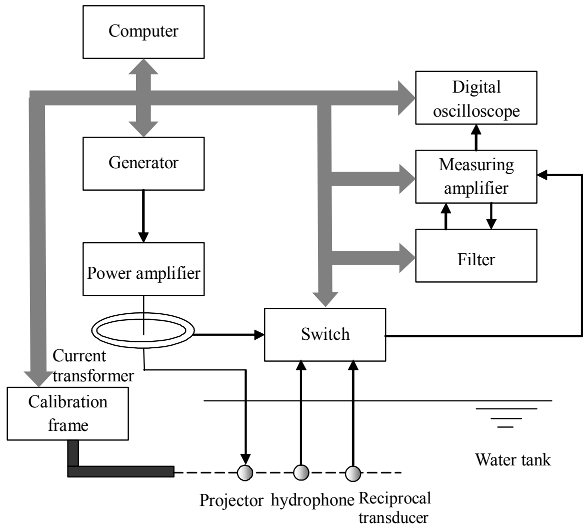

Figure 2. Schematic diagram of standard facility using the free-field reciprocity method

3.2 Calibration method and. standard facility used in VNIIFTRI

3.2.1 Free-field calibration method using CMWA technique

At frequencies from 250 Hz to 5 kHz, the calibration water tank has presently a reverberant field. In order to get free-field calibration results, a continuous frequency band signal was transmitted, and a signal processing algorithm of Complex Moving Weighted Averaging (CMWA) was used to remove the boundary echoes [5,6]. Figure 3 depicts the principle of generating a radiant continuous chirp signal of unit amplitude, $\exp[j\varphi(t)]$, and the algorithms for calculating the frequency responses of a projector–receiver pair in a reverberant water tank, $\dot{Z}'(St)$,for which $\dot{Z}(St)$ equals to one in free–field. Here, $\varphi(t) = St^2/2$ where S is rate of frequency changes and $\partial\varphi(t)/\partial t = St$ is the instantaneous frequency of chirp signal. Two methods were used for calibrations: the free-field comparison method is applied for the frequency range 250 Hz to 500 Hz, and the free-field reciprocity method for the frequency range 630 Hz to 200 kHz (cf. Appendix).

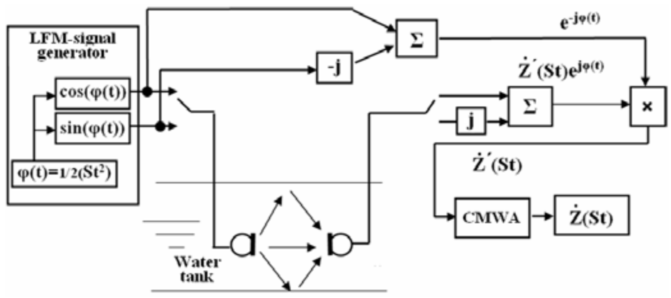

Figure 3. Schematic diagram of a radiant continuous chirp signal and its signal processing.

3.2.2 Free-field reciprocity method using a quadrature added tone–burst signal

At frequencies from 6.3 kHz to 200 kHz, the free-field reciprocity method was used for calibrations, and a quadrature added tone-burst signal was transmitted. The principle of generating a quadrature added tone-burst signal of unit amplitude with carrier frequency ω_0 and its signal processing algorithm is schematized in Figure 4 [1].

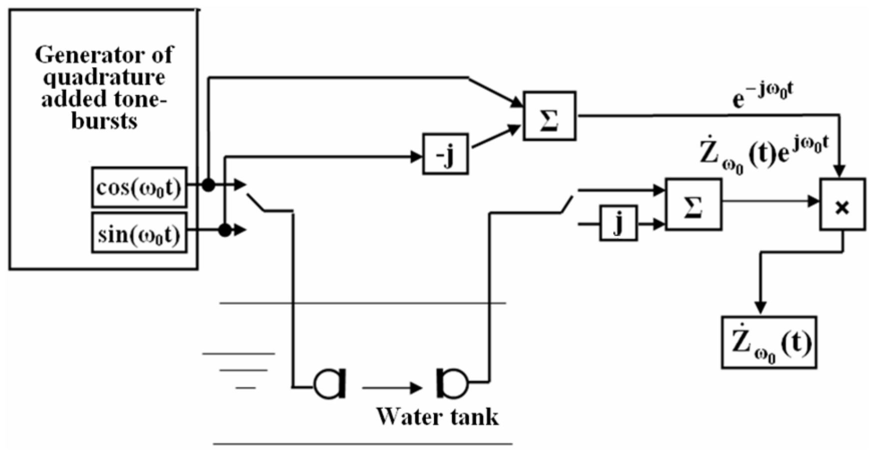

Figure 4. Schematic diagram of generation of a quadrature added tone – burst and its signal processing.

3.2.3 Standard facility used in VNIIFTRI

The hydrophone calibrations at the VNIIFTRI were carried out in a reverberant water tank of (10 m long; 6.5 m wide; 5.8 m deep). The schematic diagram of the standard facility used at VNIIFTRI is shown in Figure 5.

The free-field sensitivities of the B&K 8104 and TC 4033 hydrophones were measured using this facility. During the comparison, the projector and hydrophone were mounted to their long steel poles through short carbon fiber poles, and they were vertically suspended into the water tank. The expanded uncertainty (k = 2) of the hydrophone calibration was estimated to 0.7 dB using CMWA technique in the frequency range 250 Hz to 500 Hz, 0.6 dB using the free-field reciprocity method including CMWA technique in the frequency range 630 Hz to 5 kHz, and 0.6 dB for the free-field reciprocity method using a quadrature added tone-burst signal.

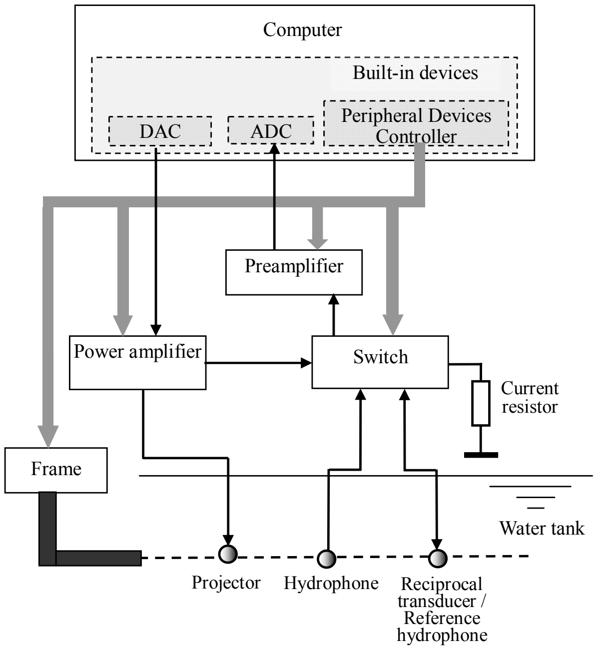

Figure 5. Schematic diagram of standard facility used at the VNIIFTRI.

4. Calibration results

4.1 Introduction

The two standard hydrophones were calibrated at different times and places, by different persons using different calibration methods and facilities. Further, the water temperature was 23 °C at HAARI but 13 ºC at VNIIFTRI. No correction for the water temperature was applied to the comparison data, as the sensitivity to temperature is not known accurately enough. This situation is similar to the key comparisons CCAUV.W–K1. However, in future comparisons, the same nominal water temperature should preferably be applied.

4.2. Calibration results of the B&K 8104 hydrophone

The pressure sensitivity calibration results of the B&K 8104 hydrophone from HAARI and the free-field sensitivity calibration results from VNIIFTRI are shown in Table 3. The mean value was used as reference value, as the uncertainties declared by participants were much similar. The calibration results from HAARI and VNIIFTRI are close where the maximum difference is 0.36 dB. However, the VNIIFTRI calibration results are larger by 0.29 dB in average than the HAARI calibration results.

Table 3. Comparison calibration results of the B&K 8104 hydrophone.

Freq. (Hz)	Vibrating column method		CMWA technique							
	M_{CH} (dB, *re*: 1V/μPa)	U_{CH} (dB)	M_{RUS} (dB, *re*: 1V/μPa)	U_{RUS} (dB)	M_{ref} ($\times 10^{-11}$ 1V/μPa)	U_{ref} (dB)	Δ_{CH} (dB)	$U_{\Delta CH}$ (dB)	Δ_{RUS} (dB)	$U_{\Delta RUS}$ (dB)
250	–206.05	0.6	– 205.90	0.7	5.029	0.46	0.08	0.39	–0.07	0.53
315	–206.03	0.6	– 205.67	0.7	5.099	0.46	0.18	0.39	–0.18	0.53
400	–206.03	0.6	– 205.74	0.7	5.082	0.46	0.15	0.39	–0.14	0.53
500	–205.98	0.6	– 205.73	0.7	5.099	0.46	0.13	0.39	–0.12	0.53
630	–206.13	0.6	– 205.83	0.6	5.023	0.43	0.15	0.43	–0.15	0.43
800	–206.20	0.6	– 205.85	0.6	5.000	0.43	0.18	0.43	–0.17	0.43
1000	–206.13	0.6	– 205.81	0.6	5.029	0.43	0.16	0.43	–0.16	0.43

Following symbols are used in this table:

M_{CH} , M_{RUS} - sensitivity level measured by HAARI and VNIIFTRI respectively;
U_{CH}, U_{RUS} - expanded uncertainties declared by HAARI and VNIIFTRI respectively;
M_{ref}, U_{ref} - a comparison reference value and its expanded uncertainty;
Δ_{CH}, Δ_{RUS} - deviation from reference value for HAARI and VNIIFTRI respectively;
$U_{\Delta CH}$, $U_{\Delta RUS}$ - degree of equivalence for HAARI and VNIIFTRI respectively.

4.2. Calibration results of the TC 4033 hydrophone

The free-field sensitivity calibration results of the TC 4033 hydrophone from HAARI and VNIIFTRI are shown in Table 4. The calibration results from HAARI and VNIIFTRI are close where the maximum difference is 0.36 dB.

Table 4. Comparison calibration results of the TC 4033 hydrophone.

Freq. (kHz)	Free – field reciprocity method M_{CH} (dB, *re*: 1V/μPa)	U_{CH} (dB)	M_{RUS} (dB, *re*: 1V/μPa)	U_{RUS} (dB)	M_{ref} (×10^{-11} 1V/μPa)	U_{ref} (dB)	Δ_{CH} (dB)	$U_{\Delta CH}$ (dB)	Δ_{RUS} (dB)	$U_{\Delta RUS}$ (dB)
0.8	–201.80	0.7	–202.01	0.6	8.031	0.46	–0.10	0.53	0.11	0.39
1	–202.13	0.7	–202.20	0.6	7.794	0.46	–0.03	0.53	0.04	0.39
2	–201.95	0.7	–202.05	0.6	7.943	0.46	–0.05	0.53	0.05	0.39
4	–202.18	0.7	–202.36	0.6	7.701	0.46	–0.09	0.53	0.09	0.39
8	–202.38	0.7	–202.60	0.6	7.508	0.46	–0.11	0.53	0.11	0.39
10	–202.63	0.7	–202.58	0.6	7.409	0.46	0.03	0.53	–0.02	0.39
20	–203.92	0.7	–203.86	0.6	6.390	0.46	0.03	0.53	–0.03	0.39
25	–204.62	0.7	–204.66	0.6	5.861	0.46	–0.02	0.53	0.02	0.39
40	–205.75	0.7	–205.81	0.6	5.140	0.46	–0.03	0.53	0.03	0.39
50	–205.92	0.7	–205.70	0.6	5.123	0.46	0.11	0.53	–0.11	0.39
80	–203.78	0.7	–204.14	0.6	6.340	0.46	–0.18	0.53	0.18	0.39
100	–197.78	0.9	–198.04	0.6	12.722	0.50	–0.13	0.75	0.13	0.33
160	–215.35	0.9	–215.20	0.6	1.723	0.50	0.08	0.75	–0.07	0.33
200	–220.30	0.9	–220.23	0.6	0.970	0.50	0.04	0.75	–0.03	0.33

5. Discussion and conclusion

The calibration results of Table 3 and Table 4, the following conclusions can be drawn:

1) For the B&K 8104 hydrophone, the HAARI and VNIIFTRI are in close agreement with a maximum difference of 0.36 dB. The uncertainty (at k=2) of HAARI using the vibrating column method is 0.6 dB; the uncertainty of VNIIFTRI using the free-field comparison method and CMWA technique is 0.7 dB.

2) The calibration results of the B&K 8104 at VNIIFTRI are in average 0.29 dB larger than the HAARI calibration results. A possible origin of this systematic effect is the comparable large difference in water temperatures (10 °C) applied by HAARI and VNIIFTRI.

3) For the TC 4033 hydrophone calibrations, the agreement between HAARI and VNIIFTRI is also close, showing a maximum difference of 0.36 dB. The uncertainty (k = 2) of HAARI is 0.7 dB (below 100 kHz) and 0.9 dB (from 100 kHz to 200 kHz) using the free-field reciprocal method and tone burst technique, whereas it is 0.6 dB for VNIIFTRI when applying the free-field reciprocity method combined with CMWA or quadrature-added tone-burst techniques.

As a conclusion, the COOMET Pilot Comparison 473/RU-a/09 between HAARI and VNIIFTRI was carried out using different calibration methods and sound fields, and in different experimental conditions. The difference between the calibration results for two hydrophones of different manufacturers of the two laboratories are within the estimated uncertainties. This result establishes the current status of hydrophone calibrations at HAARI and VNIIFTRI and confirms the feasibility to extend the frequency range of hydrophone free-field calibration in reverberant water tank towards lower frequencies.

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Appendix: Uncertainty estimation of calibration method used in comparison

A1. Vibrating column method used in HAARI

Uncertainty estimation of calibration of hydrophone using vibrating column method is listed in Table A.1.

Table A.1 Uncertainty estimation of vibrating column calibration method

	Source of uncertainty	Value (dB)
type B	Open–circuit voltage of the hydrophone	0.12
	Open–circuit voltage –of the accelerometer	0.12
	Immersion depth of the hydrophone	0.1
	Water density	0.03
	Sensitivity calibration of accelerometer	0.1
	High frequency Influenced by correctional factor in the assumed	0.1
type A	Standard uncertainty of measurement of sensitivity	0.09
	Expanded combined uncertainty (*k*= 2)	**0.6**

A2. Free-field reciprocity method used in HAARI

Uncertainty estimation of calibration of hydrophone using free-field reciprocity method is listed in Table A.2.

Table A.2 Uncertainty estimation of free－field reciprocity calibration method

	Source of uncertainty	Value (dB)
type B	Input impedance of preamplifier assumed	0.06
	Current transformer	0.05
	Quantization of digital oscilloscope	0.06
	Reciprocal transducer	0.15 (<100 kHz) or 0.29 (≥100 kHz)
	Nonlinearity of transducer	0.12 (<100 kHz) or 0.29 (≥100 kHz)
	Directivity of transducer	0.10
	Vertical position of transducer	0.10
	Distance	0.05
	Water density	0.02
	Generator frequency	0
	Steady state of tone－burst	0.23
	Interference from irregular noise	0.06
	Interference from electromagnetism	0.05
type A	Standard uncertainty of measurement of sensitivity	0.13 (<100 kHz) or 0.16 (≥100 kHz)
	Expanded combined uncertainty (*k*=2)	**0.7 (<100 kHz) and 0.9 (≥100 kHz)**

A3. Free-field calibration method used in VNIIFTRI

Uncertainty estimation of hydrophone free－field calibration is listed in Table A.3.

Table A.3 Uncertainty estimation of free-field calibration method

	Source of uncertainty	Value (dB)
type B	Transducer directivity	0.05 (16 - 50 kHz) or 0.2 (≥ 50 kHz)
	Violation of far–field conditions	0.07 (< 125 kHz) or 0.11(≥ 125 kHz)
	Reciprocity criterion for reciprocal transducer	0.13 (≥ 160 kHz)
	Transducer voltage ratios	0.06 (for ratios < 60 dB) or 0.11 (≥ 60 dB)
	Reciprocal transducer	0.04 (≥100 kHz)
	Transducers separation distance	0.04
	Interference due to water tank boundary reflections	0.17 (< 1000 Hz)
	Interference due to sound waves scattering	0.17 (≥100 kHz)
	Scattering on the reference hydrophone	0.03 - 0.09 (80 - 200 kHz)
	Accuracy of the reference hydrophone	0.21 (≤ 500 Hz)
	Averaging of projector–receiver free–field transfer impedance frequency response	0.15 (≤ 6.3 kHz)
	Tone－burst steady state	0.11 (6.3 - 18 kHz)
	Crosstalk	0.08 (< 3000 Hz) or 0.04 (3 - 8 kHz)
	Electrical noise, including high frequency interference	0.04
	Electrical load correction	0.05
type A	Standard uncertainty of measurement of sensitivity	0.14 (<100 kHz) or 0.18 (≥100 kHz)
	Expanded combined uncertainty (*k*=2)	**0.7 (<500Hz) and 0.6 (≥500 Hz)**