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KN.U-K2 International Laboratory Comparison of Ultrasound Power Measurements Emitted from an Ultrasonic Transducer

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An international comparison of ultrasound power measurements was conducted among the ultrasound laboratories of the Korea Research Institute of Standards and Science (KRISS), the National Metrology Institute of Japan (NMIJ) and the National Institute of Standards (NIS, Egypt). The measurand for comparison is the electro-acoustic radiation conductance G, which is defined as the amount of ultrasound power divided by the square of the input signal voltage to the transducer. The reference device is an ultrasonic transducer, model number KRISS-2MHz-14LN, manufactured by KRISS using a Lithium-Niobate ($LiNbO_3$) piezoelectric single crystal. This comparison, reference number KN.U-K2, was piloted by KRISS, including the preparation of the protocol and the reference device, and the analysis of measurement results by the participants. This paper reports the comparison results.

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I. INTRODUCTION

Korea Research Institute of Standards and Science (KRISS), National Metrology Institute of Japan (NMIJ) and National Institute of Standards (NIS) are National Metrology Institutes (NMI) representing Korea, Japan and Egypt respectively. One of the most important missions of a NMI is to ensure equality of measurement between countries. To ensure the execution of these missions, each NMI collaborates with the others. Some memorandum of understandings (MOUs) are signed between the NMIs for the legitimacy of cooperation. This international comparison is one of the collaborative activities among these NMIs.

The ultrasound power is the acoustic energy per unit time radiated from a device called an ultrasonic transducer. This power is very important because it relates to safety in terms of exposure to medical ultrasound. In this paper, we report a comparison of measurements of ultrasound power according to the excitation voltage of an ultrasonic transducer.

Based on the two MOUs between KRISS and NMIJ and that between KRISS and NIS Egypt, an inter-laboratory comparison among KRISS, NMIJ, and NIS for ultrasound power was conducted. KRISS conducted pilot laboratory's work. The reference number of the comparison was coded as KN.U-K2 by the pilot laboratory. The KN.U-K2 is the second inter-laboratory comparison piloted by KRISS to help participating laboratory check their measurement results, conditions of measurement system, problems of measurement procedures and others things to affect their measurement results. This comparison uses almost same protocol except schedule and comparison artifact as the previous International Committee for Weights and Measures (CIPM) International Comparison CCAUV.U-K3.1 [1]. Therefore, this comparison is intended to compare ultrasound power measurements in the frequency range from 2 MHz to 15 MHz and the power range from 10 mW to 15 W. A new transducer, KRISS-2MHz-14LN, was manufactured and characterized by the pilot laboratory for this com-

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Table 1. Time schedule of the inter-laboratory comparison KN.U-K2.

No.	Calibration Laboratory	Starting date	Finishing date	Dispatch date	Reporting date
1	KRISS, Korea	4-July-16	25-July-16	1-Aug-16	22-Aug-16
2	NMIJ, Japan	22-Aug-16	19-Sep-16	26-Sep-16	17-Oct-16
3	NIS, Egypt	17-Oct-16	14-Nov-16	21-Nov-16	12-Dec-16
4	KRISS, Korea	12-Dec-16	9-Jan-17	-	6-Feb-17

parison.

II. COMPARISON PROTOCOL

Generally, before an international comparison is started, the protocol is prepared and approved by all the participants. The protocol generally describes the artifact device specifications, schedules, transport, conditions of use, measurement conditions, and reporting methods for the consistency of the comparison. This paper describes only the device specifications and schedules that are different from those of the protocol of CCAUV.U-K3.1 [1].

An ultrasonic standard transducer is circulated as a standard artifact. The specifications of the transducer are as follows:

- Identification number: KRISS-2MHz-14LN
- Electrode shape: coaxial type
- Electrode: chrome-gold
- Frequency band type: narrow band
- Active material: lithium niobate crystal
- Backing: air backing (half-wave resonant, narrow band)
- Transducer shape: cylindrical
- Length: 102 mm
- Diameter: 30 mm
- Weight: 114 g
- Connector type: female BNC

The transducer does not contain any electronic components and is not matched to 50 Ω. The transducer front is covered by a red rubber cap to prevent damage and contamination of the active piezoelectric element. The transducer is intended to be used as a standard device for transmission-only operation at its fundamental resonance and in the third, fifth, and seventh harmonics, and has stable output characteristics. All three participants agreed to take part in the comparison and the following schedule in Table 1 was prepared and kept.

Table 2. Frequency and voltage setting specifications for measurement.

FPL	f_s[MHz]	*level*	U_s [V]
A	1.8861	Very low	1.30
B		Medium	17.0
C		High	50.0
D	6.3318	Very low	1.24
E		Low	4.00
F	10.6284	Very Low	1.24
G		Low	4.00
H	14.9085	Low	3.70

The task of the comparison was to measure the total, time-averaged ultrasound power, P_{out}, emitted by the provided transducer under specified conditions of electrical excitation into an anechoic (*i.e.*, free-field) water load for a known rms-voltage U_{in} at the transducer input port. Finally, the electro-acoustic radiation conductance G was calculated according to

$$G = P_{out}/(U_{in})^2. \quad (1)$$

All laboratories delivered data for G, but not to all frequency power levels (FPLs) specified in Table 2. Therefore, the number of results used to calculate the reference values of each FPL is not the same. The symbols f_s and U_s in Table 2 are the specified frequencies and input voltages, respectively. The capitalized alphabetic characters A through H in Table 2 denote the specific FPL of the corresponding column. The actual input voltage U_{in} must be measured and reported by the participants, who used their own methods and instruments. That values should agree with the respective U_s in Table 2 within ±5% under the same conditions as in the reference [1]. It was also recommended in the protocol that the measurement should be conducted at a temperature as close as 21.5 °C within ±2.0 °C under the same conditions as in the reference [1]. The use of degassed water was also highly recommended and was mandatory at the "high" level where the oxygen content was to be measured and reported under the same conditions as in the reference [1]. The actual frequency, f_a, should also be reported and should agree with the specified one, f_s, within ±0.0010 MHz [1].

Table 3. Results of the re-measurements and the mean value for the acoustic radiation conductance G with declared uncertainties $ku(G)$ ($k = 2$) of the pilot lab.

FPL	f	*Level*	U_{in}	Re1		Re2		KRISS mean value	
	MHz		V	G[mS]	ku[%]	G[mS]	ku[%]	G[mS]	ku[%]
A	1.8861	very low	1.30	5.75	5.2	5.72	5.2	5.73	5.2
B		med	17.0	5.64	4.9	5.67	4.9	5.66	4.9
C		high	50.0	5.71	4.6	5.72	4.6	5.71	4.6
D	6.3318	very low	1.24	6.53	6.0	6.55	6.0	6.54	6.0
E		low	4.00	6.45	5.3	6.51	5.3	6.48	5.3
F	10.6284	very low	1.24	6.66	6.0	6.73	6.0	6.70	6.0
G		low	4.00	6.68	5.3	6.69	5.3	6.69	5.3
H	14.9085	low	3.70	7.05	6.2	7.03	6.2	7.04	6.2

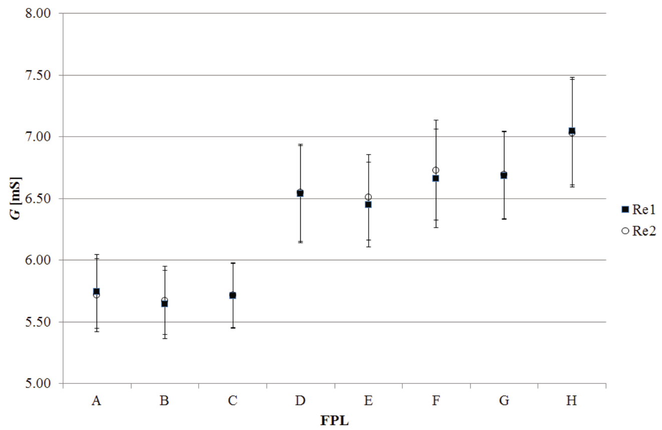

Fig. 1. Results of the re-measurements for the acoustic radiation conductance G and declared uncertainties $ku(G)$ ($k = 2$) of the pilot lab.

III. ARTIFACT STABILITY

The transducer was circulated to the participants during the comparison, and re-measurements were carried out by the pilot laboratory after circulation. A total of four sets of measurements were made including measurements at the start (Re1) and the end (Re2) of the comparison by the pilot laboratory. The results of the measurements at the pilot laboratory are given in Table 3 and Fig. 1. As shown in Table 3 and in Fig. 1, the values of Re2 measured after circulation agree well with those of Re1 measured before circulation. The differences between Re1 and Re2 are much less than the uncertainties of KRISS measurement system. Hence, the circulated transducer can be regarded to have been stable throughout the international laboratory comparison.

IV. COMPARISON RESULTS

In Table 4, the final results for the radiation conductance G and the uncertainties as reported by all participants are listed. The uncertainties are generally understood as relative uncertainties in percent. The stated expanded uncertainties $ku(G)$ are based on a coverage factor $k = 2$. The level of confidence is approximately 95%. According to the conventional rule of international comparison, the measurements, which were the carried out in July 2016, and contributed to the KRISS comparison values in Table 4, are Re1 in Table 3.

Table 4. Results of the comparison participants.

FPL	KRISS		NMIJ		NIS		RV1	
	G[mS]	ku[%]	G[mS]	ku[%]	G[mS]	ku[%]	G[mS]	u[mS]
A	5.75	5.2	5.61	8.9	12.70	4.7	6.74	0.11
B	5.64	4.9	5.73	6.5	4.90	3.2	5.49	0.10
C	5.71	4.6	5.67	6.2	NA	NA	5.69	0.11
D	6.53	6.0	6.65	6.9	11.23	9.4	6.90	0.14
E	6.45	5.3	6.63	4.4	4.84	6.9	6.03	0.09
F	6.66	6.0	7.20	6.2	12.36	5.2	7.87	0.14
G	6.68	5.3	7.05	5.8	5.96	5.8	6.51	0.11
H	7.05	6.2	7.87	8.0	7.16	10.5	7.29	0.16

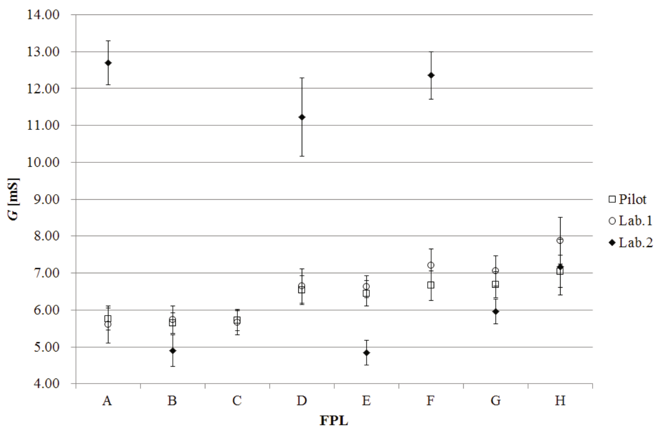

Fig. 2. Results of the key comparison from all three participants. Error bars indicate the expanded uncertainties $k{\cdot}u(G)$ ($k = 2$), as given in Table 4.

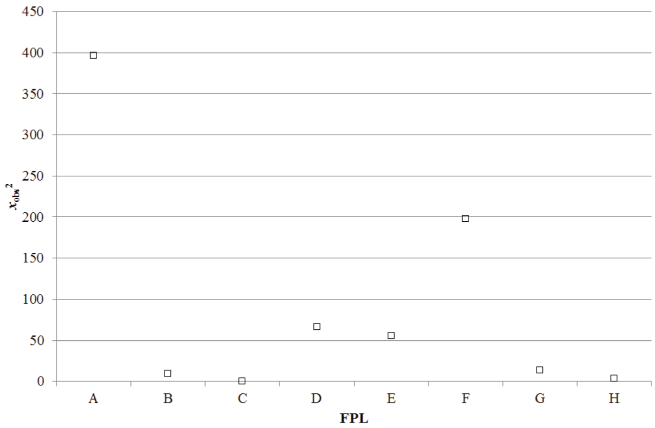

Fig. 3. Consistency check for the different frequency power levels when all results are considered.

Figure 2 is a graph showing the results with their uncertainties submitted by all participants. The Pilot in the legend of Fig. 2 is KRISS. The Lab. 1 and Lab. 2 in the legend of Fig. 2 are NMIJ and NIS, respectively. As seen in Fig. 2, some data are seriously deviate from the results of other laboratories. This is likely due to the inclusion of outliers. The term 'outlier' means that the considered measurement results, including uncertainties, deviate completely from the reference values [1, 2]. In the next section, the outlier test method of Cox [2] is described briefly and applied to the results of this measurement comparison.

V. ANALYSIS

In key comparisons a common practice is to analyze the data to check for consistency before evaluating the reference values (RVs). The methodology to derive a RV is not strictly defined and is still a matter of research [1]. The BIPM (Bureau International des Poids et Mesures) Advisory Group on Uncertainties recommends methods described in a paper by Cox as a basic technique [1,2]. That technique was applied for a first analysis of the data and a weighted mean was determined:

$$\overline{G_l} = \frac{\sum_{j=1}^{j=N}(G_{l,j}/[u(G_{l,j})]^2)}{\sum_{j=1} j = N[1/u(G_{l,j})]^2}, \tag{2}$$

where $N = 3$ is the number of participants, $G_{l,j}$ is the radiation conductance value for FPL l reported by participant j, and $u_2(G_{l,j})$ is the respective standard uncertainty. Next, the standard deviations of the weighted means were calculated as

$$\frac{1}{u^2(\overline{G_l})} = \sum_{j=1}^{j=N} \frac{1}{u^2(G_{l,j})}. \tag{3}$$

To check the consistency of the complete data set, we calculated the observed χ^2-values:

$$\chi^2_{obs,l} = \sum_{j=1}^{j=N} \frac{(G_{l,j} - \overline{G_l})^2}{u^2(G_{l,j})}. \tag{4}$$

The consistency check fails for one of the FPLs if

$$\Pr[\chi^2(\nu) > \chi^2_{obs,l}] < 0.05, \tag{5}$$

where ν is the degree of freedom (with $\nu = N-1$) and Pr denotes 'the probability of'. This leads to an upper limit on $\chi^2_{obs,l}(\chi^2_{max} = 5.99$ for $N = 3)$. Figure 3 shows the values of $\chi^2_{obs,l}$ from Eq. (4). Obviously, for all frequency-power setting levels (FPL) except for FPL C and H, the criterion is not fulfilled.

In order to identify discrepant measurement results, we calculated the deviations from the weighted means, $d_{l,j} = G_{l,j} - \overline{G_l}$, as well as their uncertainties, $u^2(d_{l,j}) = u_2(G_{l,j}) - u^2(\overline{G_l})$. With these two quantities, the outlying criterion

$$|d_{l,j}| > ku(d_{l,j}) \leftrightarrow \frac{|d_{l,j}|}{ku(d_{l,j})} > 1 \tag{6}$$

was tested for all measurement results. All calculated values are given in Table 6, with "Outlier test" being $|d_{l,j}|/k \cdot u(d_{l,j})$. This means that a particular result is considered as discrepant if "Outlier test" is > 1. Those

Table 5. Basic analysis of the results when all results are considered.

FPL	KRISS		NMIJ		NIS		x^2_{obs}
	d[mS]	u[mS]	d[mS]	u[mS]	d[mS]	u[mS]	
A	−1.00	0.19	−1.13	0.25	5.95	0.32	396
B	0.15	0.17	0.24	0.21	−0.60	0.22	9
C	0.01	0.17	−0.02	0.20			0.02
D	−0.37	0.24	−0.25	0.25	4.32	0.54	66
E	0.42	0.19	0.60	0.17	−1.19	0.19	55
F	−1.19	0.24	−0.69	0.26	4.47	0.35	196
G	0.18	0.21	0.54	0.23	−0.55	0.20	14
H	−0.24	0.27	0.58	0.35	−0.12	0.41	4

Table 6. Final results excluding outlying results.

FPL	KRISS		NMIJ		NIS		RV2	
	G[mS]	u[mS]	G[mS]	u[mS]	G[mS]	u[mS]	G[mS]	u[mS]
A	5.75	0.15	5.61	0.22			5.70	0.12
B	5.64	0.14	5.73	0.19			5.67	0.11
C	5.71	0.13	5.67	0.18			5.69	0.11
D	6.53	0.20	6.65	0.21			6.59	0.14
E	6.45	0.17	6.63	0.15			6.55	0.11
F	6.69	0.20	7.20	0.22			6.90	0.15
G	6.68	0.18	7.05	0.20			6.84	0.13
H	7.05	0.22	7.87	0.31	7.16	0.38	7.29	0.16

Table 7. Basic analysis of the results excluding outlying results.

FPL	KRISS			NMIJ			NIS			x^2_{obs}
	d[mS]	u[mS]	$\|d\|/ku$	d[mS]	u[mS]	$\|d\|/ku$	d[mS]	u[mS]	$\|d\|/ku$	
A	0.04	0.19	0.11	−0.09	0.26	0.18				0.18
B	−0.03	0.18	0.09	0.06	0.22	0.13				0.10
C	0.01	0.17	0.04	−0.02	0.20	0.06				0.02
D	−0.05	0.24	0.11	0.06	0.25	0.12				0.11
E	−0.10	0.20	0.26	0.08	0.18	0.21				0.43
F	−0.24	0.25	0.48	0.30	0.27	0.56				2.17
G	−0.16	0.22	0.35	0.21	0.24	0.43				1.23
H	−0.24	0.27	0.44	0.58	0.35	0.83	−0.12	0.41	0.15	3.59

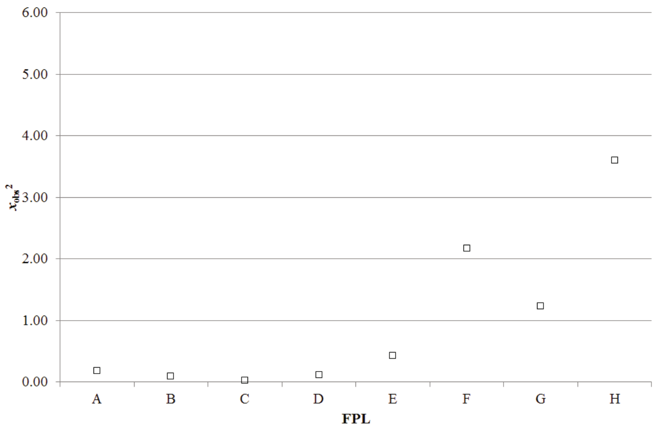

Fig. 4. (Color online) Consistency check for the different frequency power levels without outlying results.

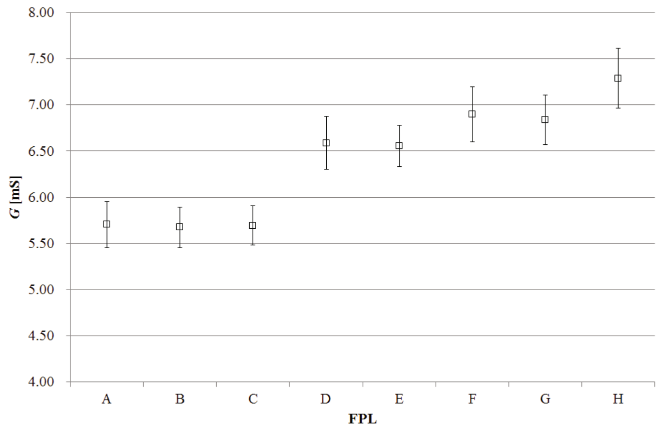

Fig. 5. Weighted means for all frequency power levels without considering outlying results.

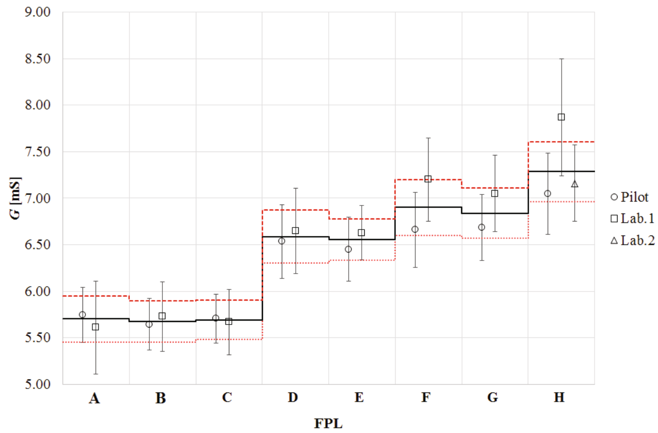

Fig. 6. (Color online) Results and weighted means (full lines) for all frequency power levels without outlying results. Error bars and the dashed lines denote expanded standard uncertainties ($k = 2$) of the results and the weighted means, respectively.

values are marked in red and printed in bold faced type. All results are plotted in Fig. 3.

For further analysis, methods that reduce the influence of particular data points on the calculation of the reference values are required. Attempts to use the median failed because at several power settings, the reference values remained strongly corrupted. A useful alternative was a method that allowed the largest subset consistent with the χ^2-test and the outlying criterion to be found. Such an alternative was developed by Cox [2] and is briefly described below [1].

We assumed that N participants yield results with a χ^2-value above the limit and with discrepant data points. In the first step, the χ^2-value is calculated, and the outlying criterion is tested for a permutation of $N-1$ participants in which one participant is successively excluded. The values for χ^2 and d_l are noted and analyzed. The final results obtained accordingly are given in Table 6, Table 7, Fig. 4, Fig. 5 and Fig. 6.

Table 6 shows the reference values obtained by excluding the outlying results of this international comparison. Table 7 shows the difference between the international comparison standard value and the value for each participant. This table also contains the results of each participant's consistency check given by Eq. 6. The normalized deviation $|d|/ku$ in Eq. 6 is called the measure of consistency. As seen in Table 7, the maximum value of normalized deviations of KRISS, NMIJ and NIS are

0.53, 0.77 and 0.20, respectively. All the values are less than 1, satisfying Eq. 6.

Figure 4 additionally shows that the consistency check by χ^2 test is fulfilled; $\chi^2 < 5.99$ for all FPLs when the outliers listed are omitted from the analysis. Figure 5 shows the final reference values for the radiation conductance of a circulated ultrasonic transducer in this international comparison. Referring to the specified frequencies of the FPLs in Table 2 and Fig. 5, the radiation conductance of the transducer can be observed to increase with increasing frequency. Figure 6 shows a graphical comparison of the results and uncertainties of the participants with the derived reference values and the corresponding uncertainty range. The Pilot in the legend of Fig. 6 is KRISS. The Lab. 1 and Lab. 2 in the legend of Fig. 6 are NMIJ and NIS, respectively. As shown in Fig. 6, the pilot lab (KRISS) matches all the measured values in the reference value range. Lab 1 (NMIJ) matches the reference value within the declared uncertainty range of their measurements. Lab 2 (NIS) matches only one measured value within the reference value range.

VI. CONCLUSION

The artifact transducer manufactured for this comparison has frequencies and radiation conductance values similar to those used in CCAUV.U-K3.1 key comparison. Also, it was shown to have been stable during the comparison circulation. RVs of radiation conductance of the transducer were derived successfully, $\chi^2 < 5.99$, by using the measurement results selected by using the outlier test from among the measurement results of the three participating laboratories. The RV2 values in Table 7 were finally derived as the reference values for the circulated transducer. For a total of eight FPLs, seven reference values were available for only two laboratories and the remaining one was available for all three labs. Thus, two laboratories can be concluded to have equivalency over the full FPL range, but one laboratory has only limited equivalency.

After the comparison, the transducer was donated to NIS Egypt for use as a standard transducer to establish a national standard for ultrasound power measurements. The final reference values of the transducer, as derived from this international comparison, can be used as standard values to renew measurement systems and procedures for quality control.

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