Round robin study of a reference sample for PU in-situ sound absorption characterization

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Abstract

The determination of acoustic material properties plays a fundamental role in simulating and designing effective noise reduction treatments. Several standardized measurement techniques are available for characterizing sound absorption, such as the Kundt's tube and reverberant room methods. Yet, most traditional methods cannot be used in-situ and require undesirable experimental constraints. The PU in-situ method can be used in a broad frequency range while hardly being affected by background noise and reflections. Furthermore, the PU in-situ approach is suitable for testing complex materials in their target environments, without deforming or changing their mounting conditions. However, the absence of a controlled environment may introduce a significant bias in the experimental sound absorption estimation. A reference sample is hereby studied to have a better understanding of how different experimental factors affect the sound absorption estimation quality. A round robin study was conducted using a reference porous material in different measurement environments, with various measuring systems and several samples. With statistical analysis on the measurement data, a confidence interval of the sound absorption was extracted. This investigation provides a qualitative evaluation of the entire measuring system and environment to ensure the reliability of the PU in-situ sound absorption setup.

Keywords: material acoustic properties, sound absorption, in-situ measurement, PU probe, reference sample.

1 Introduction

PU in-situ absorption technique has been introduced as an alternative way next to the standardized microphone-based methods to characterize sound absorption since the invention of the particle velocity sensor. The PU-based method was first applied to measure the impedance and absorption in 2003 [1]. It has the advantages of strong restriction of background noise and reflections, broad frequency range, and no necessity to deform the material under test or change its mounting conditions [2]. The PU-based method has been widely used in automotive industries [3, 4, 5, 6], road construction [7, 8, 9], building industries [10, 11] and end of line quality control [12].

Measurement errors are unavoidable, especially in in-situ situations. Although the PU in-situ method enables measuring materials with the presence of background noise, it is still worth investigating the uncertainty and how to characterize it. The measurement uncertainty of the absorption coefficient was simulated and analyzed using the Monte Carlo method [13]. Uncertainties caused by the setup geometry and transfer function between the pressure and particle velocity were studied and demonstrated. The uncertainty of sound absorption measurements by the PU ensemble averaging technique was examined in 1/3 octave bands [14]. In in-situ environments, a car interior, for example, the deviations of surface impedance and absorption were also reported [4]. Quite recently, the accuracy of the PU in-situ method in terms of repeatability and reproducibility was evaluated with varying calculation models, measurement environments and different distances between the probe and material [15]. However, the materials used and measurement environments from the previous work are different, making it not straightforward to compare or estimate the quality of the measured sound absorption, although uncertainties were provided in some of the work.

Reference materials are used for calibration, quality control and method validation purposes, and thus can help overcome the aforementioned limitation. The idea of reference materials was thoroughly described in ISO GUIDE 35, which includes the development of valid methods to assign values to the properties of a reference material, as well as the assessment of the associated uncertainty that comes with the material [16]. The reference material aids the comparability, accuracy and compatibility of measurement results on a national or international scale. A reference sample was created for the qualification of the reverberation rooms and correction of the measured absorption coefficients for the standardized reverberant room method, with a round robin test being performed in five European labs [17]. To the authors' best knowledge, there is no reference sample study for the PU in-situ method.

This work proposes a reference sample for the PU in-situ method, to have a quantitative understanding of how different experimental factors affect the quality of absorption estimation. A round robin test is carried out with various factors being considered. Here the round robin is a more generalized concept, which means not only inter-environment measurements are investigated, but also comparisons between measurement steups and reference samples are included. Analysis of variances (ANOVA) is used to analyze the measurement data, calculate the uncertainties and extract the confidence interval.

2 PU-based absorption model

The absorption coefficient of a material surface is defined as, if no sound transmission is considered

$$\alpha = 1 - |R|^2, \tag{1}$$

where R is the reflection factor. If a spherical incident wave and a plane reflected wave are assumed for impedance measurements above a surface, R is the plane wave reflection factor. With the aforementioned assumption, the mirror source model can be applied with the following relation between R and the normalized specific impedance Z_r at the receiver [18]

$$R = \frac{Z_r(1 + \frac{1}{jk(h_s-h)}) - 1}{Z_r(1 + \frac{1}{jk(h_s+h)}) + 1}(\frac{h_s + h}{h_s - h})e^{2jkh}, \tag{2}$$

where c is the speed of sound, h_s is the source height, h is the receiver height, k is the wavenumber and j is the imaginary unit. $Z_r = \frac{Z_m}{Z_0}$, with Z_m and $Z_0 = \rho c$ being the measured specific impedance and characteristic impedance of the air. With the PU probe, the sound pressure P and particle velocity U can be directly measured at the receiver and the ratio yields $Z_m = \frac{P}{U}$. Z_0 can be easily derived from a free field calibration measurement with the measured pressure P_0 and particle velocity U_0 [2]. Assuming a spherical wave propagation [19],

$$Z_0 = \rho c = Z_{ff}(1 + \frac{1}{jk(hs - h)}) = \frac{P_0}{U_0}(1 + \frac{1}{jk(hs - h)}). \tag{3}$$

Therefore, the normalized specific impedance is

$$Zr = \frac{Z_m}{Z_{ff}}(1 + \frac{1}{jk(h_s - h}) = \frac{P/U}{P_0/U_0}\frac{1}{1 + \frac{1}{jk(h_s-h)}}. \tag{4}$$

The advantage of the calibration measurement is that it makes the calibration of the sensors irrelevant, because the same corrections are applied to the pressure and particle velocity signals, leading to their ratio equal to 1 in $\frac{Z_m}{Z_{ff}}$ [20].

Combining Equation. 1, 2 and 4, the absorption coefficient can be derived with the signals acquired from the free field calibration measurement and test measurement above the material.

3 Uncertainty model

A reference sample can be measured in various environments with different PU in-situ setups, which leads to variations due to random factors. Variations also exist between different units of reference samples. Two scenarios with two random factors are considered here: various units of samples measured in various environments with one setup, various units of samples measured by various setups in one environment. In each scenario, measurements are repeated for each combination of the levels of random factors. Figure. 1 shows the ANOVA lay-outs of the two scenarios.

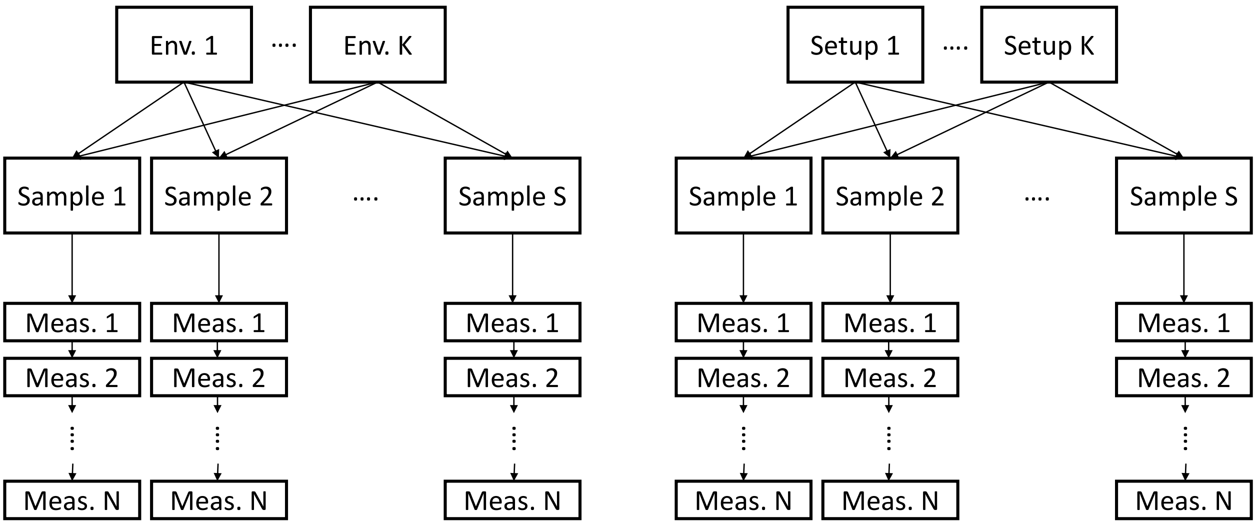


Figure 1: Lay-out of a two-way crossed ANOVA measurement campaign study: (left) environment-sample model; (right) setup-sample model.

The model for a two-way crossed ANOVA is

$$\begin{aligned} &\alpha_{ksn} = \mu + A_k + B_s + \omega_{ks} + \epsilon_{ksn}, \\ &k = 1, ..., K, s = 1, ..., S, n = 1, ..., N, \end{aligned} \tag{5}$$

where α_{ksn} is the absorption coefficient of the nth repetition of the kth measurement environment/setup, sth reference sample, μ is the expectation of α_{ksn} which is calculated as the grand mean, A_k is a bias term due to the random differences in the kth measurement environment/setup, B_s is a bias term due to the random differences in the sth reference sample, ω_{ks} is the (k, s)th interaction effect between the environment/setup and sample, and ϵ_{ksn} is the independent error. Here and below in this paper, α_{ksn} refers to the absorption coefficient in a particular 1/3 octave band. The data is assumed to be normally distributed, with zero mean and constant variance.

From Section. 2 it can be seen that the absorption coefficient α is determined by six input quantities, which can be denoted by $\alpha = f(P, U, P_0, U_0, h, h_s)$, where f is the functional relationship between α and the input quantities. Some of the input quantities, e.g. P and U or P_0 and U_0, are correlated. Additionally, f is a nonlinear function. These two factors make the expression of the combined uncertainty quite complex following the GUM suggestion [21]. This paper focuses on a preliminary investigation on proposing a reference sample to evaluate the measuring system and environment to ensure the reliability of the PU in-situ method, thus a simplified uncertainty model derived directly from the output quantity α is used.

Following the two-way crossed ANOVA model, the mean square [22]

$$MS_{within} = \frac{\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{n=1}^{N}(\alpha_{ksn} - \overline{\alpha}_{ks})^2}{KS(N-1)}, \tag{6}$$

$$MS_A = \frac{SN\sum_{k=1}^{K}(\overline{\alpha}_k - \overline{\alpha})^2}{K-1}, \tag{7}$$

$$MS_B = \frac{KN\sum_{s=1}^{S}(\overline{\alpha}_s - \overline{\alpha})^2}{S-1}, \tag{8}$$

$$MS_{A\times B} = \frac{N\sum_{k=1}^{K}\sum_{s=1}^{S}(\overline{\alpha}_{ks} - \overline{\alpha}_k - \overline{\alpha}_s + \overline{\alpha})^2}{(K-1)(S-1)}, \tag{9}$$

where the grand mean $\overline{\alpha} = \frac{1}{KSN}\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{n=1}^{N}\alpha_{ksn}$, $\overline{\alpha}_{ks}$ is the group mean for the kth measurement environment/setup and sth sample, $\overline{\alpha}_s$ is the group mean for the sth sample, and $\overline{\alpha}_k$ is the group mean for the kth measurement environment/setup.

The mean squares can be converted into variances as follows

$$\sigma^2_{within} = MS_{within}, \tag{10}$$

$$\sigma^2_A = \frac{MS_A - MS_{A\times B}}{SN}, \tag{11}$$

$$\sigma^2_B = \frac{MS_B - MS_{A\times B}}{KN}, \tag{12}$$

$$\sigma^2_{A\times B} = \frac{MS_{A\times B} - MS_{within}}{N}. \tag{13}$$

Note that the last three variances can be negative. If this is the case, the variance is set to zero [22].

The overall variance of the grand mean is written as [21, 23]

$$Var(\overline{\alpha}_{ksn}) = \frac{\sigma^2_{within}}{KSN} + \frac{\sigma^2_A}{K} + \frac{\sigma^2_B}{S} + \frac{\sigma^2_{A\times B}}{KS}. \tag{14}$$

The combined uncertainty is the standard deviation of the grand mean [21], which can be denoted as

$$u_c = \sqrt{Var(\overline{\alpha}_{ksn})}. \tag{15}$$

The expanded uncertainty is then calculated

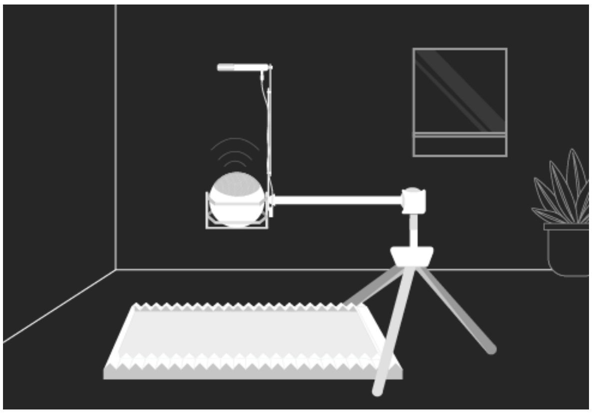
$$U = k_c u_c, \tag{16}$$

where k_c is the coverage factor.

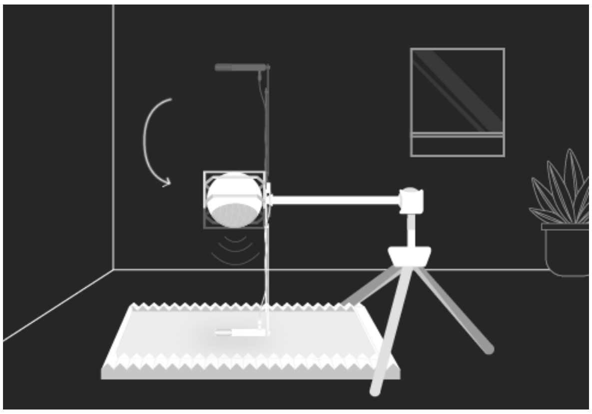
Combining the uncertainties of the two ANOVA models delivers

$$U_{combi} = k_c\sqrt{Var(\overline{\alpha}_{ksn}) + \frac{\sigma^2_{A'}}{K} + \frac{\sigma^2_{A'\times B}}{KS}}. \tag{17}$$

Since the data is assumed to be normally distributed, for a 95% confidence interval, $k_c = 1.96$.



Free field calibration



Test above the sample

Figure 2: Measurement procedures on the reference sample.

4 Measurements on the reference samples

The reference sample contains three parts: a piece of rectangular Melamine foam, a piece of Polyurethane foam circling the Melamine foam to avoid damaging the Melamine foam, and a plastic plate as the backplate. The sound absorption measured from the Melamine foam is taken as the reference.

Four units of reference samples, two setups and two measurement environments are included in the measurement campaign. One environment is a regular office room, which represents a commonly used place to perform in-situ measurements with the PU setup, and another is in a large basement with significant reverberation, which can be regarded as a "worst-case scenario". Therefore, $K = 2$ is the number of measurement environments or setups, $S = 4$ is the number of reference samples, and $N = 15$ is the number of repeated measurements in Section. 3. The PU probe is placed above the center point on the reference sample, with the distance between the probe and sample surface $h = 0.005$ m. The distance between the probe and the speaker $h_s = 0.26$ m. Each measurement is repeated 15 times, i.e. $N = 15$ in the uncertainty model.

Figure. 2 shows the two measurement procedures to calculate the absorption using the PU in-situ setup. The first measurement is the free field calibration to obtain the characteristic impedance of the air.

5 Uncertainty and confidence interval

The individual uncertainties of each term on the right-hand side in Equation 14 and 95% confidence intervals are shown for each ANOVA model. Here the individual uncertainty is equal to the standard deviation of the mean [21]. In Figure. 3 and Figure. 4, the individual uncertainties and 95% confidence intervals of the environment-sample ANOVA model are shown in 1/3 octave bands in 315 - 10000 Hz.

It can be observed that there is a large variation between the two measurement environments at low frequencies below 600 Hz and at 1 kHz. This is due to the strong reflections in the basement that cause large biases in the frequency range where the absorption is low. No significant uncertainty exists in the interaction between the environment and sample, or in the repeated measurements within the group. Variations between samples are low, except for the 1/3 octave band of 1.25 kHz. Figure. 5 shows the measured absorption of the four reference samples in the office room with Setup 1. The variation of repeated observations for each sample is small and consistent. However, large deviations among samples are found in 600 - 1600 Hz, particularly in the band of 1.25 kHz. Unlike similar oscillation effect in [13] that is caused by different sample sizes, the four samples are of the same size and thickness. It can be assumed that there are structural differences inside the materials among various sample units. This cannot be avoided even the samples are from the same batch, and thus has to be included in the uncertainty budget and confidence interval.

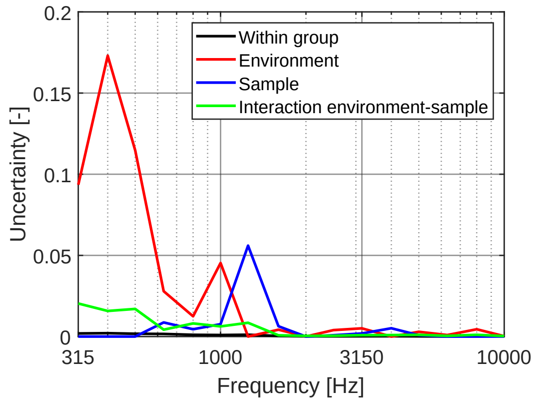


Figure 3: Individual uncertainties of the environment-sample ANOVA model.

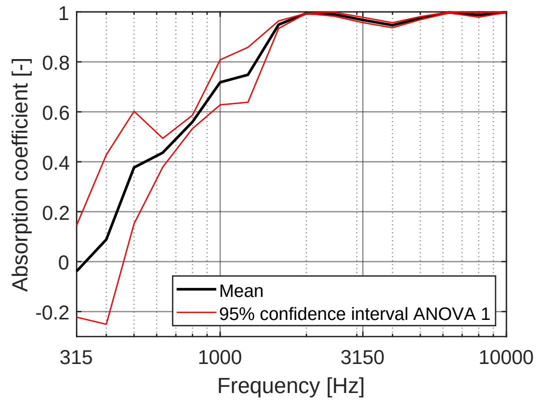


Figure 4: 95% confidence interval of the environment-sample ANOVA model.

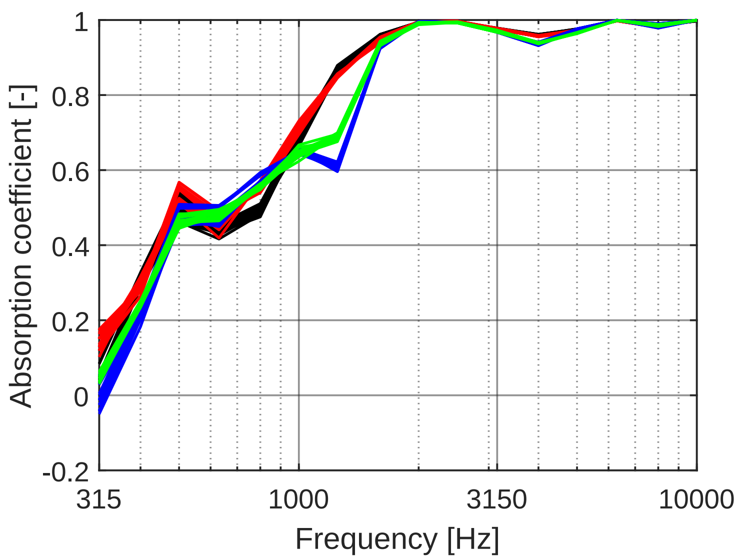


Figure 5: The absorption coefficients (in 1/3 octave bands) of the four reference samples measured 15 times in the office room with Setup 1. Each color represents one sample.

For the setup-sample model, similar large uncertainty at 1.25 kHz is also present among samples. Again, no significant deviation is observed in the interaction between the environment and sample, or in the repeated measurements. Moreover, it is quite consistent between setups as the individual uncertainty of the setup is low in Figure. 6. The confidence interval is much narrower for this model than the environment-sample model (Figure. 7).

Following Equation. 17, the overall expanded uncertainty combining the two ANOVA models is calculated and displayed in Figure. 8. Note that the confidence interval of ANOVA 2-1 means that A' in Equation. 8 refers to the bias term of the setup-sample model, added to the expanded uncertainty of the environment-sample model, and the other way round applies to ANOVA 1-2. Since the bias term caused by the environment difference is quite significant, it can be seen that the 95% confidence intervals from only ANOVA 1, or from combining the two ANOVA models are almost the same. Different measurement environments and inherent structures of samples are the two main factors that can cause large uncertainties at some frequencies.

The reference sample and together with the confidence interval can be provided as quality control to check if the measurement environment and system are appropriate to perform a reliable evaluation of sound absorption. For example, with a given setup and reference sample, if the measured absorption at low frequencies is out

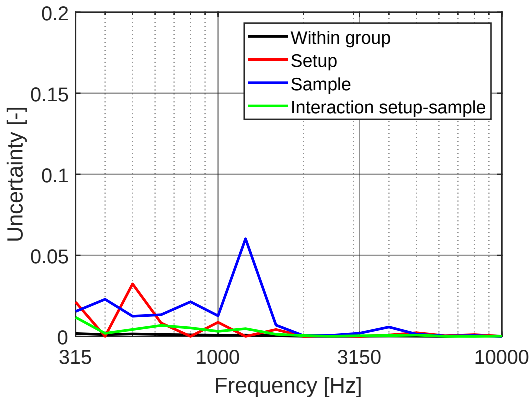


Figure 6: Individual uncertainties of the setup-sample ANOVA model.

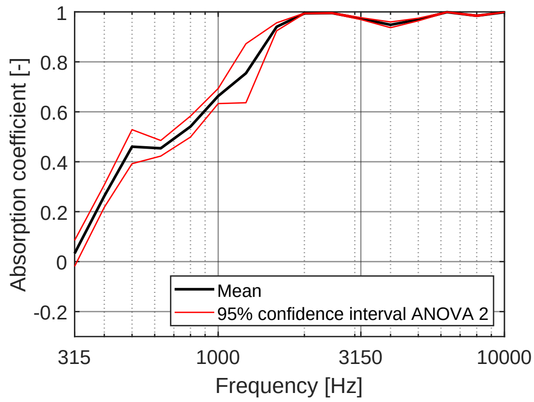


Figure 7: 95% confidence interval of the setup-sample ANOVA model.

of the range of the confidence interval, it would be suggested to relocate the measurement to a less reflective environment. What could also be checked is the equipment connection and the way to set the setup, which can lead to undesired failure that biases the result to a large extent. The confidence interval of ANOVA 1 (environment-sample model) can be provided with the reference sample for quality control.

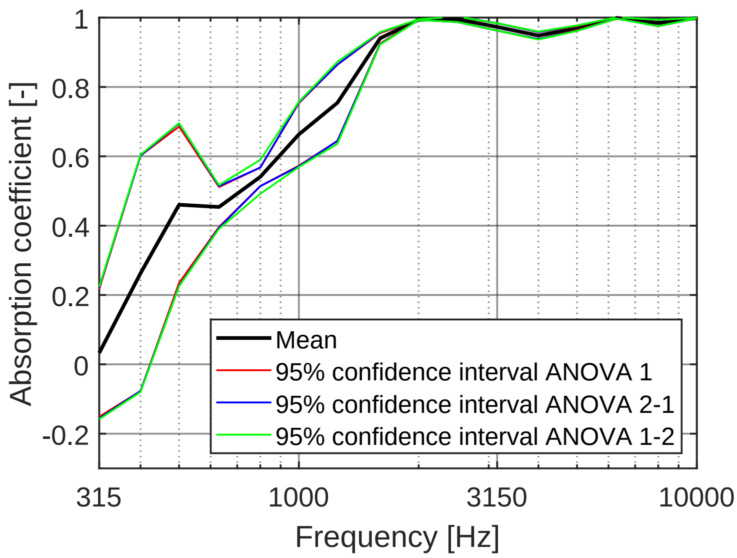


Figure 8: 95% confidence intervals combining the expanded uncertainties from the two ANOVA models. 95% confidence interval ANOVA 2-1: A' refers to the bias term of the setup-sample model in Equation. 8; 95% confidence interval ANOVA 1-2: A' refers to the bias term of the environment-sample model in Equation. 8.

6 Conclusions

This paper proposed the idea of a reference sample with its associated confidence interval, as an indication to check the quality of the estimated sound absorption using the PU in-situ method. ANOVA models were built to evaluate the uncertainties of the multi-factor measurements. The uncertainties and confidence intervals were extracted from the given measurement data using the ANOVA models. It was discovered that the measurement environment plays the main role in deviating the absorption coefficients at low frequencies, and the differences between different units of reference samples can bias the estimation as well. On the contract, different measurement setups showed good consistency.

The approach in this paper is not intended to be comprehensive due to the limited data. It is more a preliminary study to propose a reference sample and corresponding statistical data for the PU in-situ method as a basic quality indication. There are several limitations in the current work that can be improved. It would be worthy to build the uncertainty model from the input quantities covering the correlation and non-linearity. More environments, setups and samples would gain the reliability of the final confidence interval. With sufficient data, more complex multi-layer ANOVA models can be built to explore potential interactions between factors. Additionally, stability as in [16] is another important factor to study to obtain a more robust confidence interval.

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