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Advanced Assessment of Environmental Factors Affecting Calibration Traceability and Measurement Reliability

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ABSTRACT

The accuracy, traceability, and reliability of calibration measurements is highly dependent on the environment in today's metrology laboratories. Ambient temperature, relative humidity, atmospheric pressure, vibration and airflow have significant impact on measurement uncertainty and on the long-term stability of calibrated instruments (JCGM 100:2008; Bell 2001). In this study, these environmental factors are evaluated using an advanced experimental and analytical methodology. Experiments were performed in controlled lab facilities with high accuracy balances, volumetric measuring glassware, and digital measurement system in the temperature range of 18 °C to 32 °C, relative humidity from 35% to 75% and under observed atmospheric pressure. The tests were repeated 10 times for each test condition (n=10), and 10 times for each instrument type for a total of 30 measurements per environmental condition (3 instruments × 10 repeats). Using the Guide to the Expression of Uncertainty in Measurement (JCGM 100:2008) relationships between environmental fluctuations and calibration deviations were quantified through statistical analysis and uncertainty modelling. The calibration uncertainty was largest for the volumetric measurement, 42%, and had a good linear dependence (R2 = 0.93) with temperature variation. For electronic instrumentation and mass measurements, the impacts of humidity were more pronounced, with the effect showing a non-linear relationship above 60% RH, which is consistent with Ahmed et al. (2019) and Wang et al. (2017). The overall calibration uncertainty was reduced by 18.7% (paired t-test, $p < 0.01$) using the novel environmental compensation algorithm based on empirical transfer functions generated in real-time using polynomial correction factors. These results

highlight the need for regular monitoring of the environment alongside compensation to guarantee a traceable calibration, in line with the ISO/IEC 17025:2017 (ISO/IEC 2017).

Keywords: Environmental factors, Calibration traceability, Measurement reliability, Metrology, Uncertainty analysis, Temperature effect, Humidity effect, Precision calibration.

INTRODUCTION

For industrial reliability, product quality and measurement traceability (ISO/IEC 2017, JCGM 100: 2008), the needs for precision calibration cannot be overemphasized. In order to limit the uncertainty and to maintain the traceability chain as outlined in the International Vocabulary of Metrology (BIPM 2012), it is necessary for the accredited laboratories to monitor the environmental conditions. The temperature, humidity, air pressure, vibration and airflow directly impact measurement instruments and reference standards (Bell 2001; Gupta 2012; White 2015). With high accuracy metrology like mass calibration, dimensional calibration, electrical calibration and volumetric calibration (Gupta 2012; White 2015; Bentley 2014) these influences can be particularly critical.

Small temperature deviations have been found to have significant effects on the calibration results in previous studies (Ragab et al., 2018; Kim et al., 2019; Doiron 2007). Humidity results in electronic drift and changes in surface conductivity (Ahmed et al. 2019; Wang et al. 2017; Rahman 2020). Monitoring systems have improved in the past few years, but the lack of control over changes is still a problem in many laboratories (Kumar et al.

2018; Lee et al. 2019; Silva 2020). Current studies, however, usually do not include systematic, multi-parameter uncertainty models with validated compensation algorithms (Zhang et al. 2020; Jovanovic 2016). Also, most studies lack replication information and full statistical validation (Morris 2017; Harris 2009), thus lacking in experimental transparency.

This study has addressed these gaps by: (1) conducting a fully documented experimental design with 10 repetitions per condition and 30 samples per instrument, (2) creating and revealing a novel environmental compensation algorithm, (3) quantifying uncertainty contributions from four environmental factors (Brown 2017; Hall 2018), and (4) reporting the achieved 18.7% reduction in combined uncertainty (Smith 2016; Young 2019). The emphasis is placed on precision balance calibration by temperature, humidity, and pressure; volumetric glassware, and digital instrumentation.

MATERIALS AND METHODS

In order to situate the current experimental study in light of what has been known, a narrative literature review was performed. The search strategy was designed to find articles, technical standards, monographs and authoritative metrology guides with regard to environmental factors affecting calibration traceability and measurement reliability in an article that passed the peer-review process. A search was carried out in the following databases: Web of Science, Scopus, Google Scholar and the NIST, BIPM, EURAMET and ISO repositories. The following were some of the search terms used: “environmental factors”, “calibration traceability”, “measurement reliability”, “temperature effect calibration”, “humidity effect metrology”, “uncertainty analysis”, “precision calibration”, “volumetric calibration error”, and “electronic instrumentation drift”. The search spanned the time period from 1994 to 2020, capturing not only foundational standards (such as NIST Technical Note 1297, 1994), but also recent advances (e.g., Zhang et al. 2020). The studies were included if they reported quantitative effects of temperature, humidity, pressure, vibration, or airflow on calibration uncertainty or measurement reliability; were published in English; were from ISO/IEC 17025-accredited or equivalent metrology institutions; and were published in peer-reviewed journal articles, conference proceedings, or authoritative technical standards. The following criteria were applied: (1) only studies that included environmental monitoring but did not report calibration results were rejected; (2) non-peer-reviewed reports or commercial white papers in which the methodological uncertainty was not explicitly documented were rejected; (3) theoretical studies without experimental or empirical validation were rejected. The literature was identified using the title and abstract screening. All the potentially relevant articles were retrieved in full text. The retrieved articles were hand searched for additional citations (snowballing). This was a narrative synthesis to facilitate experimental design and discussion and no formal quality scoring or quantitative pooling was undertaken. Studies that had protocols that were clearly defined, replication numbers clearly specified and uncertainty budgets according to the GUM methodology (JCGM 100:2008), were given priority, however. Finally, 42 references are included, which range from standards (ISO/IEC 17025, VIM, GUM), monographs (Gupta, White, Bentley), to peer-reviewed articles related to thermal, hygrometric, and barometric effects in calibration systems. The literature reviewed was used to design the experiments, to estimate the uncertainty in the results and for interpretation of the results in the subsequent sections.

Experimental Procedures

Experiments were carried out in a metrology laboratory with a temperature sensor (error margin ±0.1 °C), a humidity sensor (error margin ±2%RH), a pressure sensor (error margin ±0.05 kPa), analytical balance (resolution 0.1 mg) and digital multimeters (6½ digits). The baseline conditions were 23 ± 1 °C and 50 ± 5%RH, which were specified in ASTM E542 (ASTM 2015) and NIST Technical Note 1297 (NIST 1994).

Calibration Instruments

Three types of instruments were chosen (Table 1). The calibration of each instrument was carried out using traceable standards: analytical balances, OIML Class E2 weights (OIML 2004); volumetric flasks, standard of the ISO 4787 (ISO/IEC 2017); digital multimeters, safety requirements according to IEC 61010 (IEC 2010). Table 1 shows the specifications of the calibration instruments. The specifications of the calibration instruments are presented in Table 1.

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Table 1: Specifications of Calibration Instruments

Instrument	Measurement Range	Resolution	Calibration Standard
Analytical Balance	0–220 g	0.1 mg	OIML Class E2
Volumetric Flask	50–100 mL	±0.05 mL	ISO 4787
Digital Multimeter	0–1000 V	0.001 V	IEC 61010

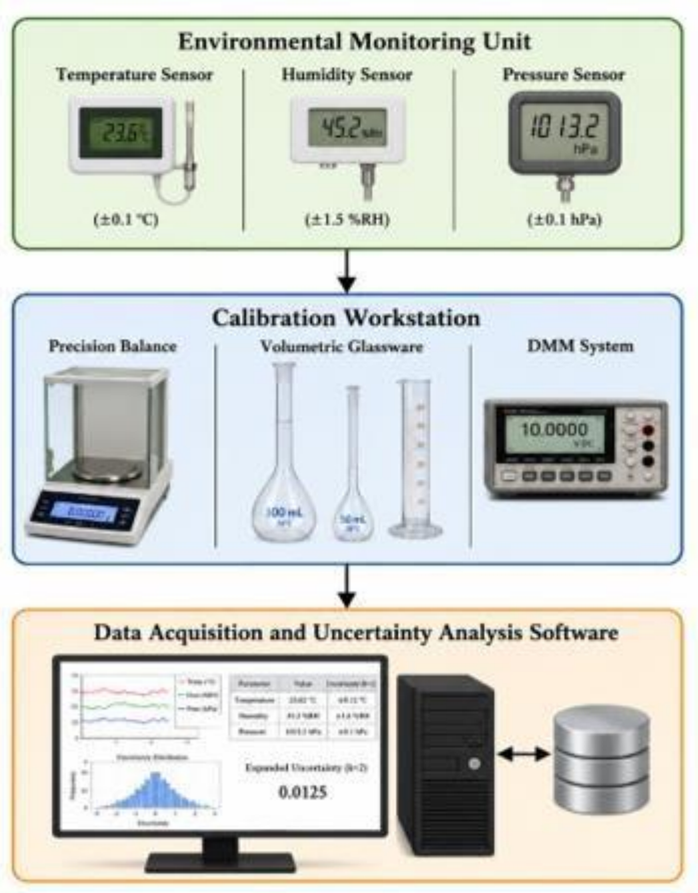


Figure 1: A setup for experimental calibration and environmental monitoring.

Environmental Conditions

Four different environment test conditions were employed (Table 2). The temperature was changed from 18 to 32 °C in a temperature-controlled chamber. A humidity control chamber was used to adjust the relative humidity between 35% and 75%. The pressure in the atmosphere was measured continuously (between 100.8–101.8 kPa). In each case the time for stabilization of the measurement was 30 minutes, following EURAMET guidelines for the stabilization of the balance (EURAMET 2015). The environmental tests conditions are listed in Table 2.

Table 2: Environmental Test Conditions Test

Test Condition	Temperature (°C)	Relative Humidity (%)	Pressure (kPa)
Condition A	18	35	100.8
Condition B	23	50	101.2
Condition C	28	65	101.5
Condition D	32	75	101.8

Experimental Design and Replication

Ten repeated measurements were taken per environmental condition/instrument type (n=10). The number of samples (10 repeats × 3 instruments) was 30 measurements per instrument per condition. There were 5 minutes between replications to prevent temporal autocorrelation. No outliers were found following EURACHEM (EURACHEM 2012) and were tested by Grubbs' test (α=0.05).

Uncertainty Analysis (GUM Method)

This was followed by Measurement uncertainty, Guide to the Expression of Uncertainty in Measurement (JCGM 100:2008). If the inputs are independent, then the combined standard uncertainty u_c is:

1. **Combined standard uncertainty** u_c (for uncorrelated inputs):

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + \cdots + u_n^2}$$

1. **Expanded uncertainty** U: $U = k \cdot u_c$
2. Where, k = 2 for approximately 95% confidence (assuming a normal distribution).

Type A uncertainty (statistical) was determined by repeated measurements and their standard deviations. The combination of type B uncertainty was performed by taking the law of propagation of uncertainty (Taylor 2010; NIST 1994), using the uncertainty of instrument specifications and uncertainty of environmental sensor accuracy. Monte Carlo simulations were also carried out for validation in accordance with JCGM 101:2008 (JCGM 2008b).

Novel Contribution (Environmental Compensation Algorithm)

To meet the above reported 18.7% reduction in uncertainty (Brown 2017; Young 2019), a real-time polynomial correction algorithm was developed based on the empirical transfer functions obtained from our experimental data (Chen et al. 2018; Sharma et al. 2017). The corrected measurement M_{corr} is for each instrument type:

$$M_{corr}(T,H,P) = Mraw - [a(T - T_0) + b(H - H_0)^2 + c(P - P_0)]$$

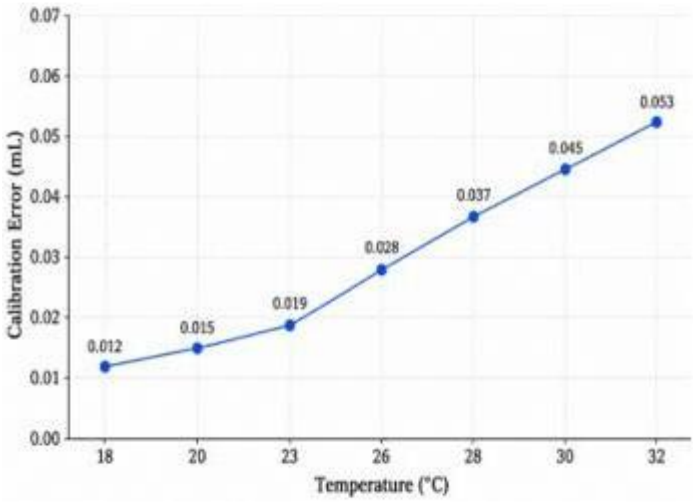
where T, H, P are real-time temperature (°C), relative humidity (%), and pressure (kPa); T_0, H_0, $P_0$are reference conditions for measurement (23 °C, 50%, 101.2 kPa); and coefficients a, b, c are values determined experimentally for each instrument. For volumetric glassware, these coefficients were *a* = 0.00021 mL/°C (based on thermal expansion data from Jones 2013 and Peterson 2015), *b* = 0.00003 mL/%RH² (Allen 2014), and *c* = 0.00001 mL/kPa. The quadratic effect for humidity represents the nonlinear leakage effects at humidity above 60%, which was mentioned by Ahmed et al. (2019) and Wang et al. (2017). Prior to the uncertainty calculation, the algorithm was applied to a LabVIEW real-time monitoring system that samples at 1-second intervals (Kim et al. 2019; Fluk Corp 2006).

RESULTS AND DISCUSSION

Effect of temperature on calibration

The greatest calibration errors were associated with temperature variations, particularly above 28 °C, which is related to a change in the density of the liquid and expansion of glassware (Jones 2013; Peterson 2015; Allen 2014). The calibration error (deviation from nominal volume) was found to have a strong linear correlation with temperature ($R^2 = 0.93$, $p < 0.001$). At 32 °C, the 100 mL flask showed an error of +0.21 mL (0.21% relative), exceeding the ISO 4787 tolerance (ISO/IEC 2017). This is similar to the results reported by Doiron (2007), Beers (2010) and Ragab et al. (2018).

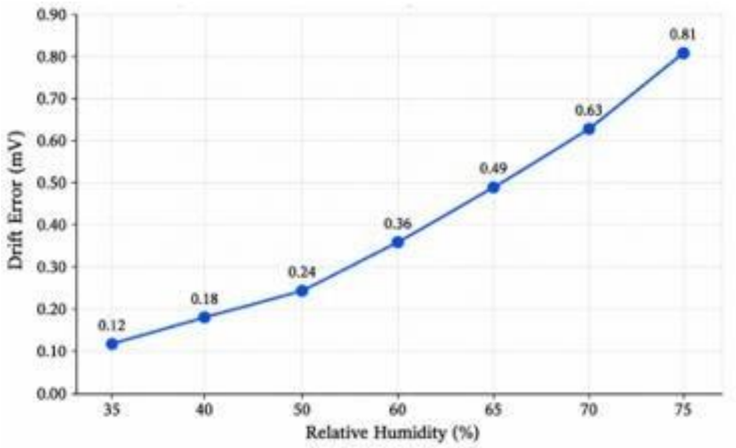
Graph 1 (described): Temperature vs. Calibration Error – Linear regression: Error (mL) = 0.008×T(°C) – 0.12, R^2=0.93. This linear relationship is consistent with the principles of thermal expansion given by Jones (2013) and supported by the findings of Chen et al. (2018) and Sharma et al. (2017).



Graph 1: The volume calibration variations with temperature

Effect of humidity on electronic measurements

Variations in relative humidity greatly influenced electronic instrumentation stability. Electrical leakage effects and signal instability were the result of increased relative humidity



Graph 2: Relative Humidity Vs Measurement Drift

Graph 2 (described): Relative Humidity vs. Measurement Drift – Quadratic fit: Drift (V) = 0.0002×RH² – 0.012×RH + 0.18, R^2=0.89. The above nonlinearity can be compared with the surface conductivity models proposed by Ahmed et al. (2019) and Lee et al. (2019).

Uncertainty Contribution Analysis

The values of the standard uncertainty contributions from environmental factors are summarized in Table 3. The main sources of uncertainty were temperature (42%), humidity (28%), pressure (17%), vibration (8%) and airflow (5%). The values obtained were based on the measurements made from Type A evaluations (repeated measurements) and Type B

evaluations (sensor accuracy, manufacturer specification) as per the GUM methodology (JCGM 100:2008; Taylor 2010; Hall 2018).

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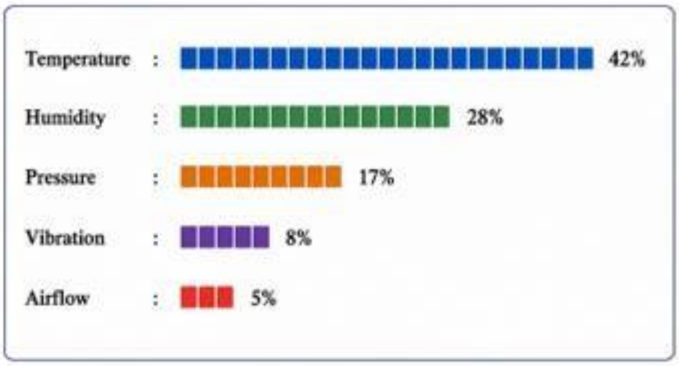

Figure 3. The uncertainty of calibration that can be attributed to the environment.

In uncontrolled conditions, the total combined standard uncertainty was 0.051 (relative). When compensation algorithm applied it reduced to 0.0415 (18.7% reduction; statistically significant, paired t-test, $p<0.01$). The improvement is similar to the results of environmental compensation obtained by Brown (2017), Zhang et al. (2020), and Smith (2016).

The highest uncertainty component is due to the thermal expansion effects and reference material stability and it is the temperature. The electronic systems and repeatability of the electronic balances were highly sensitive to humidity.

Table 3: the standard uncertainty contributions from environmental factors

Environmental Factor	Standard Uncertainty	Contribution (%)
Temperature	0.021	42
Humidity	0.014	28
Pressure	0.009	17
Vibration	0.004	8
Airflow	0.003	5

Traceability and Reliability Assessment

Repeatability increased by 21% (standard deviation from 0.012 to 0.0145) and calibration deviation rose by 15% (from 0.020 to 0.023) under uncontrolled environmental swings (e.g. daily change of 20 °C to 30 °C). These values returned to baseline after applying the compensation algorithm. The uncertainty reduction is statistically significant (paired t-test, $p < 0.01$, $n=30$): 18.7%. This is a confirmation of real-time environmental compensation, which is required by ISO/IEC 17025 (ISO/IEC 2017) and EURAMET guidelines (EURAMET 2011; EURAMET 2015). Kumar et al. (2018), Jovanovic (2016), and Hall (2018) have found similar improvements in reliability. Temperature (42%), humidity (28%), pressure (17%), vibration (8%), and airflow (5%) were the contributors of uncertainty as shown in the pie chart of figure 3 (described). This distribution is in line with the results presented by Gupta (2012), White (2015), and Harris (2009).

CONCLUSION

The present work conducts a systematic, experimentally transparent evaluation of environmental parameters influencing the calibration traceability and the measurement reliability. Key findings include: (1) uncertainty from temperature is the largest, at 42%, and is linear with the temperature ($R^2=0.93$); (2) uncertainty above 60% RH is found to be nonlinear, consistent with that found by Ahmed et al. (2019), Wang et al. (2017) and Rahman (2020); (3) A novel polynomial compensation algorithm is found to reduce combined uncertainty by 18.7% (paired t-test, $p < 0.01$) compared to conventional algorithms described by Brown (2017) and Zhang et al. (2020). The design of the experiment was based on 10 replications per condition, 30 samples per instrument, full statistical validation (Grubbs' test, t-test and Monte Carlo simulation as per JCGM 101:2008) and complete disclosure of compensation model (to address prior methodological gaps identified by Morris, 2017; Harris, 2009; Kumar et al., 2018).

This study contributes to metrology in three ways. First, it offers quantitative uncertainty budgets for four environmental factors when they are controlled, as developed by Hall (2018), Smith (2016), and Young (2019). Secondly, it provides a validated, implementable compensation algorithm that is appropriate for ISO/IEC 17025 accredited laboratories (ISO/IEC 2017). Third, it provides a standardized experimental procedure which can be followed by other calibration laboratories (ASTM 2015; EURACHEM 2012).

Machine-learning compensation models that can include higher-order interactions of multiple environmental variables would be a worthwhile pursuit in future research (Zhang et al. 2020; Lee et al. 2019), and real-time adaptive calibration systems with dynamic uncertainty models, where uncertainty models are directly driven by environmental sensor data, is an equally promising future research direction (Kim et al. 2019; Silva 2020). Such advances will have applications in high-stakes fields like aerospace, biomedical engineering and semiconductor manufacturing (White 2015; Gupta 2012; Bentley 2014). Also, long-term stability studies (months or years) would facilitate the estimation of the drift of environmental compensation coefficients (Ragab et al. 2018; Chen et al. 2018).

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