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Original

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ABSTRACT

In metrology, comparison measurements are essential for testing and verifying the calibration and measurement capabilities of calibration laboratories. We highlight the benefits of reporting participants' results using a standardized digital calibration certificate (DCC) and performing automatic comparison analysis with a digital metrology expert (DME). These advantages will be examined in the context of the ongoing international comparison in the field of non-contact body temperature measurement, CCT K11.

1. Introduction

During the Covid-19 pandemic it became obvious that there is a big demand of reliable non-contact body temperature measurements. As a result, a Consultative Committee for Thermometry (CCT) task group was founded with one of their main objectives being, to initiate a key comparison for non-contact body temperature measurements (TG Body Temperature Measurement). Thus, CCT K11 Blackbody temperature from 34.5 °C to 41.5 °C was initiated [1]. The comparison comprises an anti-STAR comparison between the Pilot NIM China and the EURAMET co-pilot PTB. In the APMP and EURAMET RMO the comparison is conducted as a round-robin type. This type of comparison was chosen to speed up the comparison with TÜBITAK UME, CEM, LNE/CNAM, PTB and INRIM being the EURAMET participants.

The transfer blackbody sources are provided by the co-pilot in EURAMET (PTB) and consists of two cavities immersed into a bath. The shape of the ear thermometer cavity is a cylinder with an inclined rear with a circular aperture 20 mm in diameter, made of copper. The cavity is in accordance with EN 12470-5 CEN 2003 [2]. The shape of the forehead thermometer cavity is a cylinder with a conical bottom and a circular aperture 50 mm in diameter, made of copper. The temperature of the blackbodies is controlled by a liquid bath that operates in the temperature range from 34 °C to 43 °C. The blackbodies and the bath were manufactured by Kambic. The temperature of the water in the bath is measured with two different thermometers. A Pt100 (PRT) and a 30 kOhm NTC thermistor both sealed in a metal tube between the two cavities. In the comparison, resistances of the Pt100 and NTC thermistor are used to monitor the stability and indicate the temperature of the blackbodies. The comparison is made at temperatures of 34.5 °C, 37 °C, and 41.5 °C.

The participants have to report the ambient conditions, i.e. room temperature and relative air humidity, the average resistance of the monitor PRT (platinum resistance thermometer), average indicated temperature of the bath, and the average radiance temperature measured by the participant. Fig. 1 shows an excerpt from the clinical infrared thermometer blackbody report form [1].

However, since the first work on the protocol of this comparison in 2020, the start of the measurements in 2023, and now the comparison running in 2024 the developments in terms of digitalization in metrology opened new possibilities. Digital calibration certificates (DCCs) have become a mature technology and EURAMET is fostering the deployment of DCCs in Europe with projects such as the TC-IM 1448 [3] aiming to harmonise DCCs. A TC-T task group "Digitalization" was founded that is fostering the harmonisation of DCCs for temperature calibrations and was carrying out a workshop on digitalization during the annual TC-T meeting in Wroclaw in 2024 that lead to a fruitful exchange among the participants on the needs that come with the use of DCCs in thermometry. The CCT TG Digitalization is considering perpetuating their efforts seeing DCCs as a topic not limited in time. Furthermore, DCCs have been used in a virtual key comparison on mass [4] and a digital metrology expert (DME) has been developed [5] that will facilitate the evaluation of key comparisons. The DKD, the German calibration service, is currently working in 13 technical committees on expert reports for the different measurands [6,7] of the accredited calibration laboratories in Germany, with an additional technical committee that is overseeing the agreement of the stated measurands in the different expert reports. Finally, DCC templates will be provided by the DKD that will be obligatory for all accredited labs in Germany.

1.1. Using DCCs in EURAMET loop of CCT K11

Given the recent developments of DCCs, the CCT K11 provides an ideal project to test the implementation in a real key comparison. The number of participants is small, the (analogue) reporting template is simple, and a digitalization of the report is straightforward. Furthermore, the participating NMIs are involved in the work in the TC-T TG Digitalization and can address their needs there.

Also, the objects that are compared during the key comparison are not only related to thermometry at the NMI level they are also related to legal metrology and clinical regulations. Thus, the DCCs and especially the refTypes called terminology [8] that are used in this comparison will be the prototype for DCCs for reference blackbodies that will be used to

Calibration results of transfer ear/forehead thermometer blackbody				
Date of measurement (Day 1)				
Room humidity (% rh)				
Set temperature (°C)	Average Resistance of monitor PRT (Ω)	Average Indicated temperature (°C)	Average Radiance temperature measured by participant(°C)	Room temperature (°C)
34.5				
37.0				
41.5				

Fig. 1. Excerpt from the clinical infrared thermometer report form of CCT K11 [1].

provide traceability for millions of clinical tympanic and forehead thermometers that are manufactured each year and will also ease up the metrological verification of clinical devices with measuring function that is mandatory in most of the countries world-wide.

1.2. Data analysis

The detailed description of the required data analysis is given in the protocol of K11 [1]. In short, a reference value will be calculated for each nominal indicated temperature (t_{nom}) using the weighted mean with cut-off of all the EURAMET participant results, including the average EURAMET-pilot results, at that t_{nom} . The weight for each participant, including the EURAMET-pilot, is the inverse of the square of the standard measurement uncertainty for that participant at that t_{nom} , with the average of the 3 smallest values of uncertainty adopted as the cut-off value for the weight.

The evaluation of the results will be based on the following two criteria which are in close accordance with the CCT Non-contact thermometry WG radiation thermometry CMC review protocol [8]:

$$|V_{NMI,SC} - V_{SCRV}| < \sqrt{U_{NMI,SC}^2 + U_{SC}^2 + U_{SCRV}^2} \quad (1)$$

$$U_{NMI,SC} > \sqrt{U_{SC}^2 + U_{SCRV}^2} \quad (2)$$

With, $V_{NMI,SC}$ being the reported temperature value by the participants.

V_{SCRV} being the comparison reference temperature value calculated as the weighted mean with cut-off of the reported values from the participating NMIs and the co-pilot.

$U_{NMI,SC}$ being the expanded uncertainty claimed by the participant NMI in the report.

U_{SC} being the expanded comparison measurement uncertainty and takes into account the instability of the transfer device.

U_{SCRV} is the expanded uncertainty of the EURAMET reference value.

2. DCC template for data exchange

The analogue report form for CCT K11 from Fig. 1 will be transferred into a digital and machine-readable format. We are using the XML based format for the Digital Calibration Certificate (DCC) as a basic data scheme [9] and adapt the representation of measurement data as much as possible to the good practice recommendation for temperature DCCs from the DKD [6].

At its core, DCCs are using the D-SI metadata model [10] to implement fundamental measurement data such as measured values, the associated unit of measurement and information on measurement uncertainty. For the temperature data points, we will use the D-SI XML list construct for real valued measurands.

Fig. 2 outlines the data of the radiance temperature. It comprises

three values corresponding to the set temperature of 34.5 °C, 37.0 °C and 41.5 °C. The D-SI Element is encapsulated by an additional quantity and result element in the DCC. These are adding human-readable descriptions and additional terminology to allow machines to understand the meaning of the results. In our case, this terminology is provided within the refType attributes. On the level of the result element, the refType 'temperature_radianceTemperature' indicates, the general kind of the result measurand. On the level of the quantity element, the refTypes 'basic_measurand', 'basic_arithmeticMean', and 'temperature ITS-90' add further metadata on the meaning of the data.

Table 1 gives a more detailed overview on the refTypes used for different parts of the reporting. It is clearly marked, where we have added own refTypes in addition to the existing DKD terms to complete the description of the comparison reporting data.

3. Development of a digital metrological expert software tool

The Digital Metrological Expert (DME) concept defines an autonomous operating software with the ability of performing data and result processing as requested for standard work by human metrology experts [11]. To fulfil its task, it considers utilizing digital standards that are extending the means of the human-based Quality Infrastructure to a machine-actionable environment. It can understand and interoperate metrological information based on data and software interfaces following the International System of Units (SI) and the FAIR (Findable, Accessible, Interoperable, Reusable) principles.

An initial proof of concept implementation of a DME software tool for the evaluation of interlaboratory comparison was established for the example of measurements of a mass standard [4,5]. The software interface, respectively the underlying application programming interface (API), can read the input data from participants from XML files in the DCC format, calculate the comparison reference value by the weighted mean method [12], access the degrees of equivalence (DoE), identify outliers through the DoEs, and create a machine-interpretable report including the evaluation results.

By adding modules for the evaluation of data for the temperature use-case, the software architecture of the DME for comparison is going

```

<dcc:result refType="temperature_radianceTemperature">
  <dcc:name>
    <dcc:content lang="en">
      Average radiance temperature measured by participant
    </dcc:content>
  </dcc:name>
  <dcc:data>
    <dcc:quantity refType="basic_measuredValue
      basic_arithmeticMean temperature ITS-90">
      <dcc:name>
        <dcc:content lang="en">Measured value</dcc:content>
      </dcc:name>
      <si:realXMLList>
        <si:valueXMLList>34.567 37.005 41.499</si:valueXMLList>
        <si:unitXMLList>\degrecelsius</si:unitXMLList>
        <si:expandedUncXMLList>
          <si:uncertaintyXMLList>1.E-3
            </si:uncertaintyXMLList>
          <si:coverageFactorXMLList>2
            </si:coverageFactorXMLList>
          <si:coverageProbabilityXMLList>0.95
            </si:coverageProbabilityXMLList>
          <si:distributionXMLList>normal
            </si:distributionXMLList>
          </si:expandedUncXMLList>
        </si:realXMLList>
      </dcc:quantity>
    </dcc:data>
  </dcc:result>

```

Fig. 2. Reporting of the participant radiance temperature measurement.

Table 1
Preliminary selected refType-attributes for blackbody temperature quantities. refTypes marked with * have been added for the comparison use-case and are not part of the DKD collection.

refType	prefix	meaning (& usage)
ITS-90	temperature_	used temperature Scale (ITS-90) (use in all temperature quantities)
temperatureMin	basic_	environmental condition: Room temperature (min)/°C
temperatureMax	basic_	environmental condition: Room temperature (max)/°C
humidityRelativeMin	basic_	environmental condition: Room humidity (min)/(% rh)
humidityRelativeMax	basic_	environmental condition: Room humidity (max)/(% rh)
nominalValue	basic_	Set temperature/°C
measuredValueSensor1*	temperature_	Average Resistance of monitor PRT/Ω
measuredValueSensor2*	temperature_	Average Resistance of monitor NTC Thermistor/Ω
referenceValue	basic_	Average Indicated temperature/°C
radianceTemperature*	temperature_	Average Radiance temperature measured by participant/°C (use at result element)

through an important structural update. On the one hand, mechanisms need to be put in place allowing a more flexible handling of data from different metrological areas and different measurands. On the other hand, it must be made easy to add additional methods for the evaluation of the data. Fig. 3 outlines the generic extensions to the DME that are considered suitable to handle the previous mentioned needs. Instead of a direct submission of the input data to the calculation of reference value and DoEs as in the mass case, interim steps are added to pre-assess the data and decide on the evaluation method.

The ‘Assessment and verification’ step comprises two modules for the temperature use case. The first is for the identification of the measured quantity (radiance temperature) subject to comparison and it checks that all inputs are complete. The second module is for the identification of all additional data (PRT resistance values, indication, room temperature) and checks that these values are within an acceptable range for the participant to be acceptable for the comparison.

The ‘Selection of evaluation methods(s)’ step uses the outcomes of the assessment and verification to decide on methods that are suitable for evaluation and which inputs from the participants are used. Depending on the evaluation method, the DME may return to the assessment step to check additional properties of the input data that could be relevant for the subsequent calculations. In the radiance temperature case, the methods of choice are (1) and (2) to assess the inputs of the participants in respect to the joint reference value. These are

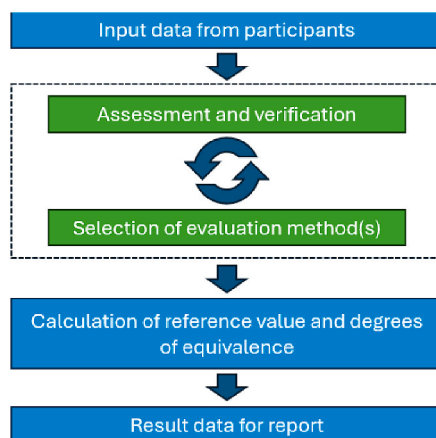


Fig. 3. Outline of the DME software extension for enabling the evaluation of radiation temperature comparison.

added to the DME software modules and integrated into the DME process for temperature comparison.

In addition to the new evaluation methods, the DME software is extended to allow automated report generation based on the input data properties and the process for evaluation that was used. This comprises

- the comparison reference results and its associated uncertainty with the correct provision of refTypes identifying the kind of reference value (median),
- the equivalence value (DoEs divided by its uncertainty) for each participant, and
- the input data for each participant (radiation temperature value, PRT resistance value, indication value and ambient temperature value).

The more different kind of measurement data and methods are considered with comparison, the more it is becoming relevant to enable software to solve issues of data interoperability on the fly. Here is where the implementation of FAIR principles and semantics in input data and the proper utilization of such data in software become of value. DCCs are already including relevant mechanisms which are enabled through the metadata fields denoted as refTypes. These allow to add machine-interpretable terminology (controlled vocabulary and semantics) to identify the meaning of data. As outlined in the previous section, there are generic terms such as ‘basic_measuredValue’ that identify the measurement result. This tag is independent of any metrological domain and should be used to filter the actual input for calculations from the participant data. Other refTypes such as ‘temperature_radianceTemperature’ allow to identify individual kinds of measurand and based on them to identify the purpose of the data and to select suitable evaluation methods.

For a future extension of the ability of software to interpret the meaning of data and to interoperate data without needs of human-interaction, an increasing digital maturity of the systems providing terminology such as refTypes also play a role. By digital maturity we consider the implementation of FAIR principles and semantics at the repositories and APIs providing the terminology. In the future, these need to be made machine-interpretable as well. The German Calibration Service DKD has setup a repository that is based on an implementation of thethesaurus type vocabularies by the Simple Knowledge Organization System (SKOS) from the Semantic Web tool stack [8,13]. SKOS-type terminology are highly interoperable with global standards for the machine-interpretable representation of data and knowledge. It allows to establish machine-actionable links across different technical approaches such as XML format for DCC, computational methods, and higher level tools such as ontologies. Each term is attributing a persistent identification number (PID) and a rich description by machine-readable metadata, that can be accessed by humans but also by software through APIs that are allowing to resolve the PIDs. The metadata uses SKOS to structure all terms according to underlying concepts such as groups of terms for different metrological domains and applications. In addition, it allows to define relations between terms that are needed to assess similarities and differences of underlying meanings as part of a correct machine-interpretation process.

Finally, SKOS allows also to define relations to terms outside of the DKD repository. The latter comes in handy, when considering interoperation of terminology coming from a wider range of providers in the quality infrastructure. Already today high benefits are expected in linking the DCC based terms to vocabularies developed with machine-readable standards [14], high-level guidelines from metrology such as terms used in the SI Digital Framework (comprising SI, VIM, and GUM) and further structured metadata in the scope of measurement services and accreditation. Through the SKOS based approach all these sources of information can be mapped by software by semantically sound means. In the longer-term, even additional product related terms can be linked in facilitating not only the interoperability of the higher levels of the quality infrastructure but also strengthening the streamlining of

outcomes of comparison to calibration information and finally to products of end-users.

4. Outlook

In addition to ensuring coherence with the ongoing strategies and efforts to digitalize metrology, the use of Digital Calibration Certificates (DCCs) for reporting data and a Digital Metrology Expert (DME) for data analysis offers practical benefits for metrologists.

When reporting the results of a key comparison, a substantial set of figures and tables typically needs to be compiled [15–17]. For example, separate tables for each participant are required, presenting their data, associated uncertainties, calculated differences from the mean value, and total uncertainty for each temperature point. Additionally, results are often displayed graphically in several diagrams, such as one diagram showing differences from the median and associated uncertainties for all data, and separate diagrams for individual participant data. Finally, the degrees of equivalence between each pair of participants can be determined and presented both as a table and as a diagram displaying the difference from the median. Using the DME, this tedious presentation work can be streamlined through automated evaluation and display routines, significantly facilitating the process.

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