Key comparison CCPR-K1.a as an interlaboratory comparison of correlated color temperature

P Kärhä1, A Vaskuri1, T Pulli1 and E Ikonen1,2
1 Metrology Research Institute, Aalto University, Espoo, Finland
2 MIKES Metrology, VTT Technical Research Centre of Finland Ltd, Espoo, Finland
E-mail: petri.karha@aalto.fi

Abstract. We analyze the results of spectral irradiance key comparison CCPR-K1.a for correlated color temperature (CCT). For four participants out of 13, the uncertainties of CCT, calculated using traditional methods, not accounting for correlations, would be too small. The reason for the failure of traditional uncertainty calculation is spectral correlations, producing systematic deviations of the same sign over certain wavelength regions. The results highlight the importance of accounting for such correlations when calculating uncertainties of spectrally integrated quantities.

1. Introduction
Spectral irradiance measurements of National Metrology Institutes (NMI) were compared in the CCPR Key Comparison K1.a [1], a measurement campaign that took place during years 2001-2003. Correlated Color Temperature CCT [2] is a quantity often derived from measured spectra, but there has not been a key comparison of CCT. We analyzed the data of CCPR-K1.a to calculate CCTs that the participants would obtain for a lamp that resembles the CIE Standard Illuminant A, and conventional uncertainties for the derived CCTs [3]. We also discuss the effects of correlated deviations of spectral irradiance values over the visible region to explain the results on CCT and its uncertainty.

2. Analysis of deviations
The report of CCPR-K1.a lists for each participant, at various wavelengths, the Degree of Equivalence (DoE) which is essentially the deviation of the spectral irradiance values from the world mean, and the uncertainty of the DoE consisting of participant’s uncertainty and the comparison uncertainty. The data were interpolated within the approximate visible region (350 nm – 850 nm) at 1 nm interval to allow calculation of the CCT as shown in figure 1. The interpolation was carried out with \( N \)th degree polynomials, where \( N \) was approximated visually for each data set. This procedure effectively separates random noise in measurements from structural deviations caused by spectral correlations. The structural deviations were further divided to offset and higher order structural deviations. Table 1 shows how the deviations of the participants separated into these three classes. Offset was calculated as the average of the spectral deviations, (random) noise as the standard deviation of the residual errors after subtracting the interpolated values, and the structural deviation was calculated as the standard deviation of the interpolation function. The key comparison reference values (KCRV) may also contain spectral structure as all NMIs did not correct their results with respect to correlations. However, there are various shapes of spectral structures present in figure 1 which could not all be explained by spectral structure in the KCRV.
Figure 1. Interpolated deviations from CCPR-K1.a reference value (unilateral DoE) for participating institutes. The abbreviations of laboratory names are defined in table 1.

Table 1. Distribution of spectral deviations to different structural classes, and the degree N used for the interpolation polynomial.

| Laboratory                                                                 | Country       | Abbreviation | Deviation / % | Structural N |
|----------------------------------------------------------------------------|---------------|--------------|---------------|--------------|
| Bureau National de Métrologie - Institut National de Métrologie            | France        | BNM-INM      | 0.24 0.29 0.45 | 3            |
| Commonwealth Scientific & Industrial Research Organisation                  | Australia     | CSIRO        | 0.08 0.28 0.30 | 2            |
| Helsinki University of Technology (Aalto University)                       | Finland       | HUT          | 0.04 0.17 0.26 | 6            |
| Instituto de Física Aplicada - Consejo Superior de Investigaciones Científicas | Spain         | IFA-CSIC     | 0.08 0.17 0.26 | 5            |
| Measurement Standards Laboratory of New Zealand - Industrial Research Limited (Callaghan Innovation) | New Zealand | MSL-IRL      | 0.18 0.22 0.10 | 1            |
| National Institute of Metrology                                            | China         | NIM          | 0.29 0.29 0.67 | 2            |
| National Institute of Standards and Technology                             | USA           | NIST         | 0.11 0.27 0.06 | 1            |
| National Metrology Institute of Japan                                      | Japan         | NMIJ         | 0.26 0.72 0.56 | 1            |
| National Physical Laboratory                                               | UK            | NPL          | 0.06 0.04 0.26 | 3            |
| National Research Council                                                  | Canada        | NRC          | 0.44 0.13 0.46 | 5            |
| Physikalisch-Technische Bundesanstalt                                     | Germany       | PTB          | 0.08 0.26 0.07 | 1            |
| All-Russian Scientific Research Institute for Optical and Physical Measurements | Russia      | VNIIOFI      | 0.07 0.48 0.14 | 3            |
| Centro Nacional de Metrologia                                              | Mexico        | CENAM        | 0.11 0.82 0.22 | 3            |
| Average deviation                                                          |               |              | 0.16 0.32 0.29 |              |
| Fraction of total deviation                                                |               |              | 21 % 41 % 38 % |              |
3. Correlated colour temperature
The interpolated deviations of spectral irradiance were used to calculate deviations that the participants would see in the CCT of a lamp resembling the CIE Standard Illuminant A. The spectrum of the CIE Standard Illuminant A was disturbed with the deviation function, and the calculated CCT was compared to 2856 K to obtain $\Delta$CCT. The results are shown in table 2. The uncertainties for DoE were wavelength dependent. To simplify calculations, an average uncertainty over the visible region was used.

As can be seen in table 2, for four of the laboratories $\Delta$CCT would exceed $U$(CCT). Statistically it would be expected that there are no or at most one participant exceeding $E_n = 1$. In spectral irradiance, there was an agreement within coverage factor $k = 2$ in the wavelength range 290 nm – 800 nm for all participants. It is worth noting that the average of the $\Delta$CCT values in table 2 is positive, which in an intercomparison would most likely be masked by the method of calculating the reference value. If we introduce an offset of -0.7 K to the deviations, i.e. the average of the $\Delta$CCTs weighted with $U^{-2}$, the $E_n$ values would change, but there would still be four laboratories with $E_n \geq 1.2$.

Table 2. Expanded uncertainties of spectral irradiance (DoE), deviations of CCT, calculated expanded uncertainties of CCT [3], and $E_n$ values. The $E_n = \Delta$CCT / $U$(CCT) indicates whether the deviation is within expanded uncertainty.

| Laboratory   | U(DoE) | $\Delta$CCT/K | $U$(CCT)/K | $E_n$ |
|--------------|--------|---------------|------------|-------|
| BNM-INM      | 2.0 %  | 8.6           | 5.6        | 1.5   |
| CSIRO        | 0.8 %  | 3.4           | 2.2        | 1.5   |
| Aalto (HUT)  | 0.8 %  | 0.4           | 2.2        | 0.2   |
| IFA-CSIC     | 3.4 %  | 5.5           | 9.5        | 0.6   |
| MSL-IRL      | 1.5 %  | 1.1           | 4.2        | 0.3   |
| NIM          | 1.0 %  | -3.8          | 2.9        | -1.3  |
| NIST         | 0.9 %  | -0.6          | 2.5        | -0.3  |
| NMJ          | 2.7 %  | 6.2           | 7.6        | 0.8   |
| NPL          | 0.6 %  | -0.2          | 1.7        | -0.1  |
| NRC          | 2.9 %  | 11.3          | 8.1        | 1.4   |
| PTB          | 1.1 %  | 0.8           | 3.1        | 0.3   |
| VNIIOFI      | 0.9 %  | 0.8           | 2.5        | 0.3   |
| CENAM        | 4.0 %  | -0.6          | 11.2       | -0.1  |

4. Discussion
It is quite evident that although there was a good agreement within $k = 2$ in the spectral irradiance intercomparison, the participating laboratories would have deviations outside their expanded uncertainties in a CCT intercomparison, if the uncertainties were analyzed by conventional methods not accounting for correlations. We conclude that this is due to systematic structures in the spectral irradiance deviations as shown in figure 1 and table 1. These structures are introduced by correlations in the uncertainties of spectral irradiance values at different wavelengths [4] that should be taken into account in the uncertainty analysis. Sources for the structures and the related correlations may include interpolation of data that introduces complicated structures in the deviations, temperature determination of black body radiators that introduce slope-like errors in the data, and geometrical factors that introduce offsets in the data. If known, these correlations should be accounted for in the uncertainty analysis.

Comparison CCPR-K1.a was never intended to be a CCT intercomparison. Therefore, one should not pay attention to the $E_n$-values of any particular laboratory. Most laboratories could take the correlations into account and the level of agreement would thus be better. In this sense, this paper highlights the importance of arranging an intercomparison of CCT or including it in the analysis of a key comparison of spectral irradiance.
For laboratories not making scale realization themselves, but rather taking traceability from an NMI, the correlation data are rarely available. Thus, when these laboratories measure CCT with their calibrated spectroradiometers, there is a danger that their uncertainty estimates may be too small. In such cases, the fractions calculated at the end of table 1 may be useful. On the average, the uncertainties of the spectral irradiance values of NMIs in the visible region may be assumed to be 20% uncorrelated (noise), 40% offset, and 40% structural. The effect of noise averages out in the spectral integration involved in the CCT calculation, offset does not affect CCT at all, but the structural uncertainty is what causes largest measurement errors. When using a purchased lamp for calibration, the noise will increase. Thus fractions of 1/3, 1/3 and 1/3 (for variances) for the introduced correlation classes could well be used to characterize a calibrated spectroradiometer.

It is complicated to take correlations into account in uncertainty analysis if they are not known. Thus, they are often neglected. We have developed a new Monte Carlo based method that can be used to study effects of possible correlations [4]. The method can be used to calculate uncertainties assuming no correlations, full correlation (offset) and severe correlations assuming worst possible scenario. Using the fractions derived above, the method can also be used to derive uncertainties assuming typical correlation scenarios. Our Monte Carlo method [4] gives higher expanded uncertainties for CCT that would cover the noted errors arising from the structural spectral deviations in table 1. We have also applied the method for total ozone column measurements of solar UV [5, 6].

Acknowledgments
This work has been supported by the European Metrology Research Programme (EMRP) within the joint research project ENV59 “Traceability for atmospheric total column ozone” (ATMOZ). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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