Preface: Uncertainty Evaluation by Monte Carlo Method

Measurement uncertainty is a parameter that is used to characterize the dispersion of the values attributed to a measurand. There are multiple definitions of measurement uncertainty that were adopted by various international working groups. The differences in definitions are small and of interest mainly to experts in the field. The methods used to estimate the uncertainty, however, were found to vary widely between different fields of metrology, even among national metrology institutes. The problem was studied, and a set of guidelines were published in the early 1980s. To implement the guidelines and harmonize the methods to estimate uncertainty, a guide with specific steps and numerous examples was developed and published as the Guide to the Expression of Uncertainty in Measurement (GUM) in 1995. The GUM is published by the Joint Committee for Guides in Metrology (JCGM), which is a group comprised of eight other international organizations. There have been periodic updates and extensions to the GUM, developed by JCGM, that included other valid methods to estimate uncertainty and it is a continuing international effort.

There were several drivers for developing these guidelines and relevant vocabulary. The purposes as mentioned by JCGM/GUM were to provide a guideline to develop uncertainty statements and a basis for international comparison of measurement results. These guidelines however had a much higher impact in the development of domestic and international commerce, science & technology, and as a decision-making tool.

The GUM provides a mathematical framework to estimate the standard uncertainty, that is based on a linear model of the measurement. This may not be reliable either due to inadequacy of the framework to represent the measurement model or when the probability density function of the measurand departs from a Gaussian distribution. To address this issue, the JCGM also publishes supplements to the GUM. These supplements address the calculation of measurement uncertainty using a method of propagation of probability distributions through a mathematical model of measurement using a Monte Carlo method (MCM). Supplement 1 of the GUM (GS1) addresses univariate measurement uncertainties, whereas, Supplement 2 (GS2) addresses multivariate measurement uncertainties. The methods described in these supplements are consistent with a more modern Bayesian statistics framework.

The methods described in the GUM and their implementations have been used in numerous areas of science and technology since their inception and have been hugely effective in disseminating scientific knowledge and improving commerce. To emphasize and promote these methods, Metrology Society of India worked on publishing this special edition. This edition of the journal focuses on the Monte Carlo method to evaluate uncertainty, which has been used by the measurement science community and enabled the rigour in this discipline.

Several researchers, both from national metrology institutes, as well as from universities around the world submitted manuscripts for this special edition. These submissions encompassed a variety of topics drawing from the disciplines such as mechanical metrology, electrical metrology and the biomedical sectors. A summary of the papers selected for this edition will be described next.

The first paper is by Rab et al. of CSIR-NPL, India. In this paper, the authors explore various uncertainty propagation models to evaluate the measurement uncertainty in Direct Pressure Indicating Devices (DPIDs). They used the MCM, Least Squares Fit (LSF) model of additive corrections and a Calibration Factor fit model of multiplicative corrections in this study. This investigation was performed for pressures in the range from 0 MPa to 69 MPa where the known experimental results were obtained from a Dead Weight Tester (DWT) pressure balance. The MCM was used to process an additive corrections algebraic model of the experimental results in order to independently specify the reference values and uncertainties. Results from this paper demonstrated that the MCM may be used as a convenient tool to simultaneously test and validate both additive as well as multiplicative correction models for DPID's in practical testing and calibration applications.

The second paper is by Elizabeth et al. of CSIR-NPL, India. The focus of this paper was on the validation of a Vickers hardness (HV) number indentation scale and involved the analysis and processing of univariate MCM results described in GUM Supplement 1 (GS1). These results were used by the authors to benchmark and validate the Calibration Measurement Capability (CMC) of their Force and Hardness Laboratory for HV calibrations. In the application of the classical GUM based approach, the mathematical inconsistency of the 'effective degrees-of-freedom' as obtained with the Welch-Satterthwaite formula is well-known. The authors chose the MCM method to avoid this issue and implemented it using an Excel spreadsheet for practicality.

The third paper is by Moona et al. of CSIR, NPL. This paper addressed the validation of CMCs for a new high accuracy line scale in the range from 300 mm to 1000 mm. This was achieved through the analysis of a physics-based Ishikawa/fish-bone cause and effect diagram of the underlying measurement system. Results for a representative 400 mm line standard obtained using the GUM approach yielded an estimate of 400.0005 mm ± 1.53 μm and the MCM approach yielded an estimate of 399.9996 mm ± 1.64 μm. This demonstrated that while the GUM supplements' approaches often produce smaller uncertainties than the conventional GUM uncertainty approach, this is not necessarily always the case. Based on this insight by the authors, it may be emphasized that any scientific metrological uncertainty analysis should carefully consider the variety of Probability Density Function's (PDFs) for a measurand's uncertainty inputs based on good physical and engineering judgement.

The fourth and fifth papers are by Wei et al. of Jiangxi Meteorological Bureau, China. The first part of their study focussed on the practicality and utility of wind speed measurements and modelling of uncertainties in terms of a complex non-linear equation. They investigated the influence of water-vapour corrections in the complex equation as the original model was considered too algebraically complex to analytically determine the sensitivity coefficients. A GUM approach for a simplified approximation of the complex model was compared and contrasted with results from an MCM approach of the complex model. This showed that two different equations may be used to conveniently represent a combined state of knowledge that is consistent with the original model. In the second part of the study, the effect of different non-Gaussian PDFs for the model uncertainty inputs was investigated. It was determined that the GUM approach was incapable of adequately resolving wind speed predictions and uncertainties when compared to that of the MCM approach. This also allows for the incorporation of more complex refinements such as turbulence intensity effects.

The sixth paper is by Garg et al. of CSIR-NPL, India. In this paper, microphone free-field calibrations in the frequency range from 125 Hz to 20 kHz was investigated using both the GUM and MCM approaches. They used an Excel spreadsheet to implement this and used a mixture of Gaussian and rectangular PDFs to model uncertainty inputs. The sensitivity coefficients used for this study were obtained from technical literature and experimental measurements from an anechoic chamber. Uncertainty results obtained using the GUM and MCM approaches were reasonably close when higher order non-linear and correlation effects were absent. The authors concluded that the MCM may offer a convenient method for CMC assessments for calibration and industrial measurement laboratories.

The seventh paper is by Thakur et al. of CSIR-NPL, India. In this paper, CMCs for gauge pressures in the range from 6.5 kPa to 350 kPa for a national primary scientific standard were studied using GUM and MCM simulations. In this study, the reference values were independently obtained with an Ultrasonic Interferometer Manometer (UIM), a primary scientific pressure standard. This study concluded that the GUM overestimates the actual uncertainty by 0.2 ppm as obtained with the MCM. Based on this, the authors recommend the MCM approach for estimating uncertainties over the GUM approach for critical scientific metrology primary standards scale realizations.

The eighth paper is by Singh et al. of CSIR-NPL, India. This paper examined the application of the MCM for determining the CMC for pneumatic pressure secondary standards . The pressure balance/piston gauge used for this effort has a maximum measuring capacity of 8 MPa. This gauge was cross-floated against another pressure balance characterized up to 4 MPa. In this study, simulations were performed using a combination of Excel spreadsheets and an in-house developed C++ code for fixed and adaptive iteration Monte Carlo simulations. Gaussian PDFs for the pressure balance's effective area and distortion coefficient were obtained using both GUM and MCM simulations. However, it was determined that the GUM approach incorrectly overestimated the associated uncertainties. As a result, this paper recommended adaptive MCM simulations for CMC quantification in calibration and testing laboratories.

The ninth paper is by Ramnath of UNISA, South Africa. This paper utilized the multivariate GUM Supplement 2 (GS2) technique to construct the joint PDF for an oil piston-cylinder pressure balance, operating in the range from 50 MPa to 500 MPa. New numerical algorithms were developed to construct the corresponding hyper-ellipsoidal and smallest coverage regions for both bivariate and trivariate joint PDFs. A simple statistical test was then proposed to estimate the extent of Gaussian characteristics for a joint PDF. This was needed for the optimal selection of either a hyper-ellipsoidal region or a smallest coverage region for the accurate calculation of expanded uncertainties in multivariate measurement models.

The tenth paper is by Pawar et al. from the University of North Carolina, Charlotte, USA. The focus of this paper was the standardization of human patient wound irrigation pressures for the removal of bacteria and debris during surgeries and post-operative care. Their investigation incorporated both the GUM and MCM approaches for wound irrigation pressure calculations and used clinical data from 20 participating medical doctors and nurses. The authors offer new insights and guidelines to assist medical practitioners in determining and assessing wound irrigation pressures and uncertainties for various medical devices.

The eleventh paper is by Jia *et al. of* Ankang University, China. The authors investigated the current noise levels in a double gate nano-MOSFET using Monte Carlo simulations (MCS). They used the MCS approach to first solve the equilibrium Poisson's equation for specified doping concentrations and then the non-equilibrium Poisson's equation. The purpose was to incorporate bias effects on the current noise levels in the nano-MOSFETs. In this study, the practicality and utility of the MCM to study the influence of various parameters in a nano-MOSFET was demonstrated. These parameters included bias voltage, temperature and doping concentrations effects on noise suppression levels. This paper highlights the utility of the MCM for simulation and uncertainty analysis in other metrology areas that use measurand models specified in terms of partial differential equations such as the Maxwell equations.

Guest Editors Biographies:

	Prem Rachakonda is a mechanical engineer in the Dimensional Metrology Group at the National Institute of Standards and Technology (NIST), USA. He has been at NIST for the past 15 years working in the field of dimensional metrology. His work primarily addresses technical and standardization topics for dimensional instrumentation capable of measuring from the nano-scale to the large-scale. He served on several standards' working groups and committees, including the ASTM and the ASME, to develop standards for laser scanners, trackers and vision systems.
	Vishal Ramnath is a mechanical engineer in the Department of Mechanical and Industrial Engineering at the University of South Africa (UNISA) since 2013. His earlier work focused on radiation thermometry whilst at the Council for Scientific and Industrial Research's National Metrology Laboratory (CSIR-NML) from 2002 to 2007, and thereafter on pressure and vacuum metrology whilst at the National Metrology Institute of South Africa (NMISA) from 2007 to 2012. His current research focus is in the area of advanced uncertainty analysis and fluid mechanics.
	Vinay Shankar Pandey is currently working as an Assistant Professor in the Department of Applied Sciences in National Institute of Technology Delhi, India. He has more than 12 years of research and academic experience and served as Postdoctoral Fellow and Research Professor at Physical Research Laboratory / Indian Space Research Organization (ISRO), India, Kyung Hee University (KHU), South Korea. He has more than 50 publications in peer reviewed journals / conferences. He has supervised several postgraduate and doctoral theses.

REFERENCES

1. Shanay Rab, Sanjay Yadav, Afaqul Zafer, Abid Haleem, P K Dubey, Jasveer Singh, Rahul, Kumar, Raman Sharma and Lalit Kumar, "Comparison of Monte Carlo simulation, least square fitting and calibration factor methods for the evaluation of measurement uncertainty using direct pressure indicating devices"
2. Indu Elizabeth, Rajesh Kumar, Naveen Garg, Mohammed Asif, Manikandan R M, "Uncertainty evaluation in Vickers hardness scale using Monte Carlo simulation"
3. Girija Moona, "Measurement Uncertainty Evaluation using Monte Carlo Simulation for newly established line scale calibration facility at CSIR-NPLI"
4. Mingming Wei, Yang Zeng, Chunhua Wen, Xiaogang Liu, Changchun Li, Shan Xu, "Analysis of the influence of water-vapor correction term on the measurement uncertainty of wind speed"
5. Mingming Wei, Yang Zeng, Chunhua Wen, Xiaogang Liu, Changchun Li, Shan Xu, "Comparison of MCM and GUM method for evaluating measurement uncertainty of wind speed by pitot tube"
6. Naveen Garg, P Surendran, M P Dhanya, A T Chandran, M Asif, M Singh, "Measurement uncertainty in microphone free-field comparison calibrations"
7. Vikas N. Thakur, Sanjay Yadav, Ashok Kumar, "Evaluation of uncertainty in the effective area and distortion coefficients of air piston gauge using Monte Carlo method"
8. Jasveer Singh, L A Kumaraswamidhas, Kapil Kaushik, Neha Bura, Nita Dilawar Sharma, "Uncertainty analysis of distortion coefficient of piston gauge using Monte Carlo Method".
9. Vishal Ramnath, "Analysis and comparison of hyper-ellipsoidal and smallest coverage regions for multivariate Monte Carlo Measurement uncertainty analysis simulation datasets"
10. Amogh Pawar, Tony L. Schmitz, "Pressure uncertainty analysis for wound irrigation devices"
11. Xiaofei Jia, Liang He, Wenhao Chen, "Research on noise suppression in double gate nano-MOSFETs based on Monte Carlo simulation"