CCL Workshop: Latest developments in the field of Length

- **Digitalization at NIMT.**

J. Buajarern (NIMT, Thailand)

Abstract:
The National Institute of Metrology Thailand (NIMT) has embarked on a comprehensive digital transformation initiative to enhance its precision measurement capabilities and service delivery. This digitalization effort focuses on integrating advanced technologies such as data analytics, cloud computing, and the Internet of Things (IoT) into metrological processes. By leveraging digital tools, NIMT aims to improve the accuracy, efficiency, and accessibility of its services, while fostering innovation in metrology. Key areas of focus include automating calibration procedures, developing digital metrological standards, and enhancing data traceability. Additionally, this transformation seeks to support Thailand's industrial and technological development by providing more robust, real-time data for sectors such as manufacturing, healthcare, and environmental monitoring. The initiative also aligns with global trends in digital metrology, ensuring that NIMT remains at the forefront of technological advancements in measurement science.

- **Latest developments in the field of Length at INRIM.**

M. Pisani (INRIM, Italy)

Abstract: An update of the measurement capabilities in the field of length at INRIM will be given, in particular in angle measurements, surface measurements and nanometrology. Also, a quick overview of the applications of length metrology for space science will be presented.

- **Dimensional Metrology: Lessons from yesterday, shaping a better tomorrow.**

Oelof Kruger (NMISA, South Africa)

Abstract: Dimensional metrology has undergone significant evolution over the past few decades, driven by advancements in technology and a growing demand for precision measurement. With over 35 years of experience in the field, this presentation offers a comprehensive overview of key developments in dimensional and length metrology, focusing on laser systems, gauge blocks, angle standards, and coordinate measuring machines (CMMs). It will explore how these technologies have transformed over the years, emphasizing their impact on the metrology landscape. In addition to technical advancements, the presentation will also examine the increasing role of automation in metrological systems and Interlaboratory Comparison (ILC) reference calculations. A particular focus will be given to the Afrimets and SADCMET regions, reflecting on more than 20 years of active engagement and development in these areas. The presentation aims to provide insights into the evolving landscape of metrology from both a technical and regional perspective.

- **A new stabilized laser @689 nm for multiwavelength interferometers**

J. Seppä & A. Lassila (VTT MIKES, Finland)

Abstract: A new iodine vapor cell stabilized laser has been developed for use in (e.g.) multiwavelength interferometers. The device (VTT MIKES DeepRed I2) is based on a semiconductor single-frequency laser stabilized to Doppler-broadened iodine absorption spectrum. The laser is locked to a wavelength of 689.02332 nm. The locking of the laser from cold start takes less than 60 seconds, and the laser maintains lock continuously over ambient temperature range 15 °C - 25 °C. Stability and reproducibility of the laser are at 1×10^{-8} - 1×10^{-9} level. The device has and optional internal shutter operated with TTL logic signal for opening and closing the default FC/APC fiber output and is housed in a 3U rackmount case. The laser provides a suitable second wavelength to add to 633 nm helium-neon laser in interferometry. Principles and results including Allan variance of the laser frequency are presented.

- **Autocollimators: plane angle measurand ambiguities and the impact of surface form**

B. J. Eves, and I. D. Leroux (NRC, Canada)

Abstract: A phase shifting interferometer and a simple deformable mirror were used to study the impact of changes in surface form on the angles measured by an autocollimator. Autocollimators detect the orientation or normal vector of a plane reflecting surface. Real surfaces are not planar and autocollimators must reduce the distribution of local normal surface vectors to a single angle and in so doing define a measurand. A new measurand definition for autocollimators is formulated that explicitly includes the summary statistic used to collapse the angle distribution to a single value. Unfortunately, the autocollimator manufacturer's choice of summary statistic is poorly documented and heavily influences the response of the autocollimator to the surface form. Plausible choices for the summary statistic can lead to variations in the reported angle of the deformable mirror (diameter of 35 mm) of 4 arcseconds for a surface standard deviation of 130 nm. Monte Carlo generation of an ensemble of random mirror surfaces using Zernike polynomials is used to generalize the impact of the summary statistic choice, i.e. the autocollimator measurand ambiguity, on autocollimator performance. The simulations identify three categories of small angle measuring devices based on their sensitivity to the different Zernike polynomials: devices that are only sensitive to the tilt term and includes phase shifting interferometers, devices that are only sensitive to the tilt term and the coma like terms and includes autocollimators that use the centroid function as the summary statistic, and devices that are sensitive to all the Zernike polynomials which likely includes the majority of autocollimators. The uncertainty due to the surface form and the autocollimator measurand ambiguity can be eliminated if the plane angle measurand is redefined in terms of a least-squares plane fit, i.e. the angle measurand realized by a phase shifting interferometer.

- **Metrology for Nanoscale Critical Dimensions in Semiconductor Manufacturing**

Wei-En Fu, Wen-Li Wu (CMS/ITRI, Chinese Taipei)

Abstract: To follow the Moore’s Law, the IC transistors has been shrinking continuously with the introduction of gate-all-around (GAA) architecture to replace tri-gate field-effect transistors (FinFET) for feature size reaching 3 nm and beyond. The fabrication of the nanoscale 3D GAA transistor structures is even more challenge and requires high precision and accurate metrology tools for yield improvements. Transmission small angle X-ray scattering (tSAXS), also known by Critical dimension small angle X-ray scattering (CD SAXS), was initiated over 24 years ago by Wen-li Wu in National

Institute of Standards and Technology (NIST) as a quantitative metrology tool, and has been extensively studied to determine 3D feature dimensions even in high aspect ratio nanostructures. Its unique capabilities include:

- High intrinsic resolution due to its short wavelength, angstrom vs micrometer for optical techniques
- High penetration power of X-ray enables its application to probe buried nanostructures and high aspect ratio (HAR) ones
- Nondestructive, for example will not cause the shrinkage of photoresist lines or other organic entities.

In this presentation, CD measurements of the 3D GAA transistor structures has been performed using a synchrotron X-ray source for its high beam flux or high brilliance, which enables tSAXS measurements of the 3D GAA structures with a minuscule scattering volume. Additionally, for future applications as a metrology tool in IC fabrications SAXS in a reflection mode, i.e. rSAXS, has also been studied and reported here. Transmission SAXS (tSAXS) are approved to measure 3D complex structures ranged from nanoscale to micro-scale successfully with sub-nanometer wavelength X-ray radiation.

- **What are we measuring when verifying ISO GPS specifications? A measurand issue**

R. Frizza, A. Balsamo (INRIM, Italy)

Abstract: A large percentage of coordinate measurements in the world is for verification of tolerances of workpieces. ISO GPS is a sophisticated language to express tolerances. Most tolerances are geometrical, that is, they specify a tolerance zone that must encompass the toleranced feature. Verifications are measurements and as such need a clear understanding of the measurand. The tolerance zone is a portion of space, whereas the measurand must be a (scalar) quantity. There is no clear definition of the measurand in ISO GPS verification, left to the metrologist to decide on his own.

The presentation proposes a unified approach for deriving measurands in verification of ISO GPS tolerances.

- **Silicon gauge block calibrated by a double-sided interferometer for two-point diameter calibration of a sphere by a micro-coordinate measuring machine**

Akiko HIRAI, Yohan KONDO, Natsumi KAWASHIMA, and Yoichi BITOU (NMIJ, Japan)

Abstract: Two-point diameter measurement system for a sphere by using a micro-coordinate measuring machine (μ-CMM) with a gauge block for calibrating the radius of the μ-CMM probe is developed. To reduce the uncertainty of the surface roughness of the gauge block, a silicon gauge block was used. The expanded uncertainty of 15 nm (k = 2) for the two-point diameter of a sphere is achieved.

- **Coordinate Metrology for large components in the PTB Competence Center for Wind Energy (CCW)**

Anita Przyklenk (PTB, Germany)

Abstract: The CC WIND is a new research building at PTB which is home to 3 different measurement facilities important for wind energy industry: a large CMM (5m x 4 m x 2 m), a reference metrology facility for large torques (5 MNm with option to be extended to 20 MNm) and a mobile LIDAR setup to measure 3D wind velocity profiles.

- A short overview of the CCW will be presented with focus on the large CMM and an example of the calibration of a large gear measurement standard will be shown and discussed.

- A new error separation method for the calibration of rotary tables will be presented which has been recently applied to a large rotary table.

- **Complex form measurement using scanning coordinate measuring machine**

Osamu Sato (NMIJ, Japan)

Abstract: Recent advancements in product design have introduced complex geometries requiring precise manufacturing processes. To ensure product quality, deviations between designed and manufactured forms must be verified, often using three-dimensional (3D) measuring systems. While precise measurement techniques for simple geometries (flats, spheres, and cylinders) are well established, methods for complex forms are still under development. This study addresses measurement uncertainty in complex form metrology by proposing a new gauge concept. The gauge captures complex product features and segments them into circular arc curvatures, ensuring well-calibrated geometric parameters and an unrestricted angular measurement range. A robust calibration method for complex forms is introduced, which measures the target cross-section and uses probe tip centers to generate an envelope for surface determination. The new approach achieves a measurement uncertainty of 1.5 µm, validating its applicability for both simple and freeform geometries in industrial metrology.

- **Testing of evaluation software used in coordinate and gear metrology**

Frank Keller (PTB, Germany)

Abstract: The test of evaluation software used in coordinate metrology is an important step to assure comparability and traceability of 3D measurement results in industrial quality control. Since about 10 years the PTB is operating an internet-based system (TraCIM) for the test of evaluation algorithms for the analysis of 3D measurement data against reference data. This service has recently been extended to include evaluation algorithms for involute gear parameters. Examples of its application will be given.