Title: Traceability for correlative microscopy

Abstract

Correlative microscopy combines multiple imaging techniques e.g. scanning probe microscopy, scanning electron microscopy, and various optical methods for enhanced nanoscale characterisation of multiple measurands. Despite its great potential, many correlative measurements are not in agreement due to lack of standardisation and understanding of the different instrument/technique-sample interactions. Proposals are sought to establish calibration strategies, software solutions with AI based data analysis, to ensure reliable and metrologically traceable correlative microscopy data. Outputs will benefit research and industrial applications in semiconductors, photonics, and nanotechnology, aligning with European metrology and manufacturing priorities.

Keywords

Nanometrology, Scanning probe microscopy, electron microscopy, 3D optical microscopy, nanotechnology, photonics, semiconductor, surface roughness, quantum dots

Background to the Metrological Challenges

The European microscope market generated a revenue of around 1750 million euros in 2022. This market is expected to grow at a Compound Annual Growth Rate (CAGR) of 6.5 % from 2023 to 2030 with nanometrology perceived as one of the major growth opportunities to support nanotechnology. Nanometrology has a prominent role to play in the realisation and implementation of standards that will support the increased adoption of correlative microscopy methods as a quality control tool. For example, the progressive miniaturisation of advanced nanomanufacturing techniques which currently deliver nanodevices with feature sizes below 22 nm and complex nano-objects in the size range below 100 nm requires the introduction of fast, accurate and traceable measurement methods for the quality control of nanostructures, nanodevice dimensions and properties during production processes. In addition, correlative microscopy will also provide benefits in material science applications such as solar cells, organic electronics, energy harvesting materials, photonic and optoelectronics devices.

Advanced manufacturing produces an increasingly large number of devices and nanostructured materials with a wide range of applications including semiconductors, data storage, sensors (quantum and MEMS based), power electronics, energy conversion and storage, communications, components for quantum computing, and novel photonic devices. Examples of applications where metrology needs are particularly clear include: (i) realising the potential of room temperature quantum dot transistors for the next generation of low power electronics whose performance is exponentially dependant on their dimensions which must be measured simultaneously with device performance, (ii) reference standards for radiofrequency (RF) nanometrology such as micro size capacitors requiring knowledge of their dimensional properties obtained from AFM and SEM measurements traceability to the SI. For these devices to be reliable and for development of new nanodevices to occur, metrology is needed to support fabrication and performance testing by correlative microscopy - the linking of different microscopy techniques.

Versatile nanometrology techniques are available utilising different underlying physics including numerous optical microscopy techniques, ion, electron and x-ray microscopy, and most often probing at an atomic level using the family of Scanning Probe Microscopes (SPM). All techniques have both strengths and weaknesses, it is often highly challenging to satisfy various industrial metrology challenges (having different needs in terms of accuracy, resolution, range, speed and physical properties) with a single tool. Although calibration of

individual instruments is possible, different results for measurement of a feature can be obtained depending on the instrument used, even though each instrument claims traceability. Today correlative microscopy is an emerging solution for meeting the challenge of obtaining agreement between the different techniques. It integrates multiple imaging modalities, either by combining data from different tools using advanced software or by integrating different measurement techniques (for single or multiple measurands) in a single tool, to provide comprehensive micro- and nano-scale characterisation.

As the drive for reduced measurement uncertainty increases, together with the need to correlate measurements from different instruments and then to relate them to other functions and measurands, an improved quantification of instrument-sample interactions and their effects on measurement uncertainty is required. These interactions can make significant contributions to the different measurement results obtained from differing micro- and nano-techniques. Some measurements involving micro- and nano-structures already have some form of traceability. For instance, for surface metrology tools, such as stylus profilometers, interference and confocal microscopes, traceability is acquired by calibration with step height and pitch reference standards. For hardness metrology the geometry and surface area function of the indenter (a dominant error source) is usually calibrated by metrological AFMs. For thin film metrology, ellipsometers are frequently calibrated to layer thickness standards certified by metrological AFMs. There is a need to extend the provision of traceability to a wider range of measurands.

The need for reliable high-accuracy instruments for the characterisation and metrology of nanostructures and devices, is well addressed in many strategy documents and roadmaps, such as the 2023 edition of the IEEE International roadmap for devises and systems IRDS [5], CIPM CCL strategy 2018–2028 [6], and the Integrated Research and Innovation Roadmap for the European Nanotechnology Roadmap as well as in the Strategic Research & Innovation Agenda for the Nanomedicine Community 2020 [7].

Novel correlative microscopes include several different types of instruments, but proposals should focus on methods combining AFM with other techniques as existing AFM plays a fundamental role in nanotechnology and traceability methods for AFMs are already well developed. AI-driven data evaluation algorithms and software for fully exploiting the value of correlative multimodal measurement data is urgently required to enable the full realisation of the benefits of correlative microscopy.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The proposal shall focus on the provision of traceability for correlative microscopy methods at the nanometre scale through the development of a European level network.

The specific objectives are:

1. To address industrial needs for high-throughput correlative microscopy by enhancing current instrumentation and methods, focussed on achieving reduced measurement uncertainty, higher reliability, and enhanced resolution at high speed.
2. To develop direct metrological traceability or traceable in-situ calibration methods based on the use of calibration samples for correlative microscopy such that dimensional measurements using different techniques can be compared and related to other sample measurands e.g. electrical properties. This is to include the quantification of uncertainties in multimodal correlative microscopy related to mutual alignment, differences in resolution, noise and imaging artefacts. In addition, Instrument-sample interactions for each instrument type (e.g. scanning probe microscope (SPM), Scanning electron microscope (SEM), optical interference (OI) shall be quantified to enable the evaluation of traceable correlations between different measurement methods and measurands.
3. To develop an innovative AI-based methodology for mutual image registration, data fusion with known uncertainty and parameter extraction from multimodal data, including validated traceable datasets for both training and for verification. These data sets may include both reference measurement data and simulated data for different types of correlative microscopy.
4. To demonstrate the usability of the developed methods in representative industrial applications, including measurements for ultra flat surfaces, photonic components, semiconductors, and/or components for quantum computing, such as atomic force microscope (AFM) with SEM for material research, AFM and optical for areal surface metrology, and parallel AFM for semiconductor. Target uncertainty is 1 nm for small structures.

5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers), standards developing organisations (CEN, ISO) and end users (semiconductor and electronics industry, materials engineering, quality control).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources both within and outside Europe, plus engagement with existing European research infrastructures and European Partnerships is recommended. A strong industry involvement is expected in order to align the project with their needs and guarantee an efficient knowledge transfer into industry and end users. Where relevant, proposals are encouraged to build on, or seek collaboration with, existing projects and develop synergies with other relevant European, national or regional initiatives and funding programmes. In particular, links are encouraged with (i) the projects funded under earlier relevant topics of the Horizon Europe programme; or (ii) other relevant European Partnerships.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMPIR projects 15SIB09 3DNano, 20IND08 MetExSPM, 20IND07 TracOptic and 20IND12 ELENA and how their proposal will build on those.

Proposers should note that the programme funds the activity of researchers to develop the capability, not the required infrastructure and capital equipment, which must be provided from other sources.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.1 M€ and has defined an upper limit of 2.6 M€ for this proposal.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 25 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the ’end user’ community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the “end user” community (e.g. letters of support) is also encouraged.

You should detail how your proposal’s results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability, or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the advanced manufacturing sector.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of the Metrology Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Timescale

The project should be of up to 3 years duration.