Annex I – JRP protocol

Version Date: 25 April 2025

24DIT02 DINAMO

Digitalisation route for dimensional nanometrology

Start date: 01 June 2025

Duration: 36 months

Coordinator
XXXXX
CMI

<u>Glossary</u>

AFM:	Atomic Force Microscopy
AI:	Artificial Intelligence
ALD:	Atomic Layer Deposition
API:	Application Programming Interface
BIPM:	Bureau international des poids et mesures
CLSM:	Confocal Laser Scanning Microscopy
DBC:	Di-block Copolymer
DCC:	Digital Calibration Certificate
FAIR:	findability, accessibility, interoperability, and reusability
GISAX:	Grazing-Incidence Small-Angle X-ray Scattering
IMEKO:	International Measurement Confederation
MBE:	Molecular Beam Epitaxy
MEMS:	Micro Electro Mechanical Systems
ML:	Machine Learning
NMI:	National Metrology Institute
QI:	Quality Infrastructure
RIE:	Reactive Ion Etching
ROI:	Region of Interest
SC:	Subcommittee
SIRE:	SI Reference Point
SEM:	Scanning Electron Microscopy
SPM:	Scanning Probe Microscopy
TC:	Technical Committee
WG:	Working Group

Contents

Section A: Key data

A1 Project data summary

Coordinator contact details:

Coordinator:	XXXXX
Organisation:	Cesky Metrologicky Institut
Email:	XXXXX

Participant details:

no.	Participant Type	Short Name	Organisation legal full name	Country
1	Internal Beneficiary	CMI	Cesky Metrologicky Institut	Czechia
2	Internal Beneficiary	CEM	Centro Español de Metrología	Spain
3	Internal Beneficiary	DFM	Dansk Fundamental Metrologi A/S	Denmark
4	Internal Beneficiary	GUM	Central Office of Measures	Poland
5	Internal Beneficiary	INRIM	Istituto Nazionale di Ricerca Metrologica	Italy
6	Internal Beneficiary	NPL	NPL Management Limited	United Kingdom
7	Internal Beneficiary	PTB	Physikalisch-Technische Bundesanstalt	Germany
8	Internal Beneficiary	VSL	VSL B.V.	Netherlands
9	Internal Beneficiary	VTT	Teknologian tutkimuskeskus VTT Oy	Finland
10	External Beneficiary	BUT	Vysoke uceni technicke v Brne	Czechia
11	External Beneficiary	NFI	Nearfield Instruments B. V.	Netherlands
12	External Beneficiary	PWR	Politechnika Wrocławska	Poland
13	External Beneficiary	TUBS	Technische Universitaet Braunschweig	Germany
14	Unfunded Beneficiary	Bruker FR	Bruker France SAS	France
15	Associated Partner - linked to all Internal Beneficiaries	Nanosurf	Nanosurf AG	Switzerland
16	Associated Partner - linked to all Internal Beneficiaries	OXINST	Oxford Instruments Asylum Research, Inc.	United States

A2 Financial summary

	Internal Beneficiaries	External Beneficiaries	Unfunded Beneficiaries	Associated Partners	Total	Total eligible
Labour (€)	992 754.00	372 000.00	17 280.00	34 560.00	1 416 594.00	1 382 034.00
Subcontracts (€)						
T&S (€)	90 535.00	24 000.00			114 535.00	114 535.00
Equipment (€)		8 000.00			8 000.00	8 000.00
Other Goods, Works and Services (€)	93 900.00	51 000.00	900.00	1 800.00	147 600.00	145 800.00
Internally Invoiced Goods and Services (€)	49 950.00				49 950.00	49 950.00
Financial Support to Third Parties (not applicable to JRPs)						
Indirect (€)	294 297.25	113 750.00	4 545.00	9 090.00	421 682.25	412 592.25
Total costs (€)	1 521 436.25	568 750.00	22 725.00	45 450.00	2 158 361.25	2 112 911.25
Costs as % of Total costs	70 %	26 %	1 %	2 %		
Total Eligible Costs (€)	1 521 436.25	568 750.00	22 725.00		2 112 911.25	2 112 911.25
EU contribution (€)	**1 521 436.25**	**568 750.00**			**2 090 186.25**	**2 090 186.25**
EU contribution as % of total EU contribution	73 %	27 %	0 %	0 %		
Months	165.2	70.3	1.1	2.2	238.8	238.8

A3 Work packages summary

WP No	Work Package Title	Active Participants (WP leader in bold)	Months
WP1	Digital information flow	**NPL**, CMI, CEM, DFM, GUM, INRIM, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST	40.1
WP2	Smart calibration samples	**INRIM**, CMI, CEM, DFM, GUM, NPL, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST	86.4
WP3	Digital assistants	**CMI**, CEM, DFM, GUM, INRIM, NPL, PTB, VTT, BUT, NFI, TUBS, Bruker FR, Nanosurf, OXINST	44.5
WP4	Uncertainty quantification in digital data workflows	**VTT**, CMI, CEM, DFM, GUM, INRIM, NPL, PTB, VSL, BUT, NFI, PWR, Bruker FR, Nanosurf, OXINST	33.7
WP5	Creating impact	**PTB**, all participants	22.1
WP6	Management and coordination	**CMI**, all participants	12.0
		Total months	**238.8**

The information in tables A2 and A3 reflect the estimates of resources as of the start of project in June 2025. The tables will not necessarily be updated during the course of the project.

Section B: Overview of the research

B1 Summary of the project

Overview

This project aims to establish a digitalisation route for dimensional nanometrology focusing mainly on the measurement of dimensions, position, form and roughness at the micro- to nano-scale level. The digital traceability chain will start from the digital metre, through smart calibration samples, algorithms for automated data processing, up to providing the results to end users. Although the primary objective of this project is to focus on Scanning Probe Microscopy (SPM), the methods developed will be applicable to other areas of metrology and nanometrology (e.g., digital transformation, materials science, quantum metrology, medical imaging) and they could be used as a template when developing a digital infrastructure for other areas such as larger scale surface topography measurements using optical or tactile methods.

B2 Excellence

B2.a Overview of the objectives

The overall objective of this project is to enable digital information flow in dimensional nanometrology, from the primary definition of units, through embedded smart calibration samples and automated routines for in-SPM automated measurements, up to industrial and academic end users.

The specific objectives of the project are:

1. To develop four classes of smart calibration samples (containing intrinsically high metrological information) for use with automated processing of the measurement data that is used to calibrate SPM. Samples will include 1) silicon steps, which are traceable to a crystal lattice, 2) lateral standards based on self-organised and locally unique patterns (fingerprints), 3) multi-scale digital patterns and 4) programmable virtual height and lateral standards. (WP2)
2. To develop a library of automated data processing routines for evaluation and quality checking, which will allow the propagation of calibration measurement data, and associated metadata that complies with the FAIR principles, and which is independent of user influence. The library will be integrable into open source and commercial microscope control software (creating “digital assistants” to process the data automatically) and a reference implementation will be developed to act as a template for digitalisation in other areas of metrology. Input will be drafted for standards development organisations and good practice guides will be written on the use of the developed software and algorithms. These will be disseminated to the SPM community and instrument manufacturers so that routines can be integrated into their software. (WP3)
3. To develop data management tools to support the transfer of SPM measurement data to manufacturing processes. These tools will include storage of the data processing steps in the metadata (in a reusable format that is directly associated with the data) and the broadening of ISO compliant data formats for advanced measurement regimes (high-speed, force volume, spectroscopic, adaptive scanning). (WP1)
4. To evaluate the uncertainties associated with the application of the routines that lead to a digital traceability chain in dimensional nanometrology. In addition, to demonstrate their use in length metrology with other instrumentation and at other scales (e.g., for stylus profilometers, optical profilometers, focus variation instruments). A database of knowledge learnt, from the application of the routines, will be used to transfer the routines to other areas of metrology. (WP4)
5. To facilitate the uptake of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, instrument manufacturers), standards developing organisations (ISO, CEN) and end users (semiconductor industry, research, precision engineering industry). (WP5)

B2.b List of deliverables

Relevant objective (Activity delivering the deliverable)	Deliverable number	Deliverable description	Deliverable type	Participants (Lead in bold)	Delivery date
3 (A1.4.5)	D1	Good practice guide for digital flow in nanometrology including aspects of data and metadata handling, data formats, and application to advanced measurement regimes (high speed, force volume, spectroscopic, adaptive scanning)	Good practice guide	**NPL**, CMI, CEM, DFM, GUM, INRIM, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST	Dec 2027 (M31)
1 (A2.1.12)	D2	Report on novel traceability routes for smart calibration samples (silicon steps traceable to a crystal lattice, lateral standards based on self-organised and locally unique patterns (fingerprints), multi-scale digital patterns and electrically programmable virtual height, and lateral, dynamic reference standards), which contain intrinsically high metrological information. Some of these samples will be used to enable the automated processing of the measurement data that is used to calibrate SPM	Report	**INRIM**, PTB, VSL, PWR, CMI, CEM, DFM, GUM, NPL, VTT, BUT, NFI, TUBS, Bruker FR, Nanosurf, OXINST	Sep 2027 (M28)
1 (A2.2.7)	D3	Report on the design and characterisation of embedded references (smart calibration samples) for in-SPM automated measurements	Report	**VTT**, CMI, BUT, DFM, NPL	Sep 2026 (M16)
2 (A3.1.4)	D4	Dataset for benchmarking automated SPM data processing routines in nanometrology	Dataset	**BUT**, CMI, NPL	Nov 2025 (M6)
2 (A3.3.6)	D5	Good practice guide on the use of a library of automated data processing routines (digital assistants) in SPM data evaluation, its reference implementation and aspects of integration into commercial microscope control software	Good practice guide	**CMI**, DFM, INRIM, NPL, PTB, VTT, BUT, TUBS, Bruker FR, Nanosurf, OXINST	Sep 2027 (M28)
4 (A4.2.4)	D6	Good practice guide on uncertainty propagation through a digital traceability chain in dimensional nanometrology	Good practice guide	**VTT,** CMI, NPL, BUT, INRIM	May 2028 (M36)
4 (A4.3.5)	D7	Report on the extension of the digital data workflow towards larger scales in dimensional measurements and towards other quantities using other instrumentation (e.g., for stylus profilometers, optical profilometers, focus variation instruments), which will create a database of the knowledge learnt from this extension	Report	**GUM,** CEM, VTT, CMI, NPL, PTB, BUT, INRIM	May 2028 (M36)

(n/a)	D8	Evidence of contributions to or influence on new or improved international guides, recommendations and standards with a specific focus on the following guides and committees: ISO/TC201/SC9, ISO/TC229/JWG2, CEN TC352, VAMAS TWA 2. Examples of early uptake of project outputs by end-users including a report on the 4 case studies (A5.2.2 - A5.2.5). Updated dissemination, communication and exploitation plan	Reporting documents	**PTB**, all participants	May 2028 (M36) + 60 days
n/a	D9	Delivery of all technical and financial reporting documents as required by EURAMET	Reporting documents	**CMI**, all participants	May 2028 (M36) + 60 days

B2.c Need for the project

Need for digitalisation in metrology

Digitalisation is a topic that is generally acknowledged to be of great potential benefit to metrology and more broadly, to the global quality system. Its importance is evidenced by the signing of a joint statement of intent[1] by bodies including BIPM, ISO and IMEKO, and the creation of a horizontal forum for Metrology and Digitalisation[2] and associated Task Groups by BIPM. Digitalisation is also of significant interest within industry. The European Metrology Network for Advanced Manufacturing mentions terms such as “intelligent design” and “smart manufacturing”, which are entirely dependent on digital data flows, throughout its strategic research agenda[3]. The European Commission has realised the importance of data and material traceability by funding a call for Digital Product Passports[4] as enablers of the circular economy.

One of the key areas where digitalisation brings benefits is automation. Automation of data capture means that more experiments can be run in a given time, and that staff can be freed up to carry out other tasks rather than having to monitor equipment. It also means that the data can be acquired in much higher quantities – increasing the number of repeated measurements or using more advanced measurement sequences to reduce the impact of some unwanted phenomena such as drift. Automation of data transfer reduces the likelihood of transcription and copy-paste errors. Automation of data processing, particularly through complex processing chains, means that estimates of measurands and their associated uncertainties can be calculated using standardised and trustworthy algorithms, and any parameters affecting the results will be recorded with the results. Automation of data annotation and storage means that data can be permanently linked with the related information (“metadata”) that makes the data meaningful in future. This storage with appropriate metadata is key to the concept of “FAIR” (Findable, Accessible, Interoperable and Reusable) data: the metadata are the terms that enable the data to be found and reused. This project will focus on developing a general framework to realise the benefits of automation for dimensional measurements that involve complicated calculations whilst retaining metrological traceability back to international standards. Examples of such problems are commonly found where imaging techniques are used to obtain an estimate of a quantitative value, for instance in Earth observation, quantitative magnetic resonance imaging, radiation dosimetry, fluorescent microscopy and thermal imaging and are also found in Scanning Probe Microscopy and in other methods used in dimensional nanometrology.

More broadly, the provision of digital data can automate the parts of processes, such as auditing and approval chains, that require simple checking (for instance whether a given piece of equipment was in calibration on the date a measurement was made). Automation typically saves time, reduces error rates, and frees up skilled staff for tasks that need human ingenuity. The provision of metrological data in a form that retains traceability is a key part of ensuring that metrology supports the use of digitalisation in multiple industries, including the semiconductor sector and bioengineering. This project will support that aim for nanometrology data, as well as providing a more general framework that can be adapted and applied in other areas.

Need for digitalisation in dimensional nanometrology

Various frameworks and tools were created in the past few years to support the digitalisation of metrology, including the SI Digital Framework[5] and Digital Calibration Certificates (DCCs)[6], however the implementation of specialised digital workflows for dedicated areas of metrology still needs to be undertaken. This is particularly important for dimensional nanometrology, where significant, complex, and varied data processing is required to determine an accurate value for the measurands. While some activities in the digitalisation of length have been realised[7], starting with the calibration of lasers (digitalisation of the metre), dimensional nanometrology is still one of the areas where more work is needed.

Dimensional nanometrology focuses on the measurement of dimensional quantities (length, form, roughness) and on the position of objects at the micro- to nanoscale, forming a basis for metrological traceability in many industrial areas (semiconductor, quantum, precision engineering, optics, life sciences). Its key workhorse is scanning probe microscopy (SPM), of which the main variant used is the atomic force microscope (AFM). This is a typical example of an advanced metrology technique, for which the gaps between the calibration measurement and the measurement result are very large and are based on relatively long traceability chains, which often involve the use of artefacts requiring calibration and complex data processing steps. Apart from a special case for the semiconductor industry where there has been long development towards automation, which gave rise to the use of a completely different class of instruments and toolchains, not much has been done to bridge this gap. This complex processing chain is the reason why most SPM are left uncalibrated and why dimensional nanometrology can serve as a good example of digital transformation in complex measurement techniques. This is also supported by the existence of the widely used open-source SPM data processing software Gwyddion[8] that has strong links to the metrology community and a broad multi sector user community that reaches both academic and industrial SPM users. Gwyddion is therefore a natural platform for disseminating and promoting the digitalisation ideas developed in this project to a wide audience. On the other hand, the only way to handle the complexity of calibration tasks systematically is to simplify the process right from the beginning, working together with instrument manufacturers to address the missing samples, methodology and data processing routines at the instrument level.

Metrological problems arising from current data management practices

The data collected by SPMs are in a raw form and include many processing steps, either at instrument or user level, in order to obtain a value for the measurand. If such results are used in any digital traceability chain, they can be very far from the original measured values, and for complete traceability, knowledge of the data processing steps, and parameters, is necessary for the reproducibility of the results. Moreover, as observed, the human influence in data processing is large[9] and without deeper knowledge of the nature of the data processing methods, users can handle data incorrectly, leading to errors in the range of tens of percent[10] or even more fundamentally, they can evaluate data using a sub-optimal method[11]. SPM data processing is based on steps that are applied for the correction of various instrument errors: tilt between the probe and the sample reference system, mismatch of the individual profiles, noise, tip convolution and instrument drift. Some of these effects might be corrected inside the microscope in a black-box manner, but some are left to be corrected by the user. The correction process removes valuable information about the microscope’s performance and if done by the random choice of the operator, this leads to bias in the results[10] or to non-repeatable results being acquired.

Even though metrology institutes have developed several calibration methodologies for SPMs[12], there is still a large gap between their recommendations and what the real instrument users are doing, as demonstrated by an AFM comparison[13]. The reference samples, which are used to calibrate the microscopes (i.e., to be used as calibration samples), are also far from being digital, as they are based on e.g., a grating with a single pitch value and they are not designed for an automated measurement process. When a reference sample is calibrated, typically using a metrological microscope, much more information is acquired (e.g., global sample flatness, local roughness, contamination) and then thrown away afterwards. Moreover, novel calibration samples containing additional (a-priori) information and information with a higher metrological quality have been developed (silicon steps which are a secondary realisation of the metre or self-assembled patterns connected to a database of positions), but currently this a-priori information cannot be taken into account during the calibration, and it is not fully reflected in the traceability chain.

In the data handling area, existing ISO standards are not frequently used, and they are unable to handle more advanced SPM big-data regimes (high-speed, force volume, etc). Data coming from different instruments cannot be processed using software from other instruments even though the measurement is the same and, in some cases, older data from the same instruments cannot be processed easily. The metadata do not contain the data processing steps, and, in principle, the stored data methods have no means to keep raw data combined with processing steps, allowing an independent review of the data processing and uncertainty propagation through it. This prevents effective long-term access to measurement data.

The steps needed to improve data handling in dimensional nanometrology

In the past, some solutions to bridge gaps in the data handling in SPMs were developed. Some of the authors of this project developed widely used open-source software called Gwyddion, which brings the necessary interoperability to the SPM world, including both data handling and processing. The goal of this project is to bring the data processing methodology and its application closer to the hardware at an instrument scale. This needs to be undertaken by metrology institutes and instrument manufacturers.

The recent advances in the development of DCCs, and the future requirement for digital product passports, offer great opportunities for structured and standardised sharing of calibration and correction information to improve confidence in measurement data. This project will provide interfaces for the digital workflow of data acquisition, data analysis and uncertainty budgets to establish a seamless integration, which will be used to identify areas for the future focussed development of DCCs in the present, and in future, states of harmonisation and standardisation. This will support complete end-to-end digital traceability.

The ability to use Partnership funding allows the creation of a consortium covering all the interested parties – metrologists, sample developers, instrument manufacturers and end users and to create digital data handling solutions that will be compatible with the concept of metrological traceability.

The project's technical objectives address the needs listed above. The need for digital calibration samples and samples suitable for automated calibration is covered by Objective 1. The need for automated and human influence free data processing is addressed by Objective 2. The need for digital data handling and storage including all the metadata and fitting the advanced measurement regimes is addressed by Objective 3. The need for propagating the measurement uncertainty digitally is addressed by Objective 4 which also includes aspects for extension of the project findings towards other types of measurements, e.g. optical, tactile or electron microscopy.

B2.d Progress beyond the state of the art

Objective 1: Samples

Current state of the art

Metrological traceability in dimensional nanometrology is based on the use of long-established reference samples, gratings and step height standards, that are calibrated by primary nanometrology instrumentation (metrology SPMs at NMIs). Even if every SPM measurement produces a full map of the topography, and often even more channels related to it, only a single value (e.g., a step height) is extracted and passed to the next stage when establishing uncertainty. When an instrument needs to be calibrated over a wider set of measurement ranges, multiple samples have to be used, making the process very labour-intensive and error-prone. Although the present *Mise en Pratique* document[14] allows the use of silicon steps as a secondary realisation of the metre for the most demanding measurements, this is not part of most of the calibration methodologies that are used in practice.

Progress beyond the state of the art

This project will progress beyond the state of the art by developing smart calibration samples for use with automated data processing of the measurement data that is used to calibrate SPM. The focus will be on the development of four classes of new calibration samples with an intrinsically higher amount of metrological information or more versatility. This includes practically usable silicon steps that will be traceable to a crystal lattice (a secondary realisation of the metre according to the *Mise en Pratique*), smart atomic layer deposition (ALD) based samples (multi-scale, suitable for automation and self-calibration purposes), self-assembled structures with locally unique Turing-like patterns (fingerprints) (statistical, small pitch, suitable for X-ray and other methods), calibration samples with digitally encoded information and active calibration samples (which will be suitable for creating advanced virtual standards with the potential for traceability via electrically programmable quantities). The proof-of-concept development of silicon calibration samples and self-assembled structures was undertaken in EMRP JRP SIB61 CRYSTAL and this project will use this knowledge. Some of the samples will be suitable for permanent integration into microscopes for use in automated SPM calibration (e.g., multi-scale ALD samples). Other calibration samples will be more advanced and their use in digital SPM calibration is foreseen (e.g., virtual standards). The aim of this project is to make these new samples digitally ready, including definition of the measurands, the metadata needed to use them in digital information flow or the incorporation of tools for the automated location of regions of interest. Most of the calibration samples developed in this project will be developed so that they will be commercially available, or ready for commercialisation, at the end of the project.

Objective 2: Data processing

Current state of the art

SPM calibration is a multi-step process needing more reference samples and more measurements if advanced instrument parameters are to be obtained. The associated data processing needs a relatively high level of expertise in order to estimate which of the measured data are free from measurement errors or to remove these errors in the post-processing phase. This creates an additional measurement uncertainty that is often not properly handled. It also creates a barrier to performing more frequent calibrations.

Progress beyond the state of the art

This project will progress beyond the state of the art by developing a library of automated data processing routines for evaluation and quality checking, allowing propagation of calibration measurement data and associated metadata that complies with the FAIR principles, and which is independent of user influence. The library of automated data processing routines will be included in new digital assistants as tools to calibrate microscopes, to handle information about the calibration samples, to acquire measurements and to process the measurement data in order to get the parameters needed for instrument calibration. These tools will be automated to minimise the likelihood of human error. The automation will cover image quality checking and decision making about the suitability of the data for calibration, data pre-processing (levelling, defects removal) and computation of the measurement results. Recording the data correction algorithms and storing it as metadata will allow the discovery of incorrect data processing and consequently the removal of the affected data. Moreover, when automated (conventional or AI-based) methods for assessing SPM image quality are implemented, images could be checked immediately after acquisition at the instrument level, so that the samples can be re-scanned if necessary. Such on-instrument data quality assurance is a key prerequisite for performing automated calibrations, for improving imaging efficiency and for decreasing staff and material costs. Real time evaluation of the measurement process will also allow the automatic detection of non-ideal measurement scenarios (e.g., drift, insufficient scan range, excessive noise, disruptions to the measurement process). The digital assistants developed in this work will also support direct data import and export between the microscope software and digital calibration certificates. All these algorithms will be provided together with reference open-source implementations of selected workflows. The library will permit integration into open source and commercial microscope control software and a reference implementation will act as a template for digitalisation in other metrology areas. Documentary standards and good practice guides on the use of the developed software and algorithms will also be drafted and disseminated to the SPM community and instrument manufacturers so that routines can be integrated into their software. The project's software and reference datasets will be issued with licenses that will allow instrument manufacturers to provide their direct integration as digital assistants.

<u>Objective 3: Data management</u>

Current state of the art

The data that are stored by SPM are in different formats, including different types of metadata being associated with the measurements and pre-processed or raw data being used in the files. The manufacturers also often make updates without informing the end users. At present, the open-source software Gwyddion can handle more than 100 SPM file formats, that were developed in the past as a result of competition between different instrument manufacturers, including all possible types of data storage. This diversity makes comparison of the different measurements and the creation of data processing toolchains hard. From a traceability point of view, most of the information is shared in the form of a few numbers written on a sheet of paper (a calibration certificate) which is far from any digital approach and a lot of additional information that was obtained during the measurements is ignored.

Progress beyond the state of the art

This project will progress beyond the state of the art by developing tools for data management including storage of the data processing steps in the metadata in a reusable format directly associated with the data and broadening ISO compliant data formats for advanced measurement regimes (high-speed, force volume, spectroscopic, adaptive scanning) to support transfer of SPM measurement data in a manufacturing process. To achieve this, the focus will be on the digital flow of data from the digital metre through SPM data collection and processing to the delivery of the required measurands to the end user via the use of “smart reference samples” and intelligent algorithms for monitoring the measurement process and data evaluation. The digital data workflow, and all the related tools, will be beyond the state of the art and they will be this project's key output.

The data management methodology, and all the tools described above, will enable at least two digital data workflow routes to be set up:

A) Vertical route: Primary realisation - NMI - instrument manufacturer - end user:

The NMI measures a reference sample, processes the data without a user influence and issues a digital calibration certificate including all the metadata, data processing steps, raw data, etc. The manufacturer or end user opens the DCC in the microscope software or in Gwyddion. If it is in the microscope, the user runs a calibration and the microscope automatically sets all the parameters, scans the sample, evaluates it, and applies corrections if needed. In offline mode, the same procedure will be undertaken in Gwyddion in the post-processing phase.

B) Horizontal route: Instrument auto-calibration at the instrument manufacturer or end user level:

A special reference sample will be permanently mounted in the instrument. When the probe is loaded, the instrument will automatically scan the sample, determine the calibration factors, noise, tip shape, and will further use this information for corrections and/or for providing it to the stored data in a form of metadata. The instrument manufacturer, or the user, will have the history of all these data available for use in checking the state of the instrument, predicting maintenance, establishing a digital twin, etc.

More potential data flow routes will be explored together with instrument manufacturers and other project stakeholders in the initial phase of the project.

<u>Objective 4: Uncertainties</u>

Current state of the art

The uncertainty of SPMs, from outside of the metrological community, are typically not evaluated, for the same reasons that the microscopes are left uncalibrated. Thus, the instruments can only be used for qualitative measurements and not for quantitative measurements, which causes problems when trying to compare measurements from different instruments or techniques.

Progress beyond the state of the art

This project will progress beyond the state of the art by evaluating the uncertainties associated with the application of the routines leading to a digital traceability chain. Uncertainty evaluation of the digital metrological infrastructure will include the analysis of the propagation of uncertainty through the traceability chain. An uncertainty of the calibration of every instrument in this chain is part of it, including end user instrumentation. This project will provide methods to evaluate the uncertainty of the instrument calibration for SPMs and a database of the knowledge learnt from the application of the routines will be used to extend the results to other areas of length metrology with other instrumentation and at other scales e.g., stylus profilometers, optical profilometers, focus variation instruments.

B2.e <u>Gender dimension</u>

The gender dimension in this project's research is minimal. The development of data workflow tools, metadata, algorithms, or new types of standards is gender agnostic. The newly developed library of automated data processing routines, which will be usable as a digital assistant will be developed to automate calibrations and to reduce the impact of human influence on measured data in general. This will have the potential to be applied in fields other than nanotechnology. It will be a generic benefit for all the instrument users, but particularly to those of both genders who are not so mathematically skilled. This project will have a strong high-level impact in nanotechnology which, mostly, will affect all genders. However, nanotechnology has potential to improve life quality in many areas, including positive impact on various gender related aspects, e.g. on nanomedicine and drug delivery systems which can lead to improved treatments and healthcare options, including breast cancer, reproductive health, and contraception, on nanosensors which can be used to detect contaminants and pathogens in food or nano-filters can be used to obtain clean water, ensuring food and drink safety which is important in communities where women are more related to food supply. Even if the project is not directly related to these areas, if focuses on providing metrological traceability for nanotechnologies itself, which is needed for their further development and use in practice. In addition, the consortium will ensure that communication materials and dissemination strategies are inclusive and accessible to all, regardless of gender and are mindful of gender-neutral language and imagery in all documentation and presentations.

B2.f <u>Open science</u>

Open science focuses on open cooperative work and systematic sharing of knowledge and tools as early and widely as possible in the process. In the project the open science practice will be implemented as an integral methodology. A large part of the project is based on the further development and use of open software tools, either for automated data processing or for propagation of results through the metrology system up to the end user.

The project will follow open science practices as per Regulation (EU) 2021/695 establishing Horizon Europe – the Framework Programme for Research and Innovation, laying down its rules for participation and dissemination. The data management plan (DMP), the data and other research outputs generated in the project will be managed responsibly, in line with the FAIR principles. The open science principles will be followed namely in these directions:

(i) early and open sharing of research

The developed algorithms for automated data processing will either be part of the open-source software "Gwyddion" or part of a standalone tool with a permissive license that will be suitable for easy integration into instrument manufacturer's software. In both cases the software will be made publicly available during the early stages of development. Pre-prints of the project manuscript(s) will be submitted to a suitable open access repository, selecting those that are most relevant to their stakeholders. The project will also pre-register its protocol for the good practice guides produced in the lifetime of the project once it has been drafted (e.g., via the Centre for Open Science), ensuring the seamless uptake of the outcomes of relevant standardisation bodies and stakeholders.

(ii) research output management

The activities in WP1 (digitalisation) are significantly focusing on data management at different levels (during the measurement, in instrument calibration, when information is shared within the metrology system, etc.), providing guidance for suitable data management not only within the project, but also towards industry and academia. In general, the project will manage the digital research data generated in the project responsibly, in line with the FAIR principles. This will include establishing a data management plan (DMP) and regularly updating it, ensuring open access under suitable licenses and using open repositories (e.g., Zenodo) to provide access to the data created in the project, including the metadata.

(iii) measures to ensure reproducibility of research outputs

The goal of all of the project's activities, related to automated data processing, is to ensure reproducibility of data evaluation outputs. All the activities in WP3 (data processing and digital assistants) and most of the activities in WP1 (digitalisation) and WP4 (uncertainty propagation) are focusing on reproducibility. The project also includes case studies where repeated measurements, and the use of the suggested digital toolchains will be made and compared between participating institutes. Participation in these case studies will also be offered to instrument manufacturers (including those outside of the consortium) and to users from academia.

The consortium will also provide information about the research outputs/tools/instruments needed to validate the conclusions of scientific publications or to validate/re-use research data and will provide digital or physical access to the results needed to validate the conclusions of scientific publications. CMI, DFM, CEN, GUM, INRIM, NPL, PTB, VSL, and VTT are either accredited to, or work in compliance with, ISO/IEC 17025. This enables the participants to demonstrate that they operate competently and generate valid results, thereby promoting confidence in their work.

(iv) providing open access to research outputs

The project will undertake responsible management of research data in line with the FAIR principles and open access to research data. The project will provide access to scientific publications and to the algorithms and methodologies. Software outputs of the project will be open access, either covered by an open-source license or covered by a more permissive license allowing manufacturers to integrate the algorithms into their microscope control software.

Furthermore, the project will provide free links to the project's reports on the project website and participants' websites to promote their availability to stakeholders, as well as the use of social media and knowledge sharing channels (e.g., Instagram, YouTube, ResearchGate) to promote the suggested digital assistants and digital toolchains for instrument calibration.

(v) involving all relevant knowledge actors in the co-creation of R&I agendas and contents

The key for project success is a tight cooperation with key stakeholders (nanometrology instrumentation manufacturers) and end users. Project workshops with them, which start in the early phases of the project will help in steering the development of the methodology and algorithms. The project's Stakeholder Committee will also provide input and feedback to the project in order to support its work plan, results and impact activities.

Research mobility between the participants from NMIs/DIs and universities will be used to support the transfer of knowledge between these communities. Young researchers and Postdocs will also be invited to participate in training events and to join stakeholder workshops to provide feedback.

B2.g Research data management and management of other research outputs

Research data management and management of other research outputs will be addressed in accordance with the requirements of the Grant Agreement. A data management plan will be produced and submitted to EURAMET at month 9 (+ 45 days) in accordance with the Reporting Guidelines issued by EURAMET. An updated version of the data management plan will be submitted to EURAMET at month 36 (+ 60 days).

B3 Potential outcomes and impact from the project

B3.a Projected outcomes for industrial and other user communities

Establishing procedures for easy SPM calibration will increase the number of calibrated instruments in industry and academia. The key outcomes to reach this goal are the data management methodologies (metadata and their handling, data containers), the library of automated data processing routines, which will be usable as digital assistant in the microscope, and novel samples with intrinsically higher amounts of information that can be acquired and passed with them when establishing metrological traceability.

The quality of SPM calibration will also be improved, which will reduce measurement errors, by eliminating user influence and user errors, via automated routines. These will increase the number of calibrations, but these will be undertaken by self-calibration methods and the data will be propagated from advanced samples through the complete chain from primary, or secondary, realisation of the unit, through the calibration samples and instruments, up to end user measurements. This will be demonstrated in the project in cooperation with key instrument manufacturers (e.g., Bruker FR, Nanosurf, OXINST) and selected end users (e.g., Sensofar, TNO, Meopta, Infinitesima, Prior Scientific).

From a wider perspective, the proposed digitalisation chain for dimensional nanometrology will support nanoscience both at a research level and in the development of new devices prior to their upscaling for mass production. Accurate measurements can help to increase the manufacturing yield in micro- and nanotechnology areas like quantum devices, the optical and electronic industry or in material sciences. The recent AFM comparison[13] showed that several users have measurement errors greater than 10 % of the measured value. This is damaging for the production of semiconductors and quantum devices where performance is exponentially dependent on device dimensions[15]. Removal of human error in data processing and the use of metadata will lead to greater reproducibility of results and confidence in measurement data. The bias that can be introduced into data by inappropriate treatment can be far beyond 10 % without users being aware of it[9]. This has been demonstrated on roughness measurement analysis, and roughness is evaluated for many purposes in nanoscience. Similar effects were already observed, or can be expected, for other dimensional quantities. The use of pre-defined data processing pipelines leading to deterministic results, combined with automated quality checks and data processing of key types of measurands, will suppress the uncertainty related to human influence and it allow uncertainty propagation through data processing algorithms. By making the SPM traceability mode widespread, this project will help support industry to meet commission regulations. These include the European commission EU definition of nanomaterials including, for example, the chemicals´ regulation REACH (2006/1907), where validated measurements of nanomaterials in the range 1 nm-100 nm and above are required. Improved dimensional nanometrology can also fit into the European Chips Act, which is aimed at bolstering Europe’s competitiveness and resilience in semiconductor technologies and applications, which is one of the key industrial application areas for this project.

This project will also produce a digital infrastructure that can be used by other areas outside of dimensional nanometrology both within, and outside, the length area. Identification of metadata and the design of data containers in WP1 will already consider the necessary additional items for compatibility with other SPM methods (electrical, magnetic, optical, mechanical, etc) and other surface topography measurement devices (tactile, confocal, etc). Also, the data processing routines will be applicable to a wider class of surface measurement types, such as those that are commonly pre-processed (noise handling, drift compensation, non-orthogonality of axes, sample levelling, etc). The applicability of the project’s results will be demonstrated using impact case studies and three good practice guides will be created to make uptake of project results easier.

B3.b Projected outcomes for the metrological and scientific communities

Metrological and scientific communities should benefit from the key outcomes from the project, which will be fully digital data handling in SPM calibration, novel smart samples, automated data processing and novel uncertainty handling concepts in the traceability chain for dimensional nanometrology. The main goal is not to develop a novel traceability chain, but to simplify its application in the daily use of SPMs and by this to convert the majority of SPMs from being uncalibrated to regularly calibrated.

The work in this project will set up and apply the digital metrology chain from the metre realisation through to end users both in NMIs and the wider scientific community. Dimensional nanometrology supports other areas which NMIs work on, such as materials science and quantum metrology, through accurate device fabrication and in the life sciences through correlative microscopy. These will directly benefit from the simple calibration processes developed within this project. This will be demonstrated in this project by participants that are active in fields beyond dimensional nanometrology. This project will develop a digital framework to act as an exemplar of how to create a digital traceability chain that will be applicable in other areas of metrology which require complex data processing to obtain a value of the measurand. Example areas outside of dimensional metrology include the measurement of other physical quantities at the microscale and nanoscale and medical imaging, where the difficulties of maintaining a chain through multiple stages can mean that traceability is lost. The implementation of a digital framework will improve the current accuracy of nanometrology in nanoscience.

The samples developed in this project will be suitable for providing metrological traceability even for the most demanding scientific experiments and scenarios. The samples and their properties have been chosen so that they can be used in conjunction with many different types of dimensional nanometrology instruments. Silicon steps have been developed in the past, however they have not reached sufficient maturity to be widely used, even if they were successfully used for both SPM and optical microscope calibration. Self-organised lateral standards have the potential of being a cost-effective alternative for lateral calibration in the range below 100 nm, where traditional gratings become very expensive, moreover, they have been tested for use with other analytical techniques, e.g., X-ray based. Multi-scale “digital” patterns developed for ALD samples will be suitable for the automated detection of multiple calibration parameters and the samples will be produced in a cost-effective manner to reduce their price. Active samples represent an alternative to traditional traceability and have the potential to be used for larger scale measurement instruments. Most of the developed samples will be available after the project (at least the silicon steps, multi-scale patterned ALD samples and the self-organised lateral standards) and the preparation of documentation, and the path to commercial availability of the samples, are part of this project (Task 5.2).

Research papers will also be submitted for publication in high impact peer-reviewed journals and as part of the knowledge transfer. Moreover, project results will be presented at various conferences, webinars and other impact related activities. To steer the key project development concepts to be applicable to as wide a community as possible, a SPM digital transform workshop will be organised at the beginning of the project where instrument manufacturers, academia and NMIs will be invited.

B3.c <u>Projected outcomes for relevant standards</u>

The consortium’s engagement with standardisation committees and metrology committees, and the projected outcomes for relevant standards are described in section C, Task 5.1.

B3.d <u>Projected wider impact of the project</u>

Economic impact

It is predicted that the nanotechnology market will be almost 20 times larger in 2030 than it was in 2020[16]. Fully automated and frequent calibrations, supported by instrument manufacturers, will not only have direct impact on the measurements, but it will also allow storage of all the metadata obtained during data pre-processing, e.g., contamination and wear. This can be used to evaluate long term metrological microscope performance and to better plan instrument maintenance, which is important in industrial environments where downtime is costly. Aggregated long term performance data coming from multiple instruments will provide valuable information to manufacturers enabling them to improve instrument performance. The digital calibration and data processing chain will lead to more reliable instrumentation and measurement results. This will bring greater confidence in quality control during manufacturing, particularly when scaling up device production from prototypes to large scale mass production. This will lead to less waste (reduced production costs) and to shorter laboratory to fabrication transfer times. The EU has identified nanotechnology as being essential for supporting the key enabling technologies for Europe[17] that are essential to enable advanced manufacturing to meet the current and future challenges of today’s society across many sectors (electronics and semiconductors, healthcare and life sciences, environmental protection, clean energy generation, quantum device manufacture and aerospace). Many macro-sized products rely on nanoscale features or components, e.g., structured surfaces on wind turbines and hard disks. Very often, the functionality of nanoscale products depends critically on their dimensions (e.g., quantum devices and semiconductors) making the accurate control and measurement of dimensions essential for successful production.

Environmental impact

Besides the strong industrial and economic impact, this project will also have significant longer-term environmental impact through improving manufacturing efficiency and the development of new nanotechnology products where performance is dependent on dimensional properties. Nanotechnology is making significant improvements in technologies for protecting the environment. Nanoscale devices are being used for enhanced sensing, treating, and remediating environmental contaminants. In the future, it may be possible to prevent pollution with the help of nanotechnology. For instance, nanosensors can be used to detect and track pathogens (germs), contaminants, nutrients, environmental characteristics (light/dark, hot/cold, wet/dry), heavy metals, particulates, and allergens[18].

From an energy point of view, the improved nanomanufacturing industry will result in products with lower energy consumption or bring better energy harvesting capability. For instance, nanotechnology is making solar power cheaper through the use of organic photovoltaic cells (OPV) instead of the more common silicon crystal solar cells. Nanometrology could help to control the nanoscale morphology, which could significantly raise conversion efficiency.

Social impact

Nanotechnology has broader societal implications and poses broader social challenges. As the APEC Centre for Technology Foresight observes: “If nanotechnology is going to revolutionise manufacturing, health care, energy supply, communications and probably defence, then it will transform labour and the workplace, the medical system, the transportation and power infrastructures and the military. None of the latter will be changed without significant social disruption”[19]. Dimensional nanometrology addresses metrological traceability not only for nanotechnology, but also for a range of other industrial sectors that have an impact on employment and quality of life, such as semiconductors.

European impact

Digitalisation is an area ripe for exploitation by NMIs and businesses of all sizes across Europe because the cost barriers are low. The main aspect that holds participation back is a lack of knowledge. This project will address that lack of knowledge by creating a generic framework for the digitalisation of a metrology process, using SPMs as an example of good practice. This approach will enable end users in NMIs and beyond to gain confidence in digital approaches and to develop their own bespoke applications that follow the SPM example. The use of SPMs in European dimensional nanometrology is widespread, however links between SPM calibration in metrology institutes and SPM use in industry and academia are still weak. There is a large SPM innovation potential in Europe, including several SPM manufacturers and many academic organisations dealing with SPM methodology. This, combined with the capabilities of European NMIs to handle the complex data processing tasks, will lead to a significant improvement in data flow in dimensional nanometrology in the route from metrologist to regular user. Competitors on the global market such as China or the USA are dramatically increasing their efforts in nanotechnology. This is reflected for instance in the number of nanoscience articles published in 2019 with China and USA in positions 1 and 2. Germany, as the leading country in Europe, is in 6th position with approximately 10 % of the output of China[20]. This underpins the need for a comprehensive reaction at the European level, in order to improve the competitiveness and resilience of European industry.

B3.e Summary of the project’s impact pathway

SPECIFIC NEEDS	EXPECTED RESULTS	DCE MEASURES
What are the specific needs that triggered this project? The EU has identified nanotechnology as essential for supporting the key enabling technologies for Europe. However, the methodologies and tools for digital data flow in dimensional nanometrology do not exist to support this, including: - missing agreed metadata and digital containers to transfer the data to the next stage of the calibration chain. - missing calibration samples that would provide more information than the few values that are currently available. - missing a unified approach to process data without human influence, and without user expertise. Getting calibration results from them can lead to errors up to tens of percents. - missing an understanding of how the uncertainties should be transferred automatically within the SPM traceability chain. - the lack of automation in SPM calibration, and the use of paper calibration certificates, means that manual errors can occur.	*What do you expect to generate by the end of the project?* KER1: Good practice guide for digital flow in dimensional nanometrology. KER2: Three types of newly developed smart calibration samples (crystalline silicon step heights, self-assembly based lateral structures (DBC) and ALD multiscale patterns) with intrinsically higher amounts of information that can be digitally transferred to the next stage of the calibration chain, and which will be commercialised or ready for commercialisation. KER3: Library, for automated data processing in SPM, with a license that permits it to be integrated into the software used by SPM manufacturers as digital assistants. KER4: Methodology for the propagation of measurement uncertainty within the traceability chain for dimensional nanometrology.	*What dissemination, communication and exploitation measures will you apply to the results?* **Dissemination towards scientific community and industry:** Participation in 15 scientific conferences and 3 stakeholder workshops / exhibitions including the SPM digital transform workshop. 3 good practice guides, open-source software, a library of automated data processing routines with a permissible license and publication of 9 scientific papers. **Dissemination towards standardisation bodies:** Participation as expert members in the activities of the technical committees and working groups. Reporting of project results at TC and WG meetings, in particular ISO/TC201/SC9 “Scanning Probe Microscopy” and ISO/TC229/JWG2 “Nanotechnologies: Measurement and characterisation”. **Communication**: Creation of a Stakeholder Committee. Project website. 5 e-newsletters. Publication of articles in the popular press and trade magazines. Social media campaigns. Flyers, posters and factsheets. Videos addressing industry

		and the public. The SPM digital transform workshop and channels to SPM users via the Gwyddion user community. **Exploitation:** Exploitable items include novel publicly available data handling methods, commercially available smart samples and data processing algorithms licensed to be suitable for SPM manufacturers' software integration. These exploitable items will be practically demonstrated in case studies, which will reach SPM manufacturers and end users.
TARGET GROUPS	**OUTCOMES**	**IMPACTS**
Who will use or further up-take the results of the project? Who will benefit from the results of the project? **Standardisation committees**: ISO/TC201/SC9, ISO/TC229/JWG2, CEN TC352, VAMAS TWA 2, CCL Task group on Digitalisation, and other international and national committees. **Industry**: Scanning Probe Microscopy (SPM) instrument manufacturers *(within the consortium: Bruker FR, Nanosurf, OXINST, stakeholders: Infinitesima, Nenovision, Prior Scientific, Mad City Labs)*, SPM end users. General scientific audience working in the area of nanotechnology, materials science, optics, semiconductors and similar areas working with samples at the nanoscale. **Metrology**: Dimensional nanometrology, length metrology.	*What change do you expect to see after successful dissemination and exploitation of project results to the target group(s)?* Commonly agreed metadata definitions and vocabulary to handle data coming from different SPMs. Significantly increased number of SPMs that are calibrated due to automation of the calibration process. Demonstrated integration of the project's data processing library in manufacturer's software for use as a digital assistant. Simplified calibration routes that are less affected by user influence. Better interoperability when transferring the measured data between different users.	*What are the expected wider scientific, economic and societal effects of the project contributing to the expected impacts outlined in the work programme and call scope?* **Scientific**: General recommendations for data handling in surface topography measurements, novel types of reference samples, and data processing routines applicable to dimensional nanometrology, but also to other areas of metrology (e.g., digital transformation, materials science, quantum metrology, life science, medical imaging). **Economic**: Components for automated calibration added by SPM manufacturers (unfunded beneficiaries and stakeholders) will result in reduced calibration costs by using automated measurements. It will also lead to reduced measurement uncertainty and to increased measurement reliability by increasing the fraction of calibrated SPMs. **Societal**: Support for nanotechnology that has an impact on the quality of life.

B4 The quality and efficiency of the implementation

B4.a <u>Overview of the consortium</u>

CMI has had expertise in dimensional nanometrology since 1999, including all the aspects of SPM instrumentation and methodology development. CMI is also active in open-source software for SPM data processing development (Gwyddion, developed together with another participant, BUT) and has experience in advanced data processing including the use of AI. CMI will coordinate the project and lead WP3, which is dedicated to data processing. CMI worked in the past on numerous national and international projects in different roles including project coordination.

CEM has extensive experience in calibrating dimensional standards, as required by accredited laboratories and cutting-edge industries, and in providing them with the necessary traceability. CEM is active in standardisation in dimensional metrology and nanometrology fields through the Spanish national standardisation body, UNE. CEM will participate in the extension of the project's results towards larger scales (all WPs) using its 3D optical profiler and laser focus sensor instruments and in the inclusion of the developed digital frameworks into the Spanish national metrology system in WP5.

DFM has built competence and calibration capabilities (including KCDB entries) with AFM/SPM since 1992. DFM has developed specialised competences in the calibration of AFM/SPM microscopes using (transfer) standards (including atomic step heights in silicon) and through its new quantum materials laboratories DFM has access to advanced fabrication techniques in ultra-high vacuum, such as MBE. DFM will mainly contribute to advanced sample manufacturing (WP2) and to the analysis of uncertainty propagation through automated algorithms and digital toolchains (WP4).

GUM has been building its competence in nanotechnology since the early 2000s when they took part in the Nano2 comparison. GUM is gradually developing its capabilities in nanotechnology within the framework of the newly developing campus in the city of Kielce, including a state-of-the-art large area nanopositioning system combining SPM and optical measurements, and will use this project to establish the digital framework for emerging nanometrology fields in Poland. GUM will contribute to the extension of the project's results towards larger scales and optical measurements (WP1, WP4, WP5).

INRIM has expertise in nanofabrication and dimensional nanometrology and will provide facilities including metrological AFM, commercial AFM, optical, focus variation and interferometric instruments, photolithography, and nanolithography by electron and ion beams and by self-assembly. INRIM will lead WP2, which focuses on the fabrication of samples with a high information content, and on the fabrication of advanced length standards based on the self-assembly of block-copolymers.

NPL has expertise in digitalisation, and traceable AFM metrology, covering both instrumentation development and the measurement techniques that are relevant to this project. NPL was instrumental in the adoption of the lattice parameter of silicon as a secondary metre realisation. It currently chairs the CCL Working Group for nanometrology. NPL's Data Science department (DS) has completed many successful digitalisation projects involving the modelling of heterogeneous and complex data flows in industrial metrology, bioimaging and healthcare. The department is involved in the activities of EPM TC-IM projects TC 1448 (Digital Calibration Certificates) and TC 1449 (Research Data Management), whilst also contributing to the development of the SI Digital Framework through a secondment into BIPM. DS will lead the activities in WP1 to design digital tools for SPM data traceability. It will also provide guidance on uncertainty propagation for WP4.

PTB has expertise in length metrology, the production of crystalline standards and is one of the leaders of digitalisation in metrology. They are actively supporting standardisation at the international scale (e.g., ISO TC229, TC-L, TC-M, VAMAS) and they contribute to the national mirror committees. PTB will contribute to all 4 WPs, namely by providing expertise in the digitalisation aspects (WP1), further developing standard samples based on crystalline silicon (WP2), developing digital assistant tools to support the identification of the region of interest (ROI) on calibration artifacts and they will lead WP5, which focuses on impact. PTB's facilities include a cleanroom centre where crystalline standards can be produced and tested using a wide range of metrology SPM and optical measurement instruments.

VSL has extensive experience in nanometrology using AFM, including custom built active samples for AFM calibration, data processing and task specific uncertainty calculation. VSL will mainly participate in WP1 and WP2, focusing on active calibration samples based on monocrystalline actuators. On top of facilities for the calibration of these virtual standards, VSL has devices and long-term experience in the area of SPM and scatterometric measurements.

VTT has long experience in ALD methods and dimensional nanometrology. Metrological AFM, commercial AFM, and optical and interferometric instruments are available in state-of-the-art laboratories, with excellent conditions, for use in this project. In WP2 VTT will design and produce step height standards based on the ALD technique. VTT will lead WP4 focusing on uncertainty propagation through digital toolchains.

BUT has experience in advanced SPM data processing, including artificial data synthesis, novel data processing algorithm development and statistical analysis. BUT has jointly led the development of the Gwyddion open-source software, which will be developed in this project, since its beginning. BUT will contribute to all the algorithms and software work in the project (WP1, WP3, WP3, WP5).

NFI, Nearfield Instruments develops and delivers ground-breaking metrology solutions for process control in the manufacturing of advanced semiconductor integrated chips. NFI products provide high-throughput inline SPM measurements of topography and subsurface structures very accurately and with high sensitivity. The volumes and rates of data acquisition, as well as massive metrology and data fusion between different modalities require unified standards, and NFI is interested in driving the industry to common standards that are compliant with semiconductor manufacturing requirements. NFI will contribute with requirements (WP1), the testing of algorithms (WP3) and extending project results towards industrial practice (WP5).

PWR, the Wroclaw University of Science and Technology Nanometrology Department has developed several methods and techniques for describing the surface of material and device parameters in a quantitative way. Various MEMS solutions have been applied in the Nanometrology Department's investigations, which makes these experiments distinguishable. PWR will contribute expertise to the design and application of active calibration devices in WP2.

TUBS TU Braunschweig, particularly the Schilde group at iPAT, excels in image processing and machine learning within particle technology. They have developed advanced frameworks using Generative Adversarial Networks (GANs) for image creation, analysis, and classification. Their work spans various imaging methods like Scanning Electron Microscopy (SEM), X-ray Computed Tomography (XRCT), and dynamic image analysis tools such as QicPic and Camsizer. The expertise of TUBS will mostly be used in WP2 and WP3 where AI based tools will be developed.

Bruker FR has led the expansion of atomic force microscope capabilities, starting with the introduction of the first commercial system in the 1980s. Today, Bruker FR has several divisions focusing on all aspects of AFM technologies & market segments: AFM probes, AFMs applied to life science applications, AFMs applied to materials science applications and AFMs optimised for industrial, automated characterisation supporting advanced in-line dimensional metrology in semiconductor and data storage manufacturing (with hundreds of installed bases in worldwide semiconductor fabs). Bruker FR will contribute to WP1, WP2, WP3 and WP5 with expertise on user expectations, and will participate in the testing of the developed methods and samples. They aim to implement these in their products where applicable.

Nanosurf is a manufacturer of atomic force microscopes. Having started in 1997 as a manufacturer of low-budget instruments for the educational sector, it has grown to now provide high-end instruments for academic research and industrial quality control. Metrological standards are a cornerstone for this technology. Nanosurf will provide expertise on end-user expectations and implementation into commercially viable solutions; it will participate in testing of the developed methods and samples and aims to implement these in its standard operating procedures and instruments, where applicable, contributing to WP1, WP2, WP3 and WP5. Nanosurf is an associated partner to all internal beneficiaries.

OXINST, Oxford Instruments is a leading manufacturer of atomic force microscopes offering both conventional and interferometric detection of the probe motion. Since 1999 they have promoted accuracy in positional and force measurements, advancing the state of the art with groundbreaking sensors and techniques. OXINST will contribute expertise on customer expectations and practical requirements for implementation (WP1, WP5), participate in the testing of samples (WP2) and libraries (WP3), including them in their products, where applicable. OXINST is an associated partner to all internal beneficiaries.

Section C: Detailed project plans by work package

The four technical work packages are aligned to the project objectives. The aim of WP1 is to build the necessary digital infrastructure and information, including vocabularies, metadata definitions, data flow models and data containers, obtaining inputs from the other WPs and providing templates and concepts for work within the other WPs. WP2 focuses on the novel calibration samples and the increased amount of information that can be digitally passed through the traceability chain. WP3 focuses on algorithms for processing the data measured on these samples, reducing the impact of human influence and enabling automation. WP4 focuses on uncertainty estimation – related to the samples from WP2 and the data processing methods from WP3 – and on extension of the project's concepts towards other types of measurements. The impact work package, WP5, brings together the technical outputs in case studies on how to use the digital workflow in practice.

C1 WP1: Digital information flow

The aim of this work package is to create the data management tools and guidance needed to support all of the digitalisation-related tasks in this project. The information flow, which accompanies dimensional nanometrology workflows, including calibration, measurement, processing and uncertainty quantification will be captured in a semantic data model, e.g., machine- and human-readable structured descriptions of the data elements and their relationships. This model will be used to help AFM and SPM users in several ways. Firstly, they will feed into recommendations on metrologically traceable data collection, aiding the reproducibility of results and saving resources. Secondly, they will be used to design an annotated SPM data container (a data format containing data and metadata) for storing nanometrology measurements. The recommendations on metrologically traceable SPM data collection will be disseminated via a good practice guide. The annotated data container will be published in an openly accessible repository such as Gitlab or Zenodo.

The use of a SPM data container will enhance artefact measurements in this project as machine-readable measurement metadata will be elaborated within other work packages, such as smart samples (WP2), measurement results and processing steps from the analysis software (WP3), as well as information about the measurement uncertainty (WP4). The annotations in the SPM data container will enhance the state-of-the-art ISO-compliant data formats for advanced measurement regimes (high-speed, force volume, spectroscopic, adaptive scanning), which are used in manufacturing industries, through the inclusion of recent developments in metrological semantic models such as DCCs and SI Reference Point. The SPM data container will be implemented in an open-source vendor-neutral format to support the FAIR principles.

This will be undertaken in the following tasks:

Task 1.1 aims to collect information about metadata related to the measurement process, data processing and uncertainty evaluation, and to build a common vocabulary for handling data coming from different sources.

Task 1.2 aims to set up a digital data flow model to support handling of the data and metadata through the traceability chain.

Task 1.3 aims to develop a data container that will be capable of storing and internally organising SPM data and metadata.

Task 1.4 aims to document the tools and concepts developed in WP1 and to provide information about it for further use by metrologists, instrument manufacturers and end users.

C1.a <u>Task 1.1: Information collection</u>

The aim of this task is to collect information for the models and standards that are currently used to describe SPM instruments, smart samples, data processing and uncertainty quantification, and to select those models that can be aligned with the SI Reference Point vocabulary and related XML schemes.

Activity number	**Activity description**	**Participants (Lead in bold)**
A1.1.1 M3	NPL will create at least 1 structured template for metadata collection, and they will share it with PTB, CMI, CEM, DFM, GUM, INRIM, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf and OXINST.	**NPL**, PTB, CMI, CEM, DFM, GUM, INRIM, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST

A1.1.2 M1	PTB, with support from NPL, CMI, CEM, DFM, GUM, INRIM, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf and OXINST, will define a standard vocabulary for the project, which will build on the existing standards and terminologies that are used in dimensional metrology. The project's standard vocabulary will be aligned with the SI Reference Point vocabulary and used in further activities in this project.	**PTB**, NPL, CMI, CEM, DFM, GUM, INRIM, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST
A1.1.3 M3	NFI, with support from the SPM manufacturers group in the project (Bruker FR, Nanosurf, OXINST) will collate state-of-the-art information about the data flows and related needs in high-end industrial segments (e.g., semiconductors). This will encompass a literature review and technical information from the SPM manufacturers group.	**NFI**, Bruker FR, Nanosurf, OXINST
A1.1.4 M3	BUT and CMI will use the structured metadata template from A1.1.1 to collate the metadata descriptors from the existing SPM data formats that are supported by Gwyddion software. The acquired information will be reviewed by the SPM manufacturers group in the project (Bruker FR, Nanosurf, OXINST) and it will then serve as a starting point for discussion at the open SPM digital transform workshop (A5.1.5), which will be attended by project stakeholders and other interested SPM manufacturers and industrial users.	**BUT**, CMI, Bruker FR, Nanosurf, OXINST
A1.1.5 M3	INRIM, VSL, PTB, TUBS and VTT will draft the metadata descriptors, which will be needed for using SPM smart calibration samples and reference objects. PTB will describe height standards (silicon steps), VSL and PWR will provide information about programmable standards (active samples), VTT will provide information about multi-scale ALD samples, while INRIM will describe self-assembled structures and give access to their fabrication database for lateral standards (so that samples can be created with specific properties). This will provide an example of a metadata source coming from the manufacturing phase of the samples. At least 10 stakeholders and manufacturers will be contacted (via email or at meetings) and asked to provide examples of use cases that may not be covered above, for example wafer flatness, SPM tip characterisation etc. The acquired information will be reviewed by the SPM manufacturers group within the project (Bruker FR, Nanosurf, OXINST) and will serve as a starting point for discussion at the open SPM digital transform workshop (A5.1.5), which will be attended by project stakeholders and other interested SPM manufacturers and industrial users.	**INRIM**, VSL, PTB, TUBS, VTT, PWR, Bruker FR, Nanosurf, OXINST
A1.1.6 M6	BUT, with support from CMI, will prepare a written summary of the typical analysis steps and software parameters that are foreseen to be used in WP3 (Digital assistants) during the data processing workflows. The summary will also include the related metadata that describes the data analysis and information on how traceability will be maintained during the data processing workflows.	**BUT**, CMI
A1.1.7 M9	VTT and VSL will collate their own pre-existing metadata that describes the uncertainty calculation that will be used in the digital data workflow uncertainty evaluation methods in A4.1.1-A4.3.5. This metadata will be attached, along with the data, to SPM calibration certificates.	**VTT**, VSL
A1.1.8 M10	GUM and CEM will review the information obtained in A1.1.4-A1.1.7 and will add the data flow descriptions and metadata that will be needed to extend the project's results to larger scales (e.g., optical and tactile measurements) or other quantities (e.g., electrical and mechanical properties).	**GUM**, CEM
A1.1.9 M12	NPL, with support from CMI, CEM, DFM, GUM, INRIM, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf and OXINST, will collate the information from A1.1.2-A1.1.8 in a digital workflow model, which will be formalised as a documented flow chart. The flow chart will be reviewed by all participants and, if necessary, amendments will be made based on the feedback received.	**NPL**, CMI, CEM, DFM, GUM, INRIM, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST

C1.b Task 1.2: Digital information flow modelling

The aim of this task is to capture the information flow, which accompanies dimensional nanometrology workflows, including calibration, measurement, processing and uncertainty quantification in a semantic data model. This model will consolidate the data and data processing descriptions that were identified in

A1.1.1-A1.1.9. It will contain raw data, instrument, calibration artefact, calibration procedure and data processing descriptions as well as metadata about all of the above. A semantic model can be represented as a structured text file that lists data elements such as the instrument's name, or measurement conditions, and it also formalises the relations between them (for example, a measurement was performed on an instrument X using calibration sample Y, processed using method Z and this yielded uncertainty U).

Activity number	Activity description	Participants (Lead in bold)
A1.2.1 M6	CMI, with support from BUT, will use the findings from A1.1.4, and the results of the SPM digital transform workshop (A5.1.5), to prepare a structured list of the minimum required metadata for raw SPM data. The SPM manufacturers group within the project (Bruker FR, Nanosurf, OXINST) will review this list and, if necessary, amendments will be made based on the feedback received.	**CMI**, BUT, Bruker FR, Nanosurf, OXINST
A1.2.2 M12	INRIM, with support from PTB, VSL, VTT and PWR, will use a template provided by NPL (A1.1.1), and the results of the SPM digital transform workshop (A5.1.5), to implement a digital workflow for the handling and refinement of SPM related data. This implementation will use the metadata descriptors for SPM smart calibration samples and reference objects from A1.1.5. PTB will focus on height standards (silicon steps), INRIM on self-assembled samples (e.g., diblock copolymer-based samples), VTT on multi-scale samples for automated SPM calibration and PWR and VSL on programmable standards (active samples).	**INRIM**, PTB, VSL, VTT, PWR, NPL
A1.2.3 M12	BUT, with support from CMI and NPL, will use the results of the SPM digital transform workshop (A5.1.5) to compile a list of metadata definitions for the analysis software used, its analysis steps, the allowed inputs and processing parameters, and the respective outputs that will be needed to capture all transformations applied to raw SPM data. This initial longer list will be used to create a shortlist of the descriptions of the workflows that will be included in the model in A1.2.5.	**BUT**, CMI, NPL
A1.2.4 M20	Using input from A1.1.1 and the results of the SPM digital transform workshop (A5.1.5), PTB, with support from CMI, NPL, VSL, VTT, INRIM, GUM and TUBS, will prepare a set of minimum metadata definitions for the administrative metadata that will be collected during the SPM calibration process and the subsequent creation of measurement data. The metadata definitions will be aligned with the DCC that are based on the XML schema and other related activities that are required for a digital infrastructure (e.g., quality infrastructure or virtual calibration) and with the SI Digital Framework via appropriate CMC identifiers, where applicable.	**PTB**, CMI, NPL, VSL, VTT, INRIM, GUM, TUBS
A1.2.5 M24	NPL, with support from CMI, CEM, DFM, GUM, INRIM, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf and OXINST, will design and test a machine-readable semantic data model by using the metadata definitions from A1.2.1-A1.2.4 and the data processing constraints defined in A1.2.3. This will include (a) calibration of SPM smart reference samples, to support the metrological traceability chain, and the calibration of an SPM using these samples (the latter will include sample specific aspects like auto-location of areas of interest, the use of 'find me' structures, or the use of multi-scale patterns) and (b) use of the calibration data within the SPM for subsequent unknown sample measurements. The model will be machine-readable, it will adopt concepts from existing digitalisation activities, such as the DCC and it will include processing workflow using the sequence, component and activity diagrams. It will also be aligned with the SI Reference point by using the Digital Object Identifiers (DOIs) provided for quantities and units.	**NPL**, CMI, CEM, DFM, GUM, INRIM, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST

C1.c Task 1.3: Design of a SPM data container that implements digital traceability

The aim of this task is a) to develop a generic annotated SPM data container (a data format containing data and metadata) using the semantic data model developed in A1.2.5 and b) to test the usability of this container for different SPM physical data acquisition, processing and storage scenarios, including the calibration of smart SPM reference samples for their use within the traceability chain, the calibration of an SPM using these samples, and the use of the calibration data for SPM measurements on unknown samples.

Activity number	Activity description	Participants (Lead in bold)
A1.3.1 M9	CMI, with support from PTB, BUT and NPL, will setup minimum working examples of SPM physical data acquisition, processing and storage scenarios including all of the considered calibration samples. NPL will provide a pre-existing software quality	**CMI**, PTB, BUT, NPL

	template, and this will be used by CMI, with support from PTB, BUT and NPL, to capture these scenarios.	
A1.3.2 M12	Using the scenarios defined in A1.3.1, BUT, with support from CMI, will generate a set of realistic synthetic end-to-end data examples, which simulate the processing and annotation of raw SPM data all the way to the measurement results. This will be used as sample data for consistency checks in A1.3.3 and file container implementation in A1.3.4.	**BUT**, CMI
A1.3.3 M18	NPL, with support from GUM, will test the data annotation consistency and the quality of the semantic data model during its development in A1.2.5 (until M18, November 2026) using the synthetic data examples from A1.3.2 and the standardised vocabulary created in A1.1.2. This will provide feedback for the use of the semantic model in A1.3.4.	**NPL**, GUM
A1.3.4 M24	NPL will implement the annotated SPM data storage in a generic file container, including all the metadata related to measurement, data processing, uncertainty, and the semantic data model, as developed in A1.2.1-A1.2.5 and A1.3.1-A1.3.3. A sample implementation file container will be tested in at least three SPMs by PTB and CMI, as well as with the synthetic data provided by A1.3.2. The container will be applicable to all the state-of-the-art data types needed in SPM data calibration tasks, including aspects of advanced SPM regimes (high-speed, force volume, spectroscopic, adaptive scanning). The developed container concept will be used when developing data processing routines, serving as a general basis for data handling in A3.2.4-A3.2.9 and for data storage development in A3.3.4.	**NPL**, PTB, CMI

C1.d Task 1.4: Software, data container and semantic data model documentation

This task aims to prepare software, data container and semantic data model documentation. The outputs of this task will be a good practice guide, documented software and the publication of an SPM data container in an open-access repository in a FAIR-compliant manner. The good practice guide will be aimed at SPM manufacturers, who will implement it, and at industrial end users, who will use it.

Activity number	Activity description	Participants (Lead in bold)
A1.4.1 M30	Using input from A1.3.1 and A1.3.4, PTB, with support from NPL, BUT and CMI, will develop software documentation for the generic SPM data container and accompanying documentation with an example of how the SPM data container will be implemented. PTB will publish the generic SPM data container and the documentation in an open access repository such as Gitlab or Zenodo. PTB will also prepare a chapter on the use of the generic SPM data container for the D1 good practice guide.	**PTB**, NPL, BUT, CMI
A1.4.2 M28	NPL, with support from CMI, INRIM, BUT and VSL, will describe the machine-readable semantic data model and processing workflow using the sequence, component and activity diagrams developed in A1.2.5, as a chapter of the D1 good practice guide.	**NPL**, CMI, INRIM, BUT, VSL
A1.4.3 M27	Using input from A1.1.5 and A1.2.2, INRIM, with support from PTB, VTT, VSL, PWR and NPL, will describe the process for the calibration of SPM smart reference samples as a chapter of the D1 good practice guide.	**INRIM**, PTB, VTT, VSL, PWR, NPL
A1.4.4 M28	Using input from A1.1.7, CMI, BUT, VTT and GUM will jointly write the D1 good practice guide sections on how to perform processing of SPM data and how to quantify SPM uncertainty.	**CMI**, BUT, VTT, GUM
A1.4.5 M31	Using input from A1.4.1-A1.4.4 and A5.1.7, NPL, with support from CMI, CEM, DFM, GUM, INRIM, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf and OXINST, will compile and review the good practice guide for digital flow in nanometrology including aspects of data and metadata handling, data formats, and application to advanced measurement regimes (high speed, force volume, spectroscopic, adaptive scanning). Once agreed by the consortium, the coordinator on behalf of NPL, CMI, CEM, DFM, GUM, INRIM, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf and OXINST will submit the good practice guide to EURAMET as **D1**: *"Good practice guide for digital flow in nanometrology including aspects of data and metadata handling, data formats, and application to advanced measurement regimes (high speed, force volume, spectroscopic, adaptive scanning)".*	**NPL**, CMI, CEM, DFM, GUM, INRIM, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST

C2 WP2: Smart calibration samples

The aim of this work package is to develop and supply smart calibration samples (containing intrinsically high metrological information) for use with the automated measurement data processing that is used to calibrate SPM. The smart calibration samples will have well-known geometrical features and will be used as inputs for the digitisation of the information flow, which accompanies dimensional nanometrology workflows. The consortium will provide a significant step forward with respect to commercial calibration standards in terms of traceability, ease of use, richness of information, dynamic performance and cost effectiveness. Four types of samples will be produced at different stages of the project, to tackle specific aspects of the digital calibration and validation routines, covering different types of SPM experiments:

- Step height crystalline standards (referred to as Group A samples) are traceable to the SI via the lattice parameter of silicon and are a secondary metre realisation. The dimensional calibration is transferred to the task of counting terraces on the sample; thus, the standards are used in a digital way. Furthermore, these samples provide unique traceability and have the capability to be used for advanced instrument characterisation, such as scanner background detection. These samples will be developed in Task 2.1.
- Self-assembled lateral standards (referred to as Group B samples) with locally unique Turing-like patterns (fingerprints), based on di-block copolymers (DBC), will be used to calibrate SPM in the x-, y- and z-directions at dimensions below 100 nm. These standards will be produced to match different geometrical topologies with controlled statistical properties in the real and Fourier space, which will be encoded as digital information. The “digital” aspect of these samples relates to their links to other characterisation techniques (existing hybrid metrological characterisation in the direct and reciprocal spaces in a VAMAS study also by GISAXS and SEM) and to their compatibility with the use of AI tools during the development and data evaluation phase. These samples will be developed in Task 2.1.
- In situ calibration samples will be designed and developed to be permanently installed on SPMs, thus enabling automated calibration/validation routines. The “digital” aspect relates to the sample composition as this sample type will include multi-scale features and structures for automated SPM calibration and basic tip shape determination. They will also include encoded digital information about the patterns, their localisation on the sample for easy navigation, the relevant metadata as well as uncertainties and tolerances of the reference. This information will be used to instruct the digital assistant that will be developed in WP3. The main fabrication techniques involved will be ALD and MBE. This topic will be developed in Task 2.2.
- Active samples (electrically programmable virtual height, and lateral, dynamic reference standards) will be designed, developed and fabricated to include active regions based on MEMS devices and piezoelectric crystals that will be capable of performing calibrated height and lateral displacement under the control of an external (referenced) voltage source. The “digital” aspect of these samples is in their potential to be made traceable using electrical measurement techniques, to use programmed motion patterns and to perform dynamic calibration. The samples will be developed in Task 2.3.

At an early stage of the project, WP2 will provide input for the definition of a user-oriented digitalisation flow according to, and for the definition of, the relevant parameters to be included in the metadata, as guided by WP1. Sample prototypes will be distributed, at the start of the project, to participants and stakeholders for an initial survey. The aim is to collect specific information and feedback from different industrial and research fields. This information will then be used in the case studies that will be carried out with different stakeholders, such as NMIs, SPM manufactures and end-users.

C2.a Task 2.1: Traceable reference samples (step height and lateral length)

The aim of this task is to provide two groups (Groups A and B) of advanced reference samples with well-known morphological properties.

The first generation will consist of traceable samples, which will be used to calibrate both height (Group A) and lateral (Group B) dimensions using a reliable reference. The purpose of these samples is to establish a traceability route for very small heights and lateral distances, being combined with new AI and ML open-source data processing tools, which will be able to be easily included in the software of new instruments (WP3). This group (Group A) includes monoatomic step height standards (created using high temperature annealing of Si(111) in UHV) for use in the calibration of the vertical (Z-direction) microscope axis and a second set of samples (Group B) that will be developed to calibrate the lateral performance (X- and Y- directions) of microscopes. They will be based on the propagation, to crystalline silicon, of a DBC pattern that will consist of lamellar structures with a periodicity ranging between 70 nm and 20 nm. Control of the molecular weight of the polymer will allow the shape of the lamellae to be varied from high contour length Turing-like patterns to insulated pillar-like round features. The control of fabrication conditions will enable the fine tuning of the statistical information associated with different topologies, and these will be embedded for digital calibration in real and Fourier spaces.

The second generation of step height (Group A), and lateral length (Group B), standard samples will have well-known morphological information for use in WP3 and WP4 and will be a result of manufacturing process improvement after the first generation is tested. They will be used in a round robin intercomparison and for implementing the digital assistant via AI and ML open-source tools, which will be able to be easily included in the software of new instruments.

Activity number	Activity description	Participants (Lead in bold)
A2.1.1 M1	PTB, CMI, CEM, DFM, GUM, INRIM, NPL, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf and OXINST will discuss and agree on a template layout for each of the nanoscale length standards (Groups A and B). This will include specification of the sample dimensions and the identification of the samples (and quick reference to the ROIs), which will be used in sample manufacturing in A2.1.2, A2.1.5, A2.1.9 and A2.1.11.	**PTB**, CMI, CEM, DFM, GUM, INRIM, NPL, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST
A2.1.2 M1	Using input from A2.1.1, PTB will fabricate and deliver up to 20 samples of silicon crystalline step height standards (Group A) to the NMI participants (NPL, CMI, DFM, CEM and GUM). These standards will also be used for test measurements in the SPM digital transform workshop (A5.1.5).	**PTB**, NPL, CMI, DFM, CEM, GUM
A2.1.3 M1	An internal survey will be conducted, within INRIM, to determine which DBC patterns (pillars, Turing-like patterns etc) (Group B) are available to be distributed within the consortium, with consideration of the statistical requirements of the project. INRIM will collect input from CMI, CEM, DFM, GUM, NPL, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf and OXINST and will then make at least 1 DBC patterned lateral standard (Group B) available to them and for the SPM digital transform workshop (A5.1.5). INRIM will also evaluate, in the internal survey, technological alternatives to silicon propagation, to reduce fabrication costs. These might include leaving one of the two polymeric phases in place or infiltrating the DBC segregated layers with ALD metal oxides (SiO_2, ZnO, TiO_2, Al_2O_3). The results will be discussed by INRIM, CMI, CEM, DFM, GUM, NPL, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf and OXINST and at least 1 alternative (plan b) approach will be agreed upon.	**INRIM**, CMI, CEM, DFM, GUM, NPL, PTB, VSL, VTT, BUT, NFI, PWR, TUBS, Bruker FR, Nanosurf, OXINST
A2.1.4 M3	PTB, together with TUBS, will perform an internal handling test on the crystalline step height standards (Group A) from A2.1.2 to identify the specific requirements (e.g., size, area, number and arrangement of steps) of a digital assistant for automatic ROI identification on these samples, using the existing software tools. The results will be used for a design update of the crystalline step height standards in A2.1.9.	**PTB**, TUBS
A2.1.5 M3	Using input from A2.1.1, INRIM will fabricate at least 5 samples of each of 2 types of lateral standards (Group B), based on the outcomes of A2.1.3, with DBC propagated to crystalline silicon by RIE. All of these samples will be tested in an initial round robin intercomparison (pilot study coordinated by INRIM) by the NMI participants (NPL, VTT, CMI, DFM and GUM) to determine the usability of these novel samples for lateral (X-Y) calibration in the spatial range from a few tens of nanometres to a few micrometres in a SPM. The results will be collated by INRIM. Additionally, a set of 10 samples (Group B, i.e., the 2 types fabricated in this activity) will be distributed to Bruker FR, Nanosurf, OXINST, NFI and the Stakeholder Committee, which will comprise manufacturers and final users according to A5.1.1. They will determine, and provide information on, the usability of these novel samples for lateral calibration in SPM.	**INRIM**, NPL, CMI, DFM, GUM, VTT, Bruker FR, Nanosurf, OXINST, NFI
A2.1.6 M3	INRIM, and the other traceable reference sample manufacturing participants (PTB, VTT, DFM and VSL), will define and write intellectual properties guidelines (in compliance with the project's Consortium Agreement), which will cover participant-specific procedures for sample creation, commercialisation of the samples, what will be shared and not shared, and the rules required to make commercialisation possible. They will also share the A1.1.5 fabrication database for lateral standards with PTB, VTT, DFM and VSL.	**INRIM**, PTB, VTT, DFM, VSL

A2.1.7 M12	NPL, DFM and CMI will conduct a metrological survey on the step height samples provided by PTB (A2.1.2 - Group A) and the lateral length calibration samples provided by INRIM (A2.1.5 - Group B). The survey report will include information obtained from NPL, DFM and CMI as well as the conclusions from the SPM digital transform workshop (A5.1.5). The aim is to determine whether the Group A and B samples can be used for metrological calibrations (ensuring that they fit SPMs, there is no wear, they are stable over time, and that they do not get scratched by the tip).	**NPL**, DFM, CMI
A2.1.8 M20	TUBS, with support from PTB, will create a ML based tool for the automatic inspection of crystalline standards (Group A) directly after production, using data from A2.1.2. This tool will be used for the optimisation and fine tuning of specific processing data for crystalline standards. In addition, this tool will ultimately be used during the production of standards at end-user sites (at PTB within the project) in order to create an initial set of data for each individual standard. Automatic identification of the ROI for calibration structures is fundamental for a digitally assisted automatic calibration process for end-users. Hence, the results will feed into A3.2.4.	**TUBS**, PTB
A2.1.9 M20	Using input from A2.1.1, and the results from A2.1.4 and A2.1.7, PTB will redesign the crystalline step height standards, which were produced in A2.1.2 (Group A), and a second generation of up to 20 samples of improved crystalline step height standards will be fabricated and delivered. The target will be to increase the vertical calibration range of the standards in order to improve the usability of the standards. This activity will provide design data and Group A samples to A4.2.1, A4.2.2. A4.2.4 and for uncertainty evaluation to A4.1.1.	**PTB**
A2.1.10 M20	Using the results from A2.1.7, INRIM will redesign the 2 types of lateral standard samples, which were produced in A2.1.5 (Group B), on the basis of the results of the initial metrological survey provided from A2.1.7. Sample features will be optimised to provide morphological information which can be easily encoded and digitised on lateral features. The target will be to increase the lateral calibration and to improve the usability of the standards and standardisation.	**INRIM**
A2.1.11 M28	Using input from A2.1.1 and A2.1.10, INRIM will fabricate a second generation of 15 samples of lateral standards (Group B) based on DBC technology and will deliver them to all NMI participants and all SPM manufacturers in the project. Information about the new samples will be disseminated to stakeholders. The samples will be used for measurements, and they will be provided with handling and tailoring information (sample size, ROI, sample holder compatibility) to suit market demands (as identified during the SPM digital transform workshop (A5.1.5)). Five of the 15 samples will be GISAXS traceable, with an appropriate ROI grid for automated calibration. These 5 samples will be distributed to NPL, CMI, DFM, GUM and VTT (one each) for interlaboratory lateral length comparison (coordinated by INRIM) by means of metrological and commercial SPM, light and stylus profilometry, SEM, focus variation and optical Microscopy. The aim will be to determine the usability of these improved samples for SPM calibration and to determine uncertainties when using different instruments. INRIM will prepare a protocol for the comparison and will collate the results. This activity will provide data for A4.1.3, use the methodology for uncertainty calculation from it and provide data for A4.3.1-A4.3.5. INRIM will update the A1.1.5 fabrication database, which was shared in A2.1.6, and will make it available as per A5.2.7.	**INRIM**, NPL, CMI, DFM, GUM, VTT
A2.1.12 M28	INRIM, PTB, VSL and PWR, with contributions from CMI, CEM, DFM, GUM, NPL, VTT, BUT, NFI, TUBS, Bruker FR, Nanosurf and OXINST, will publish the results of the fabrication and preliminary testing of the samples, including samples from A2.1.1-A2.1.11 and A2.3.1-A2.3.8, in a report on novel traceability routes for smart calibration samples (silicon steps traceable to a crystal lattice, lateral standards based on self-organised and locally unique patterns (fingerprints), multi-scale digital patterns and electrically programmable virtual height, and lateral, dynamic reference standards), which contain intrinsically high metrological information. Some of these samples will be used to enable the automated processing of the measurement data that is used to calibrate SPM. Once agreed by the consortium, the coordinator on behalf of INRIM, PTB, VSL, PWR, CMI, CEM, DFM, GUM, NPL, VTT, BUT, NFI, TUBS, Bruker FR, Nanosurf and OXINST will submit the report to EURAMET as **D2**: *"Report on novel traceability routes for smart calibration samples (silicon steps traceable to a crystal lattice, lateral standards based on self-organised and locally unique patterns (fingerprints), multi-scale digital patterns and electrically programmable virtual height, and lateral, dynamic reference standards), which contain intrinsically high metrological information. Some of these samples will be used to enable the automated processing of the measurement data that is used to calibrate SPM"*.	**INRIM**, PTB, VSL, PWR, CMI, CEM, DFM, GUM, NPL, VTT, BUT, NFI, TUBS, Bruker FR, Nanosurf, OXINST

C2.b Task 2.2: Embedded references for in-SPM automated measurements

The aim of this task is to design, produce and characterise reference samples which will be suitable for use in the automated multiscale calibration of SPMs with potential extension to other nanoscale dimensional measurement instruments (optical microscopes, scatterometry instruments, scanning electron microscopes). These reference samples will cover both height and lateral dimensions and will be developed to be permanently installed in the SPM setup to enable the digital assistant (WP3) to implement and perform validation and calibration routines. The reference samples will include accessible data, which will ease navigation to different ROIs and the retrieval of sample information (e.g., QR code). This task will have a key role as it will routinely interface with the digital assistant (WP3). Two fabrication techniques will be used: atomic layer deposition (ALD) and Molecular Beam Epitaxy (MBE). ALD will provide a very controlled method to produce a film to an atomically specified thickness over a large area (millimetres). As it is a key process in fabricating semiconductor devices, it will ensure the very reliable and repeatable production of nano- and microscale structures, and it relies on well-known protocols and materials. MBE is an ultra-high vacuum technique, which is used to grow atomically pure materials layer by layer. MBE provides a unique opportunity to analyse samples in-situ, at the atomic scale, due to their low growth rate in pure conditions. With in-situ characterisation tools, DFM's MBE cluster comes with in-situ processing techniques that provides the option to fabricate pure samples for the project.

Activity number	Activity description	Participants (Lead in bold)
A2.2.1 M3	BUT, NPL and CMI, with support from Bruker FR, Nanosurf and OXINST, and under guidance from VTT and DFM, will design reference samples with large area (millimetre) isotopic multi-scale patterns that will be built-in into SPMs for automated measurements. The reference samples will include encoded digital information about the patterns, their localisation on the sample for easy navigation, the relevant metadata as well as uncertainties and the tolerances of the reference. Specifically, BUT and CMI will design at least 1 multi-scale calibration and tip estimation sample and NPL will design at least 1 sample with embedded digital information that supports automated location of the region of interest and unique sample and feature identifiers. Design documents will be prepared for each design.	**BUT**, NPL, CMI, VTT, DFM, Bruker FR, Nanosurf, OXINST
A2.2.2 M6	DFM will manufacture 25 MBE fabricated reference samples using one of the designs developed in A2.2.1. The samples will include vertical and horizontal patterns with features ranging from a few tens of nanometres up to a few tens of micrometres. This will allow calibration with multiple techniques and different spatial resolution, aside from SPM.	**DFM**
A2.2.3 M9	VTT will use the design selected in A2.2.2 and will manufacture 50 ALD based reference samples of the same design. The samples will all have three different step heights (up to 500 nm) and line widths down to 800 nm.	**VTT**
A2.2.4 M12	NPL, CMI, DFM, VTT and INRIM will characterise enough of the ALD and MBE reference samples, produced in A2.2.2 and A2.2.3 to meet homogeneity requirements. SPM techniques will be used with a focus on their metrological properties and statistical homogeneity. This set of samples will be used in A3.3.4 and A4.1.2 and shared with SPM manufacturers (Bruker FR, Nanosurf, OXINST, NFI). This activity will provide a comparison between the samples produced by ALD and MBE. This activity will also provide data for A4.1.2.	**NPL**, CMI, DFM, VTT, INRIM
A2.2.5 M12	INRIM, PTB, GUM, DFM, VTT and CEM will characterise enough of the ALD and MBE reference samples, produced in A2.2.2 and A2.2.3 to meet homogeneity requirements. This will be undertaken at large scale (millimetres) with optical and stylus profilometers, optical microscopy, focus variation and SEM. This set of samples will be used in A4.1.2 and A4.3.2-A4.3.4 and shared with SPM manufacturers.	**INRIM**, PTB, GUM, DFM, VTT, CEM
A2.2.6 M12	DFM will design a MBE lithographic pattern (e.g., stencil mask) to encode additional information (from both A2.2.1, and A1.2.5 (as available by M12, May 2026)) in the sample. The MBE lithographic pattern will be used in this activity to e.g., embed a QR code on a first set of 5 prototypes from A2.2.2. This set of samples will be used in A4.1.2 and shared with SPM manufacturers.	**DFM**

A2.2.7 M16	Using input from A2.2.1-A2.2.6, VTT, CMI, BUT, DFM and NPL will prepare a report on the design and characterisation of embedded references (smart calibration samples) for in-SPM automated measurements. Once agreed by the consortium, the coordinator on behalf of VTT, CMI, BUT, DFM and NPL will submit the report to EURAMET as **D3**: *"Report on the design and characterisation of embedded references (smart calibration samples) for in-SPM automated measurements"*.	**VTT**, CMI, BUT, DFM, NPL

C2.c Task 2.3: Active samples (electrically programmable virtual height, and lateral, dynamic reference standards)

The aim of this task is to provide active samples (electrically programmable virtual height, and lateral, dynamic reference standards) for calibrating both low and high-speed SPMs for dimensional metrology using two complementary approaches. The first approach uses previously developed piezoelectric actuator-based samples that can be used to generate known displacements both out-of-plane (vertical) and in-plane (lateral). These devices can be used for displacements from 2 pm up to 20 nm and are calibrated by interferometry. The programmable height standard can be driven to generate step height profiles or more complex patterns, while the SPM probe remains stationary. Dynamic application to fine tune the SPM feedback parameters will be investigated for a bandwidth up to several hundred kHz. The programmable lateral standard includes a recognisable arbitrary pattern whose traceable displacement allows lateral calibration up to the micrometre range. Samples will be supplied with a voltage generator and a calibration document to assure traceability.

The second approach is to develop MEMS based SPM reference standards, where vertical displacement on the samples can be electrically controlled via a referenced voltage source. Samples will be calibrated using optical interferometry as a function of the applied voltages in a dynamic range up to few hundred kHz. On the upper side of a silicon nitride membrane, metal paths will be deposited to enable electromagnetic deflection of the membrane. Through appropriate SPM tip biasing, the samples will have the sensitivity needed to measure in other SPM modes. MEMS deflection actuators will be characterised by NPL using high resolution and traceable interferometry. PWR will deliver a set of MEMS deflection references for use by other participants.

Activity number	Activity description	Participants (Lead in bold)
A2.3.1 M6	NPL, PWR, INRIM and VSL will design at least 2 active samples (electrically programmable virtual height, and lateral standards to calibrate the SPM, dynamic reference standards to test SPM dynamic phenomena, e.g. feedback loop parameters), based on piezoelectric actuators and MEMS and they will agree on the format and content of the metadata that will be associated with the samples' electrical and dimensional parameters. Design documents will be prepared for each design by PWR and VSL.	**NPL**, PWR, INRIM, VSL
A2.3.2 M1	VSL will make two different types of existing "off the shelf" piezoelectric actuator-based samples available to be circulated amongst PWR, NPL, INRIM and GUM. One sample will be for vertical displacement and the second sample will be for lateral displacement. Both will include the driving electronics (a voltage generator) and a calibration document to assure traceability.	**VSL**, PWR, NPL, INRIM, GUM
A2.3.3 M12	Using the designs from A2.3.1, PWR, with support from NPL, will develop at least 2 MEMS based samples for vertical displacement and force electrical and thermal measurements through appropriate SPM tip biasing. The targeted specification is a 10 nm displacement with a 5 mA excitation current at a resonant frequency of 200 kHz.	**PWR**, NPL
A2.3.4 M18	VSL and INRIM (piezo), and NPL and GUM (MEMS), will evaluate the performance of the two types of electrically programmable virtual height, and lateral dynamic reference standards from A2.3.2 and A2.3.3. They will determine the measurement uncertainty, at low frequency with the SPM in quasi static mode, using multiple techniques (e.g., SPM and interferometry). This activity will supply data to A4.1.4 and A4.3.1-A4.3.5.	**VSL**, INRIM, NPL, GUM
A2.3.5 M24	VSL, PWR, NPL and INRIM will explore the response of the two types of electrically programmable virtual height, and lateral dynamic reference standards from A2.3.2 and A2.3.3. They will determine the dynamic behaviour of the samples and the impact of fast transients on relevant parameters, e.g., accuracy and linearity. This activity will supply data to A4.1.4.	**VSL**, PWR, NPL, INRIM

A2.3.6 M24	Using input from A2.3.3, NPL and PWR will evaluate the PWR measurements and their potential use in other SPM modes. This will extend the use of MEMS electrodes to the calibration of SPM electrical properties. This activity will supply data to A3.1.1-A3.3.6, A4.2.1-A4.2.4 and A4.3.1-A4.3.5.	**NPL**, PWR
A2.3.7 M28	INRIM, PWR, VSL and NPL will define an electrically programmable virtual height, and lateral dynamic reference standard, based on the results of A2.3.1-A2.3.6. The reported data, to be used further in A2.3.8, will include the calibration of the response in the frequency domain and the definition of a set of voltage patterns, which will allow the digital assistant to calibrate and benchmark the instrument's (SPM) response in an effective way. This work will be undertaken in connection with A3.1.1-A3.3.6, which will enable the fine tuning of the placement of the SPM tip on the sample and/or force feedback parameters, as well as tracking/re-tuning of the SPM's performance over time.	**INRIM**, PWR, VSL, NPL
A2.3.8 M28	Using input from A2.3.1-A2.3.7, PWR, VSL, NPL, INRIM and GUM will summarise the active samples description for use in D2 (A2.1.12).	**PWR**, VSL, NPL, INRIM, GUM

C3 WP3: Digital assistants

The aim of this work package is to develop a library of automated data processing routines (including algorithms) for the evaluation and quality checking of SPM calibration. This will allow the propagation of calibration measurement data, and the associated metadata, in compliance with the FAIR principles, and independent of user influence. The routines will implement the digitalisation workflows established in WP1, and they will be largely automated to minimise human error in data analysis. The library will both consume and produce data in FAIR-compliant formats incorporating the sample and process descriptions specified in WP1, WP2 and WP4. This will apply to both height standards (e.g., silicon steps) and lateral standards (e.g., periodic structures). The developed algorithms will combine optimised statistical treatment and machine learning methods. The library will permit integration into open source and commercial microscope control software to create a "digital assistant" for performing SPM calibration and to act as a template for digitalisation in other areas of metrology. Documentary standards and good practice guides on the use of the developed software and algorithms will be drafted and disseminated to the SPM community and instrument manufacturers so that the data processing routines can be integrated into their software.

This will be undertaken in the following tasks:

Task 3.1 aims to create guidance, and a related dataset, for benchmarking automated routines (i.e., free from human influence) for SPM data processing.

Task 3.2 aims to develop individual algorithms to automatically process the data from calibration samples.

Task 3.3 aims to collate the algorithms developed in Task 3.2 in a library which can be used for digital assistants in SPM manufacturer's software.

C3.a <u>Task 3.1: Guidance, datasets and criteria for benchmarking automated SPM data processing routines in nanometrology</u>

The aim of this task is to collect requirements for automated data processing in SPM from the digitalisation, metrology and impact perspectives. This will include inputs from the SPM manufacturers group in the project (Bruker FR, Nanosurf, OXINST) and from stakeholders, in order to drive the development of the library of automated data processing routines so that it is integrable with their control software.

Activity number	Activity description	Participants (Lead in bold)
A3.1.1 M4	CMI, BUT, VTT and NPL, with support from the SPM manufacturers group in the project (Bruker FR, Nanosurf, OXINST) and the SPM manufacturers from the Stakeholder Committee (A5.1.1), will prepare a document defining the main requirements and constraints for the use of a library of automated SPM data processing routines in "digital assistants" (measurement aspects (e.g., scanning ranges, speeds); integrability aspects (e.g., the form of the library); critical application programming interface (API) aspects), so that they will be suitable for use with the control software in their SPMs. This will be undertaken together with the SPM digital transform workshop (A5.1.5) in M4 (September 2025) and detailed written guidance will be provided for use in A3.2.9 and A3.3.1-A3.3.5.	**CMI**, BUT, VTT, NPL, Bruker FR, Nanosurf, OXINST

A3.1.2 M5	CMI, BUT, VTT and NPL, with support from Bruker FR and Nanosurf, will prepare a set of real benchmarking SPM data and instrumentation error source limits (noise, scanner background, particle density, etc.), for use in the subsequent development of a library of automated SPM data processing routines in “digital assistants” or in its comparison with any other data processing approaches.	**CMI**, BUT, VTT, NPL, Bruker FR, Nanosurf
A3.1.3 M6	BUT and CMI will setup at least 1 software tool (e.g., Gwyddion, Python) for data generation. They will use these tools to generate at least 10 sets of synthetic benchmarking SPM data with known ground truth, using the information from A3.1.2.	**BUT**, CMI
A3.1.4 M6	Using input from A3.1.1-A3.1.3, BUT, CMI and NPL will produce a dataset for benchmarking automated SPM data processing routines in nanometrology. This will include both generated and measured data with a description of the algorithms that were used to generate the data and their settings. Once agreed by the consortium, the coordinator on behalf of BUT, CMI and NPL will submit the dataset to EURAMET as **D4**: *“Dataset for benchmarking automated SPM data processing routines in nanometrology”*.	**BUT**, CMI, NPL

C3.b Task 3.2: Automated data processing routines (algorithms) for robust data evaluation

The aim of this task is to develop automated data processing routines (algorithms) for the novel types of standards developed in A2.1.1-A2.1.12 and A2.2.1-A2.2.7, including both lateral and height measurements, and to reduce human error in data analysis. The algorithms will be tested on large sets of synthetic data (from A3.1.3), including different realistic error sources and real data (from A3.1.2).

Activity number	Activity description	Participants (Lead in bold)
A3.2.1 M6	CMI and BUT will develop at least 1 synthetic data generator (e.g., Gwyddion, Python) for the generation of at least 10 sets of synthetic benchmarking SPM data, by applying the methodology from A3.1.3 to meet the requirements of the algorithms that will be developed in A3.2.2-A3.2.8. These data will be used in the statistical analysis of the performance of the automated data processing routines (algorithms) developed in this task, for step-height and lateral calibration samples based on crystalline surfaces and by self-organised patterns, as defined in A2.1.1-A2.1.6 and A2.2.1-A2.2.2. The SPM error sources identified in A3.1.3 will also be taken into consideration. INRIM and PTB, as key manufacturers of these sample types, will provide guidance and feedback on the developed tools.	**CMI**, BUT, INRIM, PTB
A3.2.2 M12	BUT and CMI will each develop at least 1 direct, and AI automated, data processing routine to automate the quality checking of scanned surface data from a calibration sample in an SPM. These tools will be tested and validated using the synthetic benchmarking SPM data from A3.2.1. They will be subsequently used in digital assistants for fast decision making about the suitability of the measured surface (for use in the calibration of the SPM).	**BUT**, CMI
A3.2.3 M12	BUT and CMI, with support from NPL and DFM, will develop algorithms for the automated pre-processing of SPM data (e.g., contamination and wear) from flat samples, e.g., crystalline silicon standards. These algorithms will be tested and validated using the synthetic benchmarking SPM data from A3.2.1.	**BUT**, CMI, NPL, DFM
A3.2.4 M24	Using input from A1.3.4, TUBS and PTB, with guidance from BUT, will develop a ML based tool, to be added to the Gwyddion software used for SPM data processing, for the automatic identification of ROI on self-organised standards, such as crystalline step height standards. The ML based tool will be tested and validated using the synthetic benchmarking SPM data from A3.2.1. Results from A2.1.8 will be used as the basis for this activity.	**TUBS**, PTB, BUT
A3.2.5 M24	Using input from A1.3.4, CMI, INRIM and BUT, with support from NPL, will develop algorithms for the automated analysis of periodic and quasi-periodic structures, such as Turing-like pattern lateral standards, including the Fast Fourier Transform-based analysis approach. The algorithms will be able to extract, and evaluate, the grains on low-cost self-organised samples and to analyse decorated silicon surfaces. The algorithms will be tested and validated using the synthetic benchmarking SPM data from A3.2.1.	**CMI**, INRIM, BUT, NPL

A3.2.6 M24	Using input from A1.3.4, INRIM, BUT and CMI will compare existing fingerprint-based feature search and analysis with the automated statistical Fast Fourier Transform-based analysis approach developed in A3.2.5 for Turing-like pattern lateral standards. This will enable the most efficient method to be selected and used in the data processing library developed in A3.3.2.	**INRIM**, BUT, CMI
A3.2.7 M24	Using input from A1.3.4, BUT and CMI, with support from DFM and NPL, will develop algorithms to reduce the influence of the user in atomic steps data background separation and 2D fitting. The algorithms will be tested and validated using the synthetic benchmarking SPM data from A3.2.1.	**BUT**, CMI, DFM, NPL
A3.2.8 M24	Using input from A1.3.4, CMI, BUT and NPL will develop SPM tip shape estimation routines from statistically isotropic multiscale ALD samples from A2.2.1-A2.2.7. The algorithms will be tested and validated using the synthetic benchmarking SPM data from A3.2.1.	**CMI**, BUT, NPL
A3.2.9 M26	Using input from A1.3.4, CMI, with support from DFM, INRIM, NPL, PTB, VTT, BUT, TUBS, Bruker FR, Nanosurf and OXINST, will summarise the results from A3.1.1-A3.1.4 and A3.2.1-A3.2.8 in a report which will be included in D5 (A3.3.6).	**CMI**, DFM, INRIM, NPL, PTB, VTT, BUT, TUBS, Bruker FR, Nanosurf, OXINST

C3.c Task 3.3: Digital assistants

The aim of this task is to develop a library including algorithms from Task 3.2 to serve as a basis for digital assistants that will provide an easy to use (e.g., single-button) interface to the library of automated data processing routines (algorithms) developed in A3.2.1-A3.2.9. This will include automated data quality checking, data pre-processing and the evaluation of key lateral and height parameters of samples using both direct and statistical algorithms. For ease of integration with SPM manufacturer's software the key functionality will be provided using a MIT (Massachusetts Institute of Technology) (or similar) license or by executables that can be run from the manufacturer's proprietary software. As an alternative, a reference implementation will be developed and the data processing functions developed in A3.2.1-A3.2.9 will also be implemented in Gwyddion open-source software.

Activity number	**Activity description**	**Participants (Lead in bold)**
A3.3.1 M18	Using input from A3.1.1 and A3.2.1-A3.2.9 (as available by M18, November 2026), BUT and CMI will continuously extend the functionality of Gwyddion to enable automated calibration to be performed on novel sample types from A2.1.1-A2.1.7, A2.2.1-A2.2.7 and A2.3.1-A2.3.4 and to establish easy to use and easy to manage software-based calibration tools for the cases where the instrument (SPM) cannot be calibrated itself during the measurement process. The software will be tested and validated using synthetic benchmarking SPM data from A3.1.4.	**BUT**, CMI
A3.3.2 M20	Using input from A3.1.1, CMI, BUT and NPL will develop a metrological framework, a reference software implementation for SPM manufacturers (as an example of how a digital assistant might be coded) and related documentation. This will be based on at least 1 open library including algorithms from A3.2.1-A3.2.9 (as available by M20, January 2027) with permissive licenses (MIT like), or executables, for use by SPM manufacturer's proprietary software. This will provide simple SPM instrument calibration using the samples developed in A2.1.1-A2.1.10 and A2.2.1-A2.2.7.	**CMI**, BUT, NPL
A3.3.3 M24	Using input from A3.1.1, NFI, with support from Bruker FR, Nanosurf and OXINST, will review the open libraries from A3.3.2 for their usability in the software used by SPM manufacturers and they will provide feedback to BUT and CMI for use in the final review of the software in A3.3.6.	**NFI**, Bruker FR, Nanosurf, OXINST
A3.3.4 M20	Using input from A1.3.4 (as available by M20, January 2027) and A3.1.1, BUT and CMI will create reference software implementations for DCC data import, export and management, based on the XML schemas developed in A1.2.4. The software will be tested and validated using synthetic data from A3.1.4 and measurements from A2.1.7, A2.1.9 and A2.2.4.	**BUT**, CMI

A3.3.5 M24	Using input from A3.1.1, VTT, with support from PTB, NPL, DFM, CEM, INRIM and GUM, will test the developed software tools (A3.3.2 and A3.3.3) and the related documentation (API and reference implementation description) using synthetic benchmarking data from A3.1.4 to ensure it is of appropriate quality and clarity (NMI-beta-test). The output will be used both for improvements of the software tools during the development and for final checks before finalising A3.3.6.	**VTT**, PTB, NPL, DFM, CEM, INRIM, GUM
A3.3.6 M28	The software tools developed in A3.2.1-A3.2.9 and A3.3.1-A3.3.5, by CMI and BUT, will be reviewed by CMI, DFM, INRIM, NPL, PTB, VTT, BUT, TUBS, Bruker FR, Nanosurf and OXINST, in order to finalise documentation for the library created in A3.3.2. They will then write a good practice guide on the use of a library of automated data processing routines (digital assistants) in SPM data evaluation, its reference implementation and aspects of integration into commercial microscope control software. Once agreed by the consortium, the coordinator on behalf of CMI, DFM, INRIM, NPL, PTB, VTT, BUT, TUBS, Bruker FR, Nanosurf and OXINST will submit the good practice guide to EURAMET as **D5**: *"Good practice guide on the use of a library of automated data processing routines (digital assistants) in SPM data evaluation, its reference implementation and aspects of integration into commercial microscope control software".*	**CMI**, DFM, INRIM, NPL, PTB, VTT, BUT, TUBS, Bruker FR, Nanosurf, OXINST

C4 WP4: Uncertainty quantification in digital data workflows

The aim of this work package is to investigate how uncertainty propagates through digital data workflows in dimensional nanometrology and to explore and ensure that the methods developed in this project can be transferred to other scales (e.g., optical and tactile measurements) and measurement techniques (e.g., confocal (optical) and electron microscopy). This will be undertaken in the following tasks:

Task 4.1 focuses on identifying and evaluating the uncertainty components associated with applying the routines which lead to a digital traceability chain. This will include analysis of the uncertainties associated with the advanced samples and analysis of the impact of automatic routines on uncertainty, and uncertainty propagation through the complete digital traceability chain from the primary realisation of the unit up to the end user.

Task 4.2 focuses on uncertainty propagation within the digital traceability chain for SPM measurements.

Task 4.3 focuses on demonstrating the potential to use dimensional metrology methods with other instrumentation and at other scales. Differences in the uncertainty aspects will be identified for each of these cases.

C4.a <u>Task 4.1: Analysis of the uncertainty components related to novel traceable reference samples and the whole digital data workflow for dimensional nanometrology</u>

The aim of this task is to determine the uncertainty components related to the novel traceable reference samples from WP2 and to the whole digital data workflow, with consideration of all the calibration and traceability scenarios. Methods will be developed to propagate the uncertainty components digitally and to provide information about metadata related to uncertainties to WP1. This will include an evaluation of the impact of automated evaluation routines, which will be part of the open libraries for integration to SPM manufacturer's software, on the uncertainty. Uncertainty aspects related to real world situations will also be considered, including where references, embedded for in-SPM automated measurements, are subject to wear or contamination.

Activity number	Activity description	Participants (Lead in bold)
A4.1.1 M28	Using input from A2.1.4, A2.1.7 and A2.1.9, PTB will evaluate the uncertainty components related to the manufacture and use of Si crystalline samples in SPM calibration. They will also determine the sample-related uncertainty components that will be shipped together with all of the project's Si crystalline samples in a digital form.	**PTB**
A4.1.2 M28	Using input from A2.2.4, A2.2.5 and A2.2.6, VTT and DFM will evaluate the uncertainty components related to the manufacture and use of ALD and MBE samples in SPM calibration. This will lead to a global uncertainty value for the whole batch of ALD samples from A2.2.3.	**VTT,** DFM

A4.1.3 M28	Using input from A2.1.3 and A2.1.11, INRIM will evaluate the uncertainty components related to the manufacture and use of self-assembled samples in SPM calibration. They will also determine the sample-related uncertainty components that will be shipped together with all of the project's self-assembled samples in a digital form.	**INRIM**
A4.1.4 M28	Using input from A2.3.4 and A2.3.5, VSL, NPL and PWR will evaluate the uncertainty components related to the use of active samples in SPM calibration. They will also develop ways to propagate the uncertainty during the use of active devices.	**VSL**, NPL, PWR
A4.1.5 M30	Using input from A3.2.3, A3.3.2 and A3.3.3, CMI and BUT will study the uncertainty components related to the library functions that will be used for automated SPM data pre-processing and evaluation. They will also determine the data processing uncertainty components, which will be added to the results.	**CMI**, BUT
A4.1.6 M30	Using input from A2.2.1-A2.2.7, VTT, CMI, NPL, BUT and INRIM will identify the uncertainty components in the automated SPM calibration process. Uncertainty aspects related to real world situations will also be considered, including where references, embedded for in-SPM automated measurements, are subject to wear or contamination.	**VTT**, CMI, NPL, BUT, INRIM

C4.b Task 4.2: SPM uncertainty and its propagation within the digital data workflow for dimensional nanometrology

The aim of this task is to combine the SPM uncertainty budget components including instrument related sources (e.g., impact of the scanner background, cross-talk, non-orthogonality, noise) and calibration sample related sources identified in A4.1.1-A4.1.6, to investigate these in different calibration scenarios (use of calibration samples to provide instrument traceability, use of calibration samples to perform automated re-calibration in daily use of the instrument), and to estimate how the uncertainty propagates within the digital data workflow for dimensional nanometrology.

Activity number	Activity description	Participants (Lead in bold)
A4.2.1 M32	Using input from A2.1.9, A4.1.1-A4.1.6, NPL and CMI will develop generic methods for using the SPM specific uncertainty parameters (background flatness, cross-talk, non-orthogonality, background noise), which will be obtained using the automated routines from A3.3.6 and samples developed in A3.1.1-A3.1.4, A3.2.1-A3.2.9 and A3.3.1-A3.3.6, to evaluate the uncertainty associated with further measurements of the samples that will be investigated.	**NPL**, CMI
A4.2.2 M32	Using input from A2.1.9 and A4.1.1-A4.1.6, NPL and CMI will modify the scanning systems in their SPMs to store the metadata needed for testing the use of stage movement correction maps or lookup tables in the post/processing phase using samples developed in A3.1.1-A3.1.4, A3.2.1-A3.2.9 and A3.3.1-A3.3.6. They will also develop methods to enable a lookup table for stage errors to be used for uncertainty propagation towards the measurement of unknown samples (samples to be investigated).	**NPL**, CMI
A4.2.3 M32	Using input from A4.1.1-A4.1.6, VTT, CMI and NPL, supported by the SPM manufacturers group in the project (Bruker FR, Nanosurf, OXINST, NFI), will investigate the uncertainty propagation for in-situ calibrations using automated routines from the data processing library developed in A3.3.2 and permanently mounted samples from A2.2.3.	**VTT**, CMI, NPL, Bruker FR, Nanosurf, OXINST, NFI
A4.2.4 M36	Using input from A2.1.9, VTT, CMI, NPL, BUT and INRIM will estimate the uncertainty propagation and validate the complete chain (NMI → DCC → manufacturer → user) for the SPM measurements selected in A4.2.1-A4.2.3. The results will be compiled as a good practice guide on uncertainty propagation through a digital traceability chain in dimensional nanometrology. Once agreed by the consortium, the coordinator on behalf of VTT, CMI, NPL, BUT and INRIM will submit the good practice guide to EURAMET as **D6**: *"Good practice guide on uncertainty propagation through a digital traceability chain in dimensional nanometrology"*.	**VTT**, CMI, NPL, BUT, INRIM

C4.c Task 4.3: Extension of the digital data workflow, developed in the project, towards other types of measurements

The aim of this task is to explore the possible extension of the digital data workflow towards larger scales in dimensional measurements (e.g., for stylus profilometers, optical profilometers, focus variation instruments) and towards other quantities (e.g., electrical, thermal, mechanical), including the evaluation of additional uncertainty components in these cases. This will be undertaken both in relation to the sample properties and data processing.

Activity number	Activity description	Participants (Lead in bold)
A4.3.1 M32	Using input from A2.1.9, A2.1.11 and A2.2.3, PTB, INRIM and VTT will determine what the additional uncertainty components are, and will estimate uncertainty values for, the silicon (A2.1.9), self-assembled (A2.1.11) and ALD (A2.2.3) samples when targeting large area (millimetre) optical or tactile measurements using microscopy, fixed focused sensor microscopy or stylus profilometers.	**PTB**, INRIM, VTT
A4.3.2 M32	Using input from A2.1.11, A2.2.5 and A2.3.4, GUM and NPL will test the use of the add-on reference samples from A2.2.3 with a white light interferometer and at least 1 confocal microscope. The focus will be on estimating the measurement uncertainty in real-world conditions, including the impact of the environment on the samples when they are permanently installed.	**GUM**, NPL
A4.3.3 M32	Using input from A4.3.1, A4.3.2 and A2.2.5, VTT, CMI, NPL, BUT, INRIM, CEM and GUM will identify the uncertainty components in the extended use of the automated calibration process using the library from A3.3.2 for tactile and optical methods.	**VTT**, CMI, NPL, BUT, INRIM, CEM, GUM
A4.3.4 M32	Using input from A4.3.1, A4.3.2 and A2.2.5, CMI and BUT will study the additional uncertainties related to the library functions from A3.3.2 when extending towards larger scales (millimetres). The focus will be on understanding the impact of statistical sample non-uniformity, and sample flatness deviations, on dimensional nanometrology data evaluation.	**CMI**, BUT
A4.3.5 M36	GUM, CEM, VTT, CMI, NPL, BUT, PTB and INRIM will estimate the uncertainty propagation and validate of the complete chain (NMI → DCC → manufacturer → user) for the measurements selected and extended to large scales in A4.3.1-A4.3.4. The information collected, forming a database of knowledge, will be used to write a report on the extension of the digital data workflow towards larger scales in dimensional measurements and towards other quantities using other instrumentation (e.g., for stylus profilometers, optical profilometers, focus variation instruments), which will create a database of the knowledge learnt from this extension. Once agreed by the consortium, the coordinator on behalf of GUM, CEM, VTT, CMI, NPL, BUT, PTB and INRIM will submit the report to EURAMET as **D7**: *“Report on the extension of the digital data workflow towards larger scales in dimensional measurements and towards other quantities using other instrumentation (e.g., for stylus profilometers, optical profilometers, focus variation instruments), which will create a database of the knowledge learnt from this extension”*.	**GUM**, CEM, VTT, CMI, NPL, PTB, BUT, INRIM

C5 WP5: Creating impact

C5.a Task 5.1: Dissemination and communication

Activity number	Activity description	Participants (Lead in bold)
A5.1.1 M36	The project will create a Stakeholder Committee of at least 6 members drawn from SPM and other microscope manufacturers and industrial users of these microscopes from at least 3 different countries. The aim of the Stakeholder Committee is to clarify the needs of the various interested parties and to feed these into the project. Additionally, the Stakeholder Committee members will be asked to provide input to technical activities e.g., A1.1.5, A2.1.5, A2.1.11 and A3.1.1 and to communicate and disseminate the project within their networks. Interaction of the Stakeholder Committee will be achieved via a central website (see below), personal contacts and ad-hoc meetings will be held at suitable events where the committee are in attendance. The Project Management Board will contact the Stakeholder Committee to obtain an external perspective on the operations and outputs of the project, as well as guidance on the future direction, and for a critical assessment of the project’s performance.	**CMI**, all participants

A5.1.2 M36	A project website will be created on the PTB website with public access and a part for participants only. The website will be regularly updated with information about the progress of the project, such as project reports, papers published by the participants, and project meetings. Other direct outputs of the project, such as software (data processing library), e-learning materials, training data sets, reference data and tutorials will also be made available on the website. The part of the website with restricted access will be dedicated to exchange of information between participants during the lifetime of the project. It will also include a digital archive of all presentations, reports and papers from the project. The project website will clearly acknowledge, in a prominent position on the homepage (e.g. in the header, footer or centre and in a readable size), the Metrology Partnership. This will be done by including either i) the Partnership project website header/footer badge and both (ii) the acknowledgement and (iii) disclaimer text (this text can be anywhere on the homepage). Alternatively, it will be done by using the Partnership acknowledgement badge (which includes all 3 points).	**PTB**, all participants
A5.1.3 M2	At the beginning of the project, the team will prepare a project flyer and poster containing all relevant information about the project and the participants. The texts will be written for a non-specialist audience. Special emphasis will be on promoting the importance of the basic principles of metrology and its implication for SPM measurements. The flyer and poster will be available for download on the website. It will be used to promote the project and its impact to a broader public. The project poster will be used to present the general outline of the project during minor conferences and meetings not mentioned below.	**INRIM**, all participants
A5.1.4 M36	An e-newsletter will be produced and sent by email to the stakeholders and other collected contacts (starting at the kick-off meeting). The e-newsletter will give updates about progress of the project and first-hand information about results and outcomes (software, samples or digital processes) achieved so far. It will also cover general information about the project, participants, and upcoming events. An e-newsletter will be circulated 1 month after each project meeting. In addition, the e-newsletter will be available in the news section of the webpage.	**PTB**, all participants
A5.1.5 M4	CMI and NPL will organise an initial 1-day SPM digital transformation workshop at CMI (hybrid) for the consortium and stakeholders (e.g., software developers). It will be used to collect information about SPM manufacturers limitations in terms of data formats, metadata, data processing libraries and the use of self-calibration samples in their instruments. The workshop will be used to discuss the metadata within WP1, to coordinate the work on the design and measurement of novel sample prototypes, including silicon steps from PTB (result of A2.1.2) and 2D standards from INRIM within WP2 (result of A2.1.3), and to discuss the library interfaces for WP3. The workshop will also introduce the concepts of digital transformation itself. The target number of external delegates will be approximately 20. The workshop will be promoted by advertisement on the project website (A5.1.2), the participant's websites and through the project's Stakeholder Committee (A5.1.1).	**CMI**, NPL
A5.1.6 M12	Dissemination to, and input from, digitalisation committees to ensure mutual exchange of information. NPL will lead the engagement with EPM TC-IM project 1449, presenting the project activities, disseminating materials and organising at least one online workshop to present the project to the community and collate feedback.	**NPL**, PTB
A5.1.7 M3	NPL and CMI will coordinate interaction with CCL WG-Nano and present the digitalisation concepts and calibration samples to the NMI community with the aim of disseminating the results internationally to non-European NMIs and to get feedback from them for deliverable D1.	**NPL**, CMI
A5.1.8 M30	CMI and BUT will create a 1-day webinar to disseminate the project's findings in the area of data processing algorithms. The materials will also be added to the Gwyddion User Guide. The target number of external attendees will be approximately 20. The webinar will be promoted by advertisement on the project website (A5.1.2), the participant's websites and through the project's Stakeholder Committee (A5.1.1). The participants will liaise with existing and potential future EMNs e.g., EMN Advanced Manufacturing or any relevant EURAMET TC, to see whether there are any other EURAMET funded projects, EU funded Partnerships or any research/industrial projects, that could be utilised to increase the outreach of the webinar.	**CMI**, BUT

A5.1.9 M36	The participants plan to present at least 34 contributions at the following international conferences (tentative list, attendance will depend on project progress and on the results which will be available). • Nanoscale, 14th Seminar on Quantitative Microscopy (QM) and 10th Seminar on Nanoscale Calibration, Standards and Methods (October 2026, NPL UK), up to 19 contributions expected • Microscale (date and location TBC), up to 1 contribution expected • Microscopy & Microanalysis (Milwaukee, US, August 2026), up to 1 contribution expected • MRS Fall Meeting (Boston, US, November 2026), up to 1 contribution expected • APS meeting (date and location TBC 2026), up to 2 contributions expected • 52nd Micro and Nano Engineering Conference (date and location TBC), up to 1 contribution expected • Sensor and Measurement Science International (Nuremberg, Germany, date TBC, 2026), up to 1 contribution expected • SPIE conferences: e.g., SPIE Photonics West (annually), SPIE Nanoscience + Engineering (annually) Metrology, Inspection, and Process Control for Microlithography (annually) (dates and locations TBC), up to 5 contributions expected • EMRS Spring, Symposium Altech, Strasbourg (Strasbourg, France, expected May 2027), up to 6 contributions expected • 25th IMEKO World Congress (Rimini, Italy, September 2027), up to 2 contributions expected Further relevant conferences may be identified during the project. The speakers at the conferences will clearly acknowledge the financial support provided as required by EURAMET.	**PTB,** all participants
A5.1.10 M36	The participants will submit at least 9 papers to peer-reviewed journals during the project. Target journals include: Metrologia, Measurement Science and Technology, Journal of Materials Science and Technology, International Journal of Precision Engineering and Manufacturing, Review of Scientific Instruments and ACS Applied Materials and Interfaces. These papers will be based on the results from: - Semantic model of nanometrology digital workflow (WP1) - Development of the samples (WP2) (2-3 papers) - Development of the analysis methods (WP3) - Uncertainty flow through the digital routines, stage mapping (WP4) - Comparison of traditional data evaluation with digital assisted data evaluation (WP3/4) The expectations are that all publications will be the result of a collaborative effort from participants from different countries. The authors of the peer reviewed papers will clearly acknowledge the financial support provided through the Partnership as required by EURAMET in accordance with Article 17, Article 18, and Annex 5 of the Grant Agreement with the following text: "The project (24DIT02 DINAMO) has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States." The authors will ensure that the following meta data is submitted and included for each paper: · Funder name: European Partnership on Metrology · Funder ID: 10.13039/100019599 · Grant number: 24DIT02 DINAMO The participants will comply with the open access requirements detailed in the Grant Agreement Annex 5 Article 17 by also depositing each paper in a suitable open access trusted repository. The participants will also submit all papers (and any associated datasets if applicable) to the EURAMET Publication Database. The authors will ensure that all data presented will be in accordance with the IP terms of the Grant Agreement.	**CMI**, all participants

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<td>A5.1.11
M36</td>
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Information on the results of the project will be disseminated to a range of standards bodies and committees and feedback sought (see details below).
Key outcomes for relevant standards are the metadata definitions, data containers and the user-influence free automated data processing algorithms in the data processing library that will become part of the digital assistant.
This project will provide input to standards and digital workflow at all levels; through CIPM consultative committees, technical committees (TC), ISO standards bodies and national standards bodies. Several participants are active in committees at all these levels across Europe. The results of this project will be directly reported to the signers of the joint statement for the SI Digital Framework, which are CIPM, OILM, IMEKO, ISO, ILAC and many more. As this project is focused on digitalisation and the implementation of a digital reference workflow for SPM calibration and measurement, the project's outputs will also be relevant for consultative committees, especially CCL. Participants are actively involved in running projects on digitalisation, such as the harmonisation of the DCC (PTB). In addition, participants are involved in the key ISO and CEN technical committees in nanotechnologies and scanning probe microscopy (see table below). The TCs will be informed about the aims and results of the project throughout its lifetime. For example, the representatives on the corresponding committee or working group from the participants will jointly request inclusion of a point in the agenda to briefly present the outputs of the project related to the working group activities and ask for comments from the other committee/working group members. Where appropriate a written report will be submitted for consideration by the TC or working group.
Definition of the metadata to support digital data flow and metrological traceability in nanometrology will direct further development of ISO compliant data storage formats and digital calibration certificates. The use of smart samples, annotated with related metrological information, will simplify the traceability chain and enable simultaneous characterisation of multiple instrument parameters. This simplification will be applicable to other fields of dimensional metrology related to surface topography, regardless the scale (confocal, tactile).
The standardisation bodies and committees that the project will interact with are provided in the following table:
<table>
<tr><th>Standards Committee / Technical Committee / Working Group</th><th>Participants involved</th><th>Likely area of impact / activities undertaken by participants related to standard / committee</th></tr>
<tr><td>ISO/TC201/SC9
“Scanning Probe Microscopy”</td><td>NPL, PTB</td><td>ISO/TC201/SC9 meets annually in October-November, generally with a 1-day meeting followed by a shorter meeting within the wider ISO TC201 (surface chemical analysis) meeting. The committee will be informed about the project from an early stage and its progress will be presented by NPL or PTB at the meeting. The participants involved will ask for feedback on the work and results presented. Feedback on the project, including the three good practice guides, will be gathered from the international experts and discussed at project meetings and appropriate measures will be taken. The ultimate aim will be to provide input for the creation of an update to standard ISO11952:2019 in the area of digitalisation or to create an ISO new work item on SPM calibration (it is unknown when this will take place).</td></tr>
<tr><td>ISO/TC229/JWG2
“Nanotechnologies: Measurement and characterisation”</td><td>NPL, PTB</td><td>ISO TC229/JWG2 meets twice a year generally in May and November. NPL is a member of the strategy group of JWG2 and a member of the chairman's advisory group (CAG). Results from the project will be presented to the committee and NPL and PTB will present project progress at the TC meetings and ask for feedback on the work and the results presented. Feedback will be discussed at project</td></tr>
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</td>
<td>PTB, NPL, VTT, CMI, CEM, DFM, INRIM, GUM</td>
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		meetings and appropriate measures will be taken. Input will be given to Technical Specification TS 21551 "Nanotechnologies – Methods for sample preparation for particle size measurements by electron microscopy methods and atomic force microscopy".
CEN TC352 Nanotechnologies	**NPL**, PTB	NPL has been actively involved in this committee for a decade and is the liaison officer for ISO TC201 and reports on ISO TC229 work. The committee meets twice a year in the spring and autumn and will be informed about the aims and outputs of the project. The involved participants (NPL and PTB) will ask for feedback from CEN experts on the work and results presented. Feedback will be discussed at project meetings and appropriate measures will be taken.
VAMAS TWA 2 (Surface chemical analysis)	**NPL**, INRIM, PTB	VAMAS is the Versailles Project on Advanced Materials Standardisation. It was founded in 1982 by G7 countries as a pre-normative organisation for advanced materials. An international interlaboratory comparison of step height measurements and lateral length will be undertaken within the framework of VAMAS. (TWA 2) NPL, INRIM and PTB will present project results that are relevant to the experts in this TWA, which meets alongside the ISO 201/SC9 meeting. The involved participants will ask for feedback on the work and results presented.
BSI CII/60 Surface chemical analysis	**NPL**	NPL has been involved in this committee since its inception. It meets approximately 3 times per year and mirrors the work of ISO TC201 and all its subcommittees including SC9 (scanning probe microscopy). NPL will ask for feedback on the work and results presented as appropriate.
BSI NTI/1, METSTA, DIN NA 062-08-17, UNE/CTN GET15 “Nanotechnologies” National mirror committees to ISO TC229	**VTT**, PTB, NPL, CEM	National Mirror committees in Finland (METSTA), Germany (DIN) and UK (BSI) will be informed about relevant project results by VTT, PTB, NPL and CEM committee members to facilitate greater standardisation in the use of SPM, SEM and TEM microscopy as key reference measurement tools for the characterisation of nano-objects and nanotechnologies. These committees meet 1–2 times per year. The involved participants will ask for feedback on the work and results presented.
BIPM CCL (length) & CCL-WG Nano CCL-Task group on Digitalisation	**PTB**, NPL, VTT, CMI, CEM, DFM, INRIM	A series of recommendations will be made to CCL WG-Nano on the use of silicon steps with a suggested update to the Mise en pratique. A report will be presented on other associated standards developed within the project together with potential achievable uncertainties. PTB, NPL, VTT, CMI, CEM, DFM and INRIM will present project results that are relevant to the experts in this consultative committee, which meets every two

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<tr><td></td><td></td><td>years. The involved participants will ask for feedback on the work and results presented.</td></tr>
<tr><td>Ad-hoc WGS & Strategy WG of BIPM</td><td>PTB</td><td>The consortium will establish a regular exchange with specific WGs on digitalisation, such as Metrological Semantics, Data Quality in Metrology or SI Digital Framework. PTB will present project results that are relevant to the experts in these working groups. The involved participants will ask for feedback on the work and results presented.</td></tr>
<tr><td>BIPM CCU (Units)</td><td>PTB</td><td>Progress and outputs of the project will be communicated to the committee, in particular about progress towards the implementation of the secondary realisation of the “Metre” (--> lattice parameter of silicon) and opportunities for the inclusion of additional secondary realisations in order to strengthen the SI Reference Point. PTB will present project results that are relevant to the experts in this consultative committee, which meets every two years. The involved participants will ask for feedback on the work and results presented.</td></tr>
<tr><td>EURAMET Technical Committee for length (TC-L)</td><td>NPL, CMI, GUM, DFM, CEM, VTT</td><td>TC-L meet once per year, normally in October.
The project’s results (Development of smart standards and automatic data processing in nanometrology) will be promoted for discussion at these annual meetings throughout the project’s lifetime by the NMI participants. The involved participants (NPL, CMI, GUM, DFM, CEM and VTT) will ask for feedback on the work and results presented.</td></tr>
<tr><td>TC digitalisation at IMEKO</td><td>PTB</td><td>The consortium will report about the implementation of digital workflow for SPM calibration and measurement at nanoscale. By establishing a constant exchange from the beginning of the project, this will ensure harmonisation with already available standards, protocols and procedures. PTB will present project results that are relevant to the experts in this technical committee, which meets every 1-2 years. The involved participants will ask for feedback on the work and results presented.</td></tr>
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The representatives on the corresponding committee or WG from the participants will jointly ask the chairperson to include a point in the agenda to briefly present the outputs of the project related to the WG activities and ask for comments. Where appropriate a written report will be submitted for consideration by the committee or WG.
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<td>A5.1.12
M36</td>
<td>Within the technical WPs, the participants will produce and publish 3 good practice guides:

Good practice guide for digital flow in nanometrology including aspects of data and metadata handling, data formats, and application to advanced measurement regimes (high speed, force volume, spectroscopic, adaptive scanning) (A1.4.5, Deliverable D1).
Good practice guide on the use of a library of automated data processing routines (digital assistants) in SPM data evaluation, its reference

</td>
<td>CMI, all participants</td>
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	implementation and aspects of integration into commercial microscope control software (A3.3.6, Deliverable D5). • Good practice guide on uncertainty propagation through a digital traceability chain in dimensional nanometrology (A4.2.4, Deliverable D6). In this impact activity, they will be advertised by email distribution, on the project website, through the stakeholder committee, direct contact with stakeholders and the networks of the consortium. The guides will be targeted in particular at industrial end users.	
A5.1.13 M2	PTB with support from all participants will set-up an on-line Discussion Group on LinkedIn in order to exchange information among the members of the project and the end-users. This Discussion Group will be used to promote the latest information from the project to end-users and on the project webpages (A5.1.2). Other social media platforms such as X (previously known as Twitter) will also be used for promoting the latest achievements obtained by the project. The consortium will tag EURAMET on X (previously known as Twitter) and LinkedIn with '@EURAMET' 'and @EURAMET' - The European Association of National Metrology Institutes' respectively so that EURAMET can share if appropriate. Also, hashtags such as #measurementscience, #metrology, #EUfunded, #EUPartnership should be used if possible.	**PTB,** all participants
A5.1.14 M36	Software, reference datasets and relevant documentation developed during the project will be disseminated via established open content sharing platforms such as Gitlab (software sharing) and Zenodo (publication of datasets). Both repositories will be linked to the project website hosted by PTB (A5.1.2).	**PTB,** NPL
A5.1.15 M18, M30	At least 2 one day workshops will be organised by PTB and INRIM to transfer the best practices of nanostructure measurements effectively to SPM users, including potential stakeholders from outside of the project. The workshops will be linked to an international conference (e.g., Nanoscale 2026 (around M18, November 2026), NanoInnovation 2027 (around M30, November 2027)) and will feature demonstrations of the project developed methods for nanometrology. The target number of attendees will be >70 drawn from the >10 community/user groups. The workshops will be promoted by advertisement on the project webpage (A5.1.2), the participant's websites, through academic contacts and the project's Stakeholder Committee (A5.1.1), and other social media platforms (LinkedIn) and by the conference organisers. The participants will liaise with existing and potential future EMN's e.g., EMN Advanced Manufacturing or any relevant EURAMET TC, to see whether there are any other EURAMET funded projects, EU funded Partnerships or any research/industrial projects, that could be utilised to increase the outreach of the workshops.	**PTB,** INRIM
A5.1.16 M30, M34	To disseminate the results of the project to as broad an audience as possible in a cost-efficient way, at least two online seminars (webinars) will be hosted. One 0.5-day webinar will be in M30 (November 2027) and another 0.5-day in M34 (March 2028), organised by PTB, INRIM, VTT, PWR and CMI and focusing on samples and methods developed in the project. The target audience will be 30 participants drawn from >5 community/user groups. These webinars will be advertised through the central project website (A5.1.2), the websites of the participants, social media (e.g., LinkedIn) and through (electronic) mailing to Stakeholder Committee members (A5.1.1). The participants will liaise with existing and potential future EMN's e.g., EMN Advanced Manufacturing or any relevant EURAMET TC, to see whether there are any other EURAMET funded projects, EU funded Partnerships or any research/industrial projects, that could be utilised to increase the outreach of the webinars.	**PTB,** INRIM, VTT, PWR, CMI
A5.1.17 M20	A two-hour session on new SPM calibration methods will be organised in a bi-annual SPM workshop targeted to SPM users (e.g., Lednice, Czech Republic 2027) in central Europe (organised by CMI). The target audience will be 50 participants. This will be advertised to stakeholders via the project webpage (A5.1.2), participant webpages, other social media (e.g., LinkedIn) and the project's Stakeholder Committee (A5.1.1).	**CMI**

A5.1.18 M24	TUBS, together with PTB, will organise a Summer School in around M24 (May 2027) on ML with a focus on image creation and processing. The target audience will be at least 20 participants from the metrology community, and the duration of the summer school will be 3 days. The summer school will be promoted by advertisement on the project website (A5.1.2), the participant's websites and through the project's Stakeholder Committee (A5.1.1).	**TUBS,** PTB
A5.1.19 M36	A number of short videos (15 minutes) for e-training on the use of the new methods for calibration will be developed by PTB and INRIM during periodic meetings (2 times per year) by recording the presentation sessions and uploading the video to a devoted YouTube channel and other suitable channels (e.g., TC IM 1449 Research Data Management website). The videos can be published, or left hidden, but with a direct link being made available to stakeholders on the project website (A5.1.2). The videos will also be promoted on the participant's websites, through the project's Stakeholder Committee (A5.1.1). The YouTube link will be sent to EURAMET for further promotion.	**INRIM**, PTB
A5.1.20 M36	To enable other stakeholders to understand and have access to the results of the projects 3 articles will be submitted to the popular press or trade journals such as Physics World, Microscopy and Analysis.	**PTB,** all participants
A5.1.21 M36	The participants will liaise with EMN Advanced Manufacturing or any other relevant EURAMET EMN or TC, to see whether there are possible synergies that could be built on. For example, to understand if there are any other EURAMET funded projects, EU funded Partnerships or any research/industrial projects, that could be utilised to increase the outreach of the projects such as organisation of joint events.	**PTB,** all participants
A5.1.22 M36	To approach the wider public at least two press statements will be released: one at the beginning and one at the end of the project and others during the project when results need to be shared with the public. The press release will be disseminated through the participating NMIs and DIs.	**PTB,** all participants

C5.b Task 5.2: Exploitation and uptake

Activity number	Activity description	Participants (Lead in bold)
A5.2.1 M36	A dissemination, communication and exploitation plan (DCE) will be created at the beginning of the project by PTB, with support from all participants, and submitted to EURAMET at M9 (February 2026). It will be reviewed and updated at least at each project meeting. The DCE plan will provide further details on the following expected Key Exploitable Results: • Key Exploitable Result 1: Good practice guide for digital flow in dimensional nanometrology. • Key Exploitable Result 2 (2a, 2b, 2c): Three types of newly developed smart calibration samples (crystalline silicon step heights, self-assembly based lateral structures (DBC) and ALD multiscale patterns) with intrinsically higher amounts of information that can be digitally transferred to the next stage of the calibration chain, and which will be commercialised or ready for commercialisation. • Key Exploitable Result 3: Library, for automated data processing in SPM, with a license that permits it to be integrated into the software used by SPM manufacturers as digital assistants. • Key Exploitable Result 4: Methodology for the propagation of measurement uncertainty within the traceability chain for dimensional nanometrology.	**PTB,** all participants
A5.2.2 M35	Case study on the implementation of a digital workflow for nanometrology end users Based on the application of D1, D2, D3, D5 and D6, NPL and CMI will create a case study where a digital workflow will be implemented for nanometrology end users. The end users will be selected from NPL's industrial contacts.	**NPL**, CMI
A5.2.3 M35	Case study on the use of samples in commercial instrumentation and software Using input from A2.1.12 and A3.3.3, and based on the application of D1, D2, D3 and D5 NFI, with support from Bruker FR, Nanosurf and OXINST, will create a case study on the use of the developed samples and algorithms in their commercial instrumentation and software.	**NFI**, Bruker FR, Nanosurf, OXINST

A5.2.4 M35	Case study on digital workflows in NMIs Based on the application of D1 and D6, CEM and GUM will create a case study for the application of a developed digital workflow in metrology institutes / national measurement systems.	**CEM,** GUM
A5.2.5 M35	Case study on the transfer of an end-to-end digital workflow to other areas (e.g., surface texture using optical and tactile instruments, SEM measurements, GISAX measurements) Using input from A2.1.11, A4.3.3, A4.3.4 and A4.3.5 and based on the application of D7, PTB, CMI and INRIM will create a case study to demonstrate the applicability and transferability of the end-to-end digital workflows to other areas: surface texture using optical and tactile instruments, SEM measurements, GISAX measurements.	**PTB,** CMI, INRIM
A5.2.6 M36	Key Exploitable Result 1: Good practice guide for digital flow in dimensional nanometrology (A1.4.5, Deliverable D1) PTB and NPL will disseminate this guide to standards bodies (detailed in A5.1.11) for uptake as a new guide. The good practice guide will also be made available on the project website.	**PTB,** NPL
A5.2.7 M36	Key Exploitable Result 2a: Transfer of ALD reference samples (A2.2.3) to industry/commercialisation: The design of the ALD reference samples, from A2.2.1, will be published in a paper. VTT, or a stakeholder, will make the samples commercially available to customers. The availability of the ALD reference samples will be promoted using the project's communication tools.	**VTT**
A5.2.8 M3, M28	Key Exploitable Result 2b: Transfer of the DBC sample to industry/commercialisation: INRIM will discuss with the participants the guidelines on sample fabrication to define intellectual processes on the fabrication protocols and on the terms and conditions for sharing relevant details on the production of reference samples, with the consortium and/or eventually as open public data. This will lead to commercial availability of the samples either during, or after the end of, the project. They will be manufactured by INRIM or by a stakeholder. The A1.1.5 fabrication database will be made available to the participants in two stages: initially (M3, August 2025) the details on available samples will be shared with the consortium to enable the pre-screening of the samples, as per A1.1.5 and A1.1.6. In the last part of the project (M28, September 2027) data will be updated after feedback from manufacturers, participants and the redesign of the lateral standards, according to A2.1.11.	**INRIM,** all participants
A5.2.9 M36	Key Exploitable Result 2c: Transfer of crystalline standards to industry / commercialisation: PTB will make the crystalline standards (from A2.1.9) and the refined production method (from A2.1.9) available to stakeholders who will be able to commercialise the product. PTB will apply for further research funding from e.g., a TransMet project to support the industrial transfer of the crystalline standards.	**PTB**
A5.2.10 M36	Key Exploitable Result 3: Distribution of library, data management and SPM data evaluation routines to end-users: Using input from A3.3.2 and A3.3.6, BUT, with the support of CMI, PTB and TUBS, will make the following available to end-users: library, for automated data processing in SPM, with a license that permits it to be integrated into the software used by SPM manufacturers as digital assistants, and a software reference implementation of the digital data management/SPM data evaluation routine via the existing open-source software for SPM data analysis (Gwyddion). This software will be distributed via the project websites, open software repositories and other appropriate distribution pathways.	**BUT**, CMI, PTB, TUBS
A5.2.11 M36	Key Exploitable Result 4: Methodology for the propagation of measurement uncertainty within the traceability chain for dimensional nanometrology. VTT, CMI and NPL will promote the uncertainty propagation methodology to stakeholders and to the general public using the project webpage and other project communication tools.	**VTT**, CMI, NPL

A5.2.12 M36	Preparation of a starter kit (samples and documentation) for stakeholders: INRIM and the participants will prepare a starter kit including a set of selected samples accompanied by a document titled ”Preparation of sample specifications and handling for further availability”, which will integrate D2 and D3 as per A2.1.12, A2.2.7 and A2.3.7. INRIM will distribute at least 5 starter kits (samples and documentation) to stakeholders (1 starter kit per stakeholder). The starter kit will enable stakeholders (mostly SPM manufacturers related, or unrelated, to the project) to test the project concepts on their equipment, including exploring the novel traceability routes, and the data processing of the measured data on the samples in a reference implementation of data processing libraries.	**INRIM**, all participants
A5.2.13 M36	The consortium will plan how their project will contribute to the Partnership KPI 2.4 (*an average of at least EUR 50 million of European turnover per year from new or significantly improved products and services*) and will collect data for reporting.	**CMI**, all participants

All IP and potential licencing/exploitation will be handled in accordance with the Grant Agreement and the Consortium Agreement.

C6 WP6: Management and coordination

C6.a Task 6.1: Project management

Activity number	Activity description	Participants (Lead in bold)
A6.1.1 M36	The project will be managed by the coordinator from CMI who will be supported by the project management board consisting of a representative from each internal beneficiary; including the leaders of each work-package. The members of the project management board will guide the project, attend the project meetings, communicate with stakeholders, organise the progress meetings at their local institutes and call additional meetings if needed to ensure the overall project’s success.	**CMI**, all beneficiaries
A6.1.2 M36	The work package leaders will coordinate the work carried out in a specific work package and will be responsible to the coordinator for reporting on the progress of individual work packages. This assignment will give the project a coherent structure and will facilitate coordination of the overall project. The work package leaders will report on the on-going progress to the coordinator by e-mail and online meetings.	**CMI**, PTB, NPL, VTT, INRIM
A6.1.3 M36	The coordinator, with support from the participants, will manage the project’s risks to ensure timely and effective delivery of the scientific and technical objectives and deliverables.	**CMI**, all participants
A6.1.4 M36	The consortium will ensure that any ethics issues identified are addressed.	**CMI**, all participants

C6.b Task 6.2: Project meetings

Activity number	Activity description	Participants (Lead in bold)
A6.2.1 M1	The kick-off meeting involving all participants will be held approximately one month after the start of the project, at CMI. The meeting will be used to refine the definitions of the prioritised SPM workflows that will be digitised.	**CMI**, all participants
A6.2.2 M36	There will be five formal project meetings. These meetings include the kick-off, mid-term (around M18, November 2026) and final meeting (around M36, May 2028). In addition, two further meetings will be held around M9 (February 2026) and M27 (August 2026). The meetings will be held prior to reporting. The meetings will review progress and will be used to ensure participants are clear as to their role for the next period. The location of the meetings will rotate among the participants. Where appropriate, meetings may be held as satellite meetings to important conferences or committee meetings. Hybrid attendance to the meetings will be allowed.	**CMI**, all participants
A6.2.3 M36	In addition, technical meetings of work package groups may be held whenever necessary and will be arranged on an ad-hoc basis. Notification of such meetings will be sent to all participants and a record of the key outcomes and actions sent to PTB.	**CMI**, all participants

A6.2.4 M36	The project management board will hold a meeting at least quarterly, which might be organised in parallel to some of the in-person meetings or organised as a virtual meeting.	**CMI**, all participants

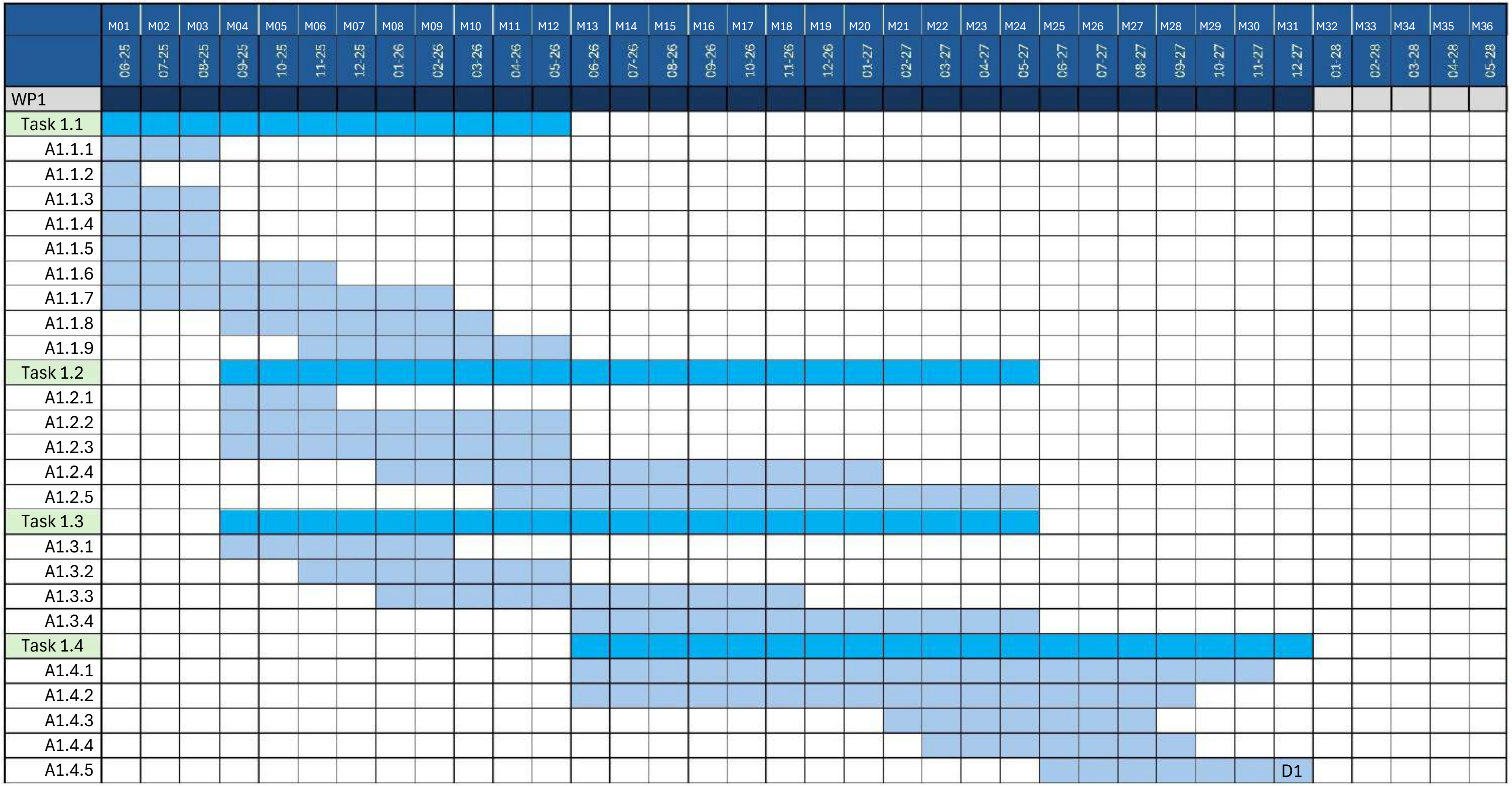
C6.c Task 6.3: Project reporting

Activity number	Activity description	Participants (Lead in bold)
A6.3.1 M1	One month after the start of the project a publishable summary will be produced and submitted to EURAMET.	**CMI**, all participants
A6.3.2 M9 +45 days	Following Articles 19 and 21 and the data sheet of the grant agreement, Interim 1 Reports will be submitted to EURAMET at month 9 (February 2026 + 45 days), in accordance with the procedures issued to enable EURAMET to comply with its obligations to report on the programme to the European Commission. The following reports will be required. • Progress report (Interim). • Data management plan (DMP). • Dissemination, communication and exploitation plan (DCE). All participants will provide input to these reports and the coordinator will provide these to EURAMET. Where necessary, additional reports and / or information may be requested to enable EURAMET to comply with its obligations to the European Commission.	**CMI**, all participants
A6.3.3 M18 +60 days	Following Articles 19 and 21 and the data sheet of the grant agreement, Period 1 Reports will be submitted to EURAMET at month 18 (November 2026 + 60 days), in accordance with the procedures issued to enable EURAMET to comply with its obligations to report on the programme to the European Commission. The following reports will be required. • Progress report (Periodic) and financial reports. • Outcomes and impact report. • Updated publishable summary. All participants will provide input to these reports and the coordinator will provide these to EURAMET. Where necessary, additional reports and / or information may be requested to enable EURAMET to comply with its obligations to the European Commission.	**CMI**, all participants
A6.3.4 M27 +45 days	Following Articles 19 and 21 and the data sheet of the grant agreement, Interim 2 Reports will be submitted to EURAMET at month 27 (August 2027+ 45 days), in accordance with the procedures issued to enable EURAMET to comply with its obligations to report on the programme to the European Commission. The following reports will be required. • Progress report (Interim). If requested as an outcome of a midterm review or periodic reporting, any, or all, the following reports may need to be delivered: updated outcomes and impact report, updated publishable summary and an updated dissemination, communication and exploitation plan. EURAMET will inform the coordinator if these reports are required at Interim 2 reporting. All participants will provide input to these reports and the coordinator will provide these to EURAMET. Where necessary, additional reports and / or information may be requested to enable EURAMET to comply with its obligations to the European Commission.	**CMI**, all participants
A6.3.5 M36 +60 days	Final Reports and Period 2 reports will be delivered at month 36 (May 2028 + 60 days) in accordance with Articles 19 and 21 and the data sheet of the grant agreement. The following reports will be required: • Progress report (Periodic) and financial reports. • Final public report. • Updated data management plan. • Updated dissemination, communication, and exploitation plan. • Updated outcomes and impact report (including impact and exploitation questionnaires).	**CMI**, all participants

	All participants will provide input to these reports and the coordinator will provide these to EURAMET. Where necessary, additional reports and / or information may be requested to enable EURAMET to comply with its obligations to the European Commission.	
A6.3.6 M22 if selected	Some projects will be subject to a midterm review in Spring 2027. Where projects are selected for a midterm review, reports (project self-assessment, updated publishable summary and presentation) will be delivered prior to the midterm reviews for Call 2024, following the schedule detailed by EURAMET for the specific review. All participants will provide input to these reporting documents and the coordinator will provide the documents to EURAMET.	**CMI**, all participants

Formal reporting will be in line with EURAMET's requirements and will be submitted in accordance with the Reporting Guidelines.

C7 Gantt chart



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Section D: Risk and risk mitigation

D1 Scientific/technical risks

Risk (description)	Likelihood, impact and severity of occurrence	Mitigation i.e., what the consortium will do to decrease the likelihood of the risk occurring	Contingency i.e., what the consortium will do if despite the mitigation the risk still occurs
Task 1.1: Information (minimum metadata definitions) from the participants is not received on time.	Likelihood after mitigation: Medium Impact: Parts of the metrological traceability chain cannot be modelled. Level of severity: High	Start information collection as early as possible. Structured templates for information collection will be provided to the participants. Responsible participants will be nominated, and regular meetings will be held to elicit information collection.	Nominate another participant to supply the information.
Task 1.2: The participants cannot reach consensus on the minimum metadata required in the SPM traceability chain.	Likelihood after mitigation: Low Impact: The agreed metadata will not be as broad as expected, which will reduce the potential applicability of the developed traceability chain. Level of severity: Medium	Use the SPM digitalisation workshop to reach consensus. Lists of metadata descriptors, for the different categories, will be prepared and shared with the participants pre-workshop. Information on the importance of the data elements will be collected via questionnaire.	Use the minimum metadata, required in the SPM traceability chain, which has been agreed by most of the participants.
Tasks 1.3 – 1.4: Non-representative, or overly complex, example digital processing workflows are selected for modelling.	Likelihood after mitigation: Low Impact: Some reference data examples (e.g., the use of a particular sample for automated calibration) may not be relevant for use by the wider community. Level of severity: Medium	All participants will be involved in the selection of the digital processing workflows for modelling. The selection will be confirmed with stakeholders, including those from the Stakeholder Committee.	The participants will ensure that at least one of the modelled digital processing workflows is suitable for wide use and that it will be relevant for the community.
Task 2.1: There is a delay in fabricating the required number (at least 10) of monatomic step height standards (traceable reference samples).	Likelihood after mitigation: Low Impact: Measurements using the traceable reference samples will be delayed. Level of severity: Low	The schedule for the different fabrication runs will be produced as soon as possible at the beginning of the project to ensure that the required number of traceable reference samples will be available.	PTB will select a smaller number of existing traceable reference samples for delivery to the NMI participants. These will be used for evaluating the usability of the step height standards (traceable reference samples).
Task 2.1: Silicon step height and lateral self-organised samples are unavailable at the beginning of the project for the Stakeholder Committee; problems redesigning samples for the consortium; delays in sample measurements.	Likelihood after mitigation: Low Impact: The step height and lateral samples will provide data for use in WP4 and WP3. The unavailability of new data will reduce instrument comparison and traceability. Measurement delays will impact the definition of relevant metadata. Level of severity: Medium	In the first phase, the participants will rely on existing silicon step height and lateral samples, which have already been produced, characterised, and labelled. Many existing samples are available, which will provide redundancy. New silicon step and self-organised lateral samples will be produced using well-established techniques and protocols that have been developed at fabrication facilities. There are sufficient fabrication capabilities in the consortium, as well as metrological and commercial SPMs and other characterisation techniques.	If some of the project's samples are unavailable, the participants will rely on their existing images and measurements.

Task 2.1: The development of software (AI based tools) for the automatic analysis of confocal microscopy pictures of crystalline standards, which are used as the basis for AI analysis, is delayed.	Likelihood after mitigation: Low Impact: The design of AI tools, based on machine learning techniques, for the rational design and manufacturing of di-block copolymers (DBC) could be delayed. Level of severity: Low	As a first step, existing software will be used for the analysis (manual) of the most relevant confocal microscopy pictures of crystalline standards. AI based tools will be developed by several participants (PTB, TUBS, CMI, INRIM), using different approaches. Hence the probability that none of them will succeed has been significantly lowered.	Several participants (PTB, TUBS, CMI, INRIM) will provide their individual expertise in AI to the development of software (AI based tools) for the automatic analysis of CLSM pictures of crystalline standards. These participants are individually connected to a worldwide network of AI experts who will be able to support the development of this software.
Task 2.2: Embedded reference sample production is delayed. The characterisation of embedded reference samples by different SPM and other instruments is delayed.	Likelihood after mitigation: Low Impact: The lack of availability of embedded reference samples for in SPM automated measurements will result in information not being provided to WP4 for the digital assistant and digital calibration certificate. Such a delay in the supply chain could affect interfacing with the digital assistant. Level of severity: Medium	Embedded reference samples will be fabricated using two different approaches, ALD and MBE, which have overlap for performing the core part of this task. Both institutes (DFM and VTT) are experts in these techniques and production will rely on established protocols and materials. Redundancy in the consortium's ability to perform SPM and other characterisation techniques will minimise the risk.	The consortium also has different fabrication capabilities available, such as laser writing and EBL, which could be used to produce a simplified and lower throughput version of the embedded reference samples. Despite higher costs, a lower number of samples and less information, a minimal set of samples will be produced.
Task 2.3: The production of MEMS based SPM reference standards is delayed. The MEMS based SPM reference standards are too big for some SPM setups. Problems with the delivery of referenced electronic drivers cannot be resolved.	Likelihood after mitigation: Medium Impact: A few MEMS based SPM reference samples will be provided with driving electronics. If there are missing or damaged samples, this will result in a reduced capability to include dynamic information in the calibration procedures. Level of severity: Low	Two different technologies, i.e., MEMS and hysteresis free piezo actuators, will be used. MEMS devices are under development, while piezo actuators are ready on the shelf. Redundancy also minimises this risk in terms of sample applicability to a particular SPM due to space constraints. This third task is designed to provide high added value and low negative impact on the project, in case of failure.	In the case of severe damage to piezo actuators and MEMS production problems, which affect the availability of both samples, the dynamic behaviour of the data will be simulated to the minimum extent that will be useful for the definition of the metadata.
Task 3.1: The dataset for benchmarking automated SPM data processing routines in nanometrology does not include sufficient real-world measurement scenarios.	Likelihood after mitigation: Low Impact: The automated SPM data processing routines cannot be tested using sufficient real-world measurement scenarios. Level of severity: Medium	The participants have extensive experience in generating virtual SPM data. In addition, there are already many existing tools in Gwyddion for doing this. It will be an easy task to regenerate datasets if some aspects are missing.	A subset of measurement scenarios will still be tested when debugging the algorithms. Any special uncovered cases will be tested subsequently.
Task 3.2: The automated quality checking and data processing algorithms do not have the expected performance (i.e., the required uncertainty cannot be achieved).	Likelihood after mitigation: Low Impact: The use of automated routines will be limited, thus reducing the potential cases when users could benefit from them. Level of severity: Low	Samples, such as crystalline step height standards, will be circulated and measurements will be performed from the beginning of the project. Therefore, realistic data will be available during the development of the algorithms.	Some of the samples will be too complex to be analysed automatically.
Task 3.3: The developed libraries of automated data processing routines are unusable or not taken up by SPM manufacturers.	Likelihood after mitigation: Medium Impact: The impact of the project will be much lower if the algorithms are not used or are not used in the SPM manufacturer's software. Level of severity: Low	The participants, and SPM manufacturers, will discuss the form that the libraries will take, their interfaces and licensing at the very beginning of the project.	The libraries will only be used by some of the SPM manufacturers, or only a part of the library will be used. An alternative off-line version of the toolchain will be used, in Gwyddion, to substitute for the other parts of the library.

Task 4.1: The uncertainty budget components of the calibration samples are not evaluated correctly by the participants.	Likelihood after mitigation: Low Impact: Measurement uncertainty is underestimated. Level of severity: Low	The NMI participants are experts in the evaluation of measurement uncertainty and these NMIs have CMCs on the measurements. Cooperation between the participants will simplify the evaluation.	Other NMI participants will be asked to help in the evaluation of uncertainty budget components in digital data workflows.
Task 4.2: The uncertainty budget components in digital data workflows are not recognised correctly by the automated routines developed in the project.	Likelihood after mitigation: Low Impact: Measurement uncertainty is underestimated. Level of severity: Low	The NMI participants are experts in the evaluation of measurement uncertainty. The uncertainty of the digital data workflow will be compared to traditional calibration.	The users of the method will estimate a case specific uncertainty for their measurement. The digital data workflow method will improve the measurement accuracy even if the uncertainty analysis remains incomplete.
Task 4.3: The uncertainty components in other types of instruments are not recognised correctly by the data handling concepts used in Task 4.2 (as real-world conditions can be very different from NMI laboratory conditions).	Likelihood after mitigation: Low Impact: The measurement uncertainty is under- or over-estimated by the data handling concepts used in Task 4.2. Level of severity: Low	The NMI participants are experts in the evaluation of measurement uncertainty and these NMIs have CMCs on the other measurements. The industrial participants have experience of performing measurements under different conditions. The environmental conditions will be defined to avoid misunderstanding.	The users of the method will estimate a case specific uncertainty for their measurement. The digital data workflow method will improve the measurement accuracy even if the uncertainty analysis remains incomplete.

D2 Management risks

Risk (description)	**Likelihood, impact and severity of occurrence**	**Mitigation** i.e., what the consortium will do to decrease the likelihood of the risk occurring	**Contingency** i.e., what the consortium will do if despite the mitigation the risk still occurs
Key personnel are lost to the project.	Likelihood after mitigation: Medium Impact: The loss of key team members would create difficulties in delivering the project, or specific tasks or deliverables. Level of severity: Low	None of the team members are planning to leave or retire within the project. Each team member has valuable experience that is not replicated exactly by other team members. The grouping of European experts within the consortium should minimise the areas where knowledge is held by a single person. All the participants will identify backups for key workers wherever possible to reduce the overall risk to the project. Project plans will be shared within the consortium and results and methodology will be documented.	If a key member leaves the project, then the participant concerned will be responsible for appointing a replacement. However, this may still lead to a delay in delivery. Where this will risk project failure, the consortium will aim to shift work between participants. Staff secondment between institutes will be investigated as a means of replacing staff capacity quickly to protect the project critical path.
Complexity of managing a large consortium.	Likelihood after mitigation: Low Impact: Failure to fully cooperate or communicate effectively within the consortium could endanger efficient delivery of the project. Level of severity: Medium	The participants are all experienced at cooperating in complex multinational projects. Many have previously developed close relationships through collaborating within other European consortia. Regular communication and feedback will ensure that potential problems are identified early and that all participants are clear on their roles.	WP leaders will play an important role in flagging up potential problems to the coordinator and the project management board, who will then decide on the best course of action to take. If necessary, work will be reassigned to an alternative participant, or parts of the work re-scoped in agreement with EURAMET.

Delayed input of data to the coordinator or delayed deliverables.	Likelihood after mitigation: Low Impact: Delay in timely submission of reports to EURAMET. Level of severity: Medium	All participants are experienced in the running of European metrology projects or similar large research projects.	All participants will be given sufficient notice of deliverable dates and the reporting schedule. CMI will maintain regular communication with participants so that any potential delays are identified and mitigated.
Problems dealing with Intellectual Property (IP) ownership and/or exploitation might occur and could be a source of potential conflict.	Likelihood after mitigation: Low Impact: Disagreement between the participants could delay the project (in implementing the work and publishing results). Level of severity: Medium	All beneficiaries will sign the grant agreement and all participants the consortium agreement, which includes IP clauses. IP will be handled accordingly.	Independent arbitrators will be used in the event of disagreement between participants.
Inter-dependencies between technical activities and tasks are too complex.	Likelihood after mitigation: Medium Impact: Tasks are delayed, or it is not possible to deliver them. Level of severity: Medium	Technical meetings run by WP leaders have been scheduled to ensure proper sharing of knowledge. The interdependencies between tasks will be considered at meetings to ensure that this is addressed properly in the planning of the work. The technical WPs will be closely managed by their WP leaders to ensure that they deliver their own outputs.	In most cases, activities on the critical path have some overlap in time and thus a delay in the output of one deliverable does not necessarily cause an immediate delay in another.
The onsite facilities of participants, and/or access to public/commercial services or sites is restricted for a period of time during the project due to an extraordinary event or situation that is beyond the participants' control e.g., COVID-19.	Likelihood after mitigation: High Impact: Activities and deliverables are delayed, or no longer able to be completed. Level of severity: High	In most cases, activities on the critical path have been scheduled to have some overlap in time and thus a delay in the output of one activity will not necessarily cause an immediate delay in another.	Where possible, work will be reassigned to an alternative participant, or rephased, therefore minimising delays and technical deviations that would have a negative impact on the project. If necessary, the consortium will contact EURAMET to discuss options according to the grant agreement.
Organisation of workshops and joint demonstrator activities in a post- or trans-COVID world.	Likelihood after mitigation: Medium. Impact: Failure to show the outputs at workshops or through joint demonstrator activities risks reducing the knowledge transfer and impact from the project. Level of severity: Low	Although most COVID travel restrictions have been removed, there is the possibility that some restrictions may be re-introduced nationally or internationally, or organisations may apply their own restrictions. Some flexibility is built into the tasks and activities with nominal locations and dates, but these will be reviewed nearer the time and the consortium will decide on the appropriate locations of such activities e.g., to take advantage of/cope with moved external events.	Alternatives such as webinars or online meetings can be used.

D3 Ethics

The Partnership Ethics Review 2024 has given JRP 24DIT02 DINAMO "Ethics clearance".

<u>Ethical integrity</u>

The participants will ensure that all ethics issues related to activities in the project are addressed in compliance with ethical principles (including the highest standards of research integrity as set out in the ALLEA European Code of Conduct for Research Integrity https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/guidance/european-code-of-conduct-for-research-integrity_horizon_en.pdf), the applicable international and national law, and the provisions set out in the grant agreement. This includes the ethics issues identified in the ethics screening and the submitted documents, and any additional ethics issues that may emerge in the course of the project. In the case where any substantial new ethics issues arise, participants will inform the granting authority EURAMET e.V, and for each ethics issue applicable, participants will follow the guidance provided in the Horizon Europe *'How to complete your ethics self-assessment' guide'*.

The consortium will ensure that appropriate procedures, policies and structures (https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/guidance/guideline-for-promoting-research-integrity-in-research-performing-organisations_horizon_en.pdf) are in place to foster responsible research practices, to prevent questionable research practices and research misconduct, and to handle allegations of breaches of the principles and standards in the Code of Conduct.

Data protection

By signing or acceding to this grant agreement and / or consortium agreement each participant asserts that the requirements of the General Data Protection Regulation (GDPR) 2016/679 which entered into force on 25 May 2018 will be met. Under the regulation, the data controllers and processors are fully accountable for the data processing operations. Any violation of the data subject rights may lead to sanctions as described in Chapter VIII, art.77-84 of the GDPR.

If personal data are transferred from the EU to a non-EU country or international organisation, such transfers will be in accordance with Chapter V of the GDPR 2016/679. If personal data are transferred from a non-EU country to the EU (or another third state), such transfers will comply with the laws of the country in which the data was collected.

Non-EU countries

The consortium will ensure that participants and collaborators, including those from non-EU countries, fully adhere to Horizon Europe ethics standards and guidelines, no matter where the research or activities are carried out and that research or activities performed outside the European Union are compatible with EU, national and international legislation and can be legally conducted in one of the EU Member States. If applicable, details on the material, samples and/or equipment which will be imported to/exported from EU must be provided and the adequate authorisations and/or export licences granted by the relevant authorities have been or will be obtained and kept on file by the consortium.

Personal Data

The ethics screening identified that there are issues arising from project work involving personal data.

By signing or acceding to this grant agreement each participant asserts that they will document and keep on file:

- The ethics risks related to the data processing activities, including an opinion if a data protection impact assessment should be conducted under art.35 GDPR 2016/679.
- Explanation of how all of the data the consortium intends to process is relevant and limited to the purposes of the research project (in accordance with the 'data minimisation' principle).
- If applicable, anonymisation/pseudonymisation techniques will be implemented or explanations will be provided as to why the data will not be anonymised/pseudonymised.
- The technical and organisational measures that will be implemented to safeguard the rights and freedoms of the data subjects/research participants.
- The processing of sensitive personal data has been justified.
- The security measures that will be implemented to prevent unauthorised access to personal data or the equipment used for processing.
- Detailed information on the informed consent procedures in regard to data processing.
- If the research involves profiling, then explanations as to how the data subjects will be informed of the existence of the profiling, its possible consequences and how their fundamental rights will be safeguarded.
- If applicable, explicit confirmation that the data used in the project is publicly available and can be freely used for the purposes of the project is provided.
- If further processing of previously collected personal data is undertaken, then each participant must have a lawful basis for the data processing and the appropriate technical and organisational measures are in place to safeguard the rights of the data subjects.

- If applicable, any derogations pertaining to the rights of data subjects or the processing of genetic, biometric and/or health data have been established under the national legislation of the country where the research takes place, have been checked and a declaration of compliance with respective national legal framework(s) submitted.

Artificial intelligence

The ethics screening identified that there are issues arising from project work involving artificial intelligence.

By signing or acceding to this grant agreement each participant asserts that any work involving artificial intelligence is carried out in agreement with ethical principles and relevant legislations.

The consortium will ensure that any AI methods used and/or developed in the project comply with the prerequisites for ethically sound AI systems in accordance with the '*Ethics Guidelines for Trustworthy AI*'.

Section E: References

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