IOPscience

PAPER

A digital framework for realising the SI—a proposal for the metre

Andrew J Lewis[3,1], Andrew Yacoot[1], Martin J T Milton[2] and Andrew J Lancaster[1]

Published 19 August 2022 • © 2022 BIPM & IOP Publishing Ltd

Metrologia, Volume 59, Number 4

Focus on Length Metrology

Citation Andrew J Lewis *et al* 2022 *Metrologia* **59** 044004

DOI 10.1088/1681-7575/ac7fce

andrew.lewis@npl.co.uk

[1] National Physical Laboratory, Teddington, TW11 0LW, United Kingdom

[2] Bureau International des Poids et Mesures, F-92312 Sèvres Cedex, France

[3] Author to whom any correspondence should be addressed.

Andrew J Lewis https://orcid.org/0000-0001-9556-3890

Andrew Yacoot https://orcid.org/0000-0001-6740-821X

Martin J T Milton https://orcid.org/0000-0002-8174-2211

Andrew J Lancaster https://orcid.org/0000-0001-5001-0459

1. Received 7 April 2022
2. Revised 28 June 2022
3. Accepted 8 July 2022
4. Published 19 August 2022

Abstract

A current focus of the international metrology community is the digitalisation of documents, certificates and services in response to initiatives underway throughout industry and to the requirement to follow the principles of data being Findable, Accessible, Interoperable, and Reusable. We propose the key elements of a digital framework for the SI metre, at the point of realisation, showing how it may be implemented in practice. We give examples of direct benefits of this approach, which may be extended to other SI units.

Previous article in issue

Next article in issue

1. Introduction: digitalisation in manufacturing and metrology

The process of digitalisation is revolutionising how products are designed, produced, used, and maintained throughout their lifecycle [1], transforming factory operations and processes and their supply chains. The drivers for digitalisation are varied, being largely focussed on improving: efficiency, productivity, accuracy, or responsiveness; and through these improvements, deriving a reduction in cost. Digitalised manufacturing also has a key part to play in design for recyclability and product end of life management [2].

Metrology lies at the heart of manufacturing, and the international system of units, the SI, lies at the heart of metrology. There are two main drivers for the digitalisation of metrology. Firstly, the need for metrology to assume the same digital status as other technologies underpinning the Industry 4.0 [3] and Factory of the Future [4] paradigms; and secondly the requirements for metrology data produced though calibration to fulfil as many Findable, Accessible, Interoperable, and Reusable (FAIR) data principles as possible, especially where a publicly-funded National Metrology Institute (NMI) is the provider [5] and they are re-using high-level information on SI unit definitions and realisations.

The digitalisation of metrology is being encouraged by the International Committee for Weights and Measures (CIPM) which has tabled a Draft Resolution for the General Conference on Weights and Measures (CGPM) which will meet for its 27th meeting in November 2022. The draft resolution, 'On the global digital transformation and the International System of Units' states:

'*The General Conference on Weights and Measures... (anticipates) ... creation of a fully digital representation of the SI, including robust, unambiguous, and machine-actionable representations of measurement units, values and uncertainties; ... encourages ... the CIPM to undertake the development and promotion of an SI digital framework, that will include the following features: a globally accepted digital representation of the SI ... facilitating use of digital certificates in the existing robust infrastructure for the world-wide recognition and acceptance of calibration and measurement capabilities; the adoption of the FAIR principles (Findable, Accessible, Interoperable, and Reusable) for digital metrological data and metadata, ...*'

The majority of members of the CIPM Consultative Committee for Length (CCL) plan to offer digital calibration certificates and digitalisation work is already underway at the International Bureau of Weights and Measures (BIPM), but concrete approaches to bridging the gap between the digital infrastructure at the BIPM and the physical unit realisations around the world have not yet emerged.

In this paper we focus on the realisations of the SI base units (the highest level of the SI which may be digitalised); we give some examples of possible benefits of a digital framework for SI realisations; and we propose a possible approach to 'digitalising the SI metre'.

2. The SI

2.1. Base units of the SI

The International System of units (the SI [6]) is the most widely used set of measurement units. New SI unit definitions were adopted on 20 May 2019 [7]. Also associated with each base unit is a method of realising the unit in practice (its so-called Mise en Pratique—MeP). The main principles of how the SI base units are realised are summarised in table 1.

Table 1. Main MeP methods for the SI base units.

Unit	Mise(s) en Pratique
kg	Kibble balance, x-ray measurements of crystal density
m	Time of flight, radiation wavelengths, Si lattice
s	Atomic clocks, frequency standards

Unit	Mise(s) en Pratique
A	Ohm's law (V/R), single electrons, (V, F, s)
K	Acoustic-, dielectric-, refractive-, noise-based
mol	Single crystal Si, gravimetry, electrolysis
cd	Source-based, detector-based radiometry

2.2. Digital approaches underway within the SI

In response to the digital transformation underway in industry, the worldwide metrology infrastructure, headed by the BIPM and the NMIs, is also undergoing a digital transformation. The reasons why the SI needs a digital framework have been described in detail [8]. Digitalisation work is underway at the BIPM to: create an application programming interface (API) access to the key comparison database [9]; prepare an XML version of the SI brochure [10]; ensure data used to support key comparisons and publications are FAIR [11]; and to grant API access [12] to the *Circular T* [13] data in a machine readable format.

Although these digitalisation efforts are underway, from table 1 it is clear that the definition and realisation of the SI base units are not themselves digital entities; they are analogue systems and processes, subject to uncertainties and experimental variation. How then may they be 'digitalised'? In section 4 we will propose an approach to a digital framework for realising the SI metre, which will sit at the interface between the official MeP documentation for the metre (BIPM) and the physical realisation at both primary and secondary levels (NMIs/DIs). This approach may be extended to cover the other six base units of the SI.

3. Benefits of a digital framework for the SI

3.1. Benefits of SI digitalisation for end users

The higher-level societal benefits of a digital framework for the SI have been described [8, 14]. On a more technical level, with a digitalised approach to reporting SI-traceable data, the provenance of the end user's equipment calibration can be more easily traced back directly to the underlying SI standards, and if there is full transparency of all intermediate links, reproducibility is improved.

Digitalisation can also deliver many of the requirements of the FAIR principles and can do so starting at the highest worldwide level of metrology—the realisations of the SI units. Digitalised SI unit realisations would be:

Findable—SI units have a globally unique and persistent identification; with suitable metadata, the data relating to the SI units (already accessible to humans via the SI Brochure) would be machine accessible at the BIPM website;

Accessible—the motto of the SI is 'for all people, for all time' and the BIPM already provides SI accessibility through its website and international coordination work, and this will be enhanced through the use of digitalised unit realisation information and the digital access to the SI Brochure;

Interoperable—the SI, by its very nature, is designed to be interoperable, being the basis for all measurements worldwide; it has a formal language which is already set out in the SI Brochure; digitalised MeP data would be in a structured format enabling and encouraging re-use through syntactic parsing of the data;

Reusable—the SI is designed for global use; the units have detailed provenance (through the CIPM); use of an agreed scheme for the unit realisation data would meet domain-relevant community standards, allowing the data to be replicated or combined with additional data lower in the calibration chain, and existing work, such as the SmartCom Digital-SI exchange format [15], can also be reused.

By offering a fully transparent calibration process at the point of realisation of the SI units, and promulgating this, digitally, through the calibration of high-level standards, the needs of FAIR are satisfied from the root of SI traceability—it is then the responsibility of the remainder of the calibration chain to continue to respect the principles of FAIR, if the end user is to receive maximum benefit.

The provision of calibration data, in machine-actionable format, directly to the customer also offers opportunities for simplification and automation of tasks. Machine-actionable data would allow, for example, a system using a calibrated laser to decide whether the laser was behaving incorrectly (e.g. worse stability) by comparison with stability information presented in the downloaded calibration data, and to then decide whether to proceed with the use of the laser or to automatically increase the uncertainty of the final result. In addition to improved efficiency, effectiveness, and productivity via these processes, the digital approach also fosters enhanced innovation and creativity rather than simply supporting traditional methods.

The Open Knowledge Foundation [16] defines machine readable data as '*data in a format that can be processed by a computer*. *Machine-readable data must be structured data*'. It is questionable whether it is sufficient to simply include all data related to a measurement or calibration in a file if a human is still required to make sense of the data. The data, including its context, must be readable and able to be parsed by software without further human intervention, in a way that uniquely and unfalteringly extracts numerical data (including units) together with any critical metadata (e.g. date of authorisation or restrictions on the use of the method) such that the data may be immediately used as part of a subsequent calibration or verification process.

Furthermore, simply transitioning from an existing paper calibration certificate to providing the same information in digital format may no longer be sufficient. International Standard ISO/IEC 17025:2017 [17] requires that all critical elements must be included in a calibration certificate, and this must hold also for Digital Calibration Certificates (DCCs). In this context, the digital data of the measurement result, including its uncertainty, is insufficient for the purposes of machine-readability. The context of the data becomes critical and must therefore be included, in order that automated systems can fully interpret the data; this will require the inclusion of metadata related to the measurement. As an example, measurement of an object's surface roughness should not only report the value of the measurand and its uncertainty, but also specify the relevant aspects of the data processing software that have been applied such as: the specific ISO roughness parameter (e.g. Ra, Rq) and which version of the ISO standard has been followed, how the raw data was filtered, the traceability path to the relevant SI units including the 'version' of the relevant unit in place at the time (e.g. was the temperature measured according to ITS90 or IPTS68, there being small, but potentially significant, differences between the two temperature scales). A DCC from a fully-digitalised measurement infrastructure should report much more (meta) data than an analogue (paper) counterpart, and to do so fully will require both an agreed format for presenting the data and a high degree of transparency of the data, necessitating stricter adherence to the requirements of FAIR than demonstrated at present.

3.2. Benefits of SI digitalisation for metrology

Digitalisation of the national and international metrology infrastructure ensures that metrology remains innately embedded in manufacturing and everyday life. Metrology would gain a higher prominence and recognition than currently achieved since the FAIR-compliant digital calibration chain would automatically acknowledge all the measurement steps underpinning the end use of the data, analogous to the way that blockchain approaches store permanent ledgers of all preceding transactions [18]. The contributions of the NMIs and the BIPM/SI would be explicitly visible in the digital calibration data and measurements outside the SI would be clearly identifiable as such. A digital 'SI enforcement' could be envisaged, based on existing quality infrastructures, but taking into account the richer meta data being provided, whereby if any item in a traceability chain cannot prove digital credentials which are SI traceable, all subsequent measurements based on the item lose their 'SI traceable' status, much like a single expired digital signing certificate causes rejection of internet-supplied credentials in critical transactions. The true underlying and underpinning nature of the SI infrastructure around the world will be exposed and clear for all to see.

3.3. Enabling AI approaches in metrology

Artificial intelligence (AI) is being used in many fields, and its performance is often evaluated using reference datasets. However it is only recently [19] that metrological approaches have been proposed for the performance evaluation of AI systems. Whilst there is clear benefit to using improved metrological practices for evaluating AI, and of course it is essential that AI uses traceable data as input for decision making, we propose that the reverse process may also be a future benefit from a digitalised SI—using AI approaches on SI-traceable, machine-readable data for the benefit of the metrology itself. As an example, an AI-based approach could detect traceability 'loops', where a device ends up being traceable to itself, through an incorrectly applied traceability path. For example gauge blocks are often calibrated by comparison against reference gauge blocks which should have an independent traceability path through interferometry. If an older calibration by interferometry has been superseded by recent calibration by comparison, there is a possibility that the gauge blocks which are now 'test' items could have been the reference item when the reference gauge blocks were calibrated, i.e. the gauge blocks being calibrated now, are actually traceable to themselves more than to an interferometer result. The meta data would currently indicate traceability of every link in the chain, but unless the chain is followed in detail (which may require an AI approach in complex situations) then the potential problem is not identified.

Also, in an ideal world, fully FAIR data would allow identification of negative trends such as instability in certain types of artefacts or instruments through automated analysis of available calibration data, as well as identifying outlying behaviour in results of some measurement providers (e.g. unrealistic drift rates). Correlations between disparate issues in separate locations, or common errors in a batch of items from a supplier could be traced back to correlations between measurements, pointing to a single error source such as a particular calibration at a single provider. Over time such approaches may be used to automatically predict future metrology needs in the same way as the future requirement for nanometrology was identified in the 1980s through human-based analysis [20]. However we realise that commercial concerns may limit the actual calibration data made public by customers; in such cases we would hope that at least the traceability meta data is offered freely (in the way that statements about SI traceability are required), even if the actual data (calibration values) are withheld for commercial reasons.

4. A proposal for a digitalised SI metre

The metre is one of the most frequently used SI units, indeed the original treaty founding the international adoption of the SI was known as the Metre Convention, so we will now propose and detail an approach by which the SI metre may be digitalised at the highest level; by extension, this approach may be applied to the other six base units of the SI and derived units.

4.1. The SI metre and its realisations

When the SI was redefined in 2019, the CCL though its working groups (especially the Working Group on Strategic Planning, and the Working Group on Dimensional Nanometrology), took the opportunity to both provide more detailed information on realising the metre through an expanded MeP document on how to realise the metre using the speed of light definition, and also to add a secondary method of realising the metre using the silicon lattice parameter, which had been determined through research work spanning several decades [21]. Along with the updated definition of the metre, the new MeP documents were issued on 20 May 2019, followed by detailed publications on their use [22, 23]. In the SI brochure [10], the metre is now defined as follows:

> 'The metre, symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum *c* to be 299 792 458 when expressed in the unit m s^{-1}, where the second is defined in terms of the caesium frequency $\Delta\nu_{Cs}$'.

The metre can be realised using any method described in the MeP documents, i.e. based on the following techniques.

Time of flight—by taking the speed of light as a constant, and timing the transit time of an electromagnetic signal, with reference to the SI second, for time traceability. This method is most suited to longer distances due to the high absolute speed making high demands on the timing precision.

Interferometry—by using light with a calibrated wavelength or a light source of known wavelength coming from the list of recommended values of standard frequencies [24, 25], approved by the CIPM. This approach is mostly used for lengths and ranges from nanometres to tens of metres.

Silicon lattice—the length scale is transferred to the nano dimensional measurement process through one of three approaches, which use the silicon {220} lattice spacing, which has a value of d_{220} = 192.015 5716 × 10^{-12} m (with standard uncertainty 3.2 × 10^{-18} m, according to CODATA [26]). Note that the value for d_{220} quoted in the current version of the MeP [27] will be shortly updated to match the current CODATA value. The three approaches are: displacement measurement using an x-ray interferometer; TEM measurements using the lattice as a lateral scale standard; and use of monatomic steps of crystalline silicon surfaces for traceability in the 'vertical' direction; the latter approach being intended for use in scanning probe microscopes, which are the workhorse of nanotechnology and nanometrology.

The approved methods for realising the SI metre all rely on access to physical systems or processes in their existing, non-digital, format: a light source and timing equipment, a source of known radiation and suitable detector, or a sample of crystalline silicon. At first sight, no obvious route to 'digitalisation' of these SI metre realisations is apparent:

- the *electromagnetic radiation* used in time of flight measurements is analogue in nature (even if it is reformatted into digital pulses by a transmitter) and the source of timing information eventually links to the caesium atomic clocks which are based on quantum transitions and an analogue waveform of the emitted radiation;
- the *radiation* used for interferometry is analogue in terms of its wavelength (even with digital control of the light sources, the wavelength of the radiation is continuously varying);
- the *silicon lattice* is already quantised, with analogue variability depending on local environment and impurities.

It is not, however, digitisation of the physical standards which we propose, but of the infrastructure that surrounds their definition, approval, dissemination, and their ongoing reliable utilisation.

4.2. Access to Mise en Pratique data

The definition of the metre will soon be available in machine readable XML format. The definition of the metre has only changed a few times throughout history, more frequently updated is the information in the MeP for the metre [27], especially the list of recommended values of standard frequencies [25] and the information relating to the silicon lattice parameter [28–30]. Therefore, at its 2021 meeting, the CCL set up a task group to prepare the MeP data for machine-readable access. Below, we propose a way to implement machine readable MeP data using an example XML schema and discuss how this may then be implemented in practice during realisation of the metre using both primary and secondary methods.

4.2.1. Recommended values of standard frequencies

The list of recommended values of standard frequencies [25] lists radiations (and their associated data) which can be used for either practical realization of the definition of the metre, or secondary representations of the second (or both). One of the most frequently used radiations is that of the He–Ne laser locked to a hyperfine component of the R(127) 11–5 transition in the $^{127}I_2$ molecule, at approximately 633 nm (474 THz). Lasers stabilised to this transition offer a relative standard uncertainty of 2.1×10^{-11} and are used to calibrate lower accuracy lasers that are used in interferometers for making length measurements (see figure 1). The stated relative uncertainty can only be achieved if the laser is operated in accordance with the conditions stated in the MeP document, ensuring: cell-wall temperature and cold-finger temperature are within a specified range; the frequency modulation is within specified bounds; as is the intra-cavity power. When these values are achieved, and the locking electronics performance is suitable, the output beam will have the frequency and wavelength values stated in the document; otherwise, the values and uncertainties may not be obtained.

From time to time, as new data is submitted for consideration by the CIPM, the frequency/wavelength values in the MeP may be updated, and the specific conditions may be changed. Unless the end users are aware of these updates, they may continue to operate their lasers using out of date specifications. The proposal from the CCL task group is to make critical aspects of the MeP data for these radiations downloadable in a machine readable format. When an MeP laser is being operated, its control PC may then automatically access up-to-date information from the BIPM server, as depicted in figure 2. Provided that the data exchange follows a defined protocol and results in a defined format information, then the MeP laser can read the relevant values and use them.

Following this approach, we now propose an example XML schema (full details are available in a public repository [31]) which may be used for transmitting relevant data of the MeP and show how this may be used in practice. Possible benefits of this proposed approach will be discussed later. At present, the largest set of data in the MeP for the metre relates to items in the list of recommended values of standard frequencies—a database of entries assembled over many decades of research worldwide. We therefore base our example XML schema around the data in this list, however a modified schema is envisaged for the secondary realisation of the metre using silicon, as described in section 4.2.2.

The critical aspects of the schema are that it makes available the most critical items of information, currently stored in text format, in a machine readable format. These are the specific wavelength (and frequency) values together with the requirements on operating condition of the light sources used in the realisation. Also included are items of metadata such as the date of authorisation of the MeP data and any date of revocation of the data. The formal XML schema is presented in a repository [31], together with comments on the meaning of various parts of the schema. The physical calibration of a customer laser, as shown in figure 1 is connected to the data exchange in figure 2 which shows a request from the MeP laser for latest data for a specific radiation (the common 633 nm iodine-stabilised He–Ne wavelength) and the response from the BIPM server with data that strictly follows the XML schema. The control computer of the MeP laser can extract relevant items directly from the returned data and use these in the calibration process. Any issues, e.g. detection of a change in validity dates for the specified entry, or a change in values (due to newly added data being approved by the CIPM) could be used to request supervisor intervention or approval prior to its use. In essence, the data, formatted as per the schema, is a digital representation of the MeP data—a digitalised SI metre.

4.2.2. Secondary realisation based on the silicon lattice parameter

The value of the silicon lattice spacing quoted in the MeP is based on the value quoted in CODATA which is available in machine readable format [26]. However, as with the laser frequencies, other information is necessary for practical realisation of the metre based on silicon [32]. Most importantly any piece of silicon used must be defect free and the impurity content known. There are several techniques available for measuring impurity content, for example, x-ray fluorescence, neutron activation, infra-red or mass spectroscopy. The effects of impurity content are tabulated in the MeP and further details can be found [33, 34].

We propose that the key data from these papers is also made available, in a different XML schema, from the BIPM server to allow users to apply a correction to the lattice parameter of their piece of silicon based on their measurements of impurity concentration. In addition, a knowledge of the thermal expansion coefficient and temperature at the point of measurement would be necessary. Data related to this correction could also be made downloadable in a format that allows for automated corrections. An alternative to measuring the impurity content of silicon is to directly compare the lattice spacing of silicon with that of a known piece of silicon using a lattice comparator [35]; currently a piece of silicon that has been extensively studied is required for a traceable measurement. With the proposed digitalisation of the data concerning lattice parameter variations with impurity content, the use of lattice comparators may be extended.

4.3. Initial implementation—example of the new NPL metre realisation lasers

Through digitalisation of measurement services, the National Physical Laboratory is updating the UK's primary length standards, the laser sources used for realising the metre and for calibrating the optical frequency of stabilised lasers and laser interferometers submitted by customers. A small single-board computer [36] is being integrated into the overall control system and will access the MeP data via the NPL network—eventually this link will go to the BIPM where we hope to download the data according to the schema we have proposed.

4.4. Initial implementation—example of the secondary realisation based on the silicon lattice spacing

Atomic force microscopes (AFMs) are ubiquitous throughout nanotechnology. Traceability for AFM measurements is achieved through the use of samples that have been calibrated using metrological AFMs (MAFMs). These are AFMs that use optical interferometers to measure the relative displacements, in their three lateral motion axes, between the sample and the AFM tip; the traceability comes through the calibrated laser wavelength, as per figures 1 and 2. However, the inclusion of the secondary metre realisation in the MeP now allows an additional traceability route to be used.

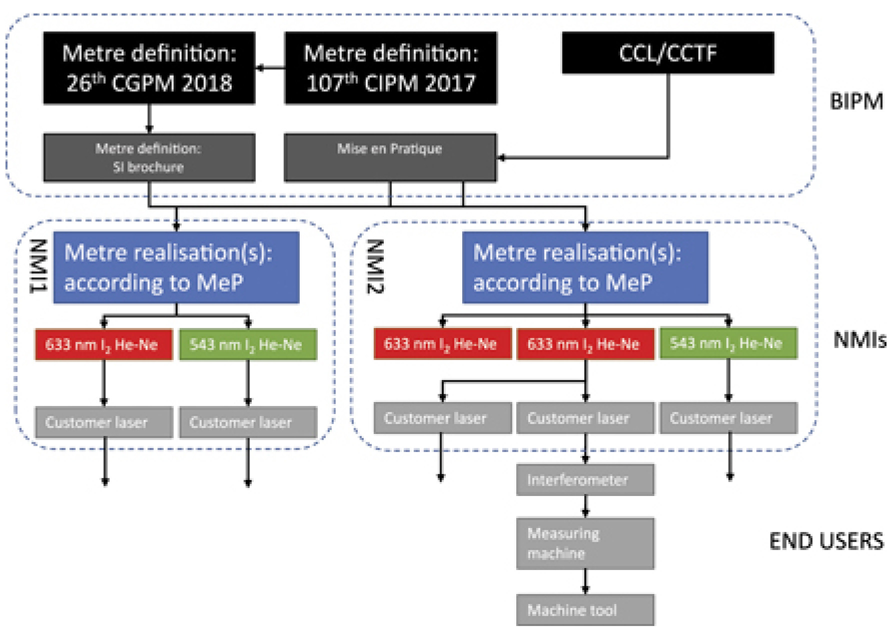

Figure 1. Schema showing SI physical length traceability links at the highest level, using MeP lasers.

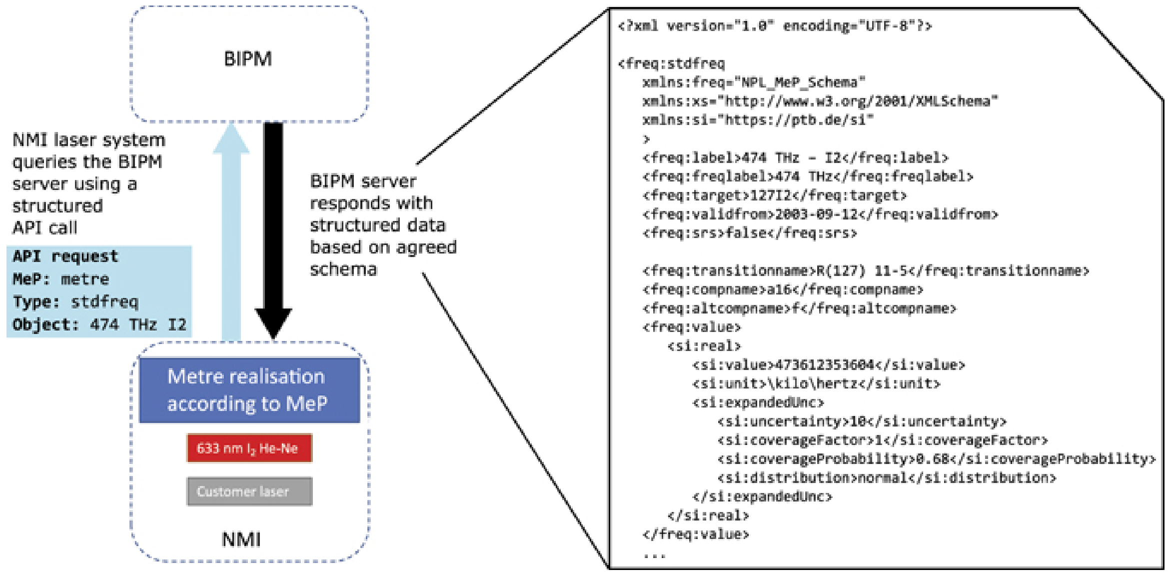

Figure 2. Data exchange between an NMI and the BIPM during calibration of a laser using an MeP laser. The data returned by the BIPM server in response to the request follows a defined XML schema which the MeP laser control computer can directly interpret and use. (API response truncated for brevity.)

As shown in [37, 38] and formalised in the MeP, silicon steps can be used as SI-traceable calibration standards in AFMs. By downloading the impurity and thermal sensitivity coefficients from the BIPM and using digital information about the measured impurities in a silicon standard, a correction to the lattice parameter can be calculated and applied by the AFM control computer. The benefit to the user is the automated approach to deriving and applying corrections, which improves the accuracy of the calibration of the AFM. This may be of greater importance when the AFM is measuring over larger distances, for example when assessing potential non-linearity errors of optical interferometers or other critical parts of the instrument, especially for non-MAFMs.

4.5. Benefits from the digitalised metre realisation

During the calibration of a customer laser by NPL, the metadata relating to the specific metre realisation in use will be downloaded. The control PC in the NPL laser will check that the operational conditions of the laser are fulfilling the requirements given in the MeP.

As an example of the next stage of the digital SI chain, we consider the calibrated laser being used to perform gauge block measurement by interferometry [39]. The data in the DCC is loaded into the gauge block interferometer computer; it is accompanied by similar DCC data for the other sensors which are part of the traceability: air pressure, temperature and humidity sensors (for refractive index) and gauge block temperature sensors (for thermal expansion corrections) (see figure 3).

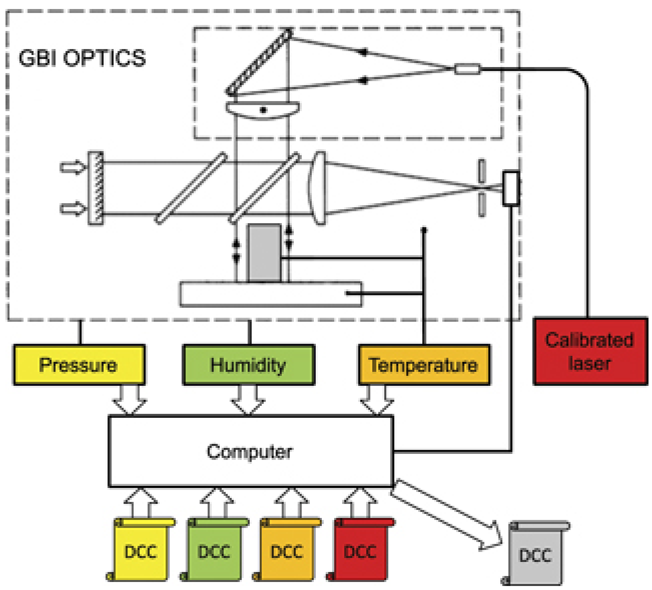

Figure 3. DCCs from the calibrated laser and critical sensors are used in the gauge block interferometer. Data from the DCCs is combined into a new DCC for the gauge block(s) being calibrated.

As well as using the main metrological data stored in the provided DCCs, the gauge block interferometer computer combines relevant metadata and outputs it, together with the measurement result, uncertainty, etc to the DCC for the gauge block(s) being calibrated, or makes the data available via a server.

The metadata continues down the traceability chain with the next use of the gauge blocks, e.g. to calibrate a micrometer. The micrometer may then digitally trace its calibration to relevant SI unit realisations through their own XML schema and MePs; in the example given here, traceability is to the metre (laser wavelength, pressure), kelvin (thermal sensors, humidity meter) and the kilogram (pressure). Some of these SI units e.g. kelvin, kilogram may not be readily appreciated as being part of a micrometer's length calibration traceability chain—the exposure of such links through the digital certification process is another benefit of a digitalised SI with digitalisation starting at the XML copy of the SI brochure and the XML schema-based MePs for the units.

The secondary realisation based on silicon steps directly lends itself to the benefits of digitalisation. In the MeP some guidance on measuring steps was given based on traditional methods of step height evaluation coming from International Standard ISO 5436 [40], however, following the MeP publication, a paper describing an areal approach for evaluating the heights of terraces has been published [38]. These routines are currently available in the open source AFM software *Gwyddion* [41] and are 'manually' operated. There is increased interest in use of the silicon atomic steps and the CCL Working Group on Dimensional Nanometrology is considering options for a comparison based around these samples. After more data has been gathered and a better understanding of uncertainties associated with use of these steps is achieved, including uncertainty coming from the instruments used to measure the steps, there will then be the possibility of automating the routines such that the user needs only to say if terraces have been correctly identified; a bimodal decision. Automating the routines and making them centrally available would remove user bias in data processing [42].

We note that a secondary benefit of a formal schema for machine readable data is that data submitted in the future for consideration in updating the MeP, such as new laser frequency data, can also be submitted in machine readable format, to simplify and automate its analysis, processing, and integration. For the metre, this is especially important as the former collation of laser frequency data by the BIPM length section halted when the section was closed; future collation work must therefore be undertaken by the NMIs and the CCL and will benefit from the increased automation enabled by a digitalised metre with formal data schema.

5. Conclusion

We have proposed a framework within which data and metadata for the realisation of the SI unit of length, the metre, may be digitalised and disseminated, at the top of the traceability chain. The approach uses a formally-agreed XML schema in which critical aspects of a metre realisation, either primary or secondary, can be downloaded automatically from the BIPM and used to validate the correct operation of the realisation. The critical data may then be added to a DCC for a calibration of a physical entity (e.g. laser) such that this important metadata can be promulgated to the next step in the traceability chain.

Nothing we have proposed for this digital framework for SI metre realisation is specifically bound to the length unit—the approach of using an XML schema at the level of the MeP is applicable to the other base units listed in table 1. In fact, the process shown in figure 3 presupposes similar approaches being used in the other units, beside the metre. We propose that similar frameworks could readily be developed to cover all the SI.

Acknowledgments

Assistance and encouragement in proposing this approach is acknowledged from the CIPM Consultative Committee for Length, and its President, Ismael Castelazo. The NPL aspects of this work were funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the UK's National Measurement System programme.

Author contributions

A J Lewis proposed the main idea of using downloadable data from the MeP in an agreed XML schema, wrote the main part of the paper, designed an initial XML schema and provided the illustrations and photograph.

A Yacoot wrote the sections concerning the silicon lattice traceability route.

M J T Milton gave feedback on the first draft of the paper, suggested additional items for inclusion, provided the text on the CIPM/CGPM decisions, and information on the FAIR and AI aspects.

A J Lancaster provided a more comprehensive version of the proposed XML schema and example python code.

---

[1] Schleich B *et al.* 2019 Shifting value stream patterns along the product lifecycle with digital twins *Procedia CIRP* **86** 3–11
Go to reference in article Crossref Google Scholar

[2] Curran R, Gomis G, Castagne S, Butterfield J, Edgar T, Higgins C and McKeever C 2007 Integrated digital design for manufacture for reduced life cycle cost *Int. J. Prod. Econ.* **109** 27–40
Go to reference in article Crossref Google Scholar

[3] Carlberg M, Kreutzer S, Smit J, Moeller C and EU Directorate General for Internal Policies 2016 *Industry 4.0* (Brussels: European Parliament) (https://doi.org/10.2861/947880)
Go to reference in article Crossref Google Scholar

[4] Ridgway K, Clegg C, David W and UK Government Office for Science 2013 *The Factory of the Future* (Sheffield: The National Metals Technology Centre, University of Sheffield AMRC)
Go to reference in article Google Scholar

[5] Research Data Alliance 2020 *FAIR Data Maturity Model : Specification and Guidelines* https://zenodo.org/record/3909 563#.YGRNnq8za70June 2022
Go to reference in article Crossref Google Scholar

[6] International Bureau of Weights and Measures 2019 *The International System of Units (SI)* 9th edn (Sèvres: BIPM)
Go to reference in article Google Scholar

[7] Stock M, Davis R, de Mirandés E and Milton M J T 2019 The revision of the SI—the result of three decades of progress in metrology *Metrologia* **56** 022001
Go to reference in article Crossref Google Scholar

[8] Brown R J C, Janssen J-T and Wright L 2022 Why a digital framework for the SI? *Measurement* **187** 110309
Go to reference in article Crossref Google Scholar

[9] BIPM 2021 API KCDB https://bipm.org/en/cipm-mra/kcdb-api (Accessed 1 November 2021)
Go to reference in article Google Scholar

[10] BIPM 2021 SI Brochure https://bipm.org/en/publications/si-brochure (Accessed 1 November 2021)
Go to reference in article Google Scholar

[11] Wilkinson M D *et al.* 2016 The FAIR guiding principles for scientific data management and stewardship *Sci. Data* **3** 160018
Go to reference in article Crossref Google Scholar

[12] BIPM 2022 Time department API web service https://webtai. bipm.org/api/v0.1/
Go to reference in article Google Scholar

[13] BIPM 2022 *Circular T* https://bipm.org/en/time-ftp/circular-t (Accessed January 2022)January 2022
Go to reference in article Google Scholar

[14] Brown R J C, Auty F, Renedo E and King M 2021 The importance of the measurement infrastructure in economic recovery from the COVID-19 pandemic *NCSLI Measure* **13** 18–21
Go to reference in article Crossref Google Scholar

[15] Hutzschenreuter D, Härtig F, Wiedenhöfer T, Hackel S G, Scheibner A, Smith I, Brown C and Heeren W 2020 SmartCom Digital-SI (D-SI) XML exchange format for metrological data version 1.3.1 (1.3.1) https://doi.org/10.5281/zenodo. 3826517
Go to reference in article Google Scholar

[16] Open Knowledge Foundation 2022 Open Data Handbook: machine-readable data https://opendatahandbook.org/gloss ary/en/terms/machine-readable/(Accessed January 2022)
Go to reference in article Google Scholar

[17] ISO/IEC 17025:2017 2017 (International Organisation for Standardization) https:/iso.org/standard/66912.html
Go to reference in article Google Scholar

[18] Sherman A T, Javani F, Zhang H and Golaszewski E 2019 On the origins and variations of blockchain technologies *IIEEE Secur. Priv.* **17** 72–7
Go to reference in article Crossref Google Scholar

[19] Welty C, Paritosh P and Aroyo L 2019 Metrology for AI: from benchmarks to instruments (arXiv: 1911.01875)
Go to reference in article Google Scholar

[20] Tanicguchi N 1983 Current status in, and future trends of, ultraprecision machining and ultrafine materials processing *CIRP Ann.* **32** 573–82
Go to reference in article Crossref Google Scholar

[21] Becker P 2001 History and progress in the accurate determination of the Avogadro constant *Rep. Prog. Phys.* **64** 1945–2008
Go to reference in article Crossref Google Scholar

[22] Yacoot A, Bosse H and Dixson R 2020 The lattice parameter of silicon: a secondary realisation of the metre *Meas. Sci. Technol.* **31** 121001
Go to reference in article Crossref Google Scholar

[23] Schödel R, Yacoot A and Lewis A 2021 The new mise en pratique for the metre—a review of approaches for the practical realization of traceable length metrology from 10^{-11} m to 10^{13} m

Metrologia **58** 052002
Go to reference in article Crossref Google Scholar

[24] Riehle F, Gill P, Arias F and Robertsson L 2018 The CIPM list of recommended frequency standard values: guidelines and procedures *Metrologia* **55** 188
Go to reference in article Crossref Google Scholar

[25] CIPM 2021 Recommended values of standard frequencies https://bipm.org/en/publications/mises-en-pratique/stan dard-frequencies (Accessed 1 November 2021)
Go to reference in article Google Scholar

[26] CODATA 2018 CODATA fundamental constants https://ptb.de/si/nline]/m2m_constants_CODATA_2018_all_v2018.1.xml
Go to reference in article Google Scholar

[27] BIPM 2021 Mise en pratique for the definition of the metre https://bipm.org/documents/20126/41489670/SI-App2-met re.pdf/0e011055-9736-d293-5e56-b8b1b267fd68?version= 1.7&download=true (Accessed 12 November 2021)
Go to reference in article Google Scholar

[28] BIPM 2021 Guidance document CCL-GD-MeP-1 for dimensional nanometrology: using the silicon lattice parameter and x-ray interferometry https://bipm.org/docu ments/20126/41489670/CCL-GD-MeP-1.pdf/b9c05265-888 7-bbc1-2480-f7e8ad75f00d?version=1.6&download=true (Accessed 12 November 2021)
Go to reference in article Google Scholar

[29] BIPM 2021 Guidance document CCL-GD-MeP-2 for dimensional nanometrology: using the silicon lattice and transmission electron microscopy https://ipm.org/docu ments/20126/41489670/CCL-GD-MeP-2.pdf/5825f890-d1c c-1ed9-7893-deae9a095262?version=1.5&download=true (Accessed 12 November 2021)
Go to reference in article Google Scholar

[30] BIPM 2021 Guidance document CCL-GD-MeP-3 for dimensional nanometrology: using the height of monoatomic steps of crystalline silicon surfaces https://bipm.org/docu ments/20126/41489670/CCL-GD-MeP-3.pdf/5240b431-73 0f-3daf-4d8a-be590de99cdb?version=1.8&download=true (Accessed 12 November 2021)
Go to reference in article Google Scholar

[31] Lancaster A J and Lewis A J 2022 NPL MeP standard frequencies XML schema https://doi.org/10.5281/zenodo.6412020
Go to reference in article Google Scholar

[32] Basile G *et al.* 2000 Combined optical and x-ray interferometry for high–precision dimensional metrology *Proc. R. Soc. A* **456** 701–29
Go to reference in article Crossref Google Scholar

[33] Ammon W v, Dreier P, Hensel W, Lambert U and Köster L 1996 Influence of oxygen and nitrogen on point defect aggregation in silicon single crystals *Mater. Sci. Eng. B* **36** 33–41
Go to reference in article Crossref Google Scholar

[34] Wolf E, Schröder W, Riemann H and Lux B 1996 The influences of carbon hydrogen and nitrogen on the floating zone growth of four inch silicon crystals *Mater. Sci. Eng. B* **36** 209–12
Go to reference in article Crossref Google Scholar

[35] Alasia F, Basile G, Becker P, Kuetgens U, Stuempel J, Servidori M and Hartwig J 2001 A Bragg silicon lattice comparator *IEEE Trans. Instrum. Meas.* **50** 608–11
Go to reference in article Crossref Google Scholar

[36] Raspberry Pi Foundation 2021 Raspberry Pi https://raspberrypi. org/ (Accessed 1 November 2021)
Go to reference in article Google Scholar

[37] Yacoot A, Koenders L and Wolff H 2007 An atomic force microscope for the study of the effects of tip-sample interactions on dimensional metrology *Meas. Sci. Technol.* **18** 350–9
Go to reference in article Crossref Google Scholar

[38] Garnæs J, Nečas D, Nielsen L, Madsen M H, Torras-Rosell A, Zeng G, Klapetek P and Yacoot A 2021 Algorithms for using silicon steps for scanning probe microscope evaluation *Metrologia* **57** 064002
Go to reference in article Crossref Google Scholar

[39] Pugh D J and Jackson K 1986 Automatic gauge block measurement using multiple wavelength interferometry *Proc. SPIE* **656** 244–9
Go to reference in article Crossref Google Scholar

[40] ISO 5436-1:2000 2000 (International Organisation for Standardization)
Go to reference in article Google Scholar

[41] Nečas D, Klapetek P and Gwyddion 2021 http://gwyddion.net/
Go to reference in article Google Scholar

[42] Nečas D and Klapetek P 2017 Study of user influence in routine SPM data processing *Meas. Sci. Technol.* **28** 034014
Go to reference in article Crossref Google Scholar