EMPIR Call 2015 – Health, SI, Normative and Research Potential

Selected Research Topic number: **SRT-s11**
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Title: Maintaining and disseminating the new SI unit kilogram via spheres of natural silicon

Abstract

It is anticipated that the 2018 Conférence Générale des Poids et Mesures (CGPM) will decide on the new definition of the SI unit kilogram in terms of the fundamental constant h. The redefinition will be based on the outcomes of two international experiments – the watt balance and the Avogadro project. Relatively few national metrology institutes are in a position to cover the investment and running costs for their own primary realisations based on the watt balance and the ^{28}Si spheres. One potential option is to realise, maintain and disseminate the unit "kilogram" via monocrystalline natural silicon spheres with a relative measurement uncertainty of 3×10^{-8}, thus tracing the mass determination back via measurements of density and volume and subsequent surface measurements. This would require the development of appropriate methods for determining the density and for the manufacture of high accuracy monocrystalline silicon spheres. There is also a need to develop measurement procedures for the dissemination of the unit "kilogram" to industry with high accuracy and at moderate prices.

Keywords

Kilogram, Planck constant, natural silicon spheres, silicon 28 spheres, primary mass standards, surface analysis, interferometric volume determination, density comparison, dissemination, secondary mass standards, traceability, storage, transport, handling

Background to the Metrological Challenges

It is currently expected that the 2018 Conférence Générale des Poids et Mesures (CGPM) will decide on the new definition of the SI unit kilogram, which will probably be expressed in terms of the fundamental constant of Planck (h).

Two international experiments, the watt balance and the Avogadro project, undertaken over many years will provide the basis for the redefinition of the SI unit kilogram [1], with a targeted relative uncertainty for both experiments of 2×10^{-8} [2]. The dissemination of the SI unit kilogram at the highest level, which is the responsibility of the national metrology institutes (NMIs) or designated institutes (DIs), will still be based on physical artefacts. Primary realisations based on the watt balance and the ^{28}Si spheres are only available in a few institutes which are in the position to cover the high investment and running cost of several million Euros (in case of the ^{28}Si spheres).

In order to provide the link between a physical artefact and the fixed value of the fundamental quantity h, the Avogadro experiment uses highly spherical and monocrystalline spheres of the silicon isotope ^{28}Si. ^{28}Si is very expensive and its limited availability and cost are the main reasons why only few NMIs have access to such spheres today.

One option to overcome some of these limitations and which would enable NMIs/DIs, calibration laboratories and industry to profit from the advantages of silicon spheres, is to use monocrystalline spheres made of natural silicon (^{nat}Si). Unlike ^{28}Si, natural silicon is readily available and the cost of the material is about 500 times less than ^{28}Si. Using ^{nat}Si spheres, NMIs with suitable facilities could determine the unit kilogram by an exact determination of the density and the volume of the spheres and then quantitative observation of the surface layer modification, with relative uncertainties of the order of 3×10^{-8}, slightly higher than for a primary realisation. In addition ^{nat}Si spheres could be used for cross-checks with watt balances reducing the risk of damage to ^{28}Si spheres. The value of industrial silicon spheres should also not be underrated. Whilst ^{28}Si spheres or high quality ^{nat}Si spheres will be used within NMIs, silicon spheres with less stringent tolerances could be used as mass standards in calibration laboratories or industry.

The form error of ^{28}Si spheres is currently between 16 nm - 20 nm, however, the manufacturing and finishing processes are challenging and high risk as many parameters such as diameter and surface quality have requirements in the nanometre range. Processes which would enable silicon spheres to be manufactured with roundness errors in the range 5 nm to 10 nm thus reducing one of the most significant uncertainty contributions are not currently sufficiently developed. Using ^{nat}Si spheres highly-accurate surface finishing could be improved without risk of damage to one of the rare and expensive ^{28}Si spheres. These improvements would have significant influence on the uncertainty of the volume measurement for the primary realisations of the kilogram. Industry is currently able to provide silicon spheres but with form errors >80 nm, due in part to the limitations of the commercial form measurement instruments which are available in the companies. Improvements enabling silicon spheres to be prepared with form errors less than 60 nm are required for calibration laboratory and industrial use.

The safe handling of silicon spheres during daily use has not yet been satisfactorily resolved. Today's methods sometimes lead to scratches on the surface of spheres when loading the measuring devices, during weighing processes or when shipping the spheres inside the laboratories or between organisations. Additional research is needed into possible effects (including complex mechanical and chemical interference) on the long-term stability of silicon spheres used for maintaining and disseminating the mass unit due to cleaning, handling, storage and shipping of the spheres. Consequently suitable constructions and materials used for clamping and handling are not available and commonly agreed methods for cleaning and characterisation of the surface of silicon spheres are also missing. ^{nat}Si spheres are almost a factor of 5 cheaper than cylindrical artefacts made of platinum iridium, however most mass balances and mass handling equipment are designed for cylindrical rather than spherical artefacts. Modifications will therefore be required to commercial mass comparators and high-level balances to enable silicon spheres to be measured on commercial products.

Objectives

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

The JRP shall focus on the traceable measurement and characterisation of natural silicon spheres to realise, maintain, and disseminate the unit kilogram via density volume and surface measurements with a relative measurement uncertainty of $u_{rel} = 3x10^{-8}$.

The specific objectives are

1. To enable the unit kilogram to be realised with a relative uncertainty of $u_{rel} = 3x10^{-8}$ via density measurements and surface characterisation of monocrystalline natural silicon spheres including the development of a density comparison facility and the manufacture of natural silicon spheres with form deviations smaller than 10 nm.
2. To develop, implement and validate techniques to characterise the surface properties of natural silicon spheres including the determination of the thickness of the amorphous surface layer, the determination of the increase in the mass of the oxide layer with time, and the preparation of a robust nitride surface layer.
3. To validate the natural silicon sphere realisations by comparisons with national mass standards and ^{28}Si spheres using mass comparators and watt balances, including the development of any ancillary equipment necessary to undertake the comparisons. In addition, comparisons shall be performed on an ensemble of silicon spheres with masses of 500 g and 200 g.
4. To establish a metrological infrastructure for the dissemination of the mass unit via natural silicon spheres to calibration laboratories and industries. This includes the manufacture of natural silicon spheres with form deviations smaller than 60 nm, the upgrade of the measuring devices for wear-free and user-friendly handling, the development of suitable transfer devices, and the specification of appropriate cleaning procedures
5. To facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain (BIPM, NMIs/DIs, accredited laboratories, mass balance and comparators manufacturers) and end users.

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources outside Europe is recommended. A strong industry involvement is expected in order to align the project with their needs and guarantee an efficient knowledge transfer into industry.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMRP projects SIB03 kNOW and SIB05 NewKILO and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.8 M€, and has defined an upper limit of 2.1 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 21 % of the total EU Contribution to the project. Any deviation from this must be justified.

Any industrial partners that will receive significant benefit from the results of the proposed project are expected to be unfunded partners.

Potential Impact

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

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies.
- Transfer knowledge to the mass balance and mass comparators manufacturing sector and calibration laboratories.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing a Joint Research Project"

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

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

Time-scale

The project should be of up to 3 years duration.

Additional information

The references were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] Resolution 1 of the 25th CGPM (2014); http://www.bipm.org/en/CGPM/db/25/1/

[2] CCM recommendation G1 (2013); http://www.bipm.org/utils/common/pdf/SI-roadmap.pdf