THE PLANCK-BALANCE – A SELF-CALIBRATING PRECISION BALANCE FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

A self-calibrating balance is proposed, which allows the calibration of weights in a continuous range from 1 mg to 1 kg. This so-called Planck-Balance (PB) is similar to the physical approach of Kibble Balances that allow the mass to be derived from the Planck constant. Using the Planck-Balance no calibrated mass standards are required during weighing processes any longer, because all measurements are traceable to the electrical quantities and the Planck constant. This allows a new approach of balance types after the expected redefinition of the SI-units by end of 2018. In contrast to many scientific oriented developments, the PB is focused on industrial use. Therefore, two balances will be developed, a PB2 and a PB1, which will allow a relative measurement uncertainty (k = 2) of 5.3×10^{-7} and 1.7×10^{-7}, respectively. Those aimed accuracies refer to the class E2 and E1 weights, as specified in OIML R 111-1. The balances will be developed in a cooperation of the PTB and TU Ilmenau in a project funded by the German Federal Ministry of Education and Research. The project started in January 2017 and will run for 3 years.

Index Terms – Watt Balance, Kibble Balance, Primary mass standard, weighing instrument, load cell

1. INTRODUCTION

The kilogram is the last SI unit that is defined by a material artefact. Thus, a small cylinder with height and diameter of about 39 mm, made of a platinum-iridium(10 %) alloy defines the primary standard of mass. This artefact, named *International Prototype Kilogram* (IPK), is at the summit of the calibration hierarchy of masses. All other mass standards must be traceable to the IPK. In order to trace a mass to the IPK a chain of mass comparisons is necessary. Each comparison goes along with a measurement uncertainty, so that the measurement uncertainty of a mass under test is increasing with decreasing hierarchical order. As the IPK defines exactly 1 kg, with zero measurement uncertainty, the smallest measurement uncertainty can be reached for a one kilogram mass value. For lower or higher mass values the relative measurement uncertainty will increase. The German *National Prototype Kilogram* (NPK), which is made from the same Pt-Ir alloy as the IPK, for example, has an estimated relative measurement uncertainty of 2.3×10^{-9}, or 6×10^{-9} [1], when considering the drift rate. Kilogram Prototypes made of stainless steel, on the other side, already have a relative measurement uncertainty that is by a factor 6.5 worse than that of the NPK, mainly due to air buoyancy effects.

In autumn of 2018 the *General Conference on Weights and Measures* (CGPM) will, most likely, on its 26th conference decide the new SI, including the redefinition of the kilogram.

The kilogram will then be defined by fixing the numerical value of the Planck constant h. From then the definition will probably sound as follows [2]:

> "*The kilogram, symbol kg, is the SI unit of mass; its magnitude is set by fixing the numerical value of the Planck constant to be exactly 6.626 069X* $\times 10^{-34}$ *when it is expressed in the SI unit for action* $J\,s = kg\,m^2\,s^{-1}$."

At the time of the redefinition the symbol *X* will be replaced by one or two digits. The value of the Planck constant is currently determined to lowest measurement uncertainty via two experiments, the Avogadro project [3] and the Kibble balance [4]. The Kibble balance – formerly called Watt balance – compares virtual[1] mechanical power with electrical power. While until now this experiment uses a well calibrated (traceable to the IPK) mass artefact to determine h, after the redefinition the same experiment can be used to determine the mass value of an artefact from the Planck constant. The Kibble balance describes a possible realization of the new kilogram. Each artefact, that will be weighed by means of a Kibble balance represents a primary standard [2]. The redefinition thus offers a new way to calibrate mass standards.

In this article a weighing instrument will be presented, which follows the principle of a Kibble balance. The instrument is named Planck-Balance (PB), as it uses the future definition of the kilogram that will be via the Planck constant. In contrast to common Kibble balances that can handle only a single nominal mass value (e.g. 1 kg), the PB will allow for a calibration over a continuous range of mass values, 1 mg to 1 kg. It is aimed primarily for industry or smaller NMIs to calibrate E1 and E2 mass standards, but can also be used to directly determine the mass of a weight under test, which is not a mass standard, i.e. following the common weighing technique.

This article is aimed to present the basic concept of the PB. In the next section 2 the principle of the Kibble balance will be explained. In section 3 the reasons and status of the redefinition of the SI unit mass will be briefly explained, which makes it possible to calibrate in the future a balance via the electrical quantities, rather than by calibrated mass standards. In the following section 4 then the concept of the PB will be explained in detail, before the article will end with a summary and outlook.

2. THE KIBBLE BALANCE, AN EXPERIMENT TO DETERMINE THE PLANCK CONSTANT *h*

The principle of the Kibble balance, as it is used today, was first proposed by Bryan Kibble in 1976 [5]. A possible route to describe its principle is via the load cell with electromagnetic force compensation (EMFC), as depicted in Fig. 1, which is the state-of-the-art in weighing technology. Here, the weight of a mass that is placed on the weighing pan (1) will be compensated by an electromagnetic force. This electromagnetic force is produced by a coil-magnet (3-4) system. A current that runs through the coil (3) can be measured via the voltage drop at a resistor (5).

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[1] "virtual" means here that power exists in eq. (3) only as a mathematical product. Mechanical and electrical power are not measured simultaneously.

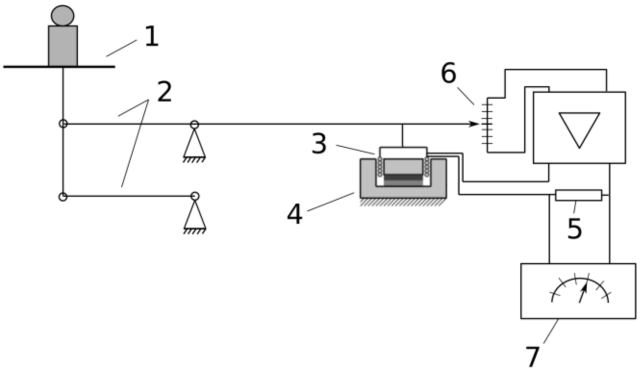

Fig. 1: Principle of a load cell with electromagnetic force compensation. 1-weighing pan, 2-parallel guide, 3-coil, 4-magnet, 5-resistor, 6-position indicator, 7-mass indicator

This voltage is then used to indicate the mass on the weighing pan. The measurement equation for this setup is

$$mg = I \cdot (Bl)\,, \tag{1}$$

where *m* denotes the mass of the weight, *g* the local acceleration due to gravity, *B* the magnetic flux density, *l* the length of the coil, and *I* the electrical current. The calibration of the instrument is done by loading the weighing pan (1) with calibrated mass standards that have been traced to the IPK. This will describe the current as a function of the load. By interpolation mass values different from those that have been used for calibration can be measured, i.e. the balance is able to measure the weight in a continuous mass range.

The step towards the Kibble balance is the introduction of a second mode in the weighing process. Kibble proposed to determine the geometrical factor *Bl* by moving the coil (3) in the magnetic field of the permanent magnet (4). This induces a voltage in the coil that can be measured. By the law of induction, the induced voltage *V* is a function of the velocity *v* and the geometric factor as

$$V = v \cdot (Bl). \tag{2}$$

By equating eqs. (1) and (2) the geometric factor *Bl* drops out which finally lead to

$$mgv = VI\,. \tag{3}$$

Eq. *(3)* shows a virtual equality of mechanical and electrical power – the reason why the Kibble balance formerly was called “Watt balance”[2]. All remaining parameters can be measured to high accuracy. The mass *m* by mass comparison with a calibrated standard, the local acceleration due to gravity *g* by means of a (free-fall) absolute gravimeter, and the velocity *v* by means of a length measurement via a laser interferometer and time measurement via a frequency standard (atomic clock). The voltage can be accurately measured by means of the Josephson effect (discovered by Brian Josephson in 1962): If a so-called *Josephson junction*, i.e. two superconductors that are separated by a thin layer of insulating material, is irradiated with electromagnetic radiation (e.g. microwave radiation) a small potential difference will be induced in this junction. This potential difference can be described by

[2] The name Kibble balance was given to the Watt balance in honor of Bryan Kibble, who passed away in 2016.

$$V_J = \frac{f_J}{K_J}, \tag{4}$$

where V_J denotes the Josephson voltage, f_J the Josephson frequency, and

$$K_J = \frac{2e}{h}, \tag{5}$$

the Josephson constant. The elementary charge e and the Planck constant h are fundamental constants. They have the same value wherever and whenever measured in space and time. As a consequence of eq. (4) any higher voltage V can be obtained by using n of such Josephson junctions in series, as

$$V = nV_J\,. \tag{6}$$

The current I can be measured to high accuracy via Ohm's law $I = V/R$ and another quantum mechanical effect, the quantum Hall effect, discovered in 1980 by Klaus von Klitzing. This effect is a two-dimensional version of the known Hall effect, which describes a voltage that is induced when a strong magnetic field is applied perpendicular to a current carrying conductor at very low temperature. The quantum Hall effect describes a fundamental resistance,

$$R_K = \frac{h}{e^2}, \tag{7}$$

Called the *von Klitzing constant*. A resistance R can thus be expressed as a multiple or fraction p of this constant,

$$R = \frac{R_K}{p}. \tag{8}$$

Combining eqs. (3)-(8) results in
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$$mgv = \frac{V^2}{R} = \frac{n^2 V_J^2 p}{R_K} = \frac{n^2 p}{4} f_J h\,, \tag{9}$$

or

$$h = \frac{4}{n^2 p} \frac{mgv}{f_J}, \tag{10}$$

which finally describes the measurement equation of the Planck constant for the Kibble balance experiment.

After the redefinition of the kilogram, i.e. after fixing the value of h the same equation and the same measurement principle can be used to determine the mass of a weight. This Kibble balance principle is one of two suggestions in the *Mise en Pratique* [2] for a future realization of the kilogram (the second one is via the Avogadro project). As a consequence, each experiment that follows this principle of comparing virtual mechanical and electrical power is a primary method for realizing the unit kilogram, or calibrating a mass standard.

3. REDEFINITION OF THE SI-UNIT MASS – A CALIBRATION VIA ELECTRICAL QUANTITIES

One of the reasons for the new definition is that the IPK is the last SI unit that is defined by an artefact. It highly probably must be seen as instable over time, moreover it could be damaged or even be stolen or lost. Fortunately, this did not happen, although we had two wars in the meantime. Thus, metrologists and scientist intended already for about 40 years [6] to find a way to define the kilogram via a fundamental constant, i.e. everybody can build an experiment to realize the kilogram. Such a constant can never be damaged or lost and, furthermore, is accessible to everybody. The other reason is its stability over time. The IPK has been compared four times [7] to the official copies since its definition in 1889. It has been observed that the weight of the IPK is drifting with respect to the official copies. This change amounts to about 80 µg (8×10^{-8} in relative units) over 100 years with respect to the mean value of the copies. As a consequence, the drift within five years already amounts to the measurement uncertainty that is attributed to the weighing procedure itself.

Many methods have been proposed in the past 40 years to redefine the kilogram, but only two methods reached the aimed accuracy, that was recommended by the CCM [8]. This recommendation says that there should be at least three experiments (including the Avogadro project and the Kibble balance) yielding relative standard uncertainties of 5×10^{-8} or better and at least one yielding 2×10^{-8} or better. One experiment is the Avogadro project[3], which defines a route via counting the number of atoms in a highly isotopically enriched monocrystalline ^{28}Si crystal. The latest publication shows a relative standard deviation of 12×10^{-9} [9]. The other route is via the Kibble balance experiments, followed by many National Metrology Institutes (NMI) world-wide. The best results, i.e. the lowest standard deviations have been reached by NRC and NIST, with 9×10^{-9} [10] and 13×10^{-9} [11], respectively. With these numbers a recommendation of the CCM for a redefinition was fulfilled. Another recommendation, however, is defines a consistency of the results at the 95 % level. This is currently a critical point as the difference between the values of the Avogadro project and the Kibble balances is currently on the order of 70 µg (7×10^{-8} in relative units). As even worse can be considered the fact that the CODATA recommended values of the Planck constant is drifting by about 12.2×10^{-9} per year (compared to 0.8×10^{-9} per year for the IPK) [12]. This would have as a consequence that if the CCU for example comes to the trade-off of defining a consensus value for h the drift of h could become superior to the uncertainty assigned to the kilogram after its redefinition. This means that the consensus value would have to be adjusted after some time. Hence, the date for a new definition is not definitive, however it will come sooner or later. A common strategy is under way.

Independently of the time when the kilogram will be redefined the new definition will come and the definition will be based on a fixed number of the Planck constant. As already mentioned above, the *Mise en Pratique* proposes two primary methods to realize the kilogram, one of which is via the Kibble balance principle. Not exactly following the Kibble balance principle, but very close, is then already the EMFC load cell. Currently the calibration is done by means of calibrated mass standards. However, the magnetic flux B and the coil length l can be measured, in principle, by other means, which do not use a mass (e.g. a Hall sensor and a caliper), and the electrical current I can be traced to h via a precision resistor and a Josephson standard. Hence, the calibration would be done without use of a mass standard and thus defines

[3] Also called XRCD (X-Ray Crystal Density) and IAC (International Avogadro Coordination)

a kind of a primary method of realizing the mass. It would not reach the measurement uncertainty one can reach with the Kibble balance principle, i.e. by applying the dynamic mode, but nevertheless it would describe a primary method. In fact, the second – the dynamic – mode, was introduced by Kibble precisely to reduce the uncertainties of the “geometric factor”, i.e. the product of the magnetic flux density B and the length of the coil l. The result of which is given by eq. (10).

The concept of tracing the mass to h now offers new possibilities in weighing technology. Every mass standard can be directly calibrated by weighing with a Kibble balance type instrument. There is, in principle, no need for the user to ask a calibration laboratory to calibrate the standards. Moreover, the standard masses are not even needed any longer, as the weight under test (e.g. a substance in a laboratory) can be directly traced back to h. However, the reality will be a bit different. Weighing instruments, based on this technology, will need to be validated by a higher authority, i.e. in Germany this would be the PTB. It is possible that on an international level the Kibble balances will be validated via key comparisons.

4. CONCEPT OF THE PLANCK-BALANCE

Within the project two balances will be developed and validated. A first balance will be called *Planck-Balance 2* (PB2) and a second one *Planck-Balance 1* (PB1). The reason for the numbering results from the aimed accuracies of the balances, as will be explained later in this text. Both balances will follow the principle of the Kibble balance. In this section the general concept and parameters will be presented.

4.1 Use of standard components

The project within which the Planck-Balance will be developed runs over three years. In order to reach the aimed accuracies in such a relatively short time, the concept differs from common Kibble balance experiments.

First of all, and this already distinguishes the Planck-Balance from conventional Kibble balances, it is aimed to use standard components as far as possible. For example, in the heart of the balance there will be used a commercially available high-end EMFC load cell, as used for analytical balances in industry. Such load cells are sophisticated sensors that can lay back on decades of knowledge in design and machining. Most Kibble balance groups design their own setup, which costs them valuable time and money. Other standard components are, e.g. the interferometer, clock, environmental sensors, etc.

Secondly, Kibble balances have a history of about 40 years. Many scientific papers have been published in the meantime, investigating many details of those balances. Moreover, different designs have been proposed giving a good overview of what is possible and what needs more attention.

Thirdly, the Planck-Balance is not aimed for measuring h to high accuracy, but describes a weighing instrument. The requirements are a bit more relaxed than in classical Kibble balances, as we aim to measure “only” at the accuracy level of E2 and E1 weights

4.2 Modular design

Besides the use of commercially available standard components the balances will have a modular design. This means that both balances will contain as many similar components as possible. Only those components that are necessary to reach the desired measurement uncertainty or need to be adjusted to a different load range, will be replaced by other adequate (but commercially available) standard components. As an example, PB1 will have the same interferometer type and frequency standard as PB2, but the load cell will be different.

4.3 Weights handling and measurement procedure

For commodity and better repeatability the balances will be equipped with an automated load changer. This will automate the measurement procedure based on the ABBA weighing cycles. The calibration cycle here is the dynamic mode (A) of the Kibble balance principle, whereas the static mode (B) corresponds to the usual weighing mode.

4.4 Aimed uncertainties and measurement range

The aimed relative measurement uncertainties U_{rel} for PB1 and PB2 are shown in Tab. 1. They result from the fact that the balances should later be capable of calibrating E1 and E2 mass standards. E1 and E2 are accuracy classes, as recommended by the International Organization of Legal Metrology (OIML) in [13], that define how much a real mass standard of the corresponding class might deviate from its nominal value. MPE denotes the maximum permissible error for the initial verification of individual weights and m_{max} is the maximum mass that is weighed with a balance (100 g for PB2 and 1 kg for PB1). $U_{m_{\mathrm{max}}}$ then is the expanded uncertainty for each weight, which is recommended to be smaller than one third of its MPE.

	PB2	**PB1**
Mass range	1 mg … 100 g	1 mg … 1 kg
m_{max}/MPE	16 x 10^{-7} (E2)	5 x 10^{-7} (E1)
$U_{rel} = U(m_{max})/m_{max}$ (k=2)	5.3 x 10^{-7} (E2)	1.7 x 10^{-7} (E1)
Environment	Air	High vacuum
Time / Weighing	10-120 s	10-120 s

Tab. 1: Parameters for the Planck-Balances (PB). The aimed relative measurement uncertainty U_{rel} results from the accuracy classes as recommended in [13]. MPE is the maximum permissible error of a weight.

An excerpt of those data is plotted in Fig. 2. It is interesting to note that below the 100 g masses the relative measurement uncertainties are linearly increasing in the log-log scale. The reason is the calibration hierarchy. The farther we get from the 1 kg mass the more mass comparisons are necessary, which increases the measurement uncertainty. As the measurement equation (10) for the Planck constant hold for all mass values, in principle we can reach the same uncertainty for measuring a 100 mg mass as for a 1 kg mass (or even better), because the Planck constant contributes with zero uncertainty to the measurement when it is defined. *Shaw et al.* [14] have already shown with an electrostatic force balance that in the milligram range at least the same measurement uncertainty can be reached as with the common weighing method. Moreover, it is expected that for lower mass values than 1 kg the magnet-coil system becomes smaller, simpler, and cheaper.

Tab. 1 shows also our planned measurement environment. In order to reach the aimed measurement uncertainty of PB1 a vacuum system with a pressure of up to 1 x 10^{-6} mbar will be necessary, while for PB2 the requirements will most probably already be met in air.

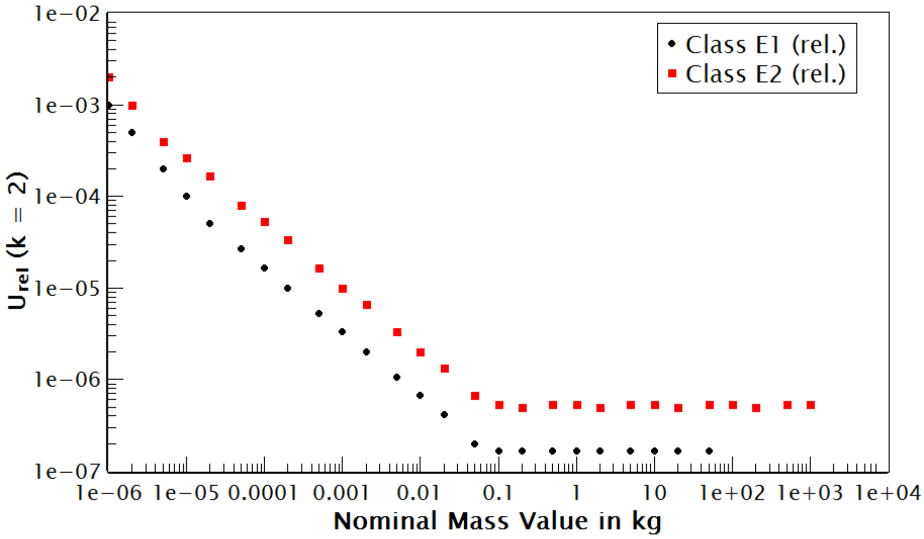

Fig. 2: Relative expanded uncertainty $U_{\mathrm{rel}} = U_{m_{\max}}/m_{\max}$ as a function of the maximum nominal mass value $m_{\max}$. PB2 and PB1 are intended to cover the nominal mass value from 1 mg up to 100 g, and from 1 mg up to 1 kg, respectively.

4.5 Traceability of measurement devices

From eq. (10) it can be seen that the following quantities must be measured: Voltage, resistance, velocity, and acceleration.

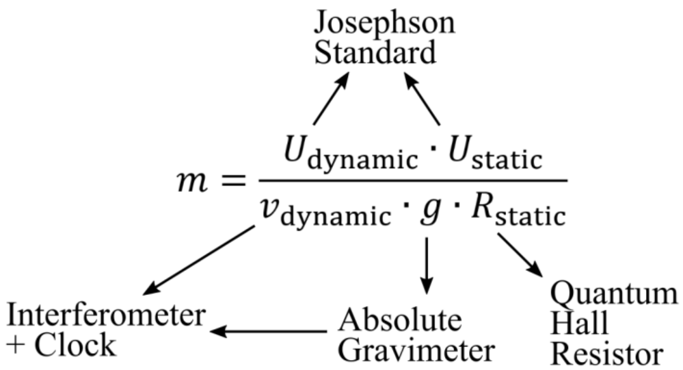

Fig. 3: The different quantities of the measurement equation must finally be traced to primary standards.

All quantities must be traceable to primary standards. Fig. 2 shows how this will be done. For the voltage, this is done with a voltmeter that is finally calibrated to a Josephson standard. The current is measured via the voltage drop at a temperature controlled precision resistor. Thus, the resistor must be calibrated to a Quantum Hall Resistor, and the voltage to a Josephson standard. The velocity is measured with a laser interferometer and a frequency standard, both of which are finally traceable to a primary frequency standard. The local gravity is measured with a free-fall gravimeter, which consists basically of a laser interferometer and a frequency standard, similar to the velocity measurement. In order to get a more accurate gravity value at the weighing pan an additional gravity gradient determination is necessary in the laboratory with a relative gravimeter. This gradient has a magnitude of about 3086 nm s^{-2}/m or 3.1 x 10-

^{7} m^{-1} relative. Thus, for reaching a relative measurement uncertainty in gravity to one part in 10^8 the gravity value must be known within a range of 3 cm. To reach highest possible accuracy levels a 3-dimensional gravity mapping in the laboratory would be possible, as is done for Kibble balance experiments (see, e.g. [15]). The relative gravimeter, in turn, can be calibrated to the absolute gravimeter.

Publications on Kibble balances show that all parameters can be measured to better than one part in 10^{-8} (see, e.g., [10]).

4.6 Size of the instrument

The final balance will not be much bigger than a usual analytical balance. Only the interferometer that is necessary for the velocity measurement, and that can have a compact design, will be directly attached to the load cell. However, due to the high accuracy required, in a first development step the measurement devices that will accompany the balance will have a relatively big size. As an example, the Josephson standard is about 2 m high, including the rod that contains the Josephson junction array. It is hoped that in the future new more compact voltage standards will be available on the market, and that most electronics can be assembled in a single rack. Furthermore, PB1 will be equipped with a vacuum system, which will enlarge the setup.

4.7 Virtual Planck-Balance

The concept of the Planck-Balances also includes a digital measuring device, called Virtual Planck-Balance (VPB). This is basically a theoretical model of the measurement system. It includes a theoretical model for the weight, interferometer system, load cell, magnet system, gravimeter, etc. After a first measurement procedure of the PB the VPB will be provided with the start parameters. The VPB then performs a Monte Carlo Simulation based on the models and provides online the estimated measurement uncertainty of the weighing procedure.

The VPB provides several features. 1) The resultant measurement uncertainty is lower and is more realistic and precise than a common uncertainty estimation based on error propagation, as it can include non-linear models. The complex interaction of different system components can be handled easier. 2) The starting parameters can be varied in order to simulate different environmental conditions. This can give an idea of how much the measurement uncertainty would in- or decrease if, e.g., the temperature changes by some degrees Celsius. 3) Thus, the process can be monitored and optimized. Online estimation of the measurement uncertainties can allow the user to change the environmental conditions or to check and substitute system components. 4) The number of measurements is drastically reduced, as a large number of measurements is done only by simulation. This increases the life-time of the instrument, the wear of mass standards, and also the costs and measurement time.

The idea of the VPB arises from the Virtual Coordinate Measuring Machine (VCMM) [16], which has been developed at PTB and is now integrated into the products of several industrial partners. In that case the measurement procedure of a coordinate measuring machine (CMM) is simulated. It considers the CMM, the environment, the probing process, as well as the workpiece.

5. SUMMARY AND OUTLOOK

A new weighing instrument, the Planck-Balance, has been presented that will be able to calibrate mass standards without comparison to other mass standards. This is possible due to the new definition of the kilogram. This definition will relate the mass to the Planck constant. The Planck-Balance is based on the Kibble-Balance principle and is thus a primary method of realizing the unit kilogram, as described in the *Mise en Pratique*.

The new instrument will be able to cover a measurement range from 1 mg up to 1 kg, with an aimed relative measurement uncertainties (k = 2) of up to 1.7 x 10^{-7}. This will be sufficient to calibrate E1 and E2 standard masses, and represents an attractive alternative for smaller NMIs, for industry or legal metrology where high accuracy is required. The main benefit of the Planck-Balance lies in the fact that at lower nominal mass values higher accuracies can be theoretically reached than possible with the present definition of the kilogram. This provides a simpler handling of masses, e.g., smaller than 1 mg, as no tiny and thus barely visible mass standards are required for calibrating the balance. Possible applications lie in pharmaceuticals or nutrients in food, but also in gems or rare metals.

6. ACKNOWLEDGEMENT

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