High-Capacity Mass Dissemination with Four-Place Mass Comparator

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Abstract

After briefly introducing the basic elements of mass dissemination, the requirements of high-capacity mass dissemination to calibrate weights and weight sets in the nominal range of a few kilograms up to 60 kg are discussed. A new mass comparator dedicated to high-capacity mass calibration is delineated. It features a four-place turntable for automatic weight exchange, a set of substitution weights, and means to control the calibration and to collect the measurement data.

Actual measurement results of this comparator are presented, and a few typical applications are commented. These comprise high-accuracy calibration of mass standards, calibration of large-size objects, calibration of disc weights of force standard machines or primary pressure balances, and high-accuracy volume determination.

Introduction

The calibration of weights and weight sets (also referred to as dissemination) is an essential step in providing traceability to the mass scale. To build a comprehensive mass scale, mass standards beyond the kilogram, the unit of mass, must be provided. Equipment to perform the required operations, namely, mass comparators, is readily available for comparative weighings of 1 kg standards and their submultiples to 1 milligram. Calibrations are carried out manually when lower accuracy or lower throughput is satisfactory. For weights of higher accuracy classes, and for higher efficiency performance, automatic comparators are preferred [1].

Comparators for mass standards heavier than one kilogram are also available. However, calibration equipment for weights above 20 kg is far from being ubiquitous, especially for high-accuracy classes and for automatic operation. Therefore, many calibration laboratories and national metrology institutes have built their own proprietary equipment [2].

Recently, a high-capacity, high-resolution mass comparator, equipped with an automatically operated four-place weight exchanger, has become commercially available. This mass comparator not only extends the range of automatic calibration of weights and weight sets beyond 60 kg, but also provides unprecedented comparison accuracy.

Mass Scale

A mass scale is established by weights (mass standards). Besides their nominal mass, these standards are distinguished by various accuracy classes. For example, OIML [1]) defines mass standards in the range from milligrams to tons in nominal steps of $(1\text{-}2\text{-}5)\times10^{n}$ kg. With few exceptions, they are available in seven accuracy classes from "rough" working weights to high-accuracy standards [3], [4]. A similar classification of weights has been established by ASTM [2]) [5]. Table 1 lists the maximum permissible error (mpe) of the four top accuracy classes of weights according to OIML R 111 and ASTM E 617.

Table 1: Maximum permissible errors (mpe) of the four most accurate OIML and ASTM weight classes according to OIML R 111 [3] and ASTM E 617 [5].

Accuracy Class	OIML: E_1	E_2	F_1	F_2	ASTM: 0	1	2	3	Unit
mpe, relative	0.5	1.5	5	15	1.3	2.5	5	10	ppm
mpe for nominal mass of									
1 kg	0.5	1.5	5	15	1.3	2.5	5	10	mg
2 kg	1	3	10	30	2.5	5	10	20	mg
3 kg					3.8	7.5	15	30	mg
5 kg	2.5	7.5	25	75	6	12	25	50	mg
10 kg	5	15	50	150	13	25	50	100	mg
20 kg	10	30	100	300	25	50	100	200	mg
25 kg					31	62	125	250	mg
30 kg					38	75	150	300	mg
50 kg	25	75	250	750	63	125	250	500	mg

The higher the accuracy class of the weight chain, the higher the comparison accuracy required of the comparator. To contain the uncertainty contribution of comparisons, the standard deviation of the weighing process should, as a rule of thumb, meet 1/10 of the maximum permissible error [3]).

Weighing Designs

To realize the mass scale for multiples and submultiples of a kilogram, all members of a weight set must be compared. The sequence of comparative weighings, also called a dissemination or weighing design, serves as link between the mass standards. With the aid of weighing designs, standards of lower and higher nominal mass are derived from the starting point, the 1 kg standard. The masses of the unknown weights can be calculated from the results of these comparative weighings and the known mass of the reference standard [4]).

For example, to calibrate a set of weights consisting of a 10 kg (U10), two 20 kg (U20 & U'20) and a 50 kg (U50) weight from a 10 kg reference standard (R10), a weighing design according to equation (1) can be used. This is a minimal and efficient design, because it requires

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1) Organisation Internationale de Métrologie Légale

2) American Society for Testing and Materials

3) This rule is based on the allocation of 1/3 of the maximum permissible error (mpe) to calibration uncertainty; with a coverage factor of 2 (confidence level ≈95%), the standard uncertainty equals 1/6 of mpe [3]. Assuming *here* that the comparison extends over three links between four standards, each of the standard uncertainties of the comparisons between standards must be reduced by a factor of the square root of 3. Thus, the allowable standard uncertainty of a comparison between two standards should, under these assumptions, meet about 1/10 of mpe.

4) Air buoyancy correction might need to be applied to the comparison results depending on the accuracy attained and on the density of the weights.

only as many comparisons as there are unknown weights, namely four. Aside from the number of comparisons and the resolution needed of the comparator, the maximum loading level defined by the weighing design is crucial. In the example given, a comparator with a weighing capacity of at least 50 kg must be available.

$$\begin{pmatrix} -1 & 1 & 0 & 0 & 0 \\ -1 & -1 & 1 & 0 & 0 \\ -1 & -1 & 0 & 1 & 0 \\ -1 & 0 & -1 & -1 & 1 \end{pmatrix} \begin{pmatrix} R_{10} \\ U_{10} \\ U_{20} \\ U'_{20} \\ U_{50} \end{pmatrix} = \begin{pmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \end{pmatrix} \quad {}^{5)} \qquad (1)$$

Clearly, other designs exist to achieve the same purpose. For example, the following design allows the calibration of the same set of four weights with a different weighing procedure [6]).

$$\begin{pmatrix} -1 & 1 & 1 & 1 & 1 & -1 \\ 1 & -1 & 1 & 1 & 1 & -1 \\ 1 & 1 & -1 & 1 & 1 & -1 \\ 1 & 1 & 1 & 0 & 1 & -1 \\ 1 & 1 & 1 & 1 & 0 & -1 \\ 0 & 1 & -1 & 1 & -1 & 0 \\ -1 & 0 & 1 & 1 & -1 & 0 \\ 1 & -1 & 0 & 1 & -1 & 0 \end{pmatrix} \begin{pmatrix} R_{10} \\ C_{10} \\ U_{10} \\ U_{20} \\ U'_{20} \\ U_{50} \end{pmatrix} = \begin{pmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \\ D_6 \\ D_7 \\ D_8 \end{pmatrix} \qquad (2)$$

Apart from an additional 10 kg weight (C10), this design requires a comparator with an increased weighing capacity of 60 kg, and it involves the standards more frequently in comparisons. The design also requires twice as many comparisons, decreasing its efficiency. However, these measures increase the accuracy of the dissemination. The additional weight can either serve as a check standard to qualify the comparison process, or it can be used as a second reference standard to reduce the mass reference uncertainty. The redundant comparisons increase the degree of freedom of the equation system, which in turn reduces the determination uncertainty.

Common to both designs are the multiple comparative weighings to be carried out with various members of the set of weights. For each individual comparison, two weight sets must be loaded, compared and unloaded. To reduce the standard deviation of the measured mass difference, it is common to repeat individual comparisons several times. While the loading of weights on the platform of a comparator is a demanding operation, it becomes ever more of a burden to the operator as the weights get heavier. Mechanical handlers to move the weights are thus a great relief, as they place the weights more precisely, thereby augmenting both productivity and accuracy of the comparative weighings. Many commercially available comparators are therefore equipped with weight movers, usually two-place exchangers. In short, carrying out a dissemination with heavy weights is a lengthy, tedious and error prone process, threatened by the confounding of weights and comparison results, especially if the dissemination is carried out manually.

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[5]) A weighing design consists of the comparison matrix, the weights vector and the difference vector. The comparison matrix defines the comparative weighings that need to be performed on the comparator. A positive sign signifies the corresponding weight is a ”B” weighing, whose value enters the difference equation as a positive value, a negative sign signifies an ”A” weighing, entering the equation as a negative value, and a zero means that the corresponding weight is not involved in this comparison. The weights vector contains the reference standard(s) and all unknown weights, and the difference vector contains all weighing differences.

[6]) [6], p.40: Design C.10, ”5,2,2,1,1,1”

A New High-Capacity, High-Resolution Mass Comparator

Recently, an automatic mass comparator dedicated to high-accuracy calibration of heavy weights has become available (figure 1). It features a weighing capacity of 64 kg and a readability of 0.1 mg. Except for initially setting the weights onto its four-place turntable, the comparator automatically performs all remaining operations required for calibrations of weights and weight sets.

Figure 1: The AX64004, a 64 kg weighing capacity automatic mass comparator.
The comparator with its four-place turntable is shown in the foreground. The electronic equipment, the comparator's display unit and a laptop PC to control the comparator, is visible on the rack in the background.

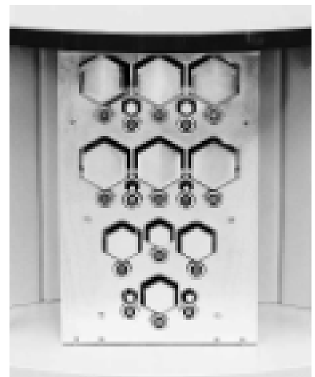

Figure 2: Front view of the comparator's substitution weight set.
The weight partition provides combinations of substitution loads from 0 to 64 kg in increments of 250 g. With the weighing cell's electrical range of 260 g, this allows for an overlapping weighing range from 0 to 64 kg. Also kept with this set is a calibration weight of 250 g.

The equipment consists of a weighing platform, a four-place turntable and a set of substitution weights. The heart of the comparator is a weighing cell with a carrying capacity of 64 kg with an electrical weighing range of 260 g and a measurement resolution of 0.1 mg. Substitution weights can be appended in increments of 250 g as the payload on the weighing platform is decreased , thereby providing a continuous comparison weighing range from 0 to 64 kg (figure 2). The comparator's sensitivity can be adjusted with a calibrated mass standard of 250 g, which is located in the same holder as the substitution weights.

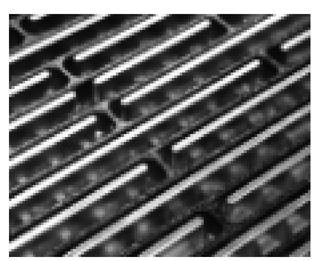

Figure 3: Top view of one of the four weight platforms of the turntable. The platforms are grid-shaped (left). They can accommodate weight sets that are arranged either adjacent to, or on top of each other. The detail on the right shows an enlarged portion of the fin-shaped weighing platform, protruding through the grid when the turntable has been lowered.

The weights to be compared are loaded onto two or more of the turntable's four places, according to the needs of the weighing design. Each loading platform is equipped with a grid onto which the weights can be positioned adjacent to each other, on top of each other, or both. That way each loading platform can accommodate virtually any combination of weights. For example, there is enough space to place OIML or ASTM shaped weight sets directly on the comparator, without the need for auxiliary weights of different shape (see figure 4; for usable diameter and height refer to table 2).

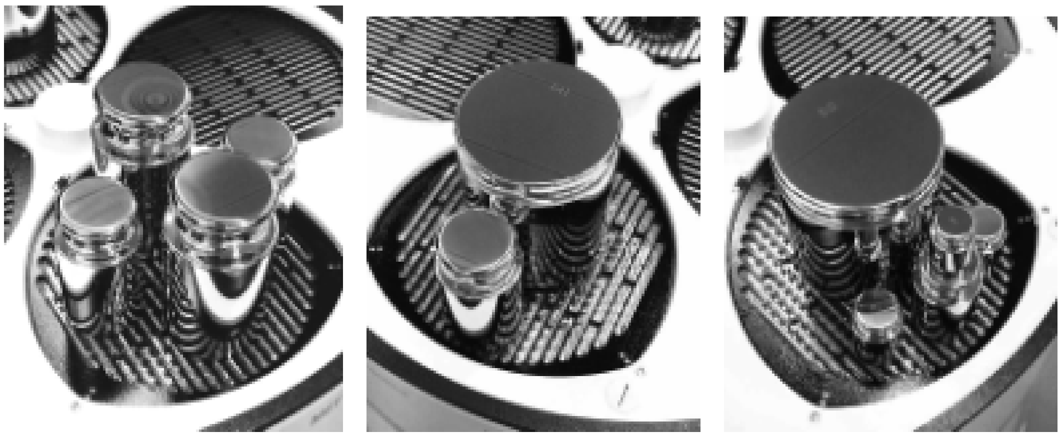

Figure 4: Various combinations of OIML weights on the platforms.
Left: 2 × (10 kg + 20 kg), middle: 10 kg + 50 kg, right: 1 kg + 2 × 2 kg + 5 kg + 50 kg.

To weigh a set of weights, the turntable moves and aligns the grid relative to the weighing platform. When the turntable lowers, fins from the weighing platform penetrate through the grid, get in contact with the weights and eventually carry them (figure 3). The automatic exchange relieves the operator from most of the strenuous work. Because the operator need not be present during the weighing process, there is less interference with the weighings, improving the accuracy.

Table 2: Main specifications of the new four-place, high-capacity mass comparator.

Property				Value	Unit
Comparative weighing range (load range) [a]				0 [b]..64	kg
Readability				0.1	mg
Substitution weights: total / switchable in increments of				64 / 0.25	kg
Electrical weighing range				260	g
Calibration weight				250	g
Repeatability (standard deviation) [c]			max (typ)	0.4 (0.2)	mg
Measuring time [c]			typ	1	h
Weight dimensions	with cover	Ø × H	max	34 × 35	cm
	with cover removed			virtually unlimited [d]	

a) Models with 32 kg and 16 kg weighing range currently in preparation.

b) The load must extend at least 2 cm to span two fins of the weighing platform (see figure 3).

c) Determined as standard deviation of 10 one-versus-one, ABA comparative weighings, after drift elimination; stabilization time set to 25 s.

d) The load's center of gravity must lie below 46 cm above the turntable, or instability may occur.

Table 2 lists the main specifications of the new high-capacity mass comparator. Except for the maximum capacity, the repeatability of the comparator is the primary parameter. For a series of ten comparisons, repeatability is specified with 0.4 mg over the entire weighing range. In well-controlled environments, this value decreases to 0.2 mg (typical) or lower. Figure 5 shows a record of mass difference and repeatability obtained from fifty series of ten measurements; table 3 lists the individual readings of one series of ten measurements.

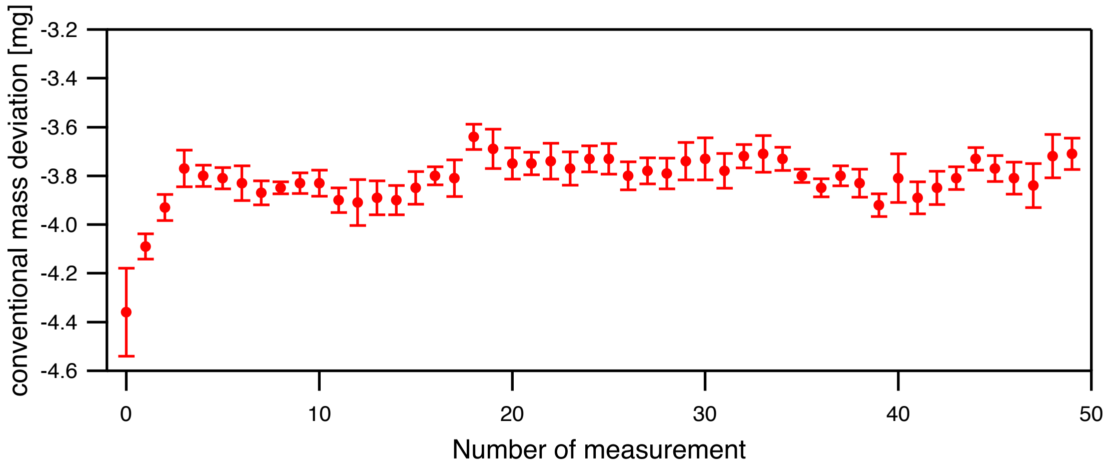

Figure 5: Measurement record obtained from 50 series of 10 comparisons between two 50 kg mass standards (measured by METAS).
Depicted is the mean (conventional) mass deviation between the two standards, calculated from groups of 10 ABBA comparisons (dots), and the corresponding group standard deviation (error bars). Effects of air buoyancy were not corrected for; however, both standards were of the same nominal density.
Except for a transient at the beginning of the measurement, probably caused by acclimatization, the mean mass difference (including uncertainty) remains within a band smaller than 0.4 mg for the remaining measurements. The group repeatability of 0.1 .. 0.2 mg stays well below the specified value of 0.4 mg.

Two influences tend to degrade the repeatability of a comparator. First, a weight, or a set of weights, which is not exactly centered about the weighing cell, may introduce a measurement error, known as eccentric load error. Special care has been given to suppress this type of error. If the center of gravity of the weights does not exactly coincide relative to the center of the weighing cell, the self-centering weighing platform moves to align the weights. This situation is prevailing after the initial loading of the weights.

Table 3: Individual measurement results of one series of 10 ABBA comparative weighings between two 20 kg mass standards.
(Measured by METAS)

No. of measurement i	ABBA mass difference Δm_i [mg]
1	39.60
2	39.60
3	39.40
4	39.45
5	39.50
6	39.45
7	39.40
8	39.35
9	39.40
10	39.30

Mean of differences $\overline{\Delta m}$ 39.445

Std.-dev. of differences s_m 0.098

Figure 6: Individual glass covers protect the loads from air drafts.

Second, as the comparator is capable of resolving load differences as small as 0.1 mg with direct readings (and even smaller ones, when readings are averaged), disturbing air drafts must be kept from the load. This is achieved with four individual glass covers (figure 6). If required, temperature sensors can be positioned inside these draft shields to monitor the actual temperature during the comparison (figure 7). This information is useful for air buoyancy correction.

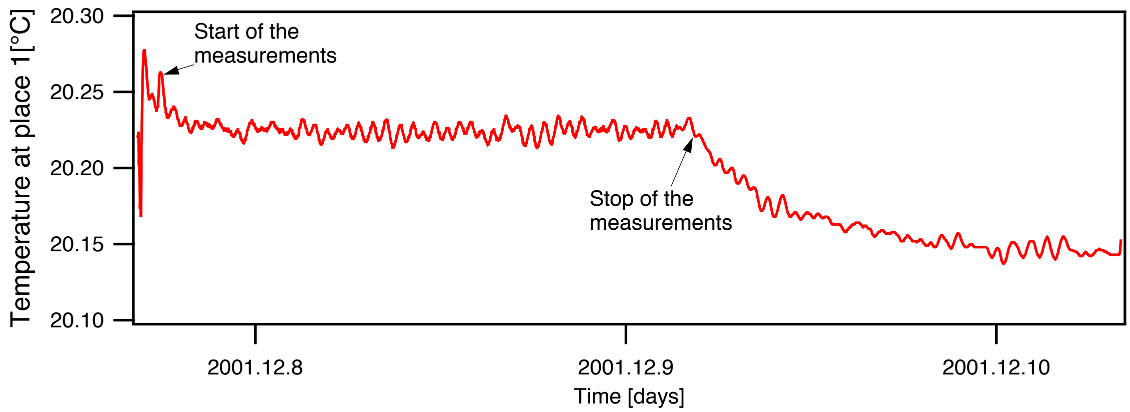

Figure 7: Typical temperature behavior inside the draft shield measured at place 1 during comparison weighings (measured at METAS). The temperature of the ambient air was held at 20 °C, with a typical control fluctuation of ±0.02 °C.

The size of weighing objects is limited only by the diameter and height of the glass cover. If the requirements on repeatability can be somewhat lowered, or the ambient air is quiet enough, the glass covers may be removed, allowing the user to place even taller objects. Similarly, if a spacer is put under the load, the comparator accommodates objects with larger diameters.

When comparing weights with high resolution, as is the case with the new high-capacity mass comparator, proper acclimatization time must be observed to allow for compact weighing objects to attain the temperature of the ambient air. According to a study of Gläser [7], a 50 kg mass standard with a temperature difference of 0.1 K above ambient appears about 1 mg too light, and it takes as long as 3 days for this temperature difference to reduce to 0.01 K, where the apparent mass offset would diminish to a value around 0.1 mg.

Applications

Due to its features, namely high-capacity, high-accuracy and automatic operation, this comparator is well suited for a variety of traditional as well as new applications. This will be illustrated here with a few examples.

The new mass comparator is the instrument of choice for the calibration and dissemination of high and highest accuracy mass standards. Because of the comparator's excellent repeatability, OIML class E_1 (ASTM class 0) weights can be calibrated in the range from 5 kg to 50 kg, class E_2 (class 1) from 2 kg and class F_1 (class 2) from 500 g. Between 10 kg and 50 kg, weights of even higher accuracy than E_1, "class E_0" [7]), can be calibrated. A 10 kg "E_0" standard would allow 1.5 mg of maximum permissible error. An uncertainty of 0.2 mg or better may be reached with several repeated comparison series. Obviously, this mass comparator is the preferred instrument

[7]) Though not defined by OIML, weights of class E_0 could be understood to comprise weights with a relative maximum permissible error (mpe) of about 1/3 of those of class E1, i.e. 0.15ppm [3].

for national metrology institutes, weights and measures verification offices, weight manufacturers and calibration laboratories.

As the comparator's weighing platform accommodates weights arranged adjacent to, and stacked on, each other, many weighing designs that are impossible to be performed on other comparators (or only with the help of auxiliary standards) can now be implemented on this comparator. The second weighing design (eq. 2) is an illustrative example. Also, there are weights, whose shape does not allow them to be stacked. Nevertheless, these can be calibrated on this comparator, because they can be arranged adjacent to each other.

A method to obtain a heavy mass standard is to combine many calibrated medium-size weights and to assemble them on a weight tray. For example, to produce a 500 kg weight, 24 calibrated 20 kg weights (i.e., 480 kg total) can be stacked on a tray with a nominal mass of 20 kg. Clearly, the mass of the empty tray must be calibrated with the same accuracy as the mass of the other weights, or the accuracy of the assembly of weights is reduced to the lowest accuracy contributor. While the calibration of the 20 kg weights is state-of-the-art, the calibration of the weight tray is more difficult as a result of its large dimensions. Because of the obstacle-free space above the turntable when the cover is removed, the new mass comparator is capable to calibrate this tray with high accuracy, despite its rather extended dimensions (figure 8). Due to this high-quality calibration of the tray, the 500 kg collection constitutes an OIML class E_1 weight.

Other applications comprise the determination of loss or gain of small amounts of mass in conjunction with a large dead mass or structures with large extensions, to an unprecedented level of accuracy. Such examples are the measurement of the amount of gas in heavy containers, or the abrasion of material on gears or turbine blades, among others.

Force standard machines and primary pressure balances use stacks of disc-shaped weights. To keep the stacks low, the individual discs are designed to have a small height, which results in rather large disc diameters. While these discs often do not fit on conventional comparators, they can be calibrated directly on the 64 kg mass comparator. Should their diameter exceed the already large diameter of the platform, a spacer may be placed under the discs to raise them and allow for even larger diameters (figure 8).

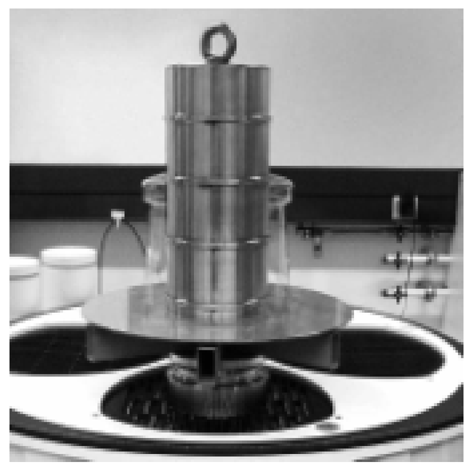

Figure 8: Large object calibration without draft shield.
This empty mass tray (nominal mass 20 kg, diameter ≈ 56 cm, height ≈ 47 cm) is being calibrated on the mass comparator without a draft shield. (Photograph by METAS)

The highly accurate determination of the volume of fluids or gases using the gravimetric method can also be envisaged directly on this high-capacity mass comparator. For a fluid of well-known density, the mass difference between the empty and full container provides a very accurate measurement of the volume of the fluid, or of the volume of the container holding it.

Conclusion

The calibration of heavy mass standards is a difficult, demanding, and lengthy process. The loading and unloading of heavy mass standards is strenuous work if done manually. The accurate placing of the weights in the center of the platform is difficult. Often, weighing designs require multiple standards to be weighed in groups. These designs cannot be considered with many comparators, because they do not provide enough loading space or weighing capacity. Typically, state-of-the-art comparators feature readabilities of 0.5 mg at 20 kg or 5 mg at 50 kg. Such resolutions are a handicap for disseminations at the highest accuracy level.

A new automatic comparator with a weighing capacity of 64 kg and a readability of 0.1 mg has become available. Its four-place turntable provides automatic exchange of the weights. The weighing platforms, equipped with individual draft covers, offer enough space to accommodate weight combinations prescribed by virtually any weighing design. There is no need for auxiliary weights. The weights self-center on the weighing platform to suppress eccentric load errors.

With its excellent comparison uncertainty, this comparator is particularly well suited for the calibration of weight classes such as OIML E_1, E_2 and F_1, or ASTM 0, 1 and 2. Its repeatability of 0.2 mg typical (0.4 mg max) also makes it the choice for mass standard laboratories with ultimate requirements for comparison accuracy, such as national mass laboratories, weights and measures offices, weight manufacturers, or any institution with high-accuracy calibration requirements.

Weights in pounds or multiples thereof, or dead weights adjusted to produce forces in Newton, constitute non-metric weights. These or any other, in terms of metric units, ”non-nominal” mass pieces or objects can be calibrated on this comparator with a small number of mass standards, because the comparator’s weighing range continuously covers 0 to 64 kg.

Other applications include the determination of mass of heavy or large structures, such as weight trays, gas containers, and the gravimetric determination of volumes.

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