Proceedings of the 17th International Conference on Force, Mass, Torque and Pressure Measurements,
IMEKO TC3, 17-21 Sept. 2001, Istanbul, Turkey

A New Mass Comparator Generation for the Automatic Calibration of Weight Sets

Arthur Reichmuth
Mettler-Toledo GmbH, Greifensee, Switzerland

Abstract

Calibrating weight sets creates some unique challenges to the metrologist. Performance and reliability of the calibration oppose its productivity. A calibration of a weight set, also called a dissemination, requires manual interventions by the operator, even if it is performed on a mass comparator with a turntable. Sometimes, a comparator does not offer enough room to accommodate an entire group of weights; then the use of custom auxiliary weights may be required. Besides, the threat of confounding weights is omnipresent. Recently, a new generation of computer controlled comparators, particularly designed for the calibration of weight sets, has become available. This equipment automatically executes all steps involved in disseminations, including the moving of the weights and the necessary comparisons, requiring neither manual intervention by the operator, nor custom auxiliary weights. This not only avoids the introduction of excess uncertainty by the operator, but also improves the productivity of the dissemination, generating more throughput in shorter time.

1. Introduction

The calibration of multiples and submultiples of a given mass standard is performed mainly according to two established methods. One is to compare the members of the unknown weight set one-versus-one with a reference set. This method requires a comparison setup for each unknown weight, and the maintenance of an entire reference set. The other method is to compare the members of the unknown weight set against one reference only. This requires various comparisons of members of the set of unknown weights among each other, as well as against the reference. The set of comparisons involved in a dissemination is usually called weighing scheme or design.

Mass comparators like the one shown in figure 1 can be used to perform these comparisons. This comparator is equipped with a turntable providing four places to accommodate the weights. Such comparators are readily available for weights up to 10kg and higher; for weights below 1g, this is not the case.

Schwartz [1] gives an example of a particular dissemination scheme according to the second method to produce sets of submultiple standards, namely, two sets consisting of a 500g/200g/100g weight each, derived from a 1kg mass standard. For reasons of process control, a second 1kg standard, whose mass is pretended unknown, is added to the set.

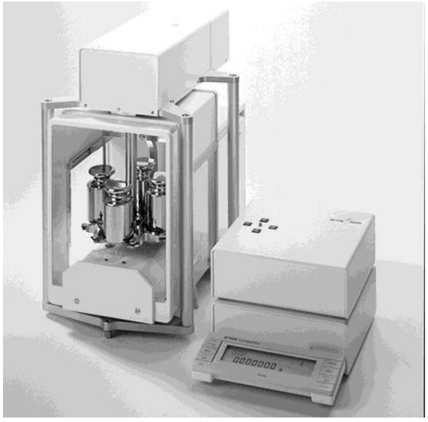

Figure 1. An example of a 1kg mass comparator with a four places turntable

Appointing the 1kg standards as R1000 and U1000, and the submultiple weights as U500, U’500, U200, U’200, U100 and U’100, respectively, the comparison scheme to be executed with this example is given below, where the elements of the comparison matrix are 1, –1 or 0 depending on whether the weight is used on the left side of the comparison equation, on the right side, or is not involved at all [1]). This matrix is multiplied by the weight vector, containing the masses of the standards and of the unknown weights, while D indicates the difference vector, the components of which are the reading differences of the comparison weighings [2]). This weighing scheme comprises 10 comparisons with 7 unknown masses.

$$\begin{pmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & -1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \end{pmatrix} \begin{pmatrix} R_{1000} \\ U_{1000} \\ U_{500} \\ U'_{500} \\ U_{200} \\ U'_{200} \\ U_{100} \\ U'_{100} \end{pmatrix} = \begin{pmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \\ D_6 \\ D_7 \\ D_8 \\ D_9 \\ D_{10} \end{pmatrix}$$

If a traditional comparator with an automatic exchanger with four weight places is used, the setup of this dissemination begins by loading R1000 on place 1, U1000 on place 2 and both U500 and U’500 on place 3. After execution of comparisons 1 through 3, the dissemination resumes by putting U500 on place 1, U’500 on place 2, and U200, U’200 and U100 all in place 3 for comparisons 4 and 5. For the third round, U100 is exchanged by U’100 for comparison 6. The fourth round sees U200 in place 1, U’200 in place 2 and both U100 and U’100 in place 3 for comparisons 7 through 9, and eventually for the fifth round, U100 is loaded in place 1 and U’100 in place 2 for comparison 10 [3]). It follows from the matrix that comparisons 1 to 3 must be carried out on a comparator of at least 1kg weighing capacity, while comparisons 4 through 10 could be carried out on comparators with lower capacities.

Performing disseminations according to this procedure causes considerable shortcomings.

First, the weights must be retrieved manually from the turntable several times, recombined to form new weight groups

[1]) The careful reader will observe that the dissemination matrix given here is the negative of the one given by Schwartz. Intentionally, the plus and minus entries in the matrix are chosen such that the differences are of the general form D = U–R. Thereby, a positive difference means that the unknown weight is larger than the reference, and vice versa.

[2]) To determine (true) mass or conventional mass, these weighing differences must be corrected for air buoyancy.

[3]) It is common practice to load either the two opposite places only, or all places of a four places turntable for the sake of symmetry. In case there are only three places required for the dissemination, the

according to the weighing scheme, and reloaded again. One reason for this is usually the lack of sufficient places on the turntable to accommodate all members of a weight set. The exchange is also compelling if the nominal mass of a group to be compared changes to another level. The dissemination just presented is an illustrative example of the fact that although only eight weights in total participate in the dissemination, and although the turntable offers four places, it takes five rounds of loadings to execute all ten comparisons. Obviously, each unloading and reloading of the comparator disrupts the weighing process and disturbs the thermal equilibrium of the weights, the comparator and its environment. A traditional comparator with a turntable usually is not even spacious enough to accommodate all members of a weight set on the turntable, let alone within its weighing chamber. Since temperature differences between the weights and the inside of the comparator may introduce significant errors [2] [3], it is mandatory to thermally acclimatize the weights not only after the initial loading, but as well after each regrouping. Depending on the dissemination scheme and the type of weights, this thermal acclimatization may take up a considerable part—as much as one third to one half—of the measurement time [4]). Moreover, a qualified operator needs to be present to attend this semiautomatic dissemination process. These manual interventions also potentially increase the uncertainty of the dissemination.

Second, members of the weight set must be compared as groups. They must therefore be placed adjacent to each other, or preferably, stacked one on top of the other. A comparator's turntable generally does not provide enough loading area on, or headroom above, its platform to accommodate multiple weights. This is especially true if the weights are of tallish shape, such as OIML or ASTM weights. In these cases, customary weights with a suitable, nonstandard shape must be used [5]. While these auxiliary weights may serve as control standards, they are useless from a standpoint of dissemination, as they cannot be considered the result of a dissemination because of their shape. Taking up the place that otherwise could be held by regular weights, auxiliary weights thus reduce the efficiency of the dissemination process, often by as much as a factor of two.

The New Automatic Comparator Generation

All of the above issues are addressed by a new comparator generation. These comparators prove especially beneficial when used to routinely calibrate weights, and weight sets, delivering productivity and quality at a sustained level.

Currently, this automatic comparator line consists of three members, namely, the a5comparator, the a100comparator and the a1000comparator with 5g, 100g and 1kg weighing capacity, respectively. Each instrument consists of a cabinet, containing a weight magazine, a comparator balance, and a robot (figures 2 and 6). The magazine holds

fourth place should be loaded with a dummy weight, which can serve as a check standard.

[4]) Ueki et al. [4] present a measurement procedure with a 24-hour cycle duration, about a third of which is dedicated to conditioning.

the weights, i.e, the reference and working mass standards, in weight carriers. The robot moves the weights in the weight carriers from the magazine to the comparator and back, according to a programmed weighing scheme.

The magazine is mounted on a massive aluminum plate which acts as a thermal equalizer, while the cabinet, consisting of acrylic glass panes enclosing all components, provides protection against air drafts and temperature fluctuations. The balances used are slightly modified standard instruments to make them compatible with the handling robot. One of these modifications is the replacement of the weighing pan with a fork-

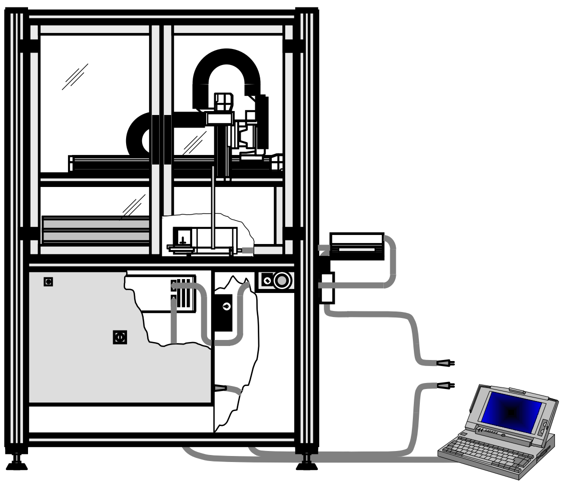

Figure 2. Schematic drawing of the automatic comparator, which consists of a cabinet containing a weight magazine, a robot, a comparator balance, and a control unit. The equipment is operated by a PC

The magazine of the a5comparator consists of 3 rows with 12 weight carriers each, providing a total allocation capacity of 36 weights. Any one dissemination scheme with up to this number of weights can be carried out on the automatic comparator. The corresponding numbers with the

shaped weight receiver, capable of simultaneously accommodating up to three weights (figure 5). The balance stands on individual posts mounted on the floor, which are separated from the base plate to provide utmost isolation from mechanical vibrations.

This magazine can hold up to 18 weights in weight carriers. They are adjustable to accommodate knob weights of various shapes. The a5comparator accommodates also wire and sheet weights (not shown here).

Figure 3. The weight magazine of the a1000comparator

a100comparator and a1000comparator are 20 and 18 weights, respectively (figure 3). The adjustable weight carriers accept knob, or knob-like, weights. In addition, the a5comparator also accepts wire and sheet weights. The weights are loaded at the beginning of the calibration and can be retrieved from there at the end of the measurement.

A three axis robot picks up the weight carriers and moves the weights sequentially to the comparator (figure 4). There, the robot lowers the carrier, thereby depositing the weights on the comparator weight receiver. The empty weight carrier is put back into the magazine. Up to three weights can be simultaneously placed on the load receiver (figure 5). To suppress eccentric load errors, the weights are arranged symmetrically about the center of the load receiver. After the weighing, the weights are retrieved from the weight receiver with the corresponding weight carriers, and together they are put back into the magazine. If required, the robot also switches the comparator to its suitable load range.

The automatic comparator is equipped with a software application running on a PC or laptop that controls the entire dissemination procedure, comprising the loading, the comparison weighing and the retrieving of the weights for all comparisons of the weighing scheme. This flexible control software accepts any standard or customary weighing scheme. The parameters required for the comparison or dissemination task can be programmed on-site. Relevant data for the comparisons comprise data about the reference standards, the test and control weights, the allocation of the weights in the magazine, the parameters of the weighing process (delays, stabilization times, comparison scheme (ABA or ABBA), etc.) and the format of the measurement report. Alternatively, this information can be provided by a suitable host controller software 5). In this remote control mode, the host application downloads a corresponding script to the automatic comparator. Measurement data from the comparison weighings, as well as a summary of the results, will be reported, or can be transferred back to the host as a data script for further evaluation, such as buoyancy correction, evaluation of the weight's mass including uncertainty, process statistics, etc.

The main features of the comparators are listed in table 1.

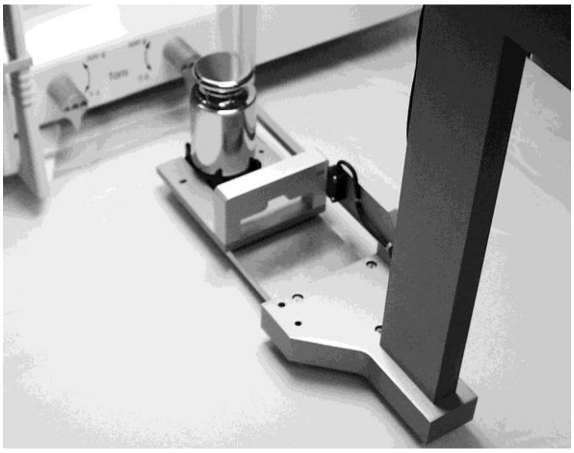

Figure 4. A weight loaded on its weight carrier is being moved from the magazine to the balance's weight receiver.

5) such as the AMMS (Automated Mass Measuring System) from Measurement Technology Laboratory (MTL), Minneapolis, USA.

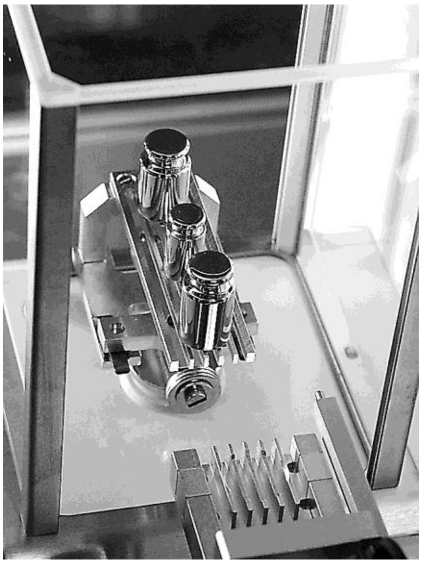

Figure 5. The weight receiver of the a100 comparator.

Table 1. Specifications of the a_comparator series

Product Designation		a5	a100	a1000
Readability	0.1	1	10	µg
Weighing capacity g		5.1	111	1109
Electrical range	5.1	11	109	g
Repeatability a) b) 10 µg		max.	0.4	0.8
typical	0.2	0.4	5	µg
< 1g typical µg		0.1	—	—
Measuring time a) 30 min		typ.	30	30
Weight classes up to OIML		E1	E1	E1
Magazine capacity weights		3x12	2x10	3x6
Control software	yes	yes	yes	

a) Repeatability and measuring time are based on a series of ten one-versus-one, independent A-B-A comparative weighings.

b) b) Repeatability is given as standard deviation, after elimination of drift

The fork-shaped weight receiver is compatible with the weight carriers and can simultaneously carry groups of up to three weights.

2. Properties of the Automatic Comparators

The automatic execution of weight comparisons or weight set disseminations on these comparators provides several advantages over disseminations performed on traditional comparators.

The comparisons of a dissemination scheme can be executed in one batch, row by row, i.e, comparison by comparison, without intervention. There are no limits to the dimensions of the matrix, which may contain as many rows as required, as long as the participating weights can be stored in the magazine.

All weights required in a dissemination can be loaded in one batch. Instead of the multiple intermediate loading and unloading of new groups of weights required with traditional comparators—a time consuming, error prone process, disturbing the thermal equilibrium—the operator can load all weights for a full comparison scheme in one batch at the beginning, and unload all of them at the end of the measurement. A further advantage emerging from this is that all weights acclimatize simultaneously after the initial loading and that they will be ready for use after this initial conditioning interval. This is a very time saving feature, as several hours may be required for the weights to acquire ambient temperature.

All comparisons needed for a complete dissemination can be executed automatically. There is no manual interaction required by an operator during this entire process, and as a consequence, there will be no interruptions of the process, either. This improves the quality of the comparison, since a stationary comparison sequence with equal intervals yields more consistent results than one that is interrupted at irregular points in time.

Once the weights are placed into the magazine, and the dissemination scheme is set up in the software application, the dissemination executes automatically. No operator needs to attend the process. This increases dissemination efficiency as fewer human resources are required.

The weights to be compared simultaneously are not stacked on the receiver, but arranged laterally to each other. There is no need to use auxiliary weights because of lack of space or height. That way, all weights used in a dissemination can be weights with regular shapes, and thus are potential outcomes of the dissemination process. If there is more than one weight, these are arranged symmetrically about the center point of the load receiver to minimize measurement errors caused by eccentric load deviation. If required, its residual can be evaluated with test measurements at all nominal load levels of interest. The results obtained from this measurement are stated in the measurement data report.

As the automatic comparator is capable of calibrating weight sets derived from a single mass standard, this is also one of its most beneficial features. To provide traceability, only this standard needs to be sent ”out of house” to be calibrated. This increases efficiency and provides savings, as there will be less down time and less cost for external calibrations of standards.

One restriction applies, though. As three is the maximum number of weights that can be simultaneously placed on the weight receiver, weighing schemes containing weight groups of more than three members are excluded from being processed on the automatic comparator.

2.1. Examples Of Disseminations

Revisiting Schwartz’s dissemination scheme presented in the introduction, it can be seen that the weighing procedure required by this scheme can be implemented on the automatic comparator, indeed. Rows 1, 4, 7 and 10 of the weighing scheme represent one-versus-one comparisons, rows 2, 3, 8 and 9 one-versus-two, rows 5 and 6 one-versus-three comparisons, with a maximum of one, two and three weights simultaneously on the weight receiver, respectively. Moreover, the total number of weights, eight, is far below the allocation capacity of any magazine. As the maximum load in this dissemination is 1kg, the scheme could be implemented on an a1000comparator. The estimated total measuring time for the entire dissemination would amount to approximately 3 1/2 hours, while the repeatability of the comparison weighings could be expected to be typically 5µg [6]). Hence, this dissemination would deliver one 1kg weight and two weights each of 500g, 200g and 100g, or roughly 2 calibrated weights per hour.

[6]) These figures are based on 5 comparative weighings per comparison, after drift elimination. Repeatability applies to the weighing differences.

The dissemination proposed by Ulrich [5] uses the following scheme

$$\begin{pmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} R_{1000} \\ U_{1000} \\ U_{500} \\ U_{200} \\ H_{200} \\ H'_{200} \\ U_{100} \\ U'_{100} \\ U''_{100} \\ H_{100} \end{pmatrix} = \begin{pmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \\ D_6 \\ D_7 \\ D_8 \\ D_9 \end{pmatrix}$$

To overcome the difficulties of standard comparators providing limited space, he introduces three auxiliary weights (H200, H'200 and H100). This design was developed for a conventional comparator, since with the aid of the auxiliary weights, more than one weight can be put in one place on the turntable. Because this weighing scheme contains a comparison with more than three weights (row 2), it is of the class of schemes that cannot be ported to the automatic comparator. The Ulrich dissemination scheme could be modified somewhat, though, to make it suitable for the automatic comparator. As there is no need for auxiliary weights on an automatic comparator anymore, they could be replaced with regular unknown weights. Adding a control weight to check the integrity of the process, we would obtain a modified scheme, containing a total of eight weights. One of them is the reference standard, another is the check weight (pretended unknown). The six remaining are the unknown weights. Seven comparisons must be carried out, from the differences of which the unknown weights can be determined.

$$\begin{pmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & -1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 1 \end{pmatrix} \begin{pmatrix} R_{1000} \\ C_{1000} \\ U_{500} \\ U'_{500} \\ U_{200} \\ U'_{200} \\ U_{100} \\ U'_{100} \end{pmatrix} = \begin{pmatrix} D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \\ D_6 \\ D_7 \end{pmatrix}$$

This modified scheme contains groups of up to three weights and is therefore compatible with the automatic comparator. Besides having a check weight (which could be left out with no consequence to the rest of the dissemination), the dissemination yields two sets of 500g/200g/100g weights, instead of one set only, as with the original scheme. This improved weighing scheme increases the throughput by a factor of two compared to the original one, as there is no need for auxiliary weights. Implemented on an a1000comparator, this dissemination scheme would execute in approximately 2 1/2 hours, equivalent to about 2.4 weights per hour, with a comparison repeatability of typically 5µg.

Cameron et al. [6] present a plethora of other weighing schemes [7]). Most of these designs can be ported to the automatic comparator, except those which require more than three weights [8]).

---

[7]) Cameron et al. discuss several types of disseminations, namely designs for nominally equal groups (A), designs for 2,2,…,1,1,… groups (B), designs for 5,3,2,1 and 5,2,2,1 groups (C), and binary and miscellaneous groups (D).

[8]) Schemes containing a group with more than three weights are:
A.3.4, A.3.6, B.5 through 7, C.2, C.3, C.6, C.7, C.10, and D.10 through 13, D.15

Figure 6. Upper front view of the a5 automatic comparator.

Visible are the weight magazine (lower left), the mass comparator (lower right), its electronic unit with display (to the right, outside) and the handling robot (upper right).

3. Conclusion

Presently, mass comparisons and weight set disseminations are carried out on traditional comparators with or without turntables, a process that is either carried out totally manually, or at least requires frequent manual interventions. Recently, a new generation of automatic comparators has become available, whose strength lies in routine calibration of weight sets of class OIML E1 and E2, or equivalent. This equipment allows an unconventional approach to calibration of weight sets. The members of this comparator line are currently available with capacities of 5g, 100g and 1kg, featuring resolutions of 0.1µg, 1µg and 10µg, respectively.

The equipment consists of a cabinet, containing a weight magazine, a mass comparator and a robot. The weight magazine stores the weights required for a dissemination scheme. The robot loads and unloads the comparator with the proper weights. The control parameters and sequence can either be entered on a PC, or they can be downloaded from a host by means of a script language. Any comparison or dissemination scheme can be implemented and executed automatically by the equipment, provided the total number of weights can be accommodated in the magazine, and provided the weighing scheme does not ask for more than three weights in a group.

The concept of these automatic comparators provides several advantages over traditional mass comparison procedures.

The entire batch of weights required for any dissemination can be loaded into the weight magazine in one step at the beginning. Contrary to disseminations on traditional comparators, there is no need for an intervention by an operator, reducing efforts of human resources. Because there is only one loading of the weights in the beginning, and one unloading in the end, the danger of confounding weights is greatly reduced.

As the entire comparison or dissemination proceeds automatically, the weights, the comparator balance and the environment in the cabinet need only one acclimatization period to reach a thermal equilibrium. This improves the uncertainty of the comparison process. Moreover, the absence of any manual intervention, besides shortening the dissemination process, also improves the quality of the comparisons.

No auxiliary or customary weights are needed for disseminations on the automatic comparator. Therefore, the places taken up by, and the time spent with measuring of, such auxiliary weights can be dedicated to ”real” weights, thereby increasing the throughput. The increased speed and efficiency in the comparison process make it feasible to derive weight sets from one mass standard on a regular basis. Only this standard needs periodic recalibration to provide traceability. There are no down times for exchanging and re-acclimatizing the weights, there is no manual intervention required and there are no auxiliary weights. All these factors not only increase the quality of the comparison or dissemination, but the productivity of the process as well, lowering its cost.

Hence, the automatic comparator is unprecedented for applications where a high throughput of large numbers of routine calibrations is essential, to be carried out with high efficiency and superior quality, depending on few internal mass standards to be calibrated externally for traceability.

4. References

[1]. Schwartz R., *Guide to Mass Determination with High Accuracy*. Physikalisch-Technisch Bundesanstalt, Braunschweig, Bericht MA-40, April 1995.

[2]. Gläser M., *Response of Apparent Mass to Thermal Gradients*. Metrologia 1990, Vol. **27**, p. 95-100.

[3]. Gläser M., Do J.Y., *Effect of Free Convection on the Apparent Mass of 1 kg Mass Standards*. Metrologia 1993, Vol. **30**, p. 67-73.

[4]. Ueki M., Nezu Y., Mizushima S., Ooiwa A., *Weight Calibration By Mass Comparators With Automatic Weight Exchanging Mechanism*. Bulletin of NRLM Vol. 48, No. 1(199), 1999.

[5]. Ulrich Jean G., *A Special Weight Set for the Determination of OIML Weight Sets and Its Use*. Bulletin OIML, No. 117, Dec. 1989.

[6]. Cameron J.M., Croarkin M.C., Raybold R.C., *Designs for the Calibration of Standards of Mass.* National Bureau of Standards Technical Note 952, June 1977.

Contact Person for Paper :

Arthur Reichmuth

arthur.reichmuth@mt.com