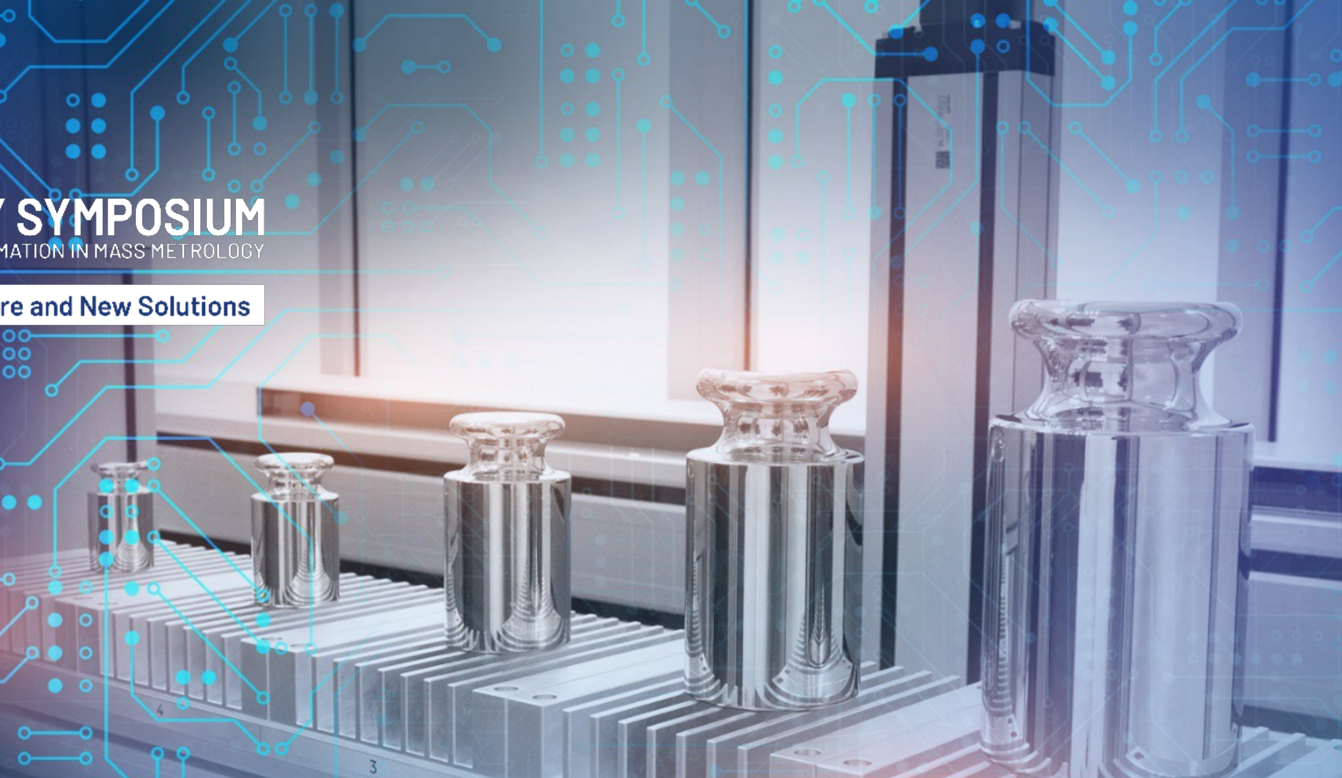
Fernsehturm, Berlin, Germany

Martin Häfner

Owner of Häfner Gewichte GmbH

Received his degree of Diploma Engineer in mechanical engineering from University of Applied Science of Aalenand his degree of Diploma Engineer in industrial engineering and management from University of Applied Science of Esslingen. Over the past decades, he has led company Häfner to become one of the market leaders in manufacturing of high-precision weights and masses, including OIML class E1 and "E0". As early as 1983, he began to set up thein-house mass laboratory “MASSCAL” for Häfner Gewichte. For over 20 years he ishead of the DAkkS-accredited calibration laboratory in accordance with ISO 17025 and since 2011 MASSCAL is accredited for calibration of OIML class E1 and for determination of volume and density. Häfner is a member of the DKD (German Calibration Service) since 2000.Here he is actively involved in many DKD subcommittees in the preparation of expert reports on digital calibration certificates (DCC) for weights and balances, in the presentation of the substitute load procedure and in determination of CMCs for balances. He was significantly involved in the development of the mass calibration software "ScalesNet" in cooperation with the company Maro. Moreover, he has been providing his customers with SimplyCal” calibration software for non-automatic weighing instruments (NAWI) in accordance with EURAMET CG 18 for more than 10 years. In the cooperation project "TransMet Si-kg", Häfner is a partner of PTB in the transfer of the redefinition of the kg based on the silicon sphere to the international world of mass. Häfner was awarded a price for this project. Finally, he is a teacher and consultant in mass metrology training and leads balance calibration laboratories to ISO 17025 accreditation.

METROLOGY SYMPOSIUM
DIGITALIZATION AND AUTOMATION IN MASS METROLOGY
Third Edition: Future and New Solutions



RADWAG
ČESKÝ METROLOGICKÝ INSTITUT

CALIBRATION AND QUALIFICATION OF MASS COMPARATORS

Content

1. Definition of a Mass Comparator

A mass comparator is a balance with

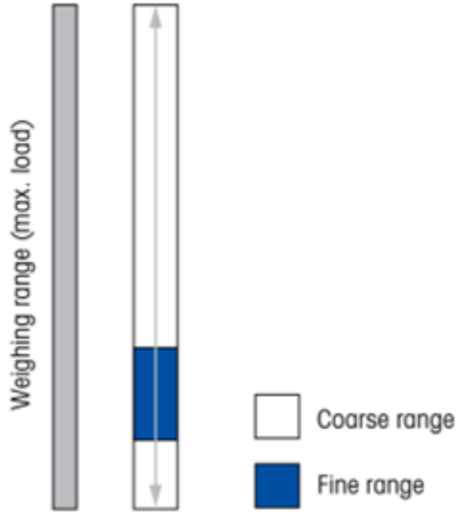
- best possible resolution n
- smallest readability d
- smallest repeatability s

for determination of smallest mass differences.

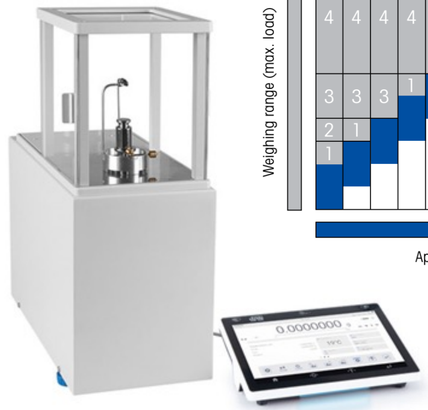
2.1. Types of Mass Comparators

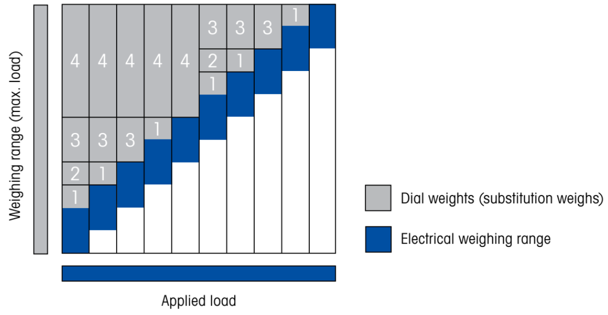
- Manual Mass Comparator
- Automatic Mass Comparator with Handling System
- Robotic Mass Comparator

2.2. Weighing Systems of Mass Comparators



- Full Range Mass Comparator
- Multi-interval Mass Comparator
- Window Range Mass Comparator





2.3. Application of Mass Comparators

- Calibration of Mass Standards and Weights
  (used as Mass Comparator)
- Differential Weighing using a Reference Object
  (used as Mass Comparator or as High Performance Balance)
- Absolute Weighing
  (used as High Performance Balance)

2.4. Use as High Performance Balance

High performance balances should be calibrated according to the calibration guide for non-automatic balances "EURAMET CG 18":

- Measurements of sensitivity, repeatability, eccentricity, errors of indication (linearity)
- Some industrial applications are:
  gas bottle filling, filter weighing, formulation,
  smallest mass or force changes in scientific research

3.1. Differential Weighing Method

A reference object (sample or substance) is compared against a test object:

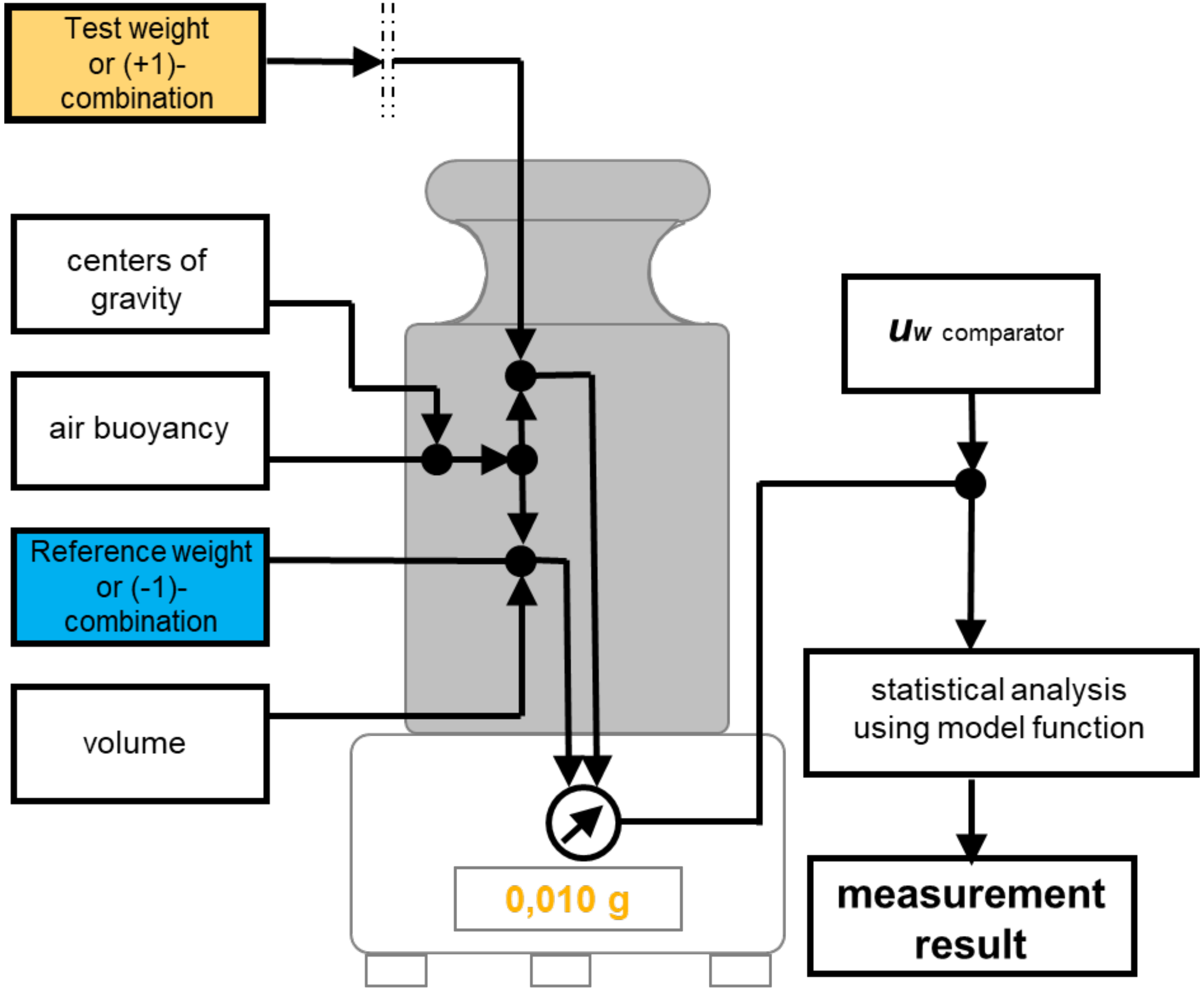
1. Use as Mass Comparator

Reference mass and test mass are within 1% of nominal mass values.

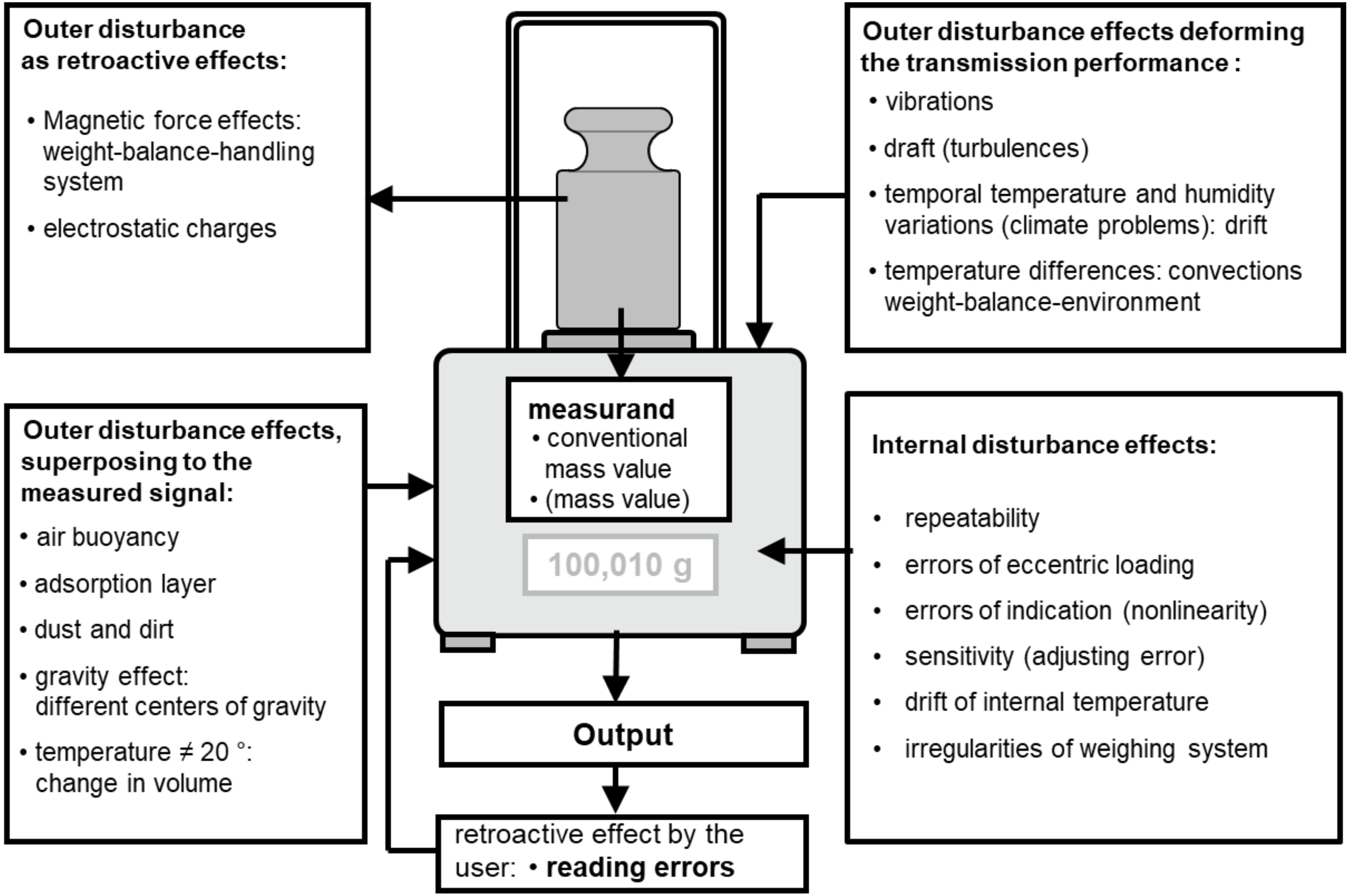
2. Use as High Performance Balance

The mass difference is larger than 1% of nominal mass.

3.2. Determination of the weighing difference Δm



4.1. Influence factors and disturbances



4.2. Requirements for Repeatability Test

Weight calibration with differential weighing method

- Determination of mass m_T or conventional mass value m_{cT}
- and of it's expanded uncertainty: $U = k * u_c(m_T)$

where $$u_c(m_T)^2 = u_A(m_T)^2 + u_B(m_T)^2$$

with $$u_A = u_A(\overline{\Delta m_w}) = s_n = \frac{s_w}{\sqrt{n}}$$

s_w is the empirical standard deviation of a single measurement value and
s_n is the empirical standard deviation of the mean of n single values

4.3. Requirements for Repeatability Test

Requirements for a coverage factor $k = 2$,
corresponding to a level of confidence of 95,45%

1. Normal distribution of type A and sufficient reliability

2. Sufficient reliability is depending on the degrees of freedom.
   A repeatability test must be applied not less than
   6 (optimal 10) differential weighing values.

5. Calibration Parameters for Mass Comparators

- Repeatability Test
  using ABBA- or ABA-Method
- Eccentricity Test
  using any drift compensated method
- Optional:
  Sensitivity Test

6. Criteria for Partial Calibration Ranges

- Nominal value of the calibration objects
- Geometric size and shape of the calibration objects
- Required calibration uncertainties for the test objects

Example:

full range mass comparator UMA 5, d = 0,1 µg,
calibration objects: 1 mg – 5 g, OIML class E1:

1.range: 1 mg – ≤ 20 mg (Criteria: sizes and required uncertainties)

required standard deviation s_w < 0,0007 µg

2.range: > 20 mg – ≤ 500 mg (Criteria: sizes and shapes)

required standard deviation s_w < 0,0009 µg

3.range: > 500 mg – ≤ 5 g (Criteria: sizes, shapes and uncertainties)

required standard deviation s_w < 0,0023 µg

7.1. Calibration of Repeatability

Preconditions for Repeatability Test

- Divide full weighing range into significant partial calibration ranges
- Measure 10 weighing cycles each on at least 3 different days using A-B-B-A- or A-B-A- method
- Take care having always normal environmental conditions
- Use 2 different test weights A and B with same nominal value (app. to Max. of partial weighing range)
- Do not exchange the weights at complete calibration process

7.2. Pooled Standard Deviation

In practice weight calibrations are done with less than 6 differential weighing cycles.
In such case pooled standard deviation s_p should be used instead of s_w for determination of u(A)

$$\boldsymbol{s_p = s(\overline{\Delta m}) = \sqrt{\frac{\sum_{j=1}^{q}(n_j - 1)\cdot s_j^2\,(\overline{\Delta m_j})}{\sum_{j=1}^{q}(n_j - 1)}}}$$

with $$\boldsymbol{s(\overline{\Delta m_j}) = \sqrt{\frac{1}{n-1}\cdot\sum_{i=1}^{n}\left(\Delta m_{ij} - \overline{\Delta m_j}\right)^2}}$$

and $$\boldsymbol{\overline{\Delta m_j} = \frac{1}{n}\cdot\sum_{i=1}^{n}\Delta m_{ij} = \frac{1}{n}\cdot\sum_{i=1}^{n}\left[\left(-I_{A_1ij} + I_{B_1ij} + I_{B_2ij} - I_{A_2ij}\right)/2\right]}$$

7.3. Sample of Pooled Standard Deviation

Repeatability Test - Calibration Protokol-No. 232-04-2024 - issued on: 04.04.2024

Balance-Ident.No.	30	Weighing Range-No.:	2	Number of ranges	3
from	0	to	500 mg	d=	**0,0001** mg
Model:	UMA 5	**Manufacturer:**	Radwag	**Serial.No.:**	B343917436

Determination of pooled standard deviation s_P :

	1. day (q = 1)	Date:	2. day (q = 2)	Date:	3. day (q = 3)	Date:
nominal value m_0 :	**500 mg**	12.02.2024	**500 mg**	14.02.2024	**500 mg**	15.02.2024
tempertature t in °C :	22,64	**operator:**	22,62	**operator:**	22,57	**operator:**
rel. humidity h in % :	45,91	Tümmler	46,09	Tümmler	45,98	Tümmler
air pressure p in hPa :	963,69		979,70		979,67	
air density ρ_a in kg/m3 :	**1,12958**		**1,14849**		**1,14867**	

r	load cycle type	I_{Ri} ; I_{Ti} in mg	ΔI_i in mg	I_{Ri} ; I_{Ti} in mg	ΔI_i in mg	I_{Ri} ; I_{Ti} in mg	ΔI_i in mg
1	R_1	500,01790		500,01660		500,01810	
1	T_1	500,02770		500,02650		500,02780	
1	T_2	500,02700		500,02620		500,02740	
1	R_2	500,01790	0,009450	500,01710	0,009500	500,01840	0,00935
10	R_{19}	500,01730		500,01640		500,01790	
10	T_{19}	500,02760		500,02690		500,02810	
10	T_{20}	500,02700		500,02630		500,02740	
10	R_{20}	500,01810	0,009600	500,01750	0,009650	500,01870	0,00945

mean of weighing difference	Δm_{qj} =	**0,0096965**	**0,00964000**	**0,00958300**
standard deviation per day	$s(\Delta m_{qj})$ =	**0,000138164**	**9,55685E-05**	**0,000129876**
variance per day	$v(\Delta m_{qj})$ =	**1,90892E-08**	**9,13333E-09**	**1,68678E-08**

pooled standard deviation s_P — s_P = **0,00012**

8.1. Eccentricity Test of Manual Mass Comparators

Manual Mass Comparators without and with centering systems

- Use a nominal value at app. maximum capacity of used partial range
- Use a single test load L_{ecc} for testing
- Eccentricity test is carried out with drift compensated method and with reduced off-centre distance (by only a few millimeters):

1. middle	2. front left	3. middle	4. rear left	5. middle
6. rear right	7. middle	8. front right	9. middle	

$$u_e = u(\Delta m_{\mathrm{ecc}}) = I \cdot |\Delta I_{\mathrm{ecc}i}|_{max} / \left(2 L_{ecc} \sqrt{3}\right)$$

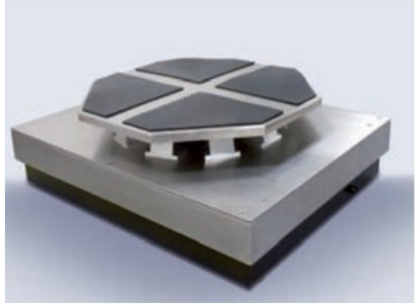
If calibration process is done with single weights the eccentricity error is included in repeatability test : $u_e = 0$

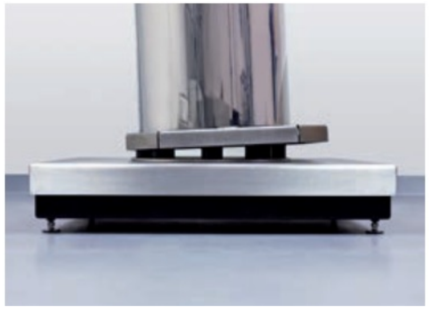
Normally an eccentricity test with centering systems is not required: $u_e = 0$

8.2. Centering Systems for Mass Comparators

Mechanical centering systems

Hanging pan self-centering pan





9.1. Exchange Error

Exchange errors of automatic and robotic mass comparators

- Exchange errors are special types of eccentricity loading effects.
- Normally exchange errors are systematical and be immediately corrected.

  The reason is based on different structural position tolerances of the change positions in relation to each other or in relation to the load introduction to the mass comparator.

- Exchange errors can have more than just mechanical causes. Temperature differences between the magazine positions, the handling tools and the weighing chamber can cause “replacement errors”. These are usually not only systematic and must additionally be taken into account by an uncertainty contribution.

9.2. Exchange Error as Systematic Error

Determination with r =10 weighing cycles with "normal" and exchanged loading of the reference and test weight positions.
The following mean value pairs (*a*+*b*) result for each of the n test weight positions:

$$\overline{\Delta I_{V_{a_n}}} = \frac{1}{r}\sum_{i=1}^{r} \Delta I_{a_i} \qquad \text{and} \qquad \overline{\Delta I_{V_{b_n}}} = \frac{1}{r}\sum_{i=1}^{r} \Delta I_{b_i}$$

with n= test weight position
a= „normal“ loading
b= exchanged loading

Systematic exchange error of position n: $f_{T_n} = \dfrac{\overline{\Delta I_{V_{a_n}}} + \overline{\Delta I_{V_{b_n}}}}{2}$

Exchange-corrected indication difference of position n: $\Delta I_{T_{i_n}} = \Delta I_{i_n} - f_{T_n}$

9.3 Exchange Error as Random Error

If the exchange deviation f_{T_n} is not systematic but random, following uncertainty contribution has to be included to the weighing process.
A rectangular distribution must be assumed:

$$u(\Delta m_{\mathrm{ecc}}) = f_{T_n} / \left(\sqrt{3}\right)$$

This eccentricity uncertainty $u(\Delta m_{\mathrm{ecc}})$ can be combined with standard deviation $s(w)$ of the weighing process:

$$u_A = u_A\left(\overline{\Delta m_w}\right) = s_n = \frac{\sqrt{u(\Delta m_{\mathrm{ecc}})^2 + {s_w}^2}}{\sqrt{n}}$$

10.1. Qualification of Mass Comparators

A. Requirement of OIML R111-1:2004: $u_c(m_T) = \frac{U(m_T)}{k} = \frac{U(m_T)}{2} \leq \frac{1}{6} mpe$

B. Guidelines based on practical experience:

1. $u_A(\overline{\Delta m_w}) \leq \frac{3}{5} u_c(m_T))$

2. $u(m_R) = u_b = u_{ba} \leq \frac{1}{3} u_c(m_T)$

C. Requirement for Weighing Process and Repeatability of Mass Comparator:

$$u_A = u_A(\overline{\Delta m_w}) = s_n = \frac{s_w}{\sqrt{n}} \leq \frac{3}{5} u_c(m_T) = \frac{1}{10} mpe$$

$$s_w = s_p = \frac{1}{10} mpe \cdot \sqrt{n}$$

10.2. Example for Qualification of Mass Comparator

Example: 100 g, class E2 (mpe = 0,16mg), 2 x ABBA,
mass comparator: WAY 500.5Y.K0: Max = 520 g, d = 0,01 mg, $s_{specified}$ = 0,02 mg

Requirements for calibration process:

A. $$u_c(m_T) \leq \frac{1}{6} mpe = \frac{1}{6} \cdot 0{,}16\, mg = 0{,}027\, mg$$

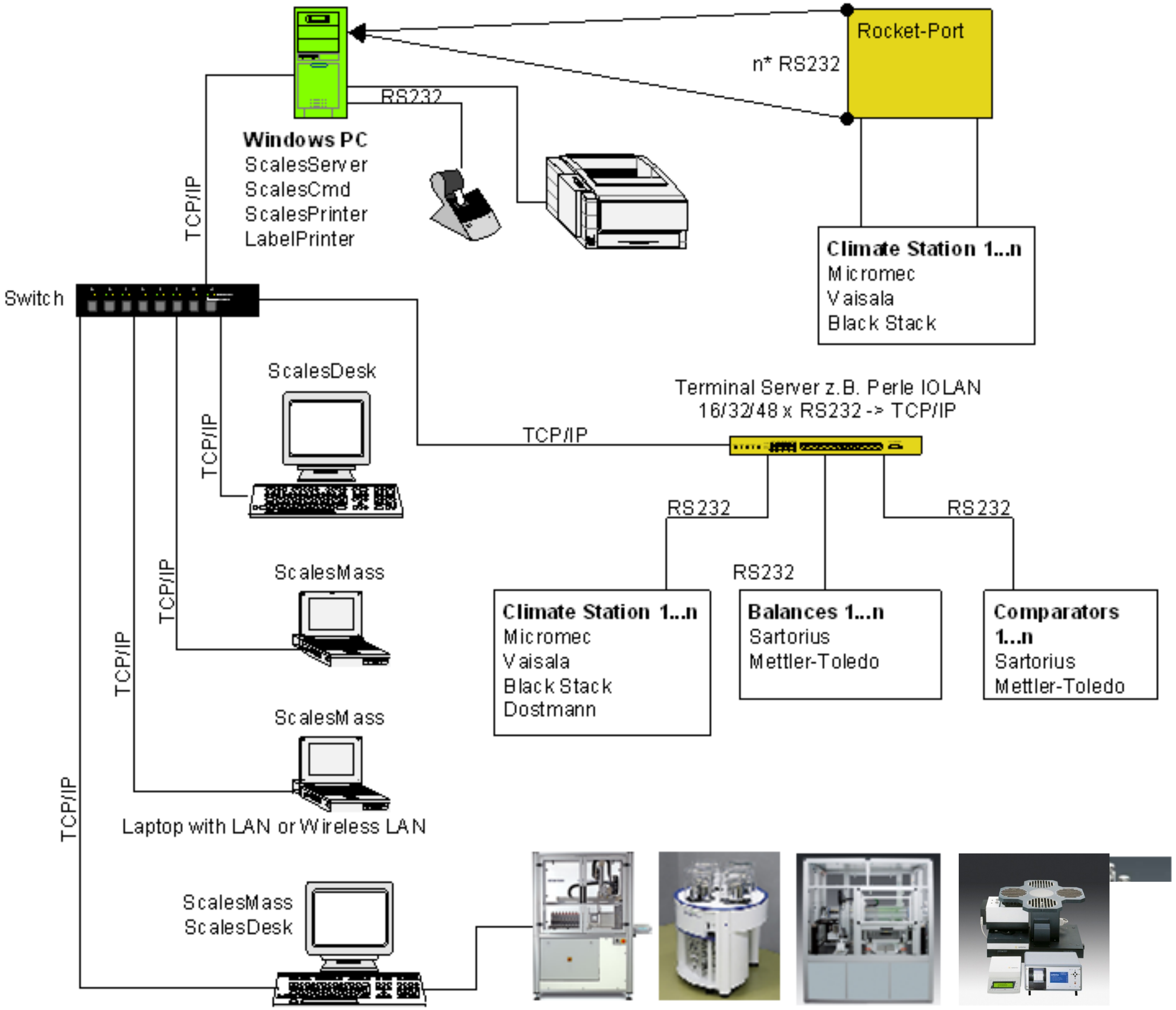
B. 1. $$u_A(\overline{\Delta m_w}) \leq \frac{3}{5} u_c(m_T) = \frac{3}{5} \cdot 0{,}0267 \text{ mg} = 0{,}016 \text{ mg}$$

2. $$u(m_R) = u_b = u_{ba} \leq \frac{1}{3} u_c(m_T) = \frac{1}{3} \cdot 0{,}027\, mg = 0{,}009\, mg$$

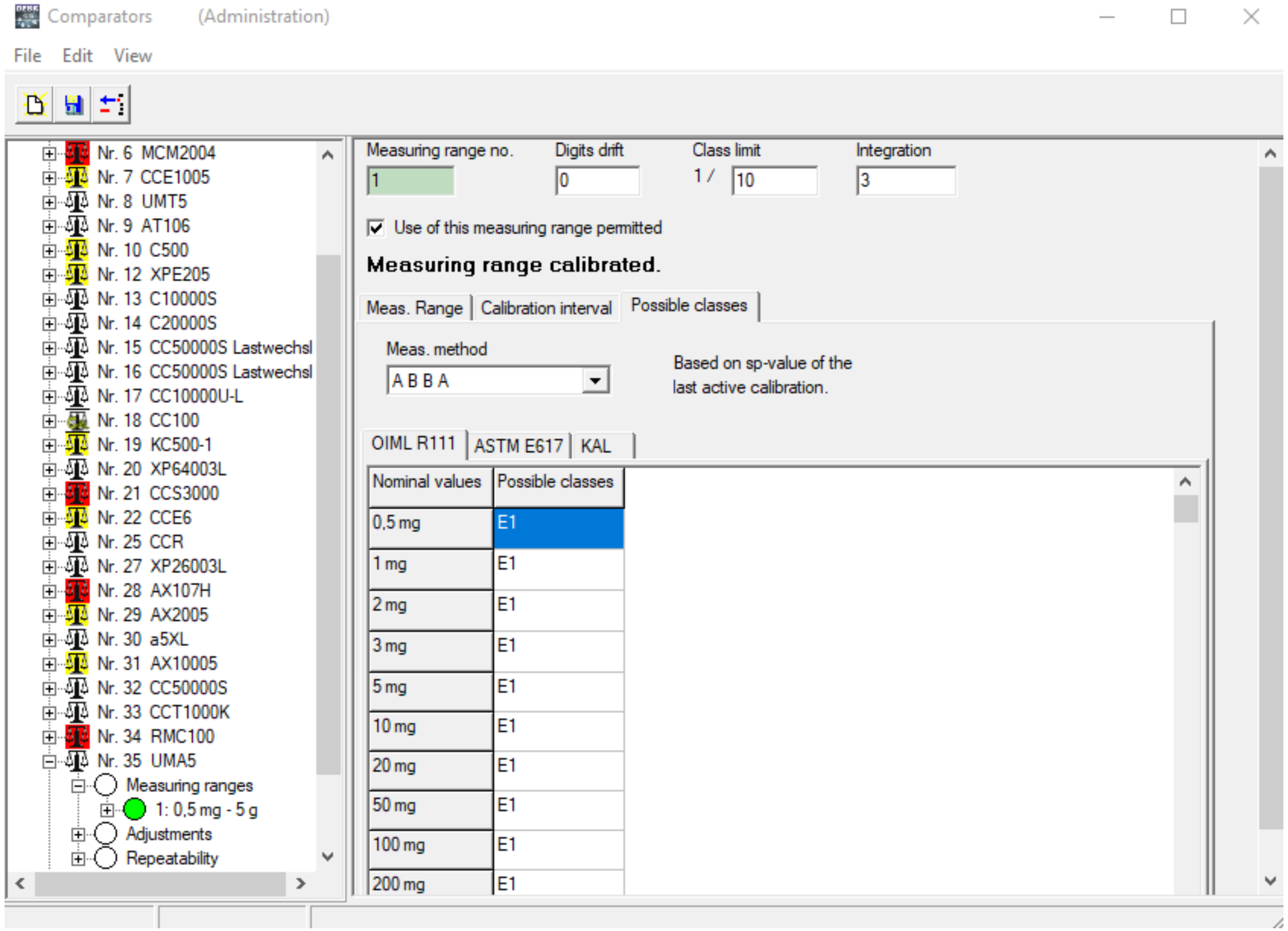
C. $$s_{w_{max}} = s_{p_{max}} = \frac{1}{10} mpe \cdot \sqrt{n} = \frac{1}{10} \cdot 0{,}16 \cdot \sqrt{2}\ mg = 0{,}023\, mg$$

Result: WAY 500.5Y.K0 fulfils the requirements for calibration of 100 g, class E2.

11.1. ScalesNet - Mass Calibration Software



11.2. ScalesNet - Qualification of Mass Comparators



12. Conclusion

- What is the use? mass comparator or high performance balance
- Which type, weighing system and weighing range is required
- What are the influence and disturbance factors
- Check the environmental conditions
- Devide the full weighing range in partial calibration ranges
- Which tests for calibration of the comparator are required: repeatability, eccentricity, exchange, sensitivity
- Qualify the mass comparator
- Which pooled standard deviation s_p or s_w is needed
- Reduce errors in calibration by using a mass calibration software


METROLOGY SYMPOSIUM
DIGITALIZATION AND AUTOMATION IN MASS METROLOGY
Third Edition: Future and New Solutions
Thank you for your attention
www.radwag.com