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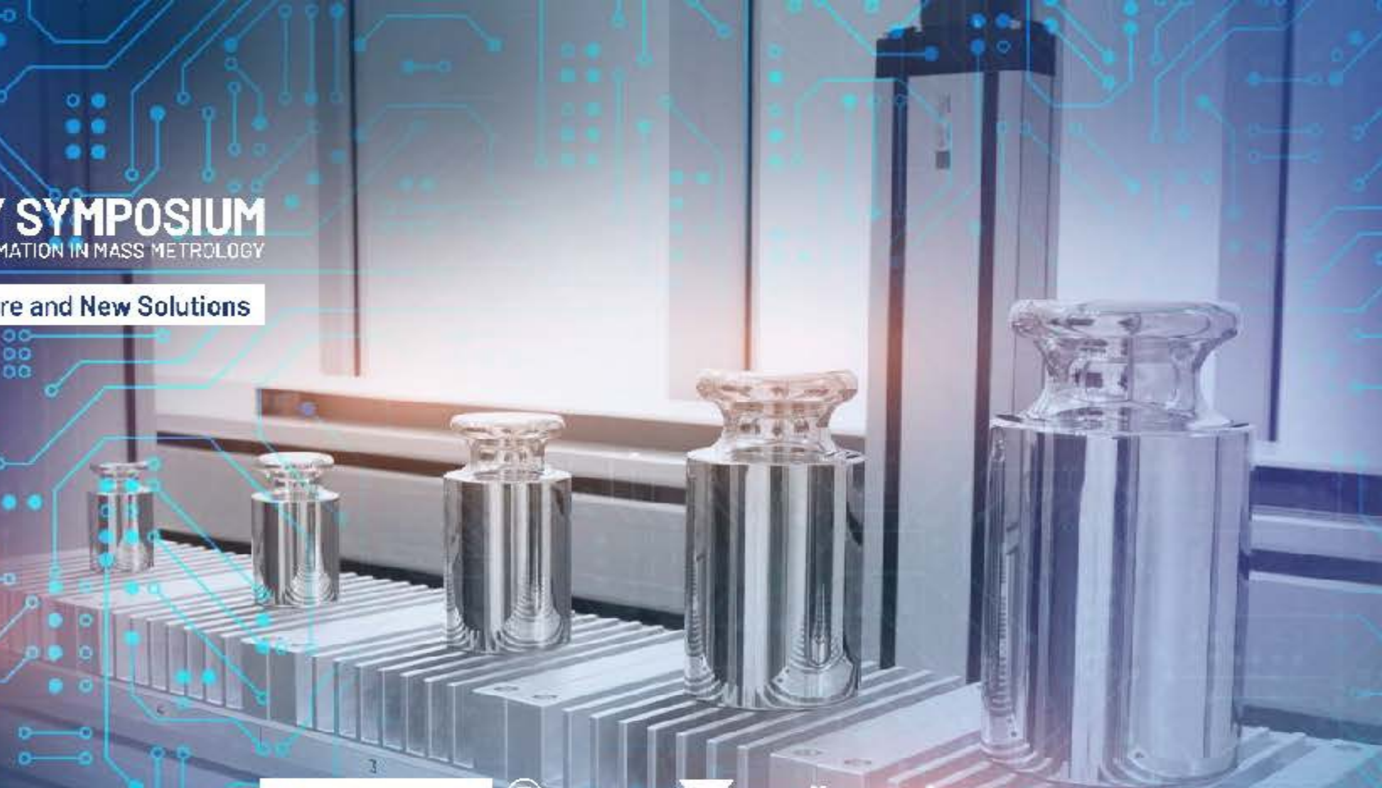
In 1988, he graduated from the Mechanical Engineering at the Technical University of Budapest. In 1992, he finished PhD studies at the Hungarian Academy of Sciences. In 2006, he graduated with a university degree in Law from the Eötvös Loránd University in Budapest. From 1998 to 2007, he worked at the National Office of Measures (OMH, the Hungarian NMI), among other positions, as Head of the Mechanical Measurements Section. He has been working in BEV since 2008, he is TC-M Chair in EURAMET and has several functions in IMEKO.

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



RADWAG

ČESKÝ METROLOGICKÝ INSTITUT

Revisiting weighing designs in mass metrology

Revisiting weighing designs

Based on project

Improvement of the realisation of the mass scale (Project - 19RPT02 RealMass)

The Project had the following specific objectives

- To **develop and implement calibration methods** to realise, improve and maintain the mass scale (e.g., from 1 mg to 20 kg
- To develop advanced mathematical and statistical tools and **software solutions** to calculate the results from the dissemination of the mass unit
- To develop a draft EURAMET **calibration guideline** for the realisation of the mass scale

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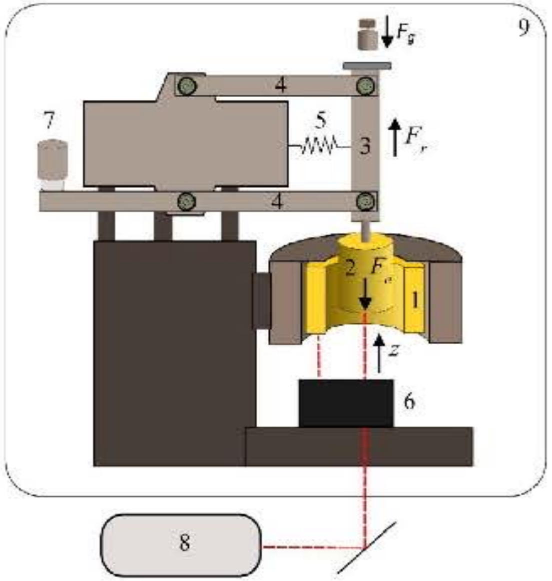
EMPIR project 19RPT02, "Improvement of the realisation of the mass scale" (EMPIR Call 2019 –Research Potential), has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

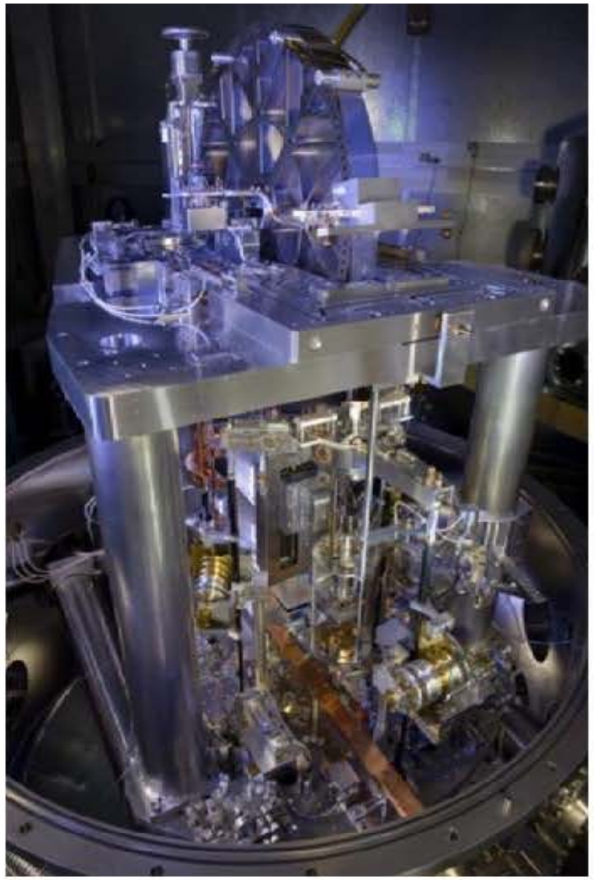
EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Bundesamt
für Eich- und
Vermessungswesen
Physikalisch-technischer Prüfdienst (PTP)

The two challenges in mass metrology

- **Realisation of the unit of mass.**

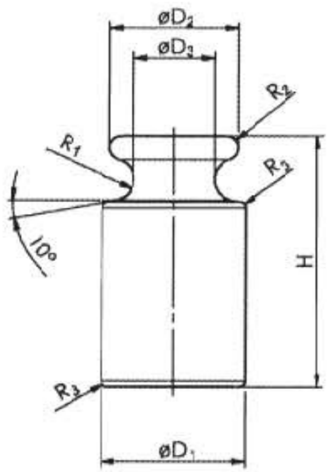




- **Realisation of the mass scale**

What is a weighing design

Weight (mass standard)



INTERNATIONAL RECOMMENDATION

OIML R 111-1

Edition 2004 (E)

Weights of classes E_1, E_2, F_1, F_2, M_1, M_{1-2}, M_2, M_{2-3} and M_3

Part 1: Metrological and technical requirements

Poids des classes E_1, E_2, F_1, F_2, M_1, M_{1-2}, M_2, M_{2-3} et M_3

Partie 1: Exigences métrologiques et techniques

C.3 Weighing designs

C.3.1 Direct comparison

Usually the test weight should be calibrated by comparison against one or more reference weights. In each comparison, the nominal mass of the test weight and the reference weight should be equal. A check standard (see 2.5) can be used to monitor the measurement process [28].

Note: **Special problems may arise when calibrating class E_1 weights of less than one gram.** This is partially due to a relatively large uncertainty of the reference weights in this range. Further, the instability of the weighing instruments and a large surface area are factors that negatively influence the uncertainty of measurement. Therefore, the subdivision method is strongly recommended for such weights.

Subdivision – design (Shortened text from OIML R111)

OIML R 111, C.3.2 Subdivision. An entire set of weights can be calibrated against one or more reference weights. This method requires several weighings within each decade in the set.

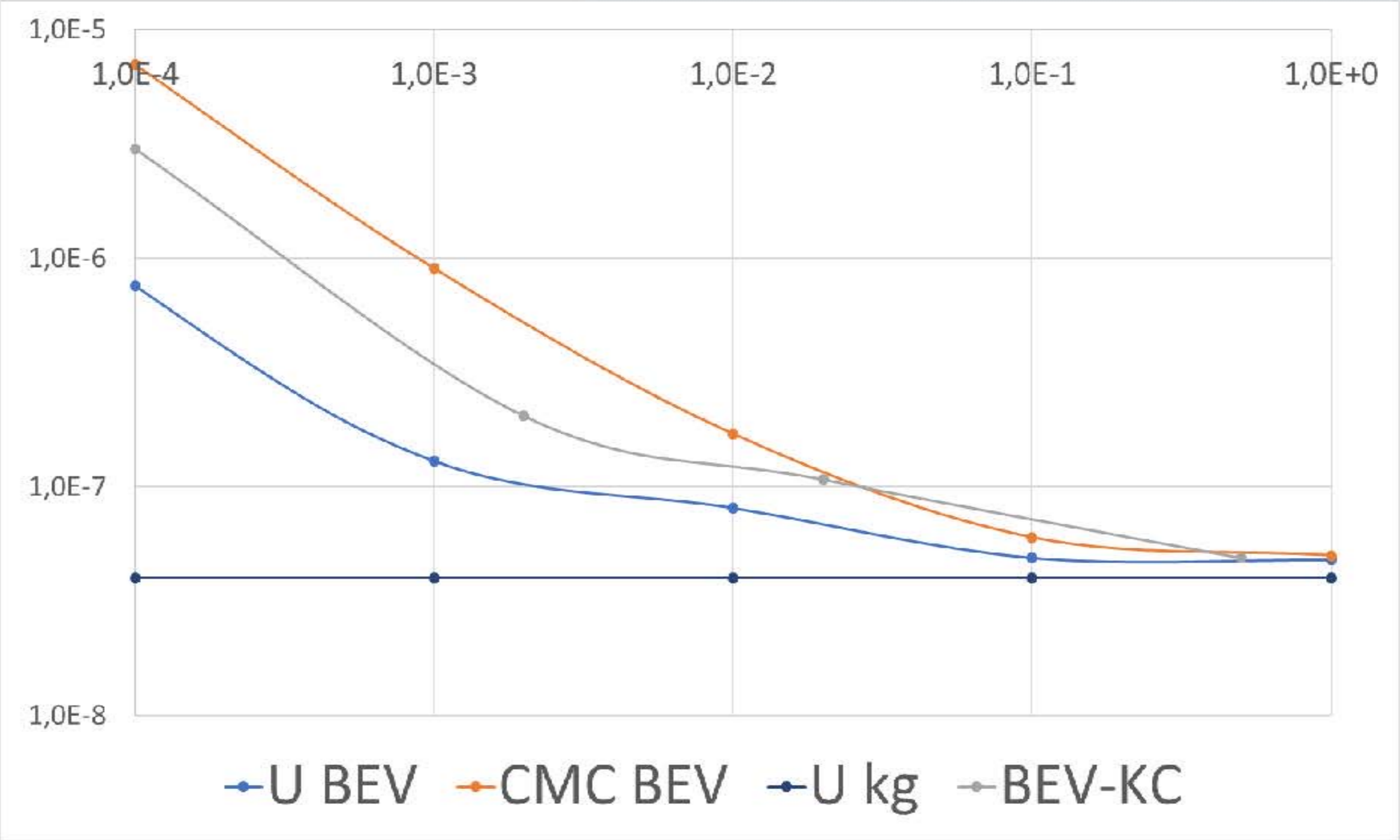
- In these weighings, **different combinations of weights of equal total nominal mass are compared**. This method is mainly used to calibrate sets when the highest accuracy is required.
- If with this method, only one reference weight is used, the **number of weighing equations should be larger than the number of unknown weights** and an appropriate adjustment calculation should be performed in order to avoid propagating errors. …
- … The advantage of such methods lies in the fact that they **include a certain redundancy** that offers greater confidence in the results.

Demonstration of uncertainties in mass metrology

- X axes, nominal values [kg] (100 mg to 1 kg)
  Y axes relative expanded uncertainties (U/nominal Value)

Explanation of the series

- U kg is the uncertainty of the kg as the uncertainty of the consensus value, relative to the nominal value
- U BEV is the uncertainty of BEV calibrations (as calculated)
- CMC BEV
- BEV-KC is the uncertainties given by BEV in EURAMET.M.M-K2.6



Design (Matrix, X), matematical point of view

An equation system is to be solved (matrix notation):

$$Y = X\beta$$

$$Y = \Delta w + \{(1 - 20\alpha)I + \alpha T\}\rho XV - \nabla gDM$$

Strategies

- Make all the corrections of the direct comparison and have a simple mathematics (Bouyance, centre of gravity heights)
  - Cannot calculate with correlations (typically ordinary or weighted least squares)
- Do not correct for all possible correction but use these parameters as input
  - Complicated method is needed (like **generalized least squares**).
  - Correlation matrix of input quantities

Published weighing designs

- Comprehensive mass metrology
  - Definitely a “spartan” model, very effective, but not robust
  - 7 measurements
  - 1 reference
  - 4 test
  - 1 controls

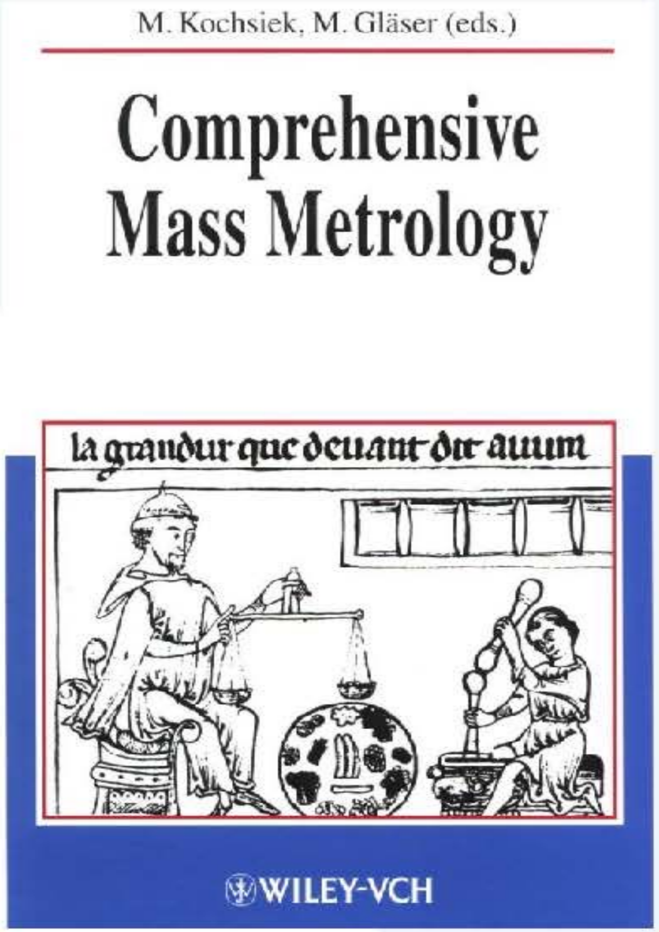
Weighing scheme N = 7 weighings
K = 5 unknown weights

Decade 100 g to 1 kg

Weighing	1 kg	500 g	200 g	200 g	100 g	100 g
x (1)	+	–	–	–	–	
x (2)		+	–	–		–
x (3)			+	–		
x (4)				+	–	–
x (5)					+	–
x (6)			+		–	–
x (7)		+	–	–	–	

Decade 10 g to 100 g

Weighing	100 g	50 g	20 g	20 g	10 g	10 g
y (1)	+	–	–	–	–	
.						
.						
y (7)		+	–	–	–	



Published weighing designs

- OIML R111
  - 12 measurements
  - 1 reference
  - 4 test
  - 1 control
  - Yellow: repeated ones (Does it make sense?)
  - Why the 2 vs 2* or 1 vs 1* not measured?

1	Reference weight	5 + 2 + 2* + 1
2	Reference weight	5 + 2 + 2* + 1*
3	5	2 + 2* + 1
4	5	2 + 2* + 1*
5	2 + 1	2* + 1*
6	2 + 1	2* + 1*
7	2 + 1*	2* + 1
8	2 + 1*	2* + 1
9	2	1 + 1*
10	2	1 + 1*
11	2*	1 + 1*
12	2*	1 + 1*

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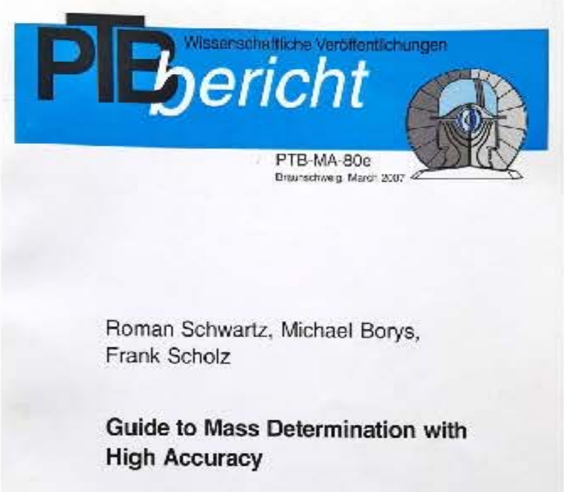
Partie 1: Exigences métrologiques et techniques

Published weighing designs

- PTB-MA-80e
  - Additional 10 and 5 weighs
  - 10 measurements
  - 1 (2) reference(s)
  - 4 test
  - 2 control
  - Note: 10 measurements with 8 unknown weights. Is it enough?

Observations	Reference: 10	Test: 10	Test: 5	Control: 5	Test: 2	Test: 2 *	Test: 1	Control: 1
1	1	-1						
2	1		-1	-1				
3		1	-1	-1				
4			1	-1				
5			1		-1	-1	-1	
6				1	-1	-1		-1
7					1	-1		
8					1		-1	-1
9						1	-1	-1
10							1	-1



Considerations on which design to use. What could be important?

General aspects

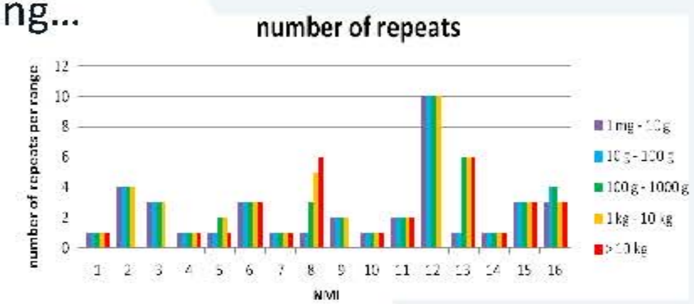
- Doable
- No danger (of mixing weights, damaging weights)
- Easy calculation (not relevant any more)
- Orthogonality (not relevant)
- Include additional parameters
- Overlapping decades

For high efficiency (higher uncertainty)

- Small number of measurements
- Simple combinations
- No additional weights
- Simple calculation

For high quality results (Small uncertainty)

- Numerous combinations and measurements
- Robust and error resistant design
- Quality assurance (like using additional check standards)
- Include additional parameters
- Repeat the whole subdivision (survey from EURAMET 1210 project)
- Iterative reweighing...



Application note

This can be applied for

- Calibration of one weight (a scenario: Using two or three standard to calibrate one weight with same nominal value)
- Calibrate a weight with different nominal value (a scenario: 2 kg against 1 kg standards)
- One decade
- Multiple decades
- Multiple sets

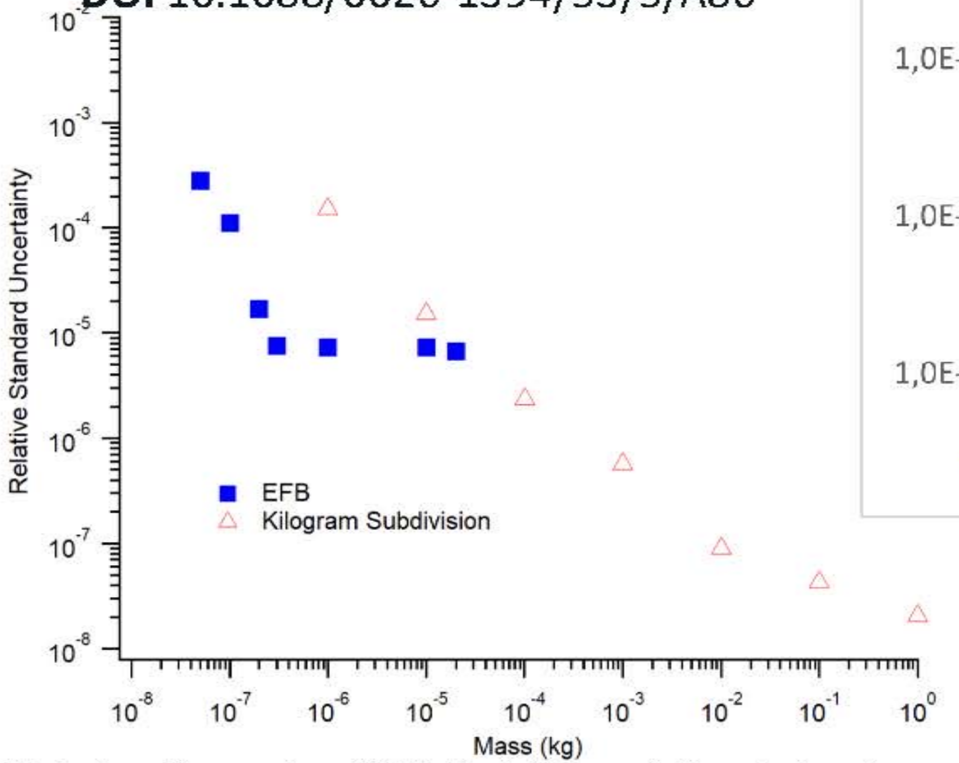
Parameters that can be calculated by a (special) design

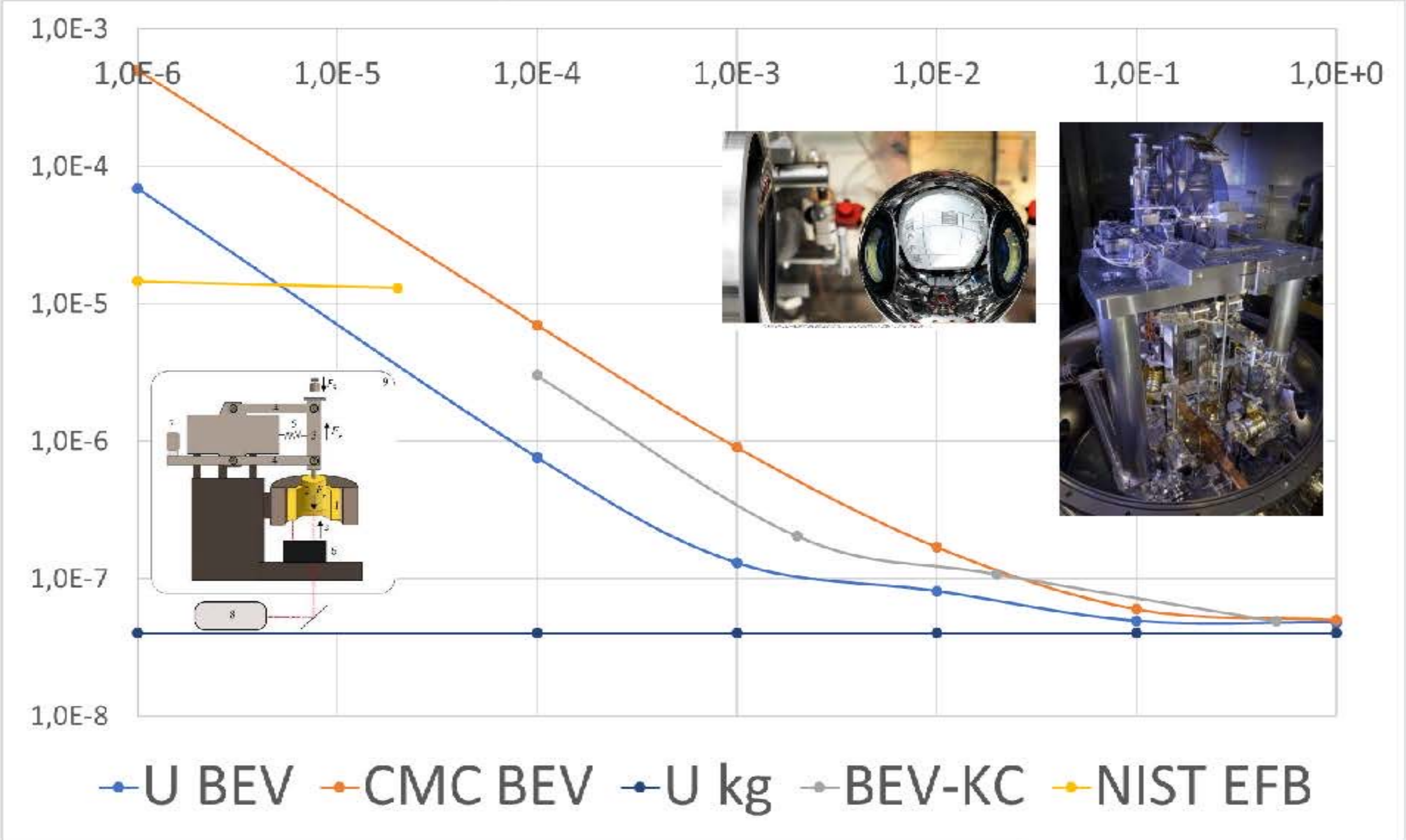
- **Mass of unknown weights**
- **Other quantities**
  - Check standards,
  - Helping weights; like disk weights
  - Special plates,
  - Position errors
  - Linearity
  - Volume of the weights (example https://doi.org/10.21014/acta_imeko.v9i5.931)
  - Drift of the mass standards

Figure 1: Mass comparators in air-tight enclosures in METAS

New developments – new realisation of the mass unit

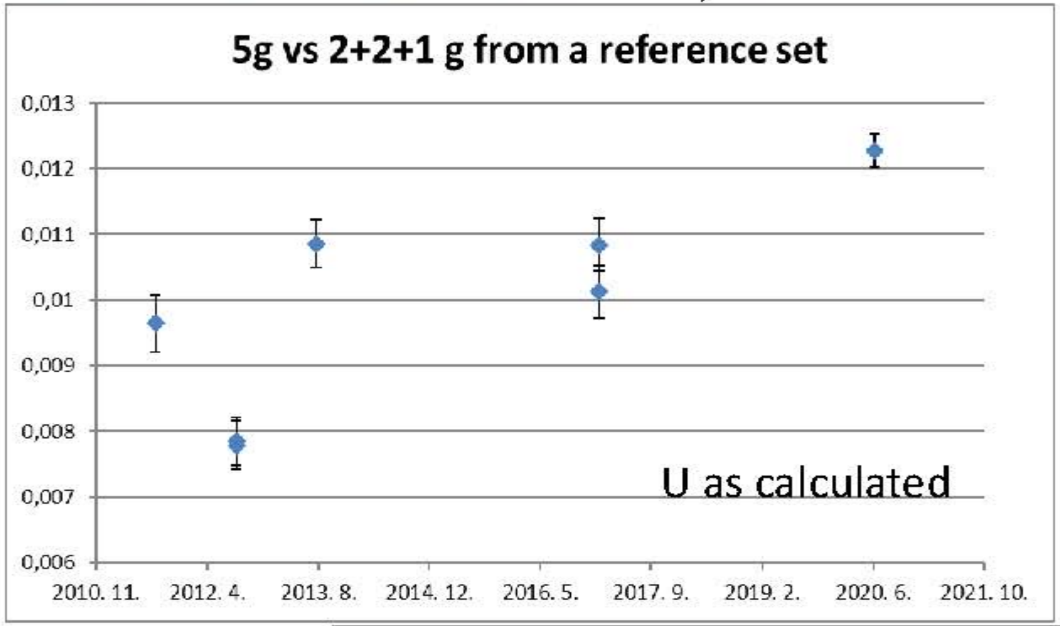
- Realisation of mass
  - Kibble balance
  - Avogadro experience
  - Milligram mass metrology using an electrostatic force balance (EFB) **DOI** 10.1088/0026-1394/53/5/A86

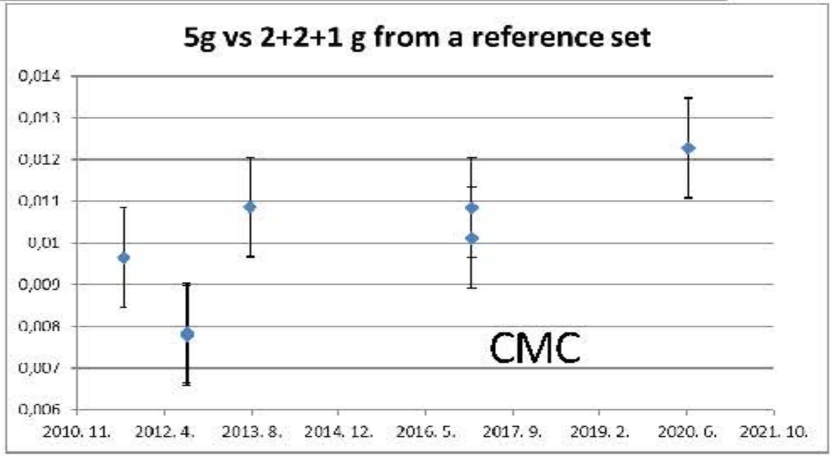




Repeatability and reproducibility

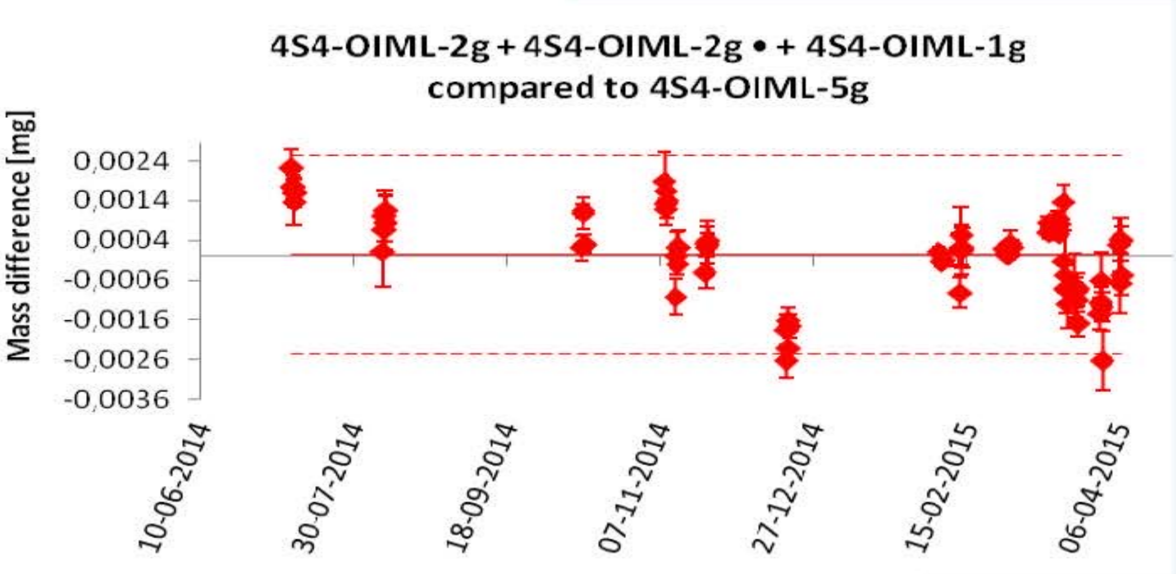
BEV measurements with a robotic system





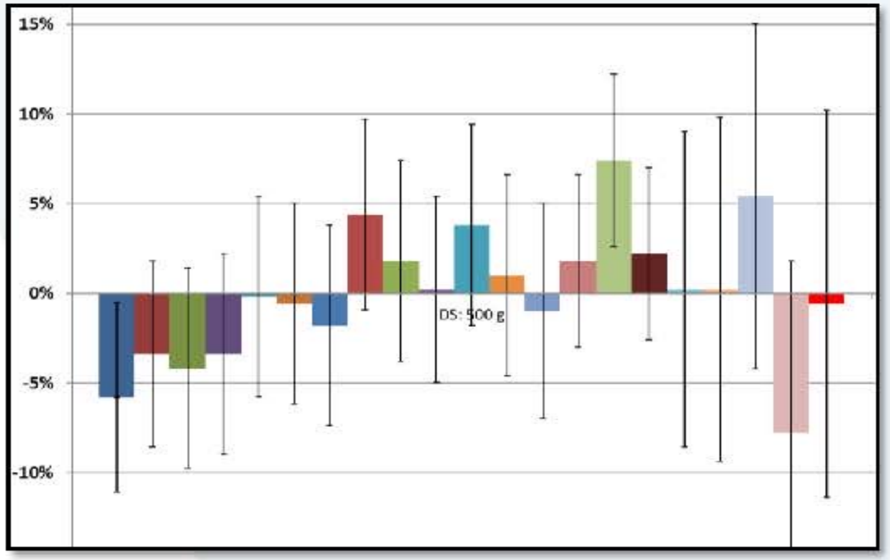
Similar results from EURAMET 1210

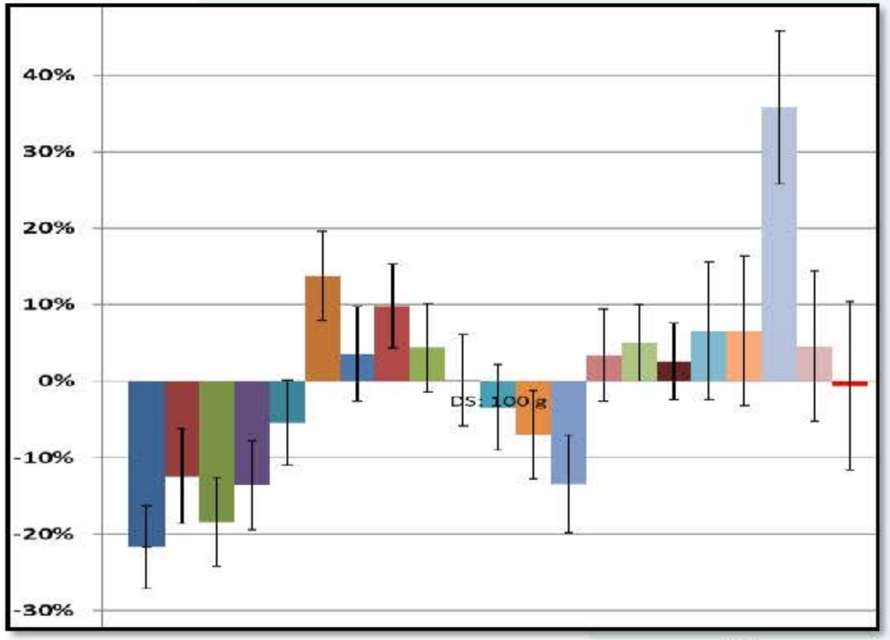
- A VSL study on repeatability versus reproducibility (using robots). Two types of repeats were compared.
  - Type I: weighing designs are repeated without pause.
  - Type II: The weights are taken out of the robot and put into their usual dust-free storage. The weights are placed again into the robot, in the same position as before.



Guaranteeing the quality of the results.

- **Number of check standards**
  - If it is affordable one for each nominal value.
  - Tests will show by the analyzed designs if the check standards indicates the error
- **Residuum analysis**
  - Precondition: robust subdivision
  - Tests will show by the analyzed designs if it indicated where can be the error
- **Comparison with previous result**
  - Precondition: previous results are available.

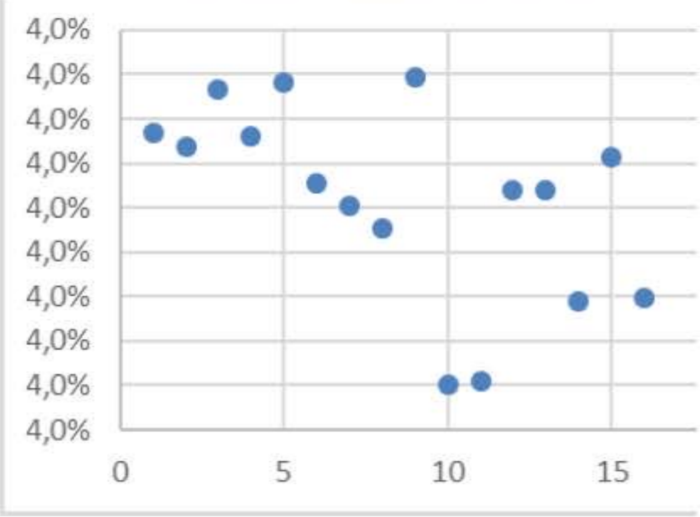




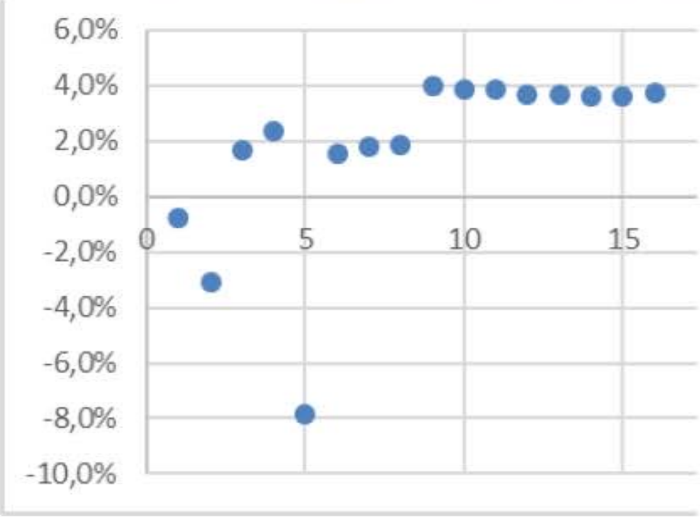
Guaranteeing the quality of the results – Iterative reweighting

- **IRLS – Assign less weight to the wrong measurements,**
  - "Increasing the uncertainty of the wrong measurements"
  - It is a common technique in several areas (enhance blurry images)
- Demonstration. All data are relative to the maximum permissible error. (U-abs(Dev))/MPE.

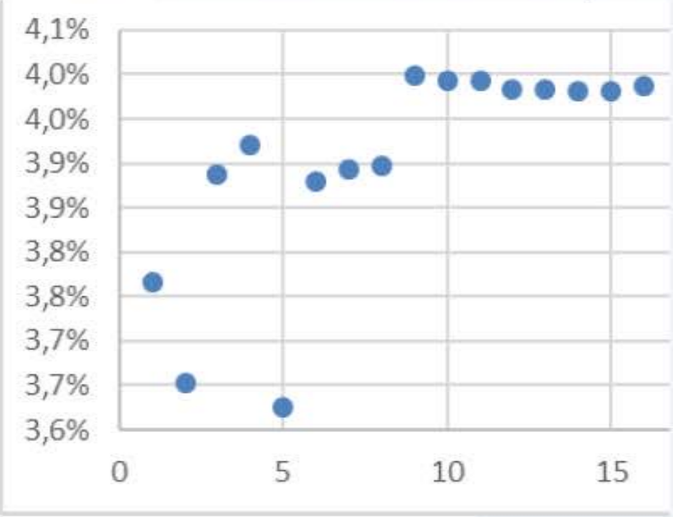
Perfect measurement,



5th is Measurement erroneous,



Corrected measurement by IRLS



More detail: https://www.imeko.org/publications/wc-2015/IMEKO-WC-2015-TC3-095.pdf

Guaranteeing the quality of the results.

- **Reviewing efficiency -** E=1/(sum(u)*n),
  - It can be calculated for all weights,
  - Alternatively calculated for the test weights only (smallest in the decade)
- * and **: “Optimal Weighing Schemes”, S Bhulai, T Breuer, E Cator, F Dekkers (one side only one weight)

Design	Minimum	Comp. Mass. M.	OIML	PTB	PTB*	PTB**	BEV	BEV (2)
n	5	7	12	10	10	10	12	16
Eff	5,6	4,1	2,4	2,2	2,2	2,2	1,85	1,5
Eff (test)	7,8	5,6	3,3	4	4	4	3,3	2,5
“Error resistant”	No	No	No	No	Yes	Yes	Yes	Yes
U 100g	10,5	10,1	10,1	10,1	10,1	10,1	10,1	10,0
U 100g without standard	3,3	1,7	1,5	1,7	1,4	1,3	1,2	1,0

Recommendations from the project

Considerations and recommendations

- Uncertainty is generally not an issue (if the single measurements are "good")
- Prefer reproducibility over repeatability.
- Use special design (if it is needed: volume, position errors, linearity, …)
- Choose optimized design (effectiveness vs robustness)
- Preferably use marked weights so you cannot mix (swap) them
- Avoid additional steps in calibration, like calibrate disks first and then compare the weights to them. Integrate the necessary disks in the design.
- Consider calculating all measurements in one (not in separate decades). It provides some advantages (correlations) but makes it less concise.

„Recommended“ design

No recommendation, but the project identified two robust designs, both tolerate one wrong measurement.

For systems that can measure 4 weights

It has extra weights for each nominal values. (16 measurements)

A: 1 kg	B: 1 kg	A: 500 g	B: 500 g	A: 200 g	A: 200 g*	B: 200 g	A: 100 g	B: 100 g
-1	1	0	0	0	0	0	0	0
-1	0	1	1	0	0	0	0	0
0	-1	1	1	0	0	0	0	0
-1	0	0	1	1	1	0	1	0
0	-1	1	0	1	0	1	0	1
0	0	-1	1	0	0	0	0	0
0	0	-1	0	1	1	0	1	0
0	0	-1	0	1	1	0	0	1
0	0	0	-1	0	1	1	1	0
0	0	0	0	-1	1	0	0	0
0	0	0	0	-1	0	0	1	1
0	0	0	0	0	-1	0	1	1
0	0	0	0	0	-1	1	0	0
0	0	0	0	0	0	-1	1	1
0	0	0	0	0	0	0	-1	1
0	0	0	0	0	0	0	-1	1

For “robotic” systems

(18 measurements)

A: 1 kg	B: 1 kg	A: 500 g	B: 500 g	A: 200 g	A: 200 g*	A: 100 g	B: 100 g	C: 100 g
-1	1	0	0	0	0	0	0	0
0	-1	1	1	0	0	0	0	0
-1	0	1	1	0	0	0	0	0
-1	0	1	1	0	0	0	0	0
0	-1	1	1	0	0	0	0	0
0	0	-1	1	0	0	0	0	0
0	0	1	-1	0	0	0	0	0
0	0	-1	0	1	1	1	0	0
0	0	0	-1	1	1	0	0	1
0	0	0	-1	1	1	0	0	1
0	0	0	0	-1	1	0	0	0
0	0	0	0	-1	0	1	1	0
0	0	0	0	-1	0	1	0	1
0	0	0	0	0	-1	1	0	1
0	0	0	0	0	-1	0	1	1
0	0	0	0	0	0	-1	1	0
0	0	0	0	0	0	-1	0	1
0	0	0	0	0	0	0	-1	1

Recommendations

Progress

- Make the measurements. Check them (individually).
- Evaluate the result and check
  - Residuals are as expected
  - Is there any measurements that could be wrong (repeat it, if necessary)
  - If the mass of the check weights are matching with the expectations
  - Compare with previous results (if available)
- Handle the possible problems
  - Remove the suspicious measurements
  - Add new measurements to improve the robustness, identify errors
  - Use IRLS
  - Repeat all the measurements (preferably removing and placing back the weights)

Thank you for your attention!

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