Comparisons of absolute gravimeters (COOMET.M.G-S1)

RMO Supplementary Comparison

COOMET.M.G-S1
(COOMET Project 634/UA/14)

COMPARISONS OF ABSOLUTE GRAVIMETERS

FINAL REPORT

Created by A. Vinnichenko[1], A. Germak[2]

Pilot laboratory:	Scientific and research laboratory of time, frequency and gravimetry
Name and abbreviation of NMI:	National Scientific Center “Institute of Metrology” (NSC “Institute of Metrology”), Kharkov, Ukraine

Vinnichenko A.
NSC “Institute of Metrology”
SC-2, SRL-20
Ukraine, Kharkov, 61002,
Mironositskaya, 42
tel.: +38 (057) 700-34-09
fax (057) 700-34-47
E-mail: vinn96@yandex.ua

Abstract:
This report describes the results of RMO supplementary comparison COOMET.M.G-S1 (also known as bilateral comparison COOMET 634/UA/14). The comparison measurements between the two participants NSC “IM” (pilot laboratory) and INRIM were started in December 2015 and finished in January 2016.
Participants of comparisons were conducted at their national standards the measurements of the free fall acceleration in gravimetric point laboratory of absolute gravimetry of INRIM named INRiM.2. Absolute measurements of gravimetric acceleration were conducted by ballistic gravimeters.
Agreement between the two participants is good.

Kharkov, Ukraine

March 2016

[1] NSC “Institute of Metrology”, Ukraine
[2] National Institute of metrological research, Italy

Content

1. Introduction

Pilot laboratory NSC "Institute of Metrology" (hereinafter – NSC "IM"), (Kharkov, Ukraine).

Comparisons of traveling standard DETU 02-02-14 (hereinafter – GBT) were carried out in the laboratory of the participant of National metrological researches (hereinafter – INRIM) (Turin, Italy) at measurement point (hereinafter GP) named INRiM.2, in the laboratory of gravitation of INRIM.

Results of comparisons of NMI are given in Chapter 8 of this report.

2. Participants of comparisons

Table 1

№	COUNTRY / NMI	CONTACT PERSON / ADDRESS
1	Ukraine National Scientific Center "Institute of Metrology" (NSC "IM")	Mr. Aleksandr Vinnichenko Scientific and research laboratory of time, frequency and gravimetry 42, Myronosytska, Kharkiv, 61002,Ukraine Tel.: +38 (057) 704-97-99 Tel.: +38 (057) 704-98-54 Fax: +38 (057) 700-34-47 E-mail: vinn96@yandex.ua
2	Italy National Institute of metrological research (INRIM)	Dr. Alessandro Germak STALT Strada delle Cacce, 91, Turin, 10133, Italy Tel.: +39 011 39 19 926 E-mail: a.germak@inrim.it

3. Organization of comparisons

3.1 Aim of comparisons – determination of the level of equivalence of primary instruments.

3.2 Scheme of conducting comparisons – bilateral.

3.3 Principle of the comparison.

Participants of comparisons from NMI are conducted at their national standards the measurements of the free fall acceleration (GA) in GP laboratory of absolute gravimetry of INRIM named INRiM.2, according to the demands of the technical protocol.

According to the results the following quantities have been calculated:

– absolute value of GA at the point of GP, named INRiM.2;

– budget of uncertainty of measurements of absolute ballistic gravimeters (for each one);

– budget of uncertainty of measurements of absolute ballistic gravimeters (for each one), depending on measurement point of INRiM.2.

3.4 Dates of conducting measurements by participants:

– December 2015, measurements of absolute value of GA at GP of INRIM;

–January 2016 – February 2016 processing of the results of measurements and their delivery to NSC “IM”.

– March 2016 preparing the report and discussion of the report A about comparisons.

3.5 Parameters of the point of INRiM.2.

Geographic coordinates, which have been used by all participants:

– name of the station: INRiM.2;

– latitude: 45,0170 ° N (North);

– longitude: 7,6427 ° E (East);

– height about sea level: 237 m.

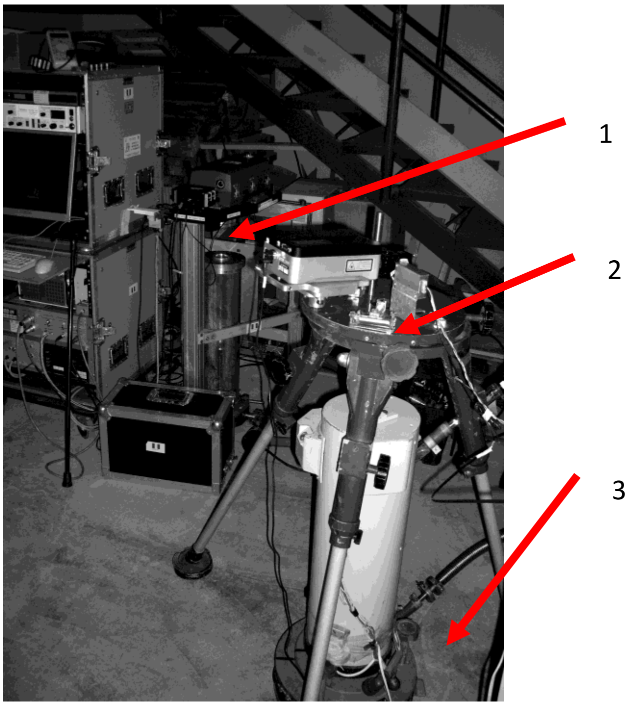
4. Methods of conducting measurements

4.1 Absolute measurements of GA are conducted by ballistic gravimeters, by placing them directly on the dedicated pillar of INRiM.2 point.

4.2 Working scheme of the comparison of absolute gravimeters of participants during the measurements of absolute unit of GA is given in picture 1.

4.3 Absolute measurements of GA at GP are conducted according to the technical description and manual for ballistic gravimeter for each model (type) of participant of the comparison.

4.4 Methods of absolute measurements of GA and main measuring instruments (hereinafter – MI), applied in absolute gravimeters by participants, are given in Table 2 and Table 3 for ballistic transportable gravimeter (hereinafter – GBT) and gravimeter IMGC-02 respectively.



Picture 1 – Scheme of the comparison of absolute gravimeters at the point:
1 – IMGC-02 (INRIM, Italy); 2 – GBT (NSC "IM", Ukraine); 3 – pillar

Table 2 – Method of the measurement of GA and main MI, applied by NSC "IM"

Name	Method/MI	Notes
Producer	NSC «IM»	
Assigned	NSC «IM»	
Model/ type of gravimeter	GBT	See chapter 6
Method of measurement	Ballistic	As a test body catapult is applied a symmetrical six-member link mechanism (pantograph)
Mean of measurement	Rise and fall	
Type of interferometer	Modified laser Michelson interferometer	With the help of interferometer method the distance covered by the test body during its free fall is measured by reconstructing the trajectory of the symmetrical path in vacuum chamber
Type of laser	*He-Ne* laser	Wavelength $\lambda \approx 633 \cdot 10^{-9}$ m
Type of atomic clock	Rb rubidium standard of frequency (time)	It is used as standard frequency reference (time)

Table 3 – Method of measurement of GA and main MI, applied by INRIM

Name	Method/MI	Notes
Producer	INRIM	
Assigned	INRIM	
Model / type of gravimeter	IMGC-02	See chapter 6
Method of measurement	Ballistic	Catapult made of iron spring system
Mean of measurement	Rise and fall	Rise and fall trajectory used to compute g (quasi-symmetrical)
Type of interferometer	Modified laser Mach - Zehnder interferometer	The distance covered by the test body in vacuum is measured via the interferometer
Type of laser	*He-Ne* laser primary reference with lock system to the Iodine peak (relative accuracy of 10^{-11})	Wavelength $\lambda \approx 633 \cdot 10^{-9}$ m
Type of atomic clock	Rb rubidium standard of frequency (time)	It is used as standard frequency reference (time)

5. Conditions of ambient environment during conducting comparisons

5.1 Conditions of ambient environment at INRiM.2 point, at which the measurements of absolute value of GA were conducted, are given in table 4.

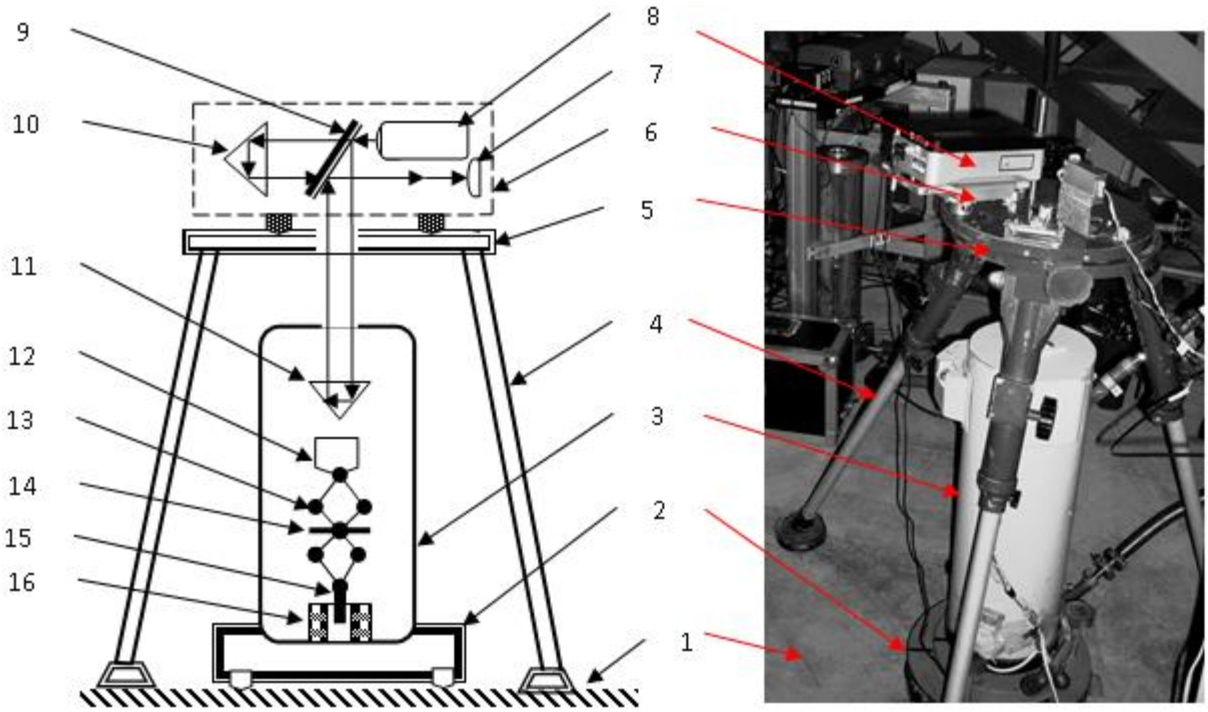
Table 4

Name of characteristic	Limit value
Temperature of ambient air	from 16 °C to 21 °C
Relative humidity of air	from 40 % to 50 %

6. Short description of standards

6.1 GBT absolute gravimeter

In a principle scheme in picture 1 (a, b) there is shown a symmetrical method of measurement of acceleration gravity g by absolute ballistic gravimeter of GBT type, which is also applied in primary standard of gravity acceleration unit DETU 02-02-14.



a) b)

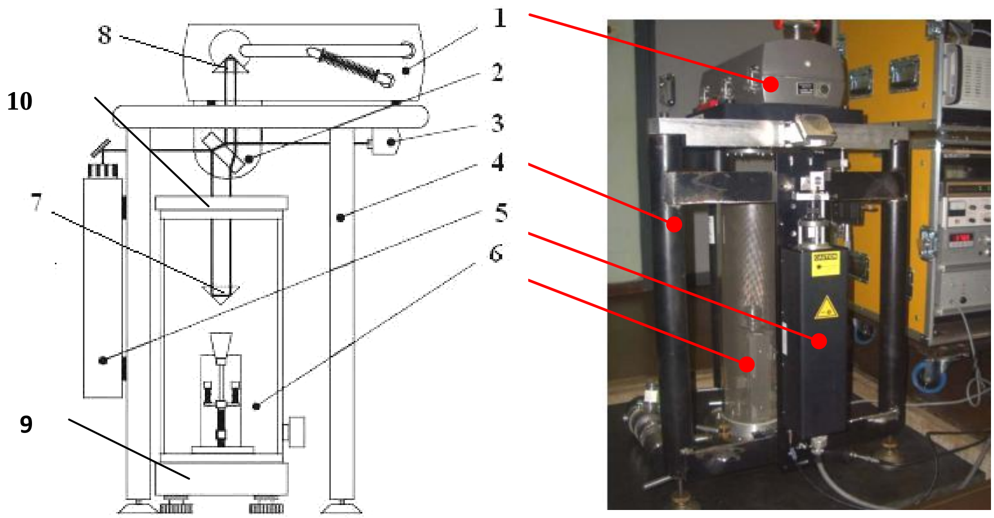
Picture 1 – Principle scheme (a) and photo (b) of absolute GBT gravimeter:
1 – pillar; 2 – technology support; 3 – dynamical block;
4 – tripod; 5 – platform; 6 – optical block; 7 – photo-detector;
8 – laser; 9 – dividing plate; 10 – referent body;
11 – test body; 12 – carriage; 13 – pusher;
14 – stationary axle; 15 – anchor; 16 – electromagnet

Specialty of symmetrical method of measurement g is such, that the start position in pusher test body (TB) with an optical reflector is located at the bottom, and laser interferometer (LI) is located on the top. Here (picture 1, a, b) in initial position TB 11 rests freely on the carriage 12 of a pusher 13 which is a symmetrical six-membered link mechanism (pantograph) with a fixed central axis 14 of the fixed conveying ball bearing on three guides. Anchor 15 of the electromagnet 16 also moves on ball bearings. The entire mechanism of the pusher is located in a vacuum chamber (residual gas pressure is about $1 \cdot 10^{-3}$ Torr) of dynamic block (DB) 3, which has a protective quartz window for interaction in flight with TB 11with the radiation of He-Ne laser 8 through the air gap. Laser 8 (wavelength $\lambda \approx 633$ nm, red radiation) is arranged in an optical block (BO) to align the screws 6 of Michelson interferometer, which is mounted on a special adjustable tripod 4 with the platform 5, and rests on a foundation 1. The interference rings which are formed as a result of the interference of two laser beams reflected from the moving corner reflector of TB 11 and a fixed reference corner reflector of test body 10 are counted by the photodetector 7. Dynamic block with pusher mechanism of TB is placed on the technology support 2, which is mounted on the fundament 1. As standard of time there is used Rb - rubidium standard of frequency (time) of the type SChV-74.

6.2 Absolute gravimeter IMGC-02

In absolute ballistic gravimeter IMGC-02 (development of INRIM, Italy), the gravity acceleration g is measured by tracking the rise and fall parts of the test body motion in vacuum. The TB it is thrown by a mechanical launching pad made of two iron springs. The distance between the TB and the reference mirror placed on the quasi-intertial system is measured using the interferometer. The time coordinate is then given by the sinusoidal fit to 700 groups of 1024 signal fringes (local fit method). The acquisition is sampled via the Rb clock. The time values are recorded and stored for the data post-processing. The space-time coordinates are then used to reconstruct the quasi-symmetrical trajectory which is fitted with a linear model to calculate the value of g at the best reference height.

Block diagram and photo of the absolute ballistic gravimeter IMGC-02 are shown in picture 2 (a, b).



a) б)

Picture 2 – Principle scheme (a) and photo (b) of absolute gravimeter IMGC-02: 1 – seismometer; 2 – interferometer; 3 – photo-detector; 4 – frame; 5 – laser; 6 – vacuum chamber; 7 – TB; 8 – referent body; 9 – basis; 10 – aluminum cover

The main parts of the IMG-02 device are modified Mach - Zehnder interferometer 2 and the long period (about 20 seconds) 1 seismometer, which supports the reference corner-cube reflector 8. The wavelength of He-Ne laser stabilized on iodine 5 is used as a reference length ($\lambda \approx 633$ nm, red radiation), and as the time reference Rb - rubidium frequency standard. Movable TB 7 in the vacuum chamber 6 (residual gas pressure is about $1 \cdot 10^{-5}$ Torr), the launch pad allows the drop. Interference fringes emerging from the interferometer 2, detected by the photo-detector 3. All measure parts of gravimeter are fixed in frame 4. The vacuum chamber 6 is made of a glass tube flange, the lower part of which is mounted on a base 9 made of stainless steel and stands on the foundation, while the upper part is sealed by aluminum pad 10. All joints are sealed with O-rings. Inside the glass tube is installed a Faraday cage (not shown in the diagram) to reduce electromagnetic parasitic effects.

7. Results of measurements

7.1 Results of measurements of absolute gravimeter GBT.

7.1.1 Results of measurements of gravity acceleration of GBT gravimeter are given in table 5.

7.1.2 Budget of uncertainty of the measurement of an absolute gravimeter GBT is given in table 6.

7.1.3 Budget of uncertainty of the measurement of an absolute gravimeter GBT, depending on point of INRiM.2, is presented in table 7.

7.2 The results of measurements of an absolute gravimeter IMGC-02.

7.2.1 Results of measurements of GA of an absolute gravimeter IMGC-02 are presented in table 8.

7.2.2 Budget of uncertainty of the measurement of an absolute gravimeter IMGC-02 is presented in table 9.

7.2.3 Budget of uncertainty of the measurement of an absolute gravimeter IMGC-02, depending on point of INRiM.2, are presented in table 10.

Table 5– Results of measurements of GA of an absolute gravimeter GBT

Date	Time UTC (from÷to)	Gravi meter	Operator /s	Site	#sets, #drops	g@ measure-ment height /μGal	Measure-ment height / cm	Standard uncertainty VGG/ μGal m^{-1}	Long-term reproducibi lity /μGal	Standard uncertainty /μGal
17-19/12/2015	16:30 – 10:20	GBT	Vinnich enko	INRiM.2	2/1500	980533569,6	71,8	-	-	10,4
The results given at height 48,3 cm										
17-19/12/2015	16:30 – 10:20	GBT	Vinnich enko	INRiM.2	2/1500	980533642,1	48,3	10	-	10,7

Table 6 – Budget of uncertainty of the measurement of an absolute gravimeter GBT

Influence parameters	Unit	Type A	Type B	Type of distribution	Equivalent variance	Sensitivity coefficients	Contribution to the variance	Equivalent standard uncertainty
Laser frequency	MHz		2,3	Gaussian	5,6	2,1E-8	2,4E-15	4,9E-8
Clock frequency	Hz		1,0E-4	Gaussian	1,0E-8	3,9E-6	1,5E-19	3,9E-10
Verticality	rad		4,8E-5	rectangular	7,7E-10	1,36E-4	1,41E-17	3,8E-9
Corner cube rotation	$rad \cdot s^{-1}$		±1,0E-2	rectangular	3,3E-5	5,8E-7	1,1E-17	3,3E-9
Residual gas pressure	Torr		1,0E-3	rectangular	3,3E-7	2,1E-6	1,4E-18	1,2E-9
Reference height	m		5,0E-4	rectangular	8,3E-8	3,0E-6	7,5E-19	8,7E-10
Finite value of speed of light effect			negligible					
Non-uniform magnetic field effect			negligible					
Temperature gradient effect			negligible					
Effect for electrostatic			negligible					
Air gap modulation effect			negligible					
			Sum of variances				2,43·10E-15	$m^2 \cdot s^{-4}$
			Combined standard uncertainty, *u*				4,93·10E-8	$m \cdot s^{-2}$
			Coverage factor, *k*				2,0	
			Expanded uncertainty (corrections applied), $U = ku$				9,86E-8	$m \cdot s^{-2}$
			Relative expanded uncertainty, $U_{rel} = U/g$				1,00E-8	

Table 7 – Budget of uncertainty of the measurement of an absolute gravimeter GBT, depending on point of INRiM.2

Influence parameters, x_i	Unit	Type A	Type B	Correction	Type of distribution	Equivalent variance	Sensitivity coefficients	Contribution to the variance	Equivalent standard uncertainty
Instrument uncertainty	$m\cdot s^{-2}$		4,93E-8				1,0E+00	2,43E-15	4,93E-8
Coriolis effect	$m\cdot s^{-2}$		2,7E-08		rectangular	2,4E-16	1,0E+00	2,4E-16	1,6E-08
Barometric pressure correction	$m\cdot s^{-2}$		1,0E-08	3,8E-08	rectangular	3,3E-17	1,0E+00	3,3E-17	5,8E-09
Tide correction	$m\cdot s^{-2}$	3,0E-09		2,1E-08		9,0E-18	1,0E+00	9,0E-18	3,0E-09
Ocean loading correction	$m\cdot s^{-2}$	2,0E-09				4,0E-18	1,0E+00	4,0E-18	2,0E-09
Polar motion correction	$m\cdot s^{-3}$			0,0E+00					
Seismic influence at 3000 throws	$m\cdot s^{-2}$	5,5E-8			Gaussian	3,0E-15	1,0E+00	$3\cdot 10^{-15}$	5,5E-8
Autoseismic effect	$m\cdot s^{-2}$		1,0E-7		arcsine	5,0E-15	1,0E+00	$5\cdot 10^{-15}$	7,1E-8
				Corr. 5,9E-08 $m\cdot s^{-2}$		Variance		1,07E-14	$m^2\cdot s^{-4}$
				Combined standard uncertainty, u				1,04E-7	$m\cdot s^{-2}$
				Coverage factor, k				2,0	
				Expanded uncertainty, $U = ku$				2,08E-7	$m\cdot s^{-2}$
				Relative expanded uncertainty, $U_{rel} = U/g$				2,12E-8	

Table 8– Results of measurements of GA of an absolute gravimeter IMGC-02

The g-values should be corrected for all known geophysical effects (tides, polar motion, atmospheric pressure, etc.) as well as for all instrumental effects (self-attraction, diffraction effects, etc.)

Date	Time UTC (from÷to)	Gravimeter	Operator/s	Site	#sets, #drops	g@ measure-ment height /µGal	Measure-ment height / cm	VGG / µGal m^{-1}	Long-term reproducibility /µGal	Standard uncertainty /µGal	Degrees of freedom
18-20/01/2016	16:30 – 10:20	IMGC-02	Germak, Origlia, Biolcati	INRiM.2	2, 1900	980533663,6	48,3	unknown	-	4,6	38

Table 9 – Budget of uncertainty of the measurement of an absolute gravimeter IMGC-02

Influence parameters, x_i	**Value**	**Unit**	**u_i or a_i**	**Type A, s_i**	**Type B, a_i**	Correction Δg	**Type of distribution**	**Equivalent variance**	**Sensitivity coefficients**	**Contribution to the variance**	**d.o.f.**	**Equivalent standard uncertainty**	$u_i^4(y)/\nu_i$
Drag effect			negligible										
Outgassing effect			negligible										
Non-uniform magnetic field effect			negligible										
Temperature gradient effect		$m \cdot s^{-2}$	±1.5E-09		1,5E-09		U	1,1E-18	1,0E+00	1,1E-18	10	1,1E-09	1,3E-37
Effect for Electrostatic			negligible										
Self-attraction correction	7,0E-09	$m \cdot s^{-2}$	±1.0E-09	1,0E-09		7,0E-09		1,0E-18	1,0E+00	1,0E-18	30	1,0E-09	3,3E-38
Laser beam verticality correction	6,6E-09	$m \cdot s^{-2}$	±2.1E-09		2,1E-09	6,6E-09	rect.	1,5E-18	1,0E+00	1,5E-18	15	1,2E-09	1,5E-37
Air gap modulation effect			negligible										
Laser effect		$m \cdot s^{-2}$	1,0E-09	1,0E-09				1,0E-18	1,0E+00	1,0E-18	30	1,0E-09	3,3E-38
Index of refraction effect			negligible										
Beam divergence correction	5,20E-08	$m \cdot s^{-2}$	5,2E-09	5,2E-09		5,20E-08		2,7E-17	1,0E+00	2,7E-17	10	5,2E-09	7,3E-35
Beam share effect	unknown		unknown										
Clock effect		$m \cdot s^{-2}$	6,0E-09	6,0E-09			rect.	3,6E-17	1,0E+00	3,6E-17	30	6,0E-09	4,3E-35
Finges timing effect			negligible										
Finite value of speed of light effect			negligible										
Retroreflector balancing	0,0E+00	m	±1.0E-04		1,0E-04		rect.	3,3E-09	6,3E-04	1,3E-15	15	3,6E-08	1,1E-31
Radiation Pressure effect			negligible										
Reference height	5,0E-01	m	±5.0E-04		5,0E-04		rect.	8,3E-08	3,0E-06	7,5E-19	30	8,7E-10	1,9E-38
					Corr.	**6,56E-08**	**$m \cdot s^{-2}$**	**Variance**		**1,4E-15**	**$m^2 \cdot s^{-4}$**		
					Combined standard uncertainty, u					**3,7E-08**	**$m \cdot s^{-2}$**		
					Degrees of freedom, ν_{eff} (Welch-Satterthwaite formula)					**17**			
					Confidence level, p					**95%**			
					Coverage factor, k (calculated with t-Student)					**2,12**			
					Expanded uncertainty, $U = ku$					**7,8E-08**	**$m \cdot s^{-2}$**		
					Relative expanded uncertainty, $U_{rel} = U/g$					**8,0E-09**			

Table 10 – Budget of uncertainty of the measurement of an absolute gravimeter IMGC-02, depending on point of INRiM.2

Influence parameters, x_i	**Value**	**Unit**	**u_i or a_i**	**Type A, s_i**	**Type B, a_i**	Corr. Δg	**Type of distribution**	**Equivalent variance**	**Sensitivity coefficients**	**Contribution to the variance**	**d.o.f.**	**Equivalent standard uncert.**	**$u_i^4(y)/\nu_i$**
Instrument uncertainty		$m\cdot s^{-2}$	3,7E-08	3,7E-08				1,4E-15	1,0E+00	1,4E-15	17	3,7E-08	1,1E-31
Coriolis effect		$m\cdot s^{-2}$	2,7E-08		2,7E-08		rectangular	2,4E-16	1,0E+00	2,4E-16	10	1,6E-08	5,9E-33
Floor recoil effect			negligible										
Barometric pressure correction	3,8E-08	$m\cdot s^{-2}$	1,0E-08		1,0E-08	3,8E-08	rectangular	3,3E-17	1,0E+00	3,3E-17	15	5,8E-09	7,4E-35
Tide correction	2,1E-08	$m\cdot s^{-2}$	3,0E-09	3,0E-09		2,1E-08		9,0E-18	1,0E+00	9,0E-18	15	3,0E-09	5,4E-36
Ocean loading correction		$m\cdot s^{-2}$	2,0E-09	2,0E-09				4,0E-18	1,0E+00	4,0E-18	15	2,0E-09	1,1E-36
Polar motion correction	0,0E+00	$m\cdot s^{-3}$	negligible			0,0E+00							
Standard deviation of the mean value		$m\cdot s^{-2}$	2,2E-08	2,2E-08				4,8E-16	1,0E+00	4,8E-16	946	2,2E-08	2,5E-34
					Corr.	**5,9E-08**	**$m\cdot s^{-2}$**	**Variance**		**2,1E-15**	**$m^2\cdot s^{-4}$**		
					Combined standard uncertainty, *u*					**4,6E-08**	**$m\cdot s^{-2}$**		
					Degrees of freedom, ν_{eff} (Welch-Satterthwaite formula)					**39**			
					Confidence level, *p*					**95%**			
					Coverage factor, *k* (calculated with t-Student)					**2,02**			
					Expanded uncertainty, *U = ku*					**9,4E-08**	**$m\cdot s^{-2}$**		
					Relative expanded uncertainty, $U_{rel} = U/g$					**9,6E-09**			

8 Evaluation of equivalence of national

Degree of equivalence d_{12} for the both standards of NMI of comparison parts is calculated according to the formula:

$$d_{12} = x_1 - x_2, \tag{1}$$

with the appropriate uncertainty

$$u^2(d_{12}) = u^2(x_1) + u^2(x_2) - 2\,\mathrm{cov}(x_1, x_2), \tag{2}$$

where x_1 – the result of measurement of NSC "IM";

x_2 – the result of measurement of INRIM;

$u(x_1)$ – summary standard uncertainty of the GBT measurement;

$u(x_2)$ – summary standard uncertainty of the measurement IMGC-02;

$u(d_{12})$ – standard uncertainty of equivalence degree;

$\mathrm{cov}(x_1, x_2)$ – covariation of the results of measurements, which have been got by NSC "IM" and INRIM accordingly.

In case of absence the borrowing the size unit by participants $\mathrm{cov}(x_1, x_2) = 0$. In this case, the equivalence degree is calculated according to the formula, at coverage factor k = 2:

$$|x_1 - x_2| \le 2 \cdot \sqrt{u_1^2(x_1) + u_2^2(x_2)}, \tag{3}$$

standards are equivalent, if the condition is followed

$$|d_{12}| \le 2 \cdot u(d_{12}), \tag{4}$$

or

$$|d_{12}| \le U(d_{12}). \tag{5}$$

The results of review of equivalence degree for standards during the measurements of gravity acceleration are given in table 11

Table 11

	Abbreviation of laboratory	
	NSC «IM»	INRIM
The result of measurements of laboratory g, 10^{-8} m·s^{-2}	980533642,1	980533663,6
Summary standard uncertainty, applied by laboratory u_j, 10^{-8} m·s^{-2}	10,7	4,6
Difference between the measured valued d_{ij}, 10^{-8} m·s^{-2}	21,5	
Standard uncertainty of equivalence degree $u(d_{ij})$, 10^{-8} m·s^{-2}	11,6	
Expanded uncertainty of equivalence degree $U(d_{ij})$, 10^{-8} m·s^{-2}	23,2	

9. Conclusions

9.1 Agreement between the two participants is sufficient.

9.2 The results of conducted comparisons of the unit of gravity acceleration of NSC "IM" and INRIM can be recognized as positive.

10. Acknowledgement

We express our gratitude for organizing and carrying out comparisons of the two absolute gravitymeters GBT (Kharkov, Ukraine) and IMGC-02 (Turin, Italy):

NSC "IM"(Kharkov, Ukraine): Kupko V., Omelchenko A., Korotkyi Y.

INRIM (Turin, Italy): Biolcati E, Origlia C.

11. References

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