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THE BALLISTIC ABSOLUTE GRAVIMETER ZZG2

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Abstract – The construction and measurement method of transportable absolute Earth's gravity meter having the relative accuracy of the order of 10^{-9} is given. The instrument is composed of few separate units. The construction of mechanical and optical units is described in brief only. The construction of electronic units, an measurement method used in the instrument, and original algorithm developed by Z. Zabek and T. Knap to obtain the result of absolute value of local earth gravity acceleration with top actually achievable accuracy are described more in detail.

Keywords: Absolute measurements of local Earth gravity, laser interferometry, time intervals measurements.

1. DESCRIPTION OF THE INSTRUMENT

1.1. General description

The task of the instrument there is to measure absolute local acceleration of gravity force „*g*" with an accuracy of the order 10^{-9} by observing the trajectory of test mass thrown vertically in free space. Symmetrical rise-and-fall method is used. The first model of the instrument, named ZZG, was put in work in 1993. This paper presents its version improved in the years 2000 and 2001, named ZZG2. The instrument is the lightest among other (few) constructions existing in the world. Its total weight including supplementary devices does not exceed 120 kg, and it is transportable by personal car. The instrument is composed of few separate units. General look of the basic parts is indicated on Fig. 1. Optical bench can be arranged as the table. A catapult placed in the bottom of the vacuum chamber (internal pressure 0.01 Pa) throws up vertically, using rubber cord, a corner cube reflector R_1. Another corner cube reflector R_2 is suspended on a long-period (20 s) compensation device (seismoscope), partially absorbing effects of microseismic movements of the Earth's surface. A laser, cube reflectors R_1 and R_2, semi-transparent mirror and photo-detector (photodiode) furnish an interferometer of the Michelson type measuring the height of the trajectory of the moving reflector R_1. Intensified pulses coming from the photodiode and corresponding to the distances of $\lambda/2$ of the laser wave-length are sent to the notebook-computer equipped with an specialised card developed by us. Forming the fringe pulses from the photodiode and time-pulses from the frequency standard, counting fringe pulses and time pulses, detecting coincidence moments of both fringe and time pulses, registering about 300 points of 20 cm long trajectory at its both sides about the apex, and sending the data of height and time to the computer for processing, are the functions of the card. Other separate units composing the instrument are: catapult controller, two vacuum pumps connected in cascade, internal pressure in vacuum chamber meter, rubidium and quartz frequency standards, multi-frequency multiplier, and two oscilloscopes. The accuracies and stabilities of laser and electrical clock frequencies (5, 10, 25, 50 or 100 MHz) are of the order of 10^{-10} or better.

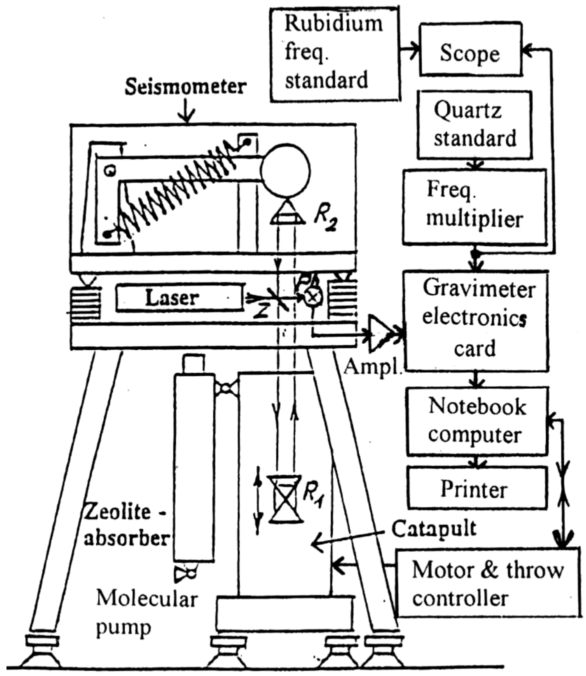

Fig. 1. General construction of ballistic gravimeter.
Z- semi-transparent mirror, Ph- photodiode.

Other method of determining the time positions of registered points on trajectory was included into the instrument also. Instead of observing the coincidence moments of time mentioned above, the time positions of zero-crossings of interference fringes are determined by counting the 10 nsec long periods of multiplied to 100 MHz standard frequency, and interpolating between two following 10 ns time marks using differential delay lines method [1]. Two delay lines of somewhat different delay of a delay unit are built as the single chain of 64 binary flip-flops inside the single programmable integrated VLSI circuit. Digitisation error of this time measurement method equals about 0.23 nsec. This interpolator was developed and built by Prof. Jozef Kalisz and his team at Warsaw Military University of Technology.

At the observatory Jozefoslaw, where the level of micro-seisms is not very small, standard deviation for gravity acceleration *g,* when using method as above, and when using coincidence method of 4 nsec long pulses and 50 MHz or 25 MHz clocks are similar. We had not the possibility to compare the methods in low microseisms environment.

An important part of the ballistic gravimeter is the test-mass. The ZZG2 instrument is equipped with a movable corner cube reflector R_1 reflecting the light beam from three external mutually perpendicular glass surfaces coated with aluminium. The reflector is formed by three glass prisms joined together by their optical contact (without glue). Such a binding ensures high stability of the light beam reflection angle. The casing of the prism is made of titanium. The optical centre of the reflector coincides with its mass centre with an accuracy of ±0.01 mm. The total weight of the device is 80 grams.

1.2. Disturbances from the laser light

Possessed by us iodine-cell-stabilised laser AXIS/BIPM IGL1 gives the light power approx. 50 µW only, and too frequently looses the stabilisation to be used directly for observations, especially at remote observatories. It is the reason we use this one as stationary standard to calibrate before and after the measurement more powerful (200 µW) two-mode Hewlett-Packard model 5518A laser used by us in normal measurements. This power is sufficient to allow the use of ordinary fast photodiode (not avalanche one), as the photodetector. The elimination of unwanted one mode was necessary to avoid the differential signal of 2.5 MHz between the modes. Our useful interference signal is of the value 600 mV pp. Its frequency reaches 7 MHz at the beginning and end of the used part of the trajectory, and its maximum period is about 2.4 ms in the apex. Full suppression of this 2.5 MHz false signal appeared to be impossible. Minimum obtainable unwanted 2.5 MHz signal from the second mode is 25 mV. Besides, the laser light includes other unwanted modulation components of approx. 40-70 KHz and 400 KHz, of the value 15 mV pp. Another unwanted component of the signal there is the amplifier noise of 7 mV pp. All that forced us to use the comparator for fringe signal squaring equipped with hysteresis in the output-input characteristics of the value of 70 mV, to be able to measure. Useful signal of the 600 mV pp value gives sufficient signal to noise relation.

2. SOME DETAILS OF ELECTRONICS OF THE APPARATUS

2.1. Time modulation in frequency multipliers

The method is based on observations of the time-height trajectory. Standard frequency 5 MHz from separate rubidium frequency source used here to build the time graduation, is multiplied to 10, 25, 50 or 100 Mhz in the multipliers using phase locked PLL loop method, or using harmonics generation and filtration method. The first are small in hardware volume, but suffer on time instability, usually up to 2 ns pp, due to effect of the phase modulation of the wave after multiplication by the 200 ns period of the input wave. These are used in transportable version of the instrument. The second are much bigger in volume, but give much better accuracy of time scale generated, having the time modulation mentioned usually up to 0.15 ns pp only. Those are used in stationary version of the instrument.

2.2. Other remarks

The wave of the multiplied frequency is sent to the specialised computer card implementing the measurement method. Its frequency, besides of building the time scale, is reduced here to obtain settable by computer value of the time distance between registered points of the trajectory. Usually used in the normal measurements is the period of 1.6 ms length. This is approximately the length of the time interval between subsequent measurement points. After crossing the moment of time N*1.6 ms (N is an integer) from the beginning of throw, an electronic circuit is enabled to look for the nearest time moment of the time coincidence between two pulses: the first one – whose origin is the time scale, and the second one – whose origin are zero-crossings at the falling edges of the fringe signal from the photodiode. The widths of these pulses equal 4 ns. At the time moment of such coincidence, the measurement point is positioned, at which the values of time dates T, height values H, and eventually the values of an amplified voltage from the piezoceramic sensor of an acceleration of the microseisms are registered. See Fig. 2.

Instead of using the coincidences, the time positions of fringe zero-crossings can be measured using interpolation method described in previous paragraph.

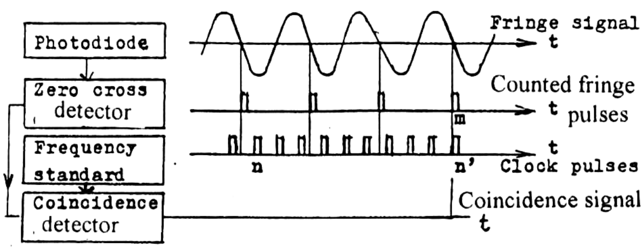

Fig.2. Time registration

3. CALCULATIONS

Co-ordinates of the ballistic trajectory observed are adjusted for both sides about the apex using the formula below [2].

$$h = h_s - \frac{1}{2} g_s (t - t_s)^2 + k(t - t_s)^3 - \frac{\gamma g}{24} (t - t_s)^4 \quad [1]$$

The unknowns g_s, h_s and t_s are referred to the apex point of the adjusted trajectory. Unknown k is an air drag parameter valid for the air drag proportionality to the reflector velocity. The last term of the formula regards an effect of the vertical gradient γ of gravity on ballistic curve. For each throw tidal correction is calculated according to the formulae of Cartwright-Tayler-Edden [3]. The observations are repeated automatically every 20 seconds. One measurement result is composed from 2000 to 4000 individual results averaged, dependent on local micro-seismic movements level of the Earth surface.

4. SOME MEASUREMENT ERRORS

4.1. General remarks

We estimate the accuracy of our instrument on 5 μGal. At the observatories, where the microseisms level is very small, as Pecny in Czech Republic, or Modra and Ganovce in Slovakia, standard deviation of the main values calculated for 3-and-1/2 hours measurement sessions containing 630 measurements each, was equal from 0.3 to 0.6 μGal, depending on the site and date of the measurements.

Main sources of errors are described by previous authors. Their results are indicated here, with references, in Table 1. This table was included to [6], materials obtained by prof. Stefan Hahn of our University from AXIS Instruments Company, Boulder, USA, for commercial purposes, together with the data of FG5 gravimeter, in 1992.

Below we give some details of another than in Table 1 errors observed by us, mainly connected with electronics, and partially with optics.

4.2. Random error from microseisms

The biggest source of random errors are microseisms – small movements of the earth surface of natural or technical origin, this last e. g. from road and railway traffic, machines, and others. In spite of some isolation means, they induce the unwanted movements of reference prism, and the occurrence of signals that displace the time points from right positions. The frequencies band of these signals is 0 to 6 Hz for natural and 0 to 25 Hz for technical origin. These signals, together with other disturbances and noise, actuate, that two trajectories adjusted using least squares method separately for the rise and fall of the test mass, as a rule do not come together to the same point in the apex. Besides, some loss of the information about height occurs, that only integer values of wave half-lengths are counted. Original method developed by Z. Zabek and T. Knap allows partially to solve this problem and to increase the accuracy of results.

The influence of microseisms, as well as other uncorrelated signals, is diminished by averaging sufficiently big number of results of measurements, minimum 2000. We have also plans to register the signals of microseisms acceleration, detected by piezoceramic sensor, and after the double integration in computer to obtain from its the corrections for height before adjusting the trajectories. We developed the hardware to implement this target.

4.3. Errors from coincidence or interpolation

Using the coincidence method, there is no digitisation error. But the error from the finite width of the coinciding pulses exists. These errors are connected with the dependence of time step of the coincidence signal on its position with reference to the apex. They are of the character

Table 1. Error budgets compared

	Uncertainty (μGal)				
Instrument/Researcher	Zumberge (1)	Faller (2)	Marson (3)	Niebauer (4)	AXIS FG5 (5)
Year	1981	1981, 1985	1985	1987	1992
Error Source					
Differential pressure	1.0	2.0	2.0	1.0	0.3
Differential temperature	1.0	1.0	1.0	1.0	0.3
Magnetic field gradients	0.5	0.5	0.5	0.5	0.3
Electrostatics	1.1	0.5	0.5	1.0	0.3
Attraction of apparatus	0.5	0.5	0.5	0.5	0.1
Verticality	0.8	1.0	1.0	0.5	0.1
Air gap	No data	1.0	0.0	0.7	0.2
Laser wavelength	1.0	1.0	1.0	1.0	0.3
Rotation of corner cube	1.0	0.5	1.0	1.0	0.3
Translation (Coriolis)	1.0	No data	No data	1.0	0.3
Floor recoil and tilt	1.0	1.5	1.5	0.5	0.2
Electronic phase shift	1.0	1.5	0.0	0.6	(6) 0.6
Frequency standard	0.5	No data	No data	0.5	0.1
Glass wedges	2.8	No data	No data	1.0	0.1
Uncorrelated error	4.2	3.7	3.3	3.0	1.1

References and Notes

(1) M.A. Zumberge: Ph.D. Thesis, University of Colorado (1981)
(2) J.E. Faller, I. Marson: Metrologia **25**, 49-55 (1988)
(3) J.E. Faller, I. Marson: Metrologia **25**, 49-55 (1988)
(4) T.M. Niebauer: Ph.D. Thesis, University of Colorado (1987)
(5) Preliminary estimates from AXIS Instruments FG5 Absolute Gravimeter
(6) This error is reduced to zero (0.0) in the throw mode, however instrument set-up and operation must be carefully monitored to achieve the necessary rotation and translation specifications. Using a value of 0.0 μGal for the phase shift reduces the uncorrelated error from 1.1 μGal to 0.9 μGal.

of the small systematic errors when away from the apex, positive before and negative after the apex, and larger random errors in the vicinity of the apex. For our case of the time length of the coinciding pulses of 4 ns these errors are about 1 ns in time. In interpolation method, standard deviation is about 0.2 ns, but integral time error up to 0.4 ns.

4.4. Parasitical synchronisation error

In both methods there exists the error from the partial synchronisation due to unavoidable penetration of the signals from H to T channel and reverse. The points of coincidence or of time measurements are slightly displaced from their right positions. There is the necessity of proper separation of the channels in space on the card to diminish the effect.

4.5. Error from non-zero level crossing by fringes on Fig.2

Important source of systematic errors dependent on time after the beginning of the throw is the difference between mean level of the output signal of photodiode amplifier, and the threshold point of the comparator forming rectangular signal from the interference fringes. Each residual curve is random in shape, mainly due to microseisms, but after averaging of big number of such residuals vs time curves, one obtains the systematic component of the residuals curve. Such curve of averaged residuals of height e. g. increases smoothly when arriving to the apex, very near to the apex reaches, say, positive maximum, in the apex rapidly changes its polarisation to negative, next, very nearly reaches negative maximum, then smoothly goes to the small negative value. The order of positive and negative values can be reversed when changing the sign of the voltage difference mentioned, or changing the slope of the fringe edge which creates the signal for counting – rising or falling. The residuals curve for each individual drop, together with averaged one for the series of drops or all measurements done before, is indicated on the notebook computer screen together with many informations about throw parameters and partial results of processing the data. These residuals are normally of the order of +/- 1 % to 5 % of half-wave-length. The curves are fairly symmetric in time and anti-symmetric in value about the apex, and their influence on g error is moderate only.

On these averaged residuals curves, floor recoil signals are visible also, in the form of 60 – 80 Hz resonance frequency of measurement pillars.

Identical in shape averaged residuals curves vs time occur from some optics adjustments, when at other adjustments do not occur. The origin is unknown for us. We have some suppositions only.

5. TEST COMPARISONS

The ZZG instrument participated in International Comparison of Absolute Gravimeters ’97 Campaign ICAG’97 in Paris in the autumn of 1997 year. Results of this campaign [5] indicate the difference between ZZG results and averaged results of all compared instruments (15 exemplars of 6 different constructions) about 5 μGal (1 Gal = 1 cm/s^2). These results are given in Table 2. The ZZG instrument is somewhat poorer in accuracy than the best ones, but is not the last. But is 3 – 5 times cheaper, 3 times lighter, much easier transportable and easier in assembly for work than commercially produced FG5 model. Commercial FG5, as is relevant when comparing Table 1 and [6] with Table 2 results, are somewhat poorer than the prototype one.

Table 2. Results from the International Comparison of Absolute Gravimeters ICAG'97

All participating instruments	A->A	A2->A	A3->A	Mean	u	d
JILAG-2	709.5	709.2	707.3	708.7	1.2	0.9
JILAG-3	713.6	712.8		713.2	0.6	5.4
JILAG-5	710.1	710.6	704.1	708.3	3.6	0.5
JILAG-6	700.6	704.5		702.6	2.8	- 5.2
FG5/101	705.1			705.1	2.4	- 2.7
FG5/103	704.7	706.1	708.7	706.5	2.1	- 1.3
FG5/105	705.0	705.4		705.2	0.3	- 2.6
FG5/107	713.3	710.1	707.3	710.2	3.0	2.5
FG5/108	707.2	704.7	706.2	706.0	1.3	- 1.8
FG5/202	710.6	709.3		709.9	0.9	2.2
FG5/206	702.9	702.5		702.7	0.3	- 5.1
Gable	714.4		707.6	711.0	4.8	3.2
IMGC		717.5		717.5	2.4	9.7
NIMA2		704.8	710.4	707.6	3.9	- 0.2
ZZG		697.5	707.0	702.3	6.7	- 5.5
Mean	708.1	707.3	707.3	707.8	2.4	
Sigma				4.2		

Table 3. Results of the test measurements performed by absolute gravimeter ZZG at the station Pecny, Czech Republic

Data	Instrument Author	g [μGal]
92.02.11	JILAG-6 D. Ruess	980 933 264.2
93.09.12	FG5 No 107 J.Friederich	980 933 269.8
95.04.21	FG5 No 101 R.Falk	980 933 270.3
95.09.26	ZZG Z. Ząbek	980 933 261.9
96.10.03	ZZG Z. Ząbek	980 933 254.5
97.10.14	ZZG Z. Ząbek	980 933 270.3
98.10.22	ZZG Z. Ząbek	980 933 268.4
98.12.01	JILAG-5 J. Mäkinen	980 933 268.0
2001.08.31	ZZG 2 Z. Ząbek	980 933 274.3

Besides, within 1995-2001 period, five measurements using ZZG and ZZG2 gravimeters on Pecny Geodetic Observatory in Czech Republic were done. At this observatory, four absolute gravity measurements by other scientists using their own high quality modern instruments were done. The comparisons of these results between itself and with the results from ZZG and ZZG2 instruments indicate differences of the order of few μGal. See Table 3. Also similar comparisons done at Modra and Ganovce indicate very small differences.

6. MEASUREMENTS

Many observations using ZZG and ZZG2 instruments in the period 1993-2001 in Central Europe, including long campaigns, were done. There are the measurements in Poland, Czech Republic, Slovakia and Germany. The results are published at geodetic and geophysical scientific conferences. In Poland, an unknown up to this time geophysical effect was discovered [4]. At the observatories, where the level of micro-seisms is very small, such as Pecny in Czech Republic, or Modra and Ganovce in Slovakia, standard deviations of *g* results were below 1 μGal.

7. CATAPULT

The instruments JILAG [7] and FG5 [6] mentioned in Tables 1 and 2 use dropping (letting to fall) of the test mass, and not throwing it up. Probably, FG5 uses the algorithm given in [8]. Maybe, this algorithm when used for rise-and-fall method will not give convergence of result in processing. The "let fall" method urges high vacuum in the test-mass chamber – of the order of 10^{-6} Pa. On the contrary, when using the rise-and-fall method, pressure of 0.1 Pa is enough. We use 0.01 Pa value. But in our method to construct good catapult is very difficult task. First (in our knowledge) such construction was published in [9]. The construction we are using, given on Fig 3, was developed by Z. Zabek in 1992. That construction was continually improved in the period 1992-2001 to obtain its contemporary maturity.

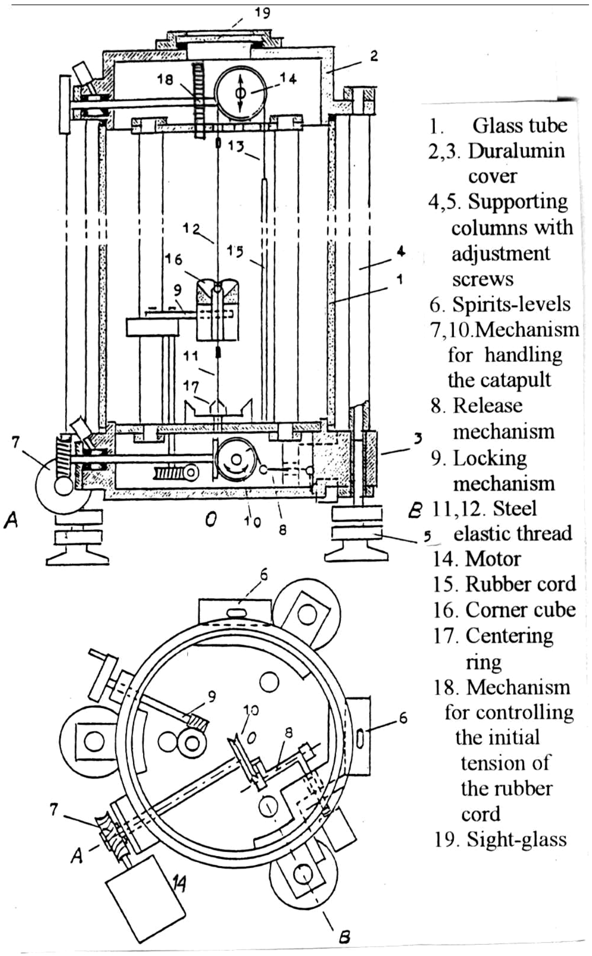

Fig. 3. Vacuum chamber and catapult construction

8. CONCLUSIONS

Relatively cheap, light and easily transportable absolute Earth gravity meter was developed, similar in accuracy than the best ones. That was possible due to very good catapult and test-mass prism construction, good original algorithm of signal processing, good quality of associated electronics developed, and good computer software. Instrument quality is confirmed by good results in measurements campaigns in the last 10 years.

Besides, some not described up to this time measurements errors, mainly from electronics, are found and explained.

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