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A TRANSPORTABLE ABSOLUTE GRAVITY METER ADOPTING THE SYMMETRIC RISE AND FALLING METHOD

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Abstract: The Gravimetry Group of the Institute of Metrology "G. Colonnetti" (IMGC-CNR), nowadays National Institute of Research in Metrology (INRIM), developed a new version of a transportable absolute gravimeter, the IMGC-02. The instrument presents several improvements mainly concerning the transportability, the measurement automation and the user-interface programs.
According to the ISO-GUM (Guide to the Expression of Uncertainty in Measurements), an extensive analysis concerning the contributors to the uncertainty budget has been conducted. At present the instrumental expanded uncertainty (p = 95 %) is believed to be about 8 parts in 10^9 of the surface gravity value. The detailed description of the IMGC-02 apparatus and an outline of its metrological characterization is the subject of this paper.

Keywords: absolute gravimeter, absolute gravimetry, uncertainty budget.

1. INTRODUCTION

The best accuracy achievable nowadays in measuring the acceleration due to gravity g is believed to be some microgal ($1\ \mu\text{Gal} = 1 \times 10^{-8}\ \text{m}\cdot\text{s}^{-2}$) and concerns instruments which adopt the so called ballistic method. The local g value is extracted from the trajectory of a free-falling test-mass by fitting a suitable motion model to the time-space data. High accuracy can be reached only if the test-mass flight is tracked by optical interferometric methods.

The IMGC-02 is one of very few working instruments which adopt the *symmetric rise and falling method* [1], where both the rise and falling trajectory is used to fit the motion model. Majority of other gravimeters adopt the *simple free falling method*, where only the falling trajectory is used [2]. The IMGC-02 was the only *rise and falling* system at the last 7th Comparison of Absolute Gravimeters ICAG05, held in Sèvres (September, 2005).

This paper describes the apparatus and presents the list of the influence factors which perturb the measurement by stressing the prevailing ones.

The apparatus can be divided into a mechanical and optical part and into an electronic part and software, fig. 1. The first one is separated into the launch, optical and quasi-inertial systems whereas the second one is separated into the personal computer, power supplies, acquisition and control units.

2. MECHANICAL AND OPTICAL PART

The energy which is necessary to throw up the test-mass is provided by pre-loaded springs and the trajectory is tracked by an optical interferometer.

There is no mechanical connection between the launch system and the optical system (except the common floor), so vibrations produced by the launch do not directly accelerate the interferometer.

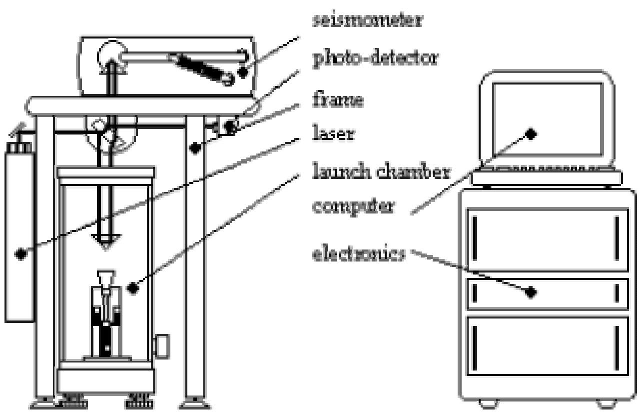

Fig. 1. Simplified scheme of the IMGC-02 absolute gravimeter

2.1. Launch system

The launch system is composed of the vacuum chamber, the pumps, the test-mass and the launching pad. The base of the vacuum chamber, made of stainless steel, is supported by three legs with levelling screws which, together with two spirit-levels, allow the vertical alignment. The main part of the vacuum chamber is a flanged glass pipe; the bottom part is fitted to the base whereas the upper part is sealed with an aluminium cover. A glass window is positioned at the centre of this cover and allows the laser beam to reach the test-mass. Connections are sealed by O-rings. Inside the glass pipe a Faraday cage shields the test-mass from electrostatic charges. The glass pipe can be easily removed, allowing full access to the test-mass and launching pad.

The base of the chamber has two arm pipes. The first one is connected to a low noise turbo pump, the second one to an ionization vacuum gauge. There is also a special vacuum connector for a wiring cable.

The coarse evacuation is carried out by a rotary pump. A long vacuum tube (≅ 5 m), connecting the pumps, smoothes the mechanical vibrations coming from the rotary pump. Such a tube make unnecessary to interrupt the evacuation during the measurement. A pressure of 1×10^{-3} Pa is reached after about 5 hours, starting from the vacuum level reached by the sealed chamber after two days from the last evacuation.

The test-mass is composed of a retroreflector (corner cube) and a mounting support (frame), fig.2. The retroreflector is a cubic corner prism which has the property that an incident ray is reflected parallel to itself independently from the angular orientation [3]. In fact for the interferometer the corner prism realizes a point in space. In case of an ideal shape, defining *n* as the refraction index of the material constituting the corner, *d* its longitudinal dimension, such a point, called optical centre, is positioned on the longitudinal axis, at a distance equal to *d/n* from the reflecting surface. Unfortunately the corner's centre of mass is far form its optical centre. The corner retroreflector is therefore fitted to a mounting support, made in aluminium, in such a way that the resulting centre of mass coincides with the optical centre. In this way any rotation of the test-mass around its centre of mass affects neither the interferometric alignment nor the measured *g* value.

The launching pad is tight fit to the base of the vacuum chamber. It supports, throws up and gently catches the test-mass at the end of its trajectory. The test-mass rests in a catcher which is fixed to a moveable carriage supported by two springs. The contact between test-mass and pad is realized with three bosses of 1 mm high on the upper surface of the catcher.

The carriage is retained by an electric magnet while it is moved down by a screw gear driven by an electric motor. At the same time the springs are loaded. The pad has been designed in such a way that the starting position of the test-mass at the beginning of the launch is always the same. The motion is triggered by cutting off the exciting current to the magnet.

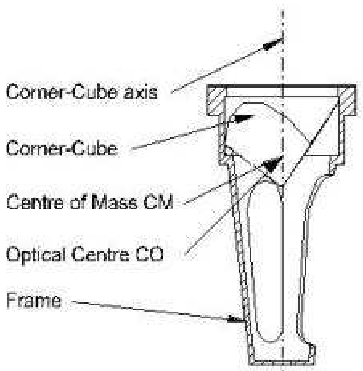

Fig. 2. Test-mass

2.2. Optical system

A Michelson-type interferometer is used to track the test-mass trajectory [4]. The schematic layout is showed in fig.3. The flying object (T_R) works as one of the reflectors in the optical arms of the interferometer, being the other retroreflector (R_R) the inertial reference during the measurement. The optical alignment is performed by adjusting the mirrors M_1 and M_2 and observing the interference pattern IP_1.

The light source of the interferometer is an iodine stabilized Helium-Neon (He-Ne) laser (100μW, spot size ≅ 1mm). The relative accuracy of a laser wavelength of this type is in the order of 1×10^{-10}.

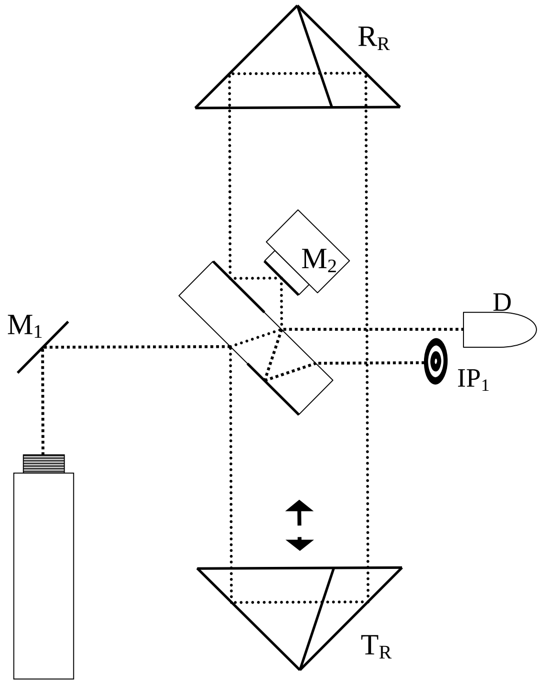

Fig. 3. Schematic layout of the optical system

The interference fringe causes cyclic variations in intensity with regard to the change in the difference between the two optical path lengths at every half wavelength displacement of the test-mass retroreflector. The output light of the interferometer is converted to an electric signal by a photodetector (D). The test-mass trajectory is measured by timing this electric signal.

2.3. Quasi-inertial system

An interferometer measures an optical path length difference. From this follows that the measurement result is the difference in acceleration between the test-mass and the reference cubic corner prism. The flying object is completely decoupled from the earth's surface after loosing contact with the pad. The reference corner cube however experiences acceleration due to motions in the earth's crust. The microseismic background is responsible for such a motion. These oscillations, which are generated by interactions between the oceans and the sea floor, are characterised by a peak at six seconds in their frequency spectrum (≅ 0.16 Hz), with typical amplitude of 1 μm.

Connecting the reference corner cube directly to the ground corresponds to measure the acceleration of the test-mass from a reference frame that can be accelerated at about 100 μm. Fortunately this acceleration is random, in the sense that there is not correlation between the phase of the oscillation and the beginning of the launches. In principle such effect can be averaged out by repeating the measurement several times.

Moreover there is the reasonable suspicion that the response of the floor during the launch could accelerate the reference retroreflector. In this case there is a quite sure coherence between the phases of the oscillations and the beginning of the launch.

To damp these effects, the reference retroreflector is tied to a quasi-inertial reference frame, provided by a mass suspended by a long spring. The mass in such a system is isolated from oscillations of the suspension point having periods shorter then the natural period of the spring-mass system. The inertial mass of a long-period vertical seismometer performs this task. This device, weighing 15 kg, is fixed to an aluminium platform together with the interferometer housing where the measuring beam emerges. The platform together with the laser body is mounted on a stainless steel frame with three levelling feet. The natural period T_n of the seismometer can be set from 10 s to 30 s by adjusting the feet of the frame and tilting the device around its pivot point. The inertial mass can travel about 10 mm above and below a central position as indicated by a pointer on a visible scale. Such a position is achieved by moving a trim weight situated on the side rail of the boom supporting the inertial mass. An electric motor is used to move this trim weight until the mass is within ± 2 mm of centre. Limit switches warns that the test-mass is touching the cast base, making an ineffective isolation.

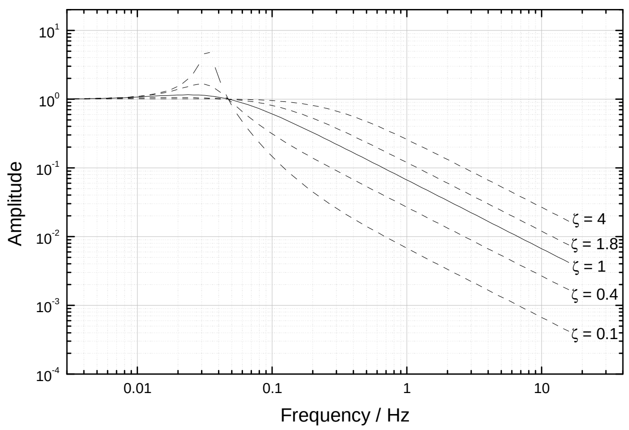

Fig.4. Schematic layout of the optical system

The seismometer has a moving-coil transducer that converts the relative speed between the inertial mass and the seismometer case into an electrical output. The device can be modeled in first approximation as a viscoelastic system. The damping is adjusted by shortcutting the moving-coil transducer circuit with the so called damping resistance R_d. The critical damping (damping factor ξ =1) for the system is obtained by setting the correct value of R_d.

The transfer function (fig.4) shows that the microseismic background can be smoothed of about a factor 0.4 (T_n = 20 s, ξ = 1). The maximum acceleration experienced by the reference retroreflector, due to microseismic background, should decrease to 40 μGal.

2. ELECTRONIC PART AND SOFTWARE

The electronic equipments are plugged into a transportable standard rack and divided into different units depending on their function. Each unit can be easily removed in case of maintenance. Except the personal computer and the power supplies, the others can be classified as acquisition or control unit. The software code which manages the instrument was purpose developed and tested.

2.2.1. Acquisition units

The present instrument adopts a unique data-processing technique to time the interference signal [5]. A waveform digitizer (NI-PCI 5112), synchronized to a 10 MHz reference rubidium (Rb) oscillator, is plugged into the personal computer. It samples and buffers directly the output signal of the detector during the test-mass trajectory. This high-speed digitizer has 2 channels and can sample at a maximum frequency of f_{Max} = 100 MHz. The aperture delay is 0.5 ns at 25°C and the time jitter is 2.3 ps rms at 25°C.

The flying distance in the present version of the instrument is set to about 20 cm, correspondent to a total flying time of about 400 ms and a maximum flying velocity of 1.96 $m \cdot s^{-1}$. The wavelength of a He-Ne laser is about 633 nm, hence the frequency of the interference fringe at the maximum speed reaches 6.2 MHz. The fringe signal can be therefore sampled in a manner consistent with the Nyquist criterion.

A multifunction acquisition board (NI-PCI 4351) is connected to the personal computer and used for temperature measurements (resistance temperature sensor) and low-frequency analog signals. It has 8 digital input-output channels that can drive the switches available into the relays module.

The vacuum and local barometric sensors are connected to the relevant acquisition units. The personal computer asks and receives the measured values via the RS-232 interfaces.

2.2.2. Control units

Users have the possibility to check the state and eventually act on the electronic devices constituting the measurement apparatus. This is accomplished via the front panel of control units which are plugged into a standard 19” rack mount.

The seismometer unit controls the electric motor which moves the trim weight used to center the position of the inertial-mass. The motor can be powered on either manually and automatically via the software by driving the relays module. Two analog signal outputs are used to monitor the state of the limit switches. A third analog output, concerning the relative speed between the inertial mass and the seismometer case, is sampled and integrated by the software during the test-mass trajectory. The resulting signal is correlated to the vertical motion of the ground and gives an idea of the floor response to the test-mass launch.

Pad loading and start of the launch can be performed by operating on the launching pad unit. The first action (pad loading) is performed by powering on the electric motor which drives the screw gear supporting the retaining magnet. The second action (start) is carried on by cutting the current to the retaining magnet. The launch system is automatically re-loaded after the pad catches the test-mass. When the system is ready for the launch it waits until the next start command. This command can be given both manually on the unit front panel and automatically via the software by driving the relays module. An analog output is available on the back panel of the control unit to monitor the pad-launch state (ready or not ready).

The mirror M_2 used to align the interferometer is glued to a 2 axis piezoelectric PZT-driven tilter actuator. The angular position of the mirror is manually adjusted acting on three potentiometers on the front panel of the PZT-driven mirror M_2 unit.

The He-Ne laser body is connected via an umbilical cable to the control unit. It is lighted on and controlled from the front panel of the He-Ne laser unit. The laser control loop is switched on (auto) after choosing the preferred iodine peak (*f* in our case). On the back panel an analog output is available to monitor the state (locked to an iodine peak or free-running). The Rb oscillator unit gives a periodic analog output signal of 10 MHz. It is converted into a TTL signal and sent to the waveform digitizer. The relays module unit houses 8 relays which are driven by digital signal sent from the NI PCI 4351. The only possibility to act on the relays is via software. It is necessary to start the personal computer and to open a communication with the acquisition board.

2.2.3. Software

The instrument is managed by a personal computer which is plugged into a 19” standard rack. Its rugged structure is suitable for the transportability of the apparatus. The processor adopted is a 1.8 GHz Pentium IV with 1 GB of RAM. The software code was developed and tested on the LabWIEW7.0™ platform and the operative system was the Microsoft Windows 2000™.

The software package consists of two different programs used to (i) control the instrument and store the experimental data during the measurement session, (Gravisoft M 1.0), (ii) elaborate and filter the data acquired during the post-processing session (Gravisoft PP 1.0).

While the Gravisoft M 1.0 is running, the personal computer sends commands to and receives data from the acquisition and control units. The program consists of a number of sequences executed inside a while loop which waits for the start of the launch. First of all the software checks the system condition. The signals concerning the state of laser, seismometer and launching pad are received via the I/O acquisition board. If all these systems are found to be ready, the software runs the following step, otherwise, depending on the device which hasn’t been found ready, it executes other subroutines. The system simply waits some seconds in case of laser unlocked or launch pad unready. A pre-defined sequence of commands is sent to the relays module, which drives the motor acting on the trim weight, in case of seismometer unready (i.e. the inertial mass is touching the case). The software checks a new time the system condition and, if all is ready, commands the relay which opens the circuit supplying the retaining magnet. The test-mass is launched upward and simultaneously the waveform digitizer samples and buffers the output signal from the photo detector. Afterwards the computer asks and receives the data concerning the ambient temperature, the local barometric pressure and the launch chamber pressure.

While the launch system is rearming, the processor elaborates the acquired data, computes the *g* value and stores the data files necessary for the post-processing session on a pre-defined directory (post_processing_data).

The user interface panel of the Gravisoft M 1.0 is showed in fig.5.

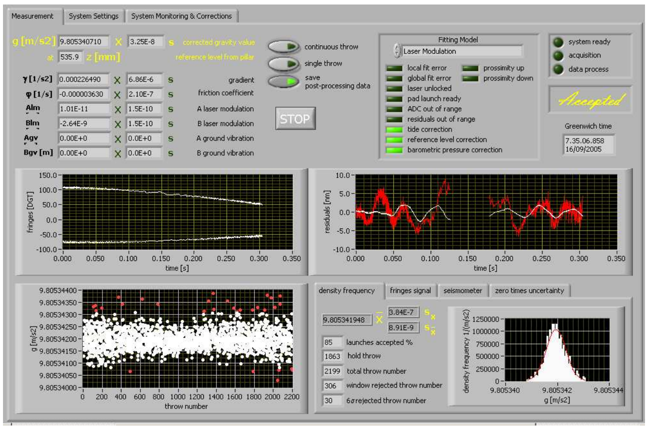

Fig.5. User interface panel of the Gravisoft M 1.0

Operators can start the measurement, record the data for post-processing, check and set the parameter of the system. Either a continuous run and a single throw is possible. At present the maximum measurement rate allowed by the apparatus is about 120 launches per hour.

When the Gravisoft PP 1.0 is executed, it loads the data files from the directory post_processing_data. Fig.6 shows the user interface panel of the Gravisoft PP 1.0.

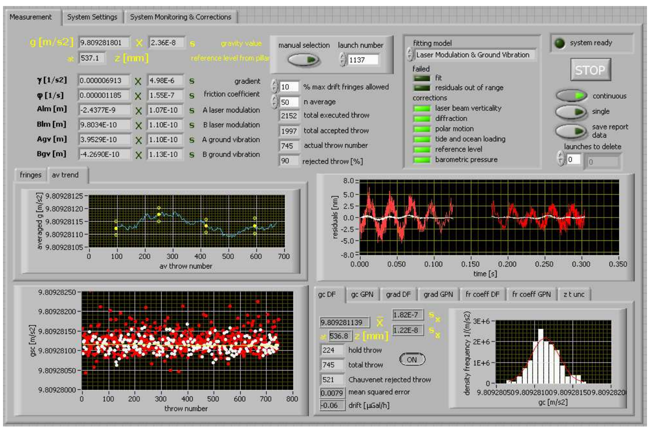

Fig.6. User interface panel of the Gravisoft PP 1.0

Users can analyze and display all the trajectories acquired during the measurement session.

Data are filtered following rejecting criteria relevant to the measurement condition. The most critical factor is the visibility variation of the interference signal. It is possible to fix an upper threshold to reject the launch.

Outliers are found by applying the Chauvenet criterion to the parameters estimated with the trajectory fit. Moreover there is the possibility to elaborate the data by applying or not the geophysical corrections relevant to the Tide and Ocean loading, the Polar motion and the local barometric pressure.

3. UNCERTAINTY BUDGET

An absolute measurement requires a thorough survey of the physical processes that can influence the experiment. At present, the measurement uncertainty budget for an absolute gravimeter is a hard task because the relative uncertainty terms are believed to be in the order of 10^{-9}.

A comprehensive approach to this subject is still missing. The scientific communities is discussing a harmonized procedure to correctly evaluate the measurement uncertainty. In this framework, starting from a careful analysis of the literature, it has been evaluated for the IMGC-02 the effect of the influence factors on the measurement result by following the ISO GUM prescriptions [6]. Only a brief summary of the analysis is here reported because the details are beyond the aim of this paper.

The budget is based on the assumption that the instrument is in normal working condition and is operated by experienced users. It was useful to separate influence factors which are (i) characteristic of the instrument from those that are (ii) dependent from the observation site.

To the former category (i) it belongs vacuum, non-uniform magnetic field, temperature gradient, electrostatic attraction, mass distribution, laser beam verticality, air gap modulation, laser accuracy and stability, index of refraction, beam divergence, beam share, clock accuracy and stability, fringes timing and finite value of speed of light, retroreflector balancing, radiation pressure and reference measurement height. The expanded uncertainty of the instrument, computed by combining all these effects, results to be about 8 μGal (p = 95%).

To the latter category (ii) it belongs the standard deviation of the mean value, the Coriolis force, floor recoil and geophysical factors such as local barometric pressure, polar motion, gravity tides and ocean loading.

The measurement uncertainty results from the combination of the instrument uncertainty with the effects relevant to the latter category. At the gravity laboratory of IMGC the expanded uncertainty of the measurement is estimated to be about 9 μGal (p = 95%).

The major contributors are the retroreflector balancing, the correction due to the divergence of the laser beam, the Coriolis effect and the standard deviation of the mean value. The effect of the first influence factor, i.e. the retroreflector balancing, is one order bigger than the remaining ones, therefore next future the relevant bias will be at least monitored and, if possible, corrected.

3. CONCLUSION

The new version of a transportable absolute gravimeter, the IMGC-02, has been described. The measurement apparatus is the result of the experience in absolute gravimetry carried out during last thirty years in this field by the IMGC gravimetry group.

Smaller size and weight characterize the IMGC-02, in particular the instrument is about 1 m height and it weights about 300 kg when packaged.

A software code was purpose developed and tested to manage the instrument during the measurement session and to post-process the acquired data.

It is believed that the measurement uncertainty could decrease next future. In fact the complete automation of the measurement allows to store a huge amount of data which make easier to check the results of any change to the measurement apparatus.

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