Design of New Launch and Interferometer Systems for the IMGC-02 Absolute Gravimeter

DESIGN OF NEW LAUNCH AND INTERFEROMETER SYSTEMS FOR THE IMGC-02 ABSOLUTE GRAVIMETER

Andrea Prato, Sergio Desogus, Claudio Origlia, Alessandro Germak

INRiM – Istituto Nazionale di Ricerca Metrologica, Torino, Italy

e-mail: a.prato@inrim.it

Abstract

For the measurement of the acceleration due to gravity, INRiM developed a transportable ballistic rise-and-fall absolute gravimeter, the IMGC-02. It uses laser interferometry to measure the symmetrical free rising and falling motion of a test-mass in the gravity field. The launch system is composed of a moveable carriage fixed to two couples of springs loaded by an electric stepper motor, which vertically throw up a corner-cube prism in vacuum. The interferometric system is a modified Mach-Zehnder interferometer where the flying object works as one of the reflectors in the optical arms of the interferometer and the other retroreflector acts as inertial reference during the measurement. However, both systems entail some practical problems and uncertainty contributions that need to be reduced. In particular, the current launch system can cause beam shear and rotational effects due to unavoidable small different loadings of the springs, while the interferometer system involves problems in the alignment of the interferometer mirrors, which is highly time-consuming and has to be performed before and, sometimes, during the measurement session. For this reason, a new launch system have been designed: it consists of an electric linear motor, which produces a linear force along its length, and a modified Jamin interferometer system entailing a simpler alignment and a better stability in time. This works deals with the description of these new systems.

Keywords: Gravimetry, absolute gravimeter, interferometer, rise-and-fall gravimeter

Introduction

Absolute measurements of the acceleration due to gravity, *g*, are performed by absolute gravimeters, traceable to the units of length and time through their primary standards. For this purpose, INRiM developed a transportable ballistic rise-and-fall absolute gravimeter, the IMGC-02, which is recognized as a national primary standard in Italy (BIPM KCDB) (WGG/04-41 resolution[1]). The measurement of the *g* value is obtained using the reconstructed rise and fall motions of a corner-cube prism, which moves vertically in vacuum. An interferometer system is implemented to obtain time and space coordinates of the trajectory using a visible laser beam. The interferometer measures the distance between a free-falling corner-cube prism and a second retroreflector mounted on the quasi-inertial mass of a vibration isolation system. The gravimeter is composed of five main parts: i) a launch system in a vacuum cylinder, i) an interferometer system connected to an anti-vibrating system, iii) a laser body, iv) a photodetector and v) a supporting frame, as shown in Fig. 1. A detailed description of the gravimeter can be found in D'Agostino (2006) and D'Agostino et *al.* (2008). However, the current launch system, which is composed of a moveable carriage supported by two couples of springs, and the interferometric systems, which is a modified Mach-Zehnder interferometer, introduce uncertainty contributions and practical problems that need to be overcome. For this reason, new launch and interferometer systems have been designed. This work deals with the description of the current systems and their future improvements.

[1] Resolution WGG/04-41 of the first joint meeting of the CCM WGG and SGCAG (26-27 May 2004, BIPM): *the first joint meeting of the CCM WGG and SGCAG recognized the absolute ballistic method of measurement of the acceleration due to gravity as a primary method*.

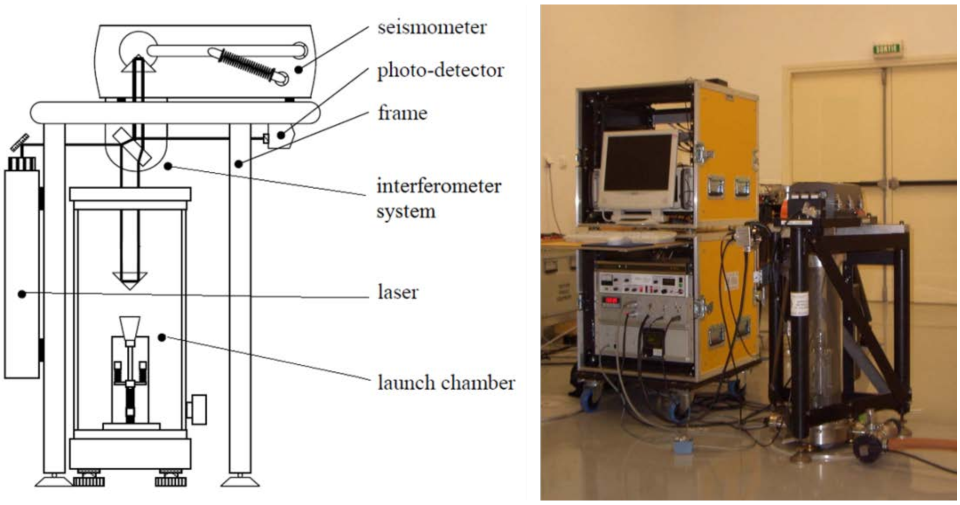


Fig. 1. Schematic drawing and picture of the IMGC-02 absolute gravimeter.

The launch system

The current launch system is composed of the vacuum chamber, the test-mass and the launching pad. The launch chamber can be approximated to a cylinder with a diameter of 14 cm and a height of 65 cm. The base of the vacuum chamber is made of stainless steel and is supported by three legs with levelling screws, which allow the vertical alignment. The main part of the vacuum chamber is a flanged glass pipe, whose bottom part is fitted to the base, whereas the upper part is sealed with an aluminium cover. A glass window (5 cm diameter, 1.27 cm thick, BK-7, $\lambda/10$ flatness, parallelism less than 2 arc seconds) is positioned at the centre of this cover and allows the laser beam to reach the test-mass. Connections are sealed by O-rings and, inside the glass pipe, a Faraday cage shields the test-mass from electrostatic charges. The base of the chamber has two arm pipes: the first one is connected to a low noise turbo pump, the second to an ionisation vacuum gauge. A rotary pump carries out the coarse evacuation. A pressure of 1×10^{-3} Pa is reached after about 5 hours.

The launching pad (Fig. 2) can be approximated to a 5 x 5 x 20 cm^3 parallelepiped and is tight to the base of the vacuum chamber. It supports, throws up and catches the test-mass at the end of its trajectory. The test-mass is a retroreflector cubic corner prism, which has the property to reflect an incident ray parallel to itself independently of the angular orientation. The corner-cube has a mass of 0.15 kg and lies horizontally on three supports, which are the vertices of an equilateral triangle. These supports constitute the upper ending part of the catcher, which is fixed to a moveable carriage (0.57 kg) on a vertical linear bearing rail, screwed to an aluminium rectangular support. The carriage, in turn, is fixed to two couples of series springs and is retained by an electric magnet. The starting horizontal position of the test-mass, when it rests on the catcher, corresponds to the best alignment of the interferometer, i.e. the best overlapping between the test and reference beams. The thrust of the system (around 65 N) is given by the two couples of series springs in parallel (elastic modulus of 2500 N/m each), which are loaded through a screw gear driven by an electric stepper motor. The vertical motion of the test-mass is triggered by cutting off the exciting current to the magnet. The impulse is transmitted through the three supporting points to the test-mass. When the mechanical action ends, the body hovers and its trajectory is tracked. The resulting total stroke of the mechanical system, before the release of the test-mass, is around 25 mm. When released, the test-mass has a speed of about 2 $m\cdot s^{-2}$ and travels in the vacuum chamber a distance of about 20 cm. The launch system is automatically re-loaded after the pad catches the free-falling test-mass.

Ideally, the corner-cube prism realizes a point in space. Unfortunately, the corner-cube's centre of mass is far from its optical centre. For this reason, the corner-cube retroreflector is fitted to an aluminium mounting support, in order that the resulting centre of mass coincides as best as possible to the optical centre. In this way, any rotation of the test-mass around its centre of mass should affect neither the interferometric alignment nor the measured *g* value. Although the highest accuracy in its realization, a small but unavoidable difference between the optical centre and the centre of mass is still present. The uncertainty in locating the optical centre and centre of mass is estimated to be ±0.1 mm. This entails that thus beam shear and rotational effects might occur due to movements and rotations of the test-mass on the horizontal plane, caused by

lateral forces and moments raising during the upward launch of the test-mass generated by small different loadings of the springs. As a consequence of the first effect, the two interfering beams can translate relative to each other. This phenomenon causes the rejection of those launches affected by a fringe visibility reduction above a fixed threshold (usually 10 % to 20 % of the maximum intensity). The rotational effect, instead, introduces a centripetal acceleration, whose vertical component is added to the local gravity acceleration *g*. Experimental tests (D'Agostino 2006) show that the average rotation of the test-mass during the trajectory is 10 mrad and the associated angular velocity is 25 mrad·s^{-1}, given a total flying time of around 400 ms. Considering the uncertainty in locating the optical centre and the centre of mass as a random variable with a uniform distribution within ±0.1 mm, the expected uncertainty due to the rotation of the corner-cube is 3.6 μGal and represents one of the largest contribution to the uncertainty budget (D'Agostino et *al.*, 2008).
To overcome these issues, a new launch system has been designed (Fig. 3). It can be approximated to a 7 x 7 x 26 cm^3 parallelepiped and consists of an electric linear motor, which has its stator and rotor unrolled to produce a linear force along its length, to which the moveable carriage and the catcher are fixed. As in the current system, the moveable carriage slides on a linear bearing rail screwed to an aluminium rectangular support. In this way, once aligned, beam shear and rotational effects should be minimized, thus the rejection of some launches and the uncertainty due to rotational effects should be strongly reduced. The linear motor has a maximum stroke of 780 mm, a peak force of 67 N and a continuous maximum force of 14 N. The presence of motor flanges enables the easy mounting of the linear motor on the aluminium structure and the clamping plate design enables quick assembly and disassembly of the linear motors without disassembling the flange. The rate of movement of the magnetic field is electronically controlled via-software to track the motion of the rotor. In this way, it is also possible to the design the downward motion profile in order to collect the test-mass at the end of its falling motion.

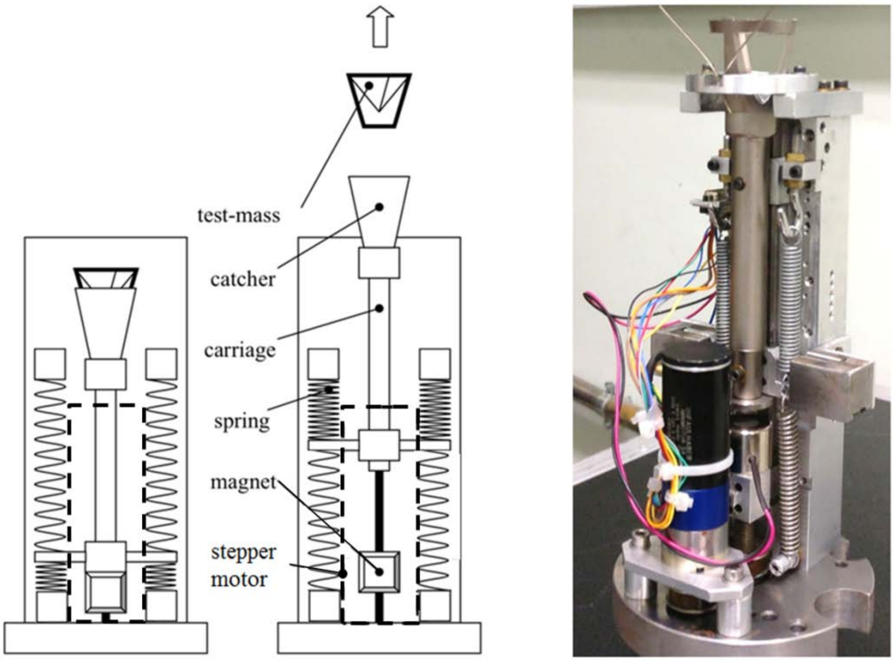


Fig. 2. Schematic drawing (left) and picture (right) of the current launching pad.

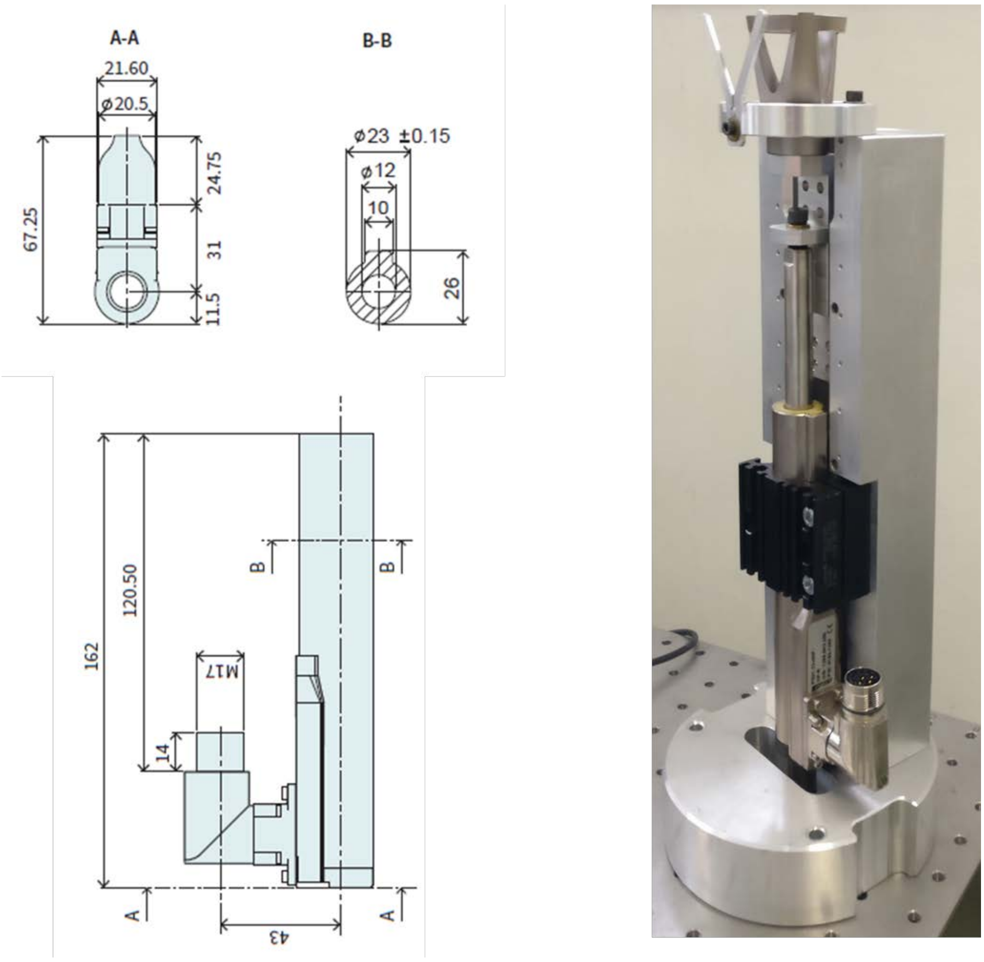
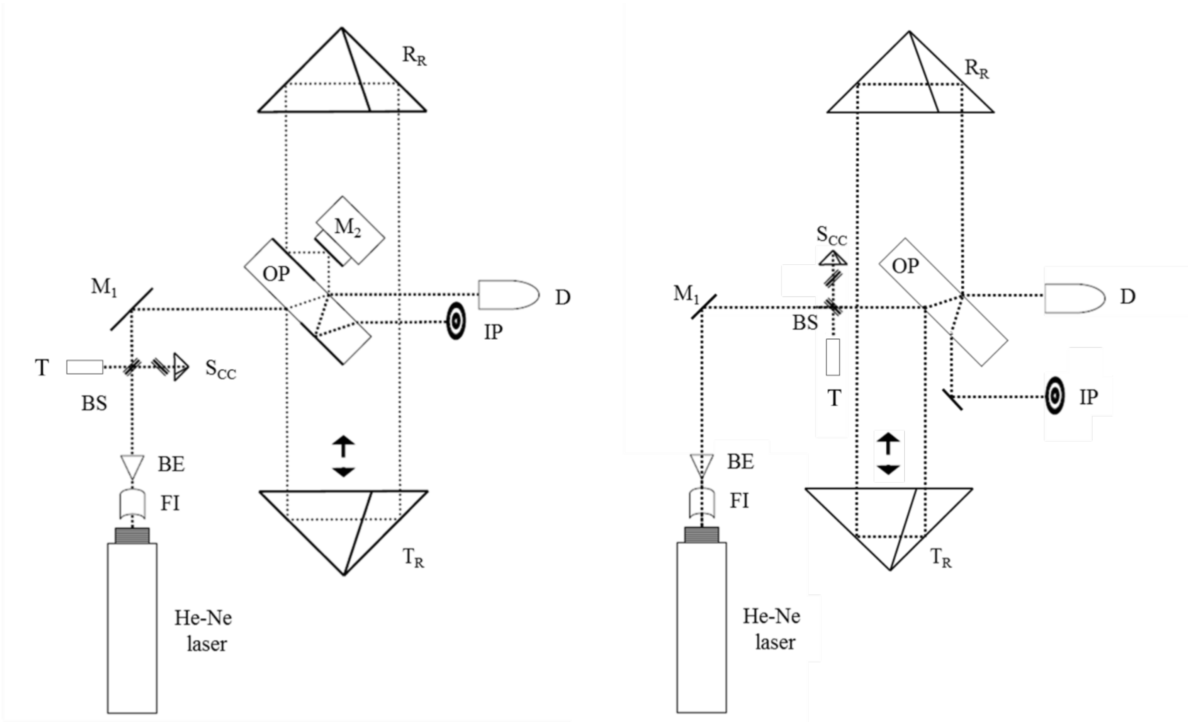


Fig. 3. Technical drawing of the electric linear motor (left) and picture (right) of the new launching pad.

The interferometer system

The current interferometer system is a modified Mach-Zehnder interferometer (Germak et *al*. 2002, D'Agostino 2006). A brief scheme is reported in Fig. 4. The light emitted by the He-Ne laser (λ ≈ 633 nm) passes through an optical Faraday isolator (FI) which works as a back talk preventer. After the Faraday isolator, the beam is enlarged to 2 mm spot size by a beam expander (BE) and proceeds vertically toward a beam-splitter (BS). One of the beams proceeds horizontally toward a small corner-cube (S_{CC}) used to observe the vertical orientation of the beam through a telescope (T). The other beam, vertically directed, is deviated by a moveable mirror (M_1) which can be rotated around two axes to adjust the direction of the shifting arm of the interferometer to the true vertical. These elements are needed to check the verticality of the laser beam. Afterwards the beam enters horizontally into the optical prism (OP) situated beneath the reference retroreflector corner-cube (R_R). The OP has been designed in such a way that half is a reflecting mirror and half is a beam-splitter. The incident light is divided into two beams by the first beam splitter. One of the beams, which represents the fixed arm of the interferometer, proceeds horizontally, strikes the second beam-splitter and goes straight toward the detector (D). The second beam generated by the first beam-splitter, travels vertically down to the test-mass's retroreflector corner-cube (T_R) and forms the shifting arm of the interferometer; it is reflected back to R_R and strikes the movable mirror (M2) after being reflected by the prism. The adjustment of M2 allows the beams to recombine at the second beam splitter of the OP. The interference fringe causes cyclic variations in intensity, which are due to the change in the difference between the two optical path lengths at every half-wavelength displacement of the test-mass retroreflector T_R. The detector converts the output light of the interferometer to an electric signal. The test-mass trajectory is measured by timing this electric signal. Since the recombining beams have to be coaxial in order to avoid distortions on the laser interference fringes, the angular position of the mirror M_2 has to be adjusted every

time before the measurement and has to be monitored during the measurement. The alignment is achieved by rotating the mirror M_2 around its two axes through a piezoelectric PZT-driven tilt actuator.
Unfortunately, this operation entails practical problems, is highly time-consuming and has to be performed before and during the measurement session. For this reason, a new modified Jamin interferometer (Shamir 1999) has been devised (Fig. 4). Such system is similar to the modified Mach-Zehnder interferometer except that the two beams directly recombine on the optical prism OP, thus the movable mirror M_2 is removed. A 3-D detail of the main part of the new system is depicted in Fig. 5, while its assembly in the gravimeter is shown in Fig. 6. The alignment of the recombined beams is possible by just shifting the reference corner-cube retroreflector R_R along the horizontal plane. The main advantages are a simpler and faster alignment of the two beams and a better stability in time. Negligible Abbe errors remain, due to the misalignment of the two upper and lower corner-cube retroreflectors, and the divergence of the retroreflectors, which are simply overcome by using corner-cubes and an optical prism with angular accuracy within 1” and a flatness within $\lambda/10 \approx 60$ nm.



The modified Mach-Zehnder interferometer **The new modified Jamin interferometer**

OP=Optical Prism	IP=Interference Pattern Control
BE=Beam Expander	M=Mirror
FI=Faraday Isolator	R_R=Reference Retroreflector Corner-Cube
BS=Beam Splitter	T_R=Test-Mass Retroreflector Corner-Cube
D=Detector	
T=Telescope	S_{CC}=Small Corner-Cube

Fig. 4. Scheme of the current modified Mach-Zehnder interferometer (left) compared to the new modified Jamin interferometer (right).

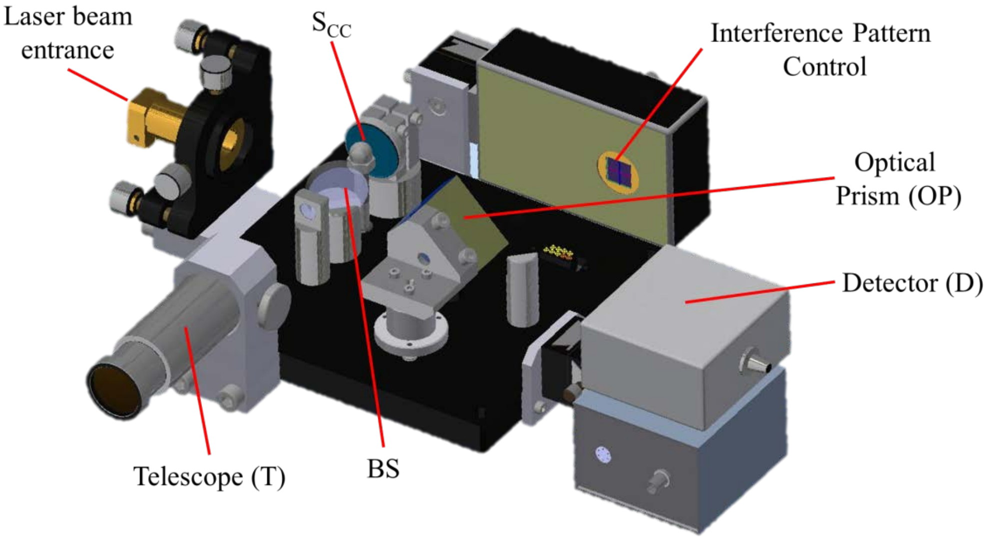


Fig. 5. 3D-Scheme of the new modified Jamin interferometer on the horizontal plane.

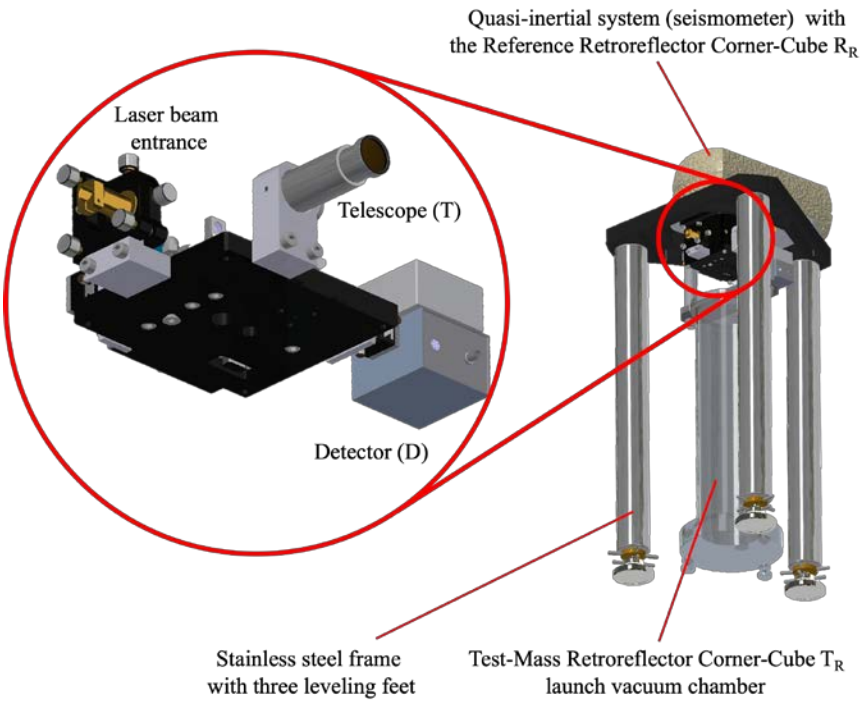


Fig. 6. Bottom view of the 3D-Scheme of the new modified Jamin interferometer integrated in the IMGC-02 rise-and-fall ballistic gravimeter.

Conclusions

For the measurement of the acceleration due to gravity, INRiM developed a transportable ballistic rise-and-fall absolute gravimeter: the IMGC-02. Currently, the launch system is composed of a moveable carriage supported by two couples of series springs in parallel, which are loaded by moving down the carriage through a screw gear driven by an electric stepper motor. Nevertheless, it is likely that lateral forces arising during the upward launch of the test-mass, caused by unavoidable small different loadings of the two springs, make the test-mass move on the horizontal plane and rotate. Therefore, the two interfering beams can translate relative to each other, so that beam shear and rotational effects may occur. To overcome these issues, it has been designed a new launch system. It consists of an electric linear motor, which has its stator and rotor unrolled to produce a linear force along its length, fixed to the moveable carriage. The rate of movement of the magnetic field is electronically controlled to track the motion of the rotor. In this way, beam shear and rotational effects should be minimized. For what concern the interferometer system, at present, a modified Mach-Zehnder interferometer is adopted. Unfortunately, the alignment operation entails practical problems, is highly time-consuming and has to be performed before and, sometimes, during the measurement session. For this reason, a new modified Jamin interferometer has been devised. This system is similar to the modified Mach-Zehnder interferometer except that the two beams directly recombine on the optical prism, thus the movable mirror is removed. The main advantages are a simpler alignment of the two beams and better stability in time. The new interferometer system should guarantee measurements that are more robust and a faster setup of the gravimeter.

References

BIPM – Mass and Related Quantities
https://kcdb.bipm.org/appendixC/country_list_search.asp?CountSelected=IT&service=M/TVHG.8

D’Agostino G (2006) Development and metrological characterization of a new transportable absolute gravimeter. PhD Dissertation, Politecnico di Torino

D’Agostino G, Desogus S, Germak A, Origlia C, Quagliotti D, Berrino G, Corrado G, D’Errico V, Ricciardi G (2008) The new IMGC-02 transportable absolute gravimeter: measurement apparatus and applications in geophysics and volcanology. ANN GEOPHYS 51(1):39-49

Germak A, Desogus S, Origlia C (2002) Interferometer for the IMGC rise-and-fall absolute gravimeter. Metrologia 39(5):471-475

Shamir J (1999) Optical systems and processes. SPIE, Bellingham, Washington, USA