Testing Newton's inverse square law at intermediate scales

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(Received 7 February 2001; published 24 September 2001)

Here we report the results of a new analysis of the data obtained in the framework of an experiment consisting of the measurement of the gravitational signal induced by varying the water mass of a lake. A more precise calibration of the superconducting gravimeter used in the experiment has been performed with the use of an absolute instrument; furthermore, a knowledge of the absolute amplitude of the solid Earth tides of the station has been improved. The result of this analysis shows an agreement between data and Newtonian theory to within a 0.17% level.

DOI: 10.1103/PhysRevD.64.082001 PACS number(s): 04.80.−y, 85.25.−j, 94.10.Jd

I. INTRODUCTION

The inverse square law of gravitation [1] has been tested in the past in three different length regions. These are the laboratory scale, that is, distances of about 1 m; the geophysical region, corresponding to hundreds of meters, and the spatial and astronomical scales, corresponding to distances more than Earth's radius. In the laboratory, the gravitational law is commonly tested by means of torsion balances and torsion pendula. Such measurements agree, within experimental uncertainty, with the inverse square law. Furthermore, they provide the experimental G values subsequently used to compute that reported in tables of physical constants. The most recent accepted value is $G=(6.673\pm 0.010)\times 10^{-11}\ \mathrm{Nm^2/kg^2}$ [2]. A thorough review of the laboratory experiments can be found, for instance, in Refs. [3,4].

At spatial and astronomical distances, observations on artificial satellites and celestial bodies (moon and planets) exclude deviations from Newton's law. In this distance scale, an independent measurement of G is not possible: only Gm can be obtained, m being the mass of the attracting body.

Nevertheless, these results cannot exclude the existence of non-Newtonian terms which disappear at distances greater than the Earth's radius and which are practically constant on the meter scale. Such correction terms would represent the contribution to gravitation of new particles with a nonzero mass, in addition to the graviton. Their potential would depend on distance as $(1/r)e^{-r/\lambda}$, with λ linked to the exchanging particle mass given by $\hbar/\lambda c$ [3]. The overall potential for a point mass m (and one correction term) would be

$$U=-G\frac{m}{r}(1+\alpha e^{-r/\lambda}), \tag{1.1}$$

where α is the relative weight of the non-Newtonian term. As a consequence, the force between two pointlike m_1 and m_2 masses is

$$F=G\frac{m_1 m_2}{r^2}\left(1+\alpha\left(1+\frac{r}{\lambda}\right)e^{-r/\lambda}\right). \tag{1.2}$$

Such a relation could also be written as

$$F=G(r)\frac{m_1 m_2}{r^2}, \tag{1.3}$$

on introducing a G dependence on r given by

$$G(r)=G\left(1+\alpha\left(1+\frac{r}{\lambda}\right)e^{-r/\lambda}\right). \tag{1.4}$$

Anomalous terms should be detected in geophysical region experiments by finding a G value for Newton's law different from that obtained in laboratory.

From an historical point of view, the first experimental attempts to measure G at the geophysical scale were stimulated by theoretical considerations [5–7] suggesting the existence of a short-range force in addition to the normal Newtonian gravity. They exploited mines or boreholes and measured gravity acceleration at different depths, from which, on using Newton's law, G can be deduced. A series of experiments by Stacey and co-workers [8–10], performed in Australian mines, systematically yielded G values larger than those obtained in laboratories. Similar conclusions were also achieved by other authors, as reported in Ref. [11].

These results prompted Fischbach *et al.* [12] to reanalyze the Eötvös *et al.*'s well known experiment [13], which compared the accelerations of materials having different compositions in the Earth's gravitational field. Their conclusion, unlike that of the original paper, was that the data of Eötvös *et al.* seemed to disagree with the weak equivalence principle, which states the trajectory independence of the composition for bodies moving in gravitational fields. Since the validity of such a principle was tested by Roll *et al.* [14] and by Braginskii and Panov [15] in the gravitational field of the Sun with a higher accuracy, the Newtonian term cannot be held responsible for the violation. It was therefore concluded in Ref. [12] that an additional term such as Eq. (1.1), usually referred to as fifth force, should exist. This term should be responsible for the violation of the weak equivalence principle.

The publication of this paper spurred a generation of experiments searching for both the existence of non-Newtonian terms and the validity of the weak equivalence principle. For a thorough review of the experiments on the weak equivalence principle, the interested reader is referred to Ref. [16]. The searches for anomalous gravitational effects produced a large number of experiments which can be divided into two groups. To the first group belong those experiments which rely on a precise knowledge of the Earth's gravitational field, such as those in mines [11]. The acceleration due to gravity was measured at different heights in towers [17–19], or at different depths in the ocean [20] and in polar ice [21]. The pitfall of these experiments is the need to know with great accuracy the vertical position dependence of the Newtonian gravity acceleration, which in turn is a function of the mass distribution. Generally, these experiments seem to agree with Newton's law, as discussed in Ref. [16].

A second group of experiments consists of measurements of variations of g due to large mass displacements, which, for practical reasons, are usually water masses. In this case the instruments which measure g are kept fixed. These experiments can be considered, in a first approximation, as model independent. The only site dependent effect is the vertical instrument displacement due to load changes. This produces a small change of the Earth's gravity, which is to be evaluated and corrected. The first attempts along this line used mechanical gravimeters [22,23] or balances [24,25] to probe g variations due to a lake whose level is changing with time.

We performed an experiment along the same line using a superconducting gravimeter (SG), which is the most sensitive instrument currently available for this kind of measurement, and a lake with interesting characteristics. In the following sections we will present the following.

(a) A concise description of a previous experiment whose result seemed to show a disagreement with Newton's law (for a complete description the reader is referred to Ref. [26]).

(b) A new data analysis, based on a SG calibration with an absolute instrument and an accurate tidal study performed during a long observation period. This new analysis removes the discrepancy and shows an agreement at the 0.17% level with the inverse square law.

(c) A G determination at distances of some tens of meters relying on a method which differs from those ordinarily used in laboratories.

II. PREVIOUS EXPERIMENT

As a changing mass source we used Lake Brasimone (845 m above sea level, midway between Bologna and Florence, Italy). This lake is exploited as a power storage by ENEL (Italian electric industry), which pumps water up in the lake during the night, and uses it during the day to produce power at peak energy requests. It has some interesting characteristics for this kind of experiments.

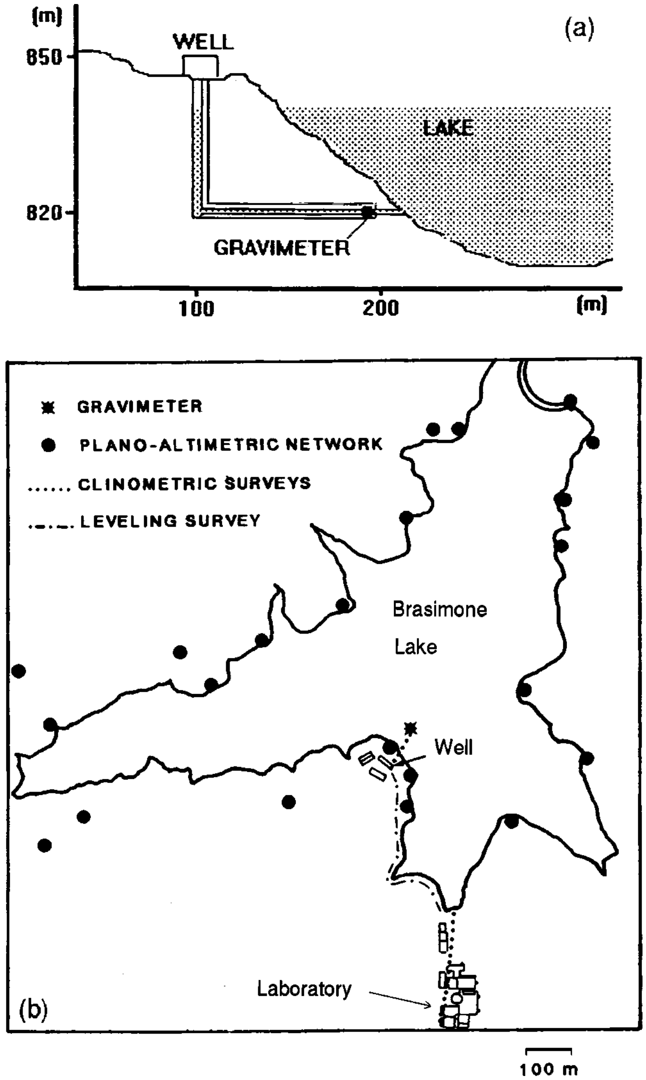

FIG. 1. Vertical profile (a) and horizontal map (b) of the measurement site. In (a) the SG position and the well used for the lake level control are visible. In (b) are shown the reference points used for the planoaltimetric survey, the calibration laboratory far from the lake and the paths of the clinometrics and first leveling surveys.

A tunnel which extends nearly to the lake center, used to locate the SG below the water mass [see Fig. 1(a)]. The practically constant temperature of the tunnel contributed to the operating of the SG at its best. The tunnel tilt due to load changes revealed itself to be important to measure the larger part of vertical displacements.

Lake Brasimone has a conical shape, so that the gravity variations in the tunnel due to the change of water level are practically independent of the level itself.

Most of the lake shore is characterized by rocks with a very low porosity (clays); the water table variations are only of a few centimeters, and their delay in response to a single filling of the lake is in the range of some days.

A SG [27] differs from traditional mechanical spring instruments because it uses magnetic levitation of a superconducting spherical mass through the field gradient generated by the persistent currents of two superconducting coils. The inherent stability of supercurrents allows for a gravimeter of high stability and precision. The overall instrumental sensitivity, on taking care of geophysical and environmental noises is of the order of 0.01 μgal or better [27], where 1 gal=1 cm/s^2. The spherical mass is kept at a constant height by means of the magnetic field generated by a current flowing in a third coil (not superconducting). Therefore, a gravity variation is measured as a voltage change in this third coil. In the tunnel one can measure a total gravity change of about 280 μgal due to water level variations. A signal of the same order of magnitude is measured as a contribution from tidal effects.

In order to compare the theoretical Newtonian effect with the measured one, the lake shore shape must be known as accurately as possible. For this reason an aerophotogrammetric survey was carried out when the lake was at its minimum level. A more detailed terrestrial photogrammetric survey was also done in order to define with better accuracy the profile of that part of the shore close to the gravimeter position. A digital model of the shore obtained by the above surveys is based on the coordinates of 50000 points distributed along 21 contour lines covering 10 m of water level variation. The position of the gravimeter in the tunnel was obtained with an uncertainty of the order of 6 cm in horizontal coordinates and of 1 cm in vertical coordinates. The contribution of water absorption into the clays was both calculated and measured. As a conclusion the relative error on the theoretical calculation of the Newtonian effect is 1.4×10^{-4}.

The signal recorded by SG in the tunnel has a contribution from the tide which adds to that given by water level variations. This tidal signal depends both on direct gravitational effects of the Moon and the Sun, and on the Earth's elastic response. Furthermore topographic features, geological features, and oceanic load induce deviations from a global Earth tide model which are not determinable without a direct measurement. For this reason we recorded the tidal signal in a calibration laboratory located in the same area [see Fig. 1(b)] far enough away from the lake and at the same height so as not to be influenced by its level variations. Such a signal was used to produce a tidal model, that is, to obtain the amplitudes and phases of the tidal wave components, except for long-term modes which are not relevant in our method of analysis. The amplitude A_i of every wave component is usually expressed by means of a gravimetric factor $\delta_i(>1)$, so that $A_i=\delta_i A_{theor,i}$, where $A_{theor,i}$ is known exactly from the positions of the Moon and Sun. In addition, a simultaneous barometric measure also allowed us to obtain the local relation between changes of pressure and gravity.

In the same laboratory the SG was calibrated in order to obtain the factor (calibration coefficient) which links changes of gravity given in volts by the instrument, with their corresponding value expressed in μgal. This was done by moving an annular object whose mass and shape were accurately measured up and down around the SG. The maximum change of gravity induced by the moving annular mass was computed to be $\Delta g=6.731(1)$ μgal. A gravity variation of this order produces an output voltage variation of about 100 mV. The absolute gravimeter of the Italian Metrology Institute G. Colonnetti was run to check the calibration factor.

Since it was impossible to perform the same operation in the tunnel for reasons of space, we adopted a transport procedure for the calibration. Our SG [28] is equipped with an electrostatic calibration system: an electrostatic force induced on the superconducting sphere produces an output voltage change simulating a gravity variation, allowing us to obtain an electrostatic calibration factor. In each experimental run in the tunnel, electrostatic calibration factors were periodically measured and compared with those obtained in the laboratory which in turn are associated with the measured values of the calibration coefficient.

In the tunnel the SG was operated in two runs for a total of 327 days, corresponding to a useful cumulative water level variation of about 1 km. Two differently filtered output signals taken at different rates (0.05 and 2 Hz) were continuously recorded on files, together with the corresponding UTC time. At the same time the lake level, atmospheric pressure, air and water temperature, and relative humidity were also measured and recorded.

The lake level was monitored by measuring the length of a stainless-steel wire fixed to a buoy, floating in the well which communicates with the lake. The wire was maintained at a constant tension and wound on a precision aluminum pulley wheel. The angular position of the pulley was monitored by an absolute digitizer having a 0.1-mm/digit sensitivity. A Distomat D4000 having an accuracy of 1 mm was used to calibrate the lake level measuring system.

Water temperatures at depths of 1 and 5 m were measured in the lake along the vertical above the gravimeter position in the tunnel. They ranged between 4 and 20 °C, while the maximum temperature difference measured at any depth in various places and in different seasons never exceeded 0.8 °C. Water samples were drawn from the lake in order to measure the water density, whose mean value measured at 21 °C resulted to be 998.145 ± 0.016 kg/m^3.

As stated in Sec. I, the ground subsidence due to the load changes must be taken into account. We used two different procedures. In the tunnel and the laboratory building we employed a hydrostatic clinometer having a sensitivity of 10^{-8}. Outside two high precision spirit leveling surveys were repeatedly performed with an empty and full lake. The total vertical displacement, obtained by combining all the measurements and taking into account the residual displacement from the last benchmark to infinity, is $\Delta h=0.57\pm0.11$ mm for 1 m of water. The corresponding correction to be applied to the gravity measurement is $\Delta g=-0.15\pm0.05$ μgal for 1 mm of subsidence.

All periods of the lake level changing were considered for data analysis. Starting from raw data, every measured gravitational value was first converted from volts to μgal by using the conversion coefficients determined by electrostatic calibration. Afterward, such a value was corrected for the following effects: gravitational variations due to pressure

TABLE I. Summary of the dominant errors. The experimental effect takes into account the statistical uncertainty of the data used in the differential analysis. The theoretical effect comes from the uncertainty on the gravimeter position and lake shape, as described in Sec. II. The other terms, relative to corrections also described in Sec. II are combined quadratically to the first two terms yielding the total error.

Source	Relative error $\times 10^{-4}$
Experimental effect	3.8
Theoretical effect	1.4
Gravimeter calibration	9.2
Water level (digitizer)	2.2
Vertical deformation	8.0
Water level (density correction)	1.0
Water specific mass	0.3
Air mass correction	0.1

changes and gravimeter drift. Successively, the tidal contribution was also subtracted. The residual signal represents the gravitational effect associated with the lake level change. A differential analysis which compares gravity signal and lake level variations was performed, obtaining the gravitational effect for every 10 cm of level change. After correcting for the vertical SG displacement, the effective water and air densities, and the water table contribution, for the ratio between experimental and Newtonian effects we obtained the value $R = 1.0127 \pm 0.0013$. Table I, taken from Ref. [26], summarizes the dominant errors of the experiment. It is clear from the table that the uncertainties on gravimeter calibration and vertical deformation set the upper limit to the precision of an experiment of this kind.

III. A NEW DATA ANALYSIS

In the experiment described above, a discrepancy between results and theory of about 1.3% was found, which is greater than the experimental uncertainties. All of the most important measurements and also the data analysis were verified with different approaches. As reported in the conclusions of the Ref. [26], "the only parameter not verified at the 0.1% level was the gravimeter calibration factor" in the tunnel obtained with the transport procedure. We have now exploited an FG5 absolute gravimeter to redetermine the calibration factor. As described in detail in Ref. [29], the absolute instrument determines g by measuring with precision the fall of a body in vacuum. The improved accuracy with respect to that of the previous generation instruments is due to an automatic control of the falls. Therefore, a great number of data can be easily acquired. Furthermore, from the time of the experiment till now, the superconducting gravimeter continuously recorded the tidal gravity signal in the calibration laboratory, thus allowing a substantial improvement of the tidal model of the Brasimone site. In this new analysis, except for the calibration factor and a more consistent model of tidal gravity variation, all the experimental data (e.g., lake survey, geological effects, pressure and temperature effects) already employed and concisely described above were used.

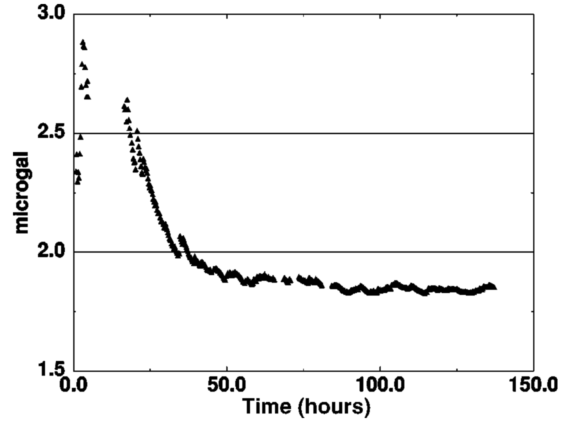

FIG. 2. Cumulative standard deviation from the mean of the absolute gravity vs time. As expected, it decreases to its limit value with the number of data collected.

The calibration of the superconducting gravimeter by means of an FG5 absolute instrument was performed in the calibration laboratory [30]. For a period of about a week the two instruments measured together the changes in the g value, mainly due to tidal effects. The method does not suffer from minor contributions to the g variations such as barometric pressure [31], since they influence equally the signal measured by the two instruments. The absolute instrument was operated in runs of 25 drops, with a drop every 15 s and 4 runs in 1 h. After correcting each run for the tide, we obtained the cumulative standard deviation from the mean of the absolute gravity, which decreases with time, as shown in Fig. 2, to a limiting value of 1.8 μgal after about 100 h. The SG calibration factor was obtained on fitting the FG5 g variations of each run versus the corresponding SG feedback voltage, as reported in Fig. 3. The linear fit of the data, also shown in Fig. 3, allows us to obtain the SG calibration factor with an accuracy of 1.4×10^{-3}.

The value of the SG calibration coefficient has been used to convert the output of the instrument from volts into μgal.

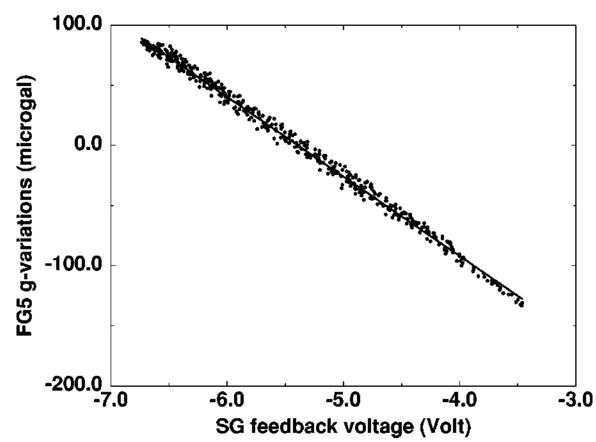

FIG. 3. FG5 g variations vs SG feedback voltage. Each point, corresponding to a 25 drop run, represents the gravity value measured by the two instruments. The line is the best fit to the data.

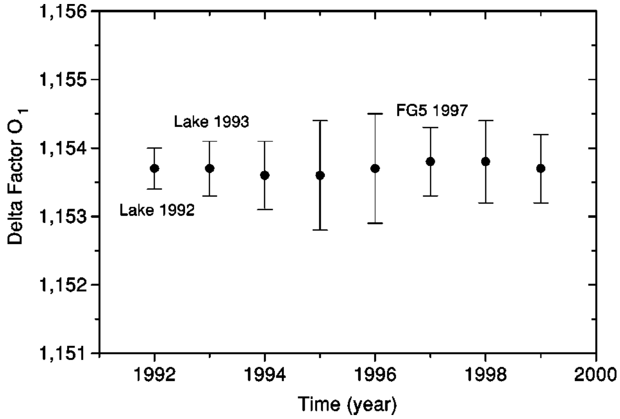

FIG. 4. δO_1 values, corrected for oceanic loading, obtained from the tidal analysis in the 1992–1999 period. The 1992 and 1993 data refer to runs in the tunnel, the others to laboratory runs.

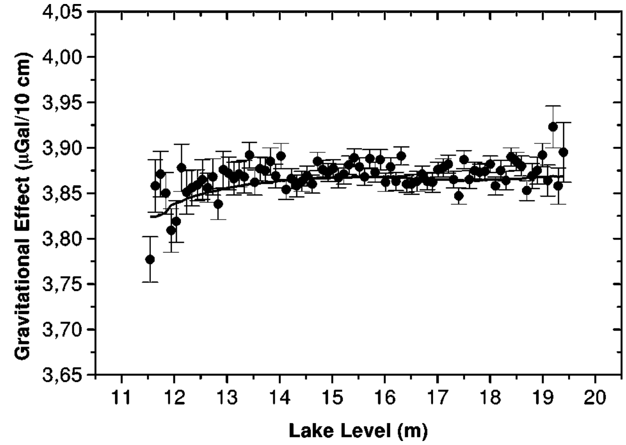

FIG. 5. Experimental and theoretical (line) gravitational effects for a 10-cm water level variation as a function of the vertical distance from the gravimeter.

A gravity signal, acquired by the SG in the calibration laboratory at a 1-min rate for a six month period centered around the FG5 calibration week was analyzed as follows. A data pre-elaboration was done using the Eterna-Preterna software [32] to correct for steps, spikes and gaps. With the same program we numerically filtered and decimated the data to an hourly rate. Then a final analysis was done to compute amplitudes, gravimetric factors and phases for the main tidal species of the Tamura 1987 catalog [33], together with a mean real barometric pressure admittance. Among these factors, as computed theoretically [34] and verified experimentally [35] in the last years as a consequence of data gathered from several SG around the world, the gravimeter factor δO_1 of the diurnal lunar wave O_1 is usually adopted as a reference wave because its amplitude is large, the ocean load is well known and the atmospheric influence is weak. For such reasons it can be used to test the calibration procedure. We obtained $\delta O_1 = 1.149(6)$, which becomes $\delta O_1 = 1.153(7)$ after correction for the oceanic loading [36]. This value is in agreement with those obtained at the other European stations, which range between 1.152 and 1.154.

The long period of observation of the SG allowed us to test the use of this property for a determination of the calibration coefficient. The above mentioned data set relative to a six month time span was used for a tidal analysis from which a complete set of phases and absolute amplitudes of the tidal components were computed. This information provided us with a high precision local tidal model, with the exception of the longest period components, whose effect can be filtered out. Other data sets collected over periods of six months were compared with the computed tide, after corrections for instrument drift and barometric pressure. A linear regression of the experimental data versus the computed tide gave the best calibration coefficient for each data run. Different values in successive runs can be due to several effects such as changes of the supercurrents or of the verticality of the SG, usually a consequence of helium refilling or instrument maintenance. A self-consistency check of the SG calibration was done, using it to determine, from the experimental tidal signal, a complete set of tidal components, including δO_1. In Fig. 4 we show the δO_1 values relative to the 1992–1999 period. The δO_1 stability, whose central value, after correction for the oceanic loading, is 1.153 with an uncertainty of 0.001, is evident. The constancy of δO_1 allows us to check the correctness of the procedure used to determine the calibration coefficient, provided it is substantially constant over time periods of months.

Let us now consider the gravity signal as recorded in the tunnel under the lake by the superconducting gravimeter. It is comprised of the following contributions: the tide, the lake mass variation, the barometric pressure effect, the instrumental drift, and a residual noise. Its value in μgal can be computed by multiplying the SG output in volts for the calibration factor, which can be obtained in the tunnel, as an alternative to the previously used method, through a procedure of residual noise minimization. Essentially, the new method is based on the knowledge of the tide in the tunnel which, in turn, is derived from that computed in the laboratory for comparison with the FG5 absolute instrument. To begin with, a reasonable value of the calibration coefficient is chosen. Then tide and barometric pressure effects are subtracted from the SG signal in the tunnel. Obviously, the subtracted tide is that computed with the above described procedure starting from the FG5 calibration; a correction for the superconducting gravimeter different position is applied. What is left is a signal due to lake effect, drift and noise. Successively, an iteration procedure betters, step by step, the computed lake admittance and the drift. It stops when the minimal residual noise relative to the chosen calibration coefficient is found. The whole procedure is repeated with a new calibration coefficient giving a new residual noise. The final solution provides the calibration coefficient and the lake admittance which yields the absolute minimal residual noise. The tidal analysis of the signal obtained by removing the lake effect with the previous described technique yields the first two points shown on the left part of Fig. 4. These δO_1 factors are in perfect agreement with the model tide obtained on using FG5 calibration run data, outside the tunnel. Notably, the lake admittance coefficient is almost insensitive to the water level, as shown by the continuous curve in Fig. 5, because of the lake shape.

The experimental weighted mean value obtained from this analysis indicating the gravity dependence Δg on changes of lake level Δh is

$$\Delta g/\Delta h = (3.859 \pm 0.006) \;\; \mu\text{gal}/10 \;\; \text{cm} \tag{3.1}$$

to be compared with its Newtonian value of

$$\Delta g/\Delta h = (3.860 \pm 0.001) \;\; \mu\text{gal}/10 \;\; \text{cm}. \tag{3.2}$$

This last value has been computed assuming a value of 1000 Kg/m^3 for the density of the removed fluid (water minus air). The experimental value was then corrected in order to take into account the change of water and air density with temperature, and also the site subsidence and uplift with lake level changing. As a consequence of these effects an overall correction factor has been evaluated starting from those relative to periods of lake level changes. The correction factor has a non-Gaussian distribution: its average value is 1.00254, with a data spread over a range of ± 0.00162. We assumed an uncertainty of 0.00054. The experimental to Newtonian ratio is then:

$$R = \text{exp/theor} = 1.0023 \pm 0.0017. \tag{3.3}$$

The new calibration factor has also been used to repeat the differential analysis described in Sec. II, which consists of the extraction of about 10000 gravitational change values corresponding to a 10-cm level change at different lake levels. These values are corrected for water and air density variations due to temperature and SG subsidence and uplift. The experimental values, grouped in bins of equal level, are plotted in Fig. 5 together with the standard error of their mean and the theoretical expectation (continuous curve). The final experimental result relative to a water level variation of 7.376 m is 285.37 ± 0.11 μgal which must be compared with the theoretical value of 284.715 ± 0.040 μgal. This differential analysis yields the same result and uncertainty reported in Eq. (3.3) for the ratio R between experimental and theoretical effects. The uncertainty of the ratio takes into account the accuracy of the new calibration factor and the other statistical error sources (mainly vertical deformation of the site) reported in detail in Table I. This ratio may be also affected by a systematic error due to the water table contribution which we have estimated to be about 0.15%. Therefore, as a consequence of this new and more accurate calibration this experiment agrees with the prediction of Newton's gravitational law for distances of some tens of meters to within 0.17%. It agrees also with the results obtained in other analogous experiments [22–25], all performed using lakes with changing water levels. Two of them [24,25] used a high-precision balance to compare the weights of two masses located above and below the variable water level of the lake. The other two [22,23] used mechanical gravimeters with a similar setup. This set of experiments measure G in an interval of effective distances ranging from 22 to 112 m. The effective distance of this experiment is 47 m.

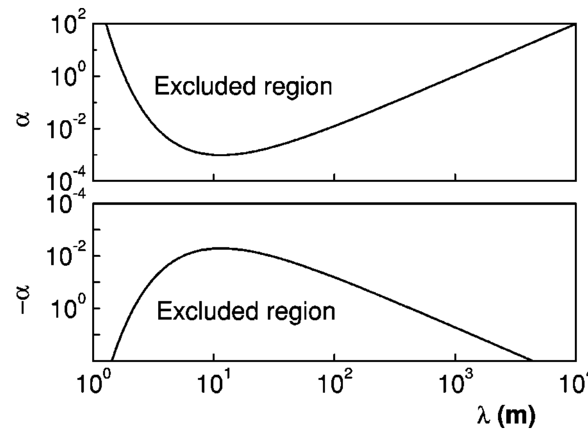

FIG. 6. Constraints on the coupling constant α as a function of λ at 2σ confidence level.

Two final points must to be mentioned. First, is the possibility, for the future, to use the increasingly well known values of the δO_1 factor from measures taken all over the world and their site independence, to verify the calibration of the superconducting gravimeters. Second, we recall how the uncertainty on the Newtonian gravitational constant has recently been increased, so that it is now considered to be at the 0.2% level. It is therefore meaningful to use our data to compute a G value, which turns out to be

$$G = (6.688 \pm 0.011) \times 10^{-11} \;\; \text{Nm}^2/\text{kg}^2. \tag{3.4}$$

This G value is evaluated assuming the validity of the gravitational law in a range up to some tens of meters, and represents a measure obtained with a different method from those previously reported in the literature. It is affected by the same systematic error due to the water table above reported.

This experiment also sets constraints on α and λ values relative to possible deviations from the inverse square law of gravitation. These limits, as computed from our data, are reported in Fig. 6 in a $\log(\alpha)$ versus $\log(\lambda)$ plot, at a 2σ confidence level. The curves set limits on α in the geophysical region comparables to those obtained in other recent geophysical experiments [25].

ACKNOWLEDGMENTS

We wish to acknowledge V. Achilli, M. Errani, and F. Pedrielli for their support in the previous part of the experiment. This research was funded by the Istituto Nazionale di Fisica Nucleare and MURST-Cofin 99, Fundamentals of Gravitation.

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