Bulletin Géodésique (1995) 69: 73–80

Bulletin Géodésique

A calibration system for superconducting gravimeters

Vladimiro Achilli [1], Paolo Baldi [2], Giuseppe Casula [3], Mario Errani [4], Sergio Focardi [2], Marco Guerzoni [2], Federico Palmonari [2], and Giuseppe Raguní [2]

[1] Istituto di Topografia, University of Bologna, Italy
[2] Dipartimento di Fisica-Settore Geofisica, University of Bologna, Viale Berti-Pichat n.8, I-40126 Bologna, Italy
[3] Istituto Nazionale di Geofisica, Roma, Italy
[4] Istituto Nazionale di Geofisica, Bologna, Italy

Received 16 July 1993; Accepted 19 October 1994

Abstract. A new method for the calibration of a superconducting gravity meter is described, in which a 273 Kg annular mass is placed around the meter and is moved up and down. The geometry of the apparatus is easy to model and the accuracy in the computation of the gravity variation induced by the mass, 6.7 μgal, is limited only by the accuracy in the knowledge of value of the gravitational constant. Measurements done in '91 and '92 for the calibration of the instrument GWR-T015 are described. The calibration factor has been determined with a precision of about 0.3%.

1. Introduction

The basic idea of the superconducting gravimeter is to replace the mechanical spring of previous instruments with a magnetic suspension. The mass of the GWR-T015 gravimeter is a 2.5 cm diameter hollow sphere, which is made of superconducting metal and operates at liquid Helium temperature. The superconducting sphere, being diamagnetic, repels the magnetic field produced by two superconducting coils and makes possible an inherently stable support system. The weak field gradient, adjusted by the ratio of the currents trapped in the coils, makes the sphere extremely sensitive to the variations of the vertical component of gravity. The variations of g are recorded measuring the voltage variations induced on the terminals of a third coil whose current represents an active feedback system keeping the sphere centered between two electrodes of a capacitive bridge (Goodkind, 1991). This method, obviously free from the typical mechanical hysteresis of other gravimeters, ensures the linearity of the response which is independent of the spatial configuration of the levitating magnetic field (the sphere is always in the same position with respect to the coils) and is sensitive only to the local variations of the gravitational field; in fact the sphere is fixed in space in a position controlled by a capacitive bridge. In conclusion, the superconducting gravimeter transforms the local variations of the vertical component of gravity into voltage variations with the sensitivity depending in principle only from the space stability of the sphere. As an example, if the vertical position of the sphere is controlled to 1 nm, with a typical gradient being about 1 gal/cm, the instrument sensitivity is of the order of 0.001 μGal (Warburton, 1993). In general, geophysical noise dominates the output of the superconducting gravimeter and limits measurement precision to order 0.01 μGal.

We have calibrated the GWR gravimeter to a precision approaching 0.3% in the frame of an experimental program meant to verify the validity of the Newton's law over distances of the order of 10-100 m (Achilli et al., 1990, 1991).

2. Calibration method

The GWR-T015 gravimeter measures an electric

Correspondence to: P. Baldi

quantity proportional to the recentering force of the ball. To transform voltage variations into gravity variations one has to know the calibration factor of the instrument. For the superconducting gravimeter the calibration factor depends on: the size and mass of the sphere; the dimensions and placement of the magnet coils, guard coils, and the feedback coil; on the final magnetic field distribution resulting from levitating the superconducting sphere. For a given gravimeter, the calibration factor can change only if the superconducting coil currents are changed. Normally, while operating continuously there will be no calibration change.

The simplest method to get the calibration consists in comparing in the same site the superconducting gravimeter tidal signal with the corresponding signal of a well calibrated instrument; adopting as reference an absolute gravimeter, one can get a calibration at 1 % level or better (Hinderer et al.,1991).

In our calibration method we used a moving mass in order to change in a known way the gravity field; the precision of the result depends upon the gravimeter sensitivity compared to the effect induced by the calibration mass, and on the accuracy in the knowledge of the mass distribution and geometry of the body.

The instrument is mounted inside a cryostat, so that it is difficult to know the exact position of the sphere to better than 1 mm. However, the particular geometry of the calibration mass adopted, consisting in a homogeneous solid circular ring with square cross-section, moving vertically along the gravimeter vertical axis, avoids the necessity of a precise knowledge of the position of the sphere. The systematic effect due to an erroneous determination of the horizontal position is in fact well below the measurement error. A similar method has been already proposed (Barta et al., 1985) and it was applied for the calibration of a mechanical gravimeter at the Budapest Geodynamical Observatory (Varga et al., 1991).

The vertical component of the gravitational force exerted by the cylindrical mass is exactly calculable in the simple geometry adopted; it can be expressed as function of the vertical distance

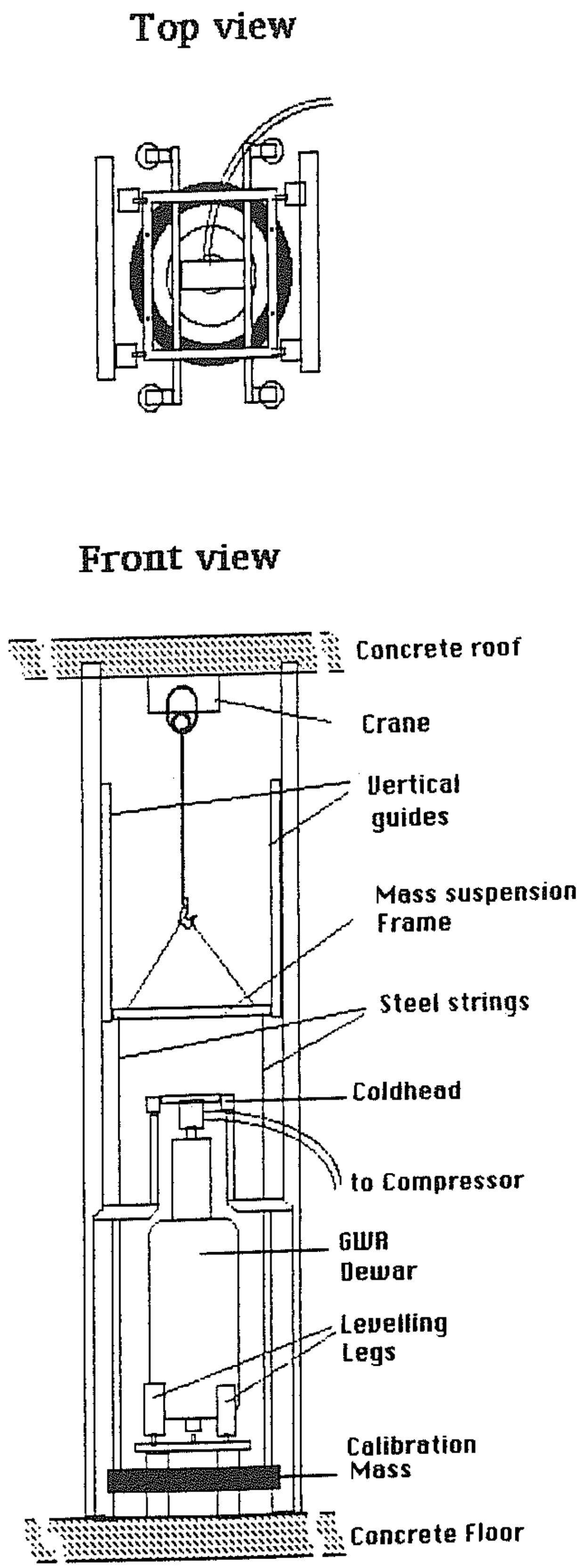

Fig. 1 - Scheme of the calibration system.

h between the mass center and the sphere center, by the following expression:

$$F_z(h) = ma_z(h) = 2\pi Gm \frac{M}{\pi(R_2^2 - R_1^2)H}\phi(h)$$

where

$$\phi(h) = \left[I_1(-) - I_2(-) - I_1(+) + I_2(+)\right]$$

and

$$I_1(\pm) = \sqrt{[(h \pm H/2)^2 + R_1^2]}$$
$$I_2(\pm) = \sqrt{[(h \pm H/2)^2 + R_2^2]}$$

where G is the gravitation constant, m and M the mass of the sphere and of the calibration mass, R_1 and R_2 the internal and external radii, H the thickness. Let z be the vertical mass position measured in a given laboratory reference frame where the gravimeter sphere center has coordinate z_G; moving the mass vertically the acceleration goes from a maximum value $a_z(z_{max})$ to a minimum $a_z(z_{min})$, being zero at $z = z_G$.

The gravimeter response $V(z)$ will be:

$$V(z) = (1/C)[g + a_z(z)]$$

The effect of the moving mass can be obtained subtracting the gravity field g:

$$V_T(z) = V(z) - V(z_G)$$

and fitted by a model experiment as function of three parameters: the vertical position of the gravimeter sphere center z_G, the reference signal $V(z_0)$, and the calibration factor C:

$$C = \Delta g_i/\Delta V_i = \left[a(z_i) - a(z_0)\right]/\left[V(z_i) - V(z_0)\right]$$

Once the best value of z_G is known, one can move the mass from z_{max} to z_{min} and measure the maximum variation of a induced by the mass, in a way that is almost insensitive to all systematics, getting directly the calibration constant:

$$C = 2a(z_{max})/(V(z_{max}) - V(z_{min}))$$

3 - Calibration set-up.

The calibration apparatus for the superconducting gravimeter has been mounted in a suitable building, on the very stable basement of a dismissed nuclear power plant at the ENEA Laboratories near Lago Brasimone. The room, 4.5 × 9 square meters in dimensions, has walls, roof and floor in reinforced concrete, and is practically free from microseismicity due to the human activity. Its characteristics enabled us to assemble the movement apparatus around the superconducting gravimeter in such a way to decouple efficiently the measuring instrument from the mechanical vibrations of the moving parts. In fact, while the first one is firmly based on the floor, the metal structures and the crane for the mass movement are fixed to the roof. Fig.1 shows schematically the calibration apparatus. The superconducting gravimeter is on a 50 cm base above the floor; the stainless steel circular ring of internal diameter 80 cm, 11 × 11 cm^2 cross-section, total mass of 273.40 ± 0.01 Kg, can move about one meter vertically. It is suspended to a light rectangular support sliding into vertical rails, and is moved by an electric crane having two speeds, 3 and 10 cm/s. The mass is kept horizontal by four steel strings 2.5 m long, having a linear mass of 26 g/m; four guiding vertical bars are used to avoid and damp small horizontal oscillations. All moving parts have been kept as distant as possible as permitted by the room dimensions. The design of the apparatus is simple and easily modeled for the evaluation of the gravity signal. The circular ring is composed from six stainless steel layers, 1.83 cm thick: five of them are half-circular segments assembled on the base layer, held together by four precision spines also used to attach the suspension cables. Besides allowing easier handling, the modular construction of the mass allowed its weight to be measured with a balance accurate to 1 g, which resulted in a maximum uncertainty on the total mass of 10 g. Furthermore the machining accuracy of the pieces ensured the global geometry specifications within 0.2 mm. The vertical position of the mass is measured continuously by a wire electronic

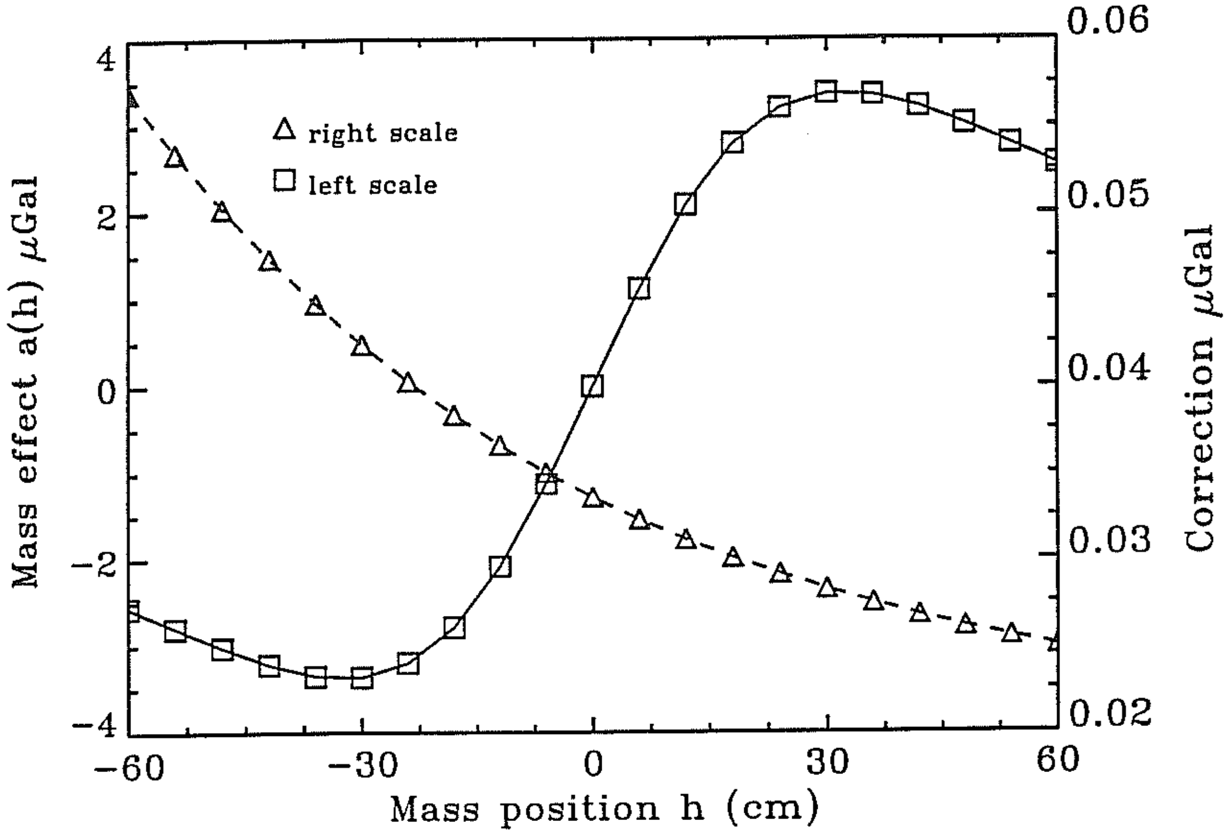

Fig. 2 - Excitation signal $a(h)$ produced by the cylindrical mass movement. The small correction due to the other moving parts of the calibration apparatus is shown superimposed as a dashed line, (notice the different vertical scales).

absolute position digitizer. Two calibration stages on the gravimeter Dewar and on vertical guiding bar allow calibration of the position digitizer and controlling its stability in time.

Adopting the known value of $G = 6.67259(85) \times 10^{-11} m^3 kg^{-1} s^{-2}$, the maximum expected effect due to the mass is:

$$\Delta g = 2a(z_{max}) = 6.75058(86)\mu Gal$$

The contributions of other moving parts have been calculated separately and their sum has been parameterized with a $4-th$ degree polynomial in z. The maximum value of this correction is 0.047 μGal. Fig. 2 shows the excitation signal $a(h)$ produced by the cylindrical mass movement. The small correction due to the other moving parts of the calibration apparatus is shown superimposed as a dashed line (notice the different vertical scales). The evaluation of the systematic error takes into account the various apparatus details discussed above: it amounts to $\sim 0.5ngal$. The error due to the uncertainty in the z position is of the same order (the effect varies of less than $0.0004\mu gal/mm$ in the interval of ± 1 cm around the maxima), while an erroneous determination in the horizontal position of 5 mm gives a relative variation of the maximum effect of about 0.01%. In conclusion the total peak to peak effect measured between the minimum z_{min} and the maximum z_{max} corresponds to a gravity change of

$$\Delta g_{calc} = 6.729(1)\mu Gal$$

with a total relative uncertainty of about 0.01%.

4 - Measurements and data analysis

The gravimeter is equipped with tilt control platforms, that is a feed back leveling system consisting in two orthogonal vertical pendulums and two thermocontrolled expansion columns, as the active elements of the feed back system.

During the calibration this system is deactivated, in order to avoid a tilt of the vertical axis of the instrument, due to the variation of the horizontal component of gravitational attraction during the movement of the mass.

Two calibration procedures have been adopted:
- the first, called *Calibration Signal Scan* (CSS), consists in a series of measurements of the gravimeter response moving up the mass from the reference position z_0 (absolute digitizer reading equal to zero) to various heights z_i, going back each time to the reference z_0, and measuring by difference of signal $V(z_i) - V(z_0)$ as function of z_i. This type of scan was necessary to control the correctness of our experiment simulation by fitting the measured signal with the calculated model excitation.

A calibration session consisted in a series of measurements following the scheme:

$$V_{t_1}(z_0), V_{t_2}(z_1), V_{t_3}(z_0), V_{t_4}(z_2), V_{t_5}(z_0) \dots$$

where $\Delta t = t_{i+1} - t_i = 3 \; min.$, is sufficiently long to smooth out the free oscillations of the gravimeter sphere, and short enough to consider negligeable the non-linear variations of g, especially when measurements are performed in those hours in which the tidal variations are small.

The calibration signal as a function of z is:

$$V(z_i) = V_{t_j}(z_i) - 0.5\left[V_{t_{j-1}}(z_0) + V_{t_{j+1}}(z_0)\right]$$

An example of the results of this approach is shown in Fig. 3.

- The second procedure, called *Peak Signal Calibration* (PSC), consisted in repeated measurements moving the mass from the position of maximum positive effect to the corresponding maximum negative effect. Adopting again a time interval of 3 min., we can compute the total effect as:

$$\Delta V_i = V_{t_i}(z_{max}) - 0.5\left[V_{t_{i-1}}(z_{min}) + V_{t_{i+1}}(z_{min})\right]$$

The position digitizer has an accuracy of the order of $0,2 \; mm$ so that the mass could be positioned easily on both peak positions (z_{max}) and (z_{min}) with the accuracy of 1 mm or less. The critical element may be the value of z_G ; nevertheless, the shape of the function $a(z)$ around the maxima allows relative low accuracy in z.

The results of the calibrations performed in two periods, July-September 1991 and December 1992, using the CSS approach, are listed in Table 1. Three parameter were computed: the position of the sphere z_G, the calibration constant $C = dg/dv$ and an additive constant for the reference signal at the reference mass position $z = 0$. Notice that the best fit z_G values are not the same:

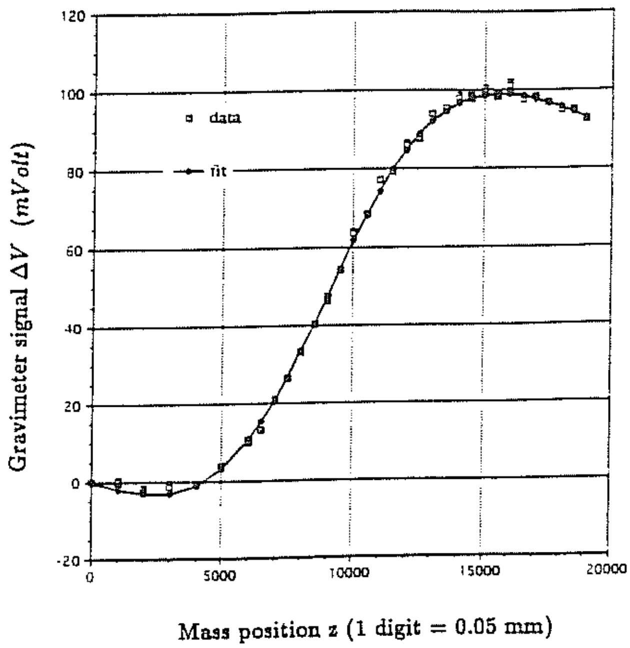

Fig. 3 - Example of a CSS measurement. The solid line is the best fitting of the experimental data represented by little squares in the figure.

EPOCH	No. of Measurements	No. of Positions	χ^2	V_0 (mV)	Z_G (digit)	C (μgal/volt)
1991	123	34	42.2	47.9 ± 0.2	9043 ± 28	66.09 ± 0.31
1992	53	30	47.7	45.3 ± 0.2	4619 ± 30	65.54 ± 0.26

Table 1 - Results of the calibrations performed in two periods, July-September 1991 and December 1992, using the CSS approach.

they correspond to different digitizers used in the two runs, having a sensitivity of 20 and 10 digit/mm respectively. All values measured in each position have been averaged and the associated error is weighted on the number of measurement. The r.m.s. dispersion of individual measurements, evaluated independently, is 1.5 mvolt.

In Fig.4 a typical series of peak to peak measurements is shown. The transition between the two peaks was made at time intervals of 3 min. The results of two runs consisting respectively of 25 and 15 repeated measurements, are:

$$(1991) \quad C = 65.89 \pm 0.16 \mu Gal/V$$

$$(1992) \quad C = 65.69 \pm 0.17 \mu Gal/V$$

This procedure, besides giving results in agreement with those obtained with the CSS method, is much more stable and allow to reduce the statistical errors. In the time interval between the two calibrations, the gravimeter was moved into another laboratory, and we had to make changes in the superconducting coil currents to recenter the levitated sphere. Since the magnetic feedback force (per unit current) is dependent on the exact current and magnetic field distribution, changes in the supercurrents will change the calibration factor. For this reason we used an independent electrostatic force to correct C for changes in the feedback force.

The instrument is provided with an electric circuit which permits application of a known constant potential difference to the capacitive plates which are used to measure the sphere's position. The relative calibration of the gravimeter is measured by its response to the electrostatic force, which acts on the sphere in the same way as a gravitational force. The electrostatic force so applied depends only on the geometry of the capacitance plates, the sphere diameter, and accumulation of electric charge on the surface of the sphere which can slowly change in time and would interfere with this measurement. However, only the force from charge reverses its sign with the sign of the applied potential; so we can remove its effect by measuring the sum of the responses to an applied equal positive and negative potentials. In this way, each electrostatic calibration consists of measuring the sum of ΔV signals for an applied voltage $+V_c$ and $-V_c$ to the plates.

$$\Delta V_S = \Delta V(+V_c) + \Delta V(-V_c)$$

This quantity is independent from the electrostatic charge of the gravimeter sphere and depends only on the geometry of the capacitance plates and sphere, which are constant in time. Therefore, ΔV_s can be used to measure either the stability in time of the calibration, or changes in the calibration caused by recentering the sphere. Although the electrostatic calibration procedure requires interruption of the gravity measurements, it is a simple and fast operation which allows frequent and effective gravimeter control.

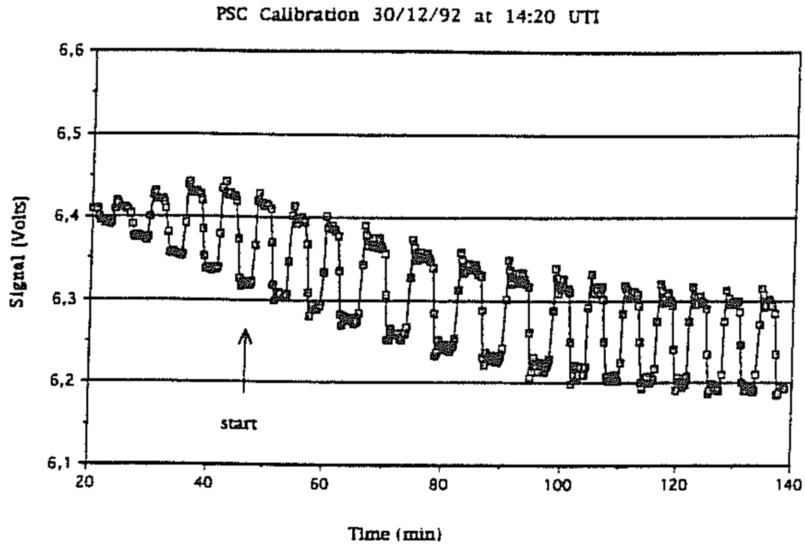

Fig. 4 - A typical series of peak to peak measurements. The transition between the two peaks was made at time intervals of 3 min.

In Table 2 we summarize the results of the calibrations performed in 1991 and 1992. In the third column all the values of C are listed together with the weighted mean of the values derived from the two methods. The weighted mean was performed by weighting the values of the calibration constants obtained with the two methods, with the inverse of the corresponding r.m.s errors.

In the fourth column the electrostatic calibration results are shown. Finally in the last column, the factors obtained in 1991 can be compared to the corresponding 1992 values, having been corrected for the small electrostatic calibration difference.

EPOCH	METHOD	C MEASURED (μ gal/volt)	ELECTROSTATIC CALIBRATION (volt)	C NORMALIZED (μgal/volt)
1991	CSS	66.09 ± 0.31	5.196 ± 0.003	65.64 ± 0.31
	PSC	65.89 ± 0.16		65.43 ± 0.16
	BEST VALUE	65.93 ± 0.14		65.47 ± 0.14
1992	CSS	65.54 ± 0.27	5.232 ± 0.001	65.54 ± 0.27
	PSC	65.69 ± 0.17		65.69 ± 0.17
	BEST VALUE	65.65 ± 0.14		65.65 ± 0.14

Table 2 - Summary of the results of the calibrations performed in 1991 and 1992. In the third column all the values of C are listed together with the weighted mean of the values derived from the two methods, (CSS and PSC).

5 - Conclusions

The apparatus described allows determination of the calibration factor of a superconducting gravimeter with very short time observations. The comparison between different approaches and two calibrations performed in 1991 a nd 1992 with slightly different coil settings, shows a repeatability of 0.3% . As soon as we will have a more accurate local model of tide, we think we could lower the uncertainty of the calibration factor to 0.1% .

The possibility to operate with a superconducting gravimeter characterized by a small drift, and calibrated at this level of precision, will allow to improve the results in the study of the response of a site to different environmental effects, ocean load, groundwater, atmosphere, and other geophysical phenomena.

Acknowledgements

This Work was partly supported by the ENEA-Brasimone Laboratory, under a collaboration agreement between Bologna University and ENEA.

We are very grateful to Dr. B. Ducarme of the Observatoire Royal De Belgique, and Dr. R. Warburton of GWR Instruments, San Diego, for helpful suggestions and critical reading of the manuscript.

We wish to acknowledge Mr. Bacchetti, Mr. Guidi, of the Dept. of Physics of the University of Bologna, and the INFN personnel Mr. Pancaldi, Eng. Cotta, Mr. Lolli ,Mr. Serra and Mr. Torromeo are for the technical support.

The experiment has been made possible by the collaboration of the National Power Agency ENEL and the strong support of the ENEA Brasimone Laboratories. Many thanks to the Director of the Laboratory, Dr. Guermani, who provided us with the necessary room and personnel for the set-up of the experiment: we could take advantage of the competence of Eng. Cassarini, of the invaluable help of the Laboratory technical staff, held by Mr. Taulli, and finally of the continuous collaboration of our contact-persons Eng. Righetti and Eng. Filotto.

References.

Achilli V, Baldi P, De Sabata V, Focardi S, Palmonari F, Pedrielli F, (1990) A measurement of the gravitational constant G in the 10-100 range distance. Frontiers in Particle Physics, Proceedings of the XII Warsaw Symposium on Elementary Particle Physics, Warsaw, Poland. Ed. Z. Ajduk et al, Word Scientific, pp 589-594.

Achilli V, Baldi P, Focardi S, Gasperini P, Palmonari F, Sabadini R (1991) The Brasimone experiment: a measurement of the Gravitational constant G in the 10-100 m range of distance. Proceedings of the Workshop: Non Tidal Gravity Changes. Walferdange, Luxemburg. Cahiers du Centre Europèen de Gèodynamique et de Sèismologie, vol 3, pp 241-246.

Barta G, Hajosy A, Varga P (1985) Possibilities for the Absolute Calibration of Recording Gravimeters. Proceedings of the Tenth International Symposium on Earth Tides, Madrid, Spain, pp 27-34.

Goodkind JM (1991) The superconducting gravimeters: principle of operation, current performance and future prospects. Proceedings of the Workshop: Non Tidal Gravity Changes. Walferdange, Luxemburg. Cahiers du Centre Europèen de Gèodynamique et de Sèismologie, vol 3, pp 81-90.

Hinderer J, Florsch N, Machinen J, Legros H, and Faller JE (1991) On calibration of a superconducting gravimeter using absolute gravity measurements. Geophys. J. Int. 106:491-497.

Varga P, Csapò G, Groten E, Becker M (1991) Laboratory calibration of LCP type gravimeters. Scientific Meeting GM 3, 20th General Assembly of IUGG/IAG, Vienna, Austria.

Warburton R (1993) Private communication.