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20 years of International Comparison of Absolute Gravimeters (ICAG) at the Bureau International des Poids et Mesures (BIPM) in Paris with participation of the BEV


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Abstract

Since 1987 the BEV (Federal Office of Metrology and Surveying) has been operating the absolute gravimeter JILAg-6 which is used for basic measurements to determine or review fundamental gravity stations in Austria and abroad. These stations are the base of the Austrian gravity reference system. A few stations are part of international projects like UNIGRACE [1] or ECGN [2]. The BEV maintains the national standard for gravimetry in Austria, which is validated and confirmed regularly by international comparisons. All these applications require high accuracy and a precise description of the measurement uncertainty. Such campaigns have been organised eight times in an interval of approximately 4 years at the BIPM in Sévres/Paris since 1981. This paper gives an overview of the uncertainty of the measurements reached by the Austrian Absolute Gravimeter and assessed by the international comparisons of absolute gravimeters (ICAG). The history and the results of these ICAGs and especially the performance of the Austrian absolute gravimeter JILAg-6 at these ICAGs are described in detail below. Since 2010 the absolute gravity measurements in Austria have been continued with the new absolute gravimeter FG5 (manufacturer Micro-g Solutions Inc., USA).

Keywords: Absolute gravimetry, metrology, international comparisons, JILAg, FG5, uncertainty

Kurzfassung

Das BEV (Bundesamt für Eich- und Vermessungswesen) betreibt seit 1987 in der Abteilung V1 das Absolutgravimeter JILAg-6 und ab 2010 das Absolutgravimeter FG5, das im Bereich Grundlagenvermessung für die Neubestimmung und regelmäßige Überprüfung von Fundamentalpunkten der Schwere im In- und Ausland eingesetzt wird. In Österreich bilden diese Punkte die Grundlage des Referenzsystems Schwere. Einige dieser Stationen sind Bestandteil internationaler Projekte wie z.B. UNIGRACE [1] und ECGN [2]. Darüber hinaus wird das Gerät im Eichwesen als Normal für die Schwerebestimmung verwendet. All diese Anwendungen erfordern eine hohe Genauigkeit und eine präzise Angabe der Messunsicherheit, die nur durch internationale Messvergleiche gewährleistet werden kann. Diese Vergleichskampagnen wurden seit 1981 insgesamt acht Mal im zeitlichen Abstand von ca. 4 Jahren an dem Bureau International des Poids et Mesures (BIPM) in Sévres/Paris veranstaltet. Dieser Artikel gibt einen Überblick über die erreichte Messunsicherheit des österreichischen Absolutgravimeters anhand der bei den internationalen Absolutgravimeter Vergleichskampagnen (ICAG) erzielten Ergebnisse. Die Geschichte und Resultate dieser Vergleichsmessungen und speziell das Abschneiden des österreichischen Absolutgravimeters JILAg-6 werden genau beschrieben. Seit 2010 werden die Absolutschweremessungen in Österreich mit dem neuen Absolutgravimeter FG5 (Hersteller Micro-g Solutions Inc., USA) fortgesetzt.

Schlüsselwörter: Absolutgravimetrie, Metrologie, Internationale Vergleiche, JILAg, FG5, Messunsicherheit

1. Introduction

The surveying part of the BEV has a very long tradition of gravity measurements dating back to the late 19th century. Absolute free-fall gravity measurements using the Italian instrument IMGC [3] started in Austria in 1980. These measurements formed the beginning of a new gravity reference network in Austria, based on absolute gravity values which replaced the gravity level of the European Calibration Line used before. In 1986 the first Austrian absolute gravity meter JILAg-6 was bought by seven Austrian scientific institutes and operated by the BEV [4]. The new instrument was used to stabilize the Austrian gravity reference network (OeSGN) as well as for scientific investigations in gravity changes. From that time on more than 70 absolute gravity stations were installed in Austria and neighbouring countries and some of them have been regularly monitored [5]. Since 1987 the BEV has been operating the absolute gravimeter JILAg-6 which is used for basic measurements to determine or monitor fundamental gravity stations in Austria and abroad. A few stations are part of international projects like UNIGRACE [1] or ECGN [2]. As a national metrology institute (NMI) the Metrology Service of the BEV maintains the national standards for the realisation of the legal units of measurement and ensures their international equivalence and recognition. Thus the BEV maintains the national standard for gravimetry in Austria, which is validated and confirmed regularly by international comparisons. Such campaigns have been organized eight times in an interval of approximately 4 years at the BIPM in Sévres/Paris since 1981. All these applications require high accuracy and a precise description of the measurement uncertainty. Due to the fact that the JILAg-6 gravimeter can not achieve the high technical standards required nowadays a new absolute gravimeter was purchased in 2010 by the BEV together with ZAMG (Central Institute for Meteorology and Geodynamics, Vienna). Since then the measurements have been continued with the new absolute gravimeter FG5-242 (manufacturer Micro-g Solutions Inc., USA).

The International Comparisons of Absolute Gravimeters (ICAGs) have been organized by the Working Group on Gravimetry of the Consultative Committee on Mass (CCM WGG) and Study Group 2.1.1 on Comparison of Absolute Gravimeters (SGCAG) of Sub-Commission 2.1 of the International Association of Geodesy (IAG) und the Bureau International des Poids et Mesures (BIPM) in Sévres/Paris, France. To determine the precision and measurement uncertainty of transportable gravimeters, you need constant environmental conditions during the campaign. All known kinds of errors arising during the absolute gravity measurements were examined and documented in a technical report. Since 1989 the Austrian absolute gravimeter JILAg-6 participated six times in the ICAGs at the BIPM in Paris (figure 1) and two times in the ECAG in Luxembourg. The results of these ICAGs and especially the performance of the Austrian absolute gravimeter JILAg-6 are reported in this paper.

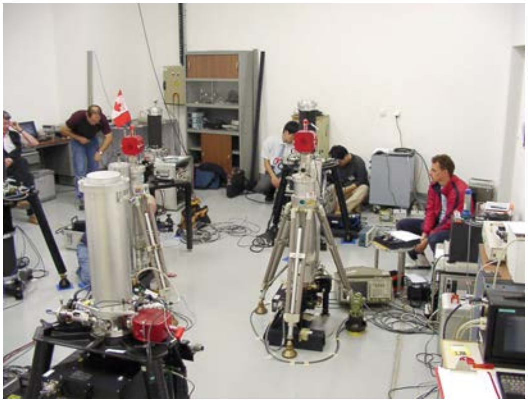

Fig. 1: Absolute gravimeters during the ICAG 2005 at BIPM, site B: In front right the JILAg-6 AG around FG5 instruments and the Canadian JILAg-2 (with the Canadian flag)

2. Description of the International Comparisons of Absolute Gravimeters (ICAGs)

From 1981 to 2009 the Bureau International des Poids et Mesures (BIPM) in Sévres organized the ICAGs. These ICAGs are carried out systematically every 3-5 years with the intention to set up the World Gravimetric Basestation network [6]. The dates are: 1981 (1.ICAG), 1985 (2.ICAG), 1989 (3.ICAG), 1994 (4.ICAG), 1997 (5.ICAG), 2001 (6.ICAG), 2005 (7.ICAG) and 2009 (8.ICAG).

Most of the absolute gravimeters participating in the ICAGs are of the “free – fall type” and only a few use the “fall and rise” method. The principle is similar to the legendary experiment of Galileo Galilei who used the free fall at the Leaning Tower of Pisa in the 16th century to calculate earth gravity acceleration.

A freely falling reflective test mass is dropped in a vacuum. This causes optical fringes to be detected at the output of an interferometer. This signal is used to determine the local gravitational acceleration. The absolute determination of the gravity acceleration arises from the use of physical primary standards of highest accuracy: a Rubidium standard for the time measurement and an Iodine stabilized laser for the measurement of the distance. At every station a few hundred to thousand drops were performed to calculate the gravity from the average of all drops.

The gravity value is determined by an absolute gravimeter at the so-called effective height (or actual height) h over the pillar, on which the gravimeter is mounted. Its magnitude h depends on the type of instrument and on the manner in which it is mounted. For JILA type gravimeters h was on an average of 84 cm and for FG5 gravimeters on an average of 128 cm. In order to compare the absolute gravimeters, it is necessary to reduce the measured gravity values to one. Therefore high precision ties were performed with relative gravimeters as well as gradient measurements calculated over the drop distance from relative measurements. The result of every single ICAG is the Comparison Reference Value (CRV).

Comparing the measurement results of absolute gravimeters of the highest metrological quality in the ICAGs at the BIPM as well as in the "Regional Comparisons of Absolute Gravimeters" (RCAG) is currently the only way to test the measurement uncertainty in absolute g-measurements and to determine the offsets of individual gravimeters with respect to the Comparison Reference Value (CRV). The CRVs in the ICAGs are the g-values from different absolute gravimeters obtained at one or more gravity station at the BIPM.

In 1986 the first Austrian absolute free fall gravity meter JILAg-6 was purchased in cooperation with seven scientific Austrian institutes (ZAMG, GBA, UNI Vienna, TU Graz (2), MUL, OeAW) and was operated by the BEV (staff: Ruess & Ullrich) [4], [5]. Regular monitoring measurements using the absolute gravimeter are carried out at the stations of the Austrian Gravity Network (ÖSGN) [15] and stations abroad (Europe) which are a valuable contribution to a common gravity reference system [5]. Up to 2009 the absolute gravity measurements were performed by the absolute gravimeter JILAg-6 and continued from 2010 onwards with the latest series of the absolute gravimeter FG5-242 (manufacturer Micro-g Solutions Inc., USA).

3. Detailed history and results of every single ICAG

1st and 2nd ICAG:

The first international comparison was carried out in 1981 in Sévres and produced five independent determinations from seven instruments (all that were available at the time). The second ICAG was carried out in 1985 and brought seven independent determinations from eight instruments. As a result of the second ICAG several instruments were found to show notable systematic errors which occasionally reached a few tens of µGals. This circumstance and the intention to set up in the nearest future the World Gravimetric Basestation Network with 3-5 µGal (1 Gal = 1cm/s^2) precision lead to the resolution to carry out comparisons systematically every four years [6].

3rd ICAG:

In autumn of 1989 ten countries participated in the 3rd ICAG. Austria was part of the campaign for the first time. These countries were: Austria, Canada, Finland, Germany, USA, and France with instruments of the JILA type (USA) and different types of instruments from China, Italy, Japan and USSR. On six different pillars 19 independent absolute determinations were conducted with approx. 44,000 drops [6]. The 3rd ICAG was the start of absolute gravity comparisons on a grand scale. From the 3rd ICAG onwards one and the same Austrian absolute gravimeter JILAg-6 participated non-stop in all six following ICAGs from 1989 to 2009. Since the BIPM cannot simultaneously accommodate and provide normal conditions for operation of such a large number of instruments during the ICAGs, it was decided to carry out the measurements in groups [6].

The complete error was determined as the squared sum of the incidental error and the sum of the systematic errors obtained from engineering-physical calculations and specialised laboratory research carried out by the holders of the instruments [7]. The known systematic error for all instruments was 4.3 µGal in this case. The complete square error of the determination of the absolute gravity value by one instrument reached +/- 7.1 µGal at this ICAG. The JILAg-6 performed two measurements at point A2 and A8. Referenced to point A (50 cm over pillar) the final results were [6]:

1. measurement JILAg-6:	980 925 985.4 µGal
2. measurement JILAg-6:	980 925 980.6 µGal
All measurements (CRV):	980 925 976.5 µGal
	(σ= +/- 7.6 µGal)
The average deviation of the Austrian JILAg-6 was:	+ 6.5 µGal.
(1 µGal = 10 nm/s2)	

4th ICAG 1994:

Eleven absolute gravimeters (some 25 were in use world-wide at that time) were operated at five sites and then compared by means of a high-precision gravity network. Since gravity is space- and time-dependent, this comparison series tried to minimize the "space" and "time" required for the measurements. Therefore each AG was allowed to occupy the assigned observation point for five days. Due to the large number of instruments, interchange of observation points was not considered [8]. This was the first time the FG5 absolute gravimeter type took part in this ICAG and FG5 AG's are nowadays the world's most widely used AGs.

The results have indeed shown that there is a systematic unsuspected error (comparator circuit) of approx. 10 µGal between FG5 and JILAg instruments and therefore the final results were corrected accordingly. This error detection underlines the importance of comparisons of AGs.

The results demonstrate that absolute gravimetry can be carried out to an accuracy of 3 µGal to 4 µGal which represents a substantial improvement since the first international comparison (1981: 10 µGal).

The final mean g value at BIPM site A0 at 90 cm was [8]:

g = 980 920 710.2 µGal (σ = +/- 3.3 µGal).

For the Austrian AG JILAg-6 we get transferred from pillar A8 to A0:

g = 980 925 706.0 µGal, which is an average deviation of -4.2 µGal.

5th ICAG 1997:

High accuracy of gravity measurements becomes increasingly important when observations are made at a site where GPS or GLONASS observing systems are operating. Therefore the task of the ICAG is to provide an experimentally based estimation of the level of accuracy of absolute gravimeters [9].

Fifteen absolute gravimeters participated in this comparison. Ideally a large number of gravimeters are ideal for a better determination of the accuracy of the gravity value. On the other hand, including more instruments also increases the chances of obtaining an erroneous determination of gravity, e.g. relative gravity ties. The transfer contributes 1-2 µGal to the scatter of the data from the complete group of gravimeters. As there are a limited number of absolute gravity sites at the BIPM, not all instruments were able to measure at all of them [9].

The mean gravity value obtained at Station A (0.9m) at the BIPM was:

g = 980 925 707.8 µGal with a standard uncertainty of 2.8 µGal.

This is consistent with the results obtained during previous comparisons at this site.

For the Austrian AG JILAg-6 we got transferred to A0:

g = 980 925 702.6 µGal,

which is an average deviation of -5.2 µGal.

Taking the uncertainty of the mean for the last two comparisons we got:

1.1 µGal for 1997 and 1.0 µGal for 1994 [9].

6th ICAG 2001:

Seventeen absolute gravimeters from twelve countries and one AG from the BIPM as well as seventeen relative gravimeters were used during this comparison. The primary objective of the ICAG 2001 was to determine the level of uncertainty for the absolute measurement of free-fall acceleration g on the ground and to try to improve the international uniformity of such measurements [10]. The increasing number of absolute gravimeters participating in the ICAGs

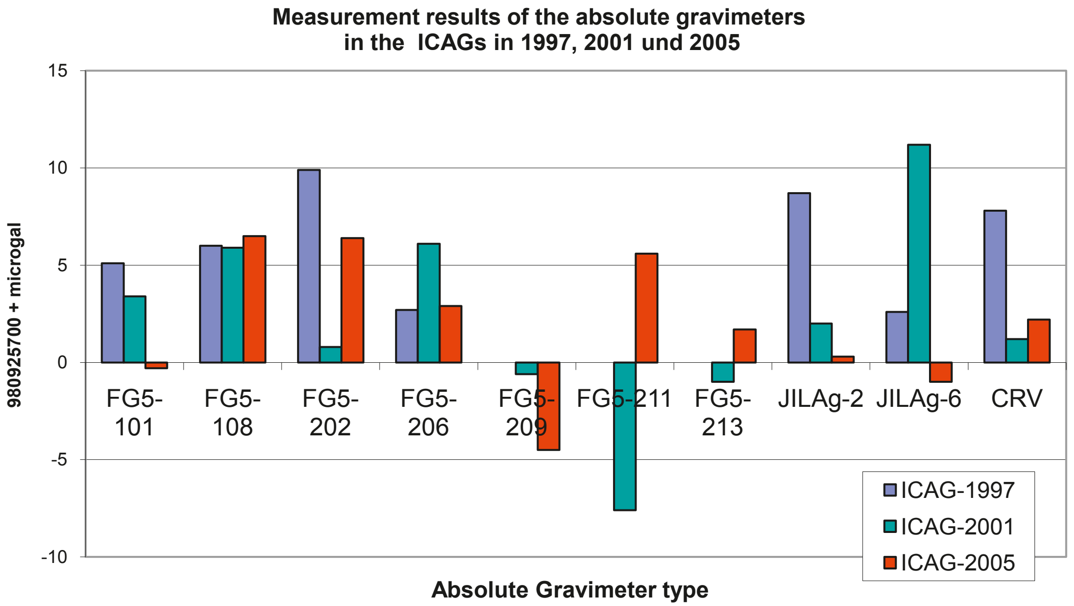

Fig. 2: The results of the ICAGs from 1997, 2001 and 2005 of different AGs [11]

requires the use of several sites at the BIPM micro network, so that these absolute measurements can be made within a relatively short time period. Therefore the sites B were created in a new building.

The g value obtained as a result of a combined adjustment of the weighted data of the absolute and relative measurements during ICAG-2001 at the point A.090 of the BIPM is: 980 925 701.2 µGal with a standard uncertainty of 5.5 µGal.

This value is 6.6 µGal lower than the CRV of ICAG-1997, which was a large discrepancy at this time. This testifies to the high potential of thoroughly maintained and properly operated gravimeters [10]. The Austrian AG JILAg-6 shows an opposite trend and we get transferred to A0: g = 980 925 711.3 µGal, which is 10.1 µGal above the CRV.

7th ICAG 2005:

Nineteen absolute gravimeters carried out 96 series of measurements of free fall acceleration g at the sites of the BIPM gravity network (11 gravity stations). For the first time a complete list of uncertainties was presented. The organization, measurement strategy, calculation and presentation of the ICAG-2005 results were described in a technical protocol pre-developed for the comparison. The expanded uncertainty of each gravimeter was evaluated according to the ISO (International Standardization Organization) guide [12]. The combined uncertainty was evaluated from instrumental and site-dependent uncertainties [11].

The ICAG-2005 was organized in such a way that one could either take part in a pilot study or a key comparison. The key comparison was organized to establish the equivalence of national measurement standards and the pilot study was addressed to geophysical institutes or services. Austria took part in the key comparison with the JILAg-6 absolute gravimeter. The CRV for the ICAG-2005 is at point A0.90: g = 980 925 702.2 µGal (+/- 0.7 µGal) [11].

For the Austrian AG JILAg-6 we got transferred to A0: g = 980 925 699.0 µGal. The combined uncertainty of the JILAg-6 was calculated and estimated with approx. 5 µGal.

In figure 2 the results of the ICAGs from 1997, 2001 and 2005 of different AGs are shown [11]. The results of the JILA-type instruments do not disperse significantly more than the FG5 instruments.

8th ICAG 2009:

The very last ICAG at the BIPM was held in autumn 2009. A total of 63 measurements were made by 21 AGs of which 11 participated in the key comparison (like Austria) and 10 in the pilot study. In the ICAG 2009, five stations located at BIPM were used and each gravimeter measured at three of them. The final report is not yet finished and therefore the CRV 2009 can not be given here. But it is possible to compare the results of the measurements from the JILAg-6 at the same pillars with the last ICAG [11] (see table 1). The deviation of the JILAg-6 measurements at the ICAG2009 from the CRV from 2005 is on an average +8 µGal.

The combined standard instrumental uncertainty of the JILAg-6 is estimated and calculated to be approximately 6 µGal. The main part of this error is due to electronically effects (electrostat-

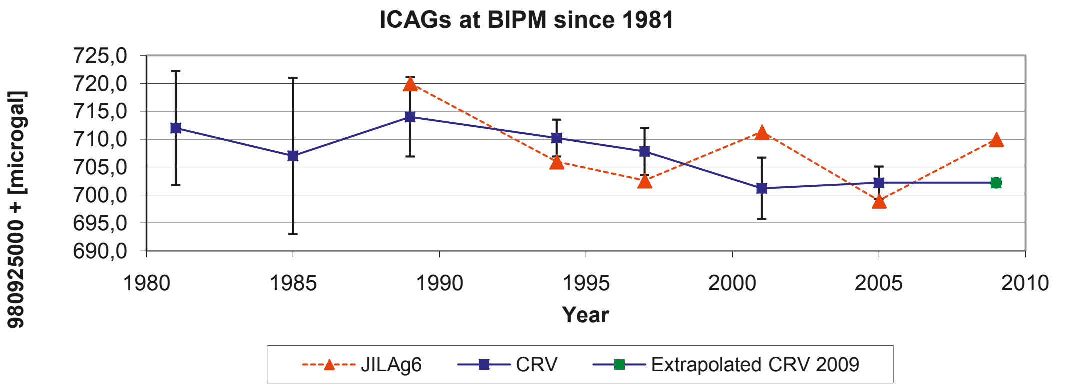

Fig. 3: Comparison Reference Value (CRV) plotted against results of JILAg-6 at the International Comparison of Absolute Gravimeters (ICAGs)

pillar	CRV-2005 [µGal]	JILAg-6 2005 [µGal]	JILAg-6 2009 [µGal]
B1	980 928 012.9	—	980 928 018.7
B2	980 927 997.2	980 928 001.0	980 928 011.4
B5	980 928 020.1	—	980 928 025.4

Tab. 1: CRV (Comparison Reference Value) of 2005 and results of JILAg-6 in 2005 and 2009 at ICAG

ic). Other (unknown) effects (due to the age of the JILAg-6) are estimated with 3 µGal.

The instrumental uncertainty value of approx. 6 µGal can also be derived from experimental comparison measurements on a very quiet station at laboratory environment conditions (Traflberg, Austria).

Due to the bad measurement conditions (site dependent uncertainty) during the measurements of JILAg-6 at ICAG09 the combined uncertainty varies between 7 and 9 µGal.

4. Overall results and interpretation of the ICAGs

Since 1981 the Bureau International des Poids et Mesures (BIPM) in Sévres has organized ICAGs eight times now.

The Austrian absolute gravimeter JILAg-6 has participated non-stop in all six ICAGs from 1989 to 2009. In comparison: the Canadian JILAg-2 participated five times and the Finnish JILAg-5 participated four times. Concerning the follow-up models of the JILA: the FG5-108 of the BIPM and the FG5-101 of the BKG Germany participated five times from 1994 onwards. The IMGC absolute gravimeter (followed by IMGC2), a special device from Italy, participated non-stop in all ICAGs, but it shows major deviations from the CRV.

The result of every single ICAG is the Comparison Reference Value (CRV) and is referenced to a pillar and a special height: like A or B at the BIPM, 90 cm above the pillar.

In figure 3 the distribution of the CRV in comparison to the result of the Austrian absolute gravimeter JILAg-6 is shown (the CRV for ICAG-2009 was extrapolated).

The expanded uncertainty U is defined by the formula:

$$\mathrm{U} = \mathrm{k}\ \mathrm{u_c}$$

where $\mathrm{u_c}$ is the combined uncertainty and k is the coverage factor. An expanded uncertainty defines an interval of the values of the measure and those have a specified coverage probability or level of confidence p. The usual value of 95% was chosen for such a probability in the case of ICAG-2005 [11]. The coverage factor k is used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty. The values of k were obtained under the assumption that the resultant probability distribution is a Student's one and with the evaluation of effective degrees of freedom from the Welch-Satterthwaite formula [12].

The combined uncertainty u_c is the square root of the sum of the squared instrumental uncertainty, the site-dependent uncertainty and the experimental standard deviation. The expanded uncertainties are then used for the evaluation of the weight of each measurement result in the CRV calculation.

From the metrological point of view figure 4 is conclusive, which shows the deviation of the Austrian absolute gravimeter from the CRV. The standard deviation of the deviations is σ = +/- 6 µGal. This value can be interpreted as well as measurement uncertainty. If we look back to the combined uncertainty estimation of the JILAg-6 from the technical protocol 2009 we will find a value of 7.9 µGal. So this value matches the measurement uncertainty of the JILAg-6. From experimental measurements at Traflberg Observatory similar results were derived for the uncertainty of the JILAg-6 gravimeter.

5. European Comparison of Absolute Gravimeters (ECAG)

Since 2003 the Luxembourg's European Center for Geodynamics and Seismology (ECGS) has organized the European Comparisons of Absolute Gravimeters (ECAGs). These ECAGs were held twice in 2003 and 2007 and the Austrian JILAg-6 participated in both comparisons. This was the first time in the history of geophysics and metrology that 15 absolute gravimeters were brought together in the same location for simultaneous observations [13]. The results for the Austrian JILAg-6 at the ECAGs were perfect: at ECAG-2003 the offset to the Comparison Reference Value (CRV) was 2.0 µGal and at ECAG-2007 the offset was -1.2 µGal to the CRV [14].

6. Future comparisons of absolute gravimeters

Absolute gravimeters have been compared in international campaigns (ICAGs) for more than 30

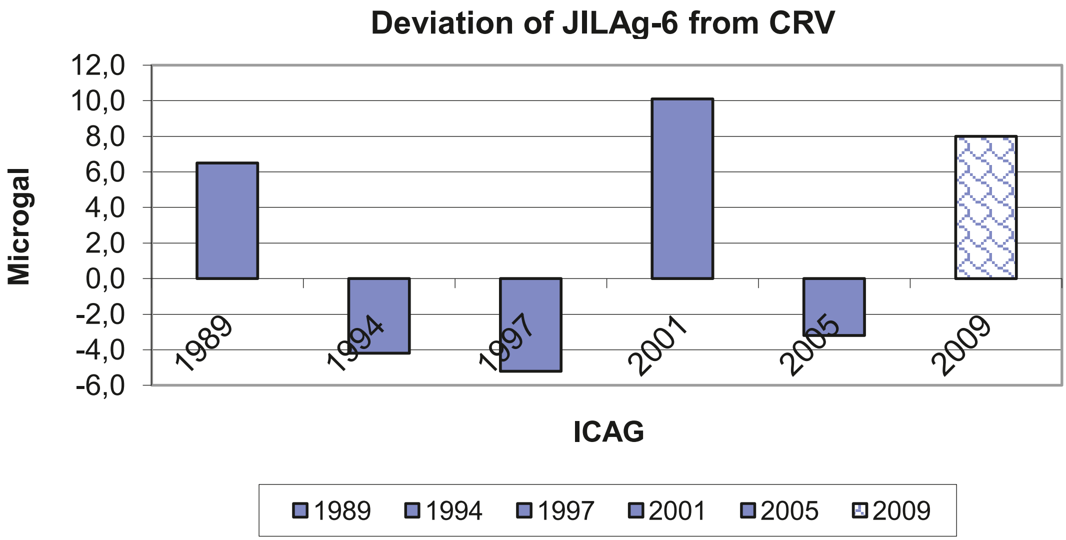

Fig. 4: Deviation of JILAg-6 from Comparison Reference Value (CRV)

years at the BIPM in a cooperation of metrological and geosciences institutions. After BIPM's decision to terminate the local support for the International Comparisons of Absolute Gravimeters, working groups of CCM and IAG came together to discuss the possibilities of continuing the comparisons.

The continuation of the CIPM (International Committee for Weights and Measures) Key Comparisons of Absolute Gravimeters and the official proposal by METAS (Switzerland) to be a pilot of CIPM KC in 2013 hosted by the laboratory in Walferdange (Luxembourg), as well as the proposals from the All-Russian D. I. Mendeleyev Research Institute for Metrology (Russian Federation) and from the National Institute of Metrology (China) to host and pilot the CIPM KC on absolute gravimetry in 2017 and 2021 respectively is under discussion.

Fig. 5: Comparison of three types of gravimeters (GWR, FG5, JILAg) in the gravity laboratory at the Conrad Observatory Traflberg of ZAMG

The definitely next ECAG will be held in November 2011 in Luxembourg, and Austria will take part for the first time with its new absolute gravimeter FG5-242.

The BEV, together with its partners from the Central Institute for Meteorology and Geodynamics (ZAMG) and the University of Vienna - Institute of Meteorology and Geophysics (IMGW) is very much interested to contribute to the realization of a Global Absolute Gravity Reference Network. Therefore the BEV together with the ZAMG proposed the geophysical "Conrad Observatory" (COBS) on Traflberg (TRFB) for the RICAG (Regional International Comparison of Absolute Gravimeters; figure 5). This site is also a station of the ECGN project and the observatory features a specified laboratory for gravity observations with a stationary GWR superconducting gravimeter (SG). The laboratory is situated underground and securely anchored to the rocks, far away from industry and traffic and provides space for up to 10 absolute gravimeters simultaneously.

Summary

The Austrian absolute gravimeter JILAg-6 has been running since 1987 and has been used for a lot of gravity observations in Europe for establishing the absolute level of the gravity reference frame in Austria and abroad. Repeated observations at some selected stations should also give information about the stability of gravity or

its changes. The precision and the uncertainty of these observations, respectively, can only be seen during comparisons with other absolute gravimeters. Therefore every four years a highly representative number of absolute gravimeters were gathered at the BIPM in Sévres / France for comparison purposes. The achievement of the JILAg-6 instrument in the course of these comparisons is presented in this paper and also allows the estimation of the quality of basic gravity values.

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