Processing of the Absolute data of the ICAG01

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Introduction

The objective of this paper is to provide a comprehensive overview of the processing of the absolute gravity data collected during the International Comparison of Absolute Gravimeters in 2001. There is, in fact, really nothing new. The merit of this exercise is to gather in the same document information that is spread through various publications. This should be viewed as a step forward to the way intercomparsions are handled. Indeed, the final results and products of such an experiment can be validated if and only if all the components of the intercomparison (raw data, instrumental set-up and data processing) are fully described and understood. A more "standard" approach to the intercomparison of absolute gravity meters should be adopted as is the case for the other types of intercomparisons organised at the BIPM.
The ultimate goal of the absolute gravity data processing is to provide an averaged absolute gravity value and the precision on this value for each epoch or session of gravity observations during the intercomparsion. This specific processing includes the inversion of the equation of motion (the gravity meter records the time and the position of the falling object during its fall; g is then obtained by inverting the equation of motion) and the corrections of the observations for geophysical or environmental effects (e.g. tides, polar motion and the atmospheric pressure loading and its attraction effect).
We discuss the instrumental and experimental set-ups. We insist that certain parameters, which are controlled by the operators on set-up, cannot be changed once the data have been collected. We also comment on the lack of procedural formality of the ICAG01 specifically in the procedure for calibrating the clocks and the barometers.
We are aware that we have made some decisions regarding the method in which the data processing was performed. We hope that the reader will find all the information he or she needs. In the future, it would be valuable to discuss, amend and agree on a standard protocol for the processing of intercomparison data. This paper, thus, serves as the first iteration to open a constructive debate on how to organize the intercomparison of absolute gravimeters.

1. Set-ups

1.1 Instrument set-up

The data processing starts after the collection of the data. It is assumed that the operator did his or her best in controlling the verticality of the instrument and in adjusting the interferometer. It is also supposed that the reference height of the drops has been correctly and accurately measured. The reference height consists of two parts: 1) one part is measured by the operator with respect to the floor, 2) the second one is measured by the manufacturer for the leg of the height (so-called factory height) inside the absolute gravimeter which is not accessible to the operator. The operator is also responsible for using a calibrated clock, laser, barometer and for checking the clock of the computer. It should be pointed out that a wrong time on the PC will only affect the tides correction.
During ICAG01, the lasers for all the gravimeters were calibrated by Dr. Chartier, Former Head of the Length Section at the BIPM (Vistuskhin et al., 2002), following strict rules laid down by calibration protocols.
Conversely, the clock calibration procedure for ICAG01 was done in a less rigorous fashion. There are currently many methods for calibrating clocks at standards institutes. The protocol used during the ICAG01 is not unanimously accepted as being optimal. In addition, not all of the calibrations were performed on site at the BIPM. Some calibrations were simply supplied by the operator themselves. We need to agree on a protocol for the clock calibration as the one in currently used everyday in standards laboratories. An independent team should be in charge of this calibration at the

intercomparison site to insure consistency for the procedure.

The situation for the calibration of the barometers is even worse. In most cases, the data processing team was provided with only the manufacturer's determination of the calibration. In a few cases, the operators who have access to a calibration device for pressure sensors provided us with their calibration factors. Again, having the ability to provide an on site calibration of the barometers would be extremely valuable and would enhance the value of an intercomparison.

2.2 Experiment set-up

During the IAG01, the parameters, that control the sequence of measurements, were chosen by the operators. The settings for the number of drops per set, the number of sets, as well as, the minimum duration of the measurements at a specific site were left to the operators' discretion. The number of recorded fringes (100, 150, 700 or 1000) is more or less standard depending on the type and the generation of the gravimeters. Further investigations are required to determine if there is a sensitivity in the intercomparsion results to the choice of these parameters. In other words, should all the gravimeters measure at the exact same time?

3. Software

The software we used for the data processing has been developed by Micro-g solutions, Inc. Different versions have been used depending on the format of the raw data. For most of the instruments, the g-soft version which runs on Microsoft Windows® has been used. If the data were taken with the DOS-software, Olivia, the data format was converted into the g-soft format using a subroutine provided as part of the g-software package. However, a few instruments operating with old electronics are not compatible and the program, Replay, (Dos or Unix version) from Olivia was required (Table 1).

The different software versions contain the same coded algorithms for computing the g-values and the geophysical corrections. The only difference is in the data input format. There is an exception concerning version 3.14 of Olivia where there is a bug in the way the clock frequency parameter is handled in the software

In this version, if the clock calibration shows that the clock is going too fast, the clock frequency value should be set as if the clock is going too slowly (S. Williams, personal communication, 2001).

Table 1. Different versions of the software used for the data processing

Instrument	Software version
IMGC/JILAg-5	Data processed by the operators
FG5-105	Replay 2.2 (Dos Version)
FG5-108	Replay 2.2 (Unix Version)
FG5-213	Replay 3.14*
Others	g-Soft Version 1.0823

* Clock correction is inverted (see text)

3.1. Equation of motion

The raw observations for each drop consist of a vector of time and position of the free-fall test body during a drop (t_i, x_i). The dimension of the vector depends on the number of recorded fringes, which is instrument dependent. For each drop, the following least-square fit is performed (Niebauer et al., 1995 a)

$$x_i = x_{top}\left(1+\frac{\gamma}{2}\tau_i^2\right)+v_{top}\left(\tau_i+\frac{\gamma}{6}\tau_i^3\right)+\frac{g_{top}}{2}\left(\tau_i^2+\frac{\gamma}{12}\tau_i^4\right)+\left(A\sin\omega_l\tau_i+B\cos\omega_l\tau_i\right)$$

where

$$\tau_i = t_i - \frac{(x_i - x_{top})}{c}$$

in order to take into account the time delay due to the finite speed of light,(t_i, x_i), the time and position of the free-fall test body during a drop, c speed of light, γ the vertical gravity gradient. The five unknowns are: position x_{top}, velocity v_{top}, acceleration due to gravity g_{top} at x=0, and A and B for the laser modulation.

In fact, we used an equivalent set of equations:

$$x_i = x_0 + v_0\left(\tau_i+\frac{\gamma}{6}\tau_i^3\right)+\frac{g_0}{2}\left(\tau_i^2+\frac{\gamma}{12}\tau_i^4\right)+\left(A\sin\omega_l\tau_i+B\cos\omega_l\tau_i\right)$$

where

$$\tau_i = t_i - \frac{(x_i - x_0)}{c},$$

where x_0, v_0, g_0 stand for the initial position, initial velocity and gravity value at t=0. The relation between the two definitions of g is

$$g_{top} = g_0 - \gamma\, x_0$$

3.2 Parameters

To run the software, values for a number of parameters are required to be defined. These parameters include: the fringes selection, the vertical gravity gradient, and corrections for tides, atmospheric pressure and polar motion.

The start and stop fringes need to be specified during the data processing. The optimal start and stop fringes (determined by a minimization of the scatter on the data) vary from instrument to instrument. The start and stop fringes that we selected is described in Table 2. We essentially adopted a standard value for all the FG5s equipped with the fast electronics card. For the other instruments, we choose the values recommended by the operators. We know that our choice is not the optimal one. In the future, a criterion to determine the optimal choice of the fringe range for each instrument needs to be specified. We did check that any reasonable selection of fringes (i.e. removing the last fringes during the catch) does not affect significantly the final results (the final values are within 1 μGal). We should point out that this not the case for all instruments. At least one of the FG5s displays a great sensitivity in the results as function of the fringe selection.

Table 2. Fringes selection

Instrument	Start Fringe	Number of fringes
FG5's/Jilag-6	30	600
FG5-105	2	90
FG5-108/206	1	150
Jilag-2	60	550
A10-003	120	630

During the data processing, we differentiated the gravity gradient γ in the equation of motion and the vertical gravity gradient used to transfer the g value from the top of the drop to a common reference height of 0.9 m. For γ, we use the vertical gravity gradient determined at 1.20 m for the FG5s and at 0.90 m for the A10 and the Jilags. For the transfer at 0.90 m, we used three different values for each of the following groups of instruments: 1) FG5s, 2) A10-003, Jilag-2 and Jilag-6, and 3) FG5-101 (small dropping chamber). The polynomial coefficients for the gravity field distributions over the sites and corresponding vertical gravity gradient at heights 0.9 m and 1.2 m can be found in Vitushkin et al. (2002) Table 3.

The raw gravity values are corrected for three geophysical effects: 1) gravity tides, 2) gravity attraction and loading due to atmospheric pressure variations, and 3) the change in the centrifugal acceleration due to the polar motion.

The tidal predictions have been estimated using observed tidal parameters from Sèvres provided by ICET (Table 3). These observed tidal parameters include the solid Earth tides and the attraction and loading effect from the ocean tides. They were obtained from the analysis of a registration of 292 days of a LaCoste-Romberg spring gravimeter at the BIPM in Sèvres.

Table 3: Observed Tidal Parameters (delta factor) for Sevres from the Data Bank of the International Center for Earth Tides

Wave	Amplitude Factor	Phase-Lead (degree)
Long Period	1.0000	0.000
M_f	1.1909	0.360
Q_1	1.1503	-0.290
O_1	1.1494	0.014
M_1	1.1446	1.945
K_1	1.1359	0.835
J_1	1.1885	1.408
OO_1	1.1514	2.680
$2N_2$	1.0885	6.610
N_2	1.1602	4.352
M_2	1.1895	3.173
L_2	1.1709	3.395
S_2	1.2000	1.404
M_3	1.0418	2.353

The pressure correction is computed using the following formula (Niebauer et al., 1995b):

$$C_p = A\,(P_o - P_n)$$

where

C_p = Barometric pressure correction (microgal)
A = Barometric admittance factor -0.3 μGal /mbar
P_o = Observed atmospheric pressure (mbar)
P_n = Nominal pressure at the site given obtained from the formula:

$$P_n = 1013.25 * (1 - 0.0065\frac{h_m}{288.15})^{5.2559}$$

where

P_n = Nominal pressure (mbar)

h_m= Elevation of the site with respect to mean sea level (m)

The polar motion correction is computed using the formula derived by Wahr (1985). The daily pole position can then be obtained from the International Earth Rotation Service (IERS):

$$\delta g = -1.164 \ \omega^2 \ a \ 2 \ \sin\varphi \ \cos\varphi \ (x \ \cos\lambda - y \sin\lambda)$$

where

δg = polar motion correction (microgal)
ω = Earth's angular rotational velocity (rad/s)
a = equatorial radius (semi-major axis) of reference ellipsoid (m)
φ = latitude of the site
λ = longitude of the site
x,y = pole coordinates as provided by IERS (rad)

Conclusions

This paper demonstrates that some improvement could be made in organizing the intercomparisons of absolute gravimeters. The idea being that improving the standard set up and data processing protocols would result in gravity determinations that are more readily interpretable in terms of the differences of the instruments and not for example operator or calibration issues. Some actions should be taken to insure that the fraction of the differences between instrument determinations of gravity derived from the operators is minimized. For example, it would be extremely valuable if each instrument set-up could be checked by another team or perhaps even by a control team. We feel strongly that we need to define the protocols for the calibration of the clocks and the barometers of the gravimeters, the calibration of the lasers being already standardized. In this way, we feel that differences in the observed gravity values will be a true measure of the differences of the instruments themselves.
Errors in the determination of certain parameters, i.e. vertical gravity gradient, tides, atmospheric pressure correction etc., will also affect the final determination of g. Because as long as the same corrections are applied to all instruments in a similar manner it is unlikely that this will affect the differences between instruments (if the data are collected very close in time), however the choice may affect the final g-value. This issue was not discussed in this paper.

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