USE OF GRAVITY MEASUREMENTS IN DEFINING AND REALIZING REFERENCE SYSTEMS FOR GEODYNAMICS

J. D. Boulanger, N. N. Pariisky
Academy of Sciences of the USSR
Institute of Physics of the Earth, Moscow
L. P. Pellinen
The Central Research Institute of Geodesy
Air Survey and Cartography, Moscow

ABSTRACT

Single measurements of gravity cannot give sufficient information about the position of measuring points with respect to some terrestrial reference system. Only a set of gravimetric stations all over the Earth combined with a determination of their coordinates allows one to determine (from the solution of Molodensky's problem) the heights of these stations with respect to a level ellipsoid with center at the geocenter. Given in addition their heights above some reference ellipsoid, whose position in the Earth's body is fixed through a set of reference points on its surface, the position of the geocenter in the same reference system may be obtained.

Wider opportunities are opened through repeated gravity measurements. They are bound up with the fact that an essential part of non-tidal variations of gravity is caused by the height variations of gravity stations. In this report the relation between gravity and height variations is considered, taking into account the latest results of gravity variation investigations.

RELATION BETWEEN GRAVITY VARIATIONS AND HEIGHT VARIATIONS OF GRAVITY STATIONS

Neglecting the centrifugal force variations, for the time being let us represent, according to [1], the variation dg of gravity anomalies on the Earth surface by expansion in spherical harmonics. For the spherical approximation we have, for harmonics of the n'th degree

$$dg_n = (n - 1)\frac{dV_n}{R} - 2\frac{\gamma}{R}\,dH_n^{\gamma} \quad . \qquad (1)$$

Here dV is the variation of the gravity potential at the Earth's surface, dH^{γ} is the normal height variation (equal to $dH - d\zeta$ where dH is the geodetic height variation, $d\zeta$ is the quasigeoidal height variation), R

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is the mean Earth radius, and γ is the mean gravity at the Earth's surface.

Zero and first degree harmonics are worth special notice. If effects associated with possible time-dependent variations of the universal gravitational constant (less than 0.1 μGal per year) are neglected, then $dV_0 = 0$ and we obtain

$$dg_0 = -2^{\gamma}/R \; dH_0 \quad . \qquad (2)$$

We assume that dg_0 and the observed variations of the angular velocity a) of the Earth's rotation are both caused by the variations of its mean density (or rather radial deformation of certain spherical layers). The known values $d\omega/\omega$ may then be used to estimate the order of possible variations of the radius of the Earth and surface gravity values. According to [2,3], observed irregular variations $d\omega/\omega$ amount to 0.5×10^{-8} for periods of 1 to 3 years, corresponding to the values $dH_0 = 1.8$ cm and $dg_0 = 5.7$ μGal when uniform expansion (or contraction) takes place. When the deformation occurs only in upper layers of the Earth's crust these values will be twice as large.

Using (1) we have for the first degree harmonics

$$dg_1 = -2^{\gamma}/R \; (dH_1 - d\zeta_1) \quad . \qquad (3)$$

If some initial reference system has been fixed the dH_1 term would characterize the general displacement of the stations of repeated gravity measurements and the $d\zeta_1$ term that of the geocenter. The result obtained is quite obvious: repeated gravity measurements yield information only about relative displacements of points on the Earth's surface and the geocenter (see also [4,5]).

Hence it is important that repeated gravity measurements be carried out at those stations that realize the global geocentric reference system. Achievement of an accuracy of 10 μGal in absolute or adequate relative (also useful in this case) measurements would allow determination of relative displacements of these stations and the geocenter with an accuracy of 3 cm, which is not yet attainable by other methods. The results obtained will be used not so much for determination of geocenter displacements relative to the Earth's crust as for studying the stability of the reference system fixed by the stations on the Earth's surface.

The work of S. M. Molodensky [1] confirms that elastic Earth deformations in general result in strongly correlated temporal variations of gravity potential and normal heights. He uses the expression for dg_n in the form

$$dg_n = -2^{\gamma}/R \; dH_n^{\gamma} \; (1 - \Xi_n) \tag{4}$$

and gives an estimate of the parameter Ξ_n that depends on the depth ℓ and the character of the deformation source causing the gravity variations. As shown in [1], $|\Xi_n| < 0.1$ for dilatation stresses, for depth ℓ less than 1930 km. For shear stresses $|\Xi_n| < 0.3$. The fact that the second term in (1) is clearly predominant shows the possibility of estimating the order of gravity variations from vertical crust movement data. The latter amount to some mm per year, and corresponding annual variations of gravity are 1-2 μGal.

Planetary gravity variations corresponding to sources located near the core-mantle boundary have some specific features. According to [1] variations of this kind need not be accompanied by height variations at all.

An estimate of possible planetary variations dg_2 is given in [2,3] under the assumption that the values $d\omega$ observed are responsible. It is supposed that the deformation axis conincides with the rotational axis of the Earth so that dg_2 comprises only the second zonal harmonic. The ratio of dg/g to $d\omega/\omega$ has its maximum value at the pole, at a depth $\ell = 120$ km. When $d\omega/\omega = 0.5 \times 10^{-8}$, the variations dg can be as much as 29 μGal. The change of dg-variations between the equator and latitudes 60° amounts to 33 μGal.

GRAVITY VARIATIONS CAUSED BY CENTRIFUGAL FORCE CHANGES

The most important effect is caused by polar motion. According to [6,7] the variations expected do not exceed 5 μGal and are largest in higher latitudes. They can be computed from polar motion data within accuracy limits not exceeding some tenths of μGal.

Irregularities in the Earth's rotation give rise to neglected gravity variations of about 0.03 μGal, if $d\omega/\omega = 0.5 \times 10^{-8}$.

ATMOSPHERIC EFFECTS AND INFLUENCE OF WATER REDISTRIBUTION IN THE EARTH'S CRUST

Air and water masses are the most mobile components of our planet and the effect of their movement on gravity variations has been pointed out by many authors.

Atmospheric corrections amount to some tens of 1 μGal but they may be easily accounted for from air-pressure distribution

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data on the Earth's surface. Only the indirect effect of Earth's crust deformations caused by air-pressure variations remains unclear.

Accounting for gravity variations caused by sub-soil water level variations is the most difficult problem of high-recision gravimetric measurements. From Vikhirev's [8] estimates the effects of natural sub-soil water level variations may be observed practically everywhere. The highest amplitudes of gravity variations caused by variations of the mean annual sub-soil water level amount to 70 μGal. The duration of such variations may be 10 years or more. They are superimposed on annual variations that cause dg-variations of as much as 100 μGal.

The effects of water quantity changes at great depths are expected to be signigicant in extensive artesian basins and may even surpass those of sub-soil water level variations.

Certain problems arise in coastal areas because of water-level variations and corresponding loading on the lithosphere.

Taking into account that high-precision gravity stations are not numerous, the sites for these stations should be chosen on bedrock outcrops. But in such places uplifts of the Earth's crust can often be observed. This is why conclusions about gravity variations based on local observations may turn out to be unrepresentative when studying global geodynamic processes and establishing an Earth reference system. In order to diminish the effect of local gravity variations other measurements should be taken at the same time as hydrogeological investigations: for example, repeated relative gravity measurements between the fundamental stations and closely located satellite stations.

RECENT INFORMATION ON VARIATIONS OF ABSOLUTE GRAVITY

In the late sixties a breakthrough took place in instrumental gravimetry. New instruments – absolute ballistic gravity meters – were developed. At present these instruments have higher accuracy than those for relative gravity measurements, and allow determination of global gravity variations even when only a limited number of stations are used. The stationary absolute gravity meter of Prof. Sakuma in Sèvres, France, and the transportable one of Prof. Faller in USA have been used to determine the origin and scale of the International Gravity Standard Net of 1971 (IGSN-71). Regular absolute gravity measurements were carried out in Sèvres from 1967 to 1973.

A transportable absolute instrument named GABL has been developed in the Institute of Automation and Electrometry of the Siberian Branch of Academy of Sciences of the USSR. The measure-

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ments with this instrument started in 1972. Since the instrument has been a somewhat improved and at present allows gravity measurements with a relative accuracy of about 6 to 8 × 10^{-9}. A little later a transportable gravity meter was developed in Italy. In 1977 the GABL-instrument was compared with the Italian absolute gravity meter and with that of Prof. Sakuma in Sèvres. This comparison has confirmed the high accuracy of all three instruments.

Let us review in detail two groups of measurements with the GABL-instrument.

Boulanger [9,10] has compared gravity values at European stations of the IGSN-71 Potsdam S-13 (two determinations), Helsinki and Sèvres A_3, obtained in 1976-78 either with the GABL-instrument or by relative methods in the system of the International gravimetric station at Ledovo (Moscow), with the results obtained in 1969-70 when establishing the IGSN-71 system. The mean increase in the value of gravity at these stations is 45 ± 2.7 μGal.

The change recorded seems to be explained as follows. According to Prof. Sakuma's data the least gravity value recorded in Sèvres was observed when establishing the IGSN-71. This value increased in 1972 by 45 μGal. When adjusting the IGNS-71 the g-value in Sèvres was given a very large weight and the gravity value obtained in 1969 was adopted as the origin of the system. The result was that gravity values at all the stations of IGSN-71 were too low.

In Figure 1 the results of repeated gravity determinations carried out with the GABL-instrument at the stations Novosibirsk, Ledovo and Potsdam are presented according to data obtained by Boulanger. For the sake of better visual demonstration all the meaurements are reduced to the gravity value at Ledovo. It can be seen that in 1975-78 the mean rates decrease in the gravity values at all three stations are practically identical and equal to 9.9 ± 1.3 μGal/year. In the first approximation the variations observed may be represented as quasiperiodical with a period of 5 years and an amplitude of about 20 μGal. Note that a similar gravity variation with about the same period and amplitude of about 25 μGal was observed in Sèvres from 1967 to 1973. The measurements with the GABL-instrument were carried out at three stations situated along a line over 5.000 km long, so this phenomenon may be said to extend over at least a considerable part of Eurasia.

For further investigations of the observed phenomenon it will be necessary to continue the observations at former stations and at the same time to extend them to other stations. It is obvious that the cause and character of gravity variations observed,

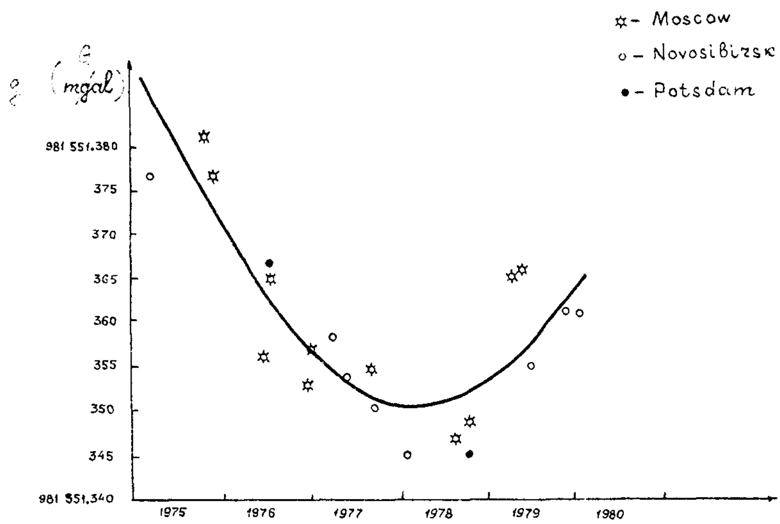

Figure 1. Secular change in gravity referred to the gravity at Ledovo.

as well as the effect of systematic instrumental errors, may be decided with greater certainty after carrying out additional regular comparisons of ballistic gravity meters of different kinds and simultaneous absolute measurements at some stations located far away from each other.

SOME CONSIDERATIONS CONCERNING GLOBAL INVESTIGATIONS OF NON-TIDAL GRAVITY VARIATIONS

For global investigations of non-tidal gravity variations aimed at realizing reference systems for geodynamics it is necessary to perform repeated measurements at a great number of stations uniformly distributed on the Earth's surface. Such a net may simultaneously decide whether irregular variations of the Earth's rotation are connected with variations of the inertia tensor or with internal motions.

Sites for these stations should be chosen to be stable hydrogeologically, if possible, on crystalline bedrock not less than 100 km seacoasts and large lakes. To diminish the effects of local vertical crustal movements and other factors resulting in local gravity variations, it is desirable to establish in the vicinity of each station special satellite-stations connected with the primary ones by high-precision relative gravity measurements carried out at regular time intervals. It is also desirable to establish a net of stations at which regular measurements by stationary instruments can be carried out. The tidal parameters should be determined at the stations of repeated measurements

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using several instruments. Data describing the hydrologic regime, atmospheric conditions and height variations with respect to sea-level should also be recorded. The published results should contain detailed information about all the reductions made, or the data necessary for calculating such reductions.

The instrumental potentialities of gravity measurements are far from being exhausted. Let us hope that these measurements will in the future become one of the most effective means of investigating geodynamic phenomena and establishing global coordinate systems.

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