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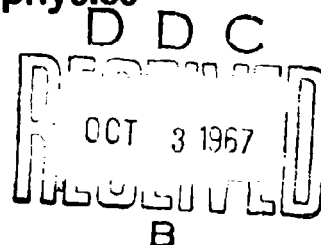


AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

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RESEARCH TRANSLATION

**Excerpt from the Report of the Soviet Geophysical
Committee, Academy of Sciences of the USSR,
to the 14th General Assembly of the
International Union of Geodesy and Geophysics**



OFFICE OF AEROSPACE RESEARCH
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CHAPTER 5. DETERMINATION OF THE FIGURE, DIMENSIONS, AND GRAVITATIONAL FIELD OF THE EARTH

In the course of the reporting period, papers have been published in the Soviet Union on the further development of Molodenskiĭ's theory. Using the derivation of Marych, Pellinen (1967) pointed out the identity of the results of computation of quasi-geoid heights and deflections of the vertical at the earth's surface by Molodenskiĭ's 1960 formulas with allowance for Arnold's corrections.

Eremeev (1967) proposed a method of numerical solution of Molodenskiĭ's integral equation for the density of a simple layer. The advantage of this method lies in the uniformity of operations in all the approximations and the absence of apparent disturbances of the process of convergence of the successive approximations for slopes of the physical surface greater than 45° .

In deriving formulas for the deflection of the vertical, one must bear in mind the correction of Brovar (1965a) and the earlier note by Marych (1964a). Since the effect of slopes of the earth's surface on the deflection of the vertical is an order of magnitude greater than their influence on quasi-geoid heights, the formulas for the deflections of the vertical must include small terms that can be neglected in the derivation of quasi-geoid heights.

Brovar (1965a) also refines the solution of Molodenskiĭ's 1960 integral equation. However, Eremeev points out in the abovementioned article that the refinement relates to terms that are negligible owing to

the approximate nature of the starting equations. The terms to be refined have an order of flattening as compared with the principal terms.

Pursuing research reported by Molodenskii in 1945 (Trudy TSNIIGAIK, No. 42), in the study of the physical surface of the earth and its external gravitational field Ereemeev and Iurkina (1967a) establish the boundary condition for the disturbing potential (a condition used in the theory of the figure of the earth) on a surface to be determined rather than referring to a sphere or ellipsoid in the determination of the regularized geoid and to a surface obtained by plotting from the reference surface of the normal heights only.

In the allowance for the effect of distant zones in Molodenskii's formulas of the first approximation, Pellinen (1965b) proposed a method of computation for the sum of the average values of the gravity anomalies and for the G_1 -correction with respect to trapezoids of the order of $1^\circ \times 1^\circ$ and greater, avoiding determination of those corrections at individual points. To the accuracy of a small term, that sum is equal to the sum of the mean partial topographic gravity anomaly and the mean Bouguer reduction with selection of the optimal density of the intermediate layer. It was also shown that in computing deflections of the vertical, one can, with a negligible error, exclude from the gravity anomalies a constant term equal to the anomaly at the point under study.

In a paper by Ereemeev and Iurkina (1965a), the derivative of the disturbing potential along a tangent to the physical surface is expressed through the values of the gravity anomaly and disturbing potential at points of that surface. In the expressions for the disturbing potential deflection of the vertical, and Stokes' constant obtained on the basis

of Molodenskii's integral equation for the disturbing potential, they isolate a part that constitutes the Stokesian approximation to those quantities. For computation with a relative accuracy of the order of the earth's flattening, the subintegral functions of the corrective terms are represented through the elevations and geodetic latitudes and longitudes of the point under study and a running element of the earth's surface, and through slopes in the running element. The expression for the deflection of the vertical is studied with a model earth in the form of a cone situated on a reference plane. This principle of computations on the basis of Molodenskii's integral equation for the disturbing potential was studied by Īurkina and Starostina with the same model. In articles by Īurkina and Aleksashina (1965) and by Īurkina, Karachanskaia, and Starostina (1966), the individual corrective terms of the expression for Stokes' constant and the mean value of the square of the slopes were evaluated for a mountainous area.

Stoĭnov (1966) expressed the direct deflection of the vertical through values of the gravity anomalies and disturbing potential at running points of the earth's surface. The derivation of Molodenskii's integral equation for the disturbing potential was used as the basis.

Ostach (1967a) synthesized a singular integral equation for the Green's function of Molodenskii's problem. The solution of that equation by expansion over the parameter k was examined. The determination of Stokes' constants with Green's functions was also examined.

In a number of papers, V. V. Brovar described his quests for new solutions to Molodenskii's problem, the determination of the external gravitational field of the earth from values of gravity on its surface. The essence of his efforts was described in brief form by Brovar in a report to

the IUGG Assembly in Berkeley published in Bull. Géod., 1964, No. 72, 167-173. As a basis for the formulas for the disturbing potential and its derivatives above the earth, Brovar (1963b) took a solution to Molodenskii's equation for the density of a simple layer.

Brovar (1964a) examined surface integrals which, outside a boundary surface, are similar in properties to the potential of a simple layer, the potential of a dual layer, and the potential of three-dimensional masses. Brovar proposes using those integrals to represent an arbitrary function that is harmonic outside the surface and to formulate on that basis new integral equations for the auxiliary densities.

In another paper, Brovar (1964b) also continued studies begun earlier. Critical remarks on that article were expressed by Mihal' (1966). In a 1966 article, Brovar presented practical conceptions about the solution of an equation for the interconnected densities of a simple layer and a dual layer.

Eremeev improved the formulas for normal heights and gave a review of Western literature on the computation of normal and other heights; he mentioned inaccuracies in determinations of the normal height and gave a critique of papers by Rune, Vignal, Simonsen, Bokun, Chojnicki, and others.

Ostach (1967b) described a method for computing the vertical gradient of gravity at the earth's surface. This gradient had been expressed through Δg -anomaly values by Īŭrkina (1965). Ignatova (1965) estimated the errors of Numerov's formula for the vertical gradient of gravity with model earths having different slopes of the surface.

Strakhov described a method, designed for use with high-speed computers, for computation of the vertical gradient of gravity from its anomalies as given on a plane. He also developed a theory of the synthesis of computational systems for the determination of the higher vertical derivatives and the analytic continuation.

Monin (1966d) proposed a modification of Molodenskiĭ's 1960 method of solution of the integral equation for the function χ , but he did not look into the obvious errors of the approximations nor point out approaches to improvement of the results. Earlier, Monin (1963a) had proposed that in the solution of the equation for the density of a simple layer of Molodenskiĭ's 1960 method, the earth's surface be subjected to transformations with the parameter k or that the normal values of gravity be varied in the computation of its anomalies. Ereemeev and Ĭurkina pointed out that the process of successive approximations might consequently be slowed down. Brovar (1965b) characterized Monin's proposal as gravely impairing the accuracy of the computations under real conditions. By computation with a model earth, Monin (1965b) saw for himself the inadvisability of his proposal.

After differentiating a somewhat modified Molodenskiĭ integro-differential equation for the disturbing potential, Monin (1966) expressed the deflections of the vertical through values of the gravity anomalies, quasi-geoid heights, and deflections of the vertical at running points of the earth's surface. In another article, Monin (1965c) applied Molodenskiĭ's method to Molodenskiĭ's integral equation for the disturbing potential. The zeroth approximation is the Stokesian. In the subsequent approximation, the curvature of the surface must be computed at each running point.

An article by Monin (1965a) is devoted to solution of one of the equations formulated by Brovar (1964). After expressing a doubt about his own results, Monin (1965b) obtained the same formulas by a different means. Individual approximations were written down by Monin (1965a) for quasi-geoid heights, deflections of the vertical, and anomalies of the vertical gradient of gravity, which in his opinion were suitable for computations. A critique of Monin's papers was given by Brovar (1965b).

Through two approaches, Monin (1966) obtained an expression for the disturbing potential in terms of the values of the gravity anomaly and its derivative along the normal to the earth's surface at running points. In both cases, the author employed an incorrect procedure, viz., the expansion of a quantity inversely related to the distance r between the fixed point and the running point on the boundary surface in Legendre polynomials. For computation of the derivative $d\Delta g/dn$, Monin formulated a Fredholm integral equation of the first kind, for which he proposed solution by expansion over the parameter k by Molodenskiĭ's method.

Monin also developed methods of determination of a regularized geoid with a relative error of the order of the square of the earth's flattening and derivations without the use of a normal field.

Filippov (1965) derived formulas defining the physical surface of the earth with allowance for second-order quantities, but without using a normal field, which Mihal' (1949) had also forgone.

The sum T' of the zeroth and first approximations to the disturbing potential after Molodenskiĭ (1960) was reduced by Marych (1965) to the form

$$T' = T_r + \frac{dT_r}{dH} H,$$

where

$$T_r = \frac{R}{4\pi} \int \left(\delta g_0 - H \frac{d\Delta g}{dH} \right) [S(\psi) - 1] d\sigma$$

$$\delta g_0 = \Delta g - \frac{2(W_0 - U_0)}{R},$$

H is the height of the earth's surface, and $S(\psi)$ is Stokes' function.

In the derivation, it was assumed that Numerov's formula defines the vertical gradient of the gravity anomaly. Furthermore, Marych obtained a formula for the deflection of the vertical in the l -direction:

$$\vartheta = \frac{1}{\gamma} \left(\frac{\partial T_r}{\partial l} - H \frac{\partial g}{\partial l} \right).$$

In the articles by Aronov et al., there are descriptions of a procedure for computation with a computer and of model-earth calculations of elements of the external gravitational field in terms of Δg -values on a reference plane that account for the Δg -values at gravity stations. There is also a review of the techniques for reducing the gravity anomalies from the earth's surface to the plane. Aronov proposes that the gravity anomalies on the lower surface be computed with a Poisson integral to be regarded as an integral equation of the first kind. The step of the integration must be approximately equal to the step of the survey. Since in the general case it is impossible to account for the field of the gravity anomalies on the physical surface of the earth through a field on the lower plane, the solution to the problem may be unstable.

The errors of computation with the models employed are one-third as great or better than when Stokes' theory is used. In a paper by Aronov and Gordin (1966b), there is a numerical evaluation of the accuracy of the interpolation of derivatives of the gravitational potential for a mountainous area on the basis of Aronov's procedure. By those authors' estimate, the accuracy is sufficiently high.

Pellinen (1967) gave a review of the methods of computation of deflections of the vertical and quasi-geoid heights in mountains. Pellinen recommends that the Aronov-Ejerhammar method be used to isolate the regional part of the gravity anomalies and that the rest of the anomalies be interpreted with a simple layer on the earth's surface.

In view of the complications involved in practical application of Molodenskiĭ's theory, Mihal' (1965) replaces the geoid by a surface $\bar{S}$ whose distances $\bar{H}$ from the physical surface of the earth at each of its points in the direction n of the vertical at the point are defined by the formula

$$\frac{W_c - W}{g} = \bar{H} + \frac{1}{2} \frac{1}{g} \frac{dg}{dn} \bar{H}^2.$$

Here W is the earth's gravity potential, W_c its sea-level value, and g gravity. The formula recommended by Mihal' is obtained by expansion of potential W in the series

$$W_c = W + \frac{dW}{dn} \bar{H} + \frac{d^2 W}{dn^2} \frac{\bar{H}^2}{2} + \dots$$

In this series, one must take the outer limiting values of all the derivatives. The author does not evaluate or allow for the influence of terms with third and higher derivatives of W .

He postulates that the surface obtained can be regarded as the external niveau surface of a planet which creates a gravitational field coinciding with the true external gravitational field of the earth.

An article by Molodenskiĭ on the accuracy of computation of the anomalous part of the earth's external gravitational field that has been prepared several years earlier was published in 1967.

Pellinen (1965a) submitted a procedure for deriving the coefficients of an expansion of the earth's gravitational potential over spherical functions from a simultaneous reduction of gravimetric and satellite data. Pellinen (1966) describes a procedure for computation of the coefficients in an expansion of the disturbing potential over spherical functions on the basis of gravity measurements at the earth's surface. The second method of Neumann is recommended. It is proposed that the gravity anomalies be smoothed by averaging over the area within a circumference with a radius that is constant for each point of the surface. Pellinen presented conceptions about the optimal relation among the number of the harmonic, the spacing of the gravity survey points, and the aforementioned radius. He examined problems of the interpolation and extrapolation of gravity and allowance for the elevation dependence of the Δg -anomalies. He also gave formulas for determination of the weights of the averaged gravity anomalies from correlational analysis of gravity and the variances and covariances of the coefficients.

Ostach and Pellinen (1966) gave formulas with which to correct the coefficients of the spherical harmonics of the disturbing potential of a regularized earth for its flattening. The corrections have the order of the product of the square of the earth ellipsoid's eccentricity times the order of the spherical harmonic. They must be applied in the determination of those coefficients from the gravity anomalies at the earth's surface with Stokes' series.

After differentiating an equation of astrogeodetic and gravimetric measurements for quasi-geoid height given earlier in a paper at the Prague symposium on the theory of the figure of the earth, Izotov (1965) obtained analogous equations for the deflection components. The free terms include astronomical and geodetic coordinates.

According to calculations by Grushinskii and Sag'itov, neglect of currents in marine determinations of gravity can introduce an error of 15 mgal under unfavorable conditions. After the corrections to the measured gravity values to allow for currents were expanded with a computer in series over the spherical functions up to order 16, it was concluded that the influence of neglect of currents can introduce an error of 0.1 in the denominator of the earth's flattening. Tables of the coefficients of the expansion were obtained for summer and winter.

Marych (1964) showed that the Stokes, Pizzetti, and Brovar formulas define the regularized geoid with an arbitrary degree of accuracy on the condition of corresponding smallness of the gravity anomalies, which can be satisfied through the choice of normal gravitational field.

Marych (1963) described the principle of determination of the regularized geoid with allowance for small quantities of n -th order without the use of a normal field.

Gromov obtained an integral formula for the disturbing potential on a regularized geoid through the anomalies of the gravity gradient on that geoid.

Molodenskiĭ merits first mention in the development of the geometric methods of the present-day theory of the earth's figure. Those methods were the subject of several papers of his published in 1949 through 1954. Using the procedure pointed out by Molodenskiĭ, recently Ereemeev and Īurkina (1966) proposed formulas for the computation of astronomical coordinates from angle measurements and examined some other problems that arise in the evolution of three-dimensional geodetic

nets. The transfer of astronomical coordinates from one point to another was also studied by Rudskiĭ (1965, 1966).

Bordering on those subjects are several papers concerning the development of a theory of joint adjustment of geodetic latitudes and longitudes and quasi-geoid heights.

Pellinen (1963) showed that the azimuthal condition is affected by only the lateral errors of a triangulation; this influence does not depend on the latitude and direction of the chain. The corresponding distortions of the azimuthal condition do not lead to additional lateral errors of the triangulation chain along a great-circle arc and indirectly influence the longitudinal shift of the chain along the parallel. The formulas given earlier by Pellinen for the transverse and longitudinal shifts (Geod. i kartografiia, 1961, No. 10, 3-9) have been improved.

Eremeev and Iŭrkina (1967c) improved Molodenskiĭ's integral formulas for the radial and longitudinal shifts in the initial reduction of a triangulation by a development method, as compared with the version of those formulas in a 1960 monograph by Molodenskiĭ et al. (Trudy TSNIIGAIK, No. 131)*), since the improved formulas allow for the angular difference between the normals to the quasi-geoid and reference ellipsoid on the one hand and the deflection of the vertical at the physical surface of the earth on the other.

The same authors (1967b) described a technique of simultaneous adjustment of geodetic latitudes and longitudes and quasi-geoid heights.

*) Engl. transl.: Methods for Study of the External Gravitational Field and Figure of the Earth. Jerusalem, Israel Program for Scientific Translations, 1962--Tr. note.

They propose that the preliminary adjustment of individual ties of the triangulation be alternated with the computation of quasi-geoid heights at astronomical triangulation points by Molodenskiĭ's formula of astro-gravimetric leveling. They adopt as directly measured quantities the lengths of arcs projected on the reference ellipsoid, the azimuths of those arcs, and gravimetric corrections (δ) for the nonlinearity of the variation of the deflection of the vertical on those arcs. Molodenskiĭ's integral formulas need not be employed in their procedure.

The technique was illustrated with a model net described by Īurkina et al. (1967). Into measurements that could be said to have been made on a niveau sphere-geoid, they introduced errors on the expectation that the RMS errors of the measurements of the arcs, azimuths, and δ -values, respectively, were equal to ± 3 m, ± 0.2 , and ± 1.5 m (the arc lengths of the model net being close to 3000 km). The results of the computations demonstrated the advantage of the proposed method over individual adjustment of plane coordinates and quasi-geoid heights.

In the solution to this problem given by Muralev, it is proposed that Molodenskiĭ's integral formulas be used. Muralev also studied questions of the practical application of Molodenskiĭ's formulas.

A paper by Pellinen, Taranov, and Shabanov described a computer procedure for computation of gravimetric quasi-geoid heights and deflections of the vertical with the Stokes and Vening Meinesz integral formulas.

Krzhizhanovskaĭa used the maps she had prepared earlier for the gravimetric deflections of the vertical in the trapezoid between latitudes

$53^{\circ}15'$ - $54^{\circ}15'$ and longitudes 59° - 60° to compute the differences of the gravimetric quasi-geoid heights with respect to one of the points of the area. The accuracy of the computation was estimated at 20 cm.

By the estimate of Surnin (1964), the coordinates of the earth's center of mass can at present be determined with an error of about ± 100 m and points of isolated geodetic systems can be tied by physical methods with an error of about ± 140 m.

A paper by Dul'tsev (1965) concerns the determination of the scale reduction constant introduced by Mihal'.

Ražinskas estimated the accuracy of the interpolation of astro-geodetic deflections of the vertical by gravimetric deflections for the territory of Lithuania and plotted maps of the deflections of the vertical and the quasi-geoid for its western part.

Andreev (1966) represented the components of attraction of a niveau ellipsoid along a radius vector from the center and along a direction perpendicular to the radius vector in the plane of the meridian, in the form of series in powers of eccentricity e and of the ratio of centrifugal force to gravity at the equator. Terms of order e^4 were retained. The expressions are real on the surface of the ellipsoid and outside it. Analogous series were used to represent the attraction components along a normal to the ellipsoid and along a direction perpendicular to the normal in the meridional plane. The series are real on the surface of the ellipsoid and at a height h above it on the condition that the ratio of h to the semimajor axis have the order of e^2 .

For the determination of gravity outside a certain surface from its values on the surface, Alek'sidze (1965) proposes two approximation

methods. The reduction of the external problem to an internal one made it possible to use a finite-difference method adapted for general-purpose digital computers. The rate of convergence of the iterations and the organization of a full automation were examined. The author reduces the second method to an expansion in Fourier series or the solution of a system of algebraic equations. The derivation of the higher derivatives of gravity on the basis of the two methods is also examined.

Historical studies and reviews were published by Zhongolovich, Sologub, and Stupis. Zhongolovich compared the possibilities of determination of the harmonics of the earth's gravitational field from a ground-based gravity survey and from the motion of artificial earth satellites. Information on determinations of the zonal harmonics (with corresponding values of the flattening of the earth) and tesseral harmonics (with corresponding values of the difference of the semiaxes of the equatorial ellipse and the longitude of its semimajor axis) has been compiled in tables.

An article by Antoniuk (1964) concerns two papers by Sludskii (1841-1897), "On the deflection of plumb lines" and "General theory of the figure of the earth," since whose publication 100 and 75 years had passed, respectively, in 1963.

Makarov (1965) noted the importance of a uniform understanding of the various anomalies of gravity and, in particular, recommended a distinction between the free-air reduction and the Faye reduction.

Gramenitskaia and Filimonov described an attachment to stereophotogrammetric instruments for determination of the corrections to

gravity measurements for the relief of the neighboring zones from aerial photographs.

In articles by Zavgorodniĭ and by Kazinskiĭ, individual problems of numerical integration are examined.

Menaker designed charts for the computation of the terrain correction with an accuracy of 0.2-.3 mgal from the elevation contours around a gravimetric point. In allowance for the topographic masses of the immediate surroundings, Zemlianov proposes the use of a formula of the attraction of thin horizontal slabs in the form of polyhedrons, as a basis for a computer program. A procedure for computation of topographic corrections to gravity with a computer was also examined by Aronov et al.

Budriukov compiled tables of normal gravity values in accordance with Helmert's formula (1901-1909) to an accuracy of 0.01 mgal with Gaussian plane rectangular coordinates in the argument, for the latitude belt $32-77^{\circ}$. He appended tables of corrections for conversion from Helmert's formula to those of Cassinis, Krasovskii, and Zhongolovich.

Zagrebin corrected an inaccuracy that appeared in one of his earlier papers (Trudy In-ta teoreticheskoi astr., 1952, No. 1, 87-222).

Mihal' expressed a doubt about the possibility of deriving deflections of the vertical on the basis of a local gravity survey with an accuracy better than $0''.5$. A reply to his article was published by Iŭrkina and Ereemov (1964).

Novoseliŭskiĭ examined a particular case of the problem of analytic continuation of gravity anomalies (with two-dimensional distribution of the attracting masses).

The articles by Brovar et al. and by Voskoboĭnikov et al. embody critiques of papers by Malovichko and his co-workers.

Research was carried out on the gravitational field of the Indian Ocean and Antarctica (Avsiuk, Frolov, Gaĭganov). The shape of geoid surfaces in Antarctica was investigated by Frolov.

An Atlas of Antarctica representing the work of a large number of specialists was published. The gravimetric maps to be found in the Atlas give an idea of the state of gravimetric research in Antarctica.

The list of references includes papers relating directly to the geological interpretation of gravity anomalies, but also offering an interest or useful information from the point of view of the study of the earth's gravitational field and figure.

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