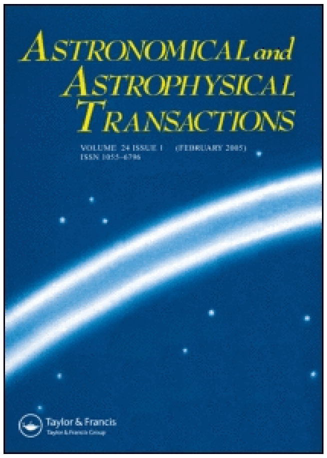

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THE EVOLUTION OF GRAVIMETRY

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1 INTRODUCTION

Of course, I would like to avoid discussing the development of gravimetry only in Russia. Anyway, this would be impossible to keep the discussion strictly within such a frame. Modern, most impressive and fascinating achievements belong not to Russian scientists and one cannot neglect them. However, it would be arrogant to aspire to cover all the results obtained by the international scientific community. I can only mention that the studies in the field of gravimetry in Russia were never behind the times, even if Russian scientists were not the world leaders. In many fields, our achievements are generally recognized and do honor to Russian gravimetry and astronomy. We mention here also astronomy because most Russian scientists active in the field of gravimetry have their roots in astronomy.

Conducting my own research in gravimetry, I have witnessed its development during sixty years, from 1933 up to now. As the starting date of this period, I consider the time when I entered the Mechanics and Mathematics Department of Moscow University where Sergey NIkolaevich Blazhko tempted me to choose this specialization by his movingly brilliant lectures on the base of astronomy, and where Alexander Alexandrovich Mikhailov infected me with the virus of gravimetry by his inimitable lectures on the theory of the figure of the Earth.

2 THE THREE BRANCHES OF GRAVIMETRY

The general field of gravimetry is conventionally divided into three parts, *geodetic* gravimetry, *instrumental* gravimetry and *exploration* gravimetry.

2.1 Geodetic Gravimetry

All the problems referring to the theory of the figure of the Earth and to the accurate determination of the position on the Earth surface, i.e., the measurements of the

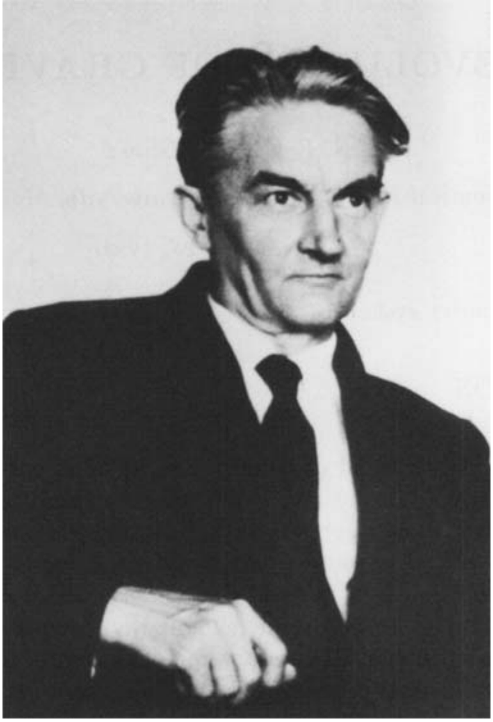

Figure 1 M. S. Molodensky.

coordinates belong to this branch. The latter represents a basic, classical problem of higher geodesy and, as a matter of fact, its main subject.

Basics of the theory of the figure of the Earth date back to Clairaut (1713–1765) and G. Stokes (1819–1903). We owe to A. A. Mikhailov for a keen presentation and systematization of this theory. His textbook *A Course of Gravimetry and Theory of the Figure of the Earth* is a unique example of a textbook which is simultaneously a creative research text. It is somewhat oversimplified since the author did not use the technique of spherical functions. Nevertheless, one can hardly find a clearer and more classically rigorously discussion of the subject.

The studies of M. S. Molodensky (1910–1992) represent a worldwide recognized progress in the field of geodetic gravimetry. He has developed a rigorous theory of the figure of the real, physical surface of the Earth.

However, let us return to earlier research in gravity in Russia. In the 1830's, when the Military Topography Corps performed triangulation near Moscow, a significant disagreement was noticed between the latitudes obtained from triangulation and from astronomical observations. V. Yu. Struve draw to this fact the attention B. Ya. Schweizer (1816–1874) who started a special study to resolve the problem. He calculated the latitude of the *Ivan the Great* bell tower in the Moscow Kremlin using different triangulation points in order to eliminate local anomalies and obtained the northward difference of $B - \varphi = 8.9''$ between the astronomical and geodetic latitudes.

In 1848, B. Schweitzer performed a special-purpose measurement of the latitudes of six sites near Moscow thereby confirming the anomalous nature of this region. In the following years, he measured the deviation of the vertical for other 90 sites. A result of this investigation was a monograph entitled *A Study of the Local Attraction Existing near Moscow*, where a map of the deviation of the vertical was published for the Moscow region. Schweitzer attempted to explain these anomalies by the presence of lower-density masses extended to the north of Moscow in a stripe 620 verst (660 km) wide and higher-density masses deposited to the south of Moscow.

In 1863, professor of Moscow University F. A. Sludsky (1841–1897) analyzed this problem in more detail. This resulted in the first Russian study of the deviations of the vertical and the first realization of the importance of the gravity anomalies for geophysics. This marked the birth of exploration geophysics.

Sludsky also undertook, in the 1880's a deep theoretical study of the figure of the Earth. In 1888, he published his *General Theory of the Figure of the Earth*. The figure of the Earth was understood by him as the sea level extrapolated to beneath the continents, i.e., the geoid. The concept of the geoid as the sea surface undisturbed by waves and streams was introduced by J. Listing (1808–1882) in 1873.

Sludsky believed that one should avoid any hypotheses and rely solely on the observed distribution of the potential at external positions because the distribution of density inside the Earth is unknown. In this he anticipated the ideas of M. S. Molodensky who has solved the boundary-value problem for the potential for the physical Earth surface.

Sludsky retained fourth-order terms in the potential expansion and used the resulting theory to calculate the Earth's oblateness, and also the deviations of the vertical and the geoid height for 134 stations. He obtained positive geoid heights for the ocean regions and negative, for the continents; the result opposite to that of Helmert. Sludsky explained such a distribution of the geoid height by a probable excess of mass beneath the ocean regions. The Earth's oblateness was estimated by him as $\alpha = 1/292.7$ for the model of two-axial ellipsoid and 1/297.1 for the three-axial ellipsoid model. R. Helmert (1843–1917) obtained 1/298.2 and 1/296.7, respectively. It should be mentioned that Sludsky appreciated that his results are not completely justified. He wrote in the *Bulletin of the Society of Nature Examiners*: "The available pendulum observations cannot resolve even the question of the existence of general anomalies. A network for the determination of the gravity force should be developed covering completely the oceans and the continents. This extremely difficult practical task will be undoubtedly resolved in future".

Somewhat later, in late nineteenth and early twentieth century, a St. Petersburg astronomer A. A. Ivanov (1867–1839) made his active academic career. He derived a fourth-order expansion of the potential using 367 worldwide pendulum observations, deduced the Earth's ellipsoid oblateness as 1/297.2 and proposed the idea of asymmetry between the north and South hemispheres. He has also performed measurements of the absolute value of g in Pulkovo using the method of free fall and a fiber pendulum.

The research of M. S. Molodensky in 1945 completed and brilliantly generalized all the studies in theory of the figure of the Earth by solving the boundary-value problem of gravimetry for a real physical Earth surface rather than for some abstract, idealized model of the Earth surface like a sphere or ellipsoid. Molodensky's theory resolves in a surprisingly simple manner a problem which seemed to be unresolved rigorously, namely the reduction problem, by introducing a system of normal heights and calculating the normal gravity field for the physical Earth surface. The transition from the geoid to the physical surface has made the knowledge of the density distribution inside the Earth redundant and the hypotheses on the Earth internal structure unnecessary. Molodensky's solution of the boundary-value problem has yielded rigorous expressions for the quasigeoid height which included Stokes' solution as a first approximation.

The ideas of Molodensky were successfully developed and realized in practice by L. P. Pellinen. Being a head of the gravimetry department at *TsNIIGAK (Central Research Institute of Gravimetry, Geodesy and Cartography)*, he had an access to classified observed gravity data which were inaccessible for other researchers. Under his supervision, modern models of the gravity field and the figure of the Earth were developed basing on space-born experiments. Unfortunately, all these results still remain inaccessible for a wide scientific community. Nevertheless, L. P. Pellinen, together with Yu. D. Bulanzhe and other coauthors, succeeded in publishing the gravity anomalies, averaged over five-degree trapeziums, for the territory of the Soviet Union which were classified until very recently. *TsNIIGAK* possesses a complete coverage of the territory of the Soviet Union by gravity anomaly measurements averaged over 15 square minutes trapeziums. These data are still practically inaccessible for researchers, even though their military value has become minuscule since the satellite systems were implemented.

L. P. Pellinen left an excellent book *The Higher Geodesy* which is rather a textbook on theory of the figure of the Earth refreshed with M. S. Molodensky ideas, as well as a number of theoretical papers.

2.2 On the Methods of Measuring the Gravity Force

While theoretical studies in the field of theory of the figure of the Earth depended for a great, if not the most part on the genius of M. S. Molodensky, instrumental efforts and gravimetric mapping were motivated mainly by practical needs, namely the progress in the efficiency of mineral prospecting and exploration on one hand and military applications to missile trajectory calculations, on the other hand.

In the last century, first absolute measurements of g were accomplished using the reversive pendulum at the accuracy of tens of mGal.

In 1881, Sternek proposed a method of relative measurements which allowed to improve the accuracy to 3–10 mGal.

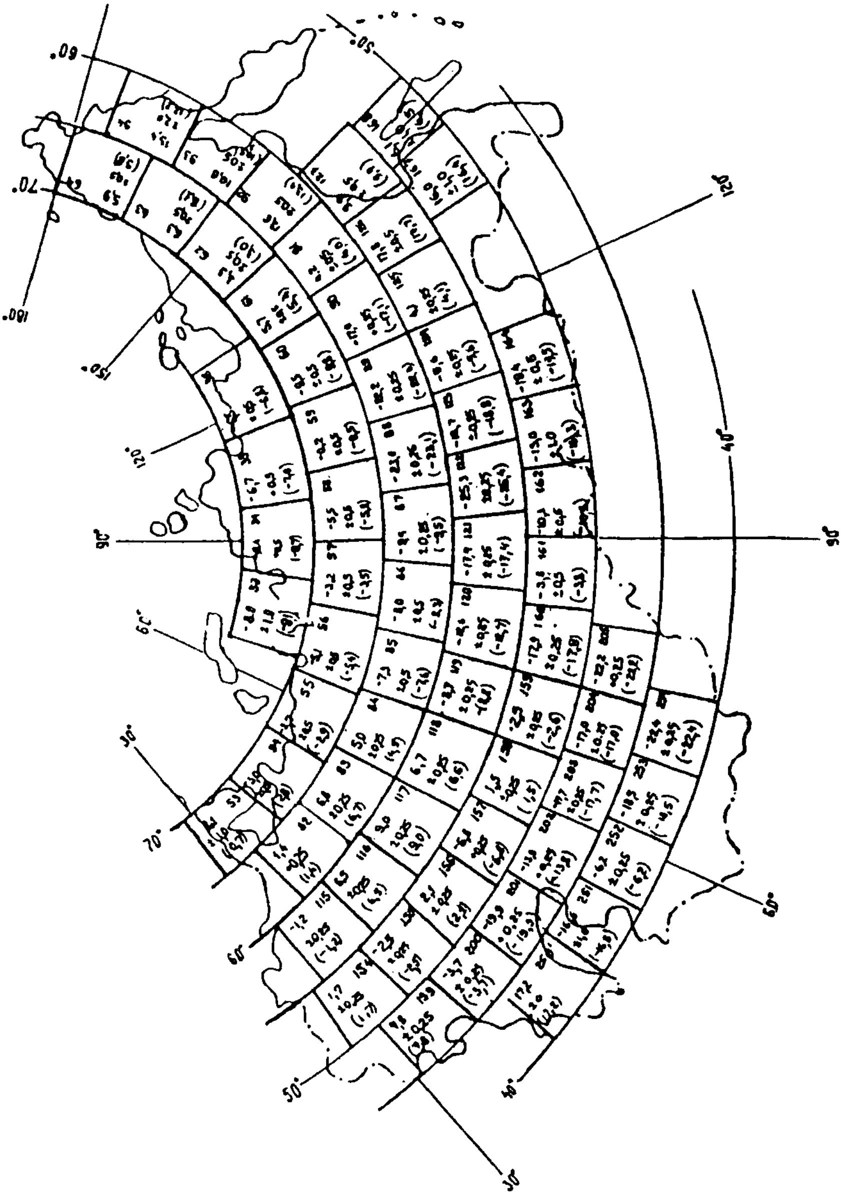

Figure 2 Mean Faye anomalies for 5°-blocks (the USSR). Number of blocks are given after R. Rapp.

In 1904, Künen and Furthwengler completed the determination of the basic reference point of the world gravimetric system in Potsdam. The observations were made with pendulum method. The root mean square error was ± (2–3) mGal. This gravimetric reference point served as a basis for all gravimetric surveys worldwide until the 1950's when its systematic error of 14 mGal was discovered.

Until the 1930's, gravimetric surveys in our country had a more or less unsystematic character. In 1932, *Soviet Truda i Oborony (Council of Labor and Defence)* passed a resolution to perform a complete pendulum survey of the territory of the USSR. *Glavnoe Upravleniye Geodezii i Kartographii (Main Department of Geodesy and Cartography)* was nominated to be responsible for this. The density of pendulum measurement stations was ordered to be one per 1000 square kilometers, which amounts to the average separation of the stations of 30 kilometers. Tens of pendulum expeditions were organized. They worked in Central Russia, in the Kara Kum desert, the taiga and tundra. At the *Aerogeopribor* works, pendulum instruments were developed and produced in tens. At the *GAISh (Sternberg Astronomical Institute)*, L. V. Sorokin designed a special low-weight pendulum instrument for using in regions not easily accessible and also developed a special method of measurements which required to remodel tens of chronometers.

In mid-1950's, this plan was basically completed. This survey covered almost the whole country, a gravity map at the scale 1:1 000 000 was produced for almost the whole territory with the contour interval of 10 mGal and a catalogue of gravity stations was completed.

Alas, this titanic undertaking yielded just a little outcome.

Already in the 50's gravitymeters began to be produced in the Soviet Union and a complete gravity mapping of the USSR was started.

The most widespread method of gravity measurements in the 50–90's was and remains the relative measurements with gravitymeters. M. S. Molodensky's genius has left its vestige in this field as well. He designed and constructed first original Soviet gravitymeters. The author had the luck to be involved in this work and to conduct first practical tests of the instrument (in 1939–1942) at the testing area between the Angara and Podkamennaya Tunguska rivers in the framework of the method of astrogravimetric levelling.

Second model of significantly improved Molodensky gravitymeters were developed and produced for field applications under the supervision of N. B. Sazhina (between 1943 and the 50's, the GKM model) and under the supervision of A. M. Lozinskaya (in 1950–1955, the GKA model). These gravitymeters ensured practically all field surveys in the 1950's and 1960's until high-precision quarts gravitymeters of the GAK model were designed and constructed by K. E. Veselov. The latter gravitymeters, being systematically modernized, are employed until now and provide the accuracy of 0.1–0.01 mGal.

We should admit, however, that gravitymeters designed in other countries were better. Already in 1935, the quarts gravitymeter of Ising and the metal spring one of Boliden were developed. At present, USA-made gravitymeters are employed worldwide ensuring the accuracy of a few μGal, like the Lacosta-Romberg, Sodin

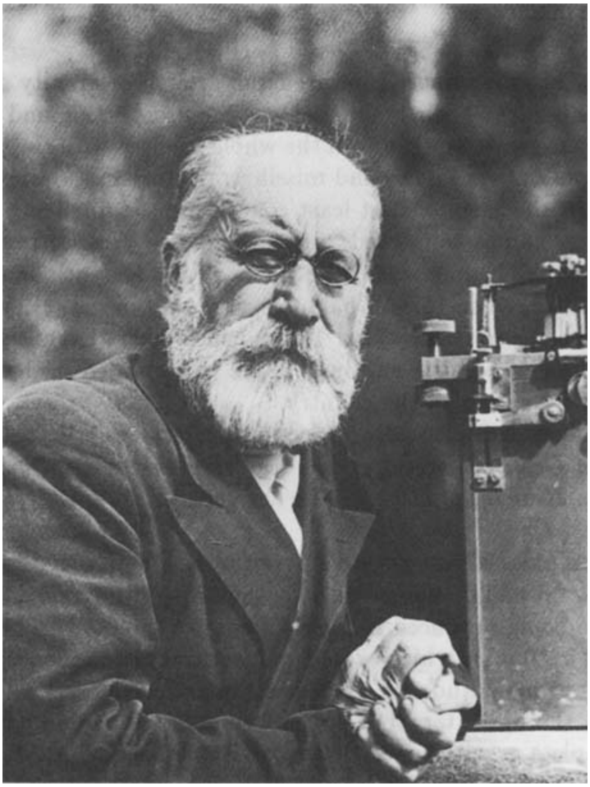

Figure 3 L. V. Sorokin.

and other gravimeters. Special gravitymeters for the use on surface marine vessels have been developed.

Two thirds of the Earth surface is covered by sea, so that it is natural to perform gravity measurements on the seas as well. Pioneering results in this field belong to Dutch geophysicist Vening-Meinesz who proposed the method of the so-called fictitious pendulum, constructed a special instrument and performed gravity measurements during several submarine expeditions. In the period 1923–1934, he performed measurements at 486 stations.

In 1930, submarine measurements were performed on the Black Sea by my teacher L. V. Sorokin with a pendulum instrument of his original design. In 1934 and 1947, he made similar measurements on the Barents Sea. One of the participants of these measurements was M. E. Kheifets. Later, in the 60's and 70's, M. E. Kheifets developed a specialized instrument with quarts pendulums for underwater (on a submarine) and ground-based observations. This instrument allows to perform a measurement in 10 minutes providing the accuracy of ± 0.1 mGal.

A similar device was developed in Canada.

2.3 Gravimetric Surveys

The availability of gravitymeters ensured the growth of gravity surveys which occurred in the 50's–80's. Their main goal was the prospecting and exploration of oil structures and the gravity mapping of the whole country with the purpose of geological surveying (an outward goal) and missile trajectory calculations (an undercover purpose, perhaps the main one, at least concerning the financing aspects).

Among many names connected with the gravity prospecting and surveys, we mention a few: B. V. Numerov, L. V. Sorokin, V. V. Fedynsky and B. A. Andreev. As early as in 1925, when torsion balances were still in use, B. V. Numerov made surveys in Emba, near Grozny and Baskunchak lake. Even earlier, in 1920, he constructed a torsion balance and in 1932 he participated in developing a general plan of the gravity survey of the country.

An outstanding organizer of prospecting projects was V. V. Fedynsky. When being a head of *Geofizicheskoe Upravleniye Ministerstva Geologii (Geophisical Department of the Ministry of Geology)*, he developed field gravity measurements at a grandiose scale.

First, torsion balance surveys were performed. Simultaneously, pendulum expeditions were organized but, since late 40's, the prospecting relied solely on gravimeters which were being produced in large amounts. The modern gravitymeters yield the accuracy of 5–10 μGal which exceeds the accuracy of the surveys of the 40's–50's by three orders of magnitude. Is not this a fantastic achievement?

As a result, the whole territory of the former Soviet Union has been covered by an almost complete gravity survey with gravitymeters.

In order to ensure a uniform accuracy of the measurements, a unified gravity reference network was developed to cover the whole country using high-precision gravitymeters carried by airplanes and the pendulum instrument of M. E. Kheifets. This was organized and accomplished by Yu. D. Bulanzhe. The accuracy of the reference network was 5–10 μGal. It served as a basis for class II and local reference networks.

Based on the results of the gravity surveys, gravity maps at the scale 1:1 000 000 were compiled and published for the whole USSR, and at the scale 1:200 000, for 80 percent of the territory. This gigantic work was performed by specialized local parties under auspices of the *VNIIGeofizika (All-Union Research Institute of Geophysics)*.

Under the supervision of N. B. Sazhina, a gravity map of the world was published at the scale 1:15 000 000 in which a huge amount of international gravity data was used. Unfortunately, because of the secrecy, our own country was represented as a huge white spot.

Our gravity science suffered a severe damage from being behind the times respect to computational facilities. In the USA and other countries, gravity data banks have been organized. So, nine million reference sites were presented in the *Defence mapping Agency Aero-Space Center* in Saint Louis as early as in 1975. Now this number is 1.6×10^6. *Bureau de Gravimetrie National* in Toulouse and a number of other centers have had rich data banks for a long time.

Finally, in late 70's and early 80's, a new aerogravimetric complex was developed in the USA featuring a helicopter, gravitymeter, inertial stabilization installation and navigation system. The Lacosta-Romberg gravitymeter is amounted on a gyrostabilized platform on board of a specially stabilized Sikorsky's helicopter S-61. Helicopters of this type are especially stable in the air. A special attention is paid to fixing the helicopter at a given height. The measurements are made at small altitudes of 100–300 m. This ensures that both the Eotvos correction and the correction for the reduction to the physical Earth surface are small. The measurements of the altitude and the stability of the latter are guaranteed by a triple system consisting of a barometric altimeter, radar altimeter and a satellite navigation system. The helicopter is steered by an autopilot in such a way as to keep the aircraft at a fixed barometric surface with deviations not exceeding a few centimeters. The radar system continuously records the local altitude which yields the altitude profile of the flight line. The gravitymeter output is also recorded continuously. The gravitymeter data and the flight altitude and speed (usually, 60–70 km s^{-1}) are the aircraft coordinates and the anomaly value in free air and in the Bouguer anomaly. The error of a measurement of the altitude above the sea level does not exceed ± 1 m. This accuracy is a result of a triple system of altitude tracking and a real-time feedback to the autopilot.

An important factor affecting the survey accuracy is a correct choice of the filtration, the averaging time and the flight speed. Under favorable conditions, the optimal filtration interval is 20 s. At the flight speed of 80 km s^{-1}, a 20-s filter provides the limiting resolution of 0.8 km for the anomalies. Such measurements are better conducted in the nighttime, from 22 to 8–9 o'clock. The atmosphere is most stable during this time.

2.4 The Cosmic Era: A Leap Forward

The launch of satellites resulted in a new approach to the studies of the gravity and the figure of the Earth. Moving in the gravitational field, a satellite experiences perturbations caused by the potential anomalies, i.e., the anomalies of the gravity force. Therefore, these anomalies can be estimated by observing the perturbations of the motion.

The gravity potential and its anomaly can be expanded into a series over spherical functions. Such expansions are the basis of the so-called standard models of the Earth and Planets. These models include: a product of the gravitational constant and the mass, GM, the major semi-axis a_e, the oblateness of the Earth ellipsoid α, the angular velocity ω, as well as the coefficients of the harmonics expansion of the Earth's gravitational potential.

The gravity field models obtained from perturbations in satellite motion provide a general, large-scale picture of the field. Even the models that include 360 harmonics have the resolution corresponding to the averaging over $1^\circ \times 1^\circ$ trapezium, i.e., regions of the size 100 × 100 km. Moreover, the higher harmonics can be calculated only with a high error. Therefore, generalized models still remain preferable. Now a multitude of models are available, GEM-2, GEM-4,..., GEM-10, GEM-10B, and a series of models GR1M. Most recent are the models GEM-T1 and GEM-T2 in which the gravity field is represented up to the terms of the order and power of 36. They yield the oblateness as $\alpha = 298.257$ and the major semi-axis, as $a_e = 6378137$.

These models give a very good generalized representation of the Earth's gravity field.

In 1975, GEOS-3 satellite was launched (on 29 April) and later, in 1978, SEASAT (on 28 July) was put on orbit. Both satellites had radioaltimeters installed on board. These instruments allow to measure to a high accuracy the distance to the sea level for a mean moment between the transmission and reception of a radio pulse. An accurate determination of the satellite position in space is ensured by radar systems and a network of reference sites, which yields the satellite coordinates in the geocentric reference frame. Thus, the geocentric distance of the satellite can be determined for any moment. Having the standard Earth parameters, this allows to calculate the radius vector of the sub-satellite point. Then the geoid height follows as a difference of the geocentric satellite altitude and the sum of the modulus of the sub-satellite point radius vector and the altitude of the satellite above the sea level. In 100 days, such a satellite covers the whole Earth by its trajectory segments separated by the 25 km distance. Averaging along the trajectory can be performed for, say a 7–10 km window. Even these two first altimetric satellites surveys the whole ocean yielding a precise geoid map for these regions. The accuracy of the SEASAT measurements is ±10 cm.

The geoid heights are related to the anomalies by the well-known Stokes' formula,

$$\zeta = \frac{1}{4\pi\gamma R} \int_\sigma \Delta g r S(r, \psi)\, d\sigma,$$

so that the gravity force anomalies Δg for the regions covered by the sea follow from the geoid heights as a solution of the inverse problem.

The third altimetric satellite GEOSAT was launched on 12 March 1985. Its orbit was planned to cover, in two months, the whole Earth by sub-satellite lines separated by 25 km at the latitude 50°. In six months, the coverage density increased to the separation of 18 km. After accomplishing three such duty cycles, GEASAT has completed the program of mapping the gravity field over all oceans.

In 1985, the Antarctic ice did not spread from the continent as far as usual, which allowed to survey the sea level from a satellite down to very low latitudes where underwater measurements were never available. This resulted in a geoid map for Antarctic coastal seas which was also used by us when compiling a geoid height map for the Atlas of Antarctica.

Later, three other altimetric satellites were launched with the purpose of studying the gravity field of the Earth, the geoid, the topography of the sea bed and the motion of the continents. These satellites are TOPEX-1987 (Ocean Topography Experiment, USA), ERS (European Research Satellite, Germany, 1988) and NROSS-1989 (Remote Ocean Sensor System, USA).

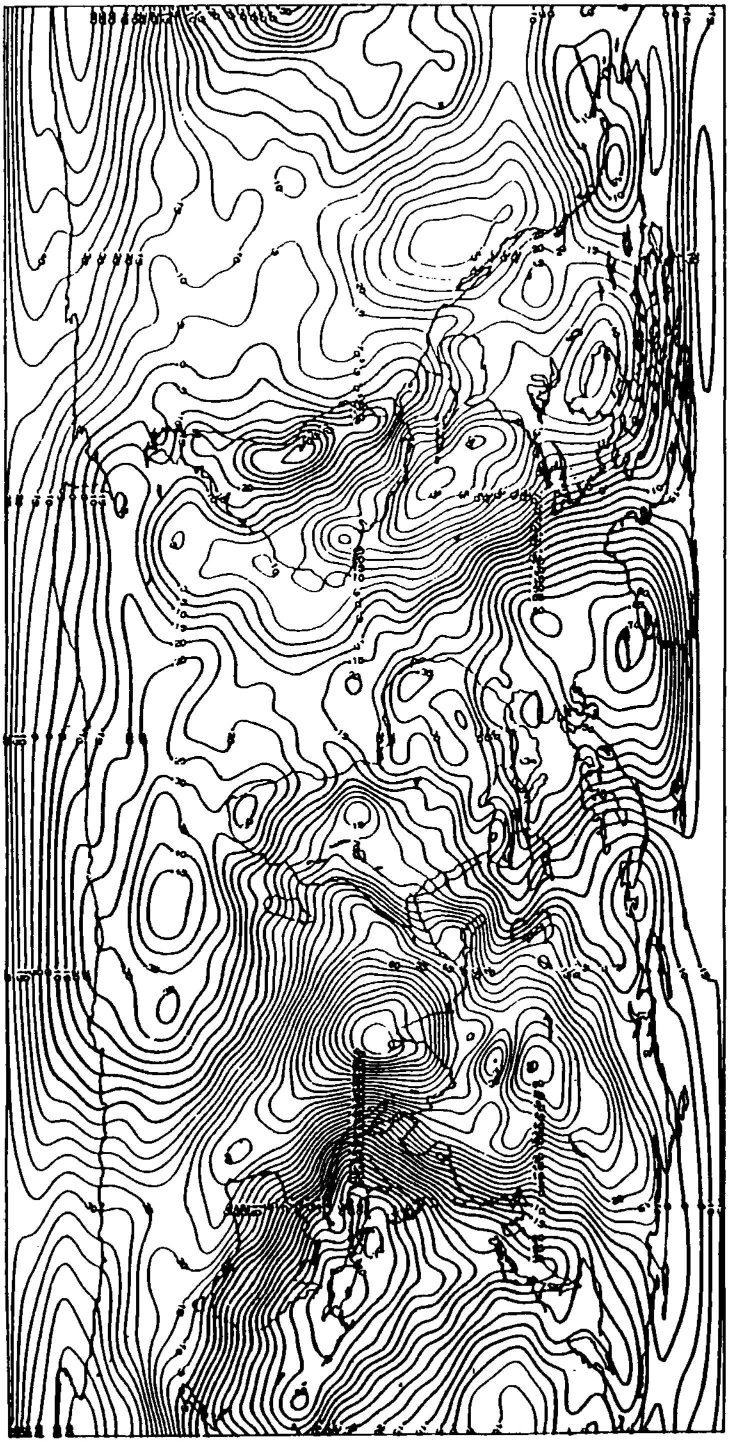

Figure 4 GRIM-3B Geoid.

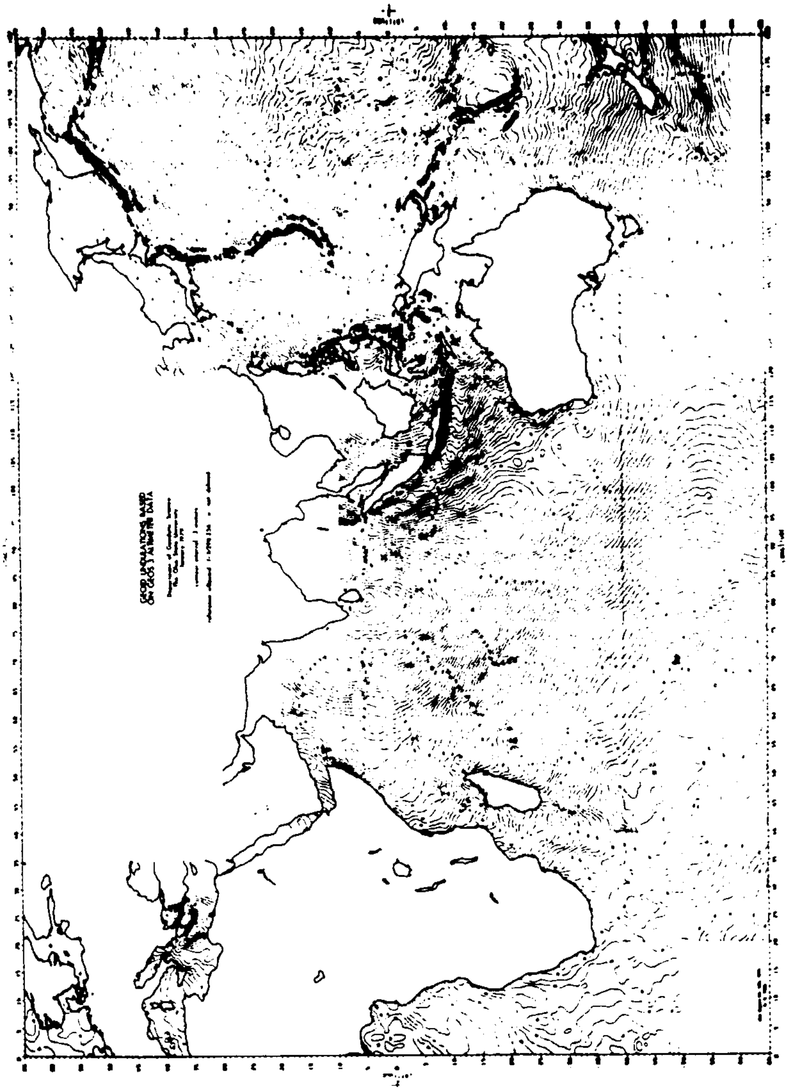

Figure 5

Figure 6

As a result of the studies with these satellites, the gravitational field on seas is now known much better than on the continents. There are big unexplored areas on the continents, especially in Africa, South America and Antarctica.

The geophysical satellites of the most recent generations allow to measure the heights of glacial arrays and smooth continental areas.

2.5 The Geoid and the Topographic Sea Surface

The new information obtained with these satellites gave birth to new concepts. Earlier, the figure of the Earth was understood as the system of the geoid heights. Now the satellite data have made clear that it is reasonable to separate the geoid surface and the topography sea surface (TSS). The latter is understood as the reflecting surface for a satellite radar. The TSS is not fixed, and streams, waves and wind-induced elevations distort it continuously. Some areas of the TSS coincide with the geoid or exhibit a very small, non-stationary difference from the latter. However, there are regions, for instance those of stable winds and streams, where the difference between the TSS and the geoid is significant (1.5–2 m) and rather stable being seasonal or even permanent.

The knowledge of the TSS is very important for tide models, the studies of sea streams and all manifestations of the physical processes in the ocean.

Altimetric methods already have wide and important applications in geodynamics. For example, the velocities of lithospheric plates have been obtained. The topography of the sea bed is very clearly represented in satellite altimeter maps showing underwater ridges, individual mountains, faults, valleys and many other details.