AN INTEGRATED SATELLITE ALTIMETRY DATABASE AND FINAL RESULTS OF THE RUSSIAN ALTIMETRY DATA PROCESSING

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ABSTRACT

The GEOIK program was started in 1985 to obtain a system of fitted parameters of the Earth (EP–90) including fundamental geodetic constants, geocentric reference system, and the parameters of the figure and the gravitational field of the Earth. Initially, this Program caried out by the Topography Service of the Ministry of Defence of the Russian Federation and was classified. In 1992 its many parts were declassified, and altimetry data processed with the application of the fitted parameters of the Earth (EP–90) were given to the organizations of the Russian Academy of Science and World Data Centers to be used. The measurements are given in the form of geophysical data records (GDRs). A huge volume of satellite altimetry data is disseminated now on optical disks and via INTERNET. The radar altimetry data of Russian satellites of GEOIK series for time interval 1985–1995 is also available to-day for international community. Satellites of GEOIK series were in near circular orbits at an altitude of about 1500 km. Most of these satellites had an inclination of 74 degrees, but some of them had an inclination of 83 degrees. To make easy for researchers to use altimetry data obtained by different satellites, the integrated satellite altimetry database was created in the Geophysical Center of Joint Institute of the Physics of the Earth. The problem oriented database management system helps a user to work with data of different satellites (GEOSAT, ERS, GEOIK, TOPEX/POSEIDON). The special review version of the database was prepared for on-line access via INTERNET. The estimation of the mean sea surface and gravity anomalies for World ocean was carried out on the basis of ten years altimetry data of the GEOIK satellites. The results was compared with the results of similar analysis on the basis of GEOSAT and TOPEX/POSEIDON data. The work was supported by the Russian Basic Research Foundation (Project N 96–07–89315).

1. INTRODUCTION

The Russian geodetic satellite GEOIK carrying a radar altimeter has been operating since May, 1985. Its main part, satellite GEOIK is one of the satellites of KOSMOS series intended for the studies of the Earth and circumterrestrial space. The satellite is placed on orbit approximately 1500 km high with inclination of 74 or 83 degrees. As of 1996, ten satellites were launched that were equipped both with radio altimeters (RA) and space-borne geodetic instruments including Doppler system, radio range system, light signaling flash system, and laser corner reflectors. Doppler system gives signals in coherent frequencies of 150 and 400 MHz twelve hours a day to measure radial velocity; light controlling system produces flashes to photograph the satellite against the stars; laser corner reflectors of effective area of 0.024 square meters and relay reflect signals of a ground-based laser ranger and re-emit signals of ground-based radio ranger.

Ground-based stations measure Doppler radial component of satellite velocity with respect to the observation station with an error of 1–3 cm/s, determine the satellite position by light flashes with reference to the stars with an error of 1–1.5", and measure distances to the satellite by laser and radio rangers with errors of 0.5–1 and 1–2 m respectively.

A great amount of altimeter data which has geodetic applications and is important for oceanographic research in the ocean surface topography and for global meteorological researches has been collected during the period from 1985 to 1995. The program for accumulating the altimeter data with GEOIK satellites is planned to be completed at the end of 1996. On completion of this work, the satellite GEOIK–2 carrying an altimeter one order of accuracy higher than this one is planned to be launched and this research will be continued. The program for accumulating the altimeter data envisaged launching of several satellites (every 2–3 years).

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Altimeter data obtained by the satellite and ground-based stations goes to the Center for Geodetic data processing, where those data are stored, processed, and used to fulfill the tasks of SGC.

The bulk of scientific results of GEOIK program includes the model of geopotential of EP–90 up to the 36th degree and EP–200 up to 200th degree, the improved coordinates of the geodetic network stations, and the catalog of the geoid heights in the World ocean.

The program has not been completed yet and collecting altimetry and tracking data by GEOIK is being in progress now. As of May 1996, the program allowed making 3.82 million measurements from ten satellites. In fact each satellite operated from several weeks to 18 months. Sometimes two satellites operated simultaneously, but it was more often that one satellite was employed. A list of the satellites, characteristics of their orbits and their operating time are given in *Table 1*.

Table 1

Russian Satellite Altimetry Program GEOIK

No sat.	Data Launch.	Incl.,deg	Period of active work	Stand. dev.	Calibr. corr., m
1	14.06.1985	73.6	08.07.1985–31.10.1986	60	-17.0
2	11.02.1986	73.6	03.03.1986–28.03.1986	140	-25.0
3	02.12.1986	83.6	21.12.1986–15.12.1987	166	-36.5
4	19.02.1987	73.6	09.03.1987–12.10.1987	105	-26,0
5	30.05.1988	73.6	20.06.1988–27.071990	88	-22.9
6	28.08.1989	73.6	18.09.1989–26.09.1990		
7	30.07.1990	73.6	19.08.1990–05.03.1993		
8	10.01.1993	73.6	10.01.1993–23.07.1993		-29.79
9	1994	73.6	18.12.1994–28.07.1995		-25.42

Altimeter. Precision of radar altimeter data (instrument error) ranged from 0.5 to 0.8 m in various spacecrafts. Frequency of the altimeter 9.5 GHz (mean square error of measurements adjusted by one-second interval and by 10–12 second interval is approximately 0.4–0.5 m and 0.1 m respectively); Measurements were conducted in steps of 1 measurement a second. The energetic resource of altimeter is 10h in one day.

Radio altimetry measurements data were recorded by space-borne tape-recorders and once a day sent to ground-based stations by telemetric channels. Deciphering, preliminary processing, calculating of satellite ephemerides, applying corrections to RA, and calculating sea-level height were conducted in Computer Center. Space-borne altimeter operated 10 hours a day and 5 days a week. The work was planned so that maximal uniformity of covering the World ocean by sub-satellite tracks could be provided. With several satellites, the criterion that each altimetry orbit was supported by tracking data was applied. It resulted in excluding altimetry data obtained in descending orbits across the Atlantic. The bulk of measurements was conducted in 1-Hz mode. Owing to technological limitations, some errors in planning, malfunctions, and space-borne equipment failures, the World ocean appears to be covered by tracking to a large extent non uniformly.

In processing altimetry data, calculating satellite ephemerides, applying corrections, calculating sea-level heights were most important.

Working cycle. The program provided that altimeter measurement were conducted 5 days a week from Monday until Friday, and on Saturday and Sunday control over serviceability of all space borne measurements, control systems was carried out, and tracking and altimeter measurements were not conducted.

Service interruptions. Besides the above-mentioned two-days breaks in accumulating high-precision data other service interruptions were noted. Some of them were connected with launching new satellites and subsequent measuring system calibration, and others were due to additional control over space borne systems and restoring the radar altimeter serviceability by change-over to duplicate facilities of the measuring system.

Records in the CD-ROM contain only high-grade measurements, therefore some 5-day working cycles are missing.

2. THE GENERAL TECHNIQUE OF PROCESSING

When preparing altimetry data from GEOIK in GDR formats the following computation stages have been completed:

- calculations of orbits of the satellites GEOIK provided with altimeter measurements from tracking data obtained by observation stations in the area of the former Soviet Union and Antarctic region;

- preliminary processing of radar altimetry data including corrections for reducing measurements to spacecraft center of mass, instrumental delays, and tropospheric effects;
- preparation of data in GDR format.

2.1. Calculations of GEOIK ephemeris

The ephemeris of GEOIK were calculated by 5-day orbits on the basis of only tracking data obtained by laser, Doppler, photo measurements, and distance ranging from the space geodetic network stations.

When calculating forces applied to the satellite, the gravitational field of the Earth, the attraction of the Moon and the Sun, tides in the solid Earth, light pressure, atmospheric resistance, precessions, nutations, and poles movements were taken into account.

To calculate orbits the model (EP–90) of gravitational field of the Earth up to 36th degree was applied. It was obtained by space geodesy technique, by combining tracking data, including altimetry data, and global gravimetry and altimetry data on the World ocean presented in catalogs of 5 x 5 degrees. Tracking data were used to determine initial conditions of 16 long (5 days) and 151 short (3 orbits) orbital arcs, geocentric coordinates of globally distributed network stations, systematic corrections to Doppler, distance ranging, and altimetry data, elements of mutual transformation coordinates (reference system of 1942), 167 coefficients of geopotential expansion by spherical functions most sensitive to the orbits of the given class. Satellite altimetry measurements (31 5-day orbital arcs) were applied to improving initial conditions of orbital arcs, the coefficients of the gravitational field model up to 20th degree, and bias correction to altimetry data. Catalogs of the heights (1041 blocks) and anomalies (1654 blocks) were used to improve the model of the gravitational field of the Earth up to 36th degree. The following parameters of the ellipsoid EP–90 were obtained:

$$a = 6378136;\ b = 1{:}298,\ 257839303.$$

The research showed that the error of ephemerides calculations by radius vector is 1 m on 5-day orbits. The estimate of the radial component of the error by variations of sea-surface heights in the points where altimetry tracks cross supports the given value. The nominal accuracy of antenna orientation is 1 degree.

2.2. Determination of altimetry data sets of sea surface height

Sets of altimetry data on sea surface were formed after satellite altimetry data were processed. Processing altimetry data was accompanied by calculating ocean tides and deviations of the quasi-stationary heights from the geoid. Taking into consideration low accuracy of the radio altimetry measurements, the program GEOIK did not include making corrections to the measured heights of the sea surface for external conditions (tropospheric and ionospheric corrections, corrections for waves heights and others). The systematic component of those effects was supposed to be excluded by bias correction. It should be noted, however, that satellite 6 had space-borne altimeter which allowed an accuracy of approximately 0.6 m. It is comparable to the tropospheric effects.

The calculations of the sea surface were made together with the calculations of correction for sea-tides heights, which was obtained with the use of Schwiderski's model for 8 main components given for crossing points with a space of 1 degree. The program for calculating tides heights includes correction members for effects of long-period tides in the solid Earth and takes into account loading and self-attraction.

Values of sea-surface heights were calculated in sessions on 5-days orbital arcs as a difference of the height component of the satellite ephemerides and altimetry data like corrections and values of the model heights of the geoid.

To obtain satellite ephemerides the geopotential model (EP–90) was applied. To calculate geoid heights above the ellipsoid model EP–200 up to the 200th degree was used. To calculate geoid heights above the ellipsoid the model EP–200 up to the 200th degree was used. It was derived from harmonic analysis and fitting of the model EP–90 with the catalog of gravity anomalies established by averaging initial gravity anomalies by 1x1 degree blocks.

Two types of initial data were used to make gravity anomalies catalog for the World. These data include geoid heights calculated as mean values of geoid heights by blocks 1 x 1 deg. from processed GEOIK altimetry data, and gravity anomalies catalog compiled by the Topography Service of Russia jointly with Scientific Research Institute of Geodesy and Cartography by use gravimetric observations on land and in the World ocean. To unite those two types of data a technique for combining radio altimetry and gravimetry data was elaborated. This technique is based on local approximation of the gravitational field of the Earth by a system of mass points. Thus, 56840 values of gravity anomalies were obtained.

2.3. Time error

Nominal accuracy of referring the time to space-borne time scale is 1 ms. Owing to the elliptical figure of the Earth and the satellite orbit, the maximal error of sea surface heights calculations caused by time error is 40 cm.

When using data on differences of sea-surface heights in crossing points of altimetry tracks, the time error was estimated for each 5-day altimetry data set. Taking this error into account, we decrease the mean square error of the differences of sea-surface heights but sufficiently increase the distribution of error of altimetry data.

2.4. Determination of bias correction

Direct bias correction (BC) of altimetry data or determination of systematic instrumental error (calibration) was not included in the GEOIK program. Therefore, instrumental error was determined by geodetic (orbital) technique from errors of closure. It was assumed that in a sufficiently long interval both altimetry data errors and ephemerides and a priori heights of the geoid were averaged.

For satellites 1, 5, and 6, bias correction was determined, while the system of fitted parameters of the Earth (EP–90) was being developed. They were -17, -25, and -36.5 m respectively. These values are sufficiently stable in the whole interval of the satellite functioning. However, for KOSMOS–2988 and KOSMOS–2037, the spread of errors was not several tens of decimeters but several tens of meters. It is likely to be related to switching of subsets of space-borne altimeter and frequency oscillator. A more accurate BC determination was needed for the above-mentioned two satellites at the stage of improving ephemerides.

2.5. Determination of BC for satellite 7.

Reference data on failures and switching on board the satellites were not sufficient to determine changes in work. Therefore, it was necessary to analyze all the 53 orbital arcs. Jump variations in bias correction of more than 3 meters allowed us to divide the whole period of its functioning into 6 parts. Beginning from 03.08.92 sharp changes in BC values are noted.

3. FORMATS.

The formats are given in *Table 2*. Their content corresponds to the analog formats of Geosat altimetry data records.

Table 2

GEOIK EP–90 GDR Format

Item	Parameter	Units	Bytes
1	UTC	sec	4
2	UTC (continued)	micro sec	4
3	LATITUDE	micro deg	4
4	LONGITUDE	micro deg	4
5	ORBIT (EP–90)	cm	4
6	H (1-s avg)	cm	2
7	GEOID (EP–200)	cm	2
8	OCEAN TIDE	cm	2
9	CALIBRATION	cm	2
10	INTEGER NUMBER	0–if over water 1–if over land 2–if over ice surface 3–if error of the measurement	2
11	SATELLITE NUMBER		2
		Total number of bytes	32

Satellite height H above the Reference System EP–90 ellipsoid
H=ORBIT(EP–90) + 100000(1500km) cm.

4. ORBIT PRECISION.

Orbits were computed by adjustment with the use of the least square method of tracking data from the stations of the former Soviet Union and Antarctic region. Computations were conducted in the geocentric reference system «The Earth's parameters of 1990»(EP–90). Values of the semimajor axis and the general earth ellipsoid in EP–90 system are

$$a = 6378136, 1/f=298.25784.$$

Preliminary parameters of the relations between this system and the system WGS–84, given in [ ] are as follows:

dX=0 dY=0 dZ=+1.5m wz=-0.076''.

The accuracy of geocentric coordinates of stations in the system «The Earth's parameters of 1990» make up 1–2 m by latitude, longitude and altitude for each constituent.

When calculating orbits (ephemeris) by 5-day intervals, the following factors were taken into account: the Earth gravity field as harmonic coefficients of expansion in terms of spherical functions up to 36th degree and the order of geopotential model which is a constituent part of the earth's geodetic parameters of 1990, gravitational pull of the Sun and the Moon, atmospheric friction, and light pressure. In addition, to improve the description of the spacecrafts tracks along with the initial conditions as Kepler's elements, the parameters of atmospheric friction and light pressure were improved by one parameter for each of the above-mentioned factor for each 5-day orbital arc.

The resulting accuracy (mean square errors) of the orbit computations by 5-day intervals makes up 2–3 m for longitudinal constituent, 1–2 m for binormal (transverse) constituent, and 0.5–1 m for radial constituent. Likely deviations in the computation values of the marine topographic surface, caused by orbital errors may reach +/- 2 m by amplitude.

When developing the reference system «Earth parameters of 1995», data on the pole coordinates and corrections UT1–UTC published in the bulletin «Vsemirnoye vremya» (VNIIFTRI, Russia) were used. Some deviations from data of the International Earth Rotation Service (IERS) may result in points coordinates differences which do not exceed 0.5 m, and thus are within the estimate of geocentric coordinates precision.

5. GEOID HEIGHT.

Geoid heights included in GDR data are computed with the use of the geopotential complete model up to the 200th degree and order which is also included in the geodetic Earth's parameters of 1990 as detailed characteristics of the Earth's gravity field. Numerical values of these coefficients have not yet been published.

The earth gravitational field model up to the 200th degree has been obtained by altimeter and surface gravimetry data. The accuracy of geoid heights in the water areas of the world ocean ranges from 0.5 to 1.0 m according to complexity of the gravity field in an individual region.

6. HOW TO USE THIS CD-ROMs.

CD-ROMs contains the GEOIK altimetry data collected during July 1985 to July 1995. These data are included on this CD-ROMs in directories GEOIK_0D where D - satellite number.

Subdirectory DATA - contains the GEOIK altimetry data in files NNYYMMDD.pc.

Subdirectory IMAGE_1D are included files NNYYMMDD.gif with images of the ground tracks for 1-day GEOIK orbital arcs.

Directory IMAGE_5D on the second CD-ROM are included files NNYYMMDD.gif with images of the ground tracks for 5-day GEOIK orbital arcs of the all satellites.

The GEOIK altimetry data are stored in files, each of which contains one day of measurements. The naming convention used for the data files is:

NNYYMMDD.pc,

where NN is the number of satellite, YY is the year, MM is the month, DD is the day. The naming convention used for the image files is:

NNYYMMDD.gif,

where NN is the number of satellite, YY is the year, MM is the month, DD is the day.

The data in the data files are exactly as the binary (PC) formatted data.

The directory HTML include hypertext HTM pages: altim_1n.htm, geoik_0d.htm (where d-satellite number) for quick view ground tracks of GEOIK satellites by months and half year periods. The pictures include summary ground tracks, number of records, number of point with measurements over sea, ice, land and number of bad measurements.

The directory DOC created for documentation and files description.

The directory SOFTWARE include three subdirectories: SELECT, ARGOS, and VIEW. The program SELECT-1 operates in the dialogue regime and is intended for rapid selection of the satellite altimetry data of the GEOIK experiment represented on the given CD-ROMs. The CD-ROM operations require introduction of the name of device (for example E). As a result, the file SUB-BAS-1.DAT contains the supplementary information satisfying the given logic of search: by time, coordinates and underlying surface. In order to make the logic of search more complicated, the ARGOS system represented in the given CD ROM can be used. VIEW_ALT program created for the reading and view altimetry data with the use monitor only. On line help to program are given by turn on F1, F2, F3, F4, F8 and F10 keys. Key F8 - indicate satellite number or residuals about geoid.

Residual = Sea surf. height - Instrumental bias - Tide - Geoid height.

Key F3 give some statistical information about data.

7. FINAL RESULTS OF PROCESSING GEOIK ALTIMETRY DATA.

Final results include:

- sea surface height for World ocean (grid 0.25 x 0.25 degree);
- gravity anomaly for World ocean (grid 0.25 x 0.25 degree);
- global gravitation field model (PZ–90);
- study sea level variations for sea around Russia.
- software and integrated data base.

For obtain gravity anomaly we use next formula:

$$dg_0 = \frac{gD}{pR}\left[\cos B_0 \ln\frac{\sqrt{1+\cos^2 B_0}+1}{\cos B_0}\left(\frac{¶^2 z}{¶B^2}\right)_0 + \frac{1}{\cos^2 B_0}\ln\left(\sqrt{1+\cos^2 B_0}+\cos B_0\right)\left(\frac{¶^2 z}{¶L^2}\right)_0\right].$$

8. HOW TO GET MORE INFORMATION.

Technical questions about reading the CD-ROM, the content of GEOIK GDRs, or scientific applications, should be addressed to WDCB and NGDC:

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3, Molodezhnaya Str., Moscow, 117296, Russia,
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