Evaluation of the modern Earth Gravitational Models over territory of the Kyrgyz Republic

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Abstract
The results of study of the satellite positioning technologies to determine normal heights in the Kyrgyz Republic based on modern digital Earth Gravitational Models are presented. The performances of the EGM96 and EGM2008 models, over territory of the Kyrgyz Republic, have been evaluated in the local conditions. Results of the study show how varies the height differences between the surfaces of the gravity model EGM2008 and Baltic Height System-1977 based on satellite observations at 65 geodetic points of the National "Kyrg-06" reference frame network in 2005-2006. The arithmetic mean of the height differences and the standard deviation are 0.394 m and 0.819 m, respectively. Calculation of height differences between the surfaces of the gravity models EGM96, EGM2008 and BHS-1977 system shows that EGM2008 has a higher accuracy. On the territory of the Kyrgyz Republic, all measured points have a negative height difference with a standard deviation of 0.413 m, which also shows the possibility of using the EGM2008 as a basic model when developing a local geoid model in the Kyrgyz Republic. The local performance of EGM96 and EGM2008 has been evaluated for the territory of Bishkek city. A local geodetic network, based on the National Geodetic Network points, is established and GNSS observed within this research work.

1. Introduction

Modern global navigation satellite systems (GNSS) - GPS (United States of America), GLONASS (Russian Federation) and COMPASS/BeiDou (China) today have become the main technologies of high-precision geodetic measurements. Global satellite constellations are expected to be equipped with new GALILEO system, which also improves and expands the capabilities of satellite geodesy in the future.

High-precision three-dimensional positioning is available using GNSS technology and various methods of space geodesy. Base distances of 10–100 km can be determined with an accuracy of up to several millimeters in the short run (Hofmann-Wellenhof et al., 2008). However, the use of GNSS technology in the Kyrgyz Republic (KR) faces some limitations in engineering survey. One of them can be considered the determination of heights of measurement points associated with the peculiarities of determination of absolute heights using satellite positioning systems. It can be said that GNSS technology in the country is mainly used to solve land register and Geographic Information Systems (GIS) problems for high-precision positioning on a two-dimensional horizontal plane, since there are no scientific and methodological developments in measuring normal absolute altitudes of points (Chymyrov, 2014 and 2017).

A number of scientific studies in the sharing of data from gravimetric measurements, geoids and quasi-geoids, GPS/GNSS observations and leveling have been performed worldwide (Li et al., 2009, Soycan, 2013, Ádám, 1999, Chen and Luo, 2004 and Martin et al., 2004). They prove that leveling using GNSS measurements in most cases is acceptable, but local gravimetric measurements, geometric leveling and development of the local geoid model based on EGM2008 or other advanced models are required.

Conversion of the ellipsoidal or geodetic height into orthometric or normal (H, mean sea level) height or the height above geoid can be realized by using the geoid-ellipsoid difference, which is known as a geoid undulation (N) or geoid height at the measurement point. Geoid is an equipotential gravity surface, which is very close approximation to the mean sea level and undulating depending on the local sub-surface mass distribution. Ellipsoidal height of a point on the Earth surface can be actually measured by GPS/GNSS observation. Geoid undulation of the region can be modelled from the gravimetric data, Earth Gravity Model and optical spirit leveling measurements from common and control points (Sjöberg, 2013).

The normal height (H) is the elevation of a point above the quasigeoid, which is the accepted height in the Kyrgyz Republic. The simplified relation among the normal height, quasigeoid height - ζ_A and geodetic or ellipsoidal height - h_A above WGS84 ellipsoid and EGM2008 undulation or geoid height - N_A are shown in Figure 1.

$$H=h_A+\zeta_A.$$
Equation 1

A new local geoid surface can be synthesized by combining the traditional gravimetric quasigeoid, EGM2008 and ellipsoid height differences suitable for 3D survey with GNSS.

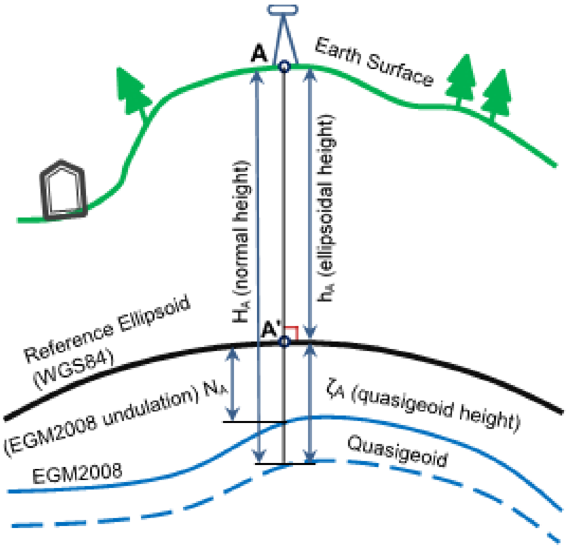

Figure 1: Relations between different heights and EGM2008 undulation

2. State Coordinate System "Kyrg-06"

The existing State Geodetic Network (SGN) of the Kyrgyz Republic is a fragment of the common SGN of the former USSR, based on the reference ellipsoid of Krasovsky 1940. In order to develop geodesic, cartographic, cadastral and navigational activities, the Decree of the Government of the Kyrgyz Republic No. 235 from 7 October 2010 introduced a new National Coordinate System "Kyrg-06" based on the International Terrestrial Reference Frame (ITRF-2005). The new system has 5 zones (EPSG: 7692-7696) and is distributed through the "Kyrg-06" Zero and First order frame networks with more than 70 control points of planar, vertical or leveling and planar-vertical SGN. Satellite observations were carried out at these geodetic points in 2005–2006 by the State Cartographic and Geodetic Service of the Kyrgyz Republic in collaboration with "Swedesurvey", the Geodetic Service of Sweden, and adjusted using the observation data from the nearest CORS of the International GNSS Service (IGS) (Abdiev and Chymyrov, 2013).

The new National Coordinate System "Kyrg-06"is based on the geocentric ellipsoid GRS 1980 and requires further development of a local geoid/quasigeoid model compatible with modern earth gravitational models. The traditional system of normal heights above the average level of the Baltic Sea in 1977 (BHS-1977), defined as the difference of geodetic heights above the ellipsoid of Krasovsky 1940, and heights of the quasigeoid should be converted using a digital gravimetric model of the Earth. Without the development of such a modern vertical local datum, the efficiency and accuracy of geodetic works using GNSS technology is significantly reduced.

3. EGM2008 based Local Geoid Height Map

With space exploration, many gravitational models of the Earth have been developed using measurement data from special artificial Earth satellites, such as CHAMP and GRACE. The most popular of these were EGM96 (Lemoine et al., 1998), GL04C and GGM02 (Forste, 2008). Currently, the new Earth Gravitational Model 2008 (EGM2008), developed by the National Geospatial-Intelligence Agency (NGA), has great advantages compared to previous models (Pavlis et al., 2008). It can replace the EGM96 model, which has served as a global geoid since 1996. A regular network with dimensions of 0.5x0.5 minutes to calculate the EGM2008 heights throughout the territory of the Kyrgyz Republic was used to calculate using the method of bi-quadratic interpolation with application of the external tide-free data base EGM2008 (Und_min1x1_egm2008_isw= 82_WGS84_ TideFree_SE). The resulting point array file was imported into the ArcGIS10.0 program and converted to a raster surface with cell sizes of 0,011111x0,01111111 (~1,2x0,9 km), using the kriging interpolation method.

Satellite observations at 65 geographic points of the Kyrg-06 frame network showed that the EGM2008 geoid heights throughout the country had negative values with a maximum of 47.82 m, a minimum of 32.08 m and average values of 38.14 m. The obtained equipotential surface is well described by the isolines of geoid heights drawn through 0.5 m (Figure 2).

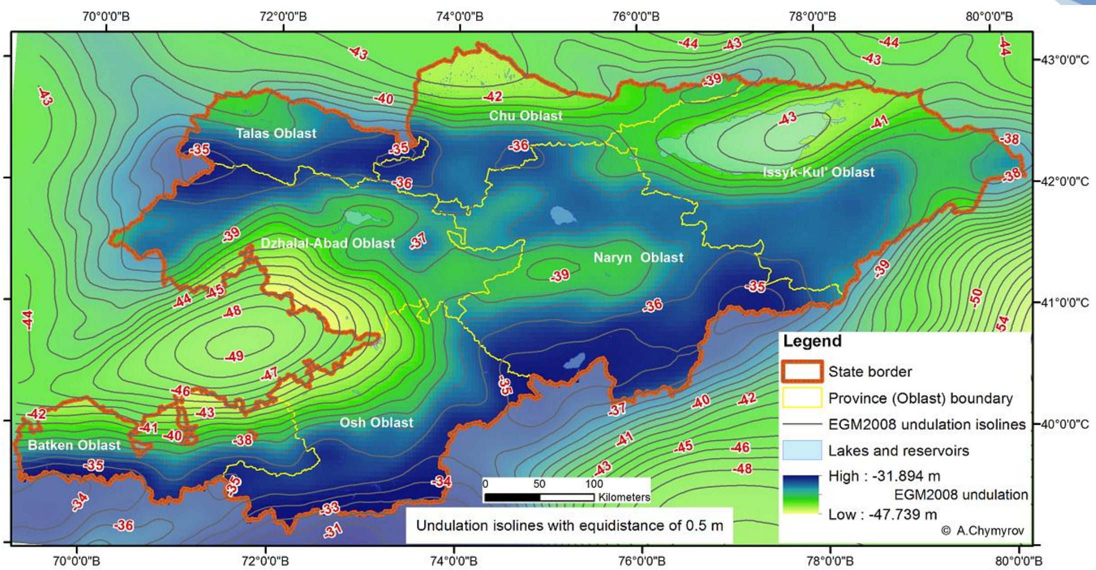

Figure 2: EGM2008 Geoid Heights Map over territory of the Kyrgyz Republic

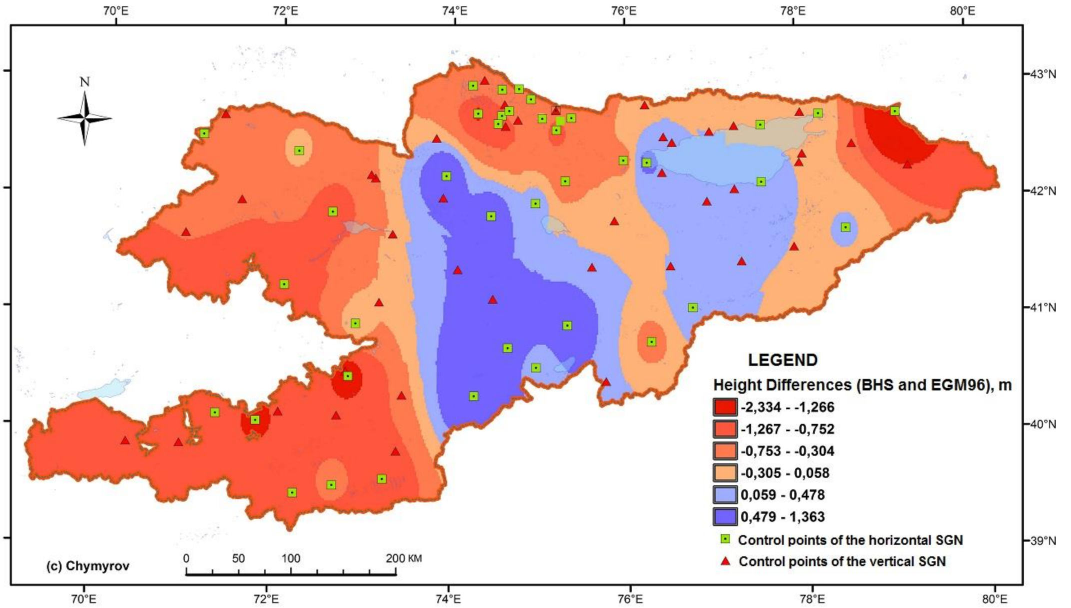

Figure 3: Map of differences in height of surfaces of EGM96 and quasigeoid (BHS-1977)

4. Comparative Analysis of the Modern Earth Gravimetric Models

Currently, various mathematical models of the geoid of the Earth have been developed. Of these, the global models EGM96 and EGM2008 are of the greatest interest in this study. EGM96 has served as a global geoid since 1996 and is used in the GPS system, as well as in many geodetic and geo-information systems as a basis for determining altitudes. Studies have shown that the mean-square error of determining the heights of a quasigeoid based on the EGM96 model, GPS measurements and levelling of 12036 points on different continents is 0.427 m (ICGEM, 2019).

Based on satellite observation data on 65 geographic points of the Kyrg-06 frame network in 2005-2006, geodetic and normal heights were determined and a map of the surface differences of the quasigeoid of the Baltic system of heights and EGM96 geoid of the territory of the Kyrgyz Republic was designed (Figure 3). This map shows how different are the heights of point above sea level calculated by GPS receivers based on the EGM96 from the normal heights in the Baltic Height System of 1977. The arithmetic mean of the height differences and the standard deviation are 0.394 m and 0.819 m, respectively.

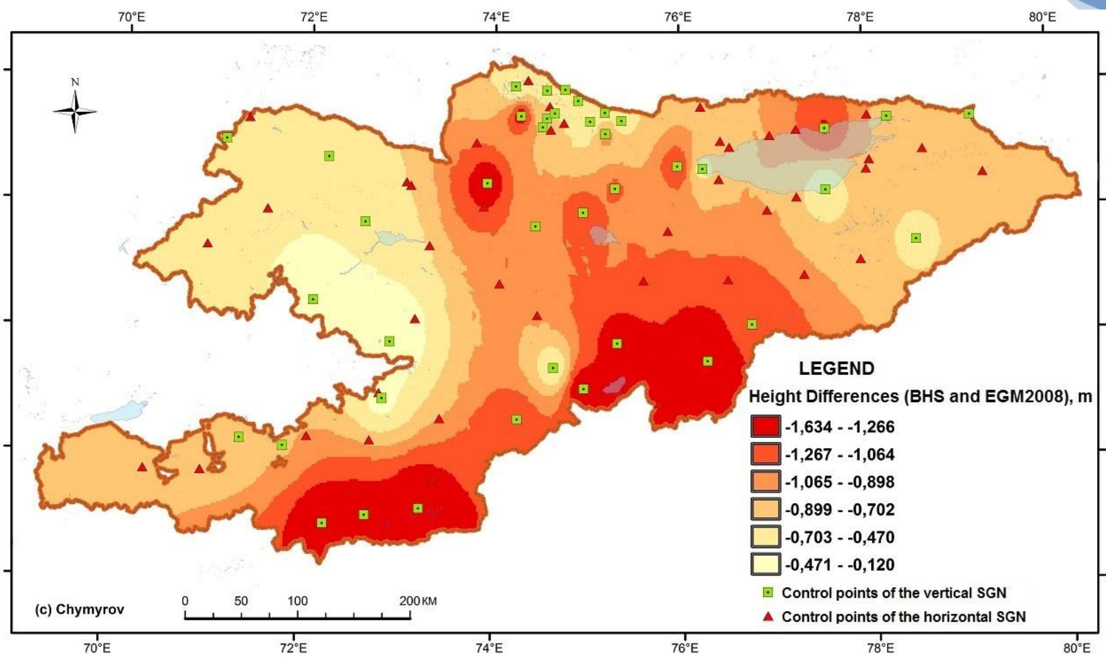

Figure 4: Map of differences in height of surfaces of EGM2008 and quasigeoid (BHS-1977)

Figure 5: Geodetic network design and reconnaissance survey

Gravitational model EGM2008 of increased accuracy and spatial resolution in the form of spherical harmonics of geopotential (N) to the 2159th degree was developed based on the WGS84 ellipsoid. In areas with qualitative data of gravimetric measurements and leveling, such as North America and Europe, the difference between the equipotential surface determined by calculations using EGM2008, GNSS and traditional leveling is from ± 5 to ± 10 cm (Pavlis et al., 2008).

Calculation of height differences between the surfaces of the gravity model EGM2008 and local quasigeoid (BHS-1977) based on satellite observations at 65 geodetic points of the frame network in 2005-2006 shows that EGM2008 has a higher accuracy and is the most suitable model for a local mathematical geoid model (Figure 4). On the territory of the Kyrgyz Republic, all measured points have a negative height difference with a standard deviation of 0.413 m, which also shows the possibility of using the EGM2008 as a basic model when developing a local quasigeoid model in the Kyrgyz Republic.

5. Evaluation of the Local Performance of the Earth Gravitational Models

An accurate geoid model is essential for determining normal heights using the GNSS technology. The present study of the EGM96 and

EGM2008 models provides a promising evidence for the future use of such models for the various geodetic applications. This study evaluated and tested the accuracy of using the EGM96 and EGM2008 for height measurements in the Bishkek city and for future research on the local geoid model development. The study area is located around the Bishkek city, which is the administrative and economic capital of the Kyrgyz Republic. It is located in the northern part of the country with geographical coordinates between longitudes 74°27′50″E and 74°43′10″E, latitude 42°46′10″N and 42°57′20″N, and is 780 m above mean sea level. The topography is generally described as a valley close to the Kyrgyz Ala-Too Ridge of North Tian-Shan Mountains.

The new Geodetic Reference Network of Bishkek is created based on the control points of the State Geodetic Network and City Survey Network. The preliminary network has been designed using the M1:10 000 topographic map and M1:500 topographic plan of the city. The reconnaissance survey has indicated the loss and damage of the most of selected geodetic control points from the former Soviet period because of the lack of proper network maintenance and regulation (Figure 5). The field investigations reported the poor situation with control and maintenance of the vertical referencing for the civil engineering and cartographic applications. The finalized Geodetic Reference Network of Bishkek has 10 stations based on 8 control points of the State Geodetic Network and 2 control points of the City Survey Network and additional control point "KSUCTA" (Figure 6). The last one is a control point of included in the local geodetic survey network of the Kyrgyz State University of Construction, Transport and Architecture (KSUCTA) in Bishkek. The GNSS observations are planned and performed in May 8-12, 2016. Three Leica GS15 CNSS receivers are used for the simultaneous 6 hrs long static measurements. The collected GNSS observation datasets are processed and adjusted using the Trimble Business Centre 3.70 software. The connection stations of the network have been observed twice in the two following observations sessions. The second session (S2) has a single base line only with two GNSS receivers working simultaneously for the 6 hrs static measurements because of malfunctioning of the third receiver during data collection.

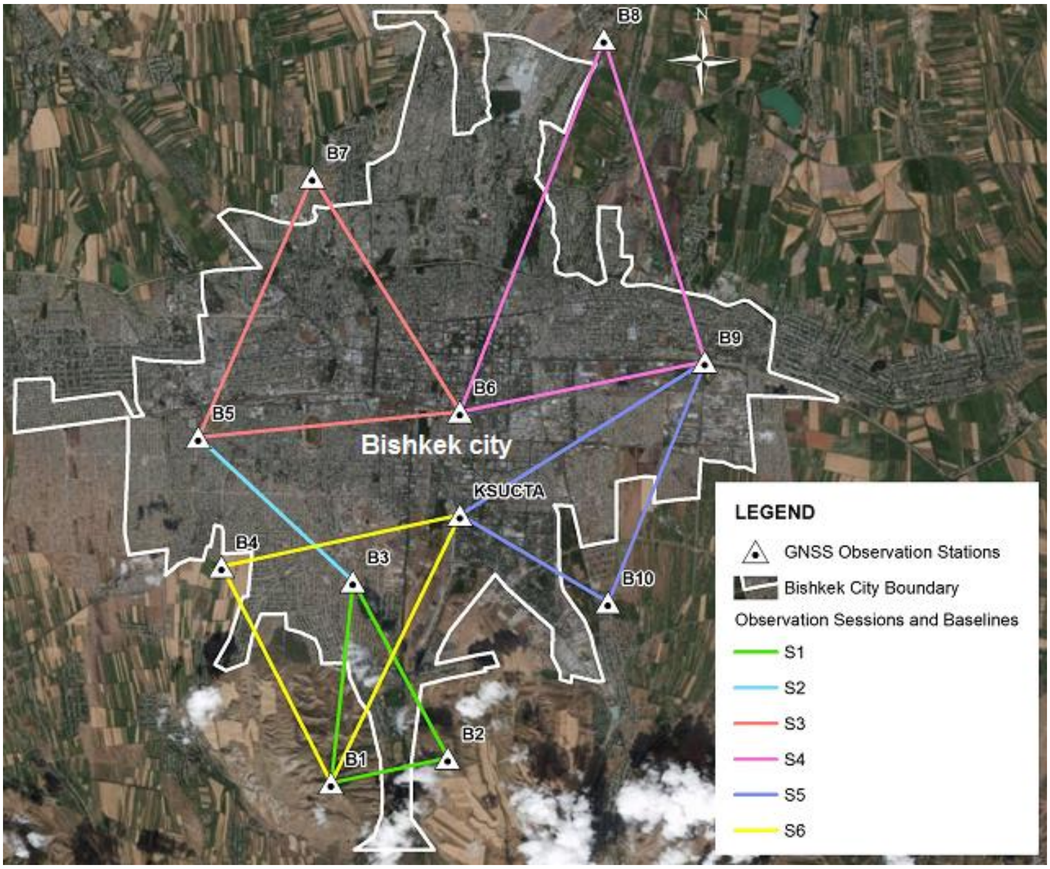

Figure 6: GNSS Observation Network of the Bishkek city

Table 1: Analysis of the Normal Heights at the GNSS Observation Stations

GNSS Station No.	GNSS Network Name (Planar/Leveling Class)	Geodetic Height, m (WGS-84)	Normal Height, m (BHS-1977)	Normal Height Difference, m (EGM96-BHS)	Normal Height Difference, m (EGM2008-BHS)
B1	Chonpeldek (2/II)	1351.923	1392.911	0.756	0.734
B2	Pospeldek 1 (2/II)	1165.78	1206.822	0.744	0.742
B3	Popenov Kurgan (2/I)	826.207	867.842	0.527	0.650
B4	Seleksia (2/II)	796.584	838.291	0.455	0.578
B5	Pishpek Station (2/IV)	715.675	757.680	0.451	0.619
B6	1276PP (1st Order City Survey Network)	736.578	778.500	0.520	0.690
B7	Kurgan (2/I)	663.584	706.046	0.357	0.527
B8	Alamedinka (2/I)	637.994	680.524	0.355	0.503
B9	1182PP (1st Order City Survey Network)	712.916	754.998	0.387	0.572
B10	Kok-Jar (2/I)	887.377	928.867	0.593	0.711
KSUCTA	KSUCTA (University Survey Network)	787.071	829.050	0.288	0.433

The control of the satellite positioning results for each station of the local network had been realized using the Precise Point Positioning (PPP) technology. It is a method to perform precise position determination using a single GNSS receiver and it becomes possible with the availability of precise satellite orbits and clock corrections from the International GNSS Service (IGS) and several other organizations (Chymyrov, 2015). The word "precise" is also used to distinguish it from the conventional point positioning techniques that use only code or phase-smoothed code as the principal observable for position determination. PPP uses differenced code and phase measurements from a single GNSS receiver and freely available precise GNSS orbit and clock data products for positioning with centimeter and sub-centimeter accuracy in the static mode and at the decimeter error level in the kinematic mode. Precise ephemeris substantially reduce the errors in GNSS satellite orbits and clocks, two of the most significant error sources in point positioning with a single GNSS receiver (Cao et al., 2010).

GNSS observation datasets have been processed to analyze the bias and spatial distribution of the station heights based on the modern Earth gravimetric models. Each of GNSS observation stations has determined geodetic or ellipsoid heights and BHS-1977 based normal heights from the static GNSS observations and the Catalogue of State Geodetic Network of the Kyrgyz Republic. The normal height differences from 0.288 m to 0.756 m with standard deviation of 0.154 m between EGM96 and BHS-1977 surfaces and from 0.433 m to 0.742 m with standard deviation of 0.101 m between EGM2008 and BHS-1977 surfaces are calculated using these geoid models (Table 1). The statistical analysis shows the EGM2008 surface with 0.101 m standard deviation of height differences can be fitted for the further local geoid model in comparison with EGM96 model with standard deviation of 0.154 m.

6. Conclusion

The study showed that the Earth Gravitational Model EGM2008 most accurately represents the model of the real gravitational potential of the Earth in comparison with others. The definition of normal heights with a standard deviation of about 40 cm in the high mountain conditions of the Kyrgyz Republic, where more than 94% of the territory is occupied by mountains, makes it possible to use the high potential of satellite geodesy when performing a number of topographic and cartographic works. Solving the tasks of engineering geodesy and geophysical studies using GNSS requires the introduction of a new local geoid model based on EGM2008 as the most appropriate model in the territory of the country. Further specification and implementation of a local model using satellite measurements, state leveling and gravimetric networks, geometric leveling and gravimetric studies allows the wide use of global satellite positioning systems in solving various applied problems.

The development of a local geoid model in conditions of the Kyrgyz Republic should be conducted in cooperation with regional and international projects in this direction, taking into account the small territory and complex geometry of the state border of the country. Vertical datum of the Republic should be based on the Baltic Height System with the further use and modification of the state plane coordinate system "Kyrg-06". The research work has determined the median value of 0.619 m of the height differences between EGM2008 and BHS-1977 surfaces with standard deviation of 0.101 m for the Bishkek city area. The EGM2008 based local quasigeoid model for the Kyrgyz Republic is recommended to synthesize in combination with additional countrywide GNSS measurements, spirit leveling and gravimetric investigations enabling the surveyors and engineers to benefit the full capacities of GNSS technology in geodetic positioning.

The research was supported by a grant from Trimble, a company working in the field of developing positioning systems based on signals from global navigation satellite systems and modern geodetic survey technologies.

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