Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 62, No 5, 2009

PHYSIQUE GEOGRAPHIQUE
Océanologie

MULTI-SATELLITE MARINE GEOID FOR THE BLACK SEA

**Valentin Kotzev, Lyubka Pashova, Ilias Tziavos*,
Georgios Vergos*, Rossen Grebenitcharsky****

(*Submitted by Corresponding Member G. Milev on February 23, 2009*)

Abstract

Altimetric data from ERS1, ERS2, GEOSAT and Topex/POSEIDON satellites are used to determine the marine geoid in the Black Sea region on a $2' \times 2'$ grid. The solution is based on corrected sea surface heights and the remove-restore technique. The used data are validated against stacked Topex/POSEIDON data. The multi-satellite geoid is obtained through combination of GEOSAT, ERS1 and ERS2 along track data after a four-parameter transformation to the more accurate Topex/POSEIDON sea surface heights. The determined geoid is compared with the quasi-geoid at 6 tide gauges situated along the western coast of the Black Sea as well as with the KMS04 mean sea surface model, and with other local geoid solutions for the region. The absolute differences with the quasi-geoid at the tide gauges when a corrector surface based on GPS levelling is used are between 0.07 m and 0.31 m. The RMS difference with the KMS04 grid is 0.16 m. The presented here marine geoid model is compatible to KMS04 and with the estimated corrector surface and provides smaller differences with the quasi-geoid heights at the tide gauges.

Key words: satellite altimetry, mean sea surface, marine geoid, Black Sea

Introduction. Accurate determination of the marine geoid is of particular interest to oceanographers, geodesists and other geoscientists, since it serves as

---

This research was supported by the National Science Fund at the Bulgarian Ministry of Education and Science, Grant NZ-1210Gr/02 and was also funded by the Greek Secretariat for Research and Technology in the frame of the 3rd Community Support Program (Op. Sup. Prog. 2000–2006), Measure 4.3, Action 4.3.6 (International Scientific and Technological Co-operation). The maps in this paper were generated using the public domain Generic Mapping Tools (GMT) software [24].

a natural reference for heights in their studies. Satellite altimetry provides a large amount of precise and globally distributed data of the instantaneous sea surface of the Earth's oceans, which can be used to model the marine geoid and gravity field.

The first efforts to determine the marine gravity field from satellite altimetry measurements originates in the early 1960s. The pioneering work of KOCH [1] was followed by the first determinations of the global gravity field by RAPP [2] and HAXBY [3]. The early models were developed using data from GEOS-3 and SEASAT satellites followed by improved determinations, which included measurements from the GEOSAT, ERS1 and ERS2 geodetic missions [4–6]. A culmination of the satellite altimetry technology was the Topex/POSEIDON (T/P) mission launched in 1992. To meet the stringent orbit accuracy requirements for that mission, three geopotential models were developed: JGM-1 (pre-launch), JGM-2 (post-launch) [7] and JGM-3 [8]. The radial orbital accuracy of T/P ephemeredes based on JGM-3 reached 3–4 cm [9]. JASON-1, launched in 2001, is the follow-on to T/P and the first satellite in a series designed to ensure continued observation of the oceans for several decades. In 2002 the European Space Agency launched ENVISAT which is the successor to the ERS satellites.

There is a rapid improvement of geoid accuracy since the first use of satellite data for gravity field recovery. One of the most comprehensive global geoid model is EGM96 [10]. This model integrates all available altimetric, marine/continental and space gravimetric data and gives a ±46 cm cumulative geoid error. One centimetre or better accuracy, however, is necessary to support the full-range of applications of satellite altimetry [11]. For example, studies of the geostrophic currents on smaller scales (down to mesoscale at mid-latitudes) require geoid accuracy of 2.0 cm on 100 km scales and better than 1.0 cm on 1000 km scales.

Altimetric data set. The analysed Black Sea altimetric measurements were extracted from five data sets including: 9 years of Topex/POSEIDON (T/P) sea surface height data between October 2, 1992 and October 8, 2001; the Phase E (April 10, 1994 to September 27, 1994) and Phase F (September 27, 1994 to March 21, 1995) geodetic missions of ERS1; 6 years of the 35-day exact repeat missions of ERS2 between April 21, 1995 and June 16, 2001; the geodetic mission phase of GEOSAT from March 30, 1985 till September 30, 1986. The number of used sea surface heights for each satellite is 164723 for T/P, 17543 for ERS1, 121447 for ERS2, and 28046 for GEOSAT, totaling to 167036 measurements. The distribution of the tracks is shown in Fig. 1.

The used T/P geophysical data records (GDR) were generated by Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) using

Fig. 1. Distribution of used tracks: *a*) ERS1, *b*) ERS2, *c*) GEOSAT, *d*) T/P →

Fig. 3. Final geoid model for the Black Sea region →

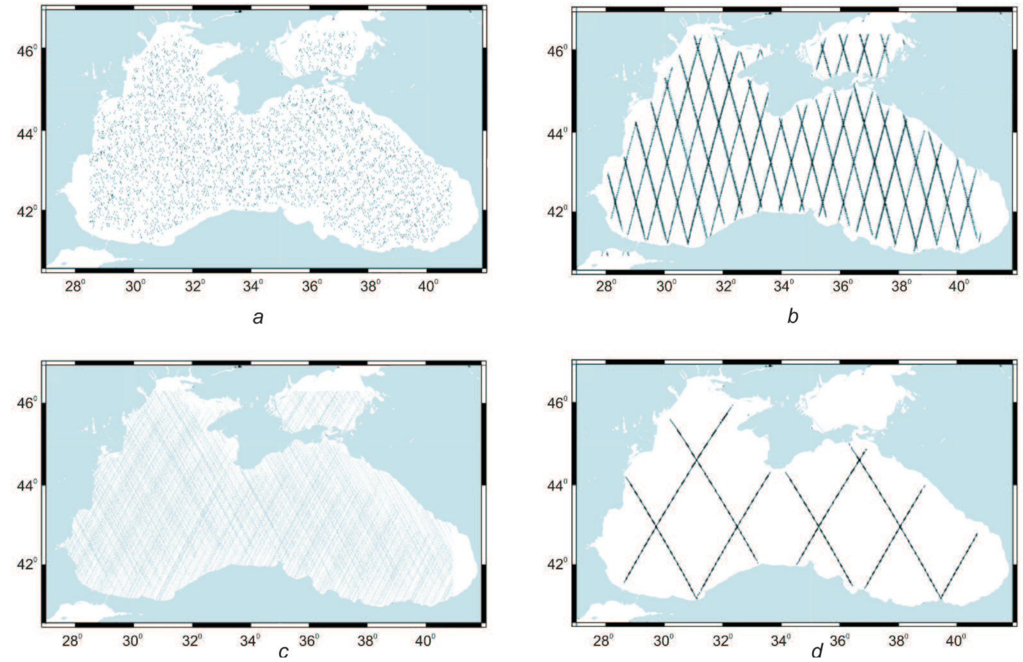
46°
44°
42°
28°
30°
32°
34°
36°
38°
40°
a
b
c
d

Fig. 1

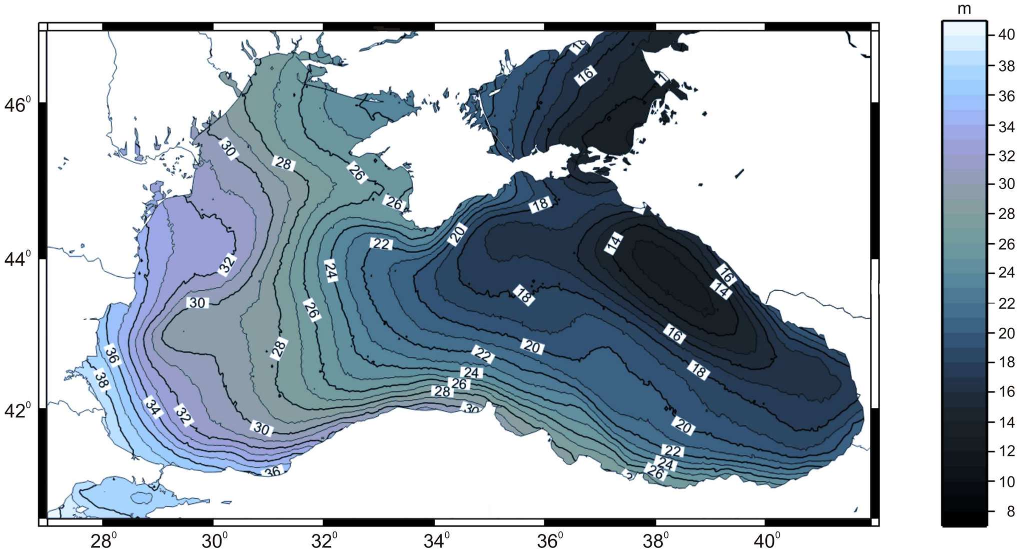
46°
44°
42°
28°
30°
32°
34°
36°
38°
40°
m
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8

Fig. 3

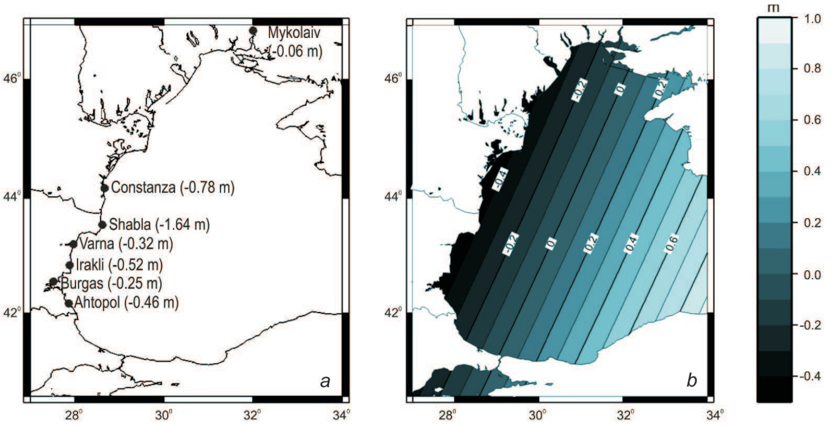

Fig. 4

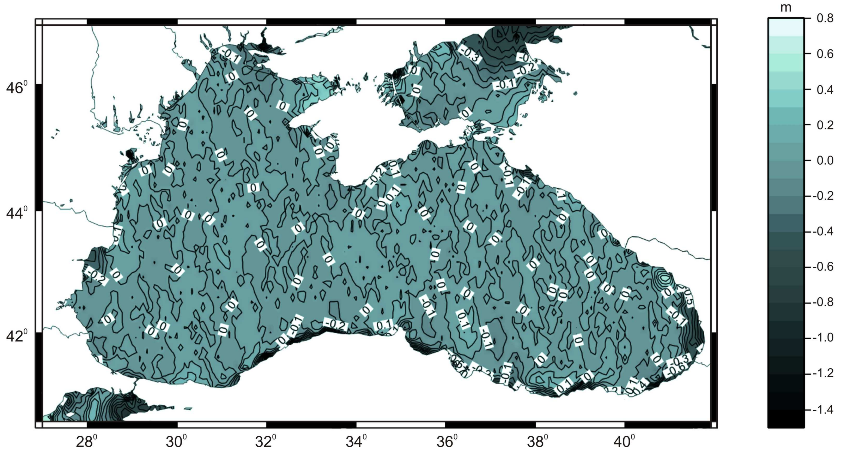

Fig. 5

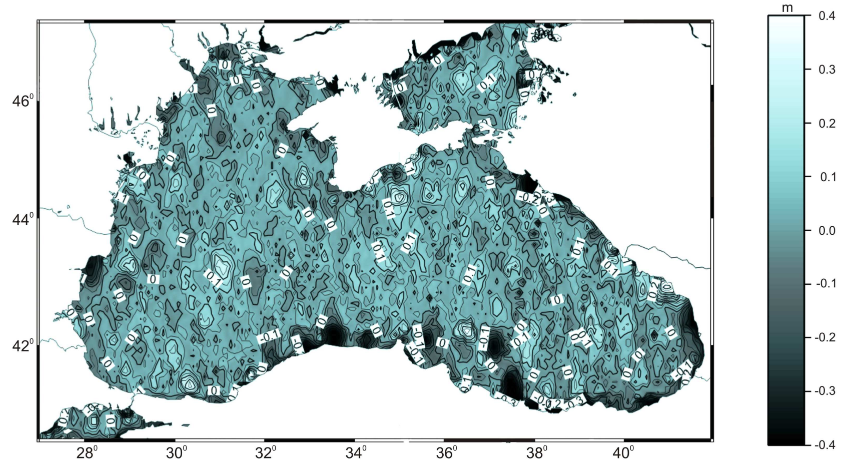

Fig. 6

orbits based on the JGM-3 gravity field [8,12,13]. ERS1 and ERS2 data are also from AVISO. They were fitted to the more precise T/P orbits using a global minimization of the ERS1 (ERS2) T/P dual crossover differences. The GEOSAT exact repeat mission data used in the computations are based on the JGM-3 orbit [14] and the GDRs were generated by National Oceanic and Atmospheric Organization (NOAA).

Methodology. The altimetric geoid is obtained through the remove-restore technique [15] from corrected sea surface heights (CORSSH) from ERS1, ERS2 and GEOSAT. Stacked Topex/POSEIDON CORSSHs data were also used but only as control points for transformation and validation of available data. The geoid is referenced to the EGM96 geopotential model complete to degree and order 360 [10]. Finally, the KMS04 global mean sea surface model [16] was used as a control solution.

The remove-restore procedure is employed by first subtracting the EGM96 geoid heights from the altimetric sea surface heights and then adding them back after fitting and patching operations. The flowchart of the procedure is shown in Fig. 2.

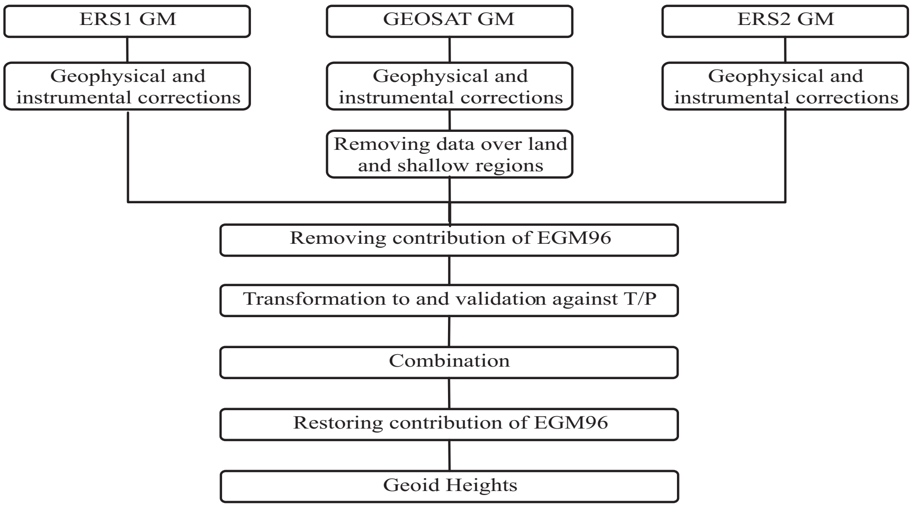

Fig. 2. Flowchart of the remove-restore procedure

← Fig. 4. (a) Differences between altimetric and quasi-geoid heights at the tide gauges before the adjustment; (b) Corrector surface. Due to inconsistency Shabla was not used in the corrector surface determination

← Fig. 5. Differences between the combined geoid solution with KMS04 [m]

← Fig. 6. Differences between the combined geoid solution with the previous model (see text) [m]

Altimetric geoid computation. Taking into account that the used altimetric data are in the form of geophysical data records, our first pre-processing step was to correct the SSHs for instrumental and geophysical errors affecting observations. The models and methods used for computation of the corrected sea surface heights are those documented by the agencies providing the GDRs, i.e., NOAA [14] for GEOSAT, AVISO [12] for ERS1, ERS2 and AVISO [13] for T/P.

After first pre-processing step, we removed data over land and shallow regions to eliminate outliers due to scattering of the radar altimetric pulse and errors in the tidal models used to apply tidal corrections. The latter procedure was performed on GEOSAT data only, not for T/P, ERS1 and ERS2 because GDR's of the last three do not contain coastal and close-to-the-coastline data due to their removal by AVISO 100 m bathymetry mask. The GEOSAT data, however, refer both to oceanic and continental areas. To remove land data, it is necessary to interpolate the depth values for the subsatellite points using a bathymetry or topography mask. The assigned depth of $-200\,\text{m}$ for GEOSAT is based on the $5' \times 5'$ CSR bathymetry model [14] computed in 1995. Since then, higher resolution and accuracy models become available. For that reason, instead of removing land data on the basis of the GEOSAT assigned depth, we interpolated the depths from the $2' \times 2'$ Smith and Sandwell [17] model and removed those above the depth of $-10\,\text{m}$ [18].

CORSSHs from satellite altimetry measurements do not refer to the geoid but to the sea surface. Therefore, they should be corrected for the quasi-stationary sea surface topography (QSST) using a dynamic ocean topography (DOT) model. Most of these models are global [10] and do not represent adequately QSST in closed sea areas like the Black Sea. Grebenitcharsky et al. [18] have estimated that QSST for the Black Sea vary between 0.4 m and +1.2 m. Comparisons made by Vergos [19] show that differences between DOT models for closed coastal areas are greater than the values of QSST themselves. Thus we have not correct data for the quasi-stationary sea surface topography signal.

To remove possible blunders in the data sets, the contribution of the EGM96 gravity model was subtracted from the CORSSHs and 3 RMS tests were per-

Table 1

EGM96-reduced CORSSHs along the tracks [m]

Altimetric mission	Max	Min	Mean	RMS	σ
GEOSAT	1.92	−1.95	−0.64	0.80	0.49
ERS1	1.93	−1.96	−0.69	0.85	0.49
ERS2	1.88	−1.88	−0.57	0.76	0.51

Table 2

Final EGM96-reduced grid CORSSHs [m]

Altimetric mission	Max	Min	Mean	RMS	σ
GEOSAT	1.84	−1.94	−0.43	0.81	0.68
ERS1	1.81	−1.93	−0.52	0.80	0.60
ERS2	1.85	−1.87	−0.25	0.79	0.75

formed (Table 1). After those tests, the CORSSH residuals for each satellite are computed on a common grid (Table 2). The gridding procedure uses the method of weighted means implemented in the GRAVSOFT software [15].

Satellite altimetry data validation. The GEOSAT, ERS1 and ERS2 data are validated against the more accurate T/P data after a 4-parameter transformation as made by Tziavos et al. [5]. For that purpose, the CORSSH residuals for each satellite are interpolated along the T/P tracks. Then, by the method of least-squares we estimated a set of transformation parameters (X_1, X_2, X_3, X_4) for each satellite using the observation equation:

$$R_{T/P} - R - V_{T/P} = X_1 + X_2 \cos\varphi_{T/P} \cos\lambda_{T/P} + X_3 \cos\varphi_{T/P} \sin\lambda_{T/P} + X_4 \sin\varphi_{T/P},$$

where $R_{T/P}$ and R are the EGM96 residuals for T/P and each satellite, $V_{T/P}$ is correction to the residual difference, $\varphi_{T/P}$ and $\lambda_{T/P}$ are longitude and latitude of the T/P subsatellite point. Statistics of EGM96 residuals and estimated differences with T/P for each satellite are shown in Table 3.

ERS2 data shows best overall agreement with the T/P along-track data. The largest discrepancy is found for GEOSAT which is the oldest data set and probably contains unaccounted systematic errors.

To remove still undetected blunders in the data, the CORSSHs residuals along the original tracks of GEOSAT, ERS1 and ERS2 passed 3 RMS tests after transformation to T/P on the basis of the determined parameters. The post-transformation RMS for all satellites is within 0.70–0.80 m. The largest reduction of RMS (~ 0.10 m) is found for ERS1.

Combined solution. The combined geoid (Figure 3) is obtained through combination of the T/P transformed CORSSHs residuals from GEOSAT, ERS1 and ERS2. Such a multi-satellite solution has two major advantages: (1) the GEOSAT data proximity to the coastline improves the geoid determination in the coastal area and (2) the solution benefits from the higher accuracy of the ERS1 and ERS2 data.

The combination is performed by merging three data sets and gridding on a $2' \times 2'$ grid by the method of weighted means. The final geoid is obtained after

Table 3

Differences between CORSSHs from GEOSAT, ERS1, ERS2 and T/P along-tracks after the 4-parameter transformation [m]

Mission	Max	Min	Mean	RMS	σ
T/P	1.85	−2.57	−0.57	0.74	0.46
GEOSAT-GM	1.61	−1.86	−0.70	0.83	0.45
Difference with T/P	1.01	−0.96	0.12	0.18	0.13
ERS1-GM	1.18	−1.81	−0.68	0.81	0.45
Difference with T/P	1.24	−0.86	0.10	0.17	0.13
ERS2-ERM	1.62	−1.80	−0.59	0.73	0.44
Difference with T/P	1.37	−1.18	0.01	0.13	0.13

restoring the EGM96 contribution to the residuals on the grid. Statistics of the combined solution and statistics of its differences with the only T/P determined geoid are given in Table 4.

Comparison of the altimetric geoid with the quasi-geoid at the tide gauges. To determine systematic differences of the obtained geoid with the quasi-geoid in the area we used height data for six tide gauges (in Ukraine, Romania and Bulgaria) along the western coast of the Black Sea. The comparisons were made under the assumption that the mean sea surface, the geoid and the quasi-geoid, on which the Baltic Height System used in these counties as a based, coincide at the tide gauges. This allowed us to determine a corrector surface by minimizing corrections to the differences between altimetric geoid heights (N) interpolated from our solution and the normal (above quasi-geoid) heights (N_{TG}) at the tide

Table 4

Statistics of the combined solution and comparison with the T/P only determined geoid T/P [m]

Description	Max	Min	Mean	RMS	σ
Combined solution	40.58	12.38	23.71	24.61	6.58
Difference with T/P	2.69	−1.19	0.04	0.31	0.31

Table 5

Differences between altimetric (N), quasi-geoid (N_{TG}) and KMS04 (N_{KMS}) geoid heights without and with corrector surface (C) added [m]

Tide gauge	$N_{TG} - N$	$N_{TG} - N - C$	$N - N_{KMS}$
Mykolaiv	−0.06	0.08	0.19
Constantza	−0.78	−0.31	−0.33
Varna	−0.32	0.17	−0.43
Irakli	−0.52	−0.07	−0.83
Burgas	−0.25	0.24	−0.80
Ahtopol	−0.46	−0.12	−0.51

gauge points. By the least-squares adjustment we estimated three parameters Y_1, Y_2, Y_3 in the model

$$N_{TG} - N - V = Y_1 + Y_2(\varphi - \varphi_m) + Y_3(\lambda - \lambda_m),$$

where V, φ, λ are correction to the height difference and latitude and longitude of the tide gauge; φ_m, λ_m are latitude and longitude of the initial tide gauge in Varna. The differences between altimetric and normal heights at the tide gauges are given in Table 5 and plotted on Figs 4*a* and 4*b*. The obtained results are close to those reported in [5].

The translation parameter at the initial point of transformation – the tide gauge in Varna, is −49 cm. This value corresponds to the difference between the presently used in Bulgaria Baltic Height System based on the Baltic Sea level and the old Black Sea Height System defined through the mean sea level of the Black Sea. According to [20] this difference reaches 30–32 cm along the Bulgarian coast. The tide gauge in Varna was used for definition of the Black Sea Height System and for link to the Baltic Height System. The estimated translation parameter also includes QSST and the datum inconsistencies between the mean sea surface and the quasi-geoid model. In our previous studies we estimated this parameter at -42.5 ± 5.8 cm [5].

The corrector surface for transformation between altimetric geoid heights and normal quasi-geoid heights (see Fig. 4*b*) is representative only for the western part of the Black Sea region, where used tide gauges are located.

Comparison with KMS04 and with previous geoid models. To compare our solution with the KMS04 geoid [16] we interpolated the KMS04 data

Table 6

Differences of the combined solution with KMS04 and with the previous geoid solution [5] along the grid [m]

Difference	Max	Min	Mean	RMS	σ
KMS04	1.87	−1.72	−0.03	0.16	0.16
Previous model in [5]	1.93	−4.62	0.02	0.17	0.17

(`ftp://ftp.spacecenter.dk`) on our $2' \times 2'$ grid and computed the differences. The results are shown in Table 6 and Figure 5. The largest discrepancies are found in the southern part of the Black Sea. In this region close-to-the-coastline data were not fully removed in the pre-processing step due to abrupt transition between sea and land surfaces. Better agreement with the KMS04 is found within the central and eastern parts of the Black Sea.

The comparison with our previous model [5] was done on a $5' \times 5'$ grid. The differences do not exceed 0.10 m and in general are randomly distributed. The largest disagreements (~ 0.20 m) occur in the eastern part of the Black Sea and close to the shoreline (Table 6 and Figure 6). Discrepancies at the open sea reflect differences in the data sets used for the two solutions.

Conclusions. An altimetric geoid for the Black Sea region is obtained from ERS1, ERS2, and GEOSAT data using the remove-restore technique. Such combination of multi-satellite data allows overcoming the problems caused by the large cross-track spacing of the exact repeat mission data.

The determined geoid model is compatible to KMS04 and with the estimated corrector surface and provides smaller differences with the quasi-geoid heights at the tide gauges along the western coast of the Black Sea.

The translation parameter of the corrector surface at the Varna tide gauge corresponds to the difference between the Baltic Height System presently used in Bulgaria and the old Black Sea Height System.

The future research will focus on: i) improvement of the geoid model by including new altimetric data (e.g., from JASON-1/2 and ENVISAT); ii) combining the altimetry data with ship borne gravity data; and iii) combination of altimetry data with measurements of the gravity field satellites CHAMP, GRACE and GOCE [22, 23].

REFERENCES

[1] Koch K. R. In: Marine Geodesy a Practical View, A Second Marine Symposium on Marine Geodesy, Marine Technology Society, Washington, D.C., 1970, 301–307.

[2] RAP R. H. Detailed Gravity Anomalies and Sea Surface Heights Derived from GEOS-3/Seasat altimeter data, 1985, Report No. 365, Department of Geodetic Science and Surveying, The Ohio State University, Columbus, Ohio, 126 pp.

[3] HAXBY W. F. Gravity Field of the World's Oceans, Boulder, CO: National Geophysical Data Center, 1987, NOAA.

[4] ANDERSEN O. B., P. KNUDSEN. J. Geophys. Res., **103**, 1998, No C4, 8129–8137.

[5] TZIAVOS I. N., G. S. VERGOS, V. KOTZEV, L. PASHOVA. In: IAG Symposia (eds C. Jekeli, L. Bastos, J. Fernandes), Vol. **129**, Gravity Geoid and Space Missions, Berlin, Heidelberg, Springer Verlag, 2004, 2005, 254–259.

[6] VERGOS G. S., I. N. TZIAVOS, V. D. ANDRITSANOS. In: IAG Symposia (ed. F. Sanso), Vol. **128**, A Window on the Future of Geodesy, Berlin Heidelberg, Springer Verlag, 2005, 332-337.

[7] NEREM R. S., F. J. LERCH, J. A. MARSHALL, E. C. PAVLIS et al., J. Geophys. Res., **99**, 1994, No C12, 24421–24447.

[8] TAPLEY B., M. WATKINS, J. RIES, G. DAVIS et al. J. Geophys. Res., **101**, 1996, No B12, 28029–28049.

[9] SMITH A. J. E., E. T. HESPER, D. C. KUIJPER, G. J. METS et al. J. Geodesy, **70**, 1996, 546–553.

[10] LEMOINE F. G., S. C. KENYON, J. K. FACTOR, R. G. TRIMMER et al. The Development of the Joint NASA GSFC and the NIMA Geopotential Model EGM96, NASA/TP-1998-206861, Greenbelt, MD, Goddard Space Flight Center, 1998.

[11] Geodetic boundary value problems in view of the one centimeter geoid (eds F. Sanso, R. Rummel), Lecture Notes in Earth Sciences, **65**, Berlin, Heidelberg, Springer Verlag, 1997.

[12] AVISO User Handbook – Merged TOPEX/POSEIDON products (GDR-Ms). AVI-NT-02-101-CN, Edition 3.0, Ramonville St-Agne, France, AVISO, 1996.

[13] AVISO User Handbook – Corrected sea surface heights (CORSSHs). AVI-NT-011-311-CN, Edition 3.1, Ramonville St-Agne, France, AVISO, 1998.

[14] The GEOSAT GM Altimeter JGM GDRs, Silver Spring, Maryland, National Oceanic and Space Administration, 1997.

[15] TSCHERNING C. C., R. FORSBERG, P. KNUDSEN. In: Proc. 1st Continental Workshop on the Geoid in Europe (eds P. Holota, M. Veermer), Prague, Research Institute of Geodesy, Topography and Cartography, 1992, 327–334.

[16] ANDERSEN O. B., A. L. VEST, P. KNUDSEN. KMS04 mean sea surface and interannual sea level variability. Poster at the Danish Ocean Science Meeting, Copenhagen, February 2005, 2005 (online at `ftp://ftp.spacecenter.dk`).

[17] SMITH W. H. F., D. T. SANDWELL. Science, **277**, 1997, No 5334, 1956–1962.

[18] GREBENITCHARSKY R., G. S. VERGOS, V. KOTZEV, M. G. SIDERIS. Multi-Satellite Altimetry Geoid Determination in the Black Sea, 2002, Presentation at EGS XXVII General Assembly, Nice, France, 21–26 April, 2002.

[19] VERGOS G. S. MSc Thesis, 2002, UCGE Reports No. 20157, University of Calgary, Calgary, Canada.

[20] HEISKANEN W. A., H. MORITZ. Physical Geodesy, San Francisco, W. H. Freeman, 1967, 364 pp.

[21] BOYADZHIEV B. Geodesy, Cartography and Land Development, **2**, 1985, 12–15 (in Bulgarian).

[22] Barzaghi R., A. Maggi, N. Tselfes et al. In: Observing our Changing Earth (ed. M. G. Sideris), Int. Assoc. Geodesy Symposia, **133**, Berlin, Heidelberg, New York, Springer, 2009, 195–202.

[23] Barzaghi R., N. Tselfes, I. N. Tziavos, G. S. Vergos. J. Geodesy, 2008, `DOI:10.1007/s00190-008-0292-z`.

[24] Wessel P., W. H. F. Smith. EOS Trans. AGU, **79**, 1998, No 47, 579.

Central Laboratory of Geodesy
Bulgarian Academy of Sciences
Acad. G. Bonchev Str., Bl. 1
1113 Sofia, Bulgaria
e-mail: `lpashova@clg.bas.bg`

**Department of Geodesy and Surveying*
Aristotele University of Thessaloniki
University Box 440
54124 Thessaloniki, Greece
e-mail: `tziavos@olimpia.topo.auth.gr`

***Geomatics Engineering Department*
University of Calgary
2500. University Dr. NW
Calgary, Alberta, Canada T2N 1N4