Accuracy assessment of the SRTM 90m DTM over Greece and its implications to geoid modelling

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Abstract. With the realization of the Shuttle Radar Topographic Mission (SRTM) and the distribution of the 3 arcsec (90 m) data over Europe, a high-resolution digital terrain model (DTM) became available for Greece. Until today, high-resolution DTMs for Greece were generated by the Hellenic Military Geographic Service (HMGS) only and present variable resolutions with the finest one being set to 100 m. These DTMs were usually determined by digitizing topographic maps and are thus of variable and sometimes unknown accuracy. When a high-resolution, e.g., 0.5 − 1 arcmin geoid is needed, it is absolutely necessary to employ a very high resolution DTM to compute the terrain effects to gravity and the indirect effect to the geoid. If this information is not available and a coarser DTM is used, then the topographic effects computed are aliased, due to the insufficient resolution of the topographic data used. The scope of this work is twofold. First, a validation and accuracy assessment of the SRTM 90 m DTM over Greece is performed through comparisons with existing global models, like GLOBE and GTOPO30, as well as with the Greek 450 m DTMs delivered by HMGS. Whenever a misrepresentation of the topography is identified in the SRTM data, it is "corrected" using the local 100 m DTM. This processes resulted in an improved SRTM DTM called SRTMG, which was then used to determine terrain and RTM effects to gravity field quantities. Then, all available DTMs were used to compute terrain effects on both gravity anomalies and geoid heights at variable spatial resolutions. From the results acquired, the performance of the SRTMG model with respect to geoid modeling was assessed and conclusions on the effect of the DTM resolution were drawn.

Keywords. SRTM, terrain effects, gravity field, geoid modelling.

1 Introduction

Digital Terrain Models (DTMs) play a crucial role in gravity field related studies, since they provide the high-frequency content of the gravity field spectrum. This is due to the high correlation of the short wavelength gravimetric features with the topography. According to Schwarz (1984) about 2% and 34% of the geoid height and gravity anomaly spectrum, respectively, are contained in the high frequencies (harmonic degrees 360 − 36000), where terrain effects play a significant role.

Furthermore, modern-day gravity field and geoid approximation is based heavily on the well-known remove-compute-restore (rcr) procedure, during which the terrain data are used to smooth gravity and geoid height observations to aid field gridding, transformations and predictions and avoid aliasing effects (Forsberg and Tscherning 1981; Forsberg 1985; Forsberg and Solheim 1988; Tziavos et al 1988, 1992; Vergos et al. 2005).

With the advent and continuous launch of new altimetric and gravity field satellite missions and the collection and availability of new and higher in resolution data, it has become apparent that high-quality and high-resolution DTMs should be available for geoid and gravity field approximation. In several countries around the world high-resolution local DTMs are not available due to confidentiality reasons, since they are most commonly generated by the respective geodetic/cartographic military agencies. Furthermore, the DTMs available are usually not homogeneous, since they are derived by a (simple in most cases) merging of available height data. On the other hand, in 2000 the Shuttle Radar Topographic Mission (SRTM) was launched on-board space shuttle Endeavour and collected a wealth of data of the Earth's topography in global scale and with homogeneous coverage. This resulted in the release of a global 3″ (roughly 90 m) SRTM DTM by NASA and the National Geospatial-Intelligence Agency (NGA). Thus, it was obvious that such a global DTM would offer a great aid in local, regional and global gravity field and geoid determinations, since it could be used to fill-in gaps and densify local and regional/continental DTMs.

The first main goal of the present contribution is the validation of the SRTM 90 m DTM over Greece through comparisons with a national DTM generated by the Hellenic Military Geographic Service (HMGS). Their differences are analyzed and a new corrected SRTM DTM called SRTMG05 is generated for the area under study. The second main objective is the evaluation of the generated SRTMG05 DTM, against the national DTM and other global models, for gravity field and geoid determination. This is achieved by estimating the contribution of all models to gravity anomalies and geoid heights through a number of terrain reduction techniques.

2 Digital Terrain Models and Area

For the evaluation of the SRTM DTM over Greece a national DTM for the area under study and the GLOBE

and ETOPO2 global DTMs were used. The SRTM mission took place in Feb 11-20, 2000 on-board the space shuttle Endeavour. Its main instrumentation was a spaceborne imaging radar modified with a mast like the one used in the International Space station and an additional antenna, so that a 60 m long interferometer could be formed. The SRTM data coverage ranges between 60° north to 54° south and covers about 80% of the Earth's total landmasses. Bamler (1999) and Farr and Kobrick (2000) should be consulted for more information on the SRTM mission and data. The data used in the present study come from the released "research grade" SRTM 90 m dataset, which means that they were unedited so could contain blunders and voids (gaps). Furthermore, no special processing of the data has been done so that in many cases the measured heights represent what was captured from the radar and not the real elevation. The latter, also known as roof effect, is especially evident over dense forests and populated areas with high trees and high buildings, respectively. The SRTM data for the area under study, bounded between $39^{\circ} \leq \varphi \leq 40.5^{\circ}$ and $21^{\circ} \leq \lambda \leq 22.5^{\circ}$, were downloaded from the corresponding US Geological Survey (USGS) ftp site (USGS 2005) and consisted of a total number of 3243601 elevations. Their statistics are presented in Table 1 while Fig. 1 depicts the SRTM 90 m DTM. The total number of undefined elevations (black dots in Fig. 1) in the area was 43199 representing roughly a 1.4% of the total dataset. They were mainly located over river basins and sea areas as well as over the Pindos range stretching from the north-west to the south-west corner of the area. The SRTM data are referenced to the EGM96 global geopotential model, the horizontal datum is WGS84 and their accuracy is at the 16 m level.

The local DTM obtained from HMGS, being identified with the same name herein, had a 15″ (~450 m) resolution and was generated from the digitization of 1:50,000 topographic maps (HMGS 2005). This is the standard set of heights available in Greece for surveying and engineering applications, it covers the entire country and the heights provided have a formal vertical accuracy of 20 m. A denser 100 m resolution DTM is also available from HMGS but its status is declared as confidential and is not available to the public. In the first part of this study, the 15″ HMGS DTM will serve as the ground truth data set against which SRTM will be compared in order to develop a corrected SRTM DTM. Then, the corrected SRTM DTM will be used as reference in the investigation of the DTM effects on the gravity field and the geoid. The statistics of HMGS are presented in Table 1 as well.

Moreover, the GLOBE and ETOPO2 DTMs were considered as well to investigate the performance of other, than SRTM, global models in the area under study. GLOBE (GLOBE 2005) is a 30″ global DTM generated from a mosaic of vector and raster data sources. Its horizontal datum is WGS84, it refers to the mean sea level and has a formal accuracy for Greece at the 30 m level. Finally, the ETOPO2 DTM (ETOPO

2005) is a global model of 2′ (about 3.7 km) resolution generated by assimilating a number of other DTMs and digital depth models (DDM). The models used in the computation of ETOPO2 were GLOBE, ETOPO5, DBDB5, DBDV and the Sandwell and Smith DDM. Using these DTMs and DDMs, ETOPO2 was constructed by regridding them to 2 arcmin resolution by bicubic spline interpolation. Its horizontal datum is WGS84 also and it refers to the mean sea level. The statistics of both GLOBE and ETOPO2 are also listed in Table 1. Gaps in the DTMs over marine areas were replaced by zeros.

Table 1. Statistics of the DTMs and their differences. Unit: [m].

DTMs	max	min	mean	std
SRTM	2884.00	-23.00	704.20	±455.04
HMGS	2734.41	-5.68	716.32	±456.33
SRTMG05	2884.00	0.00	707.16	±457.77
GLOBE	2710.00	1.00	703.75	±457.41
ETOPO2	2552.00	-95.00	690.09	±460.28
SRTM-HMGS	653.54	-407.59	-11.87	±70.43
SRTMG05-HMGS	598.26	-406.94	-11.73	±70.13
SRTM-SRTMG05	33.35	-60.54	0.00	±0.94

The first step of the present work was the validation of the SRTM DTM against HMGS and its correction in places where voids in the data existed. Table 1 presents the statistics of the differences between SRTM and HMGS, which have a mean value of -11 m only and a standard deviation (std) of ±70 m. Taking into account that the topography in the area under study varies significantly, it can be concluded that SRTM provides very good results. The absence of a significant bias between the two models can be attributed to the fact that no roof effect is present in the data, at least in the area under study. Therefore, the only processing done to construct a "corrected" SRTM dataset was to fill-in existing voids with heights predicted from HMGS using spline interpolation. This resulted in the so-called SRTMG05 (SRTM Greece 2005) DTM with the statistical characteristics presented in Table 1. SRTMG05 presents a smaller range of differences with HMGS compared to SRTM by about 60 m. For both models, the larger differences with HMGS are located over the Pindos mountain range and the smallest ones over the plain of Thessaly (central and central-east part of the area). Finally, some large differences can be found approximately at $\varphi=39.5^{\circ}$ and $\lambda=21.5^{\circ}$ where the Valia Calda national park, a densely forest-covered area, is located. Nevertheless, the comparisons against the national DTM give significant evidence that the SRTM dataset gives a realistic picture of the topography of the area under study.

3 DTM effects on the gravity field and geoid

To investigate the performance of the SRTM DTM and its implications to gravity field and geoid modelling, all
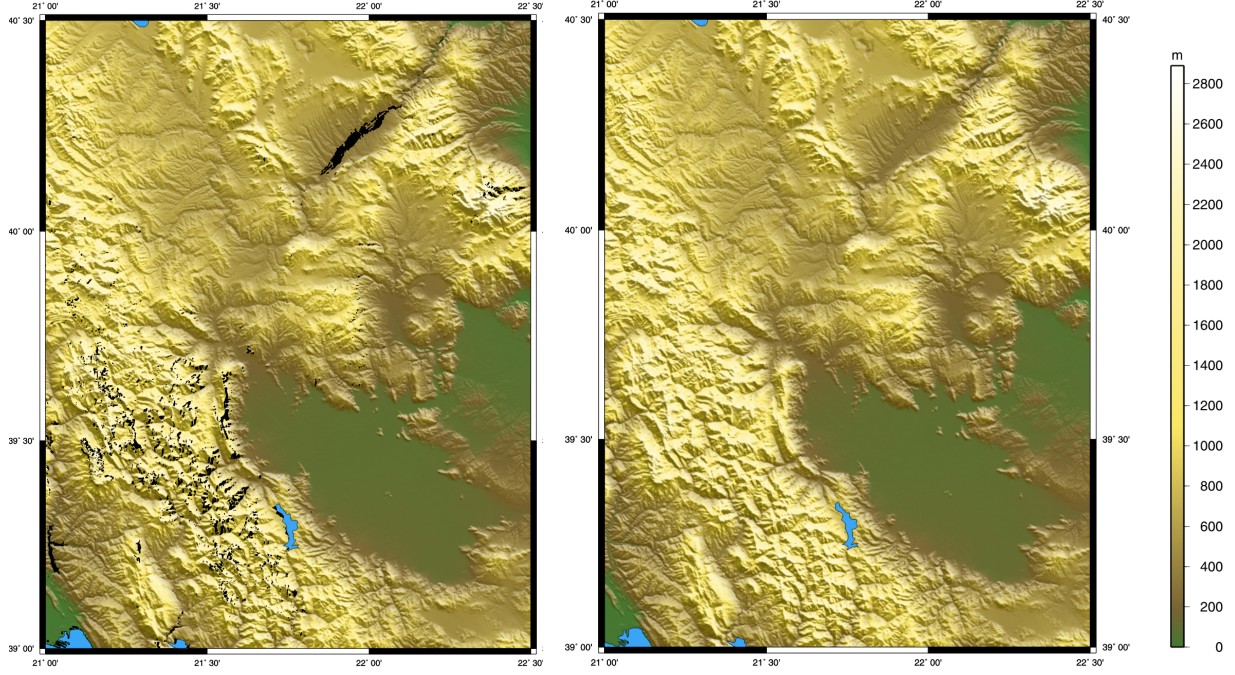
Fig. 1: The original (left) SRTM and the corrected (right) SRTMG05 90 m DTMs. Gaps in data are shown as black dots.

available DTMs (SRTMG05, HMGS, GLOBE and ETOPO2) have been used to estimate various types of topographic corrections on both gravity anomalies and geoid heights. Furthermore, aliasing effects on terrain corrections, i.e., the loss of detail when using coarser in resolution DTMs was studied. This was achieved by constructing lower resolution SRTMG05 DTMs at resolutions of 15″, 30″, 1′, 2′ and 5′. The topographic effects on gravity and the geoid computed were (a) full topographic effects, i.e., the combined effect of the Bouguer and terrain corrections, (b) terrain correction (TC) effects, (c) residual terrain model effects and (d) isostatic effects using the Airy model. Furthermore, indirect effects on the geoid have been computed estimating all three terms. The effects from all models were estimated and then compared on a $1′ \times 1′$ grid for the area under study, which corresponds to cases that a geoid and/or gravity field model of that resolution is needed. Such a high resolution $1′ \times 1′$ geoid model is clearly within reach nowadays in the presence of new gravity-field related data. Due to the limited space available no formulations are given since the evaluation of topographical effects is well documented. A very detailed analysis can be found in Forsberg (1984), Heiskanen and Moritz (1967) and Tziavos (1992). The indirect effect on the geoid is explicitly described in Wichiencharoen (1982).

Tables 2, 3, 4 and 5 present the statistics of the estimated full topographic effects, terrain corrections, RTM and isostatic effects on gravity from the available DTMs, respectively. From these tables it is evident that the performance of SRTMG05 is directly comparable to that of the HMGS DTM. Their difference in the computed full topographic effect is at the ±6.5 mGal level in

terms of the std and ranges between -33 to +36 mGal. This is a very encouraging result, since it shows clearly that the SRTM DTM is indeed accurate and does not introduce any errors when used in gravity field and geoid determination. The same conclusions hold for the computation of the other topographic effects on gravity, since the std of the differences between SRTMG05 and HMGS is ±3.3 mGal in the terrain corrections and ±6.6 mGal for the RTM and isostatic effects.

On the other hand, the differences almost double in magnitude when comparing the topographic effects computed from GLOBE with those derived from either SRTMG05 or HMGS. For example the std of the differences between the TC effects on gravity computed from SRTM and GLOBE are at the ±6.5 mGal and reach the ±13 mGal on the rest of the effects computed. Moreover, the range of the differences increases from about 60 mGal to 120 mGal. This is evidence that indeed SRTMG05 manages to depict more detail of the topography in the area under study, while GLOBE's

Table 2. Full topographic effects on gravity. Unit: [mGal].

DTMs	max	min	mean	std
SRTM3″	244.47	-1.86	72.88	±46.93
SRTM15″	248.29	-1.56	72.57	±46.56
SRTM30″	246.42	-2.07	71.63	±45.99
SRTM1′	250.87	-1.69	74.64	±45.56
SRTM2′	238.54	-1.16	75.07	±45.30
SRTM5′	209.52	-9.55	75.88	±44.37
HMGS	257.96	-1.37	75.37	±46.96
GLOBE	252.79	-3.57	73.64	±46.97
ETOPO2′	249.30	-3.05	73.78	±47.39

Table 3. Terrain corrections on gravity. Unit: [mGal].

DTMs	max	min	mean	std
SRTM3"	47.00	0.04	6.58	±5.92
SRTM15"	52.54	0.03	7.14	±6.38
SRTM30"	52.71	0.08	8.64	±7.55
SRTM1'	56.84	0.02	8.09	±7.92
SRTM2'	68.89	0.01	6.36	±8.17
SRTM5'	125.61	-0.02	9.37	±13.41
HMGS	50.56	0.01	5.47	±5.91
GLOBE	70.87	0.02	8.24	±9.26
ETOPO2'	134.24	0.03	12.49	±16.04

Table 4. Residual terrain model effects on gravity. Unit: [mGal].

DTMs	max	min	mean	std
SRTM3"	183.03	-91.38	-3.93	±37.76
SRTM15"	183.51	-91.41	-4.26	±37.39
SRTM30"	180.91	-88.63	-5.16	±36.77
SRTM1'	185.15	-88.77	-2.27	±38.04
SRTM2'	174.35	-83.48	-1.76	±36.57
SRTM5'	141.38	-82.10	-1.28	±33.08
HMGS	191.79	-84.68	-2.81	±37.51
GLOBE	183.57	-101.90	-3.42	±38.31
ETOPO2'	190.82	-87.52	-1.39	±38.94

Table 5. Isostatic effects on gravity. Unit: [mGal].

DTMs	max	min	mean	std
SRTM3"	215.27	-35.88	37.63	±43.62
SRTM15"	217.41	-34.54	37.23	±43.25
SRTM30"	214.70	-36.28	36.21	±42.66
SRTM1'	218.81	-34.57	39.01	±44.21
SRTM2'	207.26	-36.17	39.09	±43.12
SRTM5'	175.09	-35.61	38.36	±40.40
HMGS	225.95	-34.67	39.42	±43.64
GLOBE	221.73	-33.60	38.59	±43.73
ETOPO2'	217.49	-33.20	38.31	±44.13

resolution is inadequate compared to the high-resolution DTMs available. The results achieved from ETOPO2 are disappointing, since the differences between its topographic effects and the ones computed by either SRTMG05 or HMGS are at the ±25 mGal in terms of the std and reach 230 mGal in terms of the range. This is a clear indication that in the presence of the SRTMG05 elevation data, DTMs of the ETOPO2 class should not be used for geoid and gravity field modeling anymore.

Comparing the topographic effects from the SRTMG05 DTMs at the generated resolutions (15″, 30″, 1′, 2′ and 5′) to those from the original 3″ DTM some aliasing effects are clear. The maximum and std values in the TC effects increase gradually as moving from the dense to the coarser resolutions. In the TC effects on gravity anomalies, the std of the differences between the 3″ and the rest of the SRTMG05 models increases from ±2.2 mGal for the 15″, to ±3.7, ±3.8, ±6 and ±10.7 mGal for the 30″, 1′, 2′ and 5′ models. For

the RTM effects the corresponding std of the differences is at the ±3.2, ±4.7, ±7.5, ±12 and ±19 mGal level. The same trends hold for the rest of the topographic effects as well. Therefore it can be concluded that aliasing occurs when using coarser resolution DTMs for gravity field and geoid modeling. Fig. 2 depicts the TC and RTM effects on gravity as computed from the 3″ SRTMG05 model. Fig. 3 (left) presents the differences between the RTM effects computed from SRTMG05 and HMGS.

The same topographic effects have been computed for geoid heights as well, considering the case when the restore step is reached in the rcr procedure and the effects of the topography previously removed from the gravity data have to be restored to the estimated residual geoid heights. Tables 6 and 7 present the TC and RTM effects on geoid heights computed from the available DTMs. Once again the 3″ SRTMG05 model agrees very well with HMGS with the std of the differences being at the ±3.5, ±2.7, ±2.1 and ±1.6 cm level for the computed full topographic, isostatic, TC and RTM effect, respectively. The corresponding range of the differences is at the 20, 17, 16 and 12 cm level showing once again the very good agreement between the two models. The differences between SRTMG05 and GLOBE are again slightly larger and reach the ±5.9 cm in terms of the std and the 40 cm in terms of the range for the computed RTM effects on geoid heights. For ETOPO2 the differences with SRTMG05 have a std at the ±9.4, ±8.5, ±8.9 and ±9.2 cm level for the computed full topographic, isostatic, TC and RTM effect, respectively. Fig. 3 (right) depicts the differences in the RTM effects on geoid heights between the 3″ SRTMG05 and HMGS.

Table 6. TC effects on geoid heights. Unit: [m].

DTMs	max	min	mean	std
SRTM3"	0.723	0.257	0.484	±0.101
SRTM15"	0.792	0.285	0.525	±0.114
SRTM30"	0.930	0.344	0.635	±0.129
SRTM1'	0.878	0.124	0.624	±0.127
SRTM2'	0.907	0.259	0.458	±0.132
SRTM5'	1.146	0.382	0.677	±0.099
HMGS	0.627	0.206	0.403	±0.090
GLOBE	0.932	0.300	0.607	±0.126
ETOPO2'	1.357	0.467	0.919	±0.177

Table 7. RTM effects on geoid heights. Unit: [m].

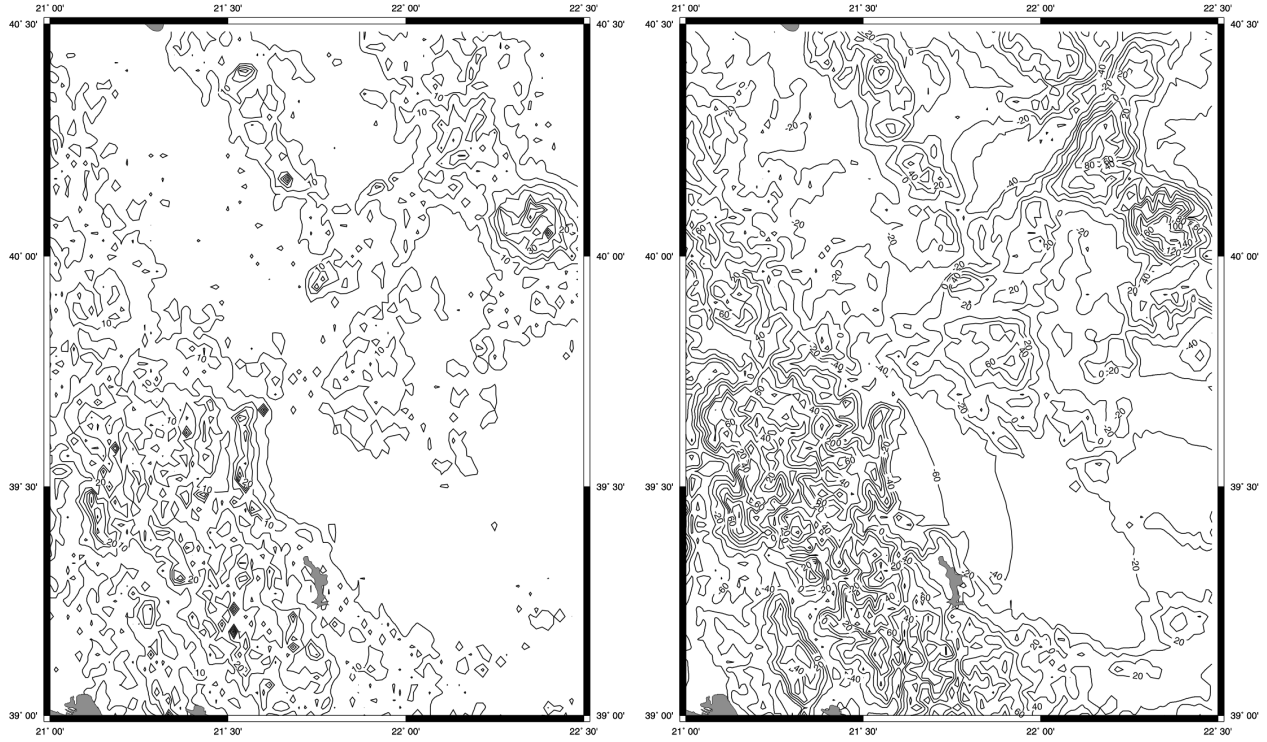| DTMs	max	min	mean	std
SRTM3"	1.184	-0.638	0.060	±0.340
SRTM15"	1.179	-0.639	0.058	±0.340
SRTM30"	1.174	-0.640	0.055	±0.340
SRTM1'	1.158	-0.643	0.049	±0.340
SRTM2'	1.102	-0.647	0.038	±0.339
SRTM5'	0.972	-0.802	0.027	±0.335
HMGS	1.154	-0.634	0.055	±0.337
GLOBE	1.011	-0.655	0.010	±0.336
ETOPO2'	1.273	-0.685	0.071	±0.386

Fig. 2: TC (left) and RTM (right) effects on gravity anomalies from SRTMG05 (C.I. 5 mGal and 20 mGal respectively).
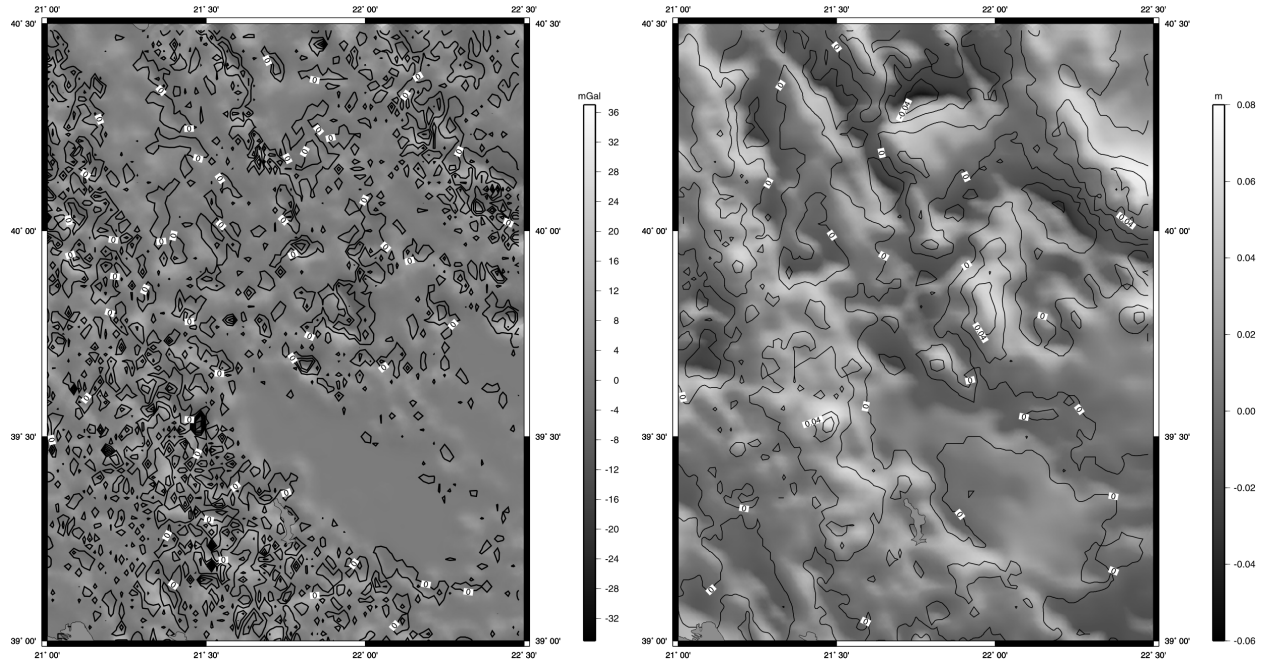

Fig. 3: Differences of TC effects on gravity (left) and of RTM effects on the geoid (right) between SRTMG05 and HMGS.

Investigating the aliasing effects on the geoid from the use of coarser resolution DTMs, the same conclusions were reached. The differences between the TC effects on geoid heights from the original 3″ SRTMG05 model and the 15″, 30″, 1′, 2′ and 5′ DTMs was at the ±1, ±2.6, ±10.1, ±10.8 and ±12 cm level, respectively.

Therefore it can be concluded that an error of that amount is introduced in geoid determination when coarser resolution DTMs are used.

The final computation performed was to estimate the indirect effect (the first three terms of the expansion) on the geoid from all available DTMs. Table 8 presents the statistics of the results acquired. Once again, SRTMG05

agrees very well with HMGS since their difference is again at the few cm level. The GLOBE model behaves much better than ETOPO2, even though the latter resulted from just a re-gridding of the former. So, the bad performance of ETOPO2 cannot be attributed to its coarser resolution alone. Aliasing is evident in the computed indirect effects on the geoid which are more pronounced when reaching the 5′ resolution. A noticing fact is the very large std of the computed indirect effect from the 5′ SRTMG05 model (±85 cm) when it is only ±3 cm for the original 3″ DTM. This is a very good example of the error introduced in geoid determination when a low-resolution DTM is used.

Table 8. Indirect effects on geoid heights. Unit: [m].

DTMs	max	min	mean	std
SRTM3"	0.121	-0.185	-0.009	±0.033
SRTM15"	0.227	-0.220	-0.012	±0.038
SRTM30"	0.146	-0.218	-0.029	±0.036
SRTM1'	0.115	-0.286	-0.078	±0.053
SRTM2'	0.435	-0.710	-0.243	±0.151
SRTM5'	0.934	-4.010	-1.417	±0.848
HMGS	0.207	-0.218	-0.012	±0.037
GLOBE	0.156	-0.219	-0.029	±0.036
ETOPO2'	0.811	-0.782	-0.239	±0.161

4   Conclusions

The SRTM 90 m DTM was evaluated over Greece through comparisons with a national DTM and the GLOBE and ETOPO2 global models. A corrected SRTM DTM called SRTMG05 was constructed by filling-in voids in the original dataset with interpolated values from the HMGS DTM. From the results acquired it can be concluded that the SRTM DTM is very accurate, at least in the area under study, since the topographic effects on both gravity anomalies and geoid heights are very close, if not identical, to those estimated using the national model. The std of the differences of the computed topographic effects between SRTMG05 and HMGS are at the ±3.3 – ±6.6 mGal and the ±1.6 – ±3.5 cm level for gravity anomalies and geoid heights, respectively. These results are comparable to those acquired in Germany by Denker (2004) and in Switzerland by Marti (2004), proving that the 3″ SRTM DTM is indeed a valuable model and can be used for gravity field and geoid determination even at national scales at the absence of higher-resolution national models.

From the results acquired for GLOBE and ETOPO2 it can be concluded that the former is indeed a good model, at least for its time, and provided a very useful set of elevation data for global geoid determinations. But, in view of the SRTM data sets, it is of little use, since it introduces an error of ±6.5 – ±13 mGal and ±3.5 – ±5.9 cm to gravity field and geoid determination, re-

spectively. The corresponding results for ETOPO2 are far more disappointing, since the error is at the ±14 – ±25 mGal and ±8.5 – ±9.5 cm.

Finally, from the study on the aliasing effects introduced in gravity field and geoid determination by using coarser resolution DTMs, it can be concluded that a DTM with at least a 15″ resolution should be used. In this case the error introduced in geoid heights does not exceed ±1 cm. If coarser resolution is used, then errors up to ±12 cm can be introduced. The use of the 15″ resolution SRTMG05 model introduced an error of ±2.5 mGal in gravity anomalies, which reached the ±10 mGal for the 5′ model. Therefore, the use of a DTM with resolution lower than 15″ is prohibitive, if a high-accuracy geoid determination is needed. The next goal is to extent the present study in a larger part of the country to validate and investigate the SRTM performance nationwide.

References

Bamler R (1999) The SRTM Mission: A World-Wide 30 m Resolution DEM from SAR Interferometry in 11 Days. In: Fritsch D and Spiller R (eds), Photogrametric Week 99, Wichmann Verlag Heidelberg: 145-154.

Denker H (2004) Evaluation of SRTM3 and GTOPO30 Terrain Data in Germany. Presented at the Gravity Geoid and Space Missions 2004 (GGSM2004) conference, August 30 – September 3, Porto, Portugal.

ETOPO (2005) 2-Minute Gridded Global Relief Data (ETOPO2), http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html.

Farr TG, Kobrick M (2000) Shuttle Radar Topography Mission produces a wealth of data. EOS Trans Amer Geophys U 81: 583-585.

Forsberg R (1984) A study of terrain corrections, density anomalies and geophysical inversion methods in gravity field modelling. Rep no 355, Dept of Geod Sci and Surv, The Ohio State University, Columbus, Ohio.

Forsberg R (1985) Gravity field terrain effect computation by FFT. Bull Géod 59:342-360.

Forsberg R, Solheim D (1988) Perfomance of FFT methods in local gravity field modeling. In Chapman conference on Progress in the Determination of the Earth's Gravity Field. Bahia Mar Hotel, Fort Lauderdale, Florida, September 13-16, 100-103.

Forsberg R, Tscherning CC (1981) The Use of Height Data in Gravity Field Approximation by Collocation. J Geophys Res 86(B9): 7843-7854.

GLOBE (2005) The Global Land One-km Base Elevation (GLOBE) Project – A 30-arc-second (1-km) gridded, quality-controlled global Digital Elevation Model (DEM), http://www.ngdc.noaa.gov/mgg/topo/globe.html.

Heiskanen WA, Moritz H (1967) Physical Geodesy. WH Freeman, San Francisco.

HMGS (2005) Hellenic Military Geographic Service Digital Terrain Model (personal communication).

Marti U (2004) Comparison of SRTM data with national DTMs of Switzerland. Presented at the Gravity Geoid and Space Missions 2004 (GGSM2004) conference, August 30 – September 3, Porto, Portugal.

Schwarz K-P (1984) Data Types and their Spectral Properties. In: Schwarz K-P (ed), Proc of the Int Summer School on Local Gravity Field Approximation, Beijing, China, 1-66.

Tziavos IN (1992) Alternative numerical techniques for the efficient computation of terrain corrections and geoid undulations. Presented at the 1st Continental Workshop on the Geoid in Europe – "Towards a Precise Pan European Reference Geoid for the Nineties", Prague, May 11-14.

Tziavos IN, Sideris MG, Forsberg R, Schwarz KP (1988) The effect of the terrain on airborne gravity and gradiometry. J of Geophys Res 93(B8): 9173-9186.

Tziavos IN, Sideris MG, Forsberg R, Schwarz KP (1992) A study of the contribution of various gravimetric data types on the estimation of gravity field parameters in the mountains. J of Geophys Res 97(B6): 8843-8852.

USGS (2005) United States Geological Survey, ftp://edcsgs9.cr.usgs.gov/pub/data/srtm.

Vergos GS, Tziavos IN, Andritsanos VD (2005) On the Determination of Marine Geoid Models by Least Squares Collocation and Spectral Methods Using Heterogeneous Data. In: Sansó F (ed) Proc of International Association of Geodesy Symposia "A Window on the Future of Geodesy", Vol. 128. Springer - Verlag Berlin Heidelberg, 332-337.

Wessel P, Smith WHF (1998) New improved version of Generic Mapping Tools released. EOS Trans Amer Geophys U 79(47): 579.

Wichiencharoen C (1982) The indirect effects on the computation of geoids undulations. Rep no 336, Dept of Geod Sci and Surv, The Ohio State University, Columbus, Ohio.