Terrain Effect on Gravity Field Parameters using Different Terrain Models

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Abstract. *This paper presents the results of several analyses considering influence of terrain models on gravity field data. In the analysis are used digital elevation model (DEM) made by digitalization of topographic maps, Shuttle Radar Topography Mission Digital Terrain Elevation Data (SRTM DTED), gravity anomalies, GPS\leveling undulations and deflections of the vertical in Croatian geoid test area. To check the influence of different terrain resolutions on residual terrain model (RTM) effects on gravity anomalies and GPS\leveling undulations, the resolutions of referent terrain models 6'x7.6', 10'x15', 20'x30' and 30'x30' are used. Influence of different referent DEM resolutions on remove-restore residual fields is showing the smoothest and smallest field for resolution 20'x30'. The comparison of DEM and SRTM DTED terrain models is made to check their quality. To judge influence on gravity field considering differences of DEM and SRTM DTED terrain models, RTM effects on gravity anomalies, GPS\leveling undulations and vertical deflections are modeled.*

Keywords. *DEM, SRTM DTED, terrain model resolution, RTM effect.*

1. Introduction

CHAMP and GRACE and further GOCE gravity models are defining new standards in gravity field modeling in global (long wave) and regional (middle wave) scale. Topographic, short wave, influence on gravity is becoming more and more important. However, the latest GRACE models are containing topographic (short wave) structure of gravity field, see Hećimović and Bašić (2004). Different characteristics of Croatian topography, on the coast very slope, high mountains and in the eastern part flat area, can be clearly recognized in the GRACE models, see Hećimović et al. (2004). Modeling of short wave gravity field, which is caused by topography and masses densities variability, is becoming the primary problem in modeling regional and local gravity field.

To investigate influence of different terrain models on gravity anomalies, deflections of the verticals and GPS\leveling undulations the test area in the northern part of Croatia has been chosen. To get a insight into the terrain resolution influences, it is interesting to analyze the influences of different terrain model resolutions on RTM gravity anomalies and RTM GPS\leveling undulations. Terrain models with the resolutions 6'x7.6', 10'x15', 20'x30' and 30'x30' are used in investigations. For every resolution, the statistical characteristics are analyzed as well the main characteristics of empirical covariance functions.

Besides the used DEM that is based on national topographic information, global topographic information, e.g. SRTM DTED is also publicly available now. Comparing of DEM and SRTM DTED we obtain the independent quality control of available topographic information. Calculating RTM influences on gravity functionals using DEM and SRTM DTED gives us the possibility to check direct influence on gravity field values as well on geoid using independent sources of topographic information. It gives us the possibility to judge systematic errors in topographic models on gravity field values.

2. Croatian Geoid Test Area

Croatian political borders have got an unpleasant shape for modeling earth gravity field. The rectangular test area (45.0° < φ < 46.5°, 15.5° < λ < 17.5°) is chosen for numerical analysis (see Figure 1).

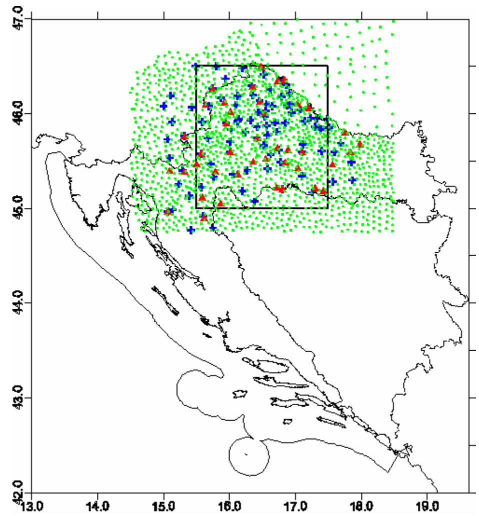

Fig. 1 Croatian geoid test area with point free air anomalies (green points), deflections of the verticals (blue crosses) and GPS\leveling data (red triangles).

There are point free air anomalies, deflections of the verticals, GPS\leveling data and different terrain models used in the analysis. Because of inconvenient Croatian shape for modeling earth gravity field, the data about the territory of other countries are also used.

To separate different gravity fields' wavelengths, and analyze smaller gravity signal, the remove-restore procedure on gravity field functionals L_i is used (Denker (1988)). Wavelengths are separated considering different sources of data after

$$L_i(T) = L_i(T_{GPM}) + L_i(T_M) + L_i(T_{RTM}) \,. \qquad (1)$$

The theoretical background to mode RTM effect can be found in Forsberg (1984a) or Forsberg and Tscherning (1981).

The main statistical characteristics of 1491 point free air anomalies are given in Table 1.

Table 1. The main statistical characteristic of gravity anomalies

	$\Delta g_{FREE\ AIR}$ [mGal[1]]	Δg_{EGM96} [mGal]	Δg_{RTM} [mGal]	$\Delta g_{REZID.}$ [mGal]
Mean	31.85	23.76	-0.86	12.70
St. dev.	23.46	9.11	10.31	12.76
Min.	-40.76	-3.06	-43.88	-22.24
Max.	135.22	47.51	74.61	64.26

From available GPS\leveling dataset, only 41 reliable GPS\leveling undulations in the test area are used. The main statistical characteristics of GPS\leveling data are shown in Table 2.

[1] 1 mGal = $1 \cdot 10^{-5}$ $m \cdot s^{-2}$

Table 2. The main statistical characteristic of GPS\leveling undulations

	$N_{GPS\backslash LEV.}$ [m]	N_{EGM96} [m]	N_{RTM} [m]	$N_{REZID.}$ [m]
Mean	45.16	46.46	-0.01	-1.29
St. dev.	0.48	0.38	0.05	0.26
Min.	44.03	45.71	-0.07	-1.83
Max.	46.44	47.07	0.14	-0.68

RTM undulations are indicating small influence on the geoid height changes, and the mean of undulations is indicating datum differences in the first approximation.
Deflections of the vertical components are used in 91 points. They are behaving irregularly in amplitude and directions. The main statistical characteristics of deflections of the vertical components are given in Tables 3a and 3b.

Table 3a. The main statistical characteristic of meridian component of deflections of the vertical

	$\xi_{MEAS.}$ ["]	ξ_{EGM96} ["]	ξ_{RTM} ["]	$\xi_{REZID.}$ ["]
Mean	0.64	0.29	0.02	0.33
St. dev.	3.61	1.64	1.28	2.35
Min.	-10.46	-4.96	-2.92	-7.16
Max.	11.02	2.95	4.70	6.18

Table 3b. The main statistical characteristic of longitude component of deflections of the vertical

	$\eta_{MEAS.}$ ["]	η_{EGM96} ["]	η_{RTM} ["]	$\eta_{REZID.}$ ["]
Mean	1.55	1.32	-0.29	0.52
St. dev.	3.07	1.61	1.57	2.11
Min.	-10.18	-4.85	-5.36	-4.62
Max.	7.56	4.75	5.76	4.96

The mean values for gravity anomalies and undulations are indicting datum differences that should be considered before geoid modeling.

3. Terrain Models

The terrain models are used for modeling of terrain influence on gravity field DEM of different resolutions and new SRTM DTED. Fine DEM is made by digitizing the maps in the scale 1:25000. Rough and referent terrain models are made by resampling of the fine DEM model. SRTM DTED for area 12 (USGS EROS Data Center (2004)) in the resolution 3"x 3" is used as a separate fine terrain model. Coverage of terrain models is shown on Figure 2.

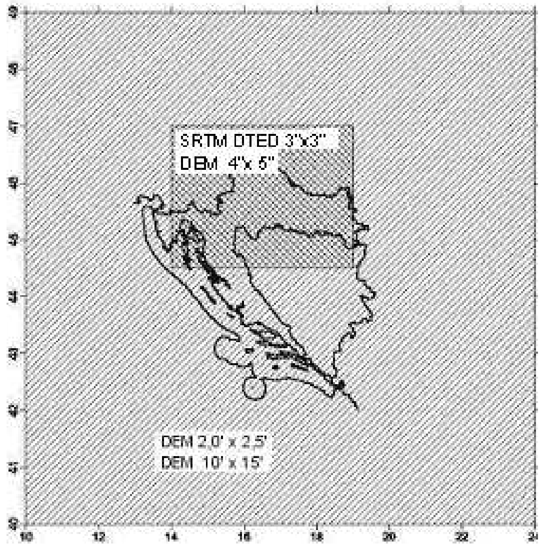

Fig. 2 Terrain models.

- fine SRTM DTED, 3"x 3" in area 44.5° < φ < 47.0°, 14.0° < λ < 19.0°,
- fine DEM, 4"x 5" in area 44.5° < φ < 47.0°, 14.0° < λ < 19.0°,
- rough DEM, 2.0'x 2.5' in area 40.0° < φ < 49.0°, 10.0° < λ < 24.0°,
- referent DEM, 10'x 15' in area 40.0° < φ < 49.0°, 10.0° < λ < 24.0°.

4. Analysis of Influence of Terrain Model Resolution Changes on Gravity Field Functionals

To judge the influence of terrain model resolution changes on modeling RTM effect, a resampling of referent DEM is made. In the analysis there are resolutions 6'x 7.5', 10'x 15', 20'x 30' and 30'x 30' used. RTM effect on gravity anomalies and GPS\leveling undulations is modeled using TC program (Forsberg (1984b)). Constant terrain density of 2670 $kg \cdot m^{-3}$ is used. The main statistical characteristics for RTM gravity anomalies and RTM GPS\leveling undulations are given in Tables 4 and 5.

Table 4. The main statistical characteristics of RTM gravity anomalies using different referent DEM resolutions

	6' x 7.5' Δg_{RTM} [mGal]	10'x15' Δg_{RTM} [mGal]	20'x30' Δg_{RTM} [mGal]	30'x30' Δg_{RTM} [mGal]
Mean	-3.72	-4.17	-4.62	-8.59
St. dev.	11.42	13.47	15.67	19.12
Min.	-77.06	-74.58	-65.98	-74.40
Max.	61.31	77.69	89.98	92.57

Table 5. The main statistical characteristics of RTM GPS\leveling undulations using different referent DEM resolutions

	6' x 7.5' N_{RTM} [m]	10'x 15' N_{RTM} [m]	20'x 30' N_{RTM} [m]	30'x 30' N_{RTM} [m]
Mean	0.01	-0.01	-0.03	-0.50
St. dev.	0.03	0.07	0.15	0.67
Min.	-0.08	-0.23	-0.40	-1.91
Max.	0.31	0.57	0.89	0.95

Increasing resolution of the referent DEM is causing the increase of standard deviations of RTM gravity anomalies and RTM GPS\leveling undulations. With increasing referent DEM resolution the mean values of RTM gravity anomalies are increasing regularly, and the data are deflecting from centering conditions. The mean values of RTM GPS\leveling undulation are increasing regularly up to the resolution 30'x30', where big jump can be observed.

5. Analysis of Influence of Terrain Model Resolution Changes on Empirical Covariance Function

Covariance function is essential for gravity field modeling in collocation techniques. To judge the influence that the changing of referent DEM resolution makes on empirical covariance function of free air anomalies, residuals of free air anomalies are calculated with different RTM values considering changing of resolutions of DEM. In Table 6 the main statistical characteristics of gravity anomalies residual fields are presented.

Table 6. The main statistical characteristics of free air anomalies residual fields in the middle wavelength calculated using different resolutions of referent DEM

	6' x 7.5' Δg_M [mGal]	10'x15' Δg_M [mGal]	20'x30' Δg_M [mGal]	30'x30' Δg_M [mGal]
Mean	11.85	12.22	12.67	16.64
St. dev.	18.37	15.68	12.76	15.66
Min.	-48.15	-27.38	-22.27	-21.15
Max.	90.77	72.92	64.19	81.08

The residual anomalies calculated by RTM effect with 20'x30' referent DEM resolution are giving the smoothest and the smallest residual fields. The mean values of residuals are bigger because of the consistency of gravimetric datums.
The associated variance for the same referent DEM resolution is also the smallest one (see Table 7).

Table 7. Variances of residual free air anomalies for different resolutions of referent DEM

DEM resolution	Variance [mGal^2]
6' x 7.5'	407.725
10' x 15'	368.381
20' x 30'	308.050
30' x 30'	535.461

Using these statistical data as criteria, referent DEM of resolution 20'x30' gives the best results, e.g. this referent DEM gives in remove-restore procedure the smallest and the smoothest residual field for geoid modeling.

6. SRTM Digital Terrain Elevation Data

NASAs Shuttle Radar Topography Mission (SRTM) made in 11 days Space Shuttle flight has scanned nearly a global Earths topography. Space borne Imaging Radar-C (SIR-C) sensors formed an interferometer with a 60-meter long baseline. The data have the potential to provide almost global elevation data in up to 30 m resolutions. SRTM Digital Terrain Elevation Data (DTED) are unrestricted for the area anywhere on the globe in 3" (~100m) resolution, but the resolution 1" (~30m) is publicly available only for the United States and its territories.
SRTM DTED terrain data have voids mainly caused by SIR-C radar shadows in rough terrain. To fill SRTM DTED voids GTOPO30 the terrain model is used (see Figure 3).

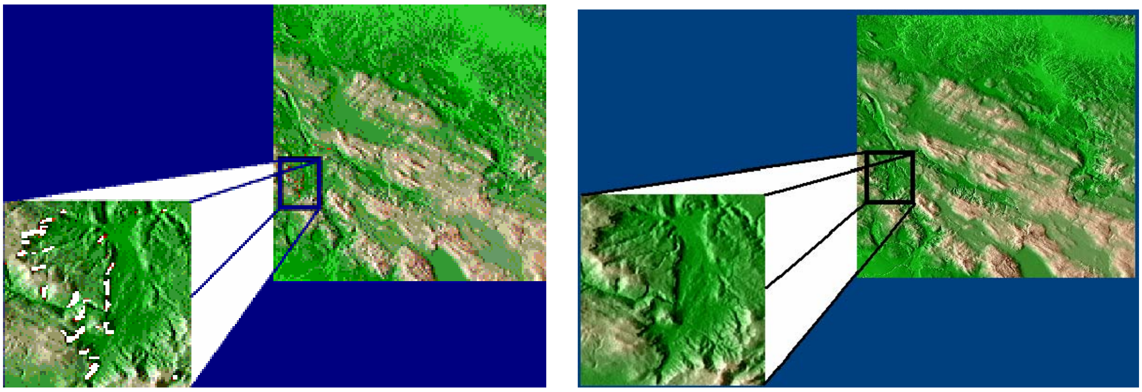

Fig. 3. a) Source SRTM DTED with voids (white holes) and b) SRTM DTED terrain model treated with GTOPO30.

The problem in using SRTM DTED terrain model is that it is related to radar reflecting surface. It does not have to be the primary terrain, but the top of the trees and buildings respectively.

7. Comparison of DEM and SRTM DTED Terrain Models

To judge the quality of DEM and SRTM DTED terrain models in test areas, SRTM DTED is resampled in fine DEM raster of 4"x5". The main statistical characteristics of DEM and SRTM DTED terrain models and their differences are shown in Table 8, and differences are presented on Figure 4.

Table 8. The main statistical characteristics of DEM and SRTM DTED terrain models and their differences

	H_{DEM}	$H_{SRTM\ DTED}$	Diff. H_{DEM} - $H_{SRTM\ DTED}$
	[m]	[m]	[m]
Mean	229	228	1
St. dev.	181	182	27
Min.	1	44	-309
Max.	1796	1770	357

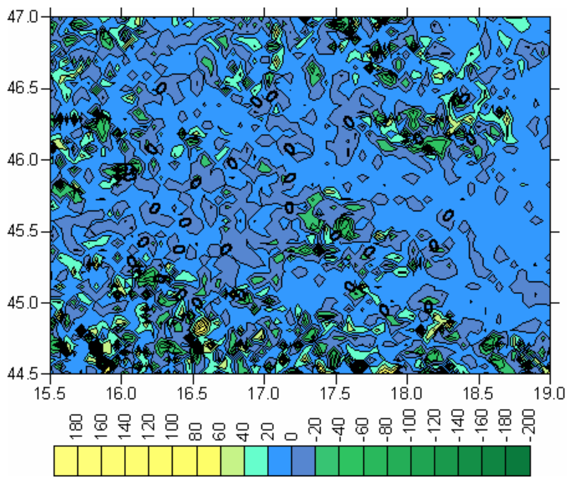

Fig. 4 DEM and SRTM DTED terrain model differences [m].

DEM and SRTM DTED differences have mean value of 1 m. It indicates, in the first approximation, terrain model datum differences. It is caused by datum differences between old Croatian height system datum defined by costal tidal station in Trieste and global geoid EGM96.
This value is showing good agreement with previous comparisons of Croatian height system and global geopotential models, see Hećimović (2001), Hećimović and Bašić (2002). In these investigations there are 121 GPS\leveling undulations well distributed over Croatian territory used. They showed differences between Croatian height system datum and global geoid EGM96 of 1,37 m, and that value has good agreement with the value obtained with DEM and SRTM DTED in table 8.

8. Influence of DEM and SRTM DTED Differences on RTM Gravity Functionals

To check influence of different topography data solutions on gravity field, RTM effects are modeled using DEM and SRTM DTED terrain models. The main statistical characteristics of RTM gravity anomalies for DEM and SRTM DTED terrain models and their differences are presented in Table 9, and on the Figure 5 the differences can be seen.

Table 9. The main statistical characteristics of RTM gravity anomalies for DEM and SRTM DTED terrain models and their differences

	Δg RTM DEM [mGal]	Δg RTM SRTM DTED [mGal]	Diff. Δg RTM DEM – Δg RTM SRTM DTED [mGal]
Mean	-4.74	-4.29	0.13
St. dev.	12.44	13.52	0.83
Min.	-74.58	-74.58	-7.74
Max.	67.37	78.91	6.36

Differences have small bias of 0.13 mGal, as well small dispersion, e.g. standard deviation.

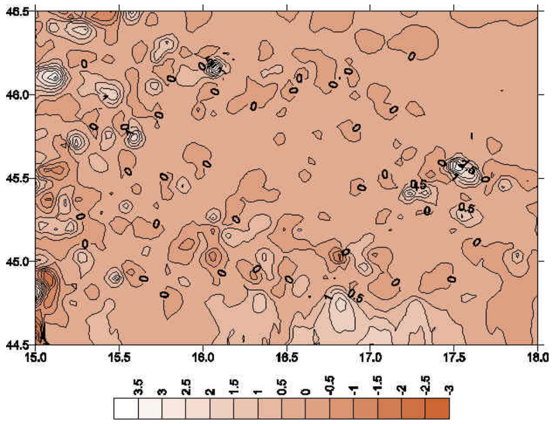

Fig. 5 Differences of DEM and SRTM DTED RTM gravity anomalies [mGal].

The main statistical characteristics of RTM GPS\leveling undulations from DEM and SRTM DTED terrain models and their differences are given in Table 10. The main statistical characteristics and Figure 6 indicate that the influence of different terrain models on RTM GPS\leveling undulations is small.

Table 10. The main statistical characteristics of RTM GPS\leveling undulations for DEM and SRTM DTED terrain models and their differences

	$N_{RTM\ DEM}$ [m]	$N_{RTM\ SRTM\ DTED}$ [m]	Diff. $N_{RTM\ DEM}$ - $N_{RTM\ SRTM\ DTED}$ [m]
Mean	-0.01	-0.01	-0.00
St. dev.	0.06	0.06	0.01
Min.	-0.07	-0.08	-0.02
Max.	0.14	0.15	0.01

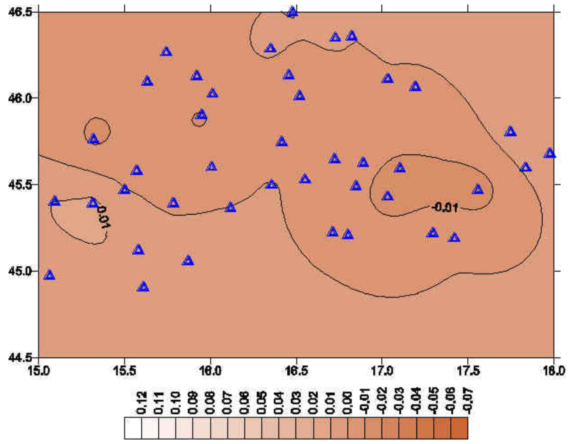

Fig. 6 Differences of DEM and SRTM DTED RTM GPS\leveling undulations [m].

RTM meridian component of deflections of the vertical of DEM and SRTM DTED terrain models and their differences (see Table 11 and Figure 7) are showing small influence of different terrain models. On the Figure 7 it can be seen that the influence is increasing in higher areas.

Table 11. The main statistical characteristic of RTM meridian component of deflections of the vertical for DEM and SRTM DTED terrain models and their differences

	ξ RTM DEM [”]	ξ RTM SRTM DTED [”]	ξ RTM DEM - ξ RTM SRTM DTED [”]
Mean	0.02	0.32	-0.30
St. dev.	1.28	1.40	0.56
Min.	-2.92	-2.33	-2.83
Max.	4.70	4.99	0.45

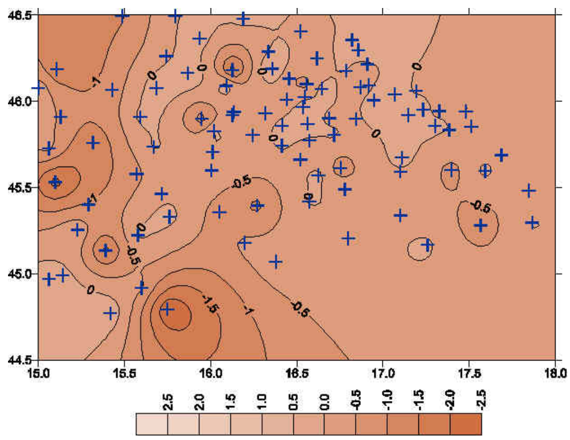

Fig. 7 Differences of DEM and SRTM DTED RTM meridian component of deflections of the vertical [arc sec].

Similar as by RTM meridian component, RTM longitudinal component of deflections of the vertical of DEM and SRTM DTED terrain models and their differences (see Table 12 and Figure 8) show small influence of different terrain models. A small increase of influence can be recognized in higher areas.

Table 12. The main statistical characteristic of RTM longitude component of deflections of the vertical for DEM and SRTM DTED terrain models and their differences

	η RTM DEM [”]	η RTM SRTM DTED [”]	η RTM DEM - η RTM SRTM DTED [”]
Mean	-0.29	-0.04	-0.25
St. dev.	1.58	1.48	0.56
Min.	-5.35	-5.03	-2.52
Max.	5.76	6.17	0.58

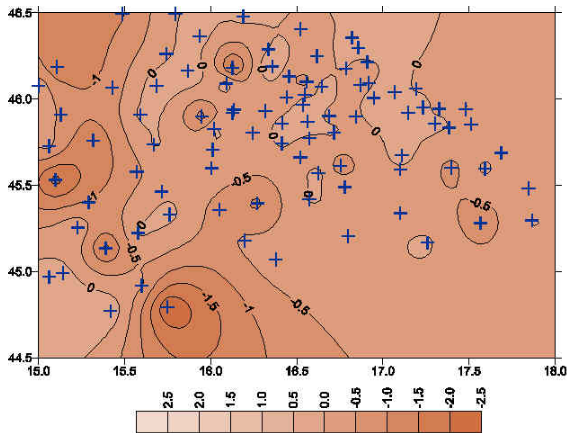

Fig. 8 Differences of DEM and SRTM DTED RTM longitudinal component of vertical deflections [arc sec].

9. Conclusions

The influence of different referent terrain model resolutions on RTM effect for gravity anomalies and GPS\leveling undulations is analyzed for resolutions 6’x7.6’, 10’x15’, 20’x30’ and 30’x30’. The increasing of DEM resolutions influences RTM gravity anomalies standard deviations from 11.42 mGal to 19.12 mGal and mean values from -3.72 mGal to -8.59 mGal. The mean values of RTM GPS\leveling undulations change along with the increasing terrain resolution from 0.01 m to -0.50 m, and standard deviations from 0.03 m to 0.67 m. The changes for RTM undulations are regular up to resolution 30’x30’ where a big jump can be observed. Despite of this irregularity, influence of different resolutions on RTM effect is significant and regular.

The changing of referent DEM resolution affects the covariance function and modeling of gravity signal in collocation technique. Anomalies have the smallest variance for 20’x30’ terrain resolution and residual field of gravity anomalies has the best results in comparison with the results when other terrain resolutions are used for modeling RTM effects. Terrain model of this resolution is giving the smoothest and the smallest residual field for modeling gravity field. Considering the criteria of the smallest variance and the best main statistical characteristic of remove-restore residual field, the optimal resolution of DEM can be found. The smoothest and the smallest residual gravity field are wanted by gravity field modeling using collocation technique.

To judge quality of different terrain models, DEM and SRTM DTED models are compared in the test area. They have vertical bias of 1 m, that is indicating datum differences in the first approximation, and the standard deviation, which is characterizing dispersion of terrain models differences, is 27 m.

To analyze the influence of differences of DEM and SRTM DTED terrain models on gravity field functionals, RTM-effects on gravity anomalies, GPS\leveling undulations and vertical deflections are modeled, and differences are analyzed. Differences of DEM and SRTM DTED terrain models are causing RTM effect on gravity anomalies that have the mean value of 0.13 mGal and standard deviation of 0.83 mGal, RTM GPS\leveling undulations have the mean value of 0.00 m and standard deviation of 0.01 m, meridian vertical deflection components have the mean value of -0.30" and standard deviation of 0.56" and longitudinal vertical deflection component have the mean value of -0.25" and standard deviation of 0.56". DEM and SRTM DTED terrain models discrepancies cause small differences in geoid modeling data, but they should be considered.
The problem that SRTM DTED is related to radar reflecting surface and not to terrain, should be considered in geoid modeling with centimeter accuracy.

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