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SRTM 3″ DEM (versions 1, 2, 3, 4) validation by means of extensive kinematic GPS measurements: a case study from North Greece

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In 2000, the Shuttle Radar Topography Mission (SRTM) provided for the first time a global high-quality digital elevation model (DEM) at resolution levels of one and three arcseconds, using single-pass synthetic aperture radar (SAR) interferometry. In January and February 2008, an extensive four-day kinematic global positioning system (GPS) (KGPS) campaign was carried out in the vicinity of the city of Thessaloniki (North Greece), during which more than 60 000 points were collected, providing an unprecedented density of measurements in the order of 20 points km^{-2}. The purpose of the present study was to assess the vertical accuracy of the four versions of SRTM 3″ DEMs that are currently available over the Internet for public use, on the basis of the KGPS data collected.

1. Introduction

Among the remarkable advances in remote sensing over recent decades, synthetic aperture radar (SAR) interferometry (InSAR), a relatively new remote sensing technique, is currently regarded as one of the best methods for obtaining the most global and the most accurate topographic maps (Massonnet and Elachi 2006). SAR interferometry basic principles and applications have been well documented (e.g. Zebker and Goldstein 1986, Gabriel and Goldstein 1988, Gabriel *et al.* 1989, Bamler and Hartl 1998, Massonnet and Feigl 1998).

In 2000, the Shuttle Radar Topography Mission (SRTM) provided for the first time a global high-quality digital elevation model (DEM) at resolution levels of one and three arcseconds, using single-pass SAR interferometry. The SRTM DEM covers the Earth between latitudes 60°N and 57°S. All data were acquired within 11 days, between 11 and 22 February 2000, using two antenna pairs operating in C- and X-bands, simultaneously illuminating the Earth's surface and recording backscattered radar signals onboard the Shuttle Endeavour. SRTM was jointly performed by NASA, the German Aerospace Center (DLR) and the Italian Space Agency (ASI). The absolute and relative vertical accuracy specifications of the SRTM DEM is respectively defined

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as ± 16 m for 90% of the data across the entire mission and ± 6 m on a local, 50–100 km scale (Farr and Kobrick 2000, Werner 2001, Rabus *et al.* 2003, Farr *et al.* 2007).

When SRTM data were released they quickly became attractive for various applications in topography (e.g. Koch and Lohmann 2000, Falorni *et al.* 2005), geomorphology (e.g. Guth 2003, Stock *et al.* 2002), vegetation cover studies (e.g. Kellndorfer *et al.* 2004), tsunami assessment (e.g. Blumberg *et al.* 2005) and urban studies (e.g. Gamba *et al.* 2002) (Gorokhovic and Voustianiouk 2006).

Due to its vertical accuracy of approximately 15 m or better on 30-m geographic cells, which is much more homogeneous than previous global coverage, and the public availability of the SRTM data, it has become very popular, even at a reduced accuracy and sampling, although the resulting accuracy might be considered as limiting for some applications (Massonnet and Elachi 2006). Several SRTM data verification attempts were made (Gorokhovic and Voustianiouk 2006) using various altimetry data (Helm *et al.* 2002, Sun *et al.* 2003) and digital elevation models (Smith and Sandwell 2003, Jarvis *et al.* 2004, Muller 2005, Bhang *et al.* 2007).

The most extensive global ground-truth effort was realized in collecting a globally distributed set of ground control points (GCPs) using kinematic Global Positioning System (KGPS) transects. The KGPS data were collected by vehicles carrying Global Positioning System (GPS) receivers. The total data collection yielded nearly 9.4 million samples covering six continents with a general accuracy of about 50 cm. Processing of the data was carried out using the Jet Propulsion Laboratory (JPL, Pasadena, CA) GIPSY software (http://gipsy.jpl.nasa.gov). In the end more than two million ground truth points were included in this validation endeavour. A thorough analysis of this effort, along with an extensive assessment of the SRTM topographic products on global scale, can be found in Rodríguez *et al.* (2005), while a synopsis of the results is presented in Rodríguez *et al.* (2006).

Nevertheless, at local scale, a case-by-case validation of the vertical accuracy of SRTM data is always essential in understanding the potential and limitations of using this dataset for a specific area. After all, one of the basic principles of remote sensing is the need for validation of its results, also referred to as 'ground truth', at least for a representative part of the study area in order to ensure reliability of the findings (Astaras 2006).

In Greece a validation for the island of Crete, based on 1:250 000 topographic maps, has been carried out in the past (Miliaresis and Paraschou 2005), concluding that the 3″ SRTM data do not meet the 16 m accuracy specifications for the area that was studied. For the same island, another study by Nikolakopoulos *et al.* (2006) compared SRTM and Terra/ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) stereo derived DEM in the areas of North Heraklion and Sitia. Kinematic GPS data covering small areas have been used in Greece for terrain creation and analysis, along with classical surveying techniques (e.g. Pikridas *et al.* 2004).

The purpose of the present study is to execute the aforementioned validation of SRTM 3″ DEMs, by means of extensive kinematic GPS measurements for an area in Northern Greece. Core validation is carried out in a geographical information system (GIS) environment, namely ArcGIS™ (ArcInfo™, ESRI, Redlands, CA, USA).

2. Study area

The broader area of interest is located in Central Macedonia, Northern Greece, around the city of Thessaloniki, which is the second most populated city in Greece

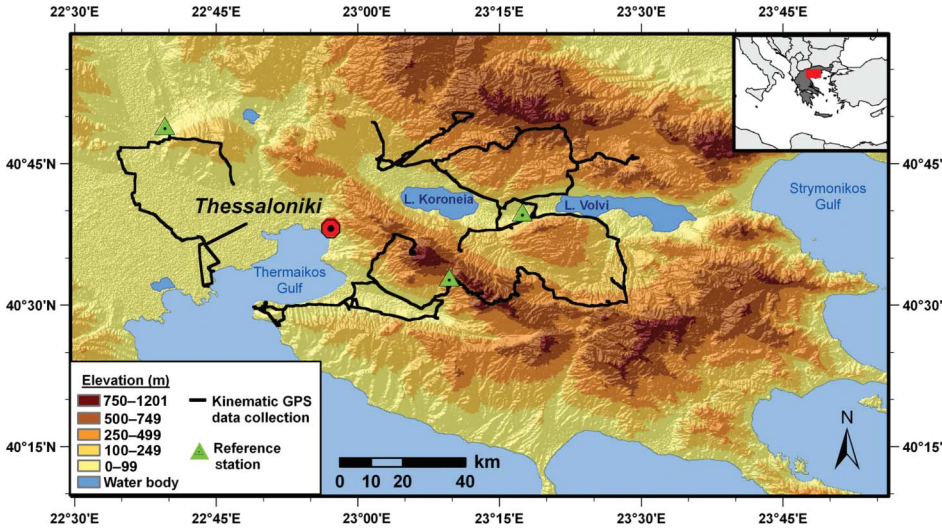

Figure 1. The broader region of interest and kinematic GPS measurements used for the validation of SRTM, defining the actual area under study.

(about 10 00 000 habitants). This region presents great interest for various scientific research disciplines where DEMs have a significant contribution, including geological and earthquake applications, subsidence and other geophysical or environmental studies. The relief of the study area varies from completely flat areas to mountainous regions with steep slopes. Elevations values vary from zero (and in some cases a few metres below mean sea level) to up to a maximum of 1201 m (Hortiatis/Kissos). Vegetation consists mainly of agricultural areas (51%), shrubs (21%), forests (12%) and pastures (7%) (Greek Ministry of Agriculture 1994), not imposing significant constraints during GPS kinematic data collection.

The actual study area is in practice defined by the kinematic GPS measurements that were carried out for the needs of this work, and covers approximately 3600 km^2 (figure 1).

3. Data and methodology

3.1 *SRTM versions*

SRTM 3″ DEMs are publicly available over the Internet, as 1° × 1° tiles, mainly from NASA (ftp://e0srp01u.ecs.nasa.gov/srtm/) and USGS (http://seamless.usgs.gov/). There are two versions available: version 1 (v1) consists of the original digital elevation models. These data are unedited and contain spurious data points in areas of low radar backscatter such as water bodies. Version 2 (v2), also known as the 'finished' version, is the result of a substantial editing effort and exhibits well-defined water bodies and coastlines and the absence of spikes and wells (single pixel errors), although some areas of missing data ('voids') are still present. These voids occur mainly over water bodies (lakes and rivers), areas with snow cover and in mountainous regions (e.g. the Himalayas has the greatest concentration of data voids). In any case, v2 is a superior product than v1 and it is recommended for most users (http://www2.jpl.nasa.gov/srtm/).

Apart from these two NASA original SRTM versions, an alternative 5° × 5° tile version 3 (v3) is provided by the Consultative Group on International Agricultural Research–Consortium for Spatial Information (CGIAR–CSI). This dataset has undergone post-processing of the NASA data to fill in the data voids through interpolation techniques. More information is provided on the CGIAR website (http://srtm.csi.cgiar.org). SRTM v3 is provided with a 'voids mask' depicting the areas of v2 voids that have been filled in. According to this mask, for the area considered in this study and excluding the water bodies, data voids do not exist in v2.

A known issue of v3 is a ½ grid pixel shift relative to SRTM v2 (Jarvis *et al.* 2006). This error has been recognized, but the direction of the shift was unclear. When this study was taking place, another version (v4) was being prepared, in order to compensate for this ½ pixel shift.

For the needs of the present study datasets v1, v2 and v3 were downloaded from the relevant internet websites and data from the newest version (v4) to be released were kindly provided by Dr. Andy Jarvis of the International Center for Tropical Agriculture (CIAT).

Two 1° v1 and v2 tiles had to be merged in order to cover the area of interest. As previously stated, v1 and v2 contained missing values. These values were deliberately not corrected in order to have a clean comparison with SRTM v3–v4. The latter are supposed to have compensated for these missing values (Jarvis 2006).

As a first pre-processing step, the area of interest was defined in each dataset and the relevant subsets were created, each containing 1162 × 778 pixels (approximately 81 × 72 km), overlapping perfectly and having identical pixel size (3″).

A few more adjustments were made to the original data, in order to facilitate the comparisons between the various datasets, which included:

1. applying the SRTM water body data (SWBD) mask (provided with v2) to v1, assigning zero values to the sea;
2. assigning 'no data' value to a few (seven) v1 pixels that were still preserving the value – 32786, representing water body areas very close to the SWBD mask, but not included in it;
3. reclassifying v3 – 32768 (sea) values to zero and
4. applying the SWBD mask to v1, in order to assign the same values as v2 and v3 to the lakes and water bodies existing in the area.

3.2 *Kinematic GPS data collection and processing*

In January and February 2008, a four-day kinematic GPS campaign was carried out in the broader area of the city of Thessaloniki (figure 1), using two Topcon™ GB-1000 dual frequency GPS and Global Navigation Satellite System (GLONASS) (the latter data were not used in this study) receivers (Topcon Corporation, Tokyo, Japan). Sampling rate was selected to 1-s intervals. The reference stations were chosen each day accordingly, so as to facilitate the receiving of the satellite signals (open horizon, no obstructions, etc.) and at the same time to ensure a maximum distance of 20 km from the rover, in order to minimize atmospheric contributions to the GPS signal. In total, three different locations had to be used for the reference station. In order to have some backup reference station, a Leica RS500 GPS receiver (Leica Geosystems AG, Heerbrugg, Switzerland) located in the University of Thessaloniki (approximately in the centre of the study area) was set to collect data at 1-s intervals during the period of measurements.

The GPS antenna of the rover was securely mounted on the top of a vehicle that was used for all measurements (figure 2). During data collection, the speed of the vehicle

Figure 2. Rover receiver antenna (*b*, *c*) mounted on the top of the vehicle (*a*) that was used during the kinematic GPS measurements. One of the two identical Topcon™ GB-1000 receivers that were used is also depicted (*d*).

had been targeted to remain below 60 km h^{-1}, in order to both ensure the stability and safety of the antenna and also to have at least one measurement every 15 m. In practice, the mean speed of the vehicle did not exceed 40 km h^{-1}, providing a much denser volume of data than theoretically expected (approximately 1 point per 11 m). On average, for each measured pixel (approximately 70 m × 90 m) of the SRTM DEM, there were 5–7 GPS points measured (figure 3).

In general, there is a good correlation of data collection density and relief, in the sense that a flat relief is well recorded with relatively sparse measurements, while mountainous areas demand denser sampling. These conditions are in practice well met, since the speed of the vehicle is by default regulated by the character of the road, which is in turn controlled by the quality of the terrain.

With the above configurations and considerations, more than 60 000 points were collected, within approximately 22 hours (approximately 720 km driven), providing a density of measurements in the order of 20 points km^{-2}.

Post-processing of the kinematic GPS data was carried out with Ashtech™ Precise Navigation (PNAV™) software (Ashtech, Santa Clara, CA), after calculating reference station coordinates (table 1) using data from the European Reference Frame (EUREF) Permanent Network (EPN). WGS'84 datum was used for all calculations. The distribution of errors for the KGPS points is presented in figure 4.

Part of the elevation data collected had to be discarded due to their low accuracy (for the purposes of this study), considering various factors.

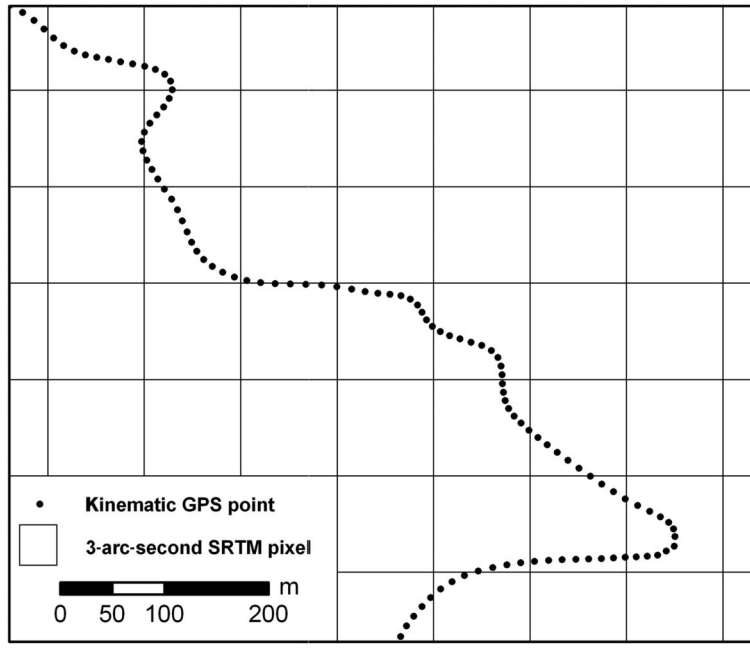

Figure 3. An extract of the GPS measurements, showing the density of the points collected in relation to the SRTM pixel.

Table 1. Absolute coordinates in WGS84 of base reference points used during the KGPS campaign.

	Latitude	Longitude	Elevation (m)
1.	040° 39′ 51.17660″N	023° 17′ 27.44348″E	100.273
2.	040° 32′ 46.86583″N	023° 09′ 48.19085″E	563.88
3.	040° 49′ 00.65308″N	022° 39′ 35.89996″E	83.555

More specifically, in regions with significant discrepancy between ground-truth and SRTM heights (e.g. near overpasses and bridges) a few points were visually eliminated during a visual query process, based on familiarity and *a priori* knowledge of the study area, and thus a good idea of what was actually being measured during data collection. Overlaying the GPS data on Google^{TM} Earth's very high-resolution images proved to be extremely useful during this process.

Additionally, following a similar methodology as the one adapted by Rodríguez *et al.* (2005), GPS data with a standard deviation of more than 1 m within a 30-m distance, or more than 5 m for 90-m distance, were removed. This two-step 'filtering' reduced the number of available GPS points to 50 923, with a general accuracy of $\pm$ 50 cm.

Finally, multiple GPS samples within a single SRTM 3″ (approximately 70 m $\times$ 90 m) data pixel were averaged, so that each SRTM pixel was equally weighted and in order to smooth possibly ambiguous GPS measurements that were not identified during the previous steps.

The procedures described above yielded in the end a total number of 10 792 remaining GPS points (table 2), optimized for validating the SRTM data.

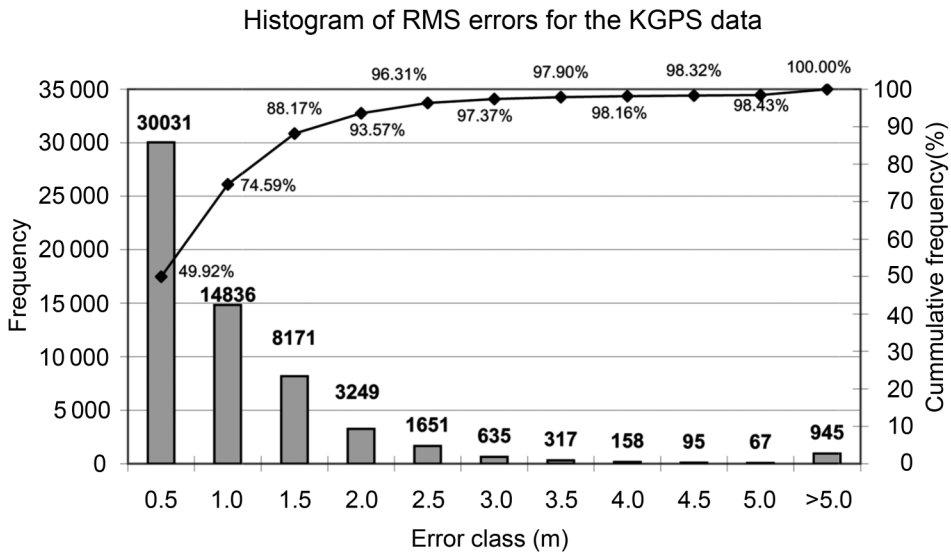

Figure 4. KGPS data accuracy after post-processing. Root Mean Square Error (RMSE) is < 0.5 m for approximately 50% of the data, whereas almost 90% of the data have an accuracy better than 1.5 m. Only 1.5% of the data are of relatively low accuracy (RMSE >5).

Table 2. Kinematic GPS points collection and processing statistics.

	Originally	After filtering	After averaging to 3″ SRTM pixel (final ground truth points)
No. of GPS points	> 60 000	50 923	10 792

3.3 *SRTM versions 1, 2, 3 and 4 comparison*

Before assessing the absolute and relative vertical accuracy of SRTM versions, using the GPS data, a relative comparison between the versions themselves was due, by means of subtracting the pixel values of one version from the equivalent values of another version. All possible calculations were computed: v2–v1, v3–v2, v4–v3, v4–v2, v3–v1 and v4–v1. The results of all subtractions are shown in figure 5 and the statistics are summarized in table 3.

The shift between v3 and v2, discussed in section 3.1, was identified for more than 70% of the study area as a difference in height determination between –104 and +68 m (depending on the relief), when subtracting v2 from v3. What is even more interesting is that in places where differences occurred, it was relatively easy to locate the corresponding pixels between v2 and v3 (with exactly the same elevation value, which would have normally produced a zero difference) just one pixel away, but the direction in which the 'corresponding' pixel had been shifted was not constant. Hence, the ½ pixel reported shift caused an up to 1 pixel shift in the study area, resulting in a maximum relative elevation difference of 104 m between the two versions. More generally, in all cases where v3 is involved in a comparison, errors increase significantly.

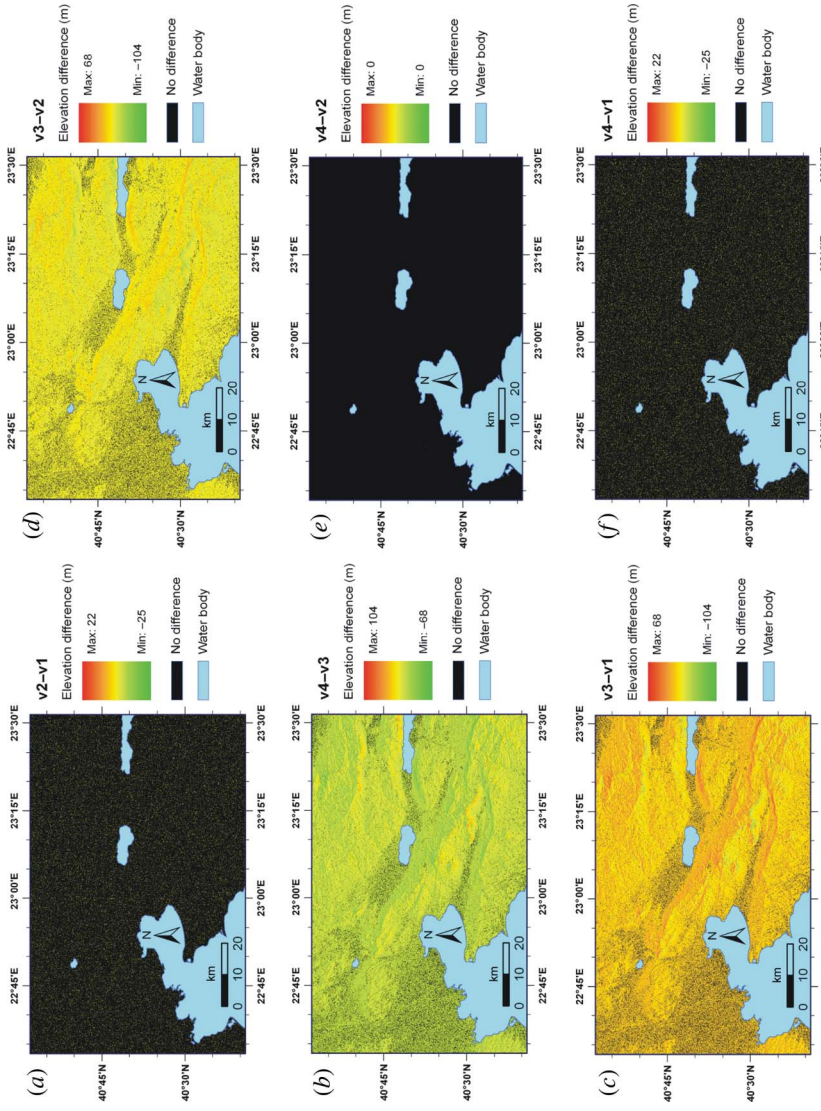

Figure 5. Differences between the four SRTM versions. The four datasets are compared in pairs (all possible combinations), by subtracting corresponding pixel values.

Table 3. Statistics of the comparisons between SRTM v1, v2, v3 and v4.

	No. of pixels	Percentage of pixels with matching value (no. of pixels)	Min. (m)	Max. (m)	Mean (m)	Standard deviation (m)
v2–v1	904 036	93.55 (845 694 pixels)	−25	22	0.0	0.3
v3–v2	904 036	22.72 (205 368 pixels)	−104	68	−0.3	8.7
v4–v3	904 036	22.72 (205 368 pixels)	−68	104	0.3	8.7
v4–v2	904 036	100.00 (904 036 pixels)	0.0	0.0	0.0	0.0
v3–v1	904 036	22.79 (206 001 pixels)	−104	68	−0.2	8.7
v4–v1	904 036	93.55 (845 694 pixels)	−25	22	0.0	0.3

On the contrary, v4 and v2 coincide by 100%. This signifies that errors (shifts) in v3 have indeed been corrected in v4.

There is also a remarkable similarity between v4 and v1, as it is indicated by the standard deviation value (0.3) and the fact that almost 94% of the pixels have the same elevation value. It is significant to note that the pixels exhibiting differences greater than ± 1 m are located around water bodies and constitute only 0.01% (837 pixels) of the total pixels. This means that v4 is practically similar with v1, but has additionally compensated for any voids and water bodies have also been taken into consideration.

3.4 *Validation with GPS measurements*

Comparing SRTM data, which are in raster format, with GPS data in vector format, requires converting both datasets to the same topological format. For this purpose two methods are possible: either converting SRTM raster data to vector format or converting GPS vector data to raster format. Both conversions can be readily executed in the ArcGIS (Spatial Analyst) environment. The former approach has been adopted by Rodríguez *et al.* (2005) for a global assessment of SRTM accuracy, whereas the latter method was followed by Gorokhovich and Voustianiouk (2006) for local validation of SRTM data in two regions in the United States and Thailand. Although both conversions were tested in this study, since vector format is much more informative and convenient for various manipulations in a GIS environment, requiring at the same time less computational effort, the second approach was chosen for further processing.

The horizontal datum for the SRTM data is the World Geodetic System 1984 (WGS84) and the vertical datum is referred to mean sea level (orthometric height) as determined by the Earth Gravity Model (EGM 96) geoid (TR8350.2 1997; in Miliaresis and Paraschou (2005)). For this, GPS geometric heights had to be converted into orthometric heights by subtracting the height of the geoid in the area of interest.

According to Andritsanos *et al.* (2000), the mean value of the geoid height in the study area, calculated with two different methods, is 43.104 m with an accuracy of ± 0.648 m, and 43.528 m with an accuracy of ± 0.502 m, respectively, while the overall variation of the geoid height over the same region is between 42.0 and 44.2 m. Additionally, according to the University NAVstar COnsortium (UNAVCO) website (http://sps.unavco.org/geoid) the geoid height, with reference to WGS84 ellipsoid in the area of interest, is approximately 43 m, a value that is also verified by The Hellenic Mapping and Cadastral Organization (OKXE). The latter value was subtracted from GPS elevations and was considered for all calculations presented thereinafter.

Absolute height accuracy was estimated with reference to the 10 792 ground truth GPS points, whereas relative elevation accuracy was computed on the basis of the same points, by randomly selecting an analogous number of height differences.

Uniformity of elevation accuracy between v1, v2 and v4 is obvious in the relevant scatter plots (figure 6). It is also clear that v3 deviates from the other three versions.

The results presented in table 4 are in good accordance with the results presented by Rodríguez *et al.* (2005) for Eurasia, apart from v3, whose standard deviation exceeds the expected values due to the ½ grid pixel shift. Relative elevations calculated from absolute elevation measurements have similar accuracy to the expected error propagation estimate for independent (uncorrelated) variables (in this case, absolute elevation errors), assuming Gaussian nature of the dataset.

The importance of slope and aspect in height accuracy determination for SRTM data has been recognized and analysed by Miliaresis and Paraschou (2005) and Gorokhovich and Voustianiouk (2006) for the respective regions studied. Reference to large slopes introducing errors in elevation estimation is also made by Rodríguez *et al.* (2005) within the global assessment of SRTM. In this study, the impact of slope was initially evident as well, since as it is shown in figure 6, with high elevations ($>$ 550 m), thus larger slopes, exhibiting proportionally more points and with elevation error greater than 20 m.

Having exhibited so far that v4 is indeed an improved version, an in-depth study of v4 was due, in order to examine the influence of slope and elevation in more detail. The first step was to visualize the spatial distribution of v4 absolute elevation errors (figure 7).

Furthermore, histograms and respective descriptive statistics of absolute and relative elevations errors (figure 8) were computed. Skewness has near zero values, indicating symmetric data. Distributions are leptokyrtic, deviating from normality (mesokyrtic) due to relative high kurtosis, which suggests possible presence of outliers.

In order to investigate outliers in both tails of the distributions (figure 8) and to interpret large elevation differences even at low elevations (figure 6), all points presenting errors larger than $\pm$ 20 m were identified, a process that yielded a total of 164 data (1.5%). The slope map from v4 was computed and was compared with reference to the position of these 164 points (figure 9). In 149 of the cases, the points were located in areas where high slopes justify the errors, whereas the errors of the 15 remaining points (clustered in two areas) could not be associated with slope or elevation variations, since they exist in fairly flat ($<2°$) and low elevation ($<$100 m) regions. Hence, for these 15 points, problems related to the GPS that have not been identified during previous processing steps should be considered as the most probable error source. It should be also noted that some of these 15 points are located in densely populated rural areas, where buildings influence both SRTM and KGPS data performance. In this context, it has to be taken into consideration that SRTM DEM is in fact a digital surface model (DSM), thus it includes elevation of buildings, trees and other objects (so actual elevation is overestimated), while KGPS data refer exclusively to the surface of the ground. In these cases, the result of subtraction of SRTM from KGPS elevation data should in principle be a negative number, a theoretical assumption that does apply for the points in question.

The next step was to plot and study the standard deviation errors of SRTM elevations against slope variations (figure 10), as well as the slope variations as a function of orthometric elevation (figure 11).

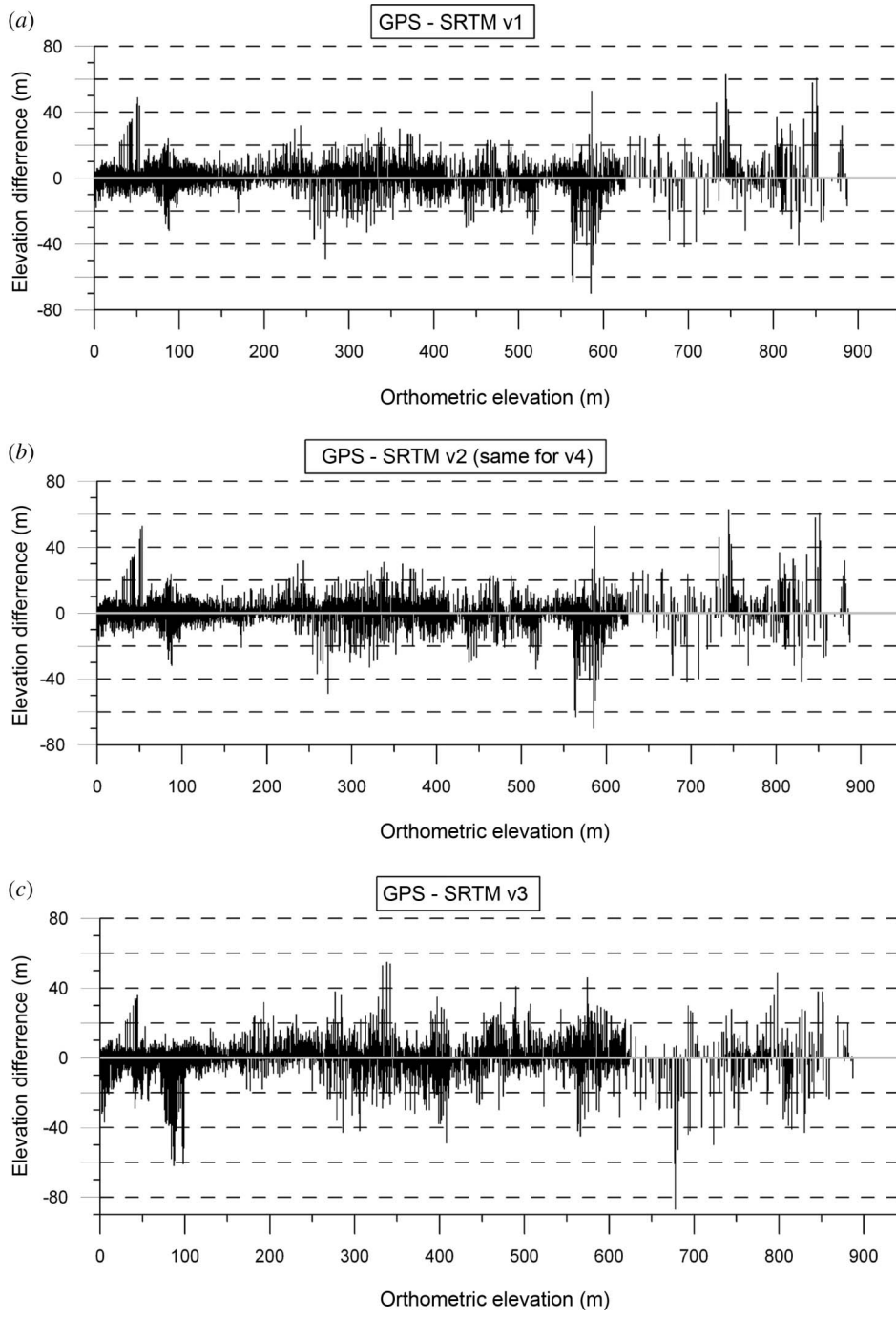

Figure 6. Absolute elevation differences between GPS and SRTM versions plotted against orthometric elevations. (*a*) GPS-SRTM vl; (*b*) GPS-SRTM v2 (same for v4); (*c*) GPS-SRTM v3.

Table 4. Statistics of SRTM v1, v2, v3 and v4 over GPS elevation data and comparison with results for Eurasia from Rodríguez *et al*. (2005).

	Absolute elevation error (m)				Relative elevation error (m)			
			Standard deviation				Standard deviation	
	Min.	Max.	This study	Rodríguez *et al.* (2005)	Min.	Max.	This study	Rodríguez *et al.* (2005)
v1	−70	63	6.4	6.2	−76	67	8.9	8.7
v2	−70	63	6.4	6.2	−76	67	8.9	8.7
v3	−87	55	7.3	6.2	−83	86	10.2	8.7
v4	−70	63	6.4	6.2	−76	67	8.9	8.7

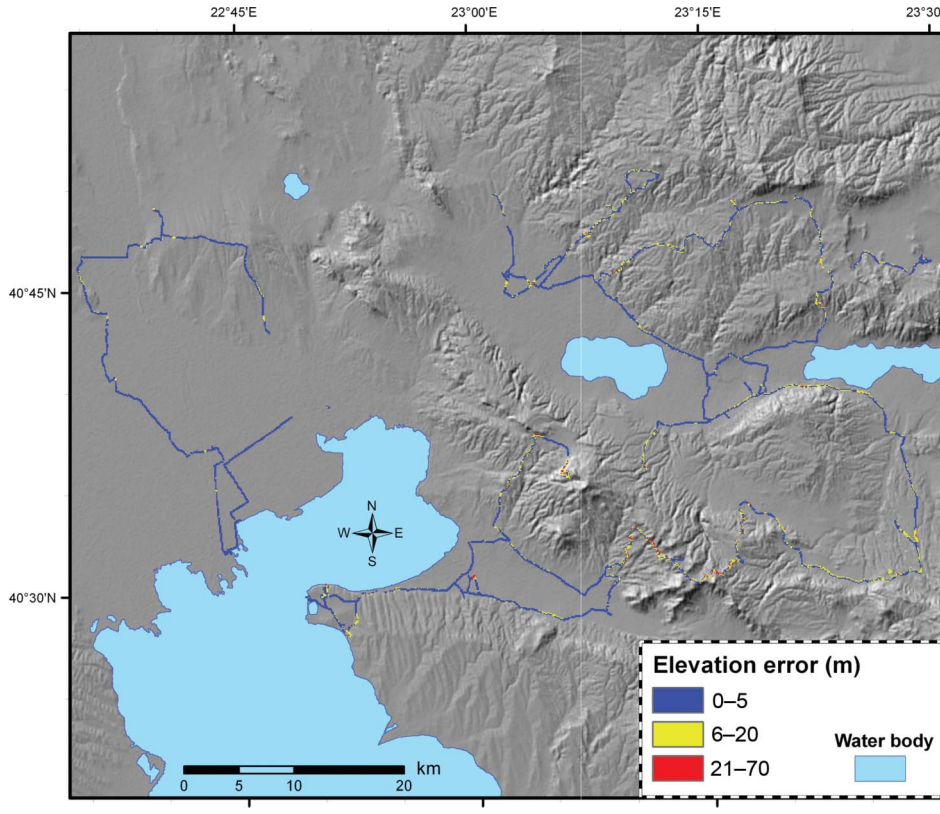

Figure 7. Spatial distribution of SRTM (v4) elevation errors.

As it is evident in figure 10, errors increase quite steadily up to 18°, i.e. the critical slope, above which errors start to dramatically escalate. For the interpretation of this result, it has to be considered that the 3″ SRTM pixel averages the elevation of a 70 m × 90 m area, hence sharp topographic variations are not detectable and therefore very steep slopes cannot be properly mapped. On the other hand, KGPS data are much more sensitive to slope variations, since they average at least 5 to 10 very

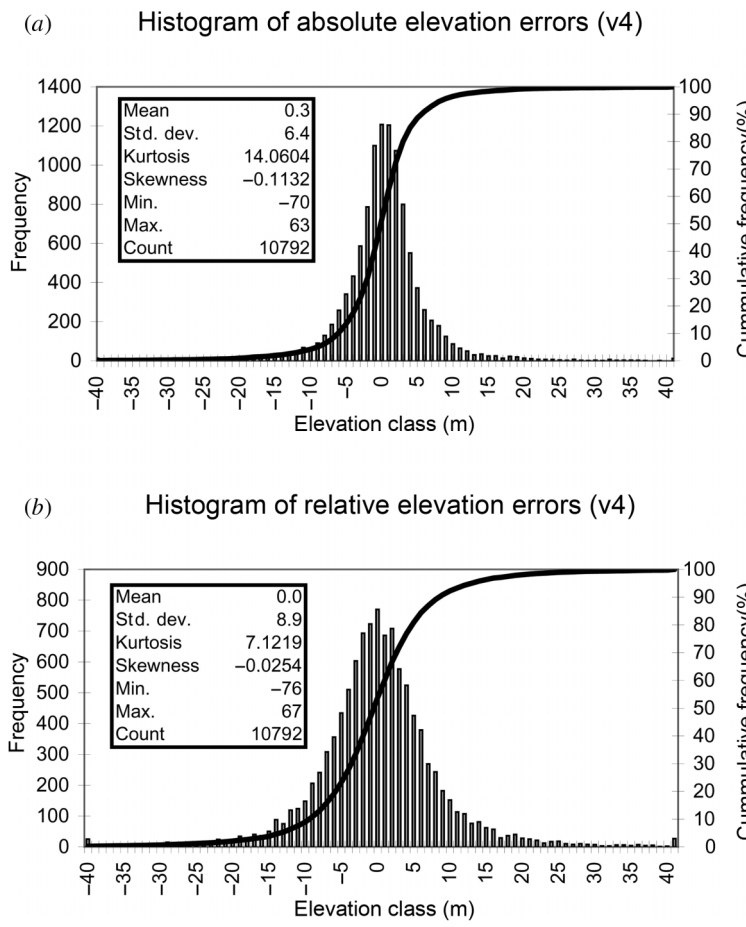

Figure 8. Histograms of elevation errors and relevant descriptive statistics. (*a*) Absolute elevation errors (v4), and (*b*) relative elevation errors (v4). Note that kurtosis refers to excess kurtosis (deviation from the kurtosis of a standard normal distribution). For better visual comparison, histogram values were restricted between –40 and 40. Values outside this range have been grouped in the far-out classes.

accurate measurements within the same pixel. Additionally, this phenomenon could be partly attributed to SRTM absolute geolocation error, which has been estimated to 8.8 m for Eurasia by Rodríguez *et al.* (2005).

A comparison of figures 6, 10 and 11 points out that high elevation errors are more correlated with slope rather than with orthometric elevation. Thus, slope is the dominant factor that controls SRTM accuracy, while orthometric elevation is only indirectly (through slope) related to elevation errors in SRTM data.

4. Conclusions

A strong point of the present study was the large number of KGPS data collected for the validation of SRTM elevation data; the density of this information was a few hundred times larger than the respective data density used for the global assessment of SRTM (Rodríguez *et al.* 2005, 2006).

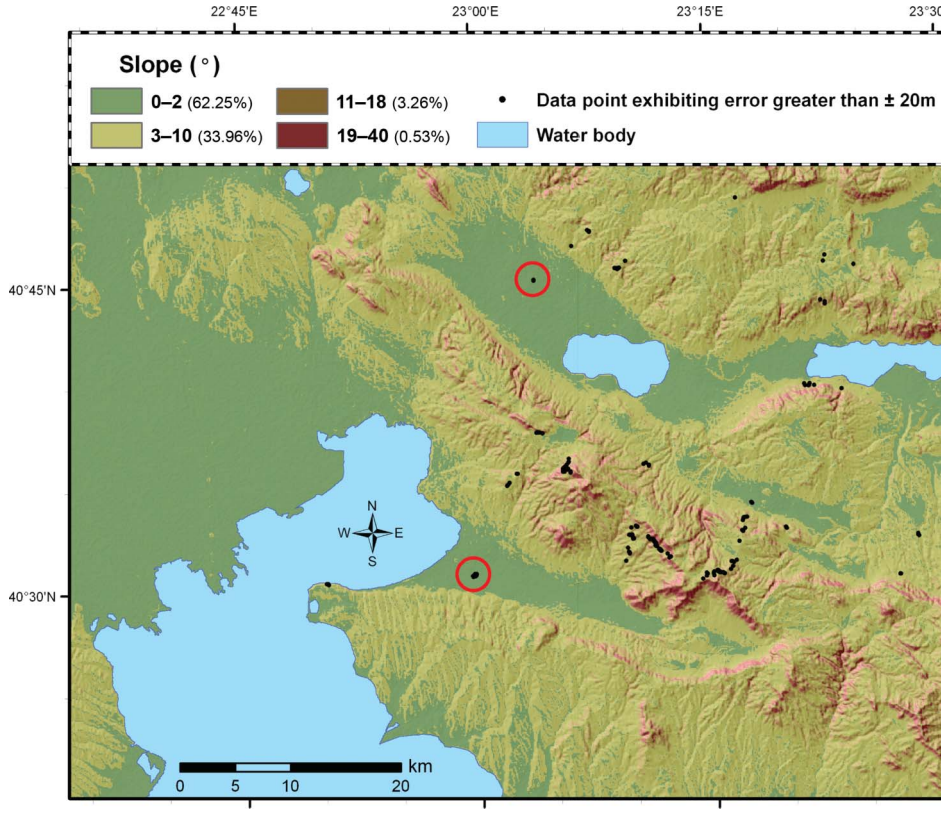

Figure 9. Slope map draped over shaded relief of the study area for the interpretation of 164 points, where significant elevation errors of v4 occur, with respect to the KGPS data. In 149 cases, the points are located in areas where high slopes justify the errors. Red circles indicate clusters of a total of 15 points exhibiting errors that cannot be attributed to slope or elevation variations.

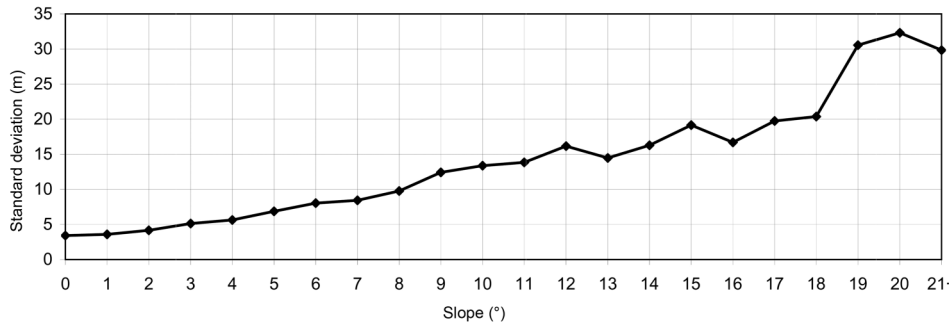

Figure 10. Standard deviation errors of v4 elevations plotted against slope variations.

Although not mandatory, it is clear that when conducting a KGPS validation of any elevation data, good knowledge of the study area is very useful and preferably people involved in the KGPS measurements, thus having the 'feeling' of what was

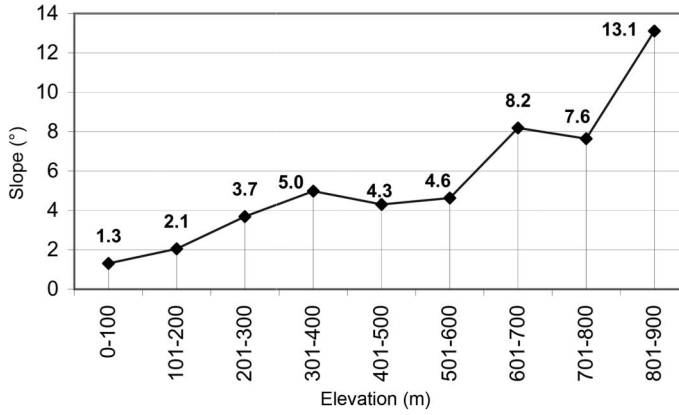

Figure 11. Average slope variations with respect to 100 m orthometric elevation classes.

actually measured, should also be present during the processing of the data, in order to optimize the final ground truth points selection. Whenever this is not feasible, appropriate standard deviation analyses of the GPS data, applied with appropriate thresholds, will eliminate most (if not all) of the unreliable data. In this study, after all processing steps, only 0.1% (15 out of 10 792) of the final KGPS points used were considered to be 'suspicious' and potentially unreliable.

It is also worth noting that Google^{TM} Earth visualization of the GPS data constitutes a free and handy method for detecting discrepancies in the dataset, especially in places where very high resolution (< 1 m) images exist.

Concerning the actual SRTM validation, the ½ pixel shift of v3 relative to v2 induces important errors in the v3 DEM. This shift does not present a systematic character but occurs in different directions. Version 4 has fully compensated for this shift. Assuming that this applies for a global scale, v3 will become obsolete as soon as v4 is officially released (v4 was eventually released in August 2008).

Absolute accuracy of 16 m for the SRTM mission is well fulfilled for the study area; in fact, the standard deviation for the absolute elevation error is much smaller (6.4 m). Relative accuracy specification of about 6 m is not met (8.9 m), but as clearly stated in Rabus *et al*. (2003, p. 256), 'this specification assumes that a user can easily correct his area of interest by adding a single corrective height value'.

Between the four existing SRTM versions, v2 could be used in places where no significant voids exist or, alternatively, in areas with considerable voids, v4 would be the ideal version since, while preserving the accuracy of the original data, it has compensated for the no data regions (voids). In any case, v4 is a superior product.

Further analysis of v4 data indicates that the presence of extreme error values (outliers) and deviation from normality is observed due to high slope values. More precisely, performance of SRTM DEM degrades with increasing elevation and slope, with critical values, above which errors dramatically escalate, being 550 m and 18° respectively. This occurs mainly due to the resolution of SRTM data and precision limitations of SAR interferometry in mountainous areas, but also the geolocation error of SRTM becomes more significant as slope and elevation increase. Nevertheless, the effect of slope proves to be much more profound than the contribution of elevation, since, even at low elevations with considerable slopes, important

errors are observed. In fact, elevation is not a crucial factor on its own, but it is only through its interdependence with slope that it affects SRTM data accuracy.

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