About some peculiarities of SRTM Digital Elevation Model usage for agricultural land use planning

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Abstract. Digital elevation models (DEM) are widely used in agricultural land use planning as a source of information about slopes, aspects, slope forms and watersheds. Among different DEM products, one of the most convenient is freely available SRTM. As well as other DEMs based on remote sensing data, SRTM, actually, represents first reflective surface of the radar signal such as top of the forest trees and bare-earth only if it is not obscured. Using of such digital terrain model (DTM) in forested areas can lead to artifacts in calculation of slopes, aspects, slope forms and watersheds. In the present study, we provide the results of the quality assessment of SRTM and different maps calculated from SRTM. We, also, proposed an easy-to-use approach for adjustment of forest influence on SRTM and tested the approach on key sites in Moscow, Russia.

Keywords: DEM, Geo-Information Systems, SRTM quality.

1 Introduction

Digital elevation models (DEM) are widely used in agricultural land use planning as a source of information about slopes, aspects, slope forms and watersheds (Shukla, 2011; Zhogolev & Savin, 2016a). As a rule, remote sensing products representing the first reflective surface of radar or laser signal are used. Such products represent the tops of buildings, trees, other objects and the bare-earth if it is not obscured (Hirt, 2016). The influence of forest vegetation and other objects obstructing the bare-earth can be adjusted.

Of laser illuminated detection and ranging (LIDAR), radar and stereo pair data (United States National LIDAR Data-set, SRTM, ALOS PALSAR, ASTER GDEM, SPOT DEM, etc.) one of the most widely used is SRTM product (Farr et al., 2007; Nelson et al., 2009; Mulder et al., 2011; Du et al., 2015). The SRTM sensor was launched on February 11, 2000 (Nelson et al., 2009). The mission lasted 11 days. Since then a few updated versions of SRTM came out, the latest version – 4.1. The spatial resolution of the SRTM is 1 arc second for the United States and 3 arc seconds for global product. In 2015, SRTM with spatial resolution 1 arc second became available globally. However, for many studies, at global and regional scales,

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there is still a lot of interest in 3 arc seconds SRTM because of suitable generalization and long practice of application. The three arc second product has improvements that is not available for one arc second data.

The evolution of the SRTM has led to the improvement of the spatial reference, filling of gaps and other improvements (CGIAR CSI, 2016). So far, there have been many studies on the impact of noise, anchor errors, gaps in the data, the effect of sensing at an angle. At the same time, there have been few studies on the problem of the influence of vegetation, which use widely available spatial data (Hofton et al., 2006; Shortridge & Messina, 2011; Gallant et al., 2012; Zhogolev & Savin, 2016b). To assess accuracy of SRTM different data are used: GPS point data of field surveys; topographic maps and accurate radar or LIDAR (Rodriguez et al., 2006; Ozah & Kufoniyi, 2008; Karwel & Ewiak, 2012; Amans et al., 2013). In terms of practical application, it is reasonable to estimate influence of vegetation on quality of SRTM by a comparison with DSM based on traditional paper topographic maps of comparable generalization scale. The generalization of topographic maps has been perfected, taking into account long-term experience in application, so the comparison can reveal the most significant errors of SRTM. Moreover, DEM based on topographic maps can be replaced by SRTM for global scale application as better-harmonized data or for local scale application in places where vectorized or up-to-date topographic maps are not available (Mulder et al., 2011).

Adjustment of the forest vegetation influence on SRTM can be made using approaches: replacing SRTM in forested areas with other DEM (Hengl et al. 2009), reducing altitudes of SRTM in forested areas and smoothing the result with filters (Hengl et al. 2009), replacing SRTM in forested areas with interpolated values (Gallant & Read 2009; Gallant et al. 2012; Amans et al. 2013), adjustment of the SRTM altitudes with the help of regressions model fitted using another DEM (Su & Guo, 2014).

In this research, we provided the results of a comparison between slope, aspect, slope form (convex-concave) and watershed maps calculated from original SRTM, SRTM corrected using the proposed method and cartographic DEM created by interpolation of isohypses of traditional topographic maps at 1:100 000 scale.

2 Study Area

As key sites, three lowland areas in the Moscow region (Russia) situated near settlements Chashnikovo, Schebanovo and Serebryaniye prudy were selected (Tab. 1). The sites have different relief conditions and the share of forested area (Tab. 2). The site "Schebanovo" has the greatest share of forests and the relief is flat. The share of forested area in the site "Serebryaniye prudy" is the smallest, erosional highly undulated relief is more pronounced than in other sites. The "Chashnikovo" site has an average share of forested area and an average pronouncement of the relief. A part of the Klyazma river floodplain is inside the boundaries of this site. The dominant tree species on the site "Schebanovo" are pine (Pinus sylvestris L.), spruce (Picea abies L.) and birch (Betula pendula Roth), with an average height of 24 m; on the site "Chashnikovo": spruce (Picea abies L.) and birch (Betula pendula Roth), average height 21 m; on the site "Serebryaniye prudy": linden (Tilia cordata Mill.) and oak (Quércus róbur L.), average height 22 m.

Table 1. Coordinates of the key sites.

The name of key site	Coordinates Lat/Long WGS84
Chashnikovo	1: 56^{0}05'15.04"N 37^{0}08'09.71"E 2: 56^{0}00'55.92"N 37^{0}08'18.50"E 3: 56^{0}05'23.08"N 37^{0}17'44.19"E 4: 56^{0}01'04.61"N 37^{0}17'55.85"E
Schebanovo	1: 55^{0}40'00.09"N 38^{0}29'56.73"E 2: 55^{0}36'57.64"N 38^{0}29'55.64"E 3: 55^{0}39'57.24"N 38^{0}46'34.15"E 4: 55^{0}36'57.70"N 38^{0}46'36.87"E
Serebryaniye prudy	1: 54^{0}35'29.90"N 38^{0}37'38.04"E 2: 54^{0}30'06.60"N 38^{0}37'43.59"E 3: 54^{0}35'29.74"N 38^{0}46'56.10"E 4: 54^{0}30'07.95"N 38^{0}46'59.12"E

Table 2. Description of the key sites.

The name of key site	Minimum altitude, m	Maximum altitude, m	Percentage of forested area	Total site area, km^2
Chashnikovo	180	240	55	80
Schebanovo	130	160	72	99
Serebryaniye prudy	130	210	24	100

3 Methods

For preparation and interpretation of satellite images Integrated Land and Water Information System (ILWIS version 3.3.1) was used. Statistical analysis was carried out in Microsoft Excel and R (https://www.r-project.org/).

Analysis of influence of vegetation on the quality of altitudes of the SRTM was performed by comparing with the reference DEM based on traditional paper topographic maps at 1:100 000 scale (further, "cartographic DEM"). The scale 1:100 000 was chosen because the mean error in the planned position of contours and various objects lies in the range from 0.5 to 1 mm, i.e. from 50 to 100 m on the ground (GKINP-05-029-84, 1984) that is close to the spatial resolution of the SRTM which is 3 arc seconds or 90 m (Hengl, 2006). The analysis described in this article was performed for three arc seconds void free SRTM v4.1 but it also can be applied with little changes to one arc second SRTM as the main limitation of SRTM is its vertical error, not spatial resolution.

Before the analysis, preparation of data was carried out. SRTM v4.1 data were reprojected into UTM projection zone 37N on an ellipsoid WGS 84 with resampling from 3 arc second (about 90 m resolution) to 30 m resolution using bilinear interpolation. Higher resolution was chosen to maintain the accuracy during the georeferencing to other data. Georeferencing error was assessed by comparison of biases between borders of the forested areas on SRTM, Landsat and topographic maps. The biases between the borders were less than one pixel (30 m resolution) for all forested areas.

Preparation of cartographic DEM consisted of paper topographic maps scanning, georeferencing, digitizing of isohypses and the construction of DEM by interpolation between them. Georeferencing of scanned topographic maps was carried out to the UTM projection zone 37N for the WGS84 ellipsoid at points of angles and the center point by the affine transformation method. RMSE value for all maps proved to be within one pixel, indicating a high quality of georeferencing. Next, digitization of isohypses and other data on the altitudes for areas of key sites and their surroundings was carried out. Additional points were placed on hilltops and in the bottoms of depressions to simplify work of interpolation algorithm. Then, cartographic DEM was built using linear interpolation algorithm built into ILWIS. The spatial resolution of obtained cartographic DEM was 30 m. Additionally the georeferencing of traditional paper topographic maps at 1:50 000 scale was also made for study areas.

The forested areas were mapped by decoding of satellite images LANDSAT 7TM+ acquired in May 2000 and 2001. These images were selected as the closest date to the SRTM mission. For the recognizing of the forested areas, a training sample set was built with the following objects: forests, croplands, grasslands, settlements and water bodies. These samples were used for the automated classification of the forested areas by maximum likelihood method. The accuracy of forests classification was assessed by error matrix technique only for "Chashnikovo" key site because of close spectral characteristics of forests on all key sites (Zhogolev & Savin, 2016b). Random validation sample set of 642 pixels was used for classification accuracy assessment. This was based on visual interpretation of Landsat images with the help of high resolution images Worldview 2 (Zhu & Liu, 2014). The overall, producer's and user's accuracies were higher than 97%.

For the analysis of the spatial influence of forests on SRTM, according to DEM, aspect, slope, slope form (convex-concave) and watershed areas maps were built. For this purpose, we used algorithms described in the manual of ILWIS 3.31 (52North, 2016). They are based on using a sliding window of 5 × 5 pixels for the analysis of surface curvature. Calculation of aspect and slope maps was done in the original resolution for the SRTM of 90 m (UTM projection) to avoid the use of interpolated altitude values. 8 points of the compass were used for aspect map. Slope maps were built in increments of 1 degree.

Estimation of the forest influence was done according to the following method. At first, SRTM was deducted from the cartographic DEM. Then statistical analysis was performed separately for the altitude differences across forested areas and areas without forests and settlements. Hypothesis of a normal distribution of DEM differences was tested using the Kolmogorov-Smirnov test; histograms, arithmetic means and the medians, extreme values, and the standard deviations of altitude differences were analyzed. In addition, linear regressions were fitted, where the independent variable was the altitude of cartographic DEM and dependent - altitude of SRTM. The slope, aspect, and slope form maps were compared by calculating the proportion of pixels with the same value to the total number of pixels. For a comparison of the watershed maps, the numbers of recognized watersheds were calculated. The difference in number of watersheds was calculated as the number of watersheds for SRTM minus the number of watersheds for cartographic DEM.

We offer an easy approach for SRTM adjustment that can be implemented in most GIS. Improvement of SRTM in forested areas can be made using a method of altitude reduction and smoothing with the help of bilinear interpolation. The idea is to resample the altitudes of the forested areas to a lower spatial resolution for catching the main profile curvature and for smoothing influence of the tree heights heterogeneity. Under the forest mask, we reduce median overestimation of altitudes due to tree heights. Then, the forested parts of SRTM are returned to the original spatial resolution also by using bilinear interpolation.

At first step, SRTM with spatial resolution 90 m was resampled to 30 m resolution (as it is of Landsat satellite images). From altitudes in the forested areas, median value of overestimation of altitudes was subtracted. Then smoothing was carried out by resampling of the SRTM to a lower resolution (180 m) using bilinear interpolation. After that, the SRTM was resampled to 30 m resolution and non-forested areas of the SRTM were replaced with the original data (not resampled to low resolution). At last step, the SRTM was resampled to the original 90 m resolution (UTM). To assess the quality of the corrected DEM SRTM an analysis similar to describe above was carried out.

4 Results

Median altitude differences between SRTM and cartographic DEM within the forested areas were 3-4 times less than the mean height of the forest according to topographic maps (Tab. 3). This is due to a systematic error of the SRTM vertical positioning, the overgrowing of clearings with shorter trees, different distances between the trees, different influence of various species of trees and other factors. The greatest influence, presumably, is caused by the systematic error of the SRTM vertical positioning.

Table 3. Descriptive statistics of the difference between DEMs.

Key site		Mean, m	Median, m	St.Dev., m	Min., m	Max., m
"Chashnikovo", (forest height– 21m)	whole site	0.8	1.3	7.5	-17.2	29.1
	forest part	5.4	6.0	6.8	-16.0	25.5
	without forests and settlements	-6.5	-7.0	4.8	-16.9	17.1
"Schebanovo", (forest height– 24m)	whole site	4.9	5.9	7.0	-14.5	22.3
	forest part	7.8	8.0	5.0	-11.5	22.1
	without forests and settlements	-2.5	-3.5	5.8	-14.5	18.8
"Serebryaniye prudy", (forest height– 22m)	whole site	-2.1	-4.0	6.3	-16.0	25.5
	forest part	5.4	6.0	6.8	-16.0	25.5
	without forests and settlements	-4.5	-4.9	3.5	-16.0	21.3
General information for all key sites	whole site	1.2	0.3	7.5	-17.2	29.1
	forest part	6.8	7.1	5.4	-16.0	25.5
	without forests and settlements	-4.5	-5.0	4.4	-16.9	21.3

As the systematic error of the SRTM vertical positioning the median altitude differences between DEMs in territories without forests and settlements can be considered (Table 3). Consequently, for all key sites median overestimation of altitudes due to the influence of forests is about 0.5 of the mean height of the forests from topographical maps, which is consistent with other studies (Hengl et al., 2009). So, this value of mean height can be used for the correction of SRTM and as an estimation of maximum variation of tree heights in forested areas.

In addition to portions of images with positive difference between the altitudes on SRTM and cartographic DEM, caused by the forests influence, there are vast areas with high negative values of the differences. The biggest negative differences between DEMs (up to -17 m) are observed in the floodplain of the Klyazma River in the key site "Chashnikovo" (Tab. 3). Comparison with the topographic maps at 1:50 000 scale showed that large in magnitude negative values are usually caused by the generalization of topographic maps at 1:100 000 scale. For example, in the floodplain on the site "Chashnikovo" on maps at 1:50 000 scale there is an additional contour, which lies close to the main contour, in comparison with maps at 1:100 000 scale, which leads to a bigger difference between SRTM and cartographic DEM based on maps at 1:100 000 scale. In accordance with the values in table 4, the SRTM DEM without correction has the same quality as DEM based on topographic maps at 200 000 scale.

The proportion of coincidences of aspects and slopes constructed from SRTM and cartographic DEM, were very low (Tab. 4).

Table 4. Comparison of maps calculated from SRTM and cartographic DEM.

Key site		Aspect matches,%	Slope matches,%	Slope form matches, %	Difference in the number of watersheds
"Chashnikovo"	whole site	31	31	37	-15
	forest part	30	29	37	-
	without forests and settlements	32	35	38	-
"Schebanovo"	whole site	16	32	40	-48
	forest part	15	28	38	-
	without forests and settlements	15	35	43	-
"Serebryaniye prudy"	whole site	37	37	42	11
	forest part	29	27	30	-
	without forests and settlements	39	40	45	-

For the forest part, the share of coincidences is always lower than for open areas. Biases of 1 degree on cartographic DEM often correspond to slopes of 2 degrees on SRTM, which is typical not only for the forests, but also for open areas, although to a much lesser extent. The proportion of such slopes for the site "Schebanovo" is more than the proportion of matched, while there are more coincided slopes on the site "Serebryaniye prudy", and on the site "Chashnikovo" an intermediate situation is observed. Decrease in the severity of the effect described above and increase of altitude differences show that the SRTM does not convey the slope relief very well. Similarly, differences in aspects decrease with the increasing of altitude differences. Smaller proportion of matches in the forested areas is probably due to the influence of SRTM by varying density and height of the trees. This effect can be adjusted by isolating the total curvature of the relief and interpolating the intermediate values.

The adjustment of the effect of forest vegetation on the SRTM using bilinear interpolation algorithm has led to an increase of the correlation with the data based on the cartographic DEM. All parameters improved, the increase was quite moderate: Spearman's correlation coefficient between the altitudes of DEMs increased by 0.05 - 0.14, the percent of coincided aspects by 1 - 4%, and the percent of coincided slopes by 2 - 8% (Tab. 5). However, on the altitude map of adjusted SRTM, the forests became hardly visible.

Table 5. Comparison of original SRTM and corrected SRTM.

Key site	Statistics	Original	Corrected
“Chashnikovo”	R^2 (linear regression between altitudes)	0.83	0.90
	p - the level of significance of the linear regression	$< 2.2 \times 10^{-16}$	$< 2.2 \times 10^{-16}$
	aspect matches, %	31	35
	slope matches, %	30	38
	slope form matches, %	37	46
	difference in the number of watersheds	-15	-12
“Schebanovo”	R^2 (linear regression between altitudes)	0.47	0.61
	p - the level of significance of the linear regression	$< 2.2 \times 10^{-16}$	$< 2.2 \times 10^{-16}$
	aspect matches, %	16	17
	slope matches, %	64	72
	slope form matches, %	40	60
	difference in the number of watersheds	-48	-46
“Serebryaniy prudy”	R^2 (linear regression between altitudes)	0.88	0.93
	p - the level of significance of the linear regression	$< 2.2 \times 10^{-16}$	$< 2.2 \times 10^{-16}$
	aspect matches, %	37	39
	slope matches, %	37	39
	slope form matches, %	42	45
	difference in the number of watersheds	11	11

The correction led to severe improvement in slope values on the edges of forests, the sharp drop on the slope maps became hardly noticeable (Fig. 1). For the aspect and slope form (convex-concave) maps, the difference between SRTM and adjusted SRTM is not evident, but these maps visually became slightly smoother that is more consistent with cartographic maps. The number of watersheds slightly increased, which is more consistent with cartographic DEM. The correction was performed by resampling the SRTM to the spatial resolution of 180 m and 360 m, however, for most cases, filtering using a spatial resolution of 180 m was more effective, so the table 5 shows data only for filtering with the resolution of 180 m.

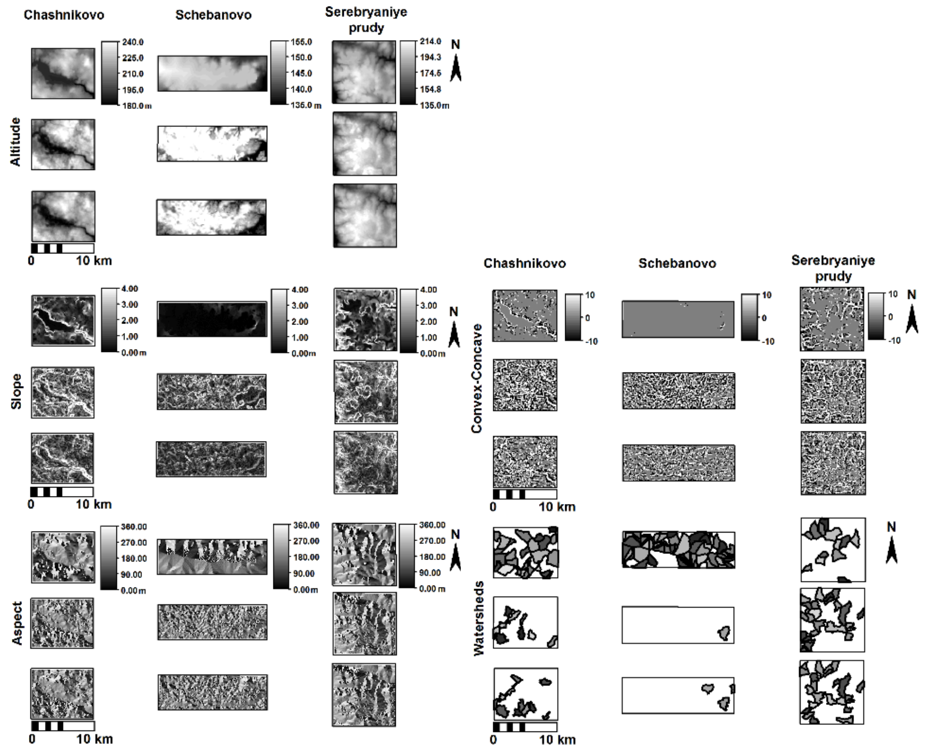

Figure 1. Maps calculated from cartographic DEM, SRTM and adjusted SRTM (maps are arranged in the following order from the top to the bottom: cartographic DEM, SRTM, adjusted SRTM).

After adjustment of the SRTM, areas with the highest values of altitude differences between the adjusted SRTM and cartographic DEM were analyzed. The visual analysis of borders of the highest difference between DEMs using Quickbird high-resolution images and topographic maps at 1:50 000 scale showed that the greatest differences are confined to areas of maps at 1:100 000 scale with a significant generalization. It could and did lead to the difference in altitude between SRTM and cartographic DEM of more than 12 meters in the key site “Chashnikovo”. Against the background of such large errors the influence of forest vegetation of varying density and species composition on altitude of the model delineated from Quickbird images proved to be insignificant. Thus, the quality of the DEM SRTM in some forested areas is probably better than the quality of cartographic DEM based on maps at 1:100 000 scale.

5 Conclusions

The influence of boreal forests on the SRTM in the studied region is clearly seen visually and by statistical analysis when comparing with the DEM based on traditional topographic maps at 1:100 000 scale. According to our data, the quality of SRTM is comparable to DEM based on traditional topographic maps at 1:200 000 scale. If forest influence is completely removed, the quality will be close to the DEM based on topographic maps at 1:100 000 or even 1:50 000 scale.

Maps of slopes, aspects, slope forms and watersheds calculated from SRTM differ significantly from the same maps built from cartographic DEM at 1:100 000 scale. After the correction of SRTM using the proposed method, based on smoothing DEM by the bilinear interpolation, the quality of aspect and watershed maps slightly improved. The quality of the slope and slope form maps improved significantly. On the slope maps, after adjustment, there was only little increase in the slope value on the border of the forests, when before correction there had been the large jump in slope value. After adjustment, the number of recognized watersheds increased which is more consistent to the DEM built from topographic maps. Therefore, the changes in SRTM after the correction would lead to the changes in land use planning, e.g. in distinguishing lands with a high risk of soil erosion or located in different watershed areas.

Proposed method based on bilinear smoothing of altitudes under the Landsat forest mask allowed moderately improving the quality of SRTM. The method is better to be applied to flat areas with forests which height varies little (less than a half of their average height). The advantage of the proposed method is the simplicity of its application and the opportunity for using in almost all GIS supporting bilinear resampling. The further improvement of the method is required to consider trees heights more accurately and to reduce noise on the forest edges associated with big difference in tree heights. Such noise can be ignored in case when the forest edge length is one pixel or less as the calculation of slopes, aspects, slope forms and watersheds usually use five pixels and will not be affected significantly.

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