# Improvement of Slope Angle Models Derived from Medium to Fine-Scale DEMs

# Key study: Skopje area

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*Abstract* - **Apart from freely available global to near-global medium-resolution DEMs (1-3"SRTM, 1"ASTER), for the territory of the Republic of Macedonia, three additional high quality DEMs are available. They are as follows: 20m and 5m DEM of the Agency of Real Estate and Cadastre (AREC) and 15m DEM filtered from original 5m DEM. For general purposes, horizontal and vertical accuracy of all of those models (even the freely available ones) is acceptable. But in fine-scale terrain applications and modellings, slope accuracy is much more sensitive and uncertain. Instead of assessment only, some kind of DEM-related slope accuracy correction and improvement is very useful. An example of such a procedure is presented in the current paper.**

## I. Introduction

In the last decade, several good quality DEMs with a global or almost global coverage and medium to high spatial resolution were released for the public domain. These include free 3"SRTM DEM (90m) realized in 2004 (with later improvements up to version 4.1), and 1"ASTER GDEM (30m) released in 2009 and upgraded to version 2 in 2011. There were many analyses and studies as to which of the said free models is better because 1"ASTER GDEM has a higher resolution, but a lower overall quality [6, 13]. Normally, both models were widely used dependent on the needs and expected results. Only recently, with realization of 1"SRTM DEM (from which 3"DEM was formerly thinned for most of the world) before the aforementioned dilemma was probably over because 30m SRTM is much better than 30m ASTER GDEM. The latest high resolution global DEM released in 2014 is 12m WorldDEM, produced from image stereo pairs of TerraSAR-X and TanDEM-X mission. From the freely accessible WorldDEM DSM (Digital Surface Model) samples (1 degree tiles), we were unable to perform a detailed assessment of its accuracy compared to the other models due to the myriad of surface artifacts (DTM samples are not available yet). However, judging by the numerous indications and preliminary analyses, this is the highest quality global DEM available to date [7]. Aside from that, this product is commercial and currently at a relatively high price per $km^2$.

Besides the free global or near-global 3"SRTM, 1"ASTER and 1"SRTM DEMs, and the commercial 12m WorldDEM, other two DEMs are available for the area of the Republic of Macedonia. They have been prepared from aerial stereo-photos and ortho-photos by the Agency of Real Estate and Cadastre (AREC) of the Republic of Macedonia with a 20 m (2006), and 5 m (2010) resolution. Actually, the former has been provided as a vector layer with point grid (20 m) datasets in .shp format, from which 20m DEM has been generated. The latter (5 m resolution) has originally been rendered as a 5m DEM. Both DEMs (especially 5m) are of much better quality and accuracy than the aforementioned free global DEMs [11]. Nonetheless, our detailed tests demonstrate a few drawbacks of these models in the form of certain shifts and large artifacts in 20m DEM and small triangular TIN-like artifacts in 5m DEM. Because of that, the better and newer 5m DEM is filtered in SAGA GIS v2.1 and Global Mapper v15 software, and reinterpolated to smooth-surface 15m DEM.

Owing to the fact that there are six DEMs with medium to high resolution (from 90 m to 5 m) currently available for the Republic of Macedonia, a problem arises concerning the selection and usage of the most appropriate DEM for topographic modellings and other applications. In our previous work, a detailed assessment of 3"SRTM DEM for the area of the Republic of Macedonia was conducted, showing that the average horizontal and vertical accuracy is ±5 m, with maximum errors up to ±15 m [10, 11]. Such height inaccuracies are generally due to the resolution and location of DEM points around the prominent peaks. In addition, a detailed comparison of the real resolution and the vertical accuracy of 5 m, 15 m, 20 m (AREC), and 30 m and 90 m (SRTM, ASTER) DEM's has been done [11].

However, it is recognized that for precise modelling of some topographic-related processes such as natural hazards (soil

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erosion, landslides, hydrological models etc.), slope accuracy is crucial [12]. A number of studies have attempted to establish direct, simplified linkages between DEM resolution, data quality, and modelling uncertainty [1, 17, 2, 16, 15, 10, 3, 11]. Most of these authors have generally concluded that as cell size increases, slope gradients tend to decrease, ranges in curvatures decrease, flow-path lengths tend to decrease, and the accuracy of terrain attributes at particular locations tends to decrease [13]. When comparing different DEMs, several things must be considered. First, the exact locations of grid points that are to be compared may not coincide at different spatial resolutions. In this situation, spatially aggregated comparisons of data resolutions are inappropriate, especially in rugged mountainous landscapes where terrain characteristics often display an enormous variation over short horizontal distances. Second, the population of grid points is small at a coarse resolution, implying unstable statistics. Third, spatial autocorrelation between neighboring sample points may be stronger at fine resolutions because of close sample distances [15].

## II. Methodology

Analysis of slope accuracy of previously mentioned available DEMs covering the area of the Republic of Macedonia has been conducted on a carefully selected test site – a rectangular area (20x20 km or 400 km$^2$) with very diverse topography (plains and valleys to steep mountains). The site is in the western part of Skopje Basin with an elevation range from 232 m to 1,378 m and a mean of 456.6 m. Four slope parameters have been analyzed: the maximal slope, mean slope, standard deviation of slope values and the terrain-slope profile. Also, the entire terrain has been divided into slope classes of 0-10°, 10-20° and higher than 20°. The results have been compared with 5m DEM, used as a reference and the most accurate model available, previously validated with 1 : 25 000 topographic and 1 : 5000 geodetic maps. According to our tests, this model is currently the closest to real topography with a very high horizontal and vertical accuracy (+/-1 m mean; +/-4 m max). For analyses, SAGA GIS v2.1 software is used with several corresponding modules (Terrain Morphometry; Grid Calculator etc.).

## III. Results and discussion

The analyses indicate that the maximal slope values have the highest differences compared to the mean slope. In correlation with spatial resolution, the highest slope differences of analyzed DEMs show 3"SRTM, whereas the mean slope value for the entire test area is only 8.8° compared to 11.0° of the 5 m reference DEM (Table 1).

TABLE 1. SLOPE VALUES OF THE TESTED DEMS COMPARED TO THE 5 M REFERENCE DEM

| Resol. | Type | Slope values / degree | | | File size Mb | |
|---|---|---|---|---|---|---|
| | | *max* | *mean* | *stDEV* | *test ar.* | *country* |
| **5 m** | **AREC-RM** | **81.2** | **11.0** | **10.2** | **61.0** | **5,500** |
| 15 m | FILTER | 72.0 | 10.8 | 10.0 | 6.7 | 630 |
| 20 m | AREC-RM | 64.0 | 10.8 | 9.6 | 5.4 | 350 |
| 30 m | SRTM | 61.1 | 10.1 | 8.7 | 2.6 | 76 |
| 30 m | ASTER | 65.5 | 10.7 | 8.8 | 2.6 | 75 |
| 90 m | SRTM | 54.8 | 8.8 | 8.0 | 0.4 | 16 |

It is peculiar that, at first sight, 1"ASTER GDEM shows better results than 1"SRTM DEM, not due to higher quality but due to many artifacts with pseudo-slopes in the model as such. When an artifacts removing tool in SAGA GIS with Mesh Denoise module [14] is used (with Threshold 0.5), slope deviations have increased significantly (60.2° for maximal and 9.9° for a mean slope).

The newly available 1"SRTM DEM shows very tolerable deviations from the reference DEM in regard to the mean slope (values lower by 8 %) but greater inaccuracies for maximal slopes (25%). In essence, the maximal slope value shifts indicate fine-scale slope refinement, which is necessary for precise landscape modelling.

For spatial distribution of slopes derived from the analyzed DEMs, all slopes have been divided into 10-degree slope classes, bar the class with slopes above 30°. Afterwards, the area of each class has been calculated and compared to other DEMs (Table 2). In DEMs with coarser resolution (30-90m), flats and gentle slopes (0-10°) cover larger area compared to the reference 5m DEM. The opposite is the case with steep-slopes, whose areas significantly decrease with a reduced DEM resolution. Thus, slopes with 20-30° and above 30° cover 180% and 210% larger area in 5m DEM compared with 3"SRTM DEM.

TABLE 2. AREA COMPARISONS OF SLOPE CLASSES DERIVED FROM THE TESTED DEMS

| Resol. | Type | Area of Slope Class in % | | | | Total |
|---|---|---|---|---|---|---|
| | | *0-10°* | *10-20°* | *20-30°* | *>30°* | *of 400km$^2$* |
| **5 m** | **AREC-RM** | 57.3 | 24.5 | 11.8 | 6.3 | 100.0 |
| 15 m | FILTER | 57.7 | 25.0 | 11.3 | 5.9 | 100.0 |
| 20 m | AREC-RM | 57.6 | 25.5 | 11.2 | 5.6 | 100.0 |
| 30 m | SRTM | 59.6 | 26.7 | 9.1 | 4.5 | 100.0 |
| 30 m | ASTER | 60.5 | 26.4 | 8.9 | 4.3 | 100.0 |
| 90 m | SRTM | 66.7 | 23.9 | 6.6 | 3.0 | 100.0 |

Similar trends show a graph of slopes along the selected topographic profile 4.0 km in length and an elevation range from 301 to 711 m (Fig. 1). It is evident that 1"ASTER GDEM has large shifts and jumps compared to the reference 5m DEM, for which this model in slope related analysis is very uncertain.

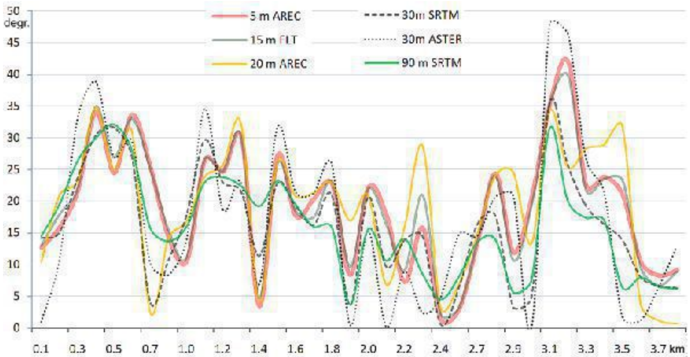


Figure 1. Graph of slope angle values (in degree) through the topographic profile of analyzed DEMs.

With detailed comparisons of the 5m DEM and other analyzed DEMs through the series of scatterplots, the appropriate regressions have been calculated and presented in Table 3.

Regressions and the correlation coefficient $R^2$ have confirmed that of the freely available DEMs, 1"ASTER GDEM has very uncertain slope angle values in relation to 5m-15m DEM and even to 1"-3"SRTM DEM. Without mesh denoise and/or other filtering, this DEM leads to unreliable results in earth processes modelling, as indicated in the number of works [12]. Pertaining to the other DEMs, the presented regressions are beneficial for correcting the slope values to a certain extent.

For further identification of the presented slope value accuracy, 400 points with 1km spatial resolution have been selected in the test area. For each point and DEM, the slope angle has been calculated. The results indicate a gradual increase of errors with the resolution decrease and the slope angle increase (Table 4.). The average correction index in connection with 5m AREC DEM is 1.25 for 1"SRTM and 1.45 for 3"SRTM for slopes >15° (for slopes of 5-10°, the values are almost identical). These values indicate that "coarse" justification of slope angle accuracy is possible with simple equations in the following form: *a*(1.25-1.25/a)* for 1"SRTM DEM and *a*(1.45-1.45/a)* for 3"SRTM DEM, where *a* is the slope angle in degrees [10, 11]. The former is partially applicable for 1"ASTER GDEM after filtering.

TABLE 3. SLOPE ANGLE REGRESSIONS OF ANALYZED DEMS IN REGARD TO THE REFERENCE 5 M AREC DEM

| Resol. | Type | Regression | $R^2$ |
|---|---|---|---|
| | | | % |
| **5 m** | **AREC-RM** | - | - |
| 15 m | FILTER | 0.090156+1.01253*a | 98.6 |
| 20 m | AREC-RM | 0.411494+0.97683*a | 84.9 |
| 30 m | SRTM | 0.732062+1.00231*a | 83.2 |
| 30 m | ASTER | 0.446229+0.98867*a | 72.8 |
| 90 m | SRTM | 1.037035+1.13559*a | 81.1 |

TABLE 4. SLOPE ANGLE COMPARISONS FOR 400 PREDEFINED POINTS WITH 5 M AREC DEM AS A REFERENCE

| Slope | 5mAREC | 15mFIL | 20mAREC | 1"SRTM | 1"AST | 3"SRTM |
|---|---|---|---|---|---|---|
| **0-5°** | 100.0 | 101.4 | 78.8 | 63.2 | 49.9 | 94.5 |
| **5-15°** | 100.0 | 100.7 | 103.9 | 110.1 | 110.0 | 123.1 |
| **15-30°** | 100.0 | 103.7 | 105.7 | 117.1 | 116.9 | 137.7 |
| **30-45°** | 100.0 | 103.4 | 109.1 | 120.4 | 121.8 | 136.9 |
| **>45°** | 100.0 | 105.3 | 125.0 | 137.9 | 137.6 | 164.7 |
| **Avr>15°** | **100.0** | **103.8** | **112.9** | **122.7** | **122.2** | **144.3** |

As regards the 15-20m DEMs for country area, the rendered regressions are very accurate and applicable to most of the terrain situations, except in areas where 20m AREC DEM have large artifacts and irregularities.

*Correcting Slope Artifacts and Pseudo-slopes in Flats*

During terrain analyses and modellings, the problem of step-like slopes and artifacts in otherwise flat or almost-flat areas (plains, flats, valley bottoms) commonly emerges. They occur in all of the DEMs used in the current study but with a different shape and extent. It is clear that these "steps" are closely related with the production of DEMs (in both DSM-like and DTM models), and it is advisable to correct them. That is mostly the case with hydrological modelling, assessment of flood, erosion, landslide and other risk areas etc. One of the better procedures is easily performed in SAGA GIS software through the Multiresolution Index of Valley Bottom Flatness - MRVBF [4]. This index classifies terrains into the following: no bottom flat areas (<0.5), small valley bottom flats (0.5-1.5), larger flats (1.5-2.5) etc. With inverse MRVBF values reclassification within the range from 0-0.5 (flats and almost flats) to 1 (other terrains) and then its multiplication with slope angle values (a raster model), acceptable corrections are yielded. Thus, flat areas with unusual or unnecessary artifacts and slopes become "real flats" with near to or zero degree slope angle (Fig. 2).

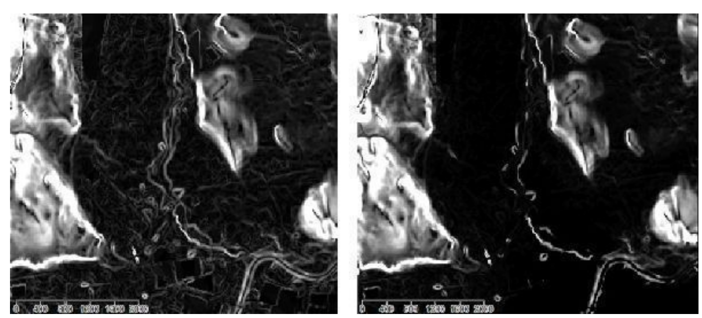

Figure 2. Corrections ("flattening") of slope artifacts (left) with MRVBF index (right) in SAGA GIS.

*Discussion*

The results of our analyses point to significant differences and a degree of inaccuracy, which increase from fine-scale to coarse scale DEMs and from flat to step-slope areas. In terms of slope accuracy, for the used test area, 3"SRTM DEM is generally better than 1"ASTER GDEM (v2), which itself has issues with high noise, many artifacts and pseudo-slopes. This issue is partially resolved with mesh denoise software modules in SAGA GIS. As for slope accuracy, both DEMs are behind 1"SRTM DEM, and far behind the 5m AREC-RM DEM, and 15m filtered DEM. Notwithstanding this fact, because of the size of 5m AREC DEM for country area (5.5 gigabytes) and the small TIN-like artifacts, an interpolated and filtered 15m DEM is a much better option to resort to (650Mb). It will probably be an upper limit for a reasonable terrain modelling and processing of areas larger than 100-200 $km^2$ to bear in mind the good spatial cover and the amount of data cells for processing. The 20m AREC DEM has a good overall horizontal, vertical and even slope accuracy but the number of rectangular artifacts significantly decreases its usability. Moreover, the two AREC DEMs (5 m and 20 m) are of commercial value, with the current price standing at 0.25 euro per $km^2$.

It is for those reasons that when high-resolution AREC DEMs are unavailable, 1"SRTM DEM is the best free compromise when availability, comparability, quality and spatial resolution for the entire country (as well as for other worldwide areas) are considered. In the extent (latitude) of Macedonia, the 1"SRTM DEM cell size is 22m*30m, which is sufficient for medium-scale modelling at a country level. The initial assessment demonstrates approximately 20-25% better horizontal and vertical accuracy (mean: ±3.5 m, max: ±11 m) with respect to 3"SRTM (mean: ±5 m, max: ±15 m). There are substantial shifts in the aspect of decreased values for steep slopes but with a correction equation $a*(1.25-1.25/a)$, where $a$ is the slope angle, slope values may be acceptable.

In certain applications, such as erosion modelling, even a minor increase of slope accuracy implies improvement of the final results [18]. Thus, with prior empirical corrections, it is feasible to greatly improve slope along with model accuracy.

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