Reconstruction of Terrain based on corrected Digital Elevation Models

A S Korotin, E V Popov
Nizhny Novgorod State University of Architecture and Civil Engineering, 65, Il’inskaya str., Nizhny Novgorod, 603950, Russia

Abstract. The paper describes the method of reducing the errors, primarily caused by vegetation, in open digital models like Aster and SRTM. These models do not usually meet the requirements of hydrological correctness due to the errors of different origin. The main errors of DEM are the distortion of the tilt angles and the absolute altitude component in the areas occupied by forest vegetation. We propose the method for eliminating vegetation cover by a local interpolation function and Lagrange polynomial interpolation. The paper also considers the comparison of the proposed method with other methods such as Triangulation Irregular Network (TIN), Inverse Distance Weighting (IDW), Natural Neighbor, Kriging, Radial Basis Functions.

Keywords. Geometric modeling, digital elevation model, forest vegetation, accuracy estimation, local interpolator, Lagrange interpolation polynomial

1. Introduction
Information about the terrestrial relief is the fundamental basis for the research in hydrology, hydrodynamics, geostatistics, geomorphology, ecology, agriculture, geodesy and other sciences. Up to recently, the lack of digital elevation models (DEM) with global coverage was an obstacle to such work. Despite the emergence of relief models covering most of the continents, the quality of them still raises questions.

The majority of DEM for various modern GIS are mainly obtained by remote sensing of the Earth [1]. Any type of DEM needs to be considered as relief without any object such as plants or buildings [2]. As Bates [3] and Yarikhani [4] noted, high-quality DEM are the most important components of the hydrological and hydrodynamic models.

The following publicly available models are mostly used in the research, namely: GTOPO30, SRTM-3, SRTM Void Filled, GMTED2010, ACE2, Aster GDEM. In practice, preference is usually given to Aster GDEM and SRTM models to assess mountainous areas, perform geomorphological studies, predict natural disasters, solve hydrological problems and study glaciers. Many researchers noted that these models do not meet the requirements of hydrological correctness due to the presence of errors of different origin, which are usually subdivided into two components: planned and high-altitude [5]. The distortion of the tilt angles and the absolute altitude component in areas occupied by forest vegetation make the main contribution to the errors of the height matrix [6, 7], that is not completely excluded when processing of the initial data of remote sensing [2, 8]. Yamazaki [9], Zandbergen [10] and Hirt [11] in addition to forest vegetation highlighted the presence of stochastic bursts caused by a change in the reflectivity of the surface during the multi-time recording of
indicators by sensors installed on satellites. They also state the presence of maximum distortions in the
areas of the junction of Earth’s surface scanning bands [9], as well as the presence of a general non-
constant absolute displacement of the model in height which can however be calculated with high
accuracy [2, 9].

To eliminate various kind of errors on digital terrain models Huili [8], for example, proposed a
method of hydraulic correction based on the readily available data and automated GIS data processing.
Christian Hirt [11] proposed to apply the gradient method, which consists of calculation of the
maximum surface slope gradients and their further interpretation. Rhys [12] described some
theoretical and practical aspects of estimating accuracy by various interpolation methods that can be
used to increase resolution when reconstructing DEM.

Thus, the issue of DEM correction and improvement is currently actual.

2. Accuracy Assessment Criteria
It should be mentioned that there is a problem associated with the lack of a large sample of input
values obtained by remote sensing of the Earth. Therefore, it is very difficult to calculate the error
distribution in DEM and to estimate errors numerically. It is usually assumed that the distribution of
errors in DEM is subject to Gauss law and has strong spatial autocorrelation. However, according to
Stefen Weiss [13], these assumptions are currently poorly proven. The few studies claiming the
applicability of the Gaussian distribution have not been confirmed further. Bonin and Rossiaks [14],
Oksanen and Saryakoski [15] noted that the error distribution in DEM is significantly different from
normal Gauss distribution and contains error values larger than pre-set limit and the majority of errors
are close to “0” at that.

To assess and compare the quality of different interpolation approaches we use the method of
cross-validation (or cross-qualification). The accuracy of interpolation methods is determined by
different criteria, namely:
- By the mean error (MEAN),
- By the mean absolute error (MAE),
- By the mean square error (RMSE),
- By maximum (MAX), and minimum (MIN) in absolute value of the sample differences.

In evaluating the accuracy of DEM, two types of reference data are used: sets of point reference
elements obtained by different methods and auxiliary or derived surfaces with a mathematical
description [16]. Point reference elements can usually be obtained either using cartometric or field
measurements or by various aircraft [17], whose heights are determined with obviously greater
accuracy.

It should be borne in mind that the quality of the input data significantly affects the results of the
evaluation of DEM accuracy. It is necessary to take into account that the input data are divided into
two groups: areas occupied by forests and areas free from vegetation. When assessing accuracy, this
circumstance should be taken into account.

3. Comparison of interpolation methods of DEM data
Analysis of the Earth’s surface is usually based on a two-dimensional raster matrix with specific
information in each element. Every element of such a matrix is an analogue of an image pixel or an
elementary object (data element) of a raster geographic information system. Interpolation methods for
restoring the surface relief values are subdivided into global and local interpolators [18].

Global interpolation methods are based on common function defined on the entire family of points
and can be used to determine systematic or gross errors. The methods of local interpolation are based
on private functions defined at neighbor points belonging to a bounded neighborhood [1]. Due to the
peculiarities of global interpolators (calculation based on the entire sample of points), they are
practically not used to restore the height function, but can be applied to assessing the accuracy of the
model as a whole. When restoring the surface relief, only local interpolation methods are used. These
methods use the autocorrelation principle, which consider points that are physically close to each other, more similar than points that are far from each other.

The main disadvantage of local interpolation methods Reuter [19] considers the limited input data amount to form an interpolation function. Therefore, the input data when calculating each function are grouped in a "sliding window" that moves through the data set. In contrast to global methods, local methods usually produce less smooth surfaces. They are not so sensitive to sudden changes in height, because their influence is not extended to the entire interpolated surface. The difficulty of local interpolation methods consists in determining the necessary and sufficient size of the “sliding window”, which affects the number of data points. In addition, the choice of the interpolating function is far from easy to make. Local interpolators can be subdivided into radially distributed (Figure 1) and orthogonally distributed (Figure 2) depending on the shape of the “sliding window”.

Currently there is a great number of interpolation methods: Triangulation Irregular Network (TIN), Inverse Distance Weighting (IDW), Natural Neighbour (NN), Kriging (Simple Kriging, Ordinary Kriging, Universal Kriging, Point Kriging, Block Kriging, etc.), Radial basis functions (RBF) etc. It is well known that different interpolation methods with the same input data create different output surfaces. Therefore, to restore the relief, it is necessary to choose a method that describes the surface without significant loss of quality, as far as possible.

4. Testing of interpolation methods
Testing of interpolation methods was offered on the basis of a regular matrix in the form of a plot of terrain with a size of 3400 × 3400 pixels (Figure 3). Within the matrix, we specially created the group of points with altered heights (Figure 4), simulating errors in height due to the presence of vegetation cover with a height of 20 m.

![Figure 1. Radial distribution on the shape of the “sliding window”](image1)

![Figure 2. Orthogonal distribution on the shape of the “sliding window”](image2)

![Figure 3. Part of the initial elevation matrix for the experimental site.](image3)

![Figure 4. Part of the original elevation matrix with altered heights.](image4)
The recoverable surface was created by traversing “sliding windows” with sizes of $3 \times 3$, $5 \times 5$, $7 \times 7$ and $9 \times 9$ pixels across the selected matrix. The distribution was taken both radially and orthogonally. The comparison of the original and aligned surface is presented in figure 5.

![Figure 5](image)

**Figure 5.** The final surfaces after approximation by traversing a modified sliding window with dimension $3 \times 3$, ..., $9 \times 9$ pixels (D = 1, ..., D = 4).

The final surfaces were compared with the reference surface, that is the original surface, and the accuracy of smoothing was evaluated (the results see in Table 1). Smoothing the surface with a local interpolator does not directly produce qualitative result, and in some cases worsens the quantitative model values. An additional procedure for eliminating vegetation cover consists of isolating a plot of vegetation, determining and eliminating the average height of trees in each plot, and smoothing newly appeared artefacts with a local interpolator. The most convenient method for isolating areas with vegetation cover in DEM is NDVI method (in reference model the boundaries are known in advance). An average tree height was obtained by means of buffer zones and by calculating average cell heights [20] (in this model, the average correction was 19.4 m). The results of the evaluation of the smoothing accuracy for a vegetation-free surface are shown in Table 1.

**Table 1.** The smoothing accuracy obtained by standard local interpolation before and after exclusion of vegetation cover

| Method                | Dimensions | Parameter estimation accuracy to the exclusion of vegetation, m | Parameter for estimation of accuracy after elimination of vegetation cover, m |
|-----------------------|------------|---------------------------------------------------------------|--------------------------------------------------------------------------------|
|                        |            | MEAN   | MAX   | MIN   | MAE   | RMSE | MEAN   | MAX   | MIN   | MAE   | RMSE  |
| **TIN**               |            |        |       |       |       |      |        |       |       |       |       |       |   |
| $D=1$                 |            | 16.742 | 23.374 | 8.898 | 16.742| 17.072| 1.224 | 6.691 | 0.023 | 1.769 | 2.255 |       |   |
| $D=2$                 |            | 15.843 | 24.425 | 5.753 | 15.843| 16.349| 1.329 | 8.760 | 0.012 | 2.713 | 3.356 |       |   |
| $D=3$                 |            | 13.989 | 27.471 | 2.207 | 13.989| 15.081| 1.505 | 15.529| 0.015 | 3.873 | 5.187 |       |   |
| $D=4$                 |            | 13.123 | 27.590 | 0.018 | 13.188| 14.925| 1.720 | 17.107| 0.024 | 5.826 | 7.161 |       |   |
| **IDW (p=1)**         |            |        |       |       |       |      |        |       |       |       |       |       |   |
| **orthogonally**      |            |        |       |       |       |      |        |       |       |       |       |       |   |
| distributed           | $D=1$     | 10.891 | 17.707 | 3.061 | 10.891| 11.288| 1.224 | 6.691 | 0.023 | 1.769 | 2.255 |       |   |
|                       | $D=2$     | 12.308 | 21.347 | 3.901 | 12.308| 12.890| 1.293 | 10.478| 0.017 | 2.756 | 3.453 |       |   |
|                       | $D=3$     | 12.595 | 24.464 | 2.296 | 12.595| 13.523| 1.437 | 13.593| 0.001 | 3.847 | 4.778 |       |   |
|                       | $D=4$     | 11.455 | 25.450 | 0.149 | 12.459| 13.839| 1.484 | 15.307| 0.061 | 4.904 | 6.027 |       |   |
| **IDW (p=1)**         |            |        |       |       |       |      |        |       |       |       |       |       |   |
| **radially**          |            |        |       |       |       |      |        |       |       |       |       |       |   |
| distributed           | $D=1$     | 9.494  | 16.947 | 0.652 | 9.706 | **10.197** | 1.224 | 6.389 | 0.021 | 1.706 | **2.169** |       |   |
|                       | $D=2$     | 12.060 | 20.906 | 3.862 | 12.060| 12.621| 1.290 | 10.212| 0.005 | 2.689 | 3.362 |       |   |
|                       | $D=3$     | 12.476 | 24.137 | 2.306 | 12.476| 13.374| 1.431 | 13.327| 0.017 | 3.773 | 4.677 |       |   |
|                       | $D=4$     | 11.399 | 25.172 | 0.030 | 12.396| 13.736| 1.477 | 15.035| 0.020 | 4.822 | 5.916 |       |   |
| **IDW (p=2)**         |            |        |       |       |       |      |        |       |       |       |       |       |   |
| **orthogonally**      |            |        |       |       |       |      |        |       |       |       |       |       |   |
| distributed           | $D=1$     | 10.891 | 17.707 | 3.061 | 10.891| 11.288| 1.224 | 6.691 | 0.023 | 1.769 | 2.255 |       |   |
|                       | $D=2$     | 11.757 | 20.071 | 3.617 | 11.757| 12.275| 1.272 | 9.281 | 0.040 | 2.436 | 3.053 |       |   |
|                       | $D=3$     | 12.044 | 21.924 | 3.203 | 12.044| 12.743| 1.364 | 11.294| 0.018 | 3.123 | 3.874 |       |   |
|                       | $D=4$     | 11.131 | 22.832 | 2.066 | 12.099| 13.012| 1.369 | 12.563| 0.016 | 3.761 | 4.625 |       |   |
IDW (p=2) radially distributed

| D=1  | 8.408 | 17.412 | 0.422 | 9.352 | **9.856** | 1.223 | 6.109 | 0.002 | 1.649 | **2.092** |
| D=2  | 11.012 | 20.000 | 3.279 | 11.012 | 11.497 | 1.267 | 8.737 | 0.031 | 2.305 | 2.875 |
| D=3  | 11.478 | 20.951 | 3.054 | 11.478 | 12.140 | 1.354 | 10.747 | 0.028 | 2.982 | 3.680 |
| D=4  | 10.733 | 22.324 | 1.550 | 11.667 | 12.589 | 1.398 | 12.421 | 0.064 | 3.698 | 4.562 |

Gauss-Kriging (RMSE=1) radially distributed

| D=1  | 17.632 | 22.958 | 11.110 | 17.632 | 17.847 | 1.595 | 5.535 | 0.015 | 1.931 | 2.335 |
| D=2  | 17.386 | 23.181 | 10.624 | 17.386 | 17.618 | 1.837 | 6.741 | 0.014 | 2.276 | 2.767 |
| D=3  | 17.396 | 23.273 | 10.595 | 17.396 | 17.635 | 1.925 | 6.985 | 0.018 | 2.364 | 2.887 |
| D=4  | 16.073 | 23.275 | 10.634 | 17.470 | 17.710 | 1.863 | 7.182 | 0.001 | 2.425 | 2.974 |

Gauss-Kriging (RMSE=2) radially distributed

| D=1  | 17.016 | 23.240 | 9.554 | 17.016 | 17.309 | 1.224 | 6.365 | 0.017 | 1.701 | 2.163 |
| D=2  | 15.982 | 24.094 | 7.659 | 15.982 | 16.396 | 1.279 | 9.632 | 0.002 | 2.535 | 3.162 |
| D=3  | 15.692 | 25.250 | 7.062 | 15.692 | 16.214 | 1.359 | 11.148 | 0.005 | 3.096 | 3.812 |
| D=4  | 14.399 | 25.478 | 6.915 | 15.651 | 16.237 | 1.330 | 11.562 | 0.003 | 3.399 | 4.143 |

Gauss-Kriging (RMSE=2) orthogonally distributed

| D=1  | 16.742 | 23.374 | 8.989 | 16.742 | 17.693 | 1.224 | 6.691 | 0.023 | 1.769 | 2.555 |
| D=2  | 15.943 | 23.737 | 7.442 | 15.943 | 16.369 | 1.269 | 9.098 | 0.040 | 2.388 | 2.993 |
| D=3  | 15.895 | 23.958 | 7.248 | 15.895 | 15.724 | 1.304 | 9.520 | 0.031 | 2.574 | 3.197 |
| D=4  | 14.727 | 23.969 | 7.240 | 16.007 | 15.193 | 1.224 | 9.541 | 0.031 | 2.639 | 3.260 |

Gauss-Kriging (RMSE=2) orthogonally distributed

| D=1  | 17.454 | 23.001 | 10.660 | 17.454 | **17.691** | 1.223 | 5.825 | 0.001 | 1.593 | **2.016** |
| D=2  | 16.854 | 23.546 | 9.493 | 16.854 | 17.147 | 1.256 | 7.853 | 0.007 | 2.086 | 2.593 |
| D=3  | 16.695 | 24.105 | 9.135 | 16.695 | 17.026 | 1.298 | 8.649 | 0.004 | 2.375 | 2.921 |
| D=4  | 15.371 | 24.235 | 9.037 | 16.708 | 17.056 | 1.253 | 8.875 | 0.001 | 2.520 | 3.081 |

RBF radially distributed

| D=1  | 16.742 | 23.374 | 8.989 | 16.742 | 17.072 | 1.224 | 6.691 | 0.023 | 1.769 | 2.555 |
| D=2  | 16.102 | 23.705 | 7.719 | 16.102 | 16.499 | 1.280 | 9.768 | 0.022 | 2.564 | 3.213 |
| D=3  | 15.931 | 24.052 | 7.330 | 15.931 | 16.374 | 1.362 | 11.366 | 0.013 | 3.135 | 3.886 |

RBF orthogonally distributed

| D=4  | 14.680 | 24.195 | 7.215 | 15.956 | 16.423 | 1.336 | 11.953 | 0.022 | 3.471 | 4.263 |
| D=1  | 15.941 | 23.720 | 7.128 | 15.941 | 16.383 | 1.225 | 7.595 | 0.001 | 1.964 | 2.525 |
| D=2  | 13.066 | 25.477 | 1.932 | 13.066 | 14.121 | 1.394 | 14.999 | 0.011 | 4.081 | 5.150 |
| D=3  | 12.085 | 30.231 | 0.078 | 12.427 | 14.436 | 1.872 | 21.720 | 0.004 | 6.556 | 8.153 |
| D=4  | 9.661 | 40.189 | 0.071 | 12.264 | 15.112 | 1.908 | 30.841 | 0.010 | 8.500 | 10.604 |

NN radially distributed

| D=1  | 16.742 | 23.374 | 8.989 | 16.742 | 17.072 | 1.224 | 6.691 | 0.023 | 1.769 | 2.555 |
| D=2  | 14.431 | 25.050 | 4.855 | 14.431 | 15.137 | 1.338 | 12.825 | 0.012 | 3.422 | 4.292 |
| D=3  | 13.262 | 29.113 | 0.011 | 13.271 | 14.836 | 1.601 | 17.950 | 0.016 | 5.333 | 6.655 |
| D=4  | 11.058 | 32.317 | 0.046 | 12.628 | 14.843 | 1.734 | 22.325 | 0.091 | 7.048 | 8.709 |

NN orthogonally distributed

Additional exclusion of plots occupied by vegetation cover and calculation of the average trees height allowed obtaining a higher-quality adjusted model, regardless of the adjustment method. Finding a suitable local interpolator, however, remains a priority.

To construct a surface by deviations, it is necessary to define a mathematical function for the most accurate geometric description of a topographic area. We consider the use of Lagrange interpolation polynomials to be the most convenient way to determine the matrix coefficients. Due to the combined application of Lagrange polynomial coefficients and IDW interpolation function (Euclidean distribution), the smoothing accuracy (elimination of artifacts) is increased compared to existing methods even when choosing a small neighborhood (D = 1 or D = 2). Table 2 shows the accuracy values of the model with homogeneous vegetation (the height of vegetation cover is constant) and with different height of vegetation.
| Method                     | Dimensions | Parameter estimation accuracy to the exclusion of vegetation, m | Parameter for estimation of accuracy after elimination of vegetation cover, m |
|---------------------------|------------|---------------------------------------------------------------|--------------------------------------------------------------------------|
|                           |            | **MEAN** | **MAX** | **MIN** | **MAE** | **RMSE** | **MEAN** | **MAX** | **MIN** | **MAE** | **RMSE** |
| Uniform height of vegetation                                            |            |           |         |         |         |          |          |         |         |         |          |
| Lagrang+IDW (p=1)          | D=1        | 16.742   | 23.374  | 8.898   | 16.742  | 17.072   | 1.224    | 6.691   | 0.023   | 1.769   | 2.255    |
| Orthogonally distributed   | D=2        | 16.102   | 23.705  | 7.719   | 16.102  | 16.499   | 1.261    | 8.658   | 0.035   | 2.274   | 2.852    |
| Lagrang+IDW (p=1) radially distributed                                  | D=3        | 15.931   | 24.052  | 7.330   | 15.931  | 16.374   | 1.308    | 9.502   | 0.020   | 2.580   | 3.205    |
| Lagrang+IDW (p=1)          | D=4        | 14.680   | 24.195  | 7.215   | 15.956  | 16.423   | 1.268    | 9.770   | 0.019   | 2.740   | 3.380    |
| Radially distributed       | D=4        | 17.610   | 22.964  | 11.055  | 17.610  | 17.828   | 0.761    | 5.182   | 0.001   | 1.359   | 1.730    |
| Lagrang+IDW (p=2)          | D=1        | 16.742   | 23.374  | 8.898   | 16.742  | 17.072   | 0.924    | 6.397   | 0.005   | 1.652   | 2.117    |
| Orthogonally distributed   | D=2        | 16.393   | 23.602  | 8.224   | 16.393  | 16.757   | 0.990    | 7.584   | 0.005   | 1.970   | 2.490    |
| Lagrang+IDW (p=2) radially distributed                                  | D=3        | 16.347   | 23.642  | 8.055   | 16.347  | 16.728   | 1.024    | 7.962   | 0.013   | 2.128   | 2.665    |
| Lagrang+IDW (p=2)          | D=4        | 15.980   | 23.645  | 8.016   | 16.423  | 16.811   | 0.998    | 8.057   | 0.031   | 2.206   | 2.748    |
| Radially distributed       | D=4        | 17.734   | 22.928  | 11.374  | 17.734  | 17.936   | 0.737    | 5.002   | 0.000   | 1.316   | 1.674    |
| Lagrang+IDW (p=3)          | D=1        | 17.517   | 23.125  | 10.688  | 17.517  | 17.743   | 0.800    | 5.785   | 0.002   | 1.527   | 1.921    |
| Radially distributed       | D=2        | 17.536   | 23.048  | 10.909  | 17.536  | 17.760   | 0.818    | 5.907   | 0.015   | 1.595   | 1.986    |
| Lagrang+IDW (p=3)          | D=3        | 16.191   | 23.052  | 10.171  | 17.598  | 17.823   | 0.794    | 5.936   | 0.015   | 1.631   | 2.024    |
| Radially distributed       | D=4        | 16.742   | 23.374  | 8.898   | 16.742  | 17.072   | 0.924    | 6.397   | 0.005   | 1.652   | 2.117    |

Thus, the proposed modified interpolator improves the geometric characteristics of the model, both before and after the exclusion of vegetation cover. The orthogonal as well as radial distribution of the coefficients affect the results. In addition, as the experiment showed, this is true for both areas with a uniform vegetation cover (+20 m), and for areas with different height trees (+20 and +10 m).

We tested the modified interpolator described above on a section of the river basin with the dimension D = 200. Input data for this were chosen from ASTER and SRTM elevation matrices [21].
Figure 6. Sequence of DEM correction in the local area of $5 \times 5$ pixels with the exception of vegetation cover by proposed interpolator (Euclidean distribution with Lagrange coefficients).

In comparison to the original ("noisy") version, the corrected surfaces have a higher degree of accuracy, and the main part of the dispersion (about 90%) is scattered within $\pm 3$ m. Thus, the proposed Euclidean distribution using Lagrange coefficients can be applied for interpolation the surface relief based on coefficient matrices from $3 \times 3$ to $5 \times 5$ pixels.

5. Conclusion

In conclusion, it should be marked that the IDW method has the best quality when using small neighborhood involved in interpolation ($D = 1$ or $D = 2$). Therefore, when restoring digital relief surfaces, in most cases it is preferable to use IDW interpolation method with a power factor of "2". The kriging method showed its weak dependence on the neighborhood during interpolation. However, it has a high dependence on the selected semivariogram model. The main criterion for restoring the relief is the preservation of the main orographic elements, i.e. the surface must meet the requirements
of hydrological correctness. Thus, the use of any interpolation method to improve accuracy requires additional coefficients.

When evaluating the accuracy of the surface geometry, the resulting data strongly depends on the number of reference values. However, the final deviations can be further used for the purpose of adjusting models and the subsequent re-shaping of the surface geometry.

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