Geospatial Aspects of Merging DTM with Breaklines

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Key words: DTM, Breaklines, TIN, Interpolation, Constrained-Delaunay-Triangulation.

SUMMARY

Digital Elevation Databases (DED) constitute a central component of the great boost to all mapping and GIS fields, as the variety of applications that are supported by it is practically infinite. A variety of sophisticated technologies resulted in huge availability of automatic elevation data. The surface data obtained by applying these automatic techniques is not sufficiently reliable, and requires additional characteristic data such as breaklines. Merging breaklines and DTM is part of the bigger challenge of modeling three-dimensional surfaces. Presented here is an analysis of improvements in the accuracy of surface representation following application of different breakline incorporation techniques. Numerous experiments were carried out in different areas, based on very accurate measurements, enabling profound analysis and conclusions. Two appropriate solutions are proposed for merging breaklines with DTM. Future research is proposed in the very challenging field of modeling elevation data.

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1. INTRODUCTION

The Digital Elevation Database, or DED, which is one of the most important databases of mapping and GIS domain, is being carried on the wave of technological development in areas such as remote sensing, image and signal processing, computerized vision etc. The variety of applications of such databases is infinite and affects many areas of life, such as engineering, mapping and geoinformation, transportation, communications, agriculture, aviation, archeology, security and many others (Weibel & Heller, 1991). The sources and processes for producing the data have also grown in recent years, and the technologies such as autocorrelation in digital photogrammetry, IFSAR, LIDAR, among others, have increased manifold the abundance and the availability of data (Maune et al, 2001).
Since most advanced technologies for creating and producing DED layers are automatic, thus saving the considerable and expensive manual labor, the resulting data cloud is nonetheless not perfect from the standpoint of reliability in respect to the three-dimensional surface that it is required to represent, and it is blocked by technological limitations as well as limitations of the source used for inputting the data. Due to this, and in order to achieve high reliability, especially in areas that are critical for describing the surface, we are required to add characteristic details, such as breaklines, which constitute linear elements describing changes in surface smoothness or continuity.

However, a paradox arises. On the one hand, we recognize the importance of integrating all the above in various models describing the relief toward obtaining a proper digital substitute of the surface, yet on the other hand, we must be aware of the very expensive input resources and the rise in the complexity level of the manner in which the data are presented, compared with other simpler systems for modeling three-dimensional surfaces.

Dealing with the issue of integrating breaklines in the data of the Digital Terrain Model (DTM) is an important foundation of every modeling and representation of three-dimensional surfaces and necessitates an overall understanding of the problem for which there is no one optimal solution. The research described in this article deals with the problem of integrating breaklines in the DTM grid, while examining the extent of quantitative effect this action bears on the accuracy of describing the relief and the manner of integrating characteristic data by employing several relevant techniques.

In the course of performing the research described in this article, a number of problems were observed in the common technique of integrating the DTM grid. Consequently, two additional algorithms for dealing with the problem were developed and implemented. One of these actually constitutes an adaptation and improvement of the current treatment, while the second is a new tool that was developed for this purpose. The two proposed tools for the proper treatment of this problem, represent two approaches for integrating breaklines in

DTM, presented as part of the theoretical background chapter. One conclusion of the study is that the best results will apparently be produced by integration of the two approaches.

The study reaches several important conclusions that can be summarized by the ability to attain high reliability and accuracy by using relatively sparse DTM grids in an optimal spacing (Ayeni, 1982) integrated with breaklines, compared with much dense grids, both from the general statistical aspect, as well as in respect to the most critical areas from the standpoint of the accuracy of the relief data.

2. THEORETICAL BACKGROUND

Breaklines (or similarly defined characteristic lines / skeleton lines) are as stated, linear elements that describe changes in smoothness or continuity of the surface. Mostly they are sampled in order to describe extreme local occurrences and thus completing the overall terrain structure and its digital representation. Their preservation and integration in the database is most essential to obtaining a reliable DED.

In professional literature they are at times classified in various ways, whether “natural” or “manmade”, whether “soft” breaklines that preserve measured features of known height (highway routes, for example) or “hard” breaklines that describe the discontinuity of the relief (riverbeds, shorelines, clifflines, etc.), and whether with a higher degree of accuracy than the rest of the DTM or with the same accuracy (Chen 1998). The manner of using or weighting breaklines, depends on their attribution to one or another of the above mentioned groups.

Breaklines are identified and inputted from some of the reviewed mentioned sources, mostly by manual processes, rich in resources, although at times automatic or semi-automatic processes are integrated, depending on the source and on algorithmic capabilities.

The input in the process of integrating breaklines in the DTM is the elevation model in one of its popular representations (gridded or triangulated networks) or less usable (quadrangles networks, elevation profiles or equal elevation vectors) and a collection of three dimensional breakline vectors. The objective is to integrate these lines in the model (by fixing or weighting them in various ways) in a representation that would facilitate obtaining a more unified and accurate database.

Even though this subject is not dealt with in a broad and detailed manner in professional literature, it is possible to recognize at least two principal approaches to dealing with this problem. The first is based on fixing the breaklines in a triangulated database, while the second is based on interpolative calculations, while taking account of the breaklines.

Most of the literature refers to the first approach, in which breaklines are integrated in triangulated networks (TIN). The integration (Chen, 1998; Heller 1991) is based on constructing a Delaunay Triangulation, with an added obligatory condition, which is using the segments composing the breaklines as mandatory segments in the triangulated network being constructed, while maintaining its legality (as defined in Berg at al, 1998). The triangulation that mandates fulfillment of this condition is known as the Constrained Delaunay Triangulation (CDT). The result of integration with this technique is a new triangulated unified model, which physically preserves the breaklines.

Less treatment is given in literature to the second approach, in which, unlike by means of CDT, the breaklines are not physically introduced into the data model, but rather weighted and entered into the database by one of the familiar interpolation methods, such as: Inverse Distance Weighting (Weng, 1998), Minimum Surface (Doytsher, 1979), Polynomial/Spline Interpolation (Maune et al, 2001), Moving Surfaces (Schut, 1976), Natural Neighbor Interpolation (Gold, 1989), or geostatistical methods, such as those of the Kriging family (Weng, 1998).

3. THE RESEARCH

As stated, the principal objective of this study is to examine the extent to which integration of breaklines affects the accuracy of the relief description, while taking note of the techniques used to implement this process. Integration of breaklines in the elevations grid is examined in the framework of experiments that facilitate a real quantitative examination of the manner and extent of the quantitative effect of this process on the accuracy of describing the relief, both from the overall statistical aspects, and in particular in respect to its most critical areas (that is the breaklines surroundings).

The study focuses on a common procedure of integrating breaklines in a DTM, where breaklines are integrated in a relatively sparse elevations grid, in a manner that the product obtained is an elevations grid of higher resolution and greater accuracy. Two test areas were chosen of varied relief character rich with characteristic features (with the terrain characterized by slopes ranging from 0% to 80%), and on which all the experiments listed below were carried out.

3.1 Measuring the Reference Base for Performing Comparative Analyses

In order to perform accurate comparative analyses to provide accurate statistical data at the range of several tens of centimeters to several meters scale, a reference base was required with the highest resolution and accuracy. An aerial photogrammetric block on a scale of 1:12,500 (including the two test areas) was chosen, and solved very accurately based on ground control (GPS measurements) data. For the two test areas, a very dense elevations grid with a resolution of 2m and high vertical accuracy of about half a meter was measured. The size of the first test area (the “northern”) is about $2km^2$ from which some 500,000 points were measured. The size of the second test area (the “southern”) is about $4km^2$, from which some 1,000,000 points were measured.

3.2 Measuring Breaklines

The basic objective was performing graduated integration and analysis, in order to facilitate future examination of the degree of vitality of the breaklines as a function of their altimetric characteristics. Thus, the manner of measuring breaklines included dividing them into several levels according to the degree of their being critical to the reliable description of the relief, as well as altimetric division into upper and lower topographic items. Altogether six layers of typical lines were measured, as follows:

- Main upper breakline
- Typical upper breakline
- Secondary upper breakline
- Main lower breakline
- Typical lower breakline
- Secondary lower breakline.

The measuring process was performed by the same experienced operator who measured the reference base (to avoid calibration problems and bias deviations) from the same aerial photographs, with a maximum vertical accuracy of about 30cm.

3.3 Methodology of Performing the Experiments and Statistical Analyses

First, the fine grids were thinned out into sparse grids with resolutions of 25m, 50m, 100m, and 200m. At the second stage, the six layers were gradually integrated (an additional two layers each time) into the sparse grids and from the obtained products new dense grids of the original resolution (2m) were computed. First the main breaklines were integrated (upper and lower), followed by the typical breaklines (upper and lower), and finally the secondary breaklines (upper and lower). At each stage comparative analyses were carried out (data was collected such as average deviation, standard deviation, maximum deviation and deviation histogram), which were compared the computed dense grids (after integrating the breaklines) with the original dense measured grids. All comparisons and statistical analyses were also carried out in three versions, taking into account in the first version the complete test areas (in order to understand the complete statistical contribution of the breaklines) and taken into account in the other two were zones (buffers of 10m and 20m) alongside the breaklines (in order to focus the contribution in the areas most critical for describing the relief). The described process was reiterated three times (for the three techniques for integrating breaklines) and for the two test areas, i.e. six times altogether. A large quantity of data was collected, a short summary of which is described below by means of graphs summarizing representative cases. It turned out that the most interesting data was observed by using standard deviation figures and thus the graphs below are based on this statistical figure.

3.4 Inserting Breaklines by a Diagonal TIN Technique

At the first stage of this method, the elevation grid is transferred to the triangulated irregular network (TIN) by adding the diagonals in the cells of the original grid. At the second stage, the breaklines are integrated in the TIN by canceling the TIN in the vicinity of the breaklines, and its reconstruction based on CDT. After recalculating the TIN, the elevations of the points on the dense elevations grid are calculated, each time by linear interpolation within the appropriate triangle.

Examination of Figures 1 and 2 and analysis of the comparative data, showed that after inserting the breaklines, general statistics usually indicated deterioration in all parameters, namely, average deviation, standard deviation and maximum deviation. Some improvement in these data was achieved in isolated cases only. On the other hand, from examination of the comparative data in the buffers an improvement can be seen in all parameters. Thus for example, in the most explicit figure (10m-buffer integrated with the two main – upper and lower - breakline layers, at a resolution of 100-200m) there is an average improvement (i.e., reduced deviation in respect to the thinned out data without the breaklines) in about 75% of the two test areas, together with the maximum improvement of about 85% (in integration of the first main breakline layers in the 200m grid).

The natural conclusion is that this insertion method leads to a reasonable integration in the vicinity of the breaklines, but also leads to a considerable weakening in the quality of the dense data achieved by his method, in places where there are no breaklines, thus causing a sharp deterioration of quality in terms of the general statistics of the test areas.

3.5 Inserting Breaklines by a Centered TIN Technique

In this case, the mechanism of integrating breaklines is totally identical to the previous mechanism reviewed, except that this time the division of the elevation grid into triangles is based on adding a central point to each cell (a point whose elevation is calculated by bilinear interpolation) and linking the four corners of the cell to it. Each cell is subdivided into four triangles, whereas in the previous technique each cell is subdivided into two triangles. In this manner we achieve better approximation of the created triangular network to the real terrain as described by the elevations grid. Further integration of the breaklines is based on removing

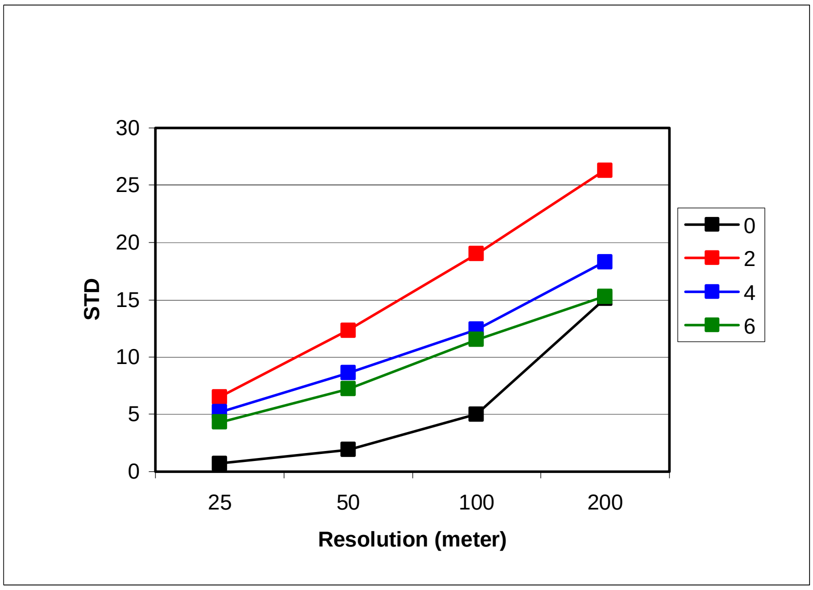

Figure 1: Diagonal TIN method – STD (meter) figures of the southern area – full coverage

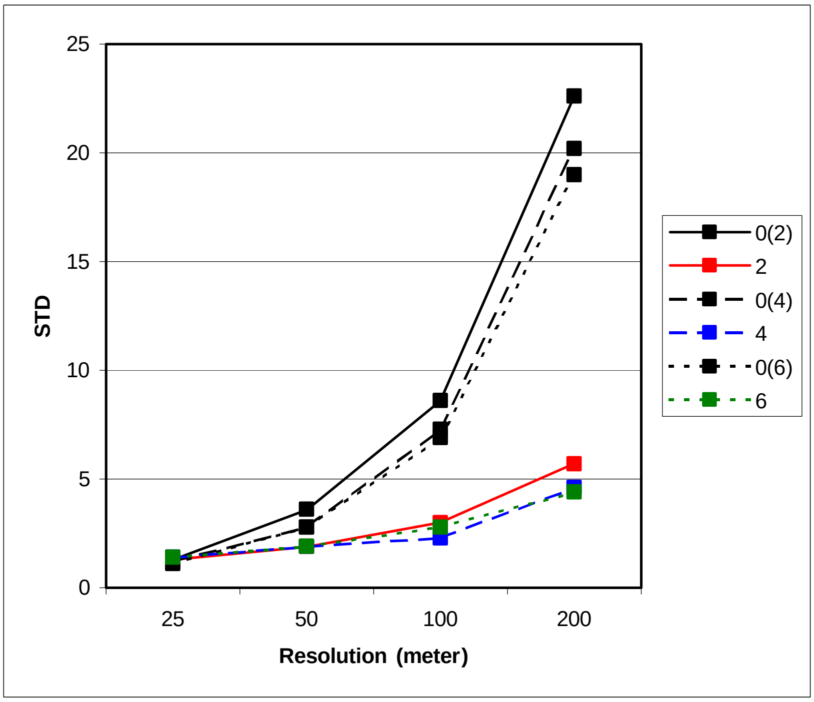

Figure 2: Diagonal TIN method – STD (meter) figures of the southern area – 10-meter buffer

the edges of the triangles in the vicinity of the breaklines and rebuilding these based on CDT. The calculation of the dense grid is performed based on linear interpolation within the appropriate TIN triangle.

From examination of Figures 3-6 and analysis of the comparative data, it emerges that in general statistics, totally contrary to the previous method, there is a decrease in deviations in all parameters and the more additional breakline layers are added the less the deviations. These results indicate that by adding the central point to each cell, based on simple bilinear interpolation and connecting the sides of the triangles to it, a most substantial improvement in accuracy is achieved, in everything related to general statistics in the complete test areas.

If we look at the general statistics of the two test areas in the grids thinned out to 100m and 200m, we can learn the degree of significance of the graduated addition of each pair of layers on the improvement in the standard deviation:

- Addition of the first two layers (main breaklines) improved the standard deviation by some 37%.
- Addition of the next two layers (typical breaklines) improved the standard deviation by some 58% (cumulative improvement).
- Addition of the last two layers (secondary breaklines) improved the standard deviation by some 66% (cumulative improvement).

From analysis of the comparative results in the zones alongside the breaklines (buffers of 10m and 20m width), it emerges that there is improvement in all parameters over the original deviations. For example, looking at the average data in the 10-meter buffer at resolutions of 100m and 200m and the two test areas jointly:

- With the first two breakline layers an average 84% improvement was achieved and a maximum of 89% (compared with the former integration technique which achieved 75% and 85%, correspondingly).
- Similar results were also achieved with the other breakline layers, with a multilayer improvement of 85%.

All analyses show that the Centered TIN technique was proven to produce satisfactory results, both from the overall statistical standpoint, over the entire test areas, as well as from a more focused observation in the buffer areas.

3.6 Inserting Breaklines by a Bilinear Profiles Technique

This technique belongs to a family of methods that employ surface interpolation algorithms together with breaklines. The algorithm is based on bilinear interpolation which takes breaklines into account by integrating them in the process of defining the perpendicular profiles while calculating the dense grid points.

Bilinear interpolation is carried out in cells through which the breaklines pass, for increasing the density of the sparse grid, while taking into account the breakline intersection points with the edges of the sparse grid to obtain two perpendicular profiles (parallel to the cell edges) that intersect at the calculation point. In cells through which no breaklines pass, a simple bilinear interpolation is carried out without any additional information.

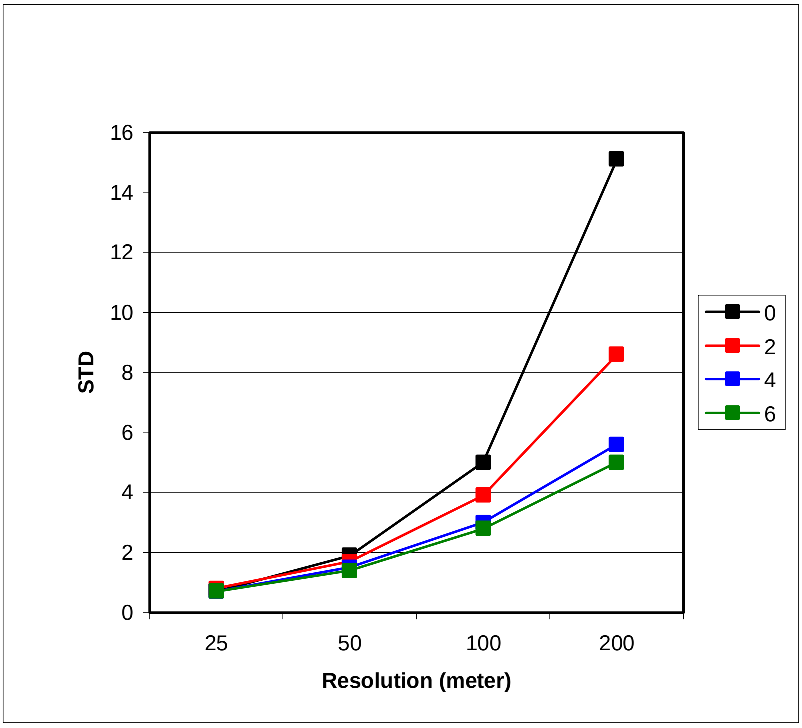

Figure 3: Centered TIN method – STD (meter) figures of the southern area – full coverage

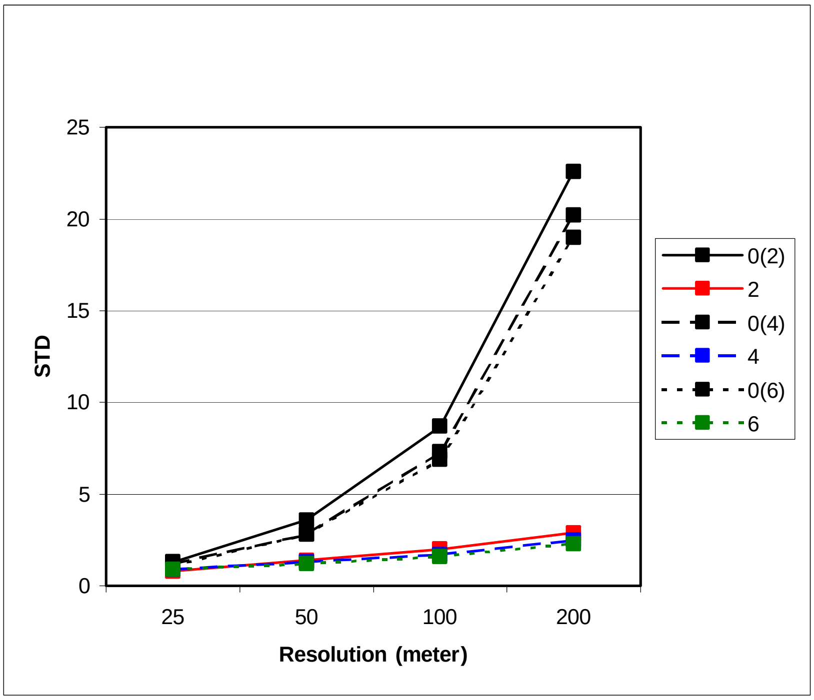

Figure 4: Centered TIN method – STD (meter) figures of the southern area – 10-meter buffer

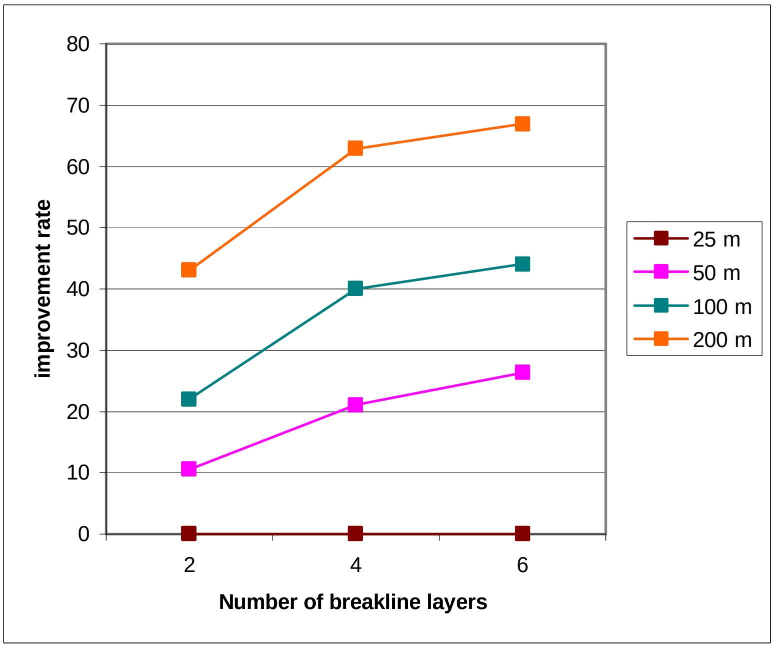

Figure 5: Centered TIN method - STD improvement rates of the southern area – full coverage

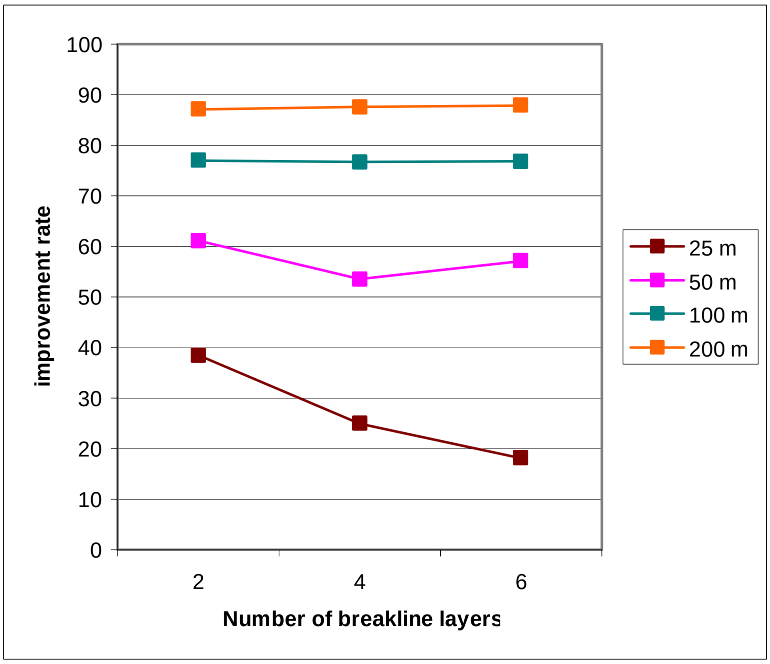

Figure 6**:** Centered TIN method - STD improvement rates of the southern area – 10-meter buffer

Calculating the elevation of a point in any profile can be carried out in various ways. In order to achieve simplicity of the algorithm, as well as preserving the character of the breaklines expressing local discontinuity in the derivative, the calculation was based on a weighted linear interpolation according to an inverse ratio to the size of the profile segment to which the calculation point belongs.

Examination of Figures 7-10 and analysis of the comparative data shows in general statistics a decrease in deviations in all parameters, and as more breakline layers are added, these deviations decrease even further. Examining the general statistics of the two test area in grids thinned out to 100m and 200m, it is possible to see the effect of the gradual addition of each pair of breakline layers on the improvement in the standard deviation:

– Adding the two main breakline layers improved the standard deviation by about 37%.
– Adding the next two breakline layers improved the standard deviation by about 57% (cumulative improvement).
– Adding the last two secondary breakline layers improved the standard deviation by about 62% (cumulative improvement).

Analysis of the comparative results in the various buffers shows a dramatic improvement in all parameters over the original deviations (without breaklines at all). For example, looking at the average data of the 10-meter buffer at a resolution of 100-200m and in both test areas together:

– In the first two layers, an average improvement of 72% was achieved and a maximum improvement of 77%.

– Similar figures were also obtained by inserting the other breakline layers, with a multilayer improvement of 73%.

It emerges from all data that the bilinear profile integration technique results in satisfactory performance over the entire test areas, also from the general statistical standpoint, as well as in more focused observation in the buffer zone areas.

4. CONCLUSIONS AND FUTURE WORK

Based on the research of which only limited portions were presented in the preceding chapters, the following summarizing comments can be made:

– By inserting breaklines into relatively sparse DTM grids, it is possible to attain very high reliability, very close to that obtained in representation by means of much dense grids. This is true both from the general statistical standpoint, as well as in limited and most critical areas.
– The major improvement in accuracy is obtained after adding the two main breakline layers (upper and lower). The additional accuracy obtained by integrating the following four layers (at the two levels of typical breaklines and secondary breaklines) is relatively small. It is thus possible, at least in view of the experience gained in this work, to classify the breaklines into just two levels of importance (to include jointly the second and third levels).
– Three methods were examined (from two families – CDT and surface interpolations) for performing the integration of breaklines in DTM grids. The Diagonal TIN method was found to be unsuitable for integrating breaklines in DTM grids. On the other hand, both the Centered TIN method (representing the CDT family) and the Bilinear Profiles method

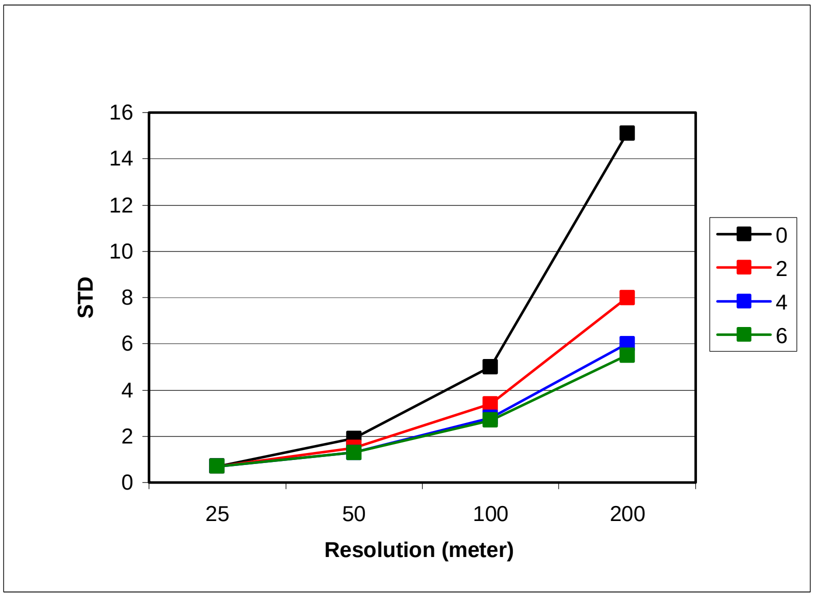

Figure 7: Bilinear Profiles Method – STD (meter) figures of the southern area – full coverage

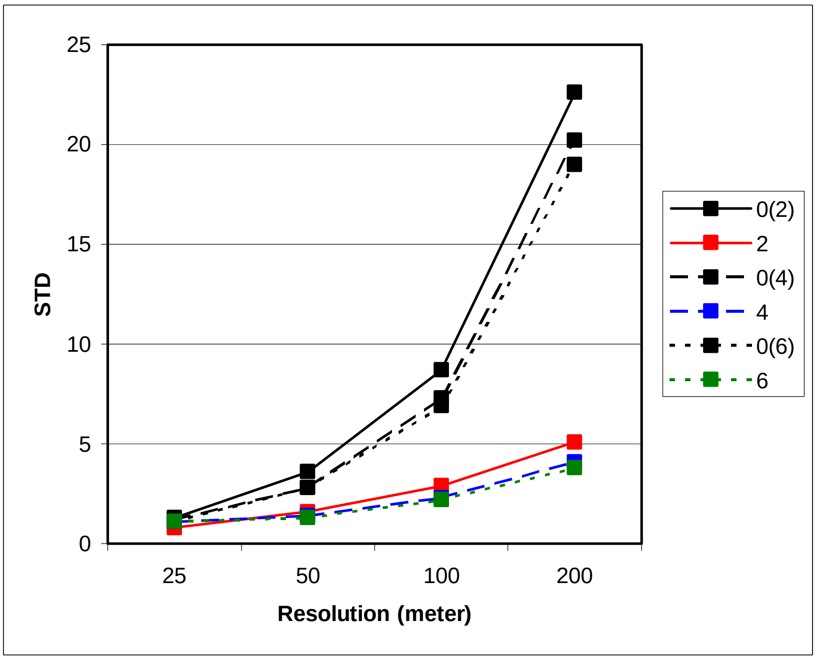

Figure 8: Bilinear Profiles Method – STD (meter) figures of the southern area – 10-meter buffer

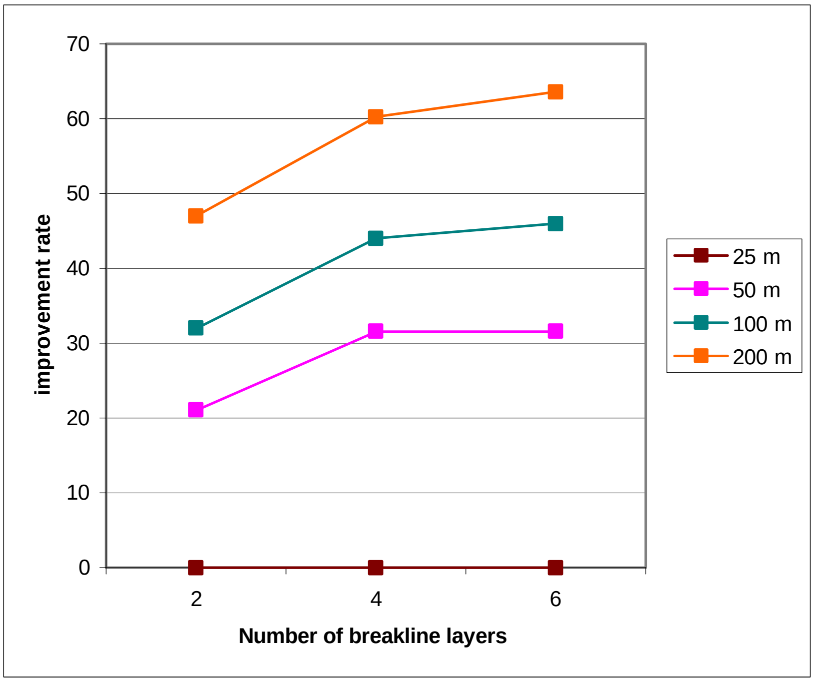

Figure 9: Bilinear Profiles Method - STD improvement rates of the southern area – full coverage

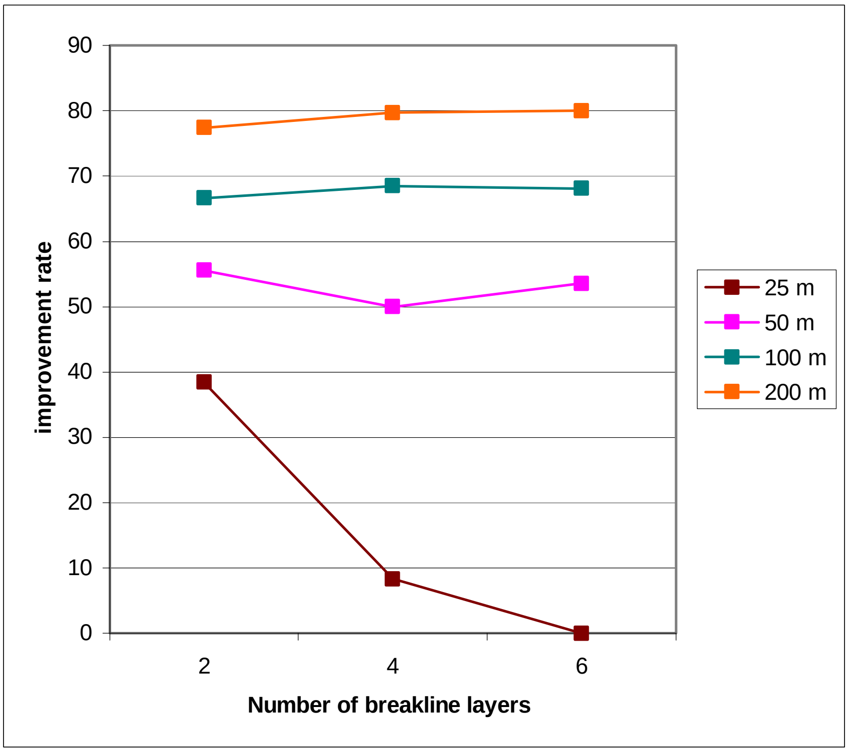

Figure 10: Bilinear Profiles Method - STD improvement rates of the southern area – 10-meter buffer

(representing the surface interpolations family) brought about a significant improvement in accuracy of surface representation. All this notwithstanding the fact that the algorithms have not been refined and problems such as dealing with edge scenarios and employing varied weighting have not been addressed as yet.

– The CDT algorithm family is better suited to the breakline areas themselves, while in other areas of relatively "rounded" nature it would be preferable to employ surface interpolations. Therefore, there is room to examine a possible integration of the two techniques that could perhaps provide better results than either of the methods separately.

The authors believe that comprehensive implementation of the solutions developed nonetheless depends on several factors that require more thorough additional examination. Among these factors are:

– Performing cost/benefit analyses in correspondence with nature of the terrain, the sources of data and the required accuracy, while handling a deeper examination of additional parameters such as the 90% or 95% threshold boundary.
– A separate examination, in the scheme that was presented, of the extent of accuracy achieved by addition of features, while separating their altimetric characteristics (cliffs and ridge lines separately, channel lines separately, etc.)

– Refining algorithms and tools that were developed for this study with the aim to optimizing them subject to criteria such as accuracy, smoothness, complexity level, and robustness.

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BIOGRAPHICAL NOTES

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