PYRAMIDAL APPROACH TOWARD MERGING TOPOGRAPHIC DATA FROM DIFFERENT DTM DATASETS

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ABSTRACT

Nowadays DTM databases, which describe terrain relief, are among the main interactions between data acquisition and a wide area of applications. One of the main problems in this discipline is data merging, which involves integrating data from different sets. Various factors cause global-systematic errors as well as local-random ones, which reflect on a different scale of spatial geometric and radiometric differences. Consequently, the required integration process yields the merging of geo-spatial datasets consisting of different resolution, accuracy, datum, orientation, and level of detailing. This paper describes a new approach to merging datasets, in which a careful examination, investigation and eventually an appropriate solution is given. The idea is to implement a hierarchical solution of pyramidal approach, in which local geometric discrepancies are monitored and prevented. The solution for the dataset matching procedure given here suggests the implementation of two working levels of topographic zoning – global and local. The suggested procedure is as follows: zonal division of the whole datasets area into patches, in which a local registration is extracted for each; sub-zonal division, in which an accurate 'local' ICP matching process is achieved while using the local extracted corresponding registration values. This new approach has good results for DTM datasets merging, therefore achieving a singular, unified and spatial continuous surface representation of the terrain relief.

INTRODUCTION

Terrain relief is playing a lead role in the representation and characterization of earth and various relevant processes. As result from recent developments in data acquisition and data processing, DTM databases are today one of the main resources for a wide range of different applications involved with terrain relief analysis. The discrepancies exist when comparing different DTMs representation of the terrain relief may occur due to natural causes or human activities that took place during the data acquisition epochs, as well as having inherent errors occurring during the observations stage or production (Hutchinson & Gallant, 2000). These various factors present global-systematic errors as well as local-random ones, which reflect on a different scale of spatial geometric and radiometric differences.

When planning to integrate or merge different DTM geo-spatial datasets, one has to deal with these various factors that may cause to phenomena of topographic differences, and thus give an appropriate solution for this problem. The common "cut and paste" matching procedure on datasets representing the same terrain relief area will produce incorrect results, mainly for the fact that there are irregularities in the topographic representation between the datasets. A sample of these phenomena is depicted in Figure 1. Consequently, the required integration process yields the merging of geo-spatial datasets consisting of different resolution, accuracy, datum, orientation, and level of detailing. Furthermore, DTMs only partly describe terrain relief, which is a continuous entity, mainly because of its discrete representation in terms of points or lines. Therefore, the integration of different geo-spatial datasets can reduce the inequality existing between reality and its representation, and thus attain a unified merged DTM to better describe the terrain relief.

One can divide the merging problem into two main stages: finding the best correspondence between datasets; and, executing the merging process itself. Rusinkiewicz & Levoy (2001) showed that the initial knowledge regarding the geometric spatial relations between the datasets must be known prior to the matching process itself in order to extract a non-biased matching solution. This can be achieved by implementing initial registration processes on the different datasets – for instance, pairing-up groups of two congruent geomorphologic features existing in the different datasets. This yields the extraction of the geometric spatial relations, i.e. a qualitative initial registration value of the two datasets (three-shift values for example).

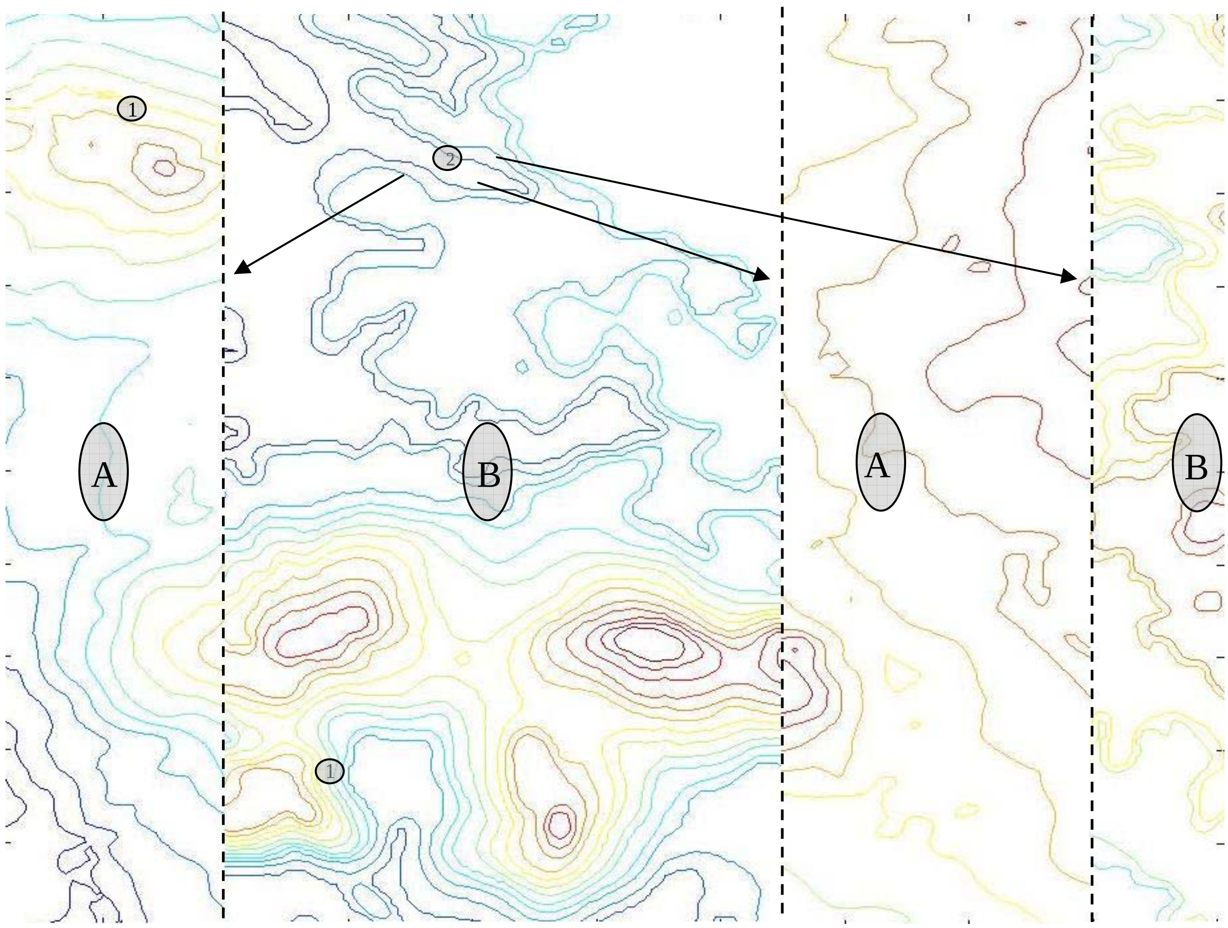


Figure 1. Contour representation of "Cut and Paste" superimposition of two datasets - *A* and *B* - showing topographic discrepancies: (1) hills existing only in one dataset; (2) vertical lines displaying planimetric and altimetric topographic shifts.

After extracting the initial registration value, a full 3-D matching procedure is feasible. This can be done by one of the available processes for spatial geometric dataset matching – ICP (Iterative Closest Point) for example – first presented by Besl & McKay (1992). This algorithm is mainly designated for point cloud matching by a nearest neighbor criteria process, using iterative LSM (Least Square Matching) (Gruen A., 1996). The calculation of the accurate spatial affine transformation (three rotation angles and three shifts for example) is more accurate and reliable when using the prior registration knowledge extracted earlier. Several papers have addressed the problem to ensure continuity of surface description - semantically, topologically, and geometrically - when a merging procedure, based on an iterative algorithm designated for rigid surfaces registration by a set of 3-D representation points, is involved (Laurini, 1998 and Feldmar & Ayache, 1994).

In the next section the algorithm stages for the implementation of a hierarchical solution of pyramidal approach are given. The detailed procedure suggests the implementation of two working levels of topographic zoning – global and local. By monitoring local zonal discrepancies and thus extracting the corresponding registration-values, an accurate 'local' ICP matching process is feasible, thus achieving a singular, unified, and spatial continuous surface representation of the terrain relief.

PROPSED PYRAMIDAL APPROACH

The various mathematical procedures given in this section address the different factors that need to be considered as part of the complete proposed solution. The pyramidal approach given here proposes the implementation of two working zonal levels – global and local – thus enabling the extraction of local discrepancies, instead of working with the entire data as a global bundle. This is achieved by two data-dividing stages performed on the entire area, as will be discussed in further detail. These working levels – global and local – are required for the registration and matching stages respectively. In addition, by a constrained ICP and merging processes that are carried out, it enables the calculation of the accurate and qualitative spatial continuous surface representation. In each one of the following sub-sections a detailed explanation and mathematical formulas are given.

First Order Division

The entire area is divided into medium-sized-patches (*msp*) (Figure 2). This division addresses the preliminary need for extracting local-discrepancies' values exist between the different datasets before carrying out the matching process. The extraction of unique local geomorphologic points, i.e. interest points, and then the calculation of the initial registration value correspond for each congruent *msp* is carried out on these zonal patches.

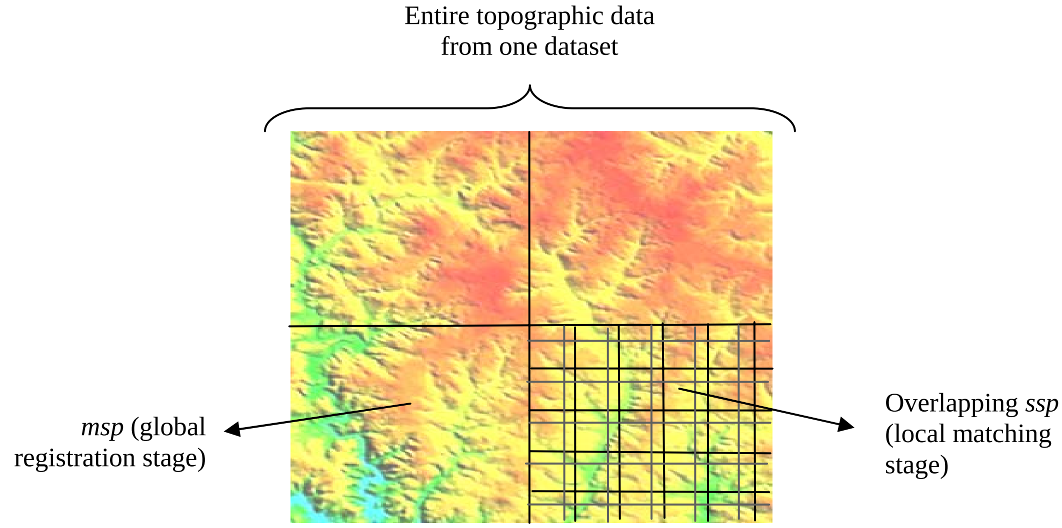


Figure 2. Two working topographic zoning levels: global registration (*msp*); and, local matching (*ssp*).

Extracting Interest Points

The idea is to rely on unique surface-derived geomorphologic points, such as mountain or hill peaks, that will probably appear in both datasets designated for merging. A pairing-up process of those geomorphologic points as homologous pair points will provide the needed initial knowledge regarding the local registration values – i.e. initial shifts – exist among the congruent *msp*s covering the entire topographic area given.

A computational approach for extracting interest points is implemented. The examination of the topological conditions around each DTM grid-point is carried-out. Statistical testes and geomorphologic definitions according to a set of rules are performed, in order to ascertain that the examined grid-point can be defined as an interest point. This is achieved according to the following steps:

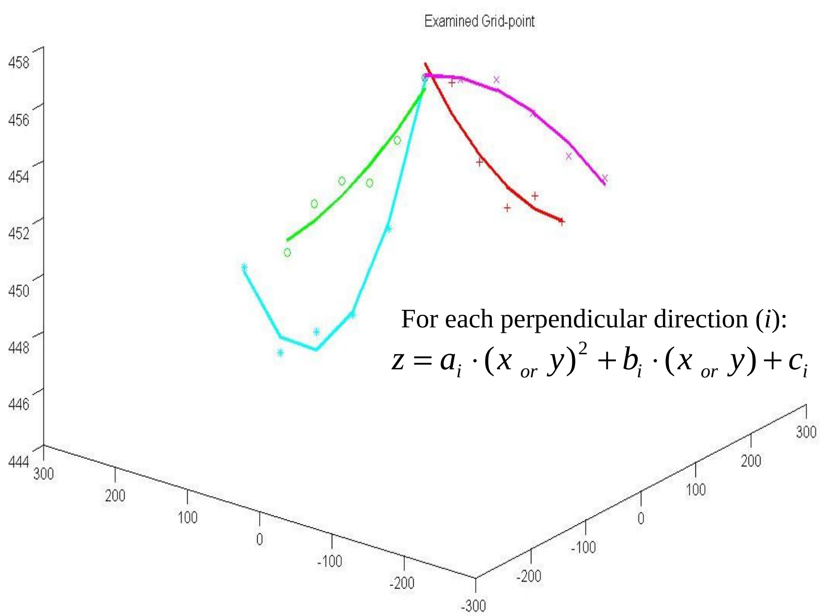
1. Extracting four perpendicular second degree polynomials, derived from the height (*Z*) and (*X*) or (*Y*) coordinates in each direction (*i*) as function of the grid's spacing (Equation 1). Each of these polynomials is defined by the geometric conditions registered by six consecutive discrete points for each direction. The extraction of the polynomials coefficients is carried out by a least squares adjustment process. The geometric conditions, described by these four polynomials, define the topographic environment of the examined grid-point (Figure 3).

$$Z_i = a_i + b_i \cdot X + c_i \cdot X^2 \qquad (1)$$

2. Calculating the integral (area) value under each of these polynomials in the *Z* direction relative to the height of the farthest point in each of the extracted polynomials. This defines whether the examined grid-point is above its surrounding and in what magnitude (Figure 4).
3. Carrying out statistical tests on the values extracted, which define topologically and geomorphologically whether a preliminary definition of the examined grid-point as an interest point can be considered. The statistical tests are carried out on two of the polynomial coefficients values - *c* and *b*, extracted on stage 1, and on the polynomial integral value, calculated on stage 2. The statistical tests are carried out on each of the polynomials in the i^{th} direction as follows: examining its topological behavior, as presented in equation 2(a) (while the second condition is a straight line generalization of the polynomial and *spc* denotes the grid's spacing); examining the integral value of the polynomial, as presented in equation 2(b). Both tests are executed with pre-defined thresholds: defining the polynomial type (ascending or descending) and its topological behavior – *threshold1*; and – *threshold2* - defining the height magnitude of the examined grid-point in respect to its surroundings.

$$for\ each\ direction\ i : (c_i < 0\ and\ b_i < 0)\ or\ (b_i + 5 \cdot spc \cdot c_i < threshold1) \qquad (2a)$$

$$for\ each\ direction\ i : (area\_value_i > threshold2) \qquad (2b)$$



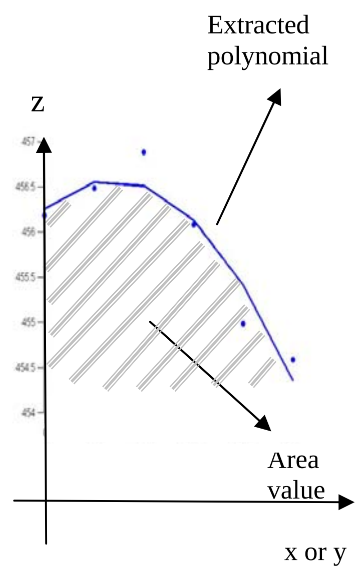


Figure 3. Four perpendicular second degree polynomials extraction.

Figure 4. Side view – area under extracted polynomial

4. Local grouping by distance criteria of the defined interest points is carried out, in which the highest grid-point is chosen (Figure 5). A pre-defined number of points' criterion, derived from surface characteristics, is declared as a group definition.
5. A local bi-directional interpolation near each of these interest points calculates the highest topographic precise location, thus achieving sub-resolution accuracy (Figure 5). This is carried out by extracting local polynomials in *X* and *Y* direction – Z_x and Z_y – as outlined in Equation 3. These two polynomials cross at the location of the highest interest point in each group. The calculation of the highest topographic location is achieved by comparing the first order derivative of these polynomials to the value 0, and hence calculating the shift value – S_x and S_y – pointing the precise location.

$$
\begin{gathered}
Z_X = a_0 + a_1 \cdot X + a_2 \cdot X^2 \\
Z_Y = a_3 + a_4 \cdot Y + a_5 \cdot Y^2 \\
\frac{dZ_X}{dX} = a_1 + 2 \cdot a_2 \cdot X = 0; \ \frac{dZ_Y}{dY} = a_4 + 2 \cdot a_5 \cdot Y = 0 \\
s_x = -\frac{a_1}{2 \cdot a_2}; \ s_y = -\frac{a_4}{2 \cdot a_5} \\
X_{\text{interest\_point}} = x_{highest} + s_x; \ Y_{\text{interest\_point}} = y_{highest} + s_y
\end{gathered}
\qquad (3)
$$

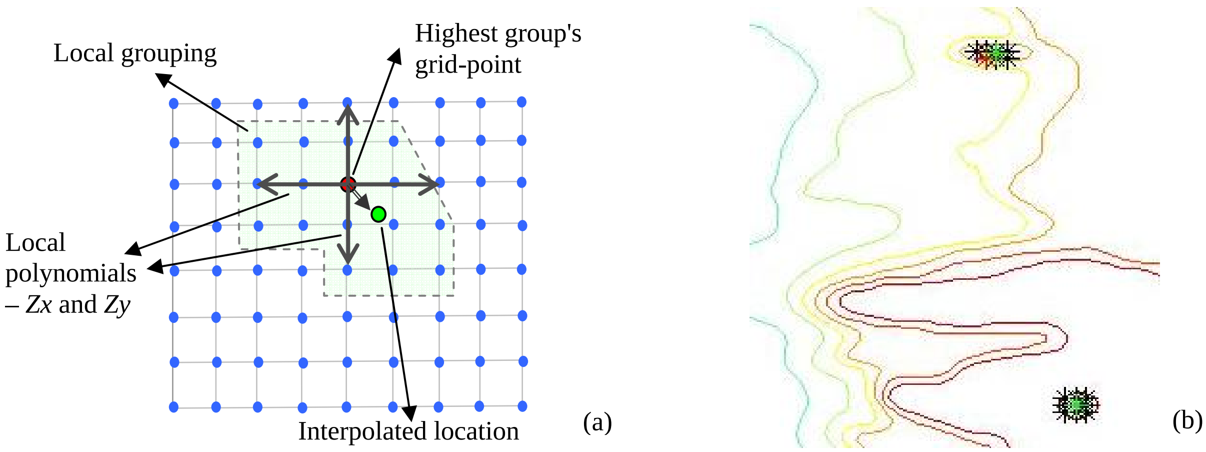


Figure 5. (a) Grid representation of a fragment from a DTM outlying grouping process and bi-directional interpolation calculation of the interest point precise location; (b) Real extraction example, where black asterisk denotes DTM grid-point, red asterisk denotes highest grid-point in group, and green asterisk denotes interpolated precise location.

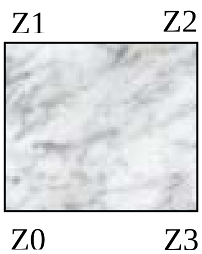
Calculation of Initial Shift Vectors

The shift vector for each congruent *msp* – *dx*, *dy*, and *dz* values - is calculated by implementing topographic registration search criteria on all interest points extracted in the previous stage. Statistical tests are implemented in this registration search process to achieve a better certainty of the three-shift values calculated.

'Local' ICP Matching

Every *msp* is sub-divided into overlapping small-sized-patches (*ssp*) – second order division (Figure 2). The assumption is that the two geo-spatial datasets represent in part or in full the same topographic structure by a 3-D point cloud: *f(x,y,z)* and *g(x,y,,z)*. A matching process is therefore designated to find the best correspondence between these datasets. The magnitude of the correspondence of the two datasets is derived from a vector error: *e(x,y,z) = f(x,y,z) - g(x,y,z)*, which include local-random errors as well as global-systematic ones. The extraction of this vector is achieved by minimizing the target function, i.e. extracting the best possible correspondence between the two datasets *f* and *g*.

A constrained ICP process is implemented locally on each congruent *ssp*, in order to extract the best correspondence between the two datasets. The constrained ICP process, as outlined in Equations 4a, 4b, and 4c, suggests a nearest neighbor search criteria process according to these three constraints: (I) the coordinates of the paired-up nearest neighbor *i* in dataset *g* (X^g_i, Y^g_i, Z^g_i), which correspond to point *i* in dataset *f*, fit a local grid-plane in dataset *g* - presented in formula (4a) (where $h_1=Z_1-Z_0$, $h_2=Z_2-Z_0$, $h_3=Z_3-Z_o$, $h_4=h_2-h_1-h_3$, and *spc* denote the grid's spacing) ; (II) the line-equation, derived from the coordinates of point *i* - *x_p*, *y_p* and *z_p* - transformed from dataset *f* to dataset *g* with the best known transformation parameters, and the paired-up nearest neighbor *i* in dataset *g* (X^g_i, Y^g_i, Z^g_i), is perpendicular to the local grid-plane in dataset *g* in *X* direction - presented in formula (4b); (III) the line-equation, derived from the coordinates of point *i* - *x_p*, *y_p* and *z_p* - transformed from dataset *f* to dataset *g* with the best known transformation parameters, and the paired-up nearest neighbor *i* in dataset *g* (X^g_i, Y^g_i, Z^g_i), is perpendicular to the local grid-plane in dataset *g* in *Y* direction - presented in formula (4c).



$$planeequation: Z^g{}_i = \frac{h_1 \cdot X^g{}_i}{spc} + \frac{h_3 \cdot Y^g{}_i}{spc} + \frac{h_4 \cdot X^g{}_i \cdot Y^g{}_i}{spc^2} \quad (4a)$$

$$plane\ slope: \frac{\partial Z^g{}_i}{\partial X} = \frac{h_1}{spc} + \frac{h_4 \cdot Y^g{}_i}{spc^2};\ line\ slope: \frac{\partial Z^g{}_i}{\partial X} = \frac{Z^g{}_i - z\_p}{X^g{}_i - x\_p};\ in\ X\ direction \quad (4b)$$

$$plane\ slope: \frac{\partial Z_i}{\partial Y} = \frac{h_3}{spc} + \frac{h_4 \cdot X^g{}_i}{spc^2};\ line\ slope: \frac{\partial Z^g{}_i}{\partial Y} = \frac{Z^g{}_i - z\_p}{Y^g{}_i - y\_p};\ in\ Y\ direction \quad (4c)$$

The initial shift vector used for each *ssp* ICP-matching is the one that corresponds to its *msp*. For each point in dataset *f* a nearest point neighbor from dataset *g* is paired-up as long as the criteria outlined above are fulfilled. Consequently, with all the pairs extracted, a local six registration-parameters calculation - three rotation angles and three shifts - is achieved. The transformation model used is shown in Equation 5a, where *M* denotes the center of mass coordinates for each congruent *ssp* in respect to the dataset (*g* or *f*), and *R* denotes the rotation matrix (Equation 5b). This process on each *ssp* is carried out iteratively until a pre-defined statistical criterion is achieved. This process yields a better localized six registration-parameters calculation, thus ensuring topographic continuity of the entire area, as well as excluding a local minima solution for the ICP process and minimizing computation time. The output of this stage is a database, a 'DTM' look like (Figure 6), assembled of six-parameter registration values corresponding to the center of mass for each congruent *ssp* index *i*.

$$\begin{bmatrix} X_g - X^M{}_g \\ Y_g - Y^M{}_g \\ Z_g - Z^M{}_g \end{bmatrix} = R(\varphi, \kappa, \omega) \bullet \begin{bmatrix} X_f - X^M{}_f \\ Y_f - Y^M{}_f \\ Z_f - Z^M{}_f \end{bmatrix} + \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix} \quad (5a)$$

$$R = \begin{bmatrix} \cos\varphi \cdot \cos\kappa & -\cos\varphi \cdot \sin\kappa & \sin\varphi \\ \cos\omega \cdot \sin\kappa + \sin\omega \cdot \sin\varphi \cdot \cos\kappa & \cos\omega \cdot \cos\kappa - \sin\omega \cdot \sin\varphi \cdot \sin\kappa & -\sin\omega \cdot \cos\varphi \\ \sin\omega \cdot \sin\kappa - \cos\omega \cdot \sin\varphi \cdot \cos\kappa & \sin\omega \cdot \cos\kappa + \cos\omega \cdot \sin\varphi \cdot \sin\kappa & \cos\omega \cdot \cos\varphi \end{bmatrix} \quad (5b)$$

Merging

The calculation of the merged geo-spatial dataset is now feasible through a merging process implemented on the entire data available: two geo-spatial datasets and the six-parameter registration database extracted earlier. This is performed iteratively by using a "reverse engineering" process on the registration values.

The process is divided into two main stages: (I) Calculating the six-registration parameters that will be used on each of the merged DTM grid-points for the two-way transformation (merged DTM to each one of the datasets). This is achieved by interpolation computation on the *ssp*'s six-registration values surrounding the point; (II) Calculating the height of the merged DTM grid-point via the "reverse engineering" process. Among other factors, this stage takes into consideration the accuracy of each dataset, which derives the average height calculated from the two datasets. The process is iterative until a certain degree of height-accuracy is achieved.

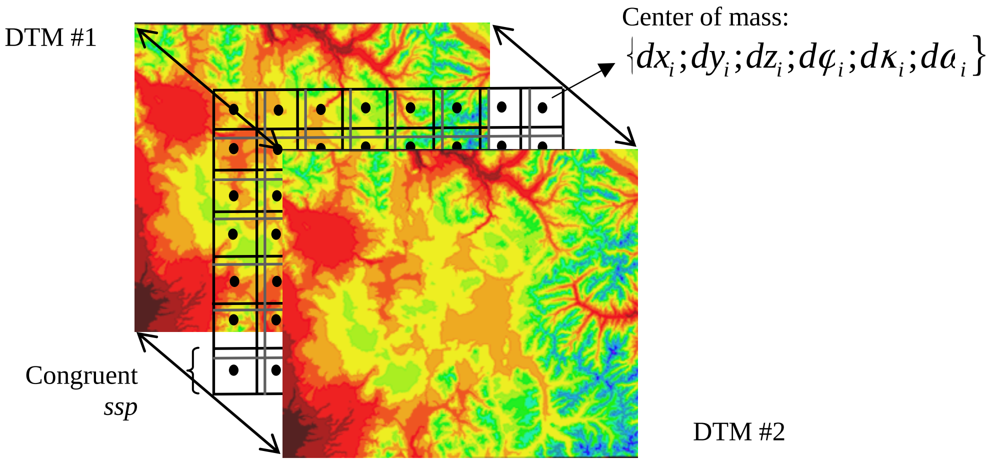


Figure 6. 'DTM' look like database representing the corresponding six-parameter registration values for overlapping congruent *ssp* zones of the two datasets.

EXPERIMENTAL RESULTS

The suggested approach was tested on different DTMs with spatial discrepancies ranging up to hundreds of meters. The interest points' extraction process proved geomorphologically to be accurate and efficient, by defining local surface-derived extremes in the topographic relief - i.e. hills and mountains (Figure 7). As can be seen from these figures the level of detailing of the two DTMs (*A* and *B*), which is mainly dependent on the resolution of the dataset, has an effect on the number of the extracted interest points. Furthermore, the precise identification of the interest points' location enabled the accurate calculation of the registration shift-vector values between the congruent *msp*s.

A merged DTM, based on an averaging procedure of different geo-datasets, will always ensure that a comparison of the height differences between any of the original datasets and the merged DTM will be smaller than the differences between the original datasets themselves. Nevertheless, the quality of a merged DTM can be examined and measured by the preservation of morphologic entities of the terrain, represented by the datasets. This criterion can be examined visually, by inspecting the merged DTM and the datasets used for its calculation. Figure 8 presents a segment from the two original datasets – *A* and *B* – and merged DTM. As can be seen from this figure, monitoring local spatial discrepancies and finalizing with the implementation of the constrained 'local' ICP and merging processes, the algorithm yielded very good results in terms of topographic accuracy and topographic topology of the merged DTM. The merged DTM presented in this figure is unified and continuous throughout the area of the datasets, and the examination of the morphologic structures represented showed that the merged dataset described the surface correctly.

DISCUSSION

When discussing the problem of merging geo-spatial DTM datasets, considering the necessity of the merging procedure itself has to be done. In the case of one dataset that is with much better accuracy and level of detailing than the other - in most cases the better one will be chosen as the correct terrain representation - while ignoring the inferior one. But still, one has to remember that the common situation is when the two datasets have 'similar' level of detailing and accuracy while having some local or global discrepancies. In that situation, the merging procedure of the two datasets must preserve the internal morphology, and thus achieve a more accurate and reliable representation of the terrain, than any of the two datasets separately.

The implementation of the new pyramidal approach and algorithms for DTM datasets merging, described here, ensures the preservation of local geometric features and their topological relations while preventing any distortions. In most cases the solution outlined here is reliable and accurate. Though, in extreme geometric conditions, such as major discrepancies or even no correspondence, or in case of very smooth surfaces, the attempt to extract the registration-values might lead to a wrong result. This fact will probably lead to a biased solution given by the ICP matching process that hence will divert to local minima instead to an implicit one. These cases are very rare, and the suggested solution in most cases will result in a satisfactory solution of the merged DTM.

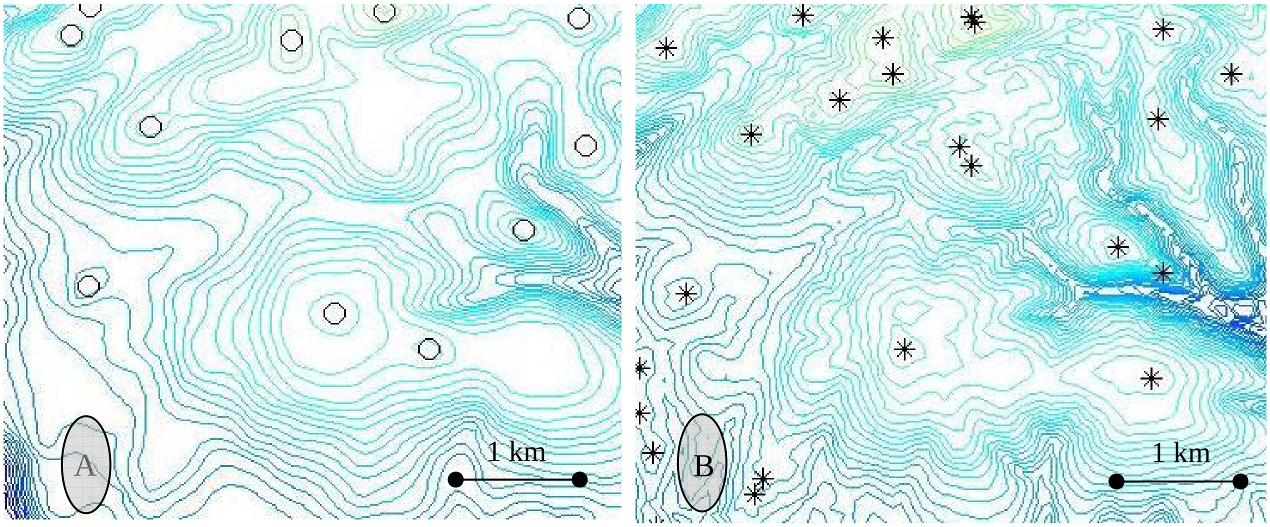


Figure 7. Extraction of interest points in both DTMs, showing effective results in identifying and extracting local geomorphologic surface-derived points.

By implementing separate levels of working-data, the pyramidal approach described here, enables monitoring local discrepancies, which exist locally among different DTM geo-datasets. This approach is in contrast to the frequent used merging procedure, in which one global transformation, derived from the entire data, is implemented. Using this global transformation in the merging procedure might lead to ignoring or 'smearing' any local geomorphologic-features. So, the implementation of this new pyramidal procedure yields obtaining unified and continuous representation of the terrain relief, while preserving the internal morphology, and thus achieve a more accurate and reliable representation of the terrain relief.

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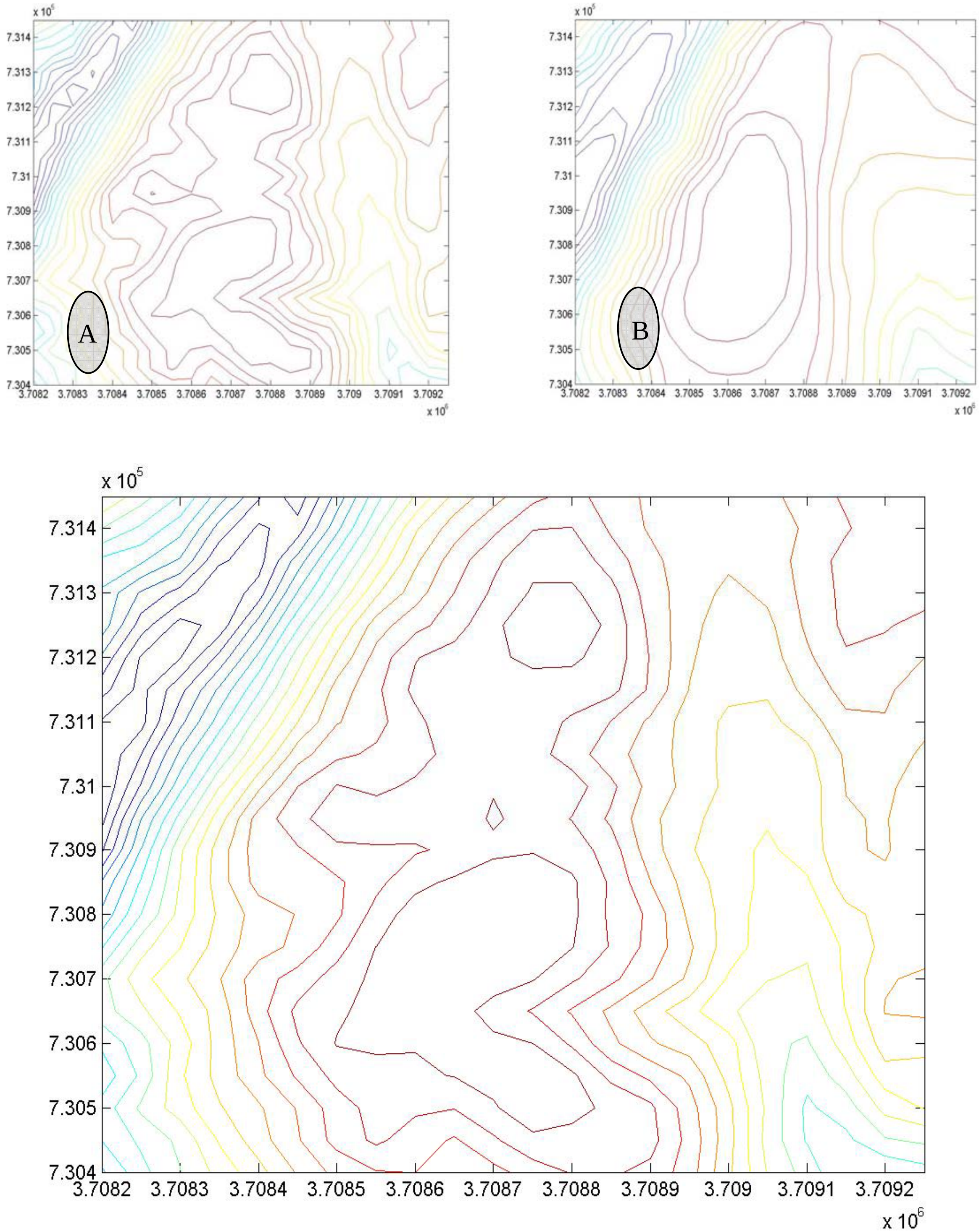

Merged DTM

Figure 8. A segment of two DTMs – A and B – and the merged DTM.