Multi-sourced 3D Geospatial Terrain Modelling: Issues and Challenges

Prof. Dr. Yerach Doytsher

Mapping and Geo-Information Engineering,
Technion, Israel

Presentation Contents

- Introduction
- Problems and issues
- Adjacent datasets
- Overlapping datasets
- Accuracies
- Summary

Introduction

DTMs origin and main concepts:

1. Originated 50 years ago: …"a statistical representation of the continuous ground surface… defined by a large selected number of points"…[1]
2. "Boosted-up" thanks to the development of groundbreaking computerized analytical systems - mainly GIS systems (20-30 years ago).
3. A quantitative and qualitative mathematical model that describes our natural environment – "real world".
4. Usually presented in a grid format with X, Y, Z coordinates.
5. Main concepts needed to be addressed are: accuracy; descriptive realism; precision; robustness; generality; (and, simplicity).

[1] Miller and LaFlamme, 1958

Introduction

The importance of DTMs:

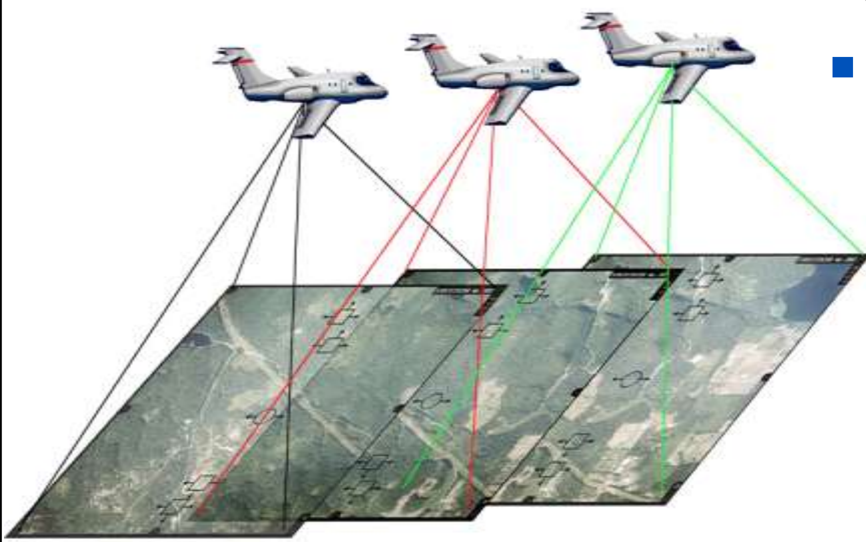
A variety of applications in the military, environmental, engineering, and geo-sciences domains:

- Civil engineering, including cut-and-fill projects and 3D landscape modelling and visualization tasks;
- Earth sciences, including modelling and analysis of geo-morphologic terrain entities for hydrologic and hazards maps;
- Planning and resource management, including remote sensing, environmental and urban planning;
- Remote sensing and mapping, including correcting images, retrieve thematic information, georeferencing;
- Military applications, including inter-visibility analysis, 3D visualization, simulations, line-of-sight;

Introduction

DTMs from different sources and of various qualities:

<u>'Traditional' data acquisition</u>



<u>Photogrammetry</u>: utilizes stereo pairs of aerial or space imagery that cover approximately the same area

- Mostly produce a grid DTM (raster like)
- DTM presents constant resolution
- Height accuracy is usually constant within a specific campaign
- Probably the most common technique nowadays

Introduction

DTMs from different sources and of various qualities:

'Traditional' data acquisition

Field Surveying: utilizes TS and GPS receivers for direct field measurements

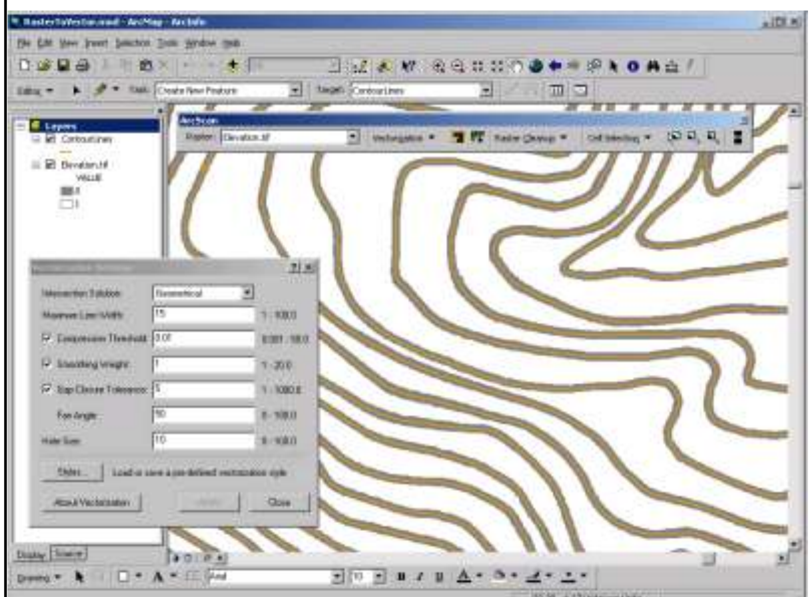
- Accuracy of a position acquired extremely high
- Deliver much fewer data samples
- Used to measure and map small areas
- Technique is rarely used for DTM production
- Can deliver missing data other techniques can not measure
- Typified by irregular and sparse position of sample data

Introduction

DTMs from different sources and of various qualities:

'Traditional' data acquisition

Cartographic digitization and scanning: utilizes raster vectorization techniques of existing topographic/contour maps



- Semi-manual digitization and quality assurance are sometimes required
- Available in off-the-shelf GIS packages
- Height accuracy is usually constant
- Mostly produces irregular data samples (contour)
- Was commonly used for DTM production – nowadays mainly in developing regions via utilizing medium-scale maps

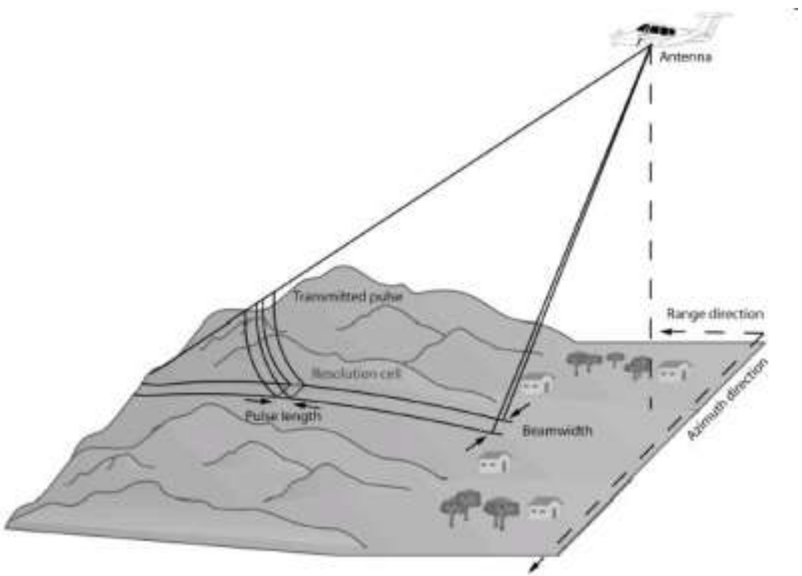
Introduction

DTMs from different sources and of various qualities:

<u>'Modern' data acquisition</u>

<u>Radar based systems</u>:
utilizes radargrammetry techniques and IfSAR imaging

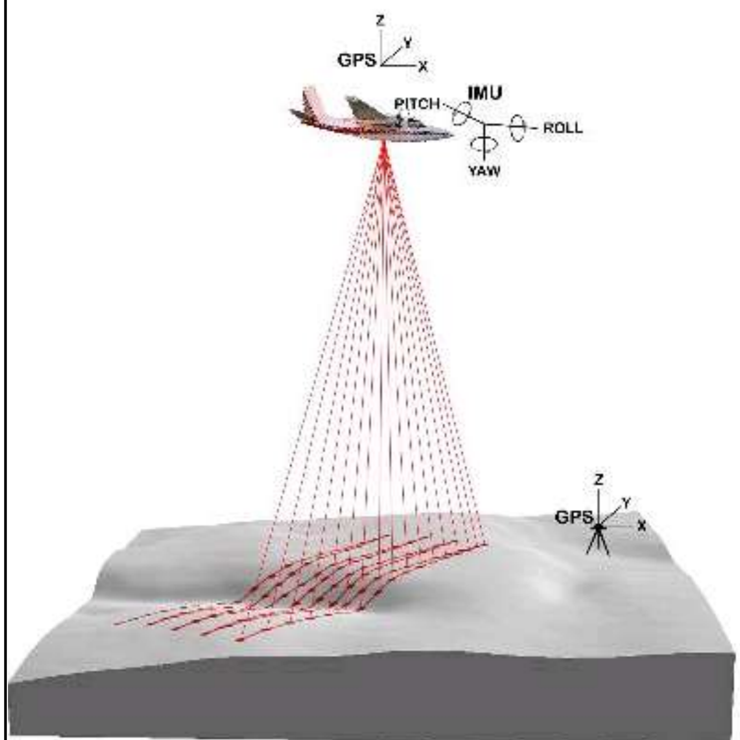
- **Radar imagery are very sensitive to terrain variations**
- **Large accuracy deviations sometimes exist**
- **Height accuracy within a DTM is usually constant**
- **Efficient for acquiring data of large regions**
- **Not affected by the lack of sun light and extreme meteorological conditions**
- **DTMs produced are mostly regular**



Introduction

DTMs from different sources and of various qualities:

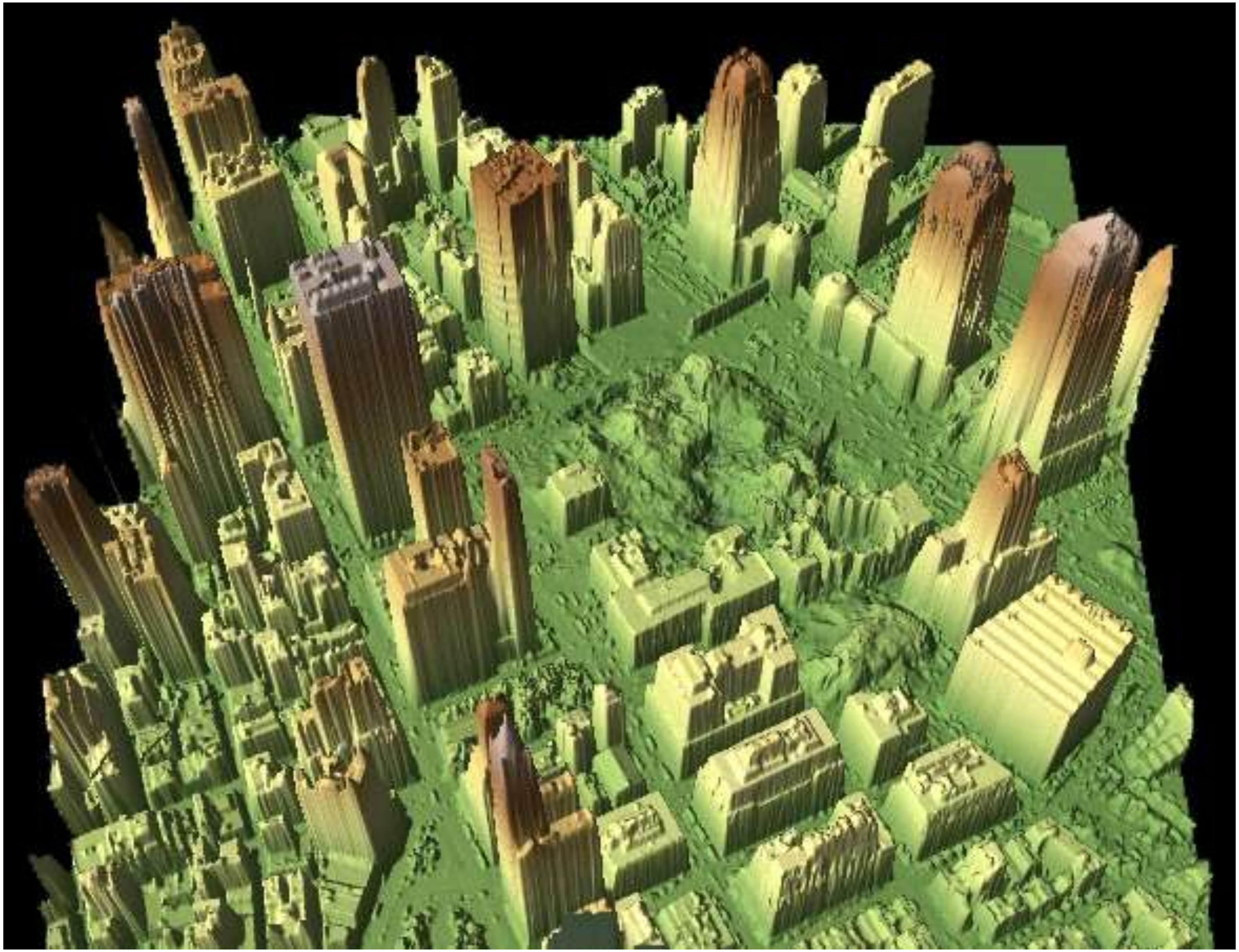
'Modern' data acquisition



ALS (LiDAR) Systems: utilizes laser ranging techniques for producing 3D point cloud

- Randomly distributed data (irregular)
- Data sample is already geo-referenced
- Accuracy of a position acquired is high
- Efficient for acquiring data of medium-sized regions
- Not affected by the lack of sun light
- DTM production requires additional algorithms - filtering, interpolation - usually performed on the raw data (raw/sample data include off-terrain objects - vegetation and buildings)
- Produces the densest DTMs

A LiDAR Sample



Introduction

Wide coverage DTMs from different sources and of various qualities: vertical accuracy assessment

Technique/Technology	Vertical Accuracy (m)
Aerial photogrammetry	0.1 – 1
Satellite photogrammetry	1 – 10
Field surveying	0.01 – 0.1
Digitization	1/3 of contouring interval
Aerial radargrammetry	2 – 5
Satellite SAR inteferometery	1 – 10
LiDAR	0.1 – 0.2

Problem Definition

- DTM applications require that:
  - Elevation models utilized are free of gaps;
  - No discontinuities exist in the models;
- Overlapping terrain databases will usually present:
  - Diverse sources and data-formats;
  - Differences in their density and/or accuracy;
  - Topographic inconsistencies;
- Consequently – integrating these models via common GIS systems will show:
  - Incomplete terrain description;
  - Require full mutual coverage of both models (will not complete missing data);

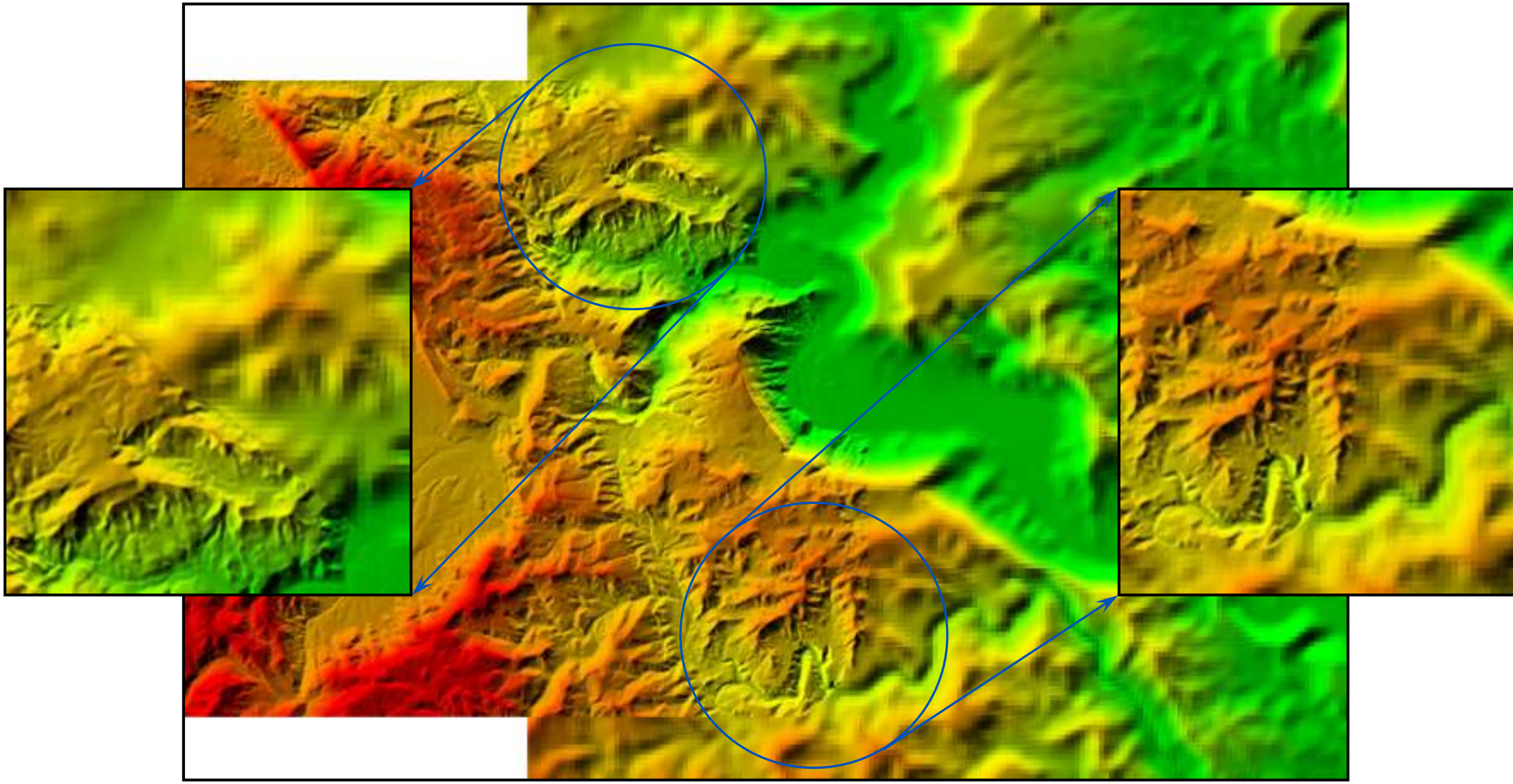
Problem Definition

- **Merging overlapping/adjacent DTM models is aimed at:**
  - Achieving complete and continuous representation of the terrain;
  - Provide continuous height and topological representations;
  - Construct a gap-free DTM;
- **Generic integration algorithms development is aimed at:**
  - Indicated aforementioned, as well as;
  - Integrating/updating topographic datasets – not influenced by their inner structure (grid, tin, etc.);
  - Preserving morphologies presented by both datasets;
  - Presenting up-to-date and continuous topography;

Multi-datasets: Challenges

- Fusion of two (or more) DTMs:
  - Coordinate-based vs. Feature-based relative geo-referencing
  - Fusion of adjacent DTMs vs. overlapping DTMs
- Aspects of non-uniformity within the DTMs:
  - Different resolutions;
  - Different coordinate systems (Cartesian vs. Geographical)
  - Levels of accuracy within the same DTM
- Comparison of separate DTMs:
  - Identifying terrain changes (landslides for example)
  - A multi-datasets approach toward determining absolute accuracy of DTMS

Problem Definition – Adjacent DTMs



Two adjacent DTM models each presenting different density.

Problem Definition

Common algorithm types aimed at DTM integration:

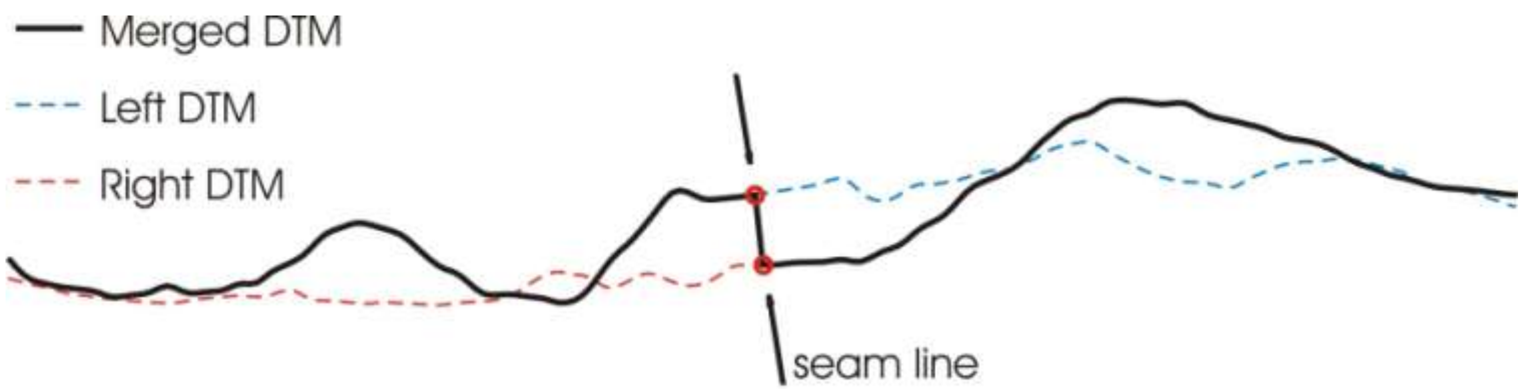
- **"Cut & Paste":**
  - The less accurate model is replaced with the more accurate one in the overlapping zones.

- **"Height Smoothing":**
  - Heights within a band (buffer) surrounding the models mutual seam line are calculated as weighted average of the heights taken from the two adjacent DTMs.

Both algorithms address only the height issue representation of the terrain, and not its characteristics – topology and morphological structures.

Problem Definition

Cut & Paste:

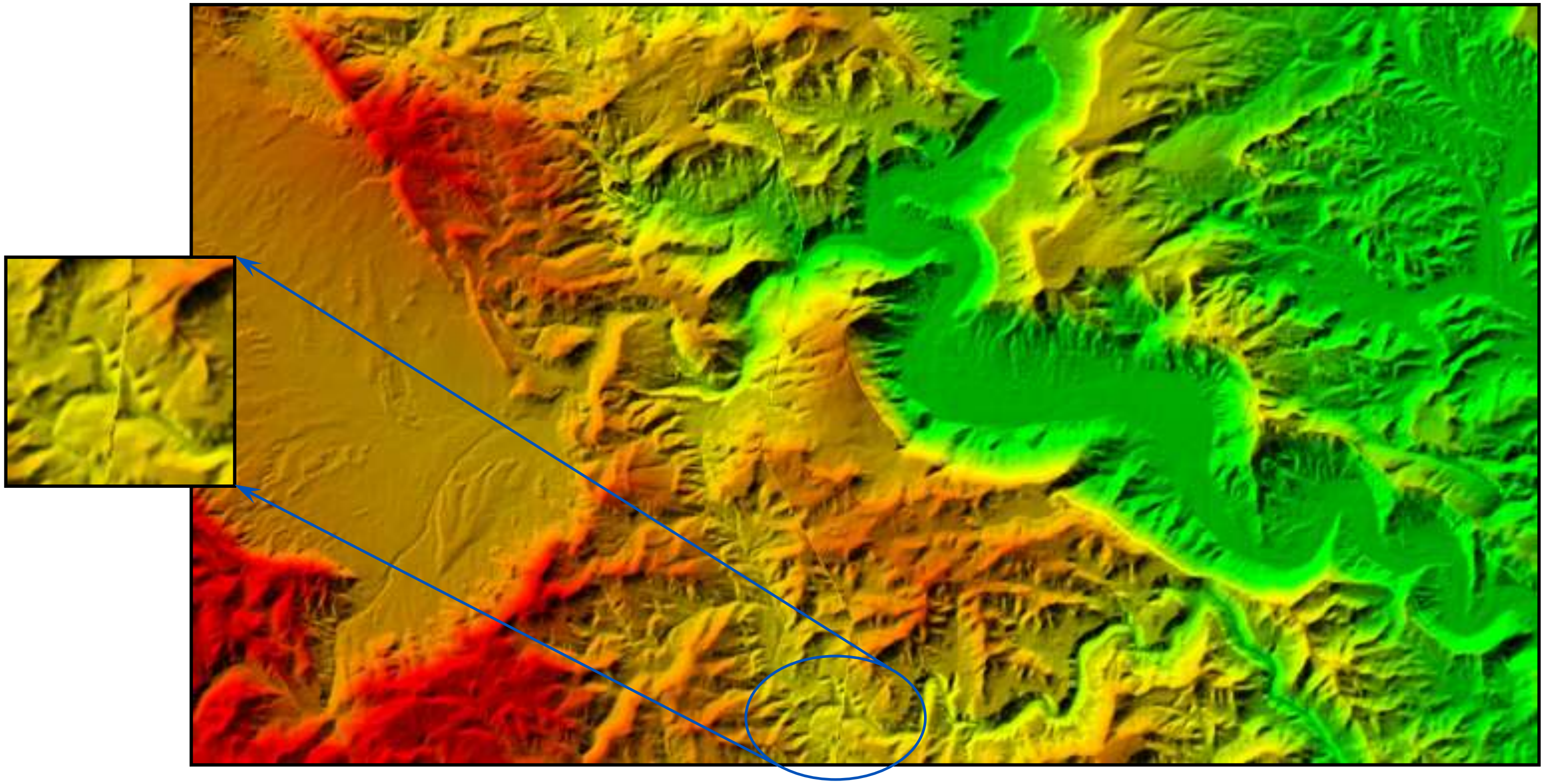


Main features:

- The left side zone of the seam line is taken from the left DTM and the right side zone of the seam line is taken from the right DTM;
- The seam line becomes a line of discontinuity in the merged DTM;
- No morphological adjustments are performed;
- No accuracy adjustments are performed;

Problem Definition

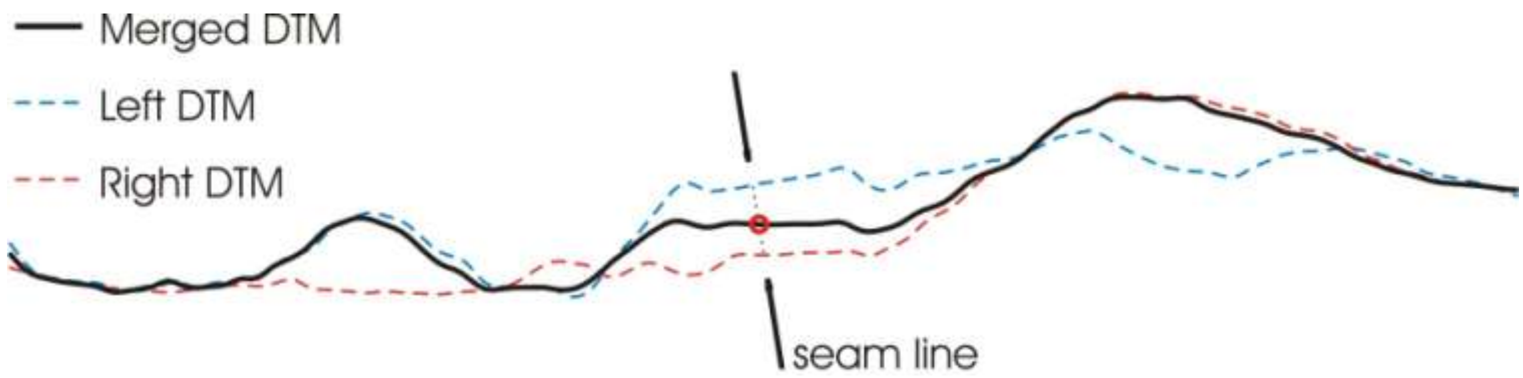
Cut & Paste:



- The seam line is clearly seen as a line of discontinuity;
- Terrain structures within the band surrounding the seam line may appear more than once in the merged DTM;

Problem Definition

Height Smoothing

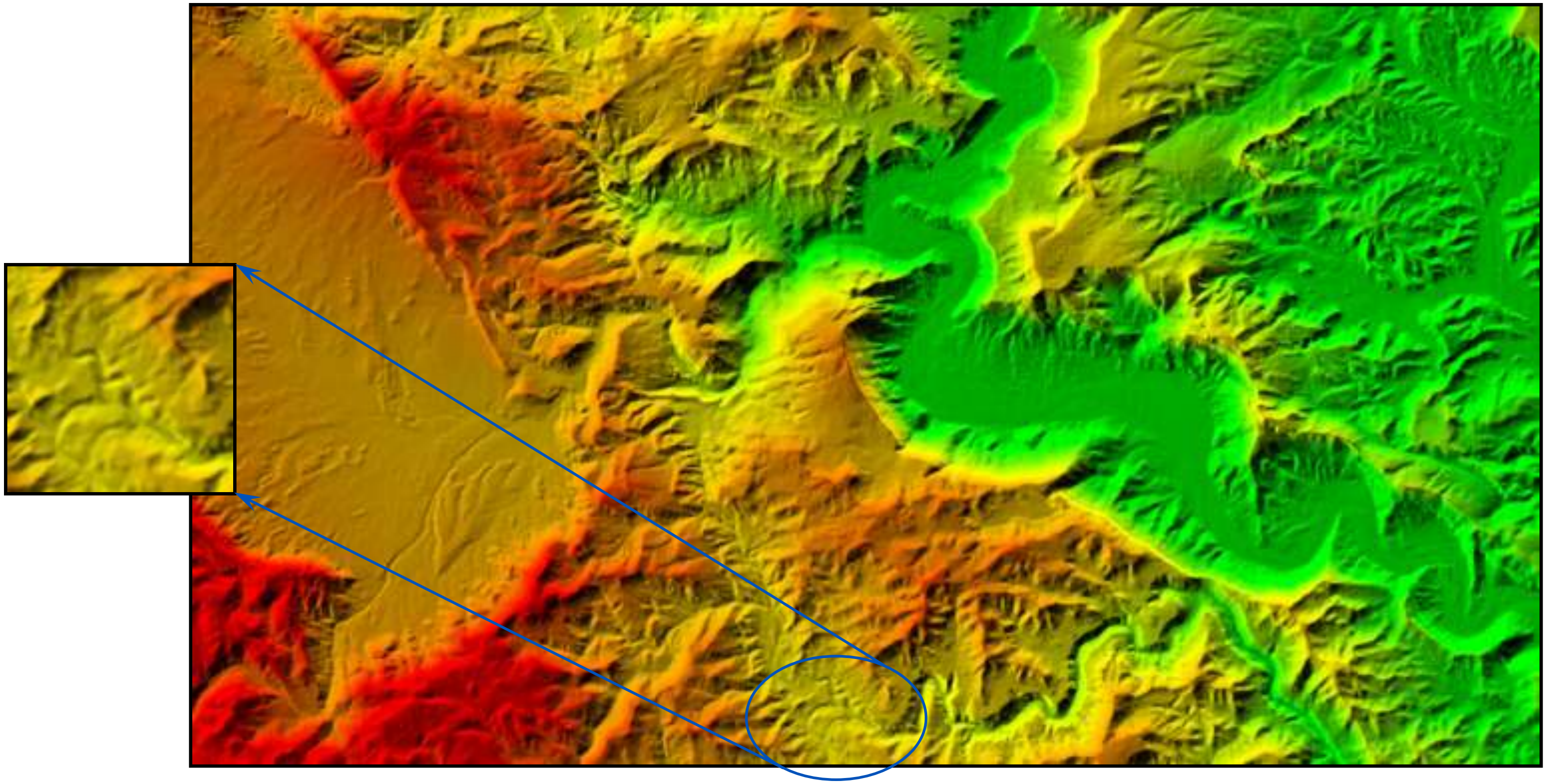


Main Features:

- Heights in the band surrounding the seam line are calculated as weighted average of the heights taken from both adjacent DTMs.
- The seam line becomes a line of continuity in the merged DTM.
- No morphological adjustments are performed. Terrain structures within the band surrounding the seam line may appear more than once in the merged DTM.

Problem Definition

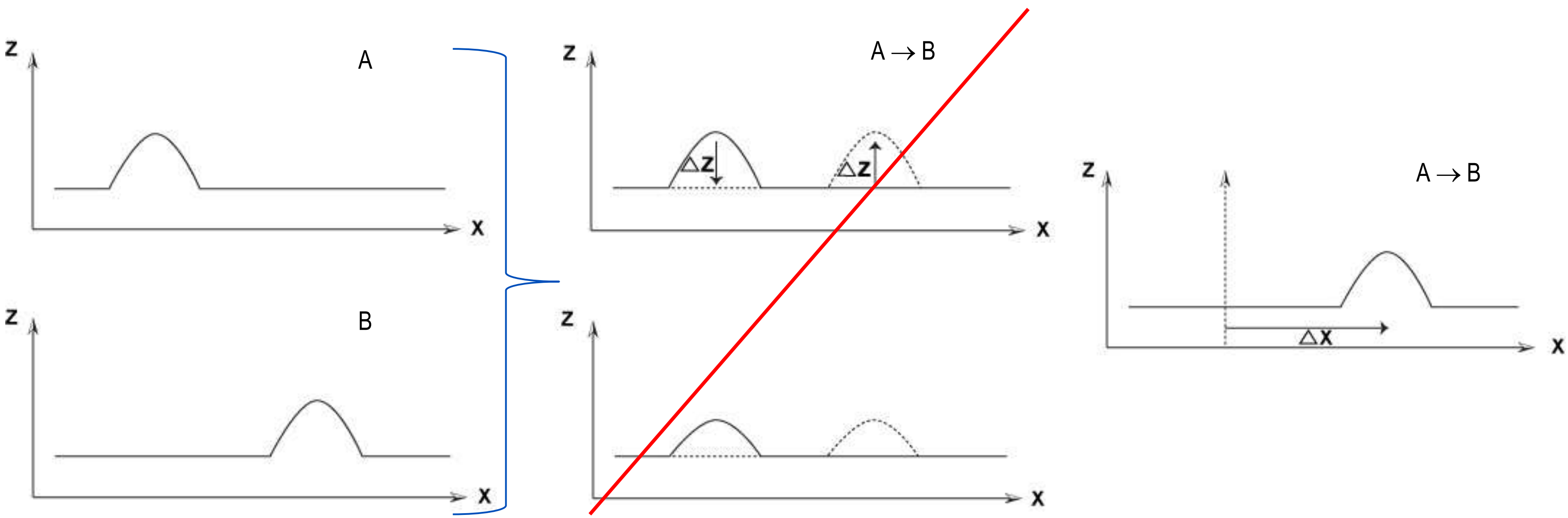
Height Smoothing



- The seam line is hardly visible.
- Terrain's topology and morphological structures are not preserved.

Overlapping Approaches

- **Coordinate-based vs. feature-based overlapping**
  - **Coordinate approach → duplication of topographic features**
  - **Feature-based → accurate geo-referencing**



Proposed Algorithms and Processes

3 Different Approaches (Algorithms)

- Adjacent DTMs
  - Spatial Rubber Sheeting Algorithm
  - Piecewise Spatial Conflation Algorithm
- Overlapping DTMs
  - Hierarchical Modelling and Integration Algorithm

Adjacent DTMs - Rubber Sheeting

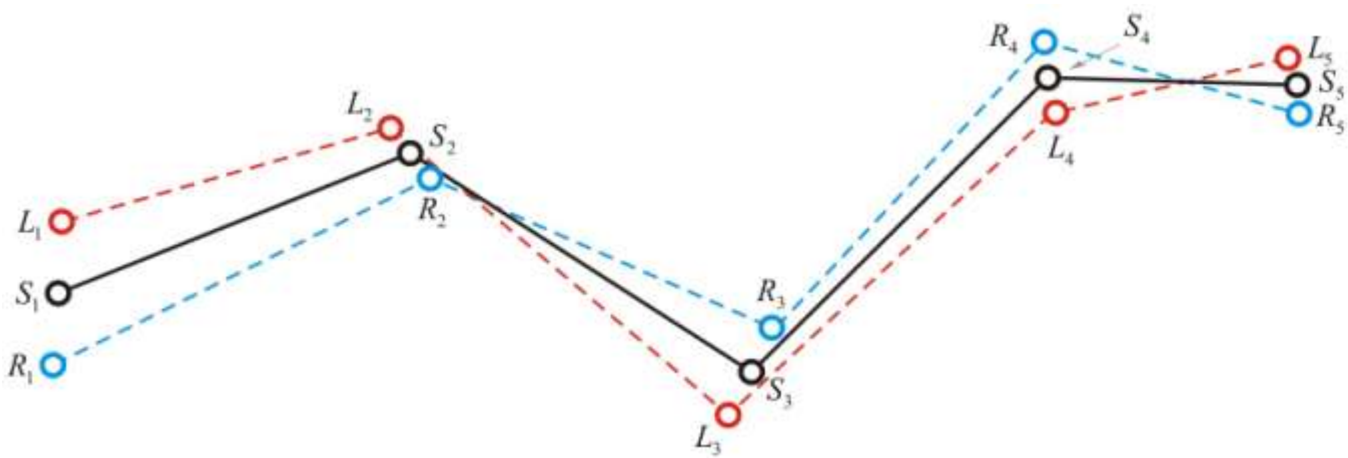
(A) Spatial Rubber Sheeting Algorithm

1. Global geometric correction of one of the adjacent DTMs toward the other DTM by a three-dimensional affine transformation based on a given set of homologous point pairs.
2. Seam line construction is based on the given set of homologous point pairs.
3. Rubber band construction surrounding the seam line.
4. Local geometric correction by morphing the rubber band of each of the adjacent DTMs to the seam line on the merged DTM.

Adjacent DTMs - Rubber Sheeting

(A) Spatial Rubber Sheeting Algorithm

2. Seam Line Construction:

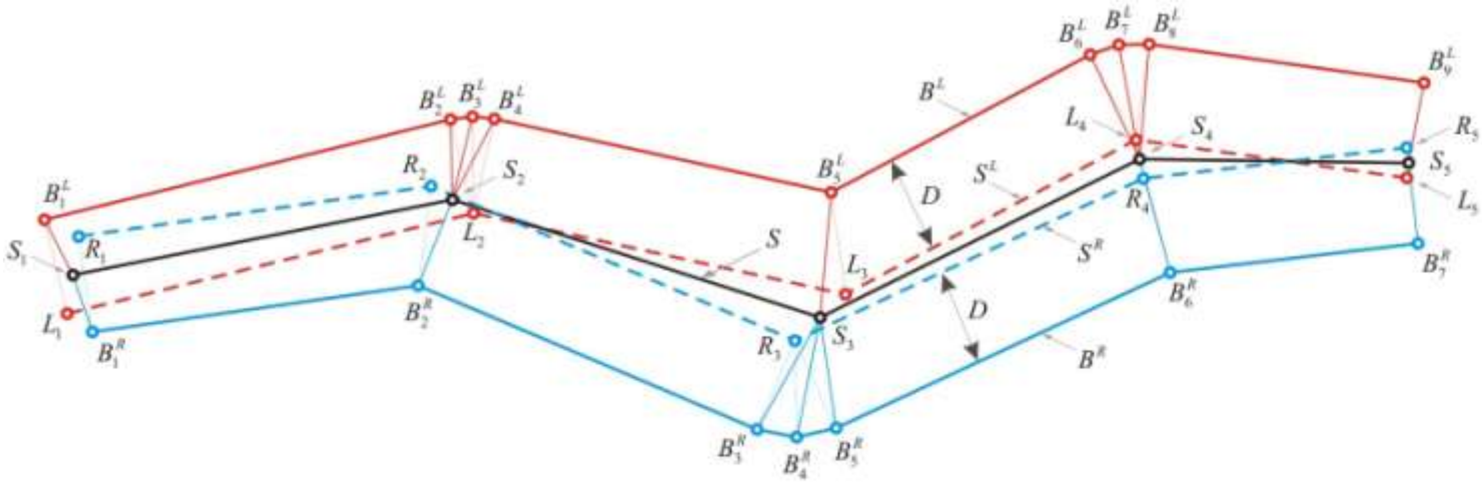


- The seam line *S* is constructed using a given set of homologous point pairs.
- Each vertex of the seam line is a weighted average (X,Y,Z) of a homologous point pair.

Adjacent DTMs - Rubber Sheeting

(A) Spatial Rubber Sheeting Algorithm

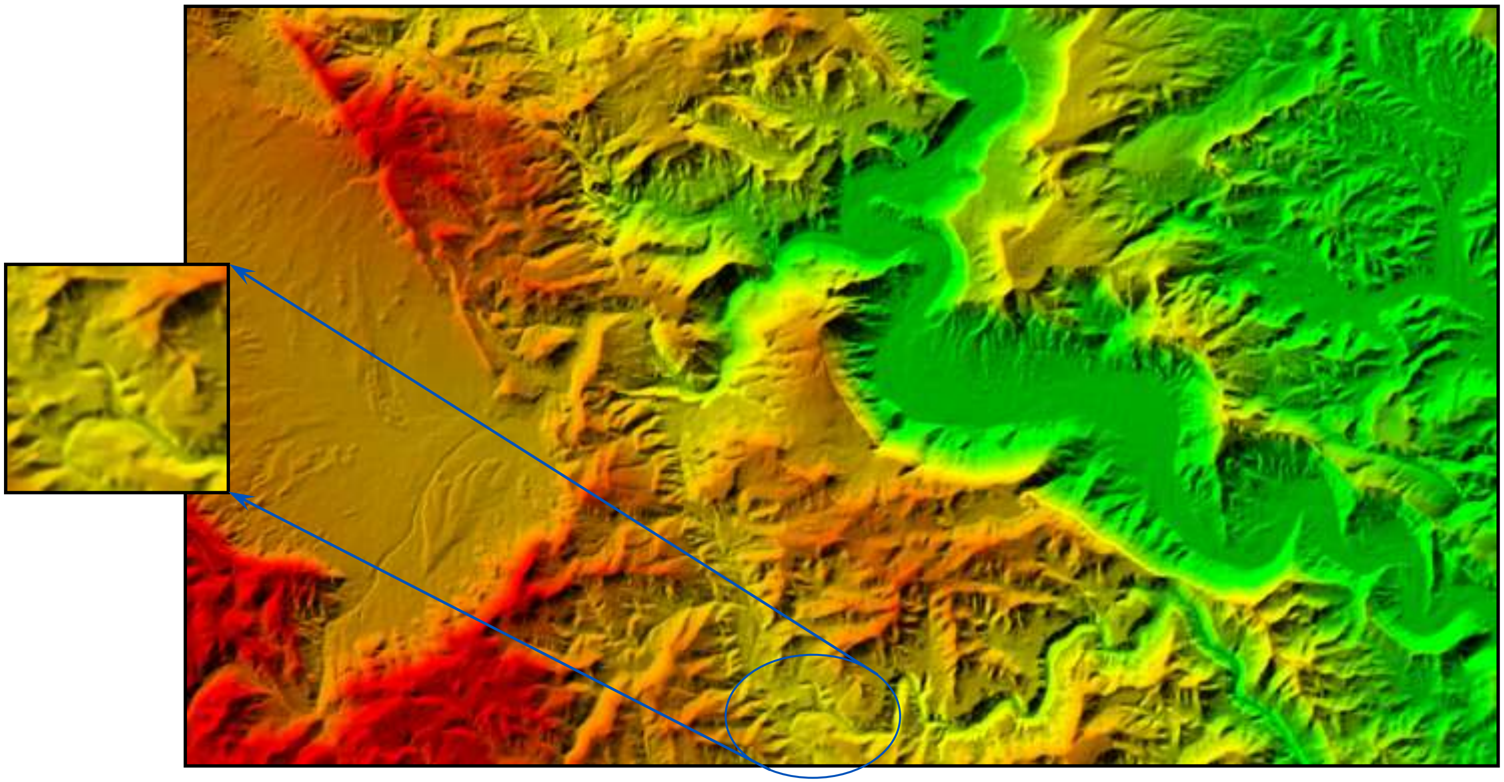
3. Rubber band construction:



- A rubber band is defined by a parallel polyline to the right or left of the seam line at a given distance *D*.
- Two rubber band quadrilateral grids are defined. One on the source DTM and the other on the target DTM.

Adjacent DTMs - Rubber Sheeting

(A) Spatial Rubber Sheeting Algorithm – Results:



- The seam line turns out to be a line of continuity in the merged DTM and it is invisible.
- Terrain's topology and morphological structures are preserved.

Adjacent DTMs - Piecewise Conflation

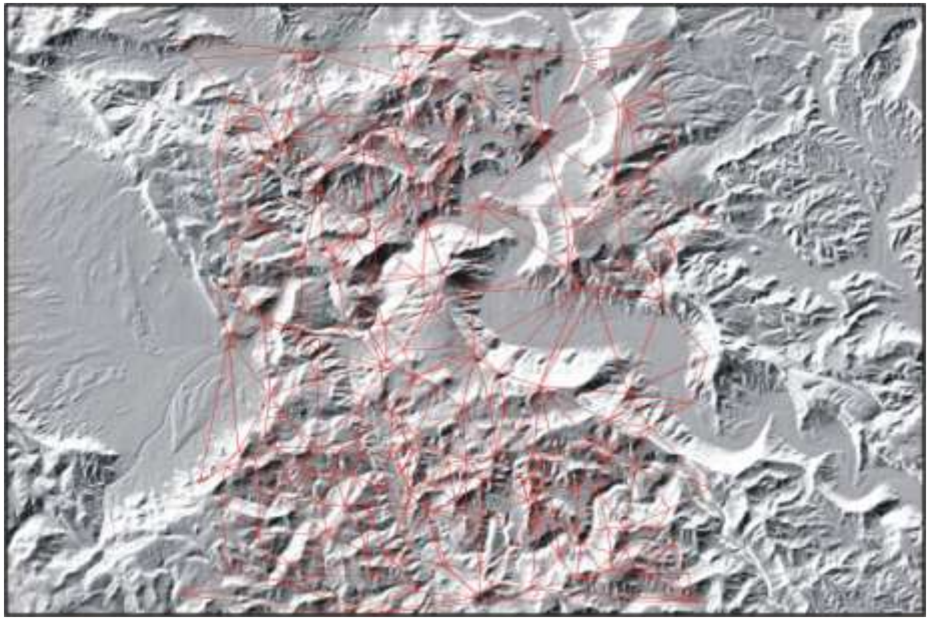
(B) Piecewise Spatial Conflation

1. Global geometric correction of one of the adjacent DTMs toward the other DTM by a three-dimensional affine transformation based on a given set of homologous point pairs.
2. Triangulation of the overlapping region based on the given set of homologous point pairs.
3. Local geometric correction by morphing each of the adjacent DTMs to the merged DTM coordinate system.

Adjacent DTMs - Piecewise Conflation

(B) Piecewise Spatial Conflation

2. Triangulation of the overlapping region:

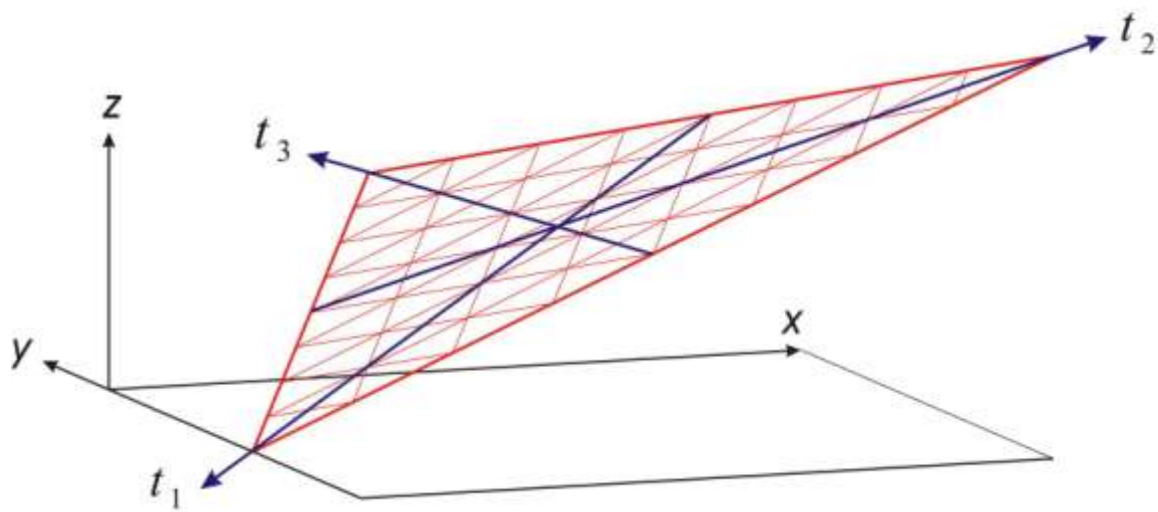


- The triangulation is constructed using Constraint-Delauny-Triangulation algorithm (CDT) given a set of homologous point pairs.
- Two triangulations are constructed, one for the left DTM and the other for the right DTM.

Adjacent DTMs - Piecewise Conflation

(B) Piecewise Spatial Conflation

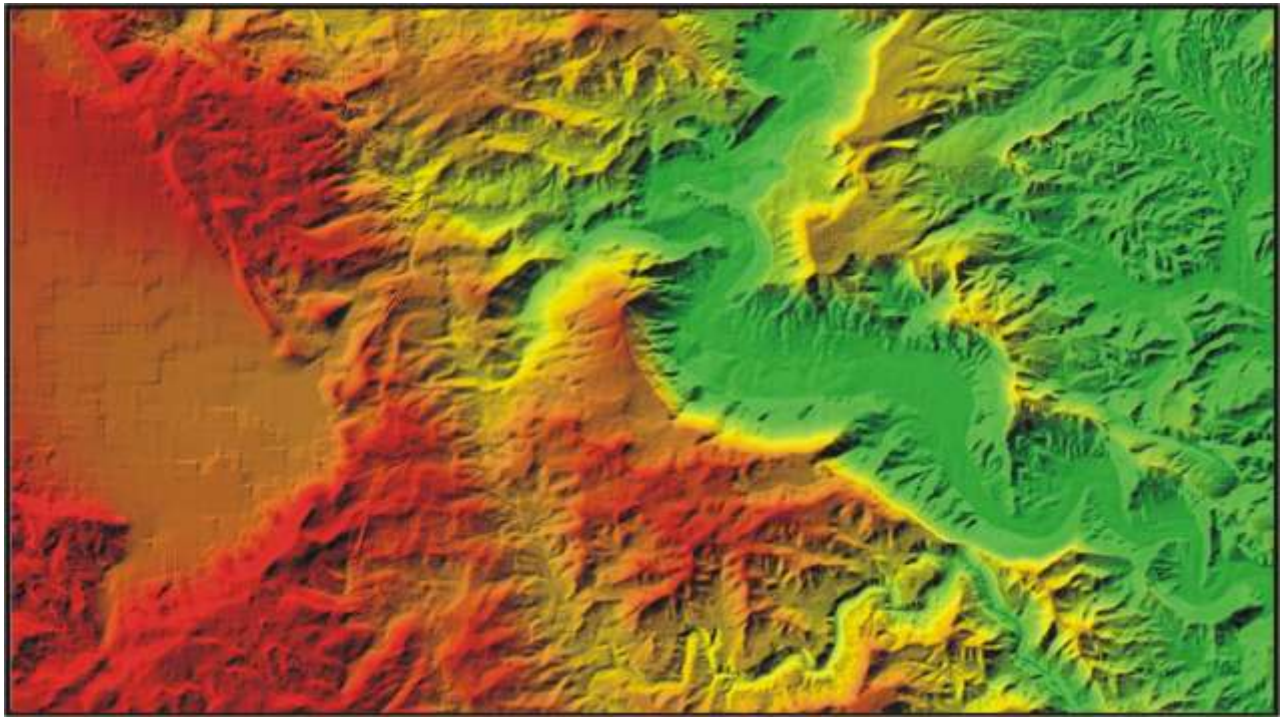
3. Target triangulation construction:



- The geometry of the triangular interpolation preserves linearity of the edges.
- Interpolation of a point on an edge of two adjacent triangles yields the same value in each of these two triangles.

Adjacent DTMs - Piecewise Conflation

(B) Piecewise Spatial Conflation – Results:



- A smooth transition from one source DTM to the other.
- No discontinuities in the merged DTM.
- Terrain's topology and morphological structures are preserved.

Proposed Algorithms and Processes

(C) Hierarchical Modelling and Integration

1. Global registration – homologous interest points extraction and mutual geo-referencing.
2. Local Iterative Closest Point matching algorithm & extraction of modelling matrix.
3. Integration based on geo-registration values stored in the modelling matrix and designated interpolation algorithms.

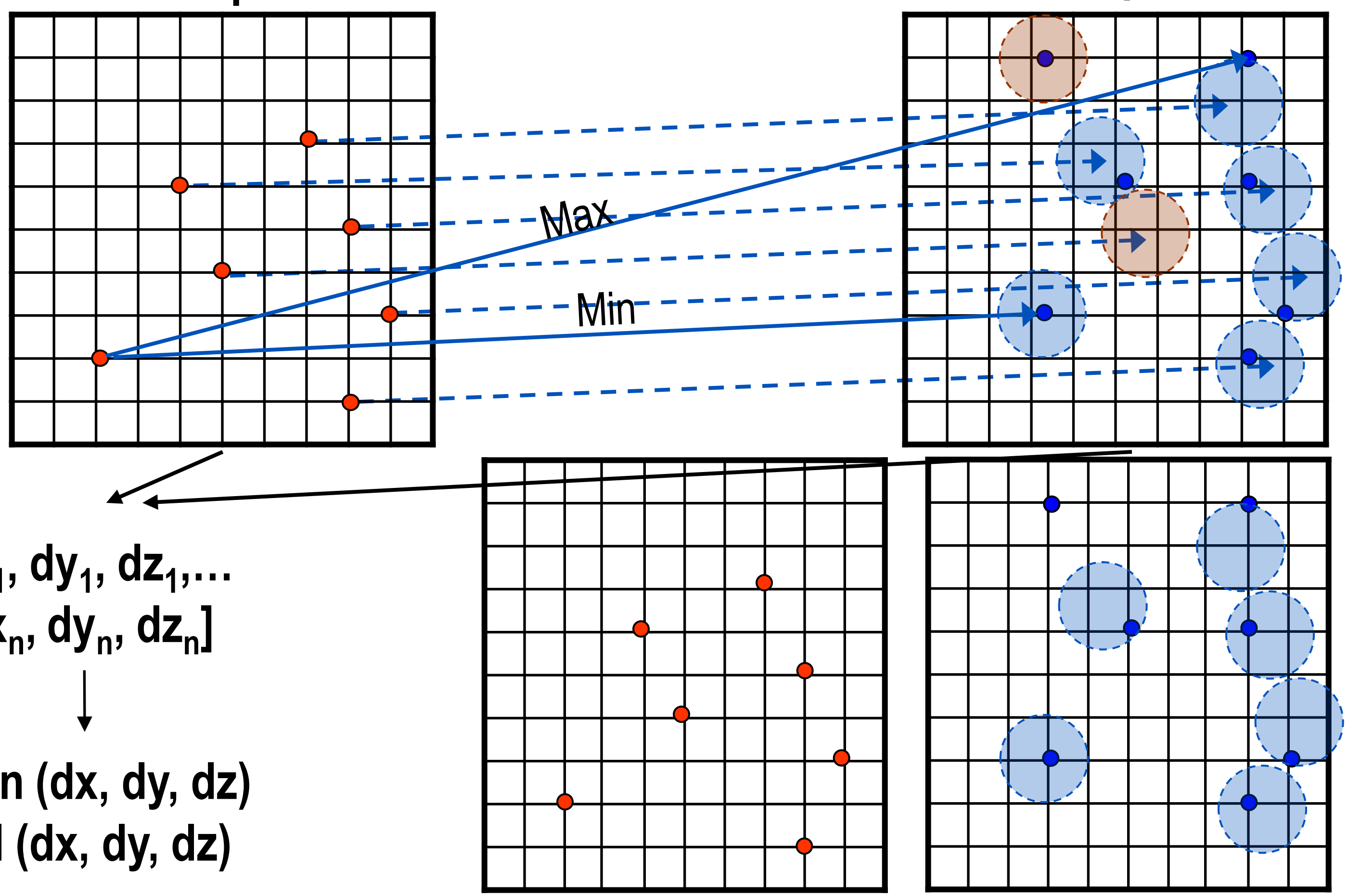
Proposed Algorithms and Processes

(C) Hierarchical Modelling and Integration

1b. Spatial geo-referencing - forward Hausdorff distance

$$h(A,B) = \max_{a \in A} \min_{b \in B} \| a - b \|$$

Interest points *a* **Interest points *b***



$[dx_1, dy_1, dz_1, \ldots, dx_n, dy_n, dz_n]$

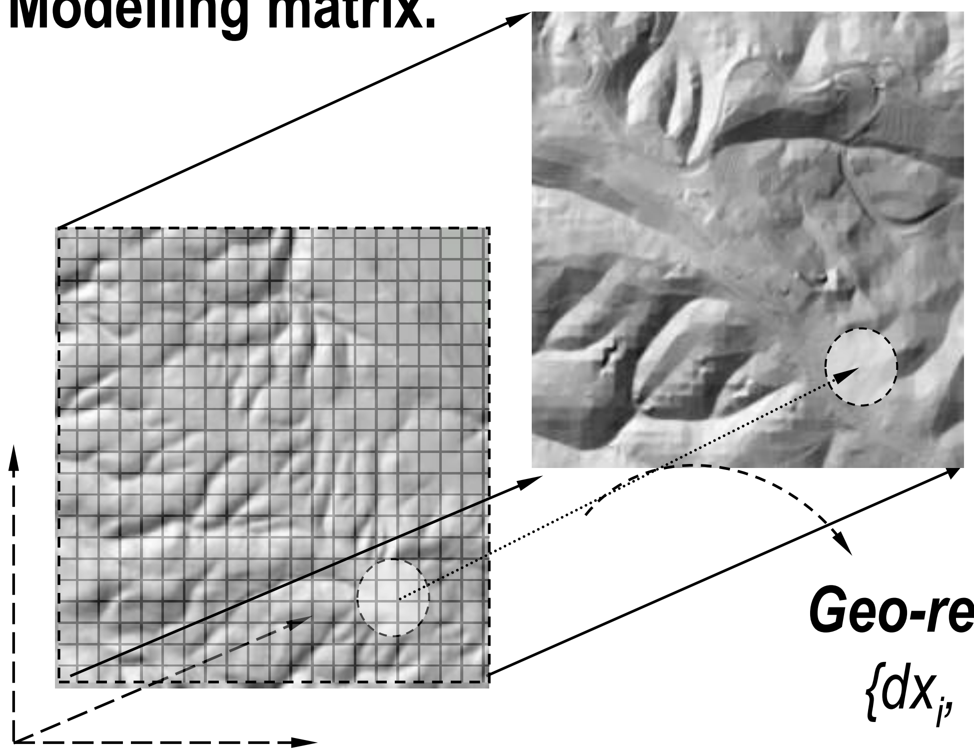
↓

Mean (dx, dy, dz)
Std (dx, dy, dz)

Proposed Algorithms and Processes

(C) Hierarchical Modelling and Integration

2b. Modelling matrix.



Geo-registration vector

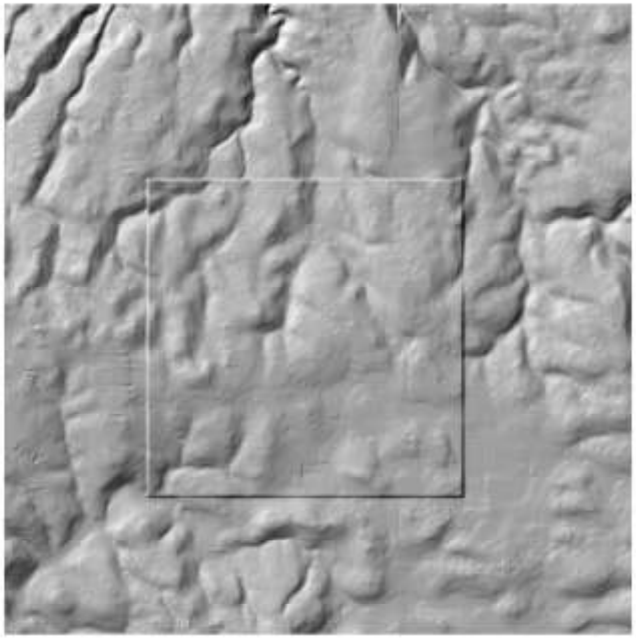
$\{dx_i,\ dy_i,\ dz_i\ \varphi_i,\ \kappa_i,\ \omega_i\}$

- Establishing a geo-spatial matrix (GeoDB) that stores the precise zonal modelling.
- Continuities modelling in the mutual coverage area.

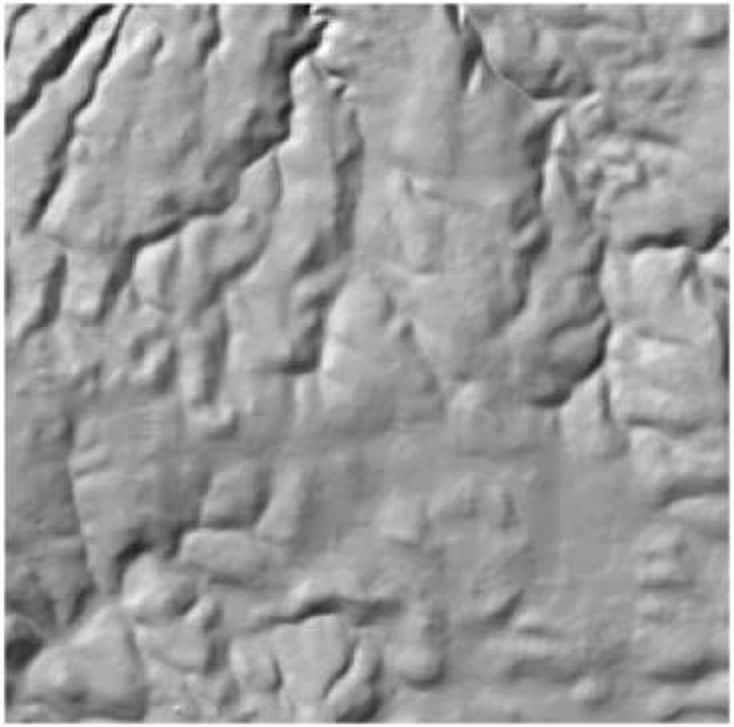
Proposed Algorithms and Processes

(C) Hierarchical Modelling and Integration – Results:

Cut & Paste:



Hierarchical Modelling:



- No seam line is visible.
- Gapless and continuities terrain relief representation in the merged DTM.
- Terrain’s topology and morphological structures are preserved.

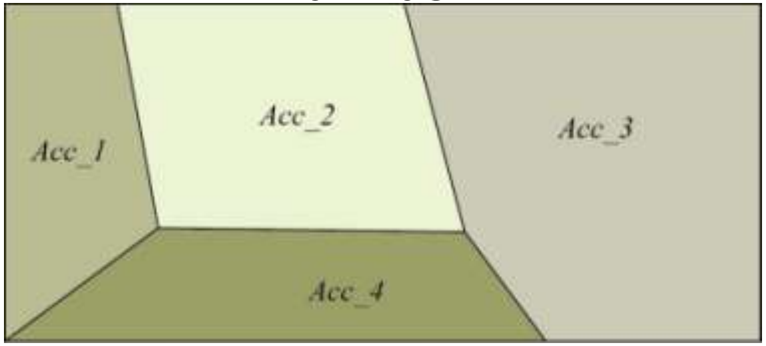
Consideration of Levels of Accuracies

Need - integration of DTMs is essential for obtaining computerized topographic infrastructure.

Status - multi-source DTM:

- Produced via various technologies and techniques;
- Influenced/affected by rapid data-updates.

Accuracy polygon map



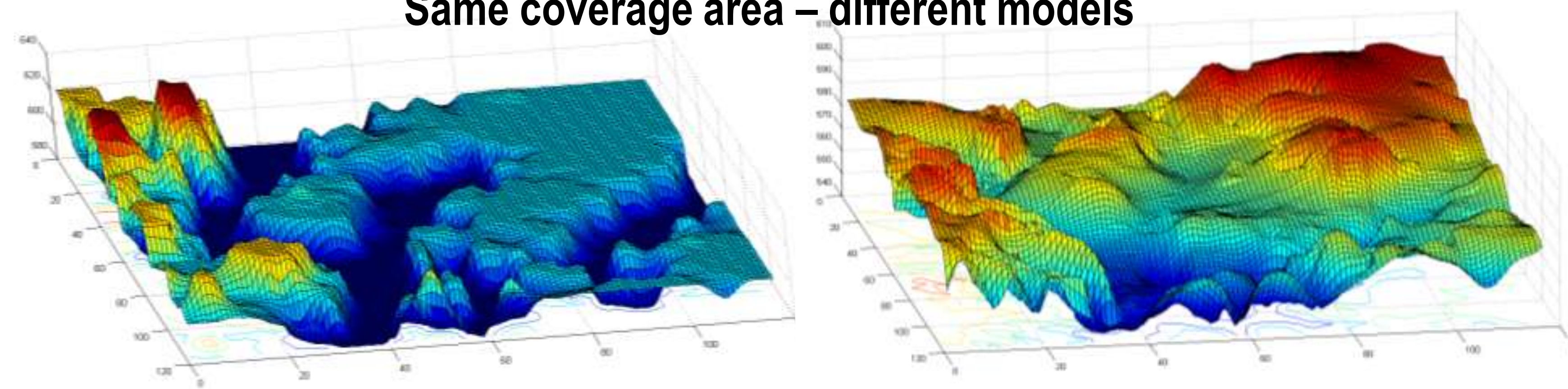
Result – integrated DTM might present:

- Changing qualities and precisions of coverage area;
- Varied data characterizations and structures;
- Different magnitude of internal data-relations and correlations.

Problem Definition

Different DTMs can vary and present different data-characterizations: structure, data-density, level-of-detail, accuracy, resolution, datum, …

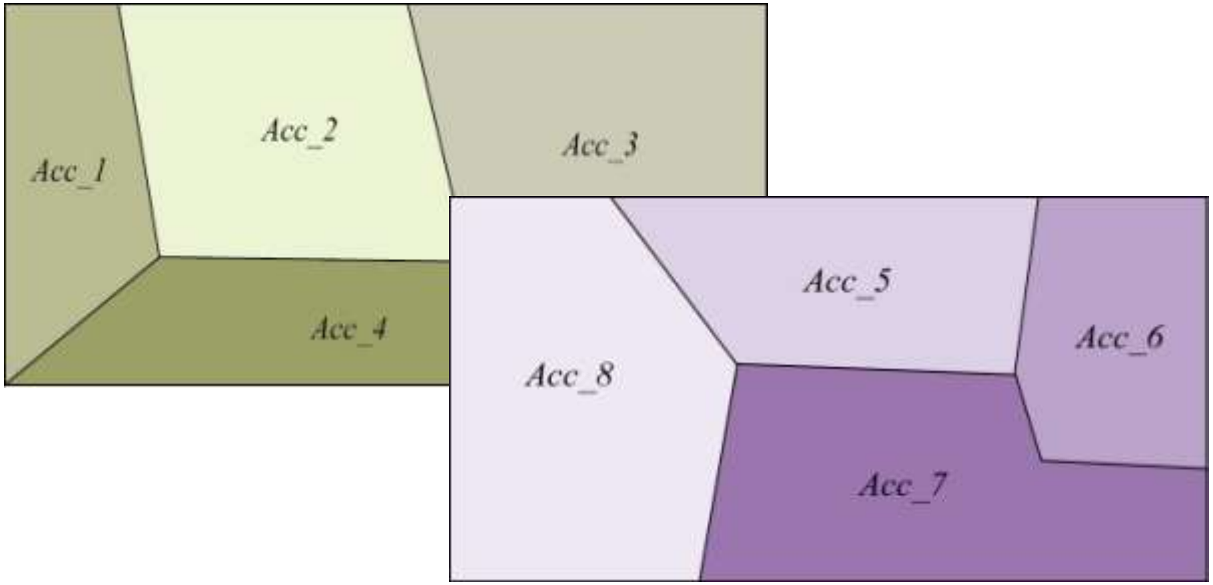
Same coverage area – different models



- Varied-scale geometric discrepancies and inconsistencies – different acquisition epochs and diverse data-sources;
- Global-systematic incongruity and local-random inaccuracies;
- Different magnitude of internal data-relations and correlations has to be addressed.

Problem Definition

Simultaneous use of several multi-source DTMs introduce, such as integration or change detection, intensifies the before mentioned problem.



Thus, It is essential to a-priori extract and quantify a reliable spatial modeling of DTMs' correlations

Problem Definition

- **Reliable integration (fusion) of multi-source DTMs is required to:**
  - **Apply morphologic and accuracy adjustments thus spatial modeling is assured;**
  - **Provide continuous height and topological representation;**
  - **Address locally the varied irregularities and inaccuracies that exist within the DTM and between DTMs;**
  - **Ensure continues and semantic modeling.**
- **All this while taking into account the local accuracies in separate sub-regions**

Proposed Algorithm

Implementing a hierarchical modeling algorithm:

Phase 0 – producing smooth and continuous accuracy polygons maps.

Phase 1 – Global registration (mutual frame work):

- Identification and extraction of topographic unique interest points;
- Spatial mutual quality-dependent skeletal registration.

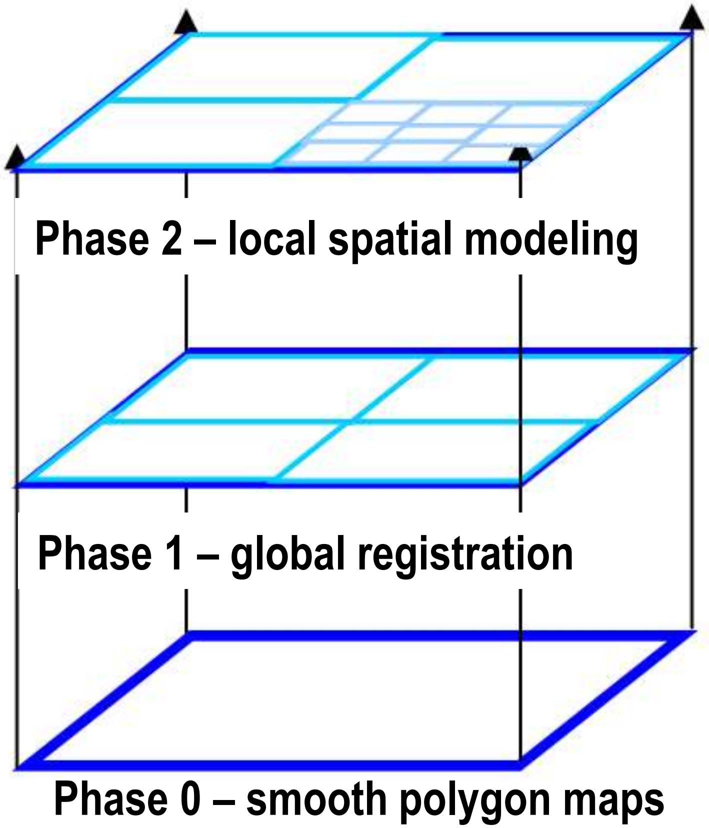
Phase 2 – Spatial modeling and matching:

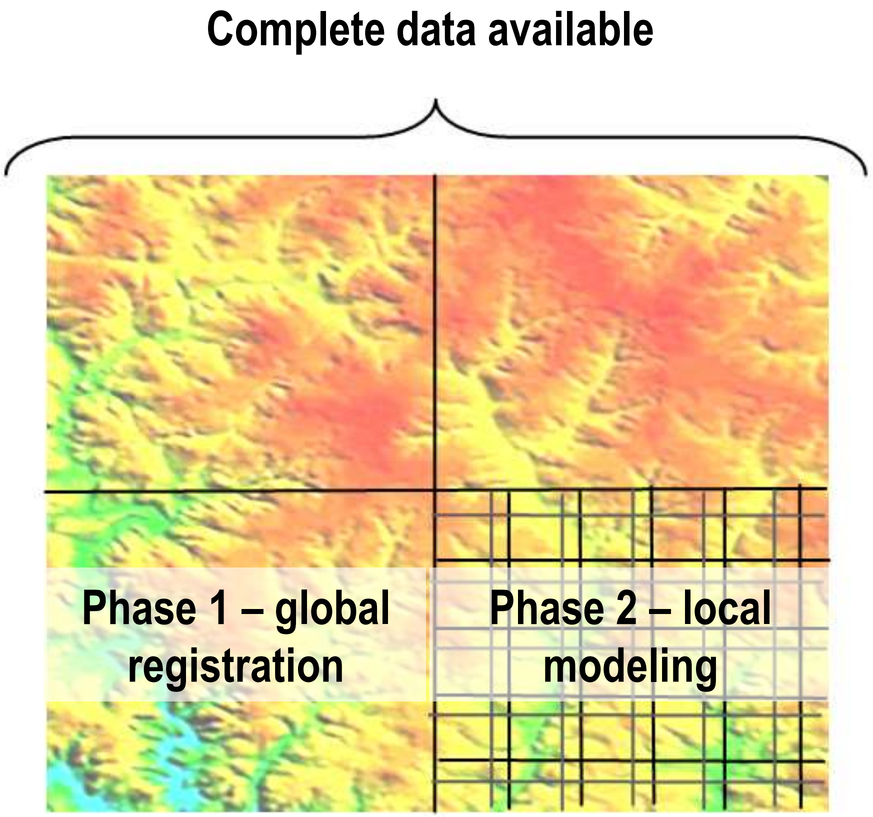
- Quality-dependent local Iterative Closest Point (ICP) matching;
- Establishment of mutual modeling matrix.

Phase 3 – integration:

- Designated data-handling interpolation concepts;
- Quality-dependent height calculation of integrated DTM - continuous, seamless and homogenous.

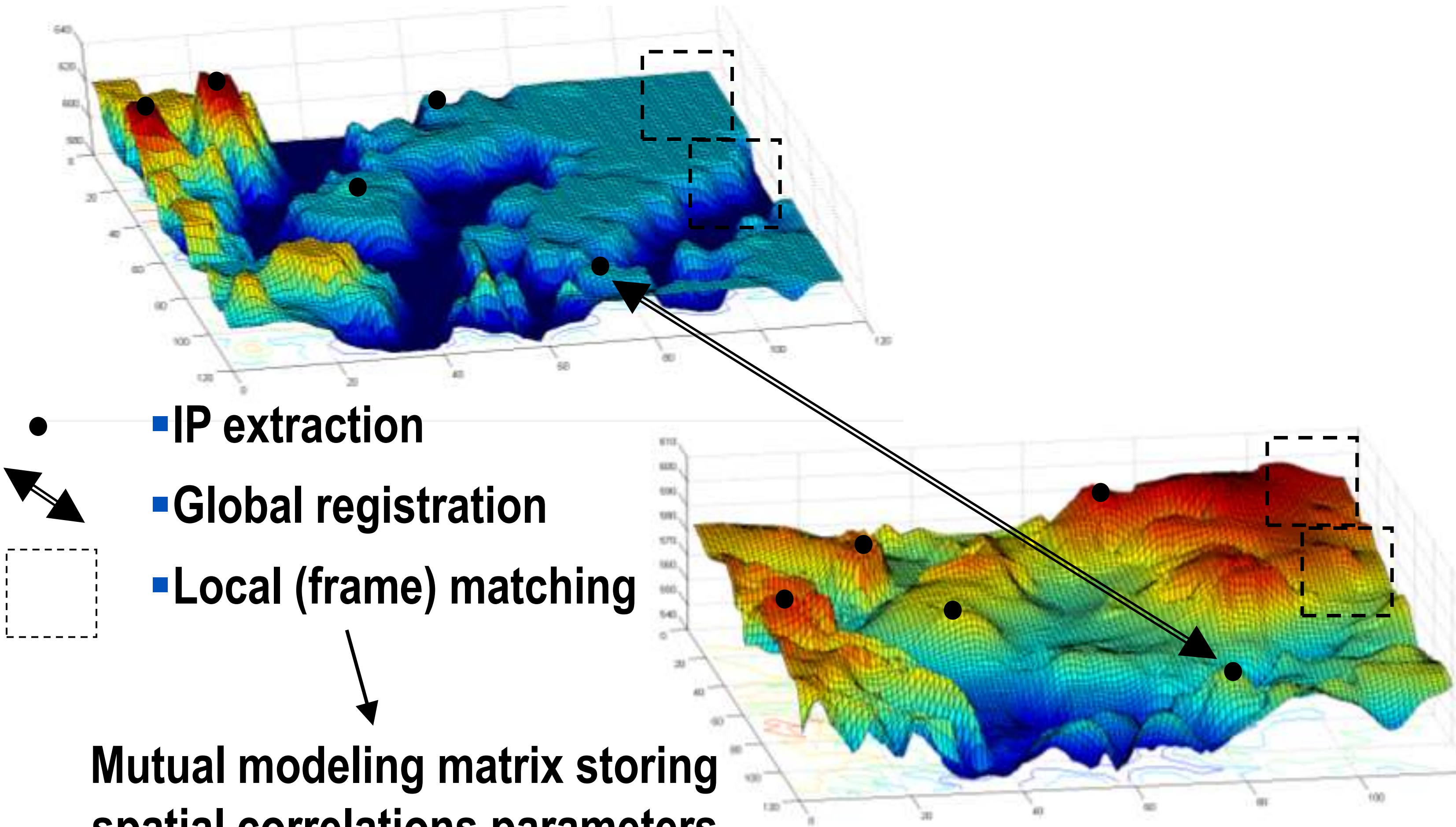
Proposed Algorithm





Proposed Algorithm

Schematics of hierarchical mechanism:

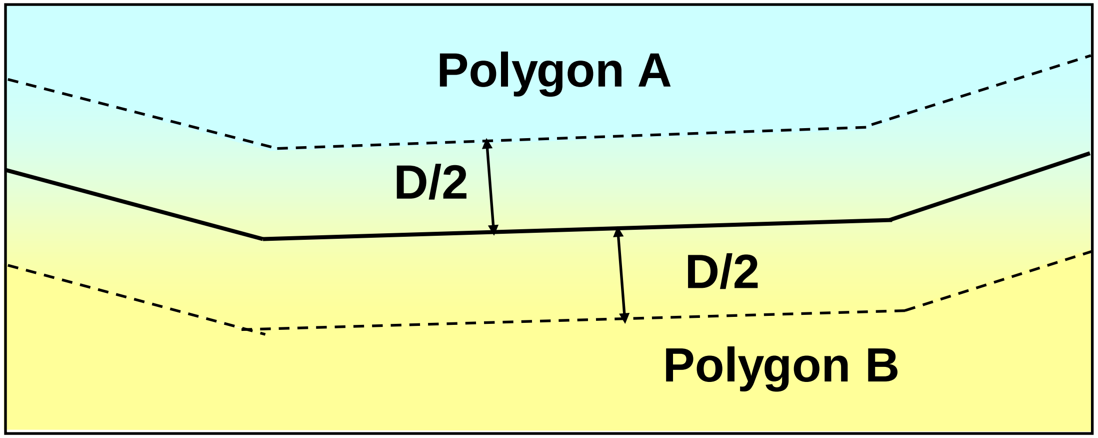


- IP extraction
- Global registration
- Local (frame) matching

Mutual modeling matrix storing spatial correlations parameters

Proposed Algorithm – Phase 0

Producing smooth and continuous accuracy polygon map:

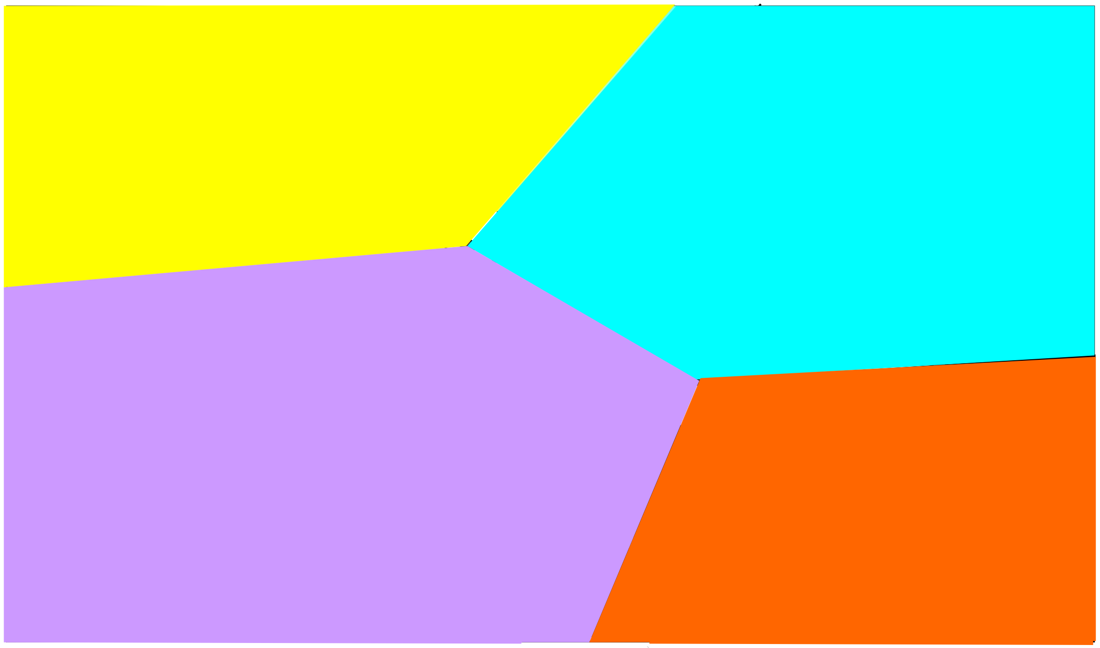


Automatic process that generates this information:

- Topologic relations extraction of geometric objects that comprise the accuracy polygon map: polygons – polylines – vertices (nodes);
- Vertices topology indexing: map borders; two polylines; three polylines; etc.;
- Buffer width (D) required for given joint polylines (derived by accuracy difference).

Proposed Algorithm – Phase 0

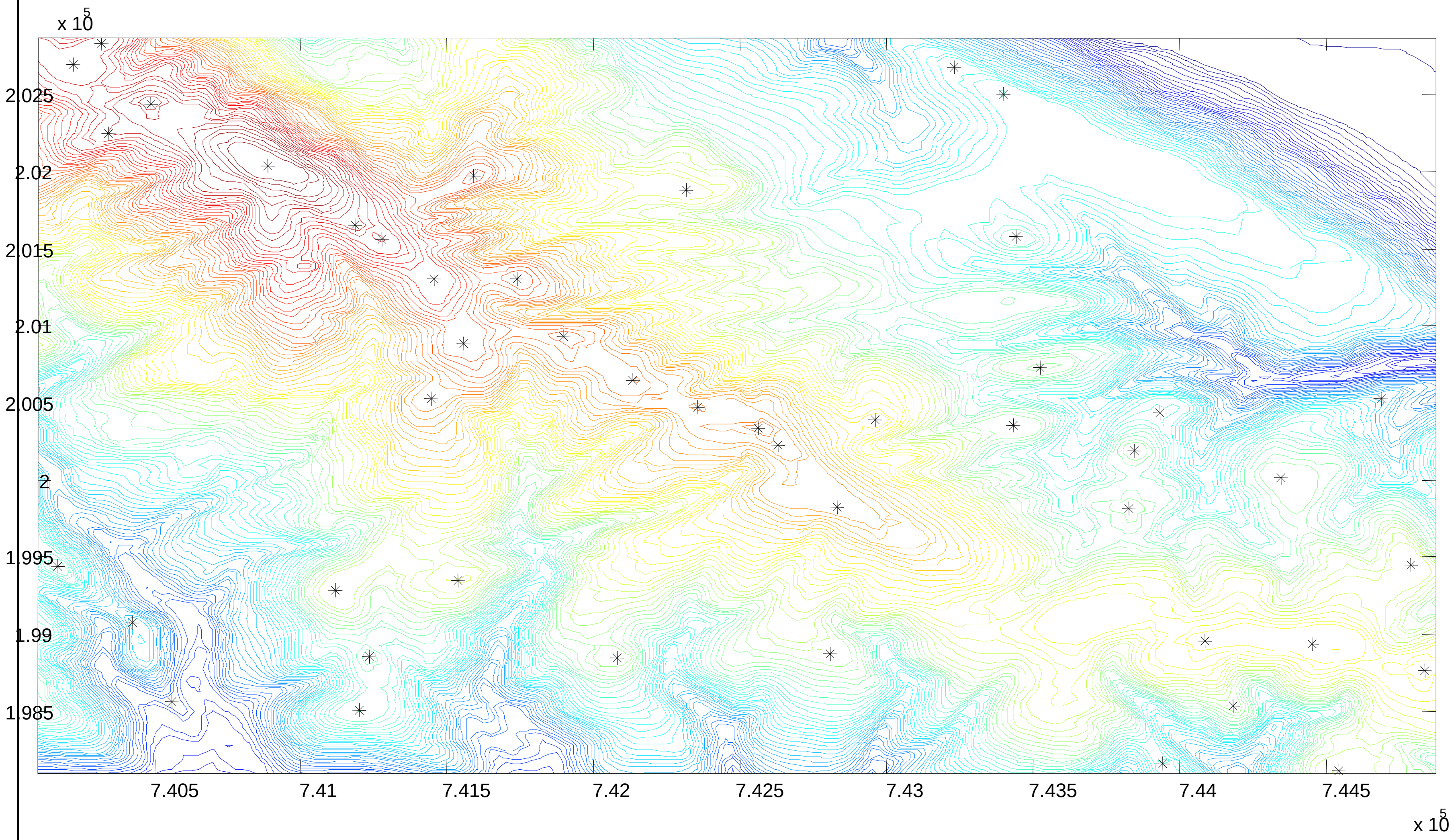
Producing smooth and continuous accuracy polygon map:



- Creating new trapeze and triangular shaped accuracy polygons (derived from existing polygons' topology);
- Accuracy values in new polygons comprise of original accuracy values.

Proposed Algorithm – Phase 1

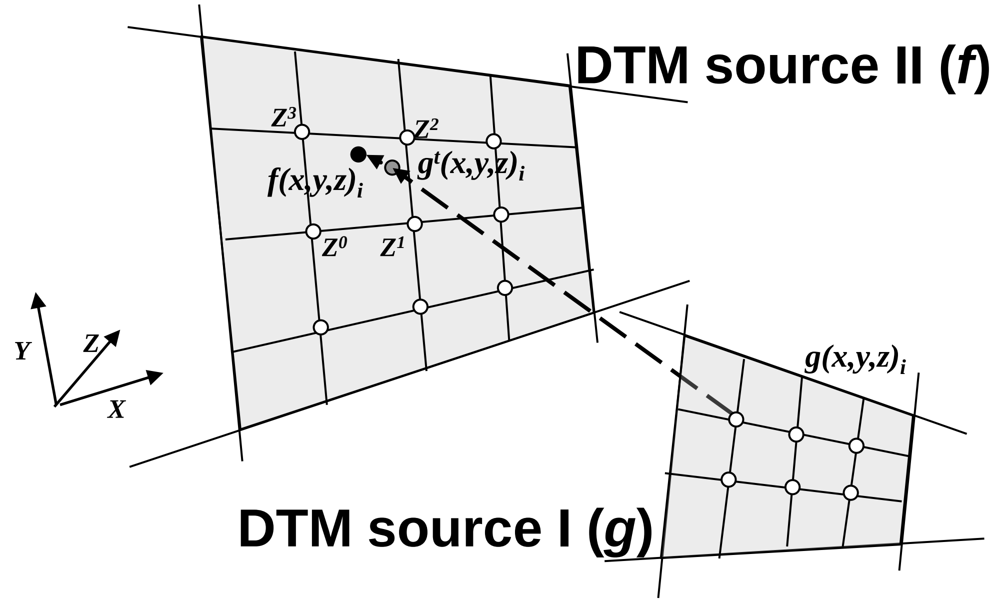
Identification of topographic unique interest points:



Proposed Algorithm – Phase 2

Quality-dependent local spatial ICP matching:

Implementing 3 geometric constraints to assure co-registration of two corresponding points - one from each DTM



$$z^f = \frac{Z_1 - Z_0}{D}\cdot x^f + \frac{Z_3 - Z_0}{D}\cdot y^f + \frac{Z_2 - Z_1 - Z_3 + Z_0}{D^2}\cdot x^f \cdot y^f$$

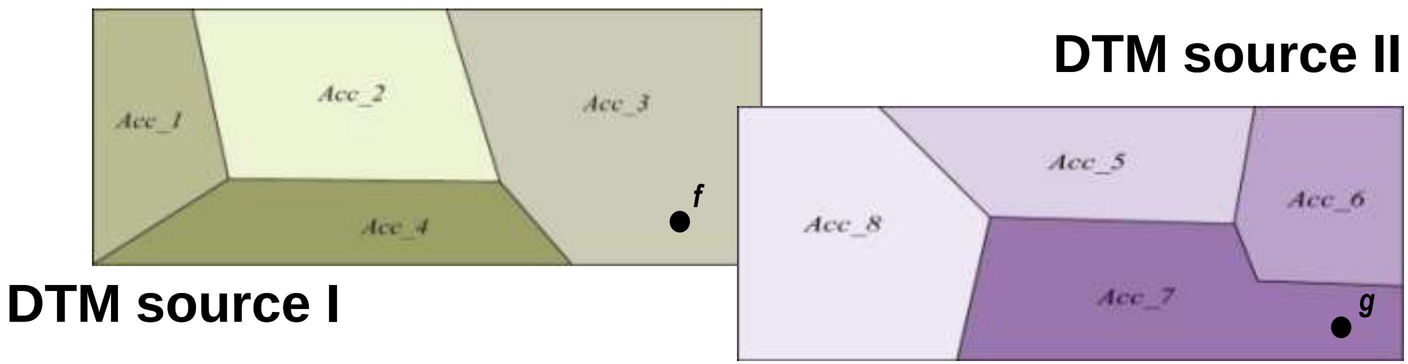
$$z_f = \frac{Z_1 - Z_0}{D}\cdot x_f - \frac{(Z_2 - Z_1 - Z_3 + Z_0)\cdot x^t{}_g}{D^2}\cdot y_f + \frac{Z_2 - Z_1 - Z_3 + Z_0}{D^2}\cdot x_f \cdot y_f + \left(z^t{}_g - \frac{(Z_1 - Z_0)\cdot x^t{}_g}{D} \right)$$

$$z_f = \frac{Z_3 - Z_0}{D}\cdot y_f - \frac{(Z_2 - Z_1 - Z_3 + Z_0)\cdot y^t{}_g}{D^2}\cdot x_f + \frac{Z_2 - Z_1 - Z_3 + Z_0}{D^2}\cdot x_f \cdot y_f + \left(z^t{}_g - \frac{(Z_3 - Z_0)\cdot y^t{}_g}{D} \right)$$

Proposed Algorithm – Phase 2

Quality-dependent local spatial ICP matching:

Due to varied accuracies – each co-registered point {'*f* & *g*'} has different accuracy value.



Weight p_{fg} for each co-registered points is introduced into adjustment process:

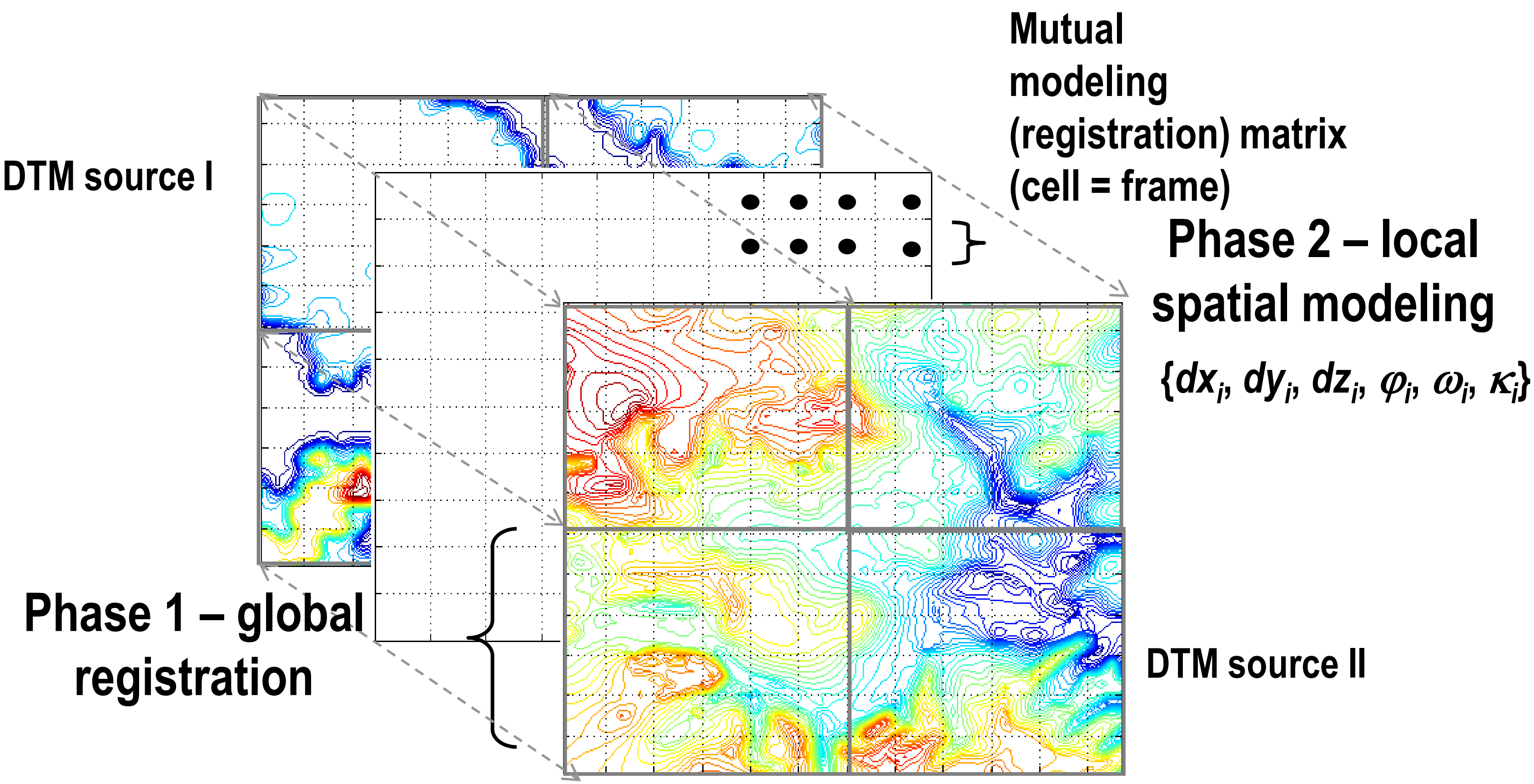
$$P_{fg} = \frac{Acc\_0}{\sqrt{(Acc\_3)^2 + (Acc\_7)^2}}$$

$$\bar{x} = \left(A^T \cdot P \cdot A\right)^{-1} \cdot \left(A^T \cdot P \cdot l\right)$$

$$\bar{x} = \left\{dx, dy, dz, \varphi, \omega, \kappa\right\}$$

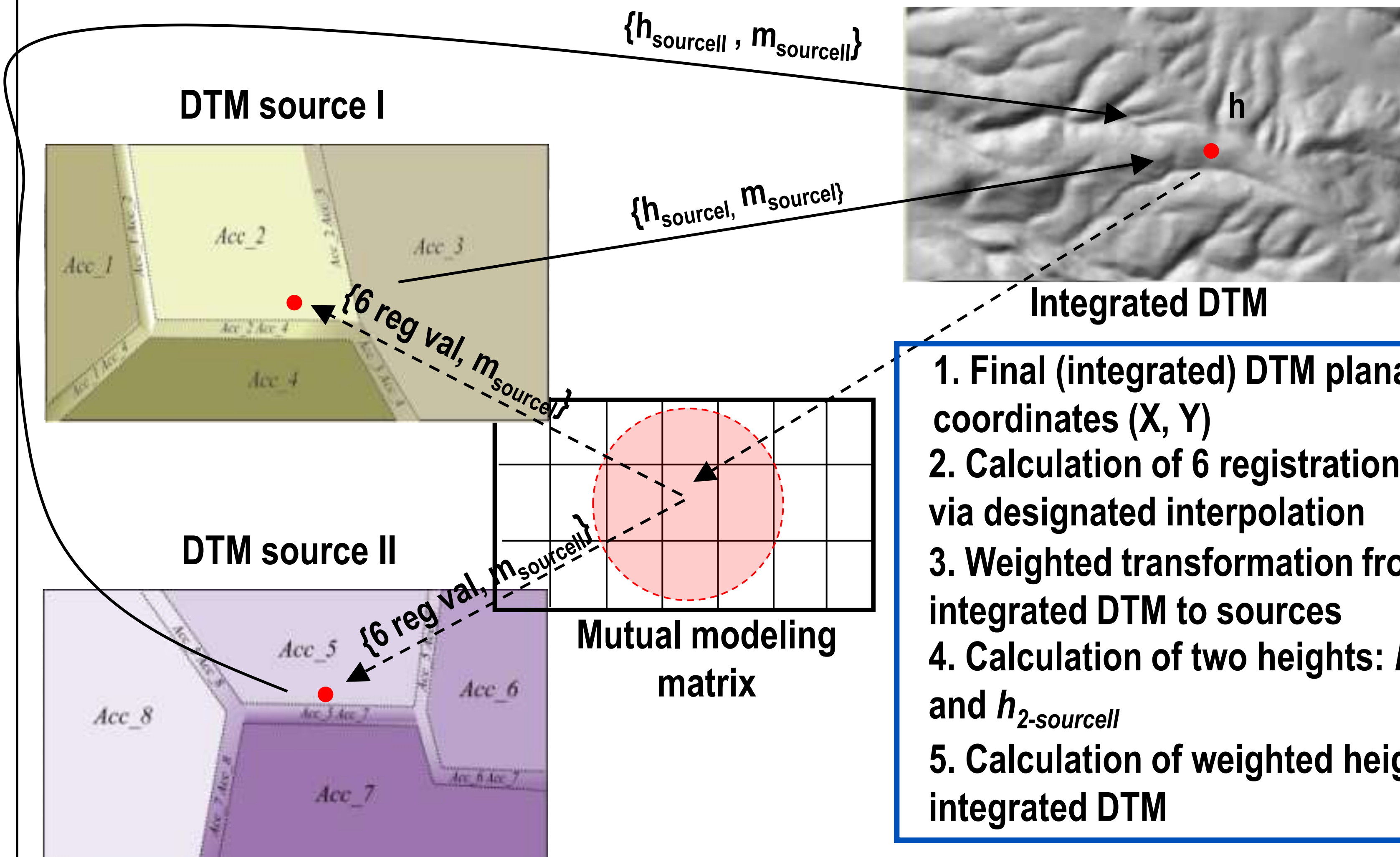
Proposed Algorithm – Phase 2

Establishment of mutual modeling matrix:



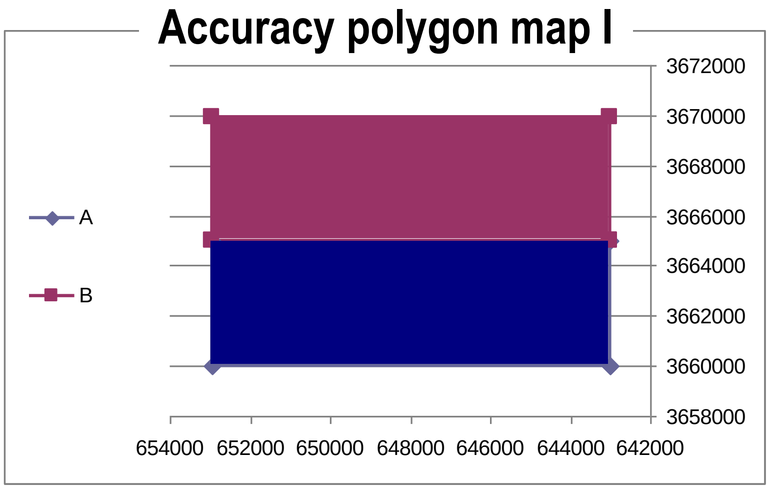
Proposed Algorithm – Phase 3

Quality-dependent height calculation of integrated DTM:

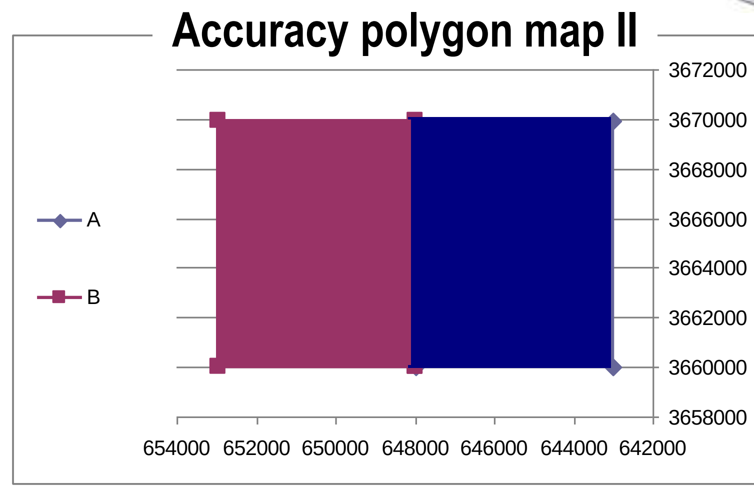


1. Final (integrated) DTM planar coordinates (X, Y)
2. Calculation of 6 registration values via designated interpolation
3. Weighted transformation from integrated DTM to sources
4. Calculation of two heights: $h_{1\text{-sourceII}}$ and $h_{2\text{-sourceII}}$
5. Calculation of weighted height in integrated DTM

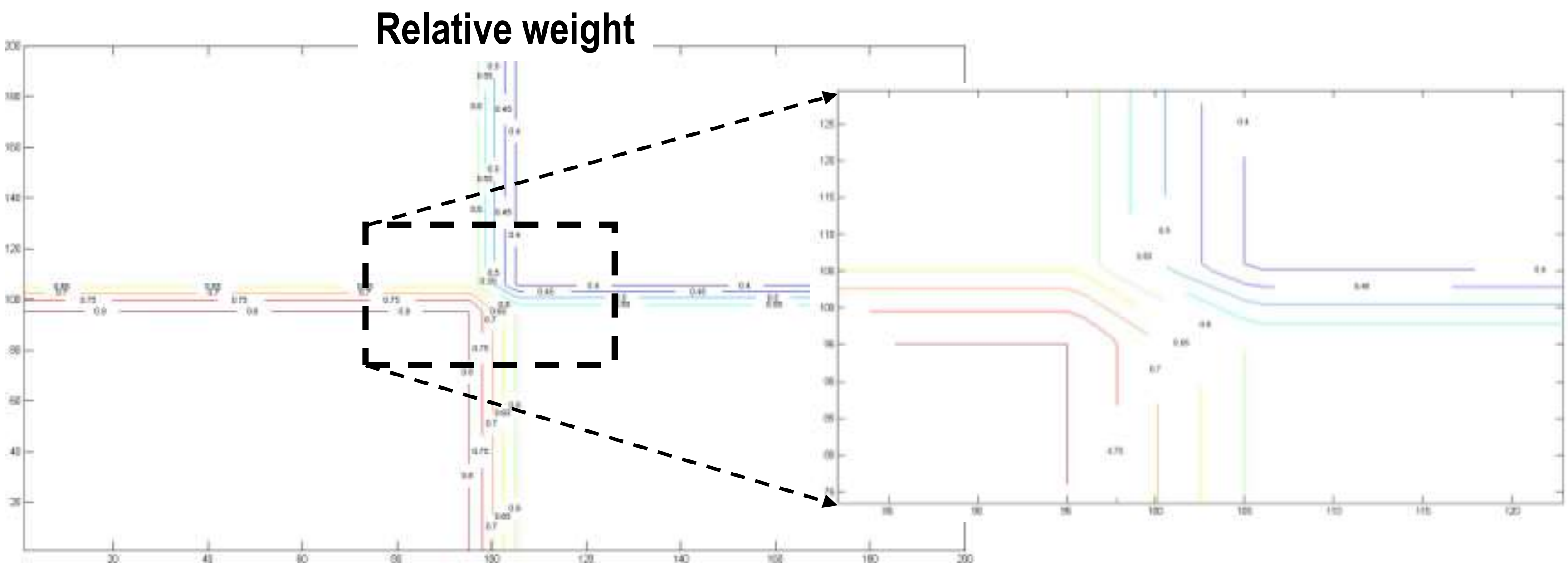
Results



Accuracy polygon map I
A
B
3672000
3670000
3668000
3666000
3664000
3662000
3660000
3658000
654000 652000 650000 648000 646000 644000 642000



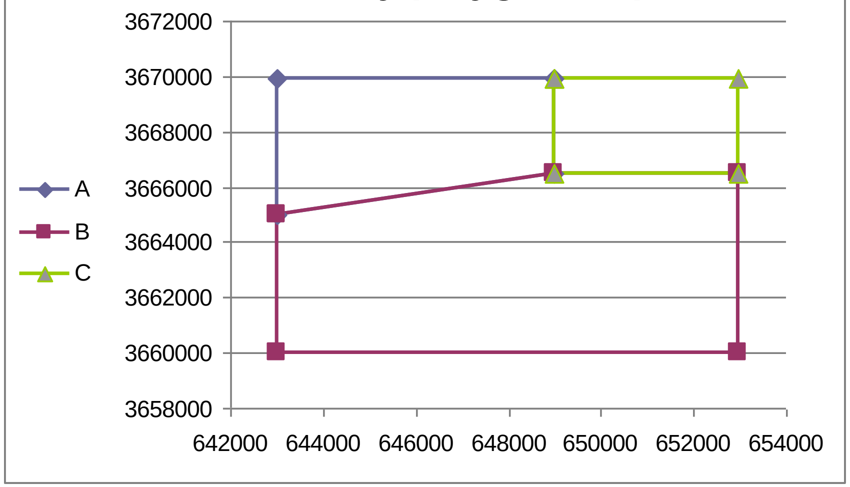
Accuracy polygon map II
A
B
3672000
3670000
3668000
3666000
3664000
3662000
3660000
3658000
654000 652000 650000 648000 646000 644000 642000



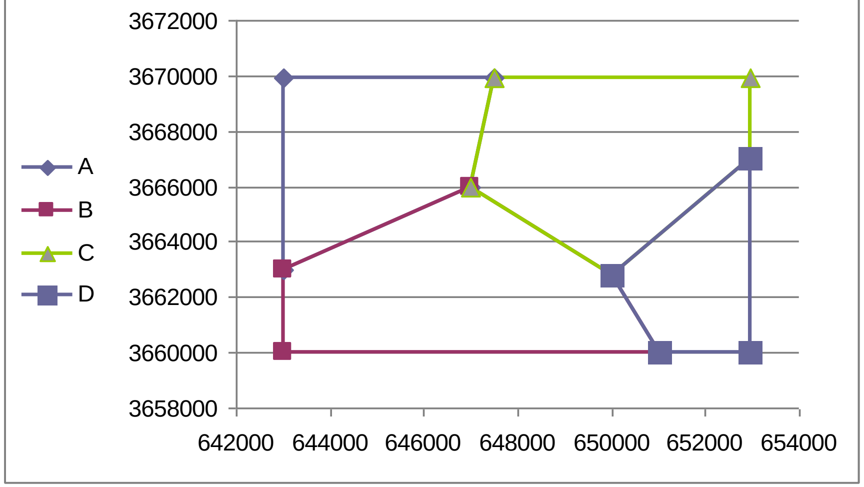
Relative weight

Results

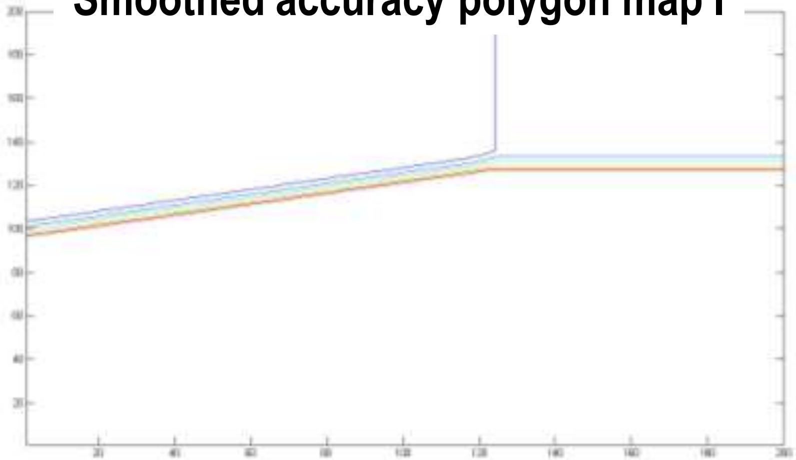
Accuracy polygon map I



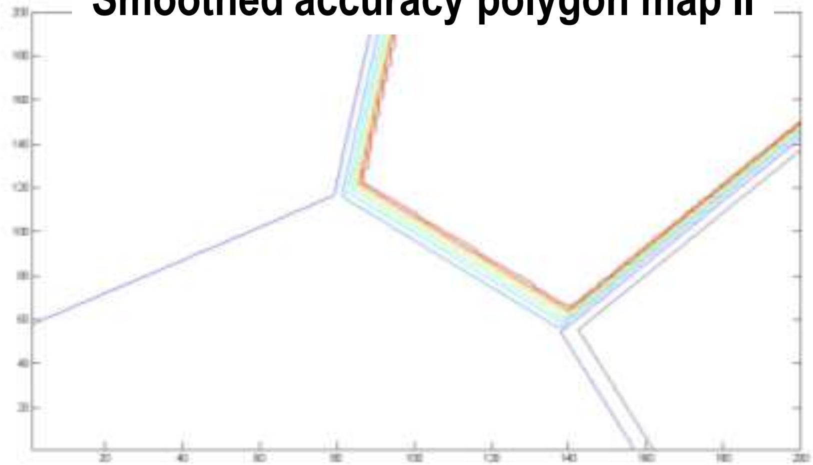
Accuracy polygon map II



Smoothed accuracy polygon map I

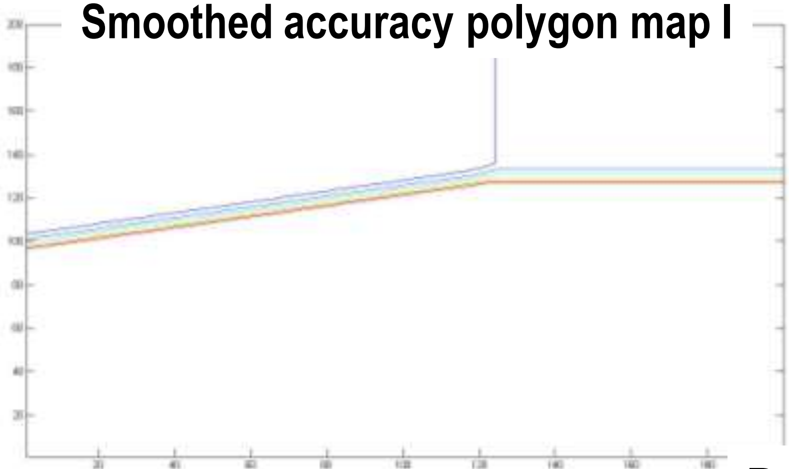


Smoothed accuracy polygon map II

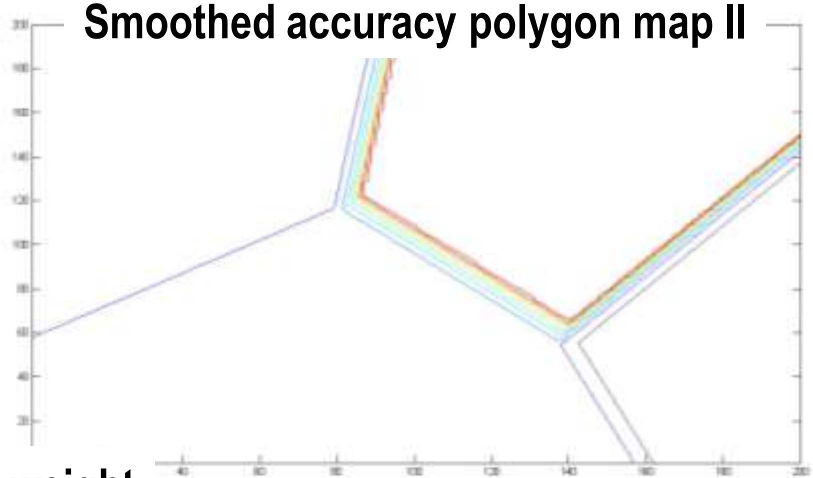


Results

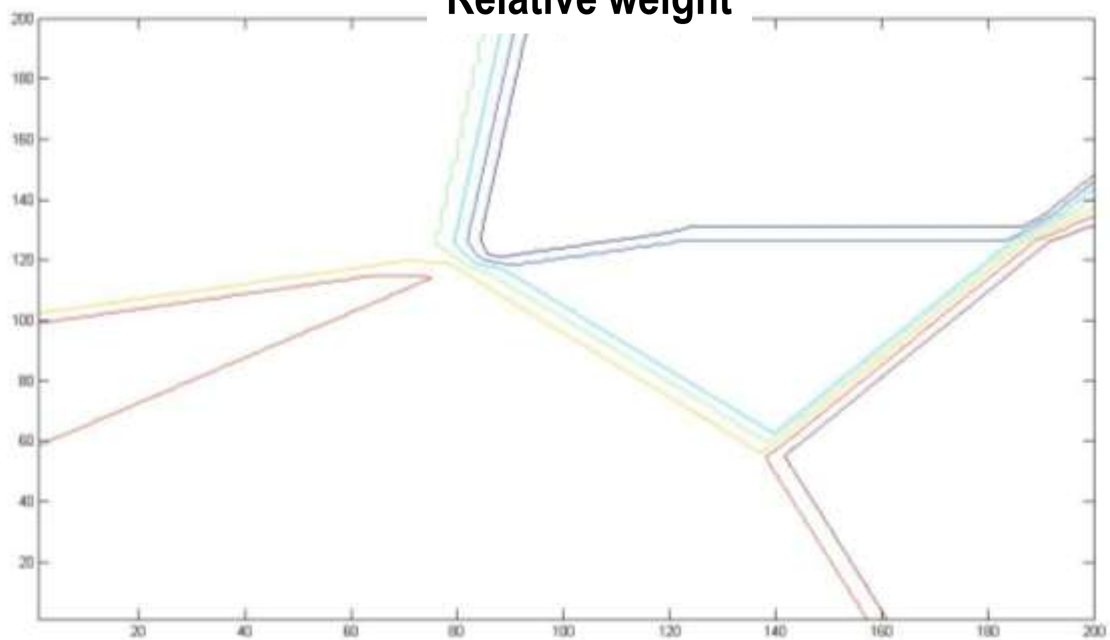
Smoothed accuracy polygon map I



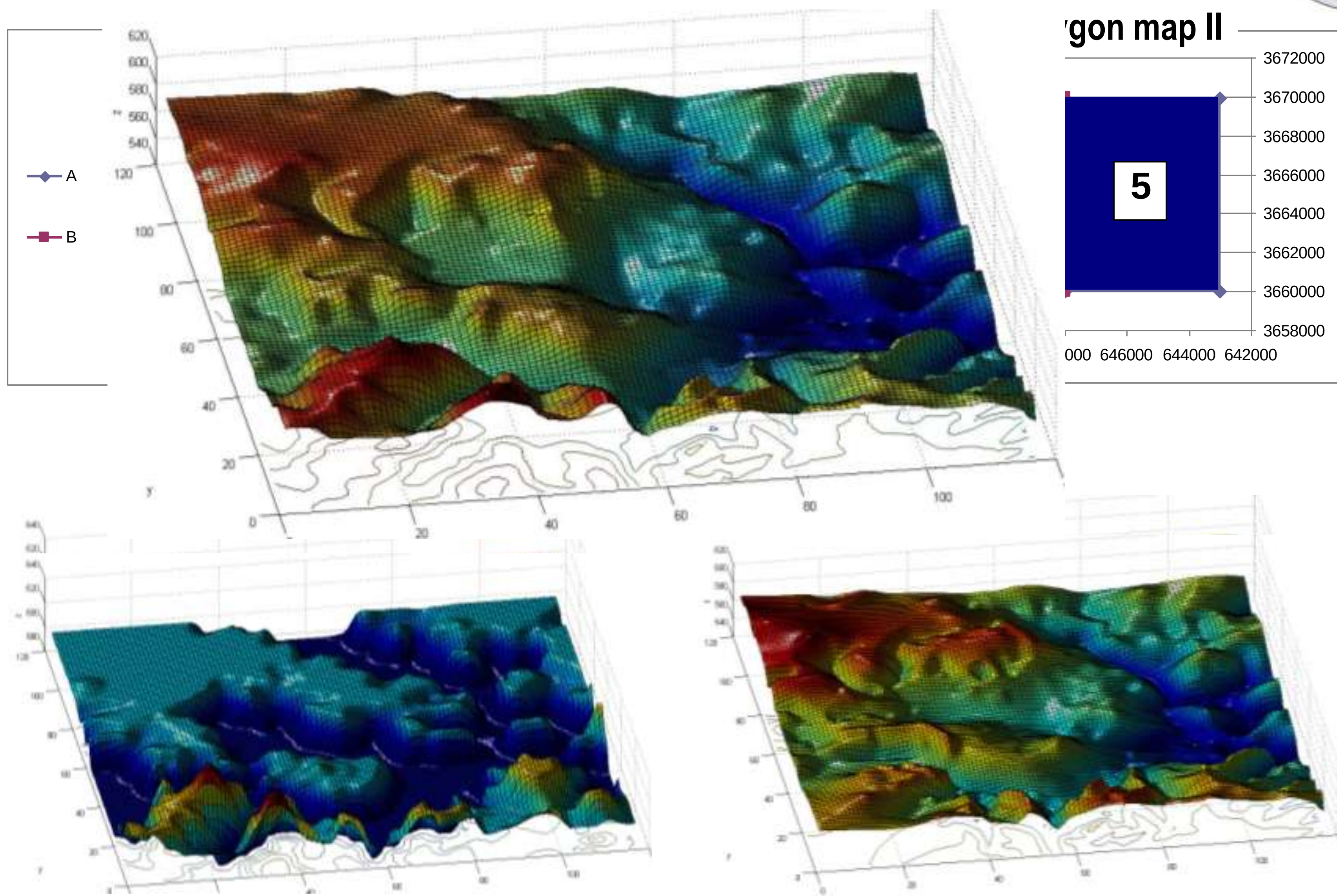
Smoothed accuracy polygon map II



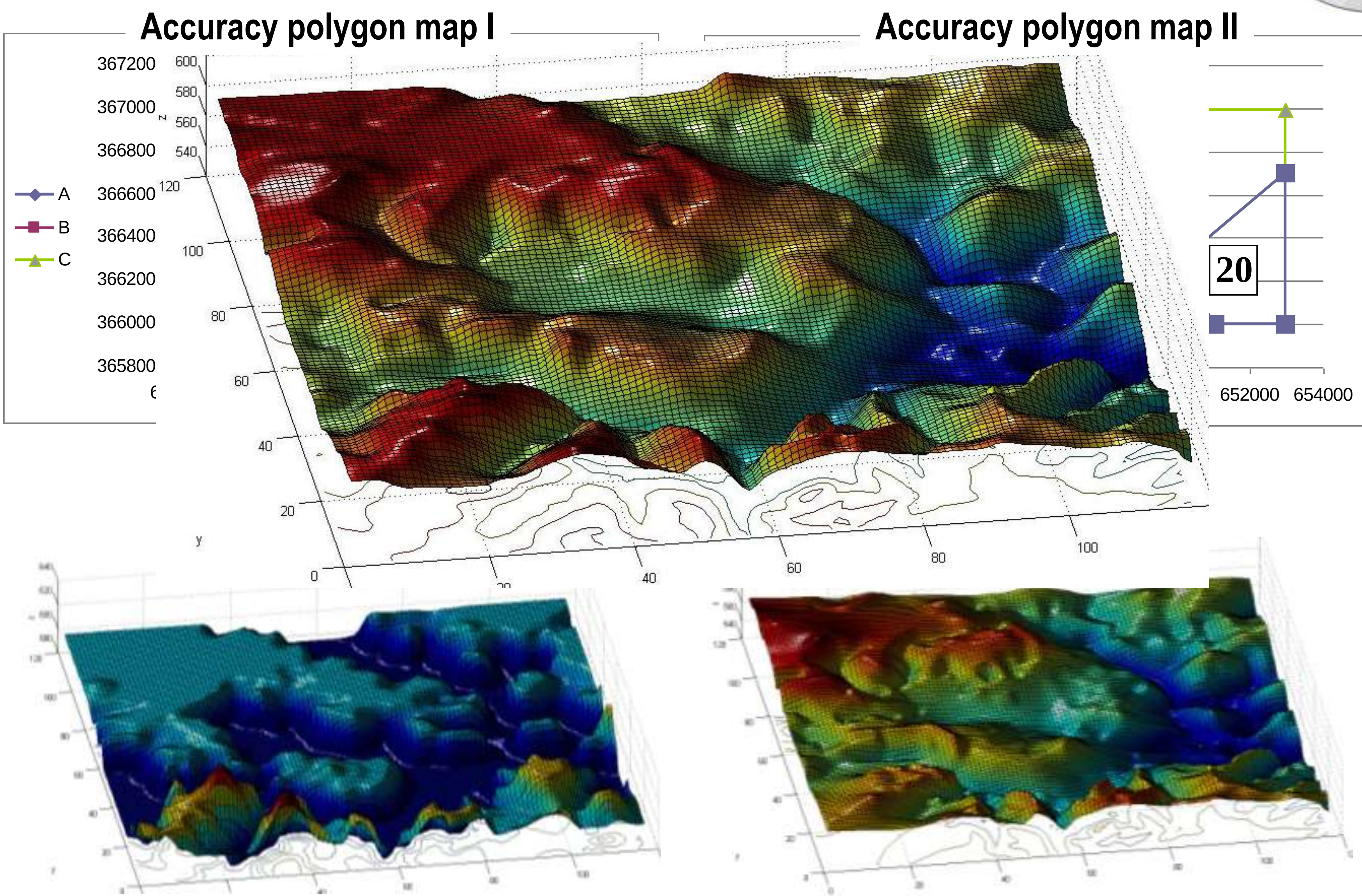
Relative weight



Results

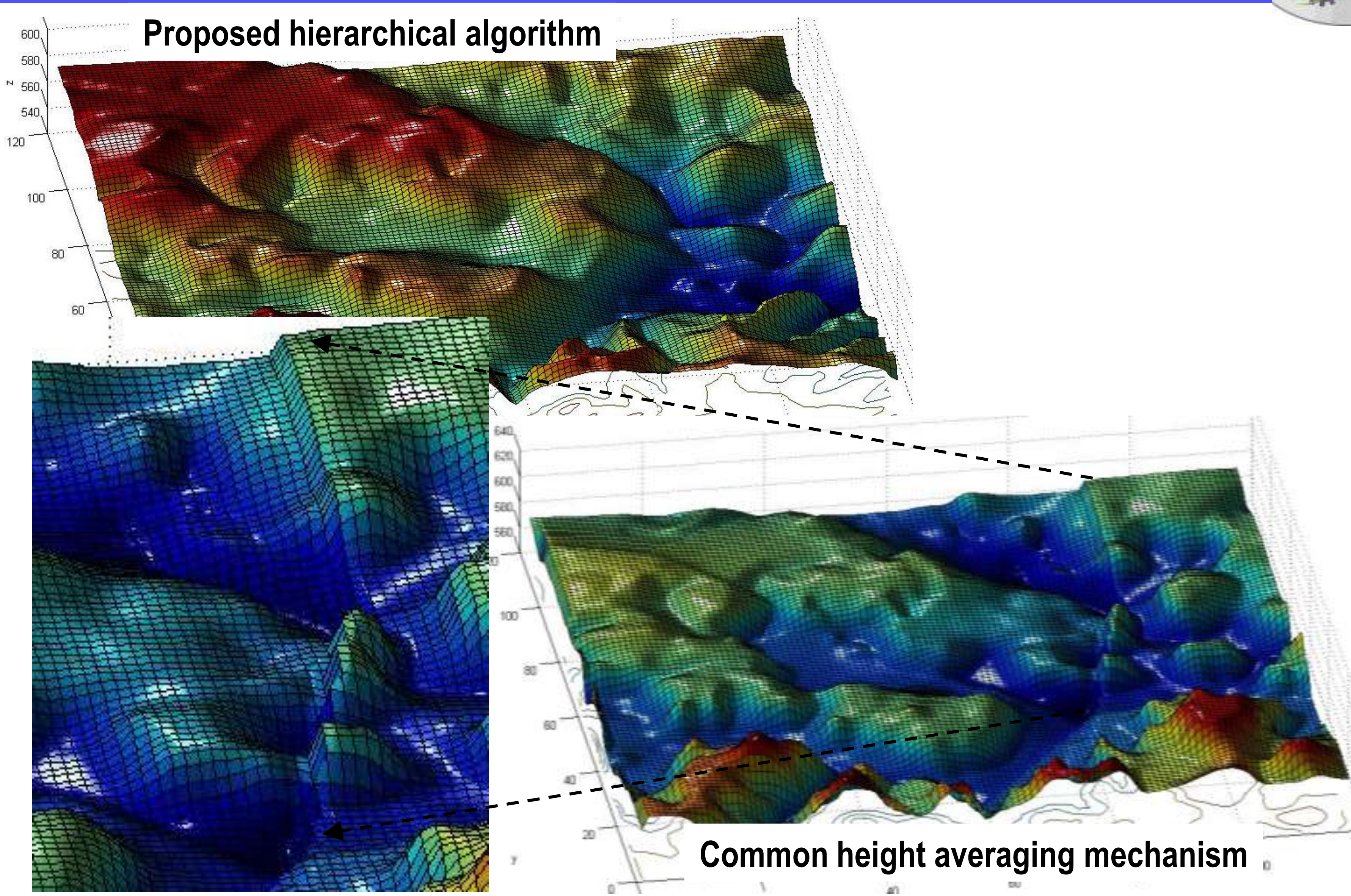

A
B
gon map II
3672000
3670000
3668000
3666000
3664000
3662000
3660000
3658000
000 646000 644000 642000
5

Results

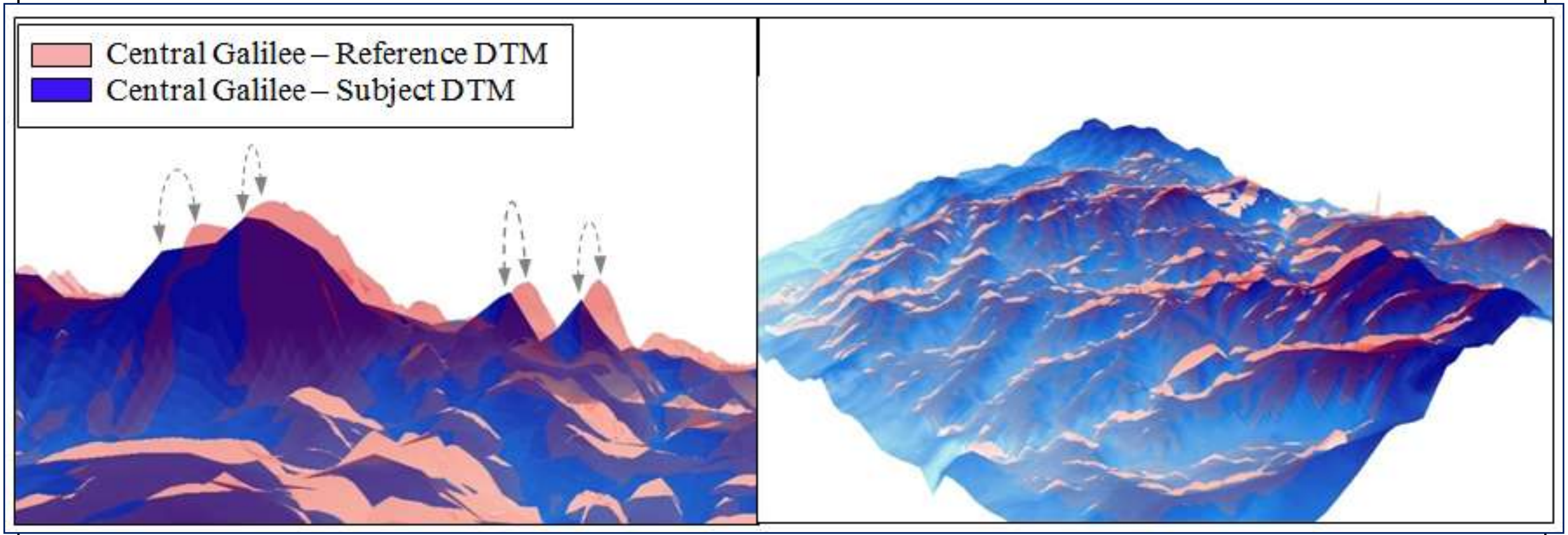


Accuracy polygon map I
Accuracy polygon map II
367200
367000
366800
366600
366400
366200
366000
365800
A
B
C
20
652000
654000

Results


Proposed hierarchical algorithm
Common height averaging mechanism

Absolute Accuracy of DTMS

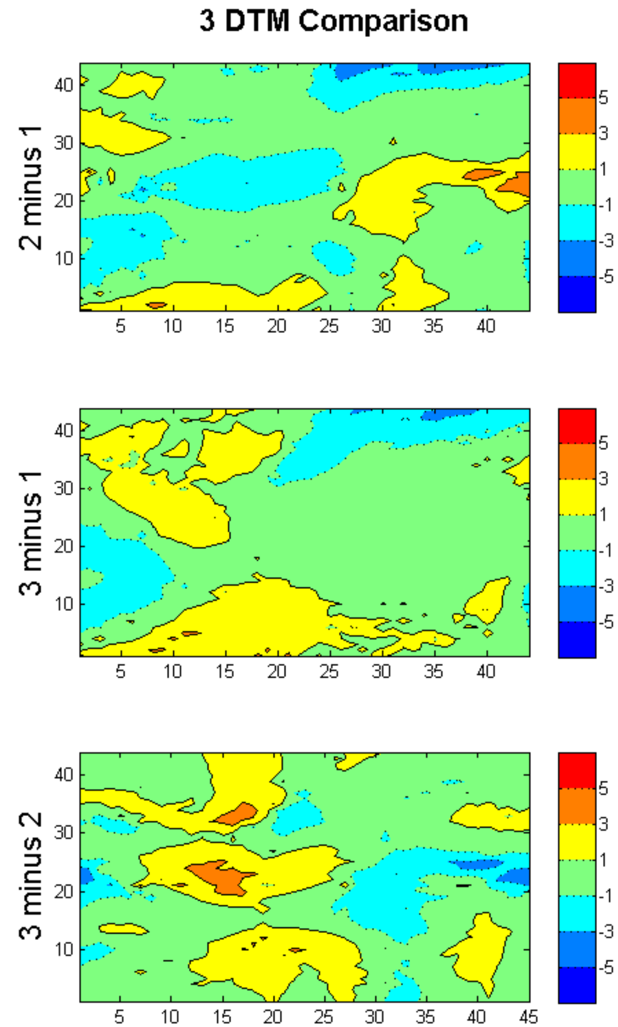


- Topography of two datasets after transformation with evident localized discrepancies
- Two DTMs enable only to determine relative accuracies
- What if we have several DTMs?

Comparing Several DTMs

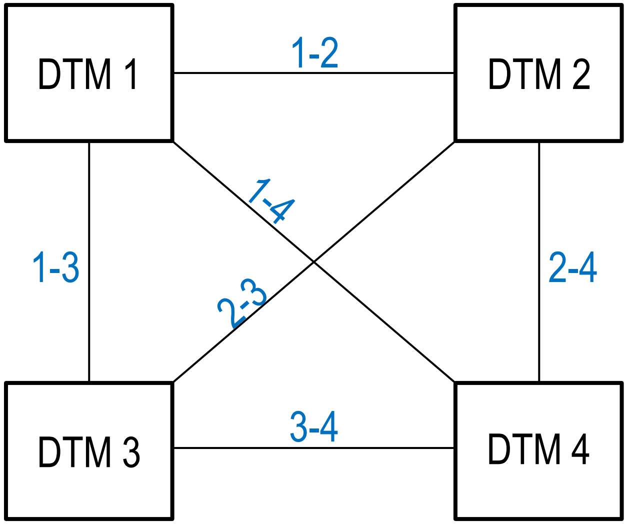
- **Initial research – a simulation:**
  - **We created 2 DTMs from a given DTM. Both were horizontally translated using continuous functions changing scale factors and cycle time. All 3 share the same height values.**

Area Characteristics	
Area [km]	1.1 x 1.1
Sample	1936
Average [m]	8.73
StD [m]	3.88
Min. Value [m]	0
Max. Value [m]	20.7



Comparing Multiple DTMs

- **4 DTMs generate 6 DTM differences**
- **The main concept: using Error Theory (as applied to Mapping and Geodesy) to determine accuracies of DTMs.**
- **The use of several DTMs representing the same area.**
- **The more differences the higher the proximity to the ‘real’ values.**



Comparing Multiple DTMs

Accuracy of each difference can be estimated by the following equations (rely on Error Theory):

- **Vector L contains n actual difference which can be estimated using N height differences between DTMs k and l:**

$$L_{k-l} = \sum_{s=1}^{N} d_s{}^2$$

- **Where:**

$$d_{k-l} = h_l - h_k$$

- **Accuracy of each k-l pair is calculated using the Error Propagation Rule:**

$$m_i{}^2 = m_l{}^2 + m_k{}^2$$

Comparing Multiple DTMs

- The weight values P_i are then computed by: $$P_i = \frac{m_0^{\;2}}{m_i^{\;2}}$$
- And therefore P matrix:

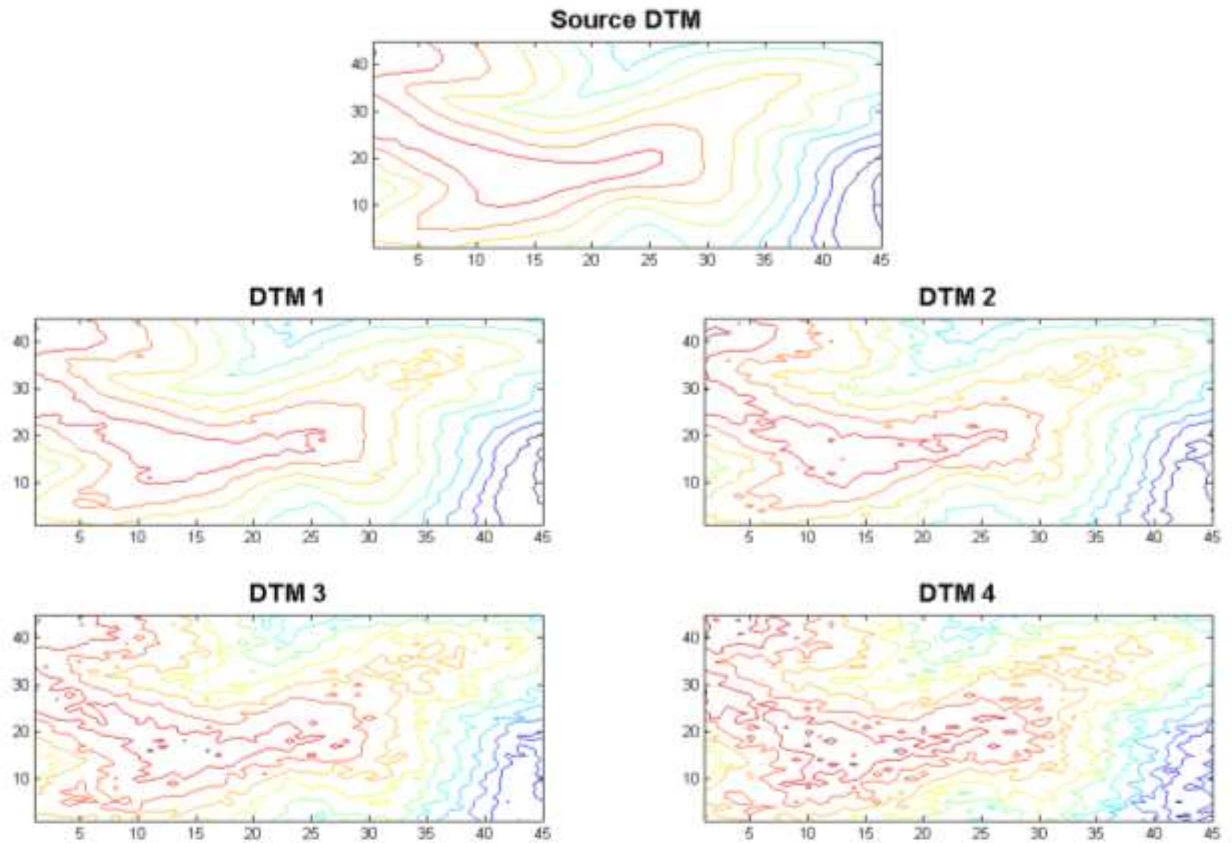
$$P_{(nxm)} = \begin{bmatrix} P_1 & & & 0 \\ & P_2 & & \\ & & \ddots & \\ 0 & & & P_n \end{bmatrix}$$

- Accuracy of each difference is calculated using the Error Propagation Rule: $$m_i^{\;2} = m_k^{\;2} + m_l^{\;2}$$
- The solution X produces the A Posteriori DTM accuracies using Least Squares Matching: $$X = (A^T PA)^{-1}(A^T PL)$$

Comparing Multiple DTMs

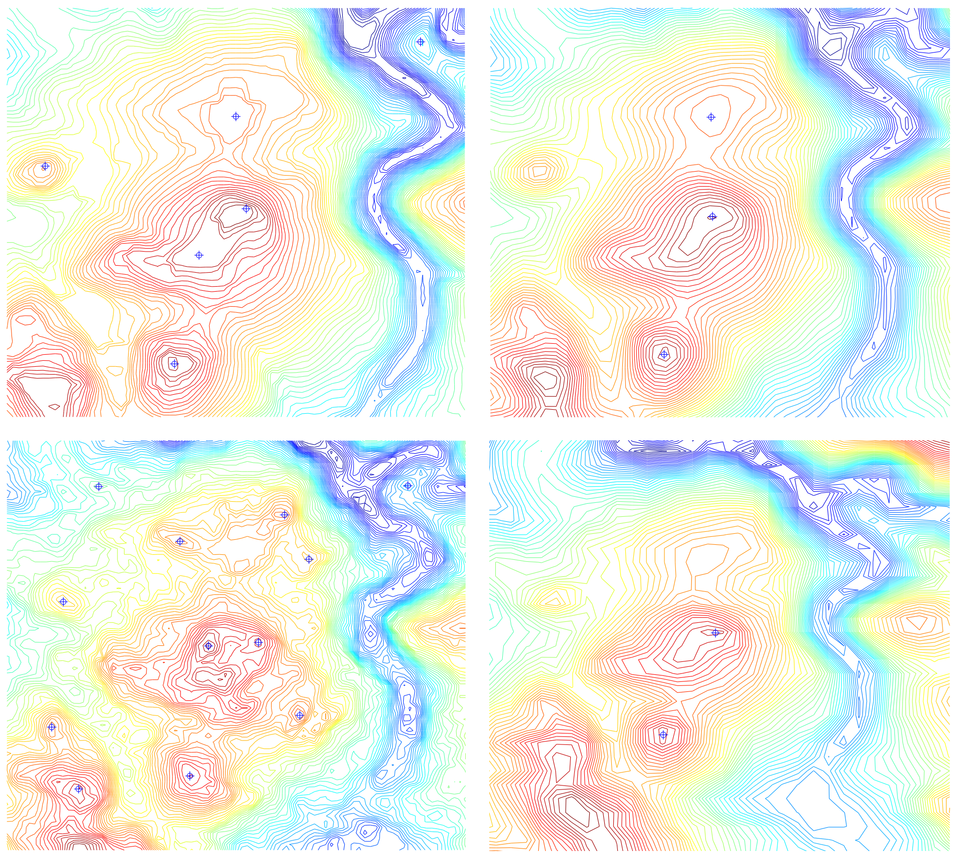
- **4 DTMs: 1, 2, 3 and 4 were generated out of a source, all 4 were vertically translated using normally distributed noise with STD as follow: 2, 4, 6 and 8 [m] respectively.**

Sigma	A Priory	Post Priori
DTM 1	2	2.01
DTM 2	4	4.04
DTM 3	6	5.89
DTM 4	8	7.88



Experiments Results – Real Data

ITM (25m) ITM (50m)



ASTER (1”) SRTM (3”)

Experiments Results – Real Data

DTM-scale analysis

	computed σ using 4 DTMs [m]		computed σ using 3 DTMs [m]	
DTM	North Area	South Area	North Area	South Area
25 meters ITM	4.42	2.81	3.47	2.79
50 meters ITM	5.07	2.05	5.07	2.35
ASTER 1 arc-second	10.39	10.74	-	-
SRTM 3 arc-second	3.15	2.65	4.09	2.4

- **The accuracy of a DTM might substantially vary in areas where topographic representation changes occur**
- **The weighting mechanism of the LSA process prevents the solution from being biased**
- **Many DTMs generate a high-redundancy system**

(All values with ± signs and in meters)

Summary

What have been presented:

- Three different fully automatic processes for fusing overlapping and/or adjacent DTMs
- Spatial approaches dealing simultaneously with locations and elevations
- These solutions are in contrast to common mechanisms that handle only the coordinate-based height representation of terrain relief
- Enabling monitoring and modelling of local distortions

Summary

Outcome of the merging processes:

- Unified and continuous dataset (DTM)
- Preservation of inner geometric characteristics and topologic relations (morphology)
- Preventing representation of terrain relief distortions
- No dependency on resolution, density, datum, format and data structure (TIN vs. grid), etc.

Summary

Accuracy aspects of DTMs

- Enable to determine regional accuracies of DTMs based on a multi-comparison of several datasets.
- Reliably computing global, regional and grid-point-scale absolute vertical accuracies (no need for preliminary a-priori accuracies)
- The more models exist, the more accurate and reliable the results are – and their positional extent

Thank You for Listening

Acknowledgments:
Dr. Sagi Dalyot, Dr. Yaron Katzil, Gev Ben-Haim, Eran Keinan, Arieal Gershkovich for their contributions on the subject