DSM / DTM Filtering

International School on Lidar Technology

2008

IIT Kanpur, India

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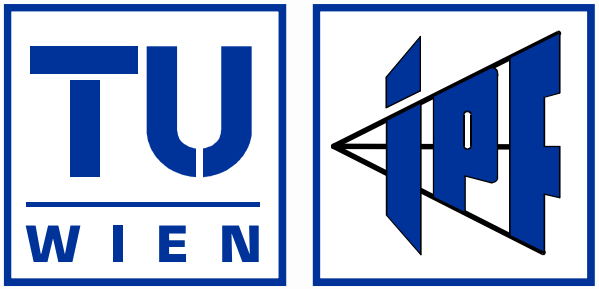

Presented material partly researched and implemented at the Christian Doppler Laboratory, I.P.F. – TU Wien

Christian Doppler Laboratory
Spatial Data from Laser Scanning
and Remote Sensing

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Risk area map: Rosenburg a.d. Drau (Carynthia)

Data: GeoConsult (Austria)

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Overview

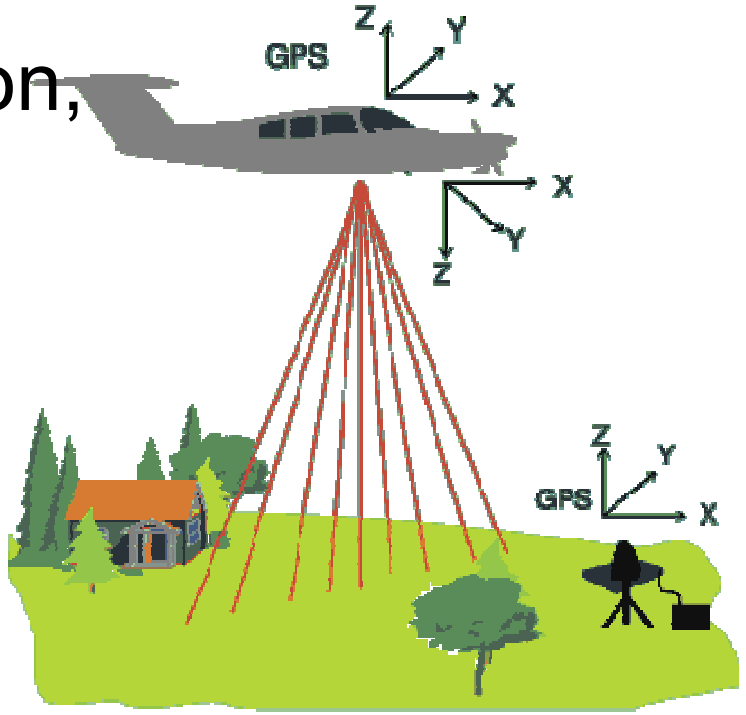
- Problem
  - DTM required
  - Observation by Laser Scanning
  - but: obstacles along the laser beam path
- Solution - Extract terrain information
  a number of different approaches can be identified
  - Block minimum filters
  - Morphological filters
  - Progressive densification
  - Surface based filtering
  - Segmentation based filters
- Improvements
  - Break lines … higher geomorphological quality
  - Thinning … efficiency w.r.t. data volume/point number

Data Acquisition

- Sampling according to system parameters

➲ Points lie on different objects/surfaces

- Examples:
  terrain, vegetation, low vegetation,
  understorey, houses,
  (light) poles, … (what else?)
  multi path effects (long ranges)
- First/last detected echo

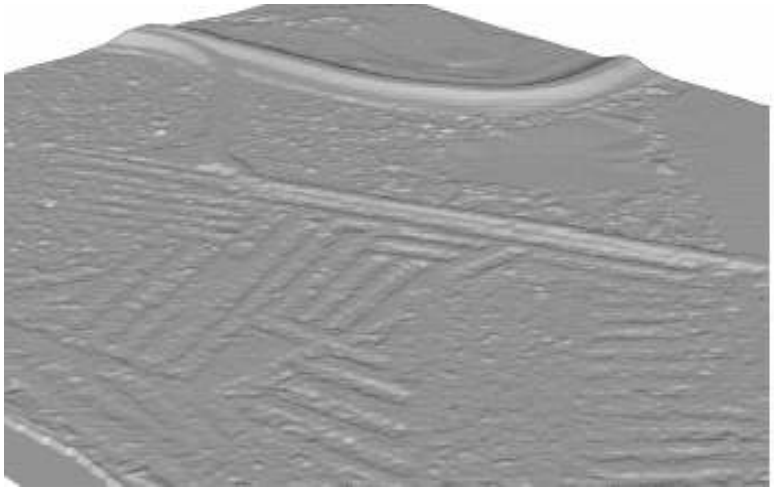


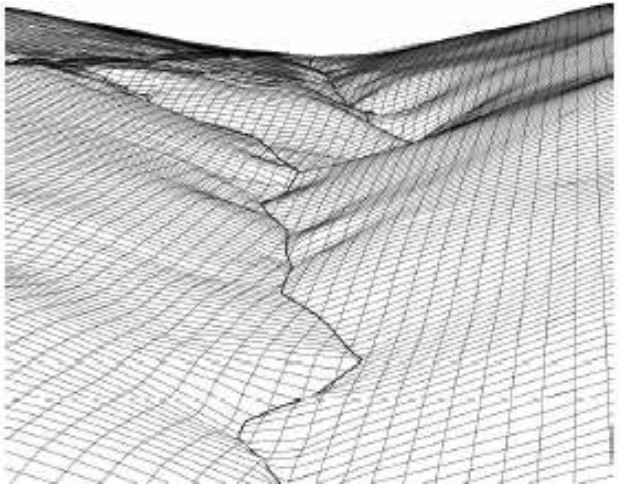
DEM / DTM / DSM / nDSM

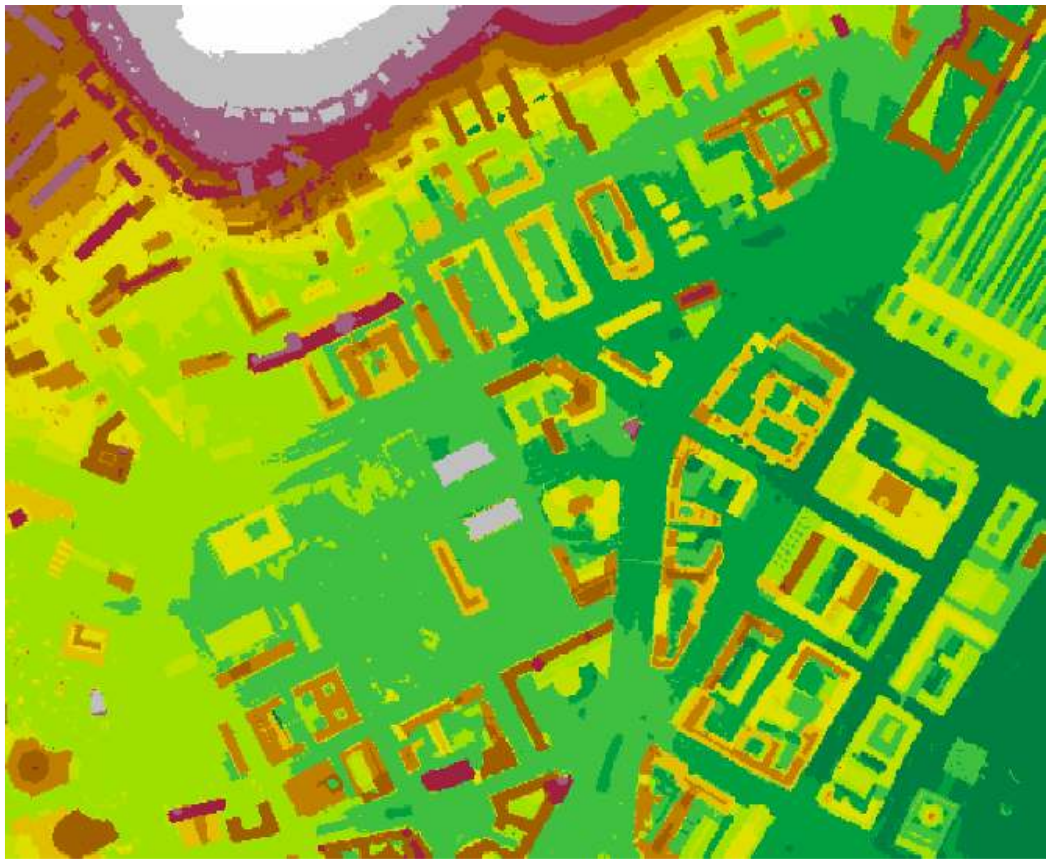
Digital models of topographic surfaces

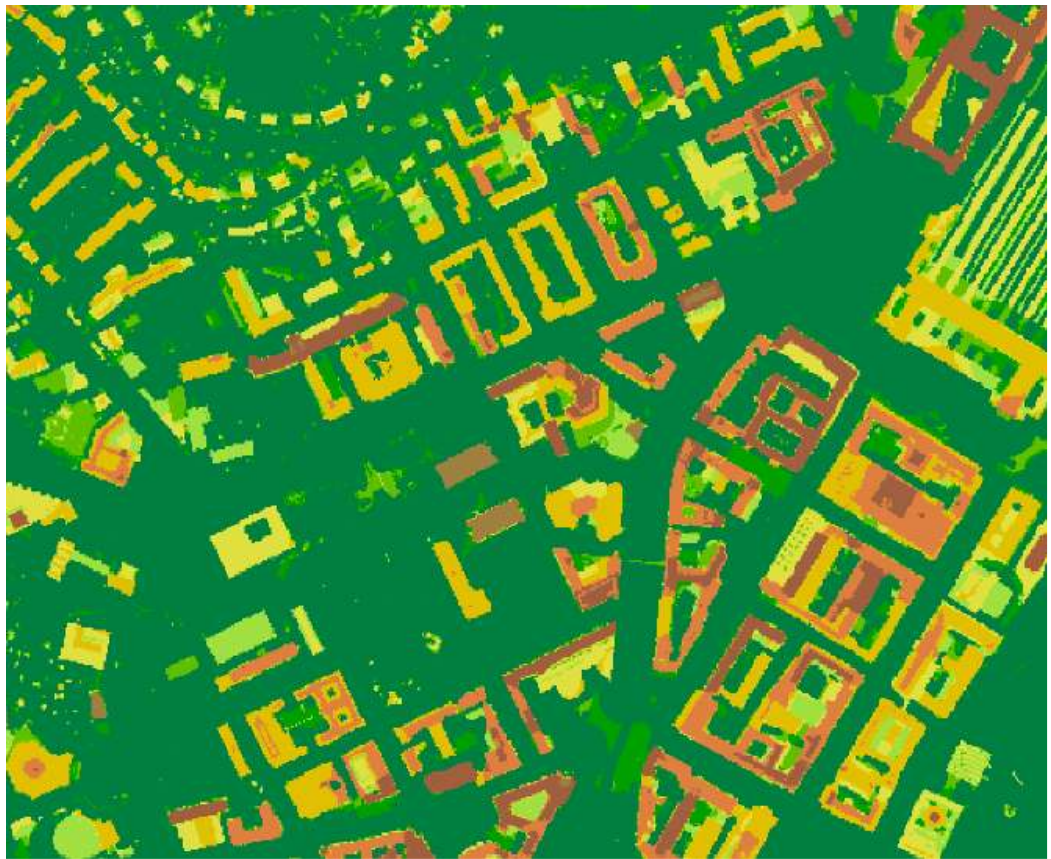
- Digital Elevation Model
- Digital Terrain Model
  (=DEM, sometime + break lines, peak points, …)
- Digital Surface Model
- normalized Digital Surface Model
- Digital Canopy/Situation/… Model

DSM DEM nDSM DSM DTM

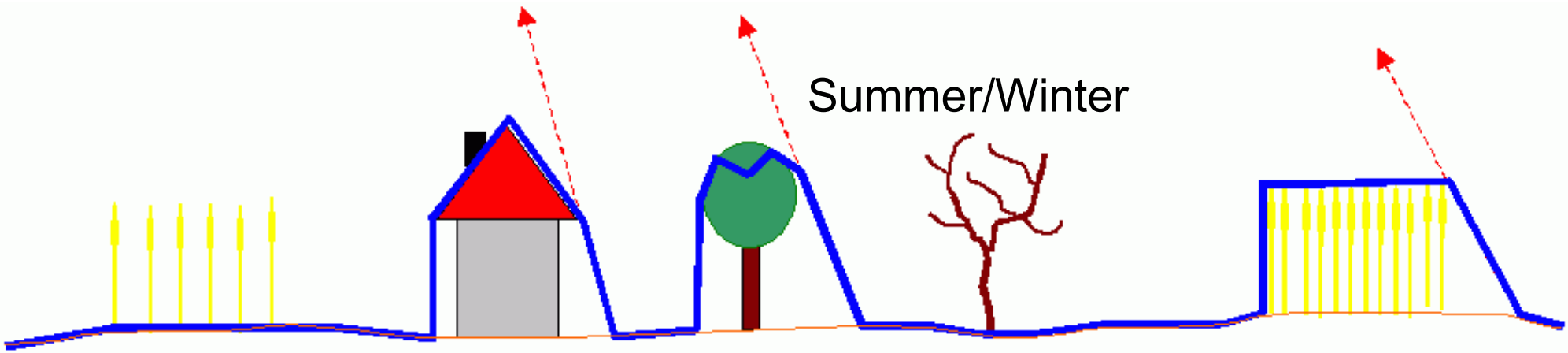








DSM from Laser Altimetry



capturing geometry

Density of crop

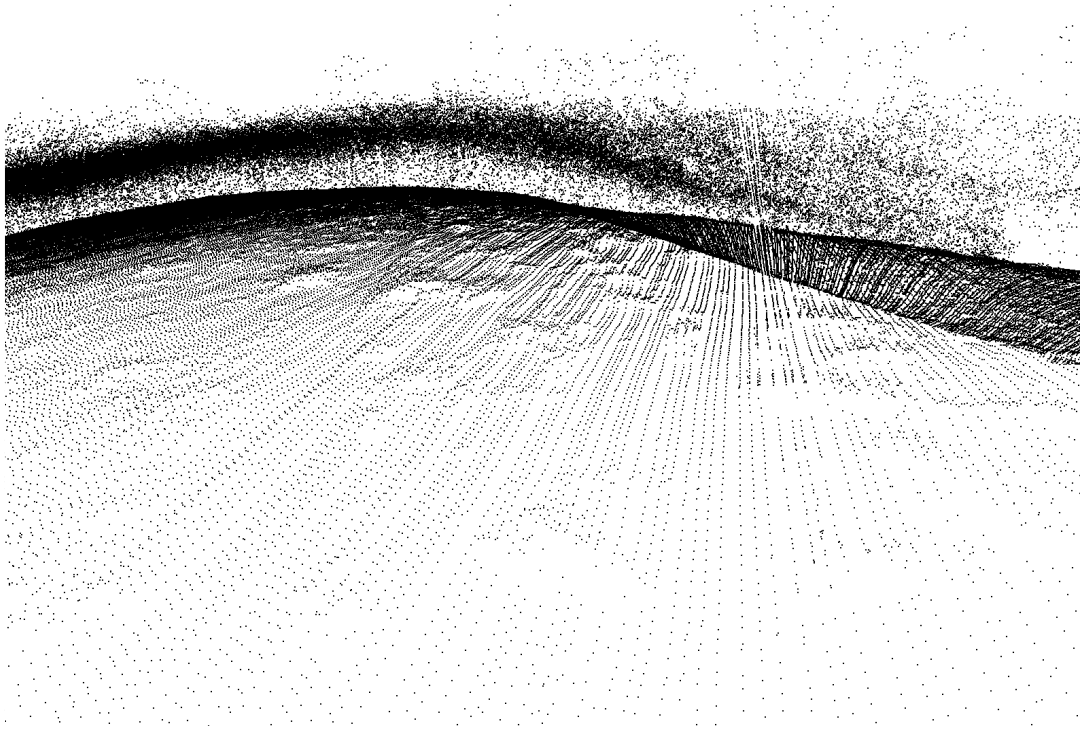
Useful for

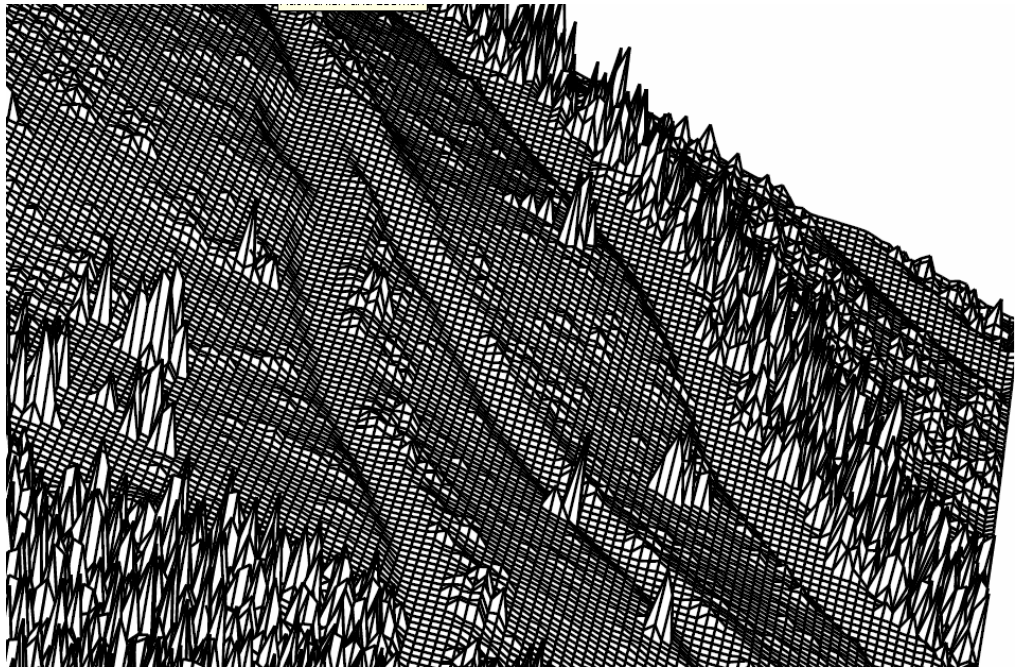
- Check completeness
- Check overlap (extent, errors, ...)
- visualization
- manual interpretation
  (e.g. measure distances)

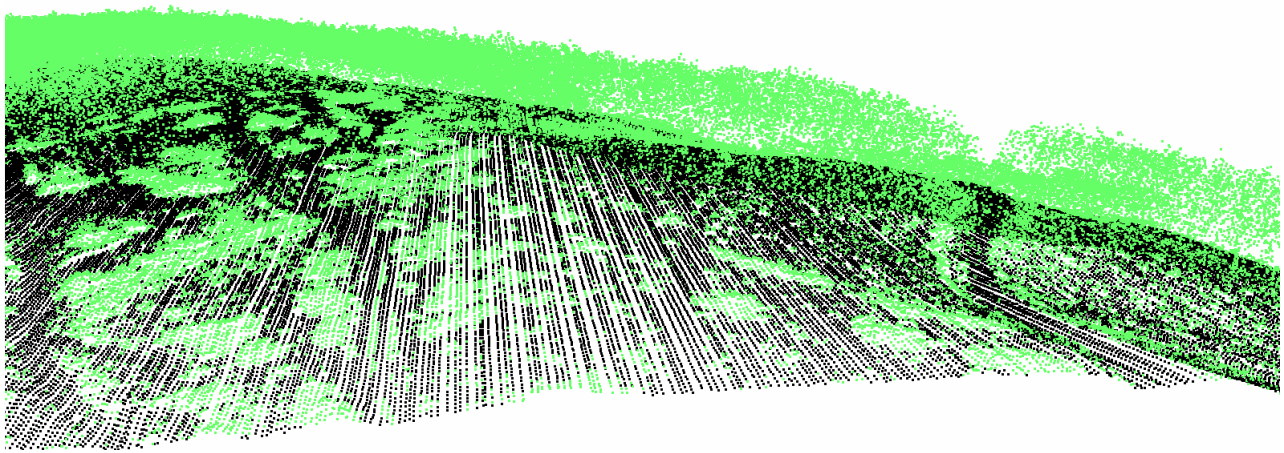
Problem definition

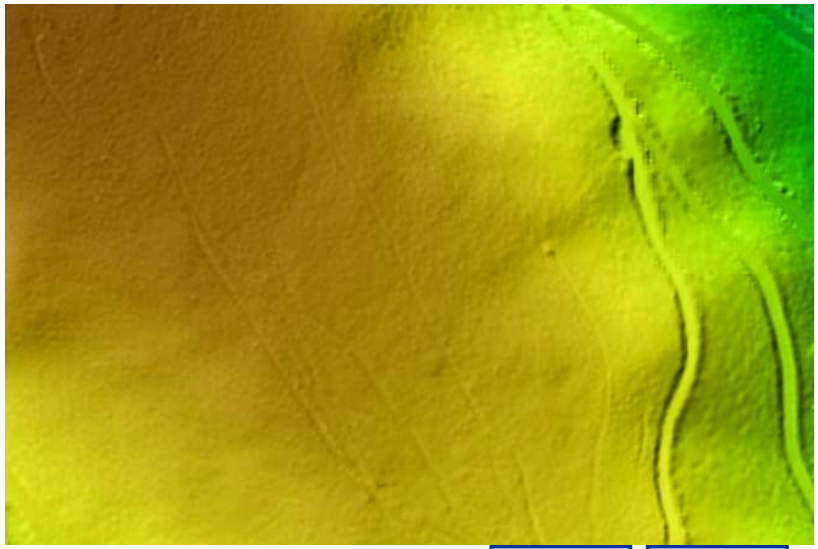
- Given:

- Required:









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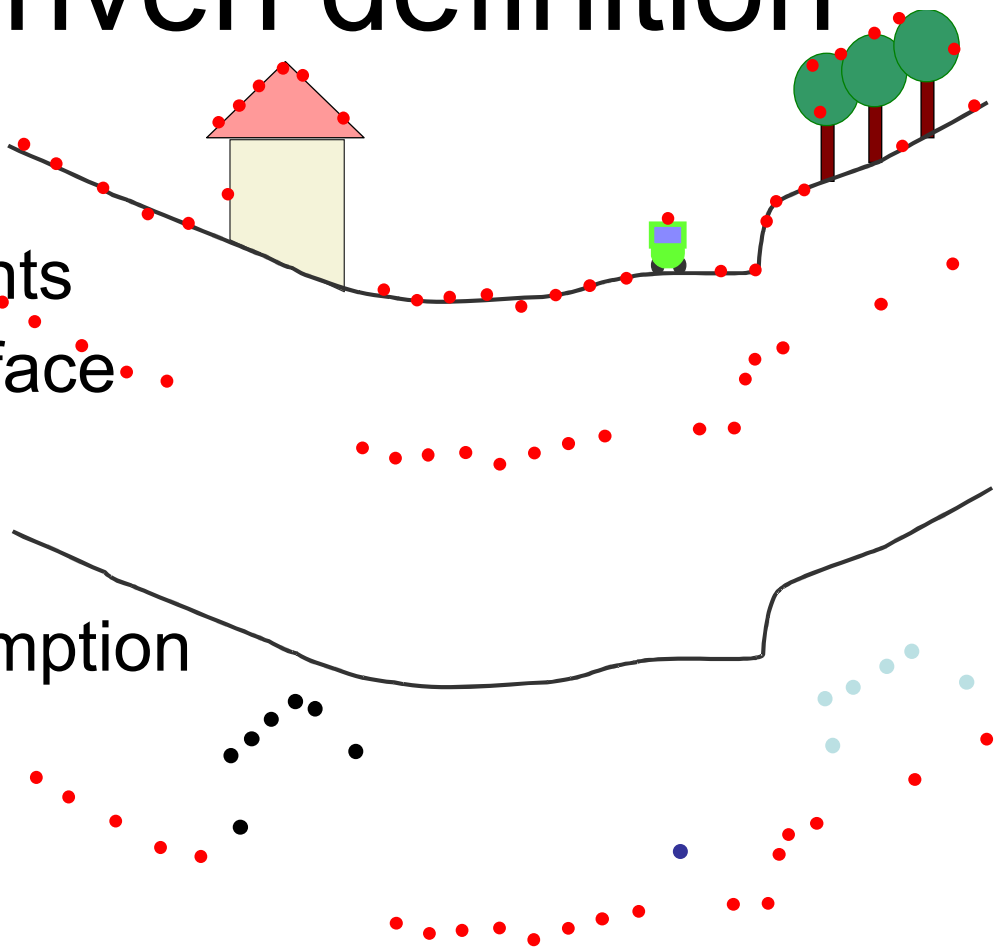
Filtering - result driven definition



- Filtering to extract ground points
- Filtering to extract ground surface
- Classification to label points

- Filtering requires terrain assumption
  e.g.:
  - No height jumps
  - Smooth surface
  - No points below terrain
  - … (what else?)

Filter algorithms overview

- Morphological filters
  Example: slope based filtering (Vosselman) + mathematical morphology
- Progressive densification
  Example: TIN densification (Axelsson)
- Surface based filters
  Example: robust interpolation (Kraus) + hierarchic extension
- Segmentation based filters

Block minimum filters

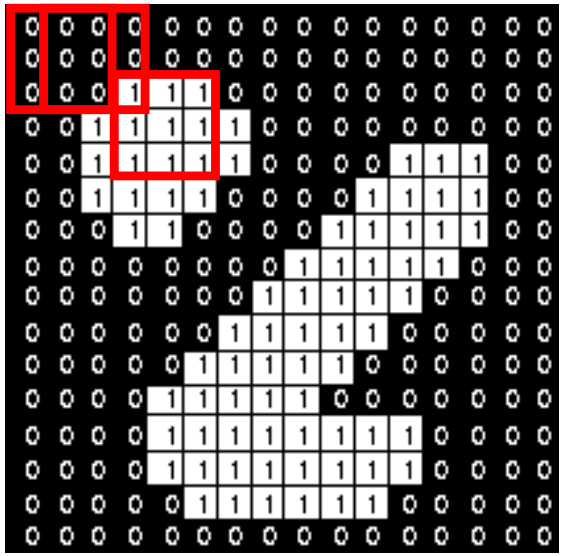
- Define regular mesh
  edge length =
- Take lowest point in each cell
- Compute DTM by interpolating set of these lowest points
- Problems:

Approach 1
Slope based filtering

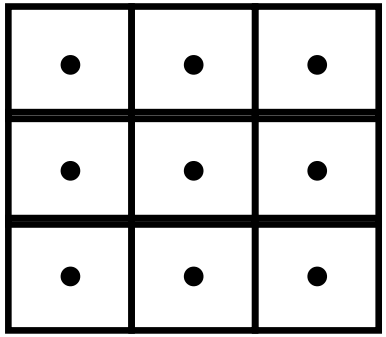
- Principles of mathematical morphology
  (Slides from Prof. Vosselman)
- Binary, rasterized data
  … continuous domain
- Slope based filtering
- Relation to mathematical morphology
- Derivation of filter kernel
- Example

Mathematical morphology

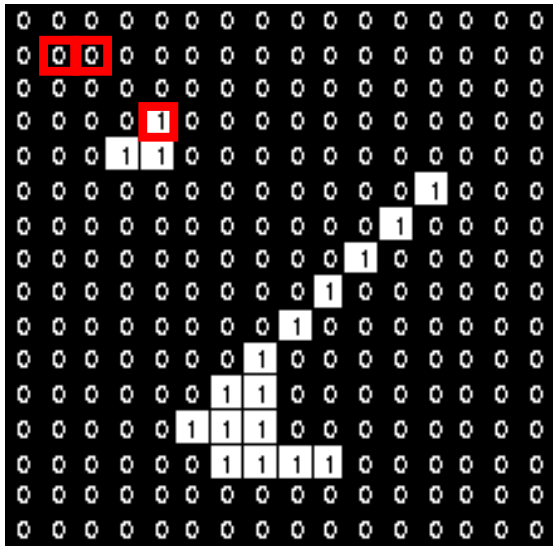
Original



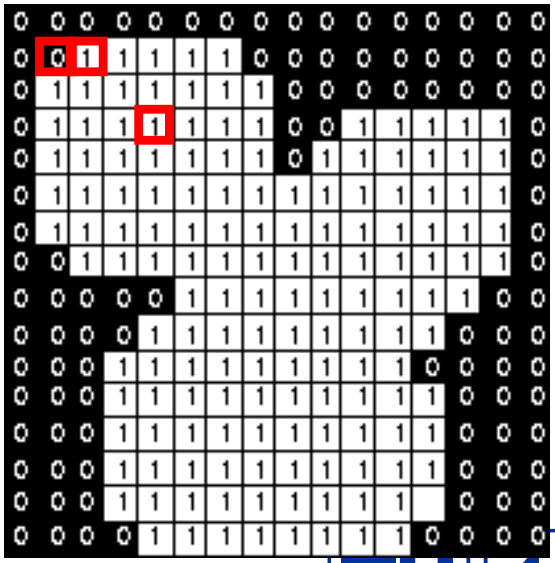
Kernel



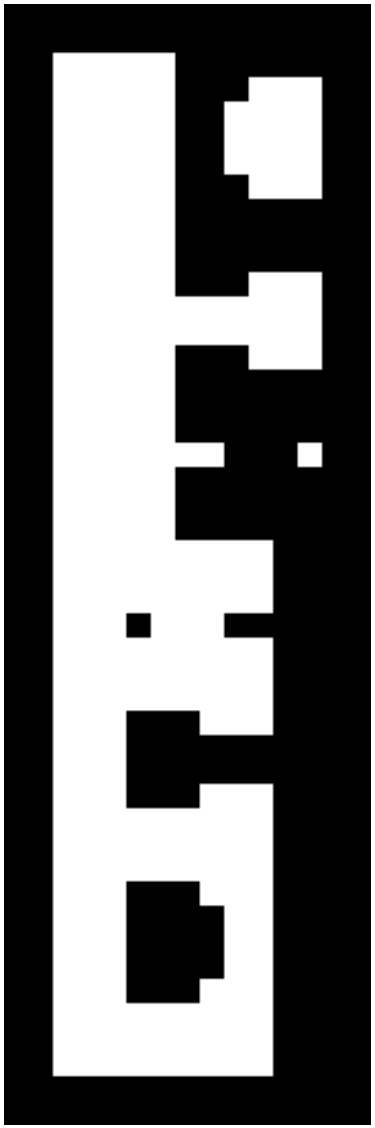
Erosion



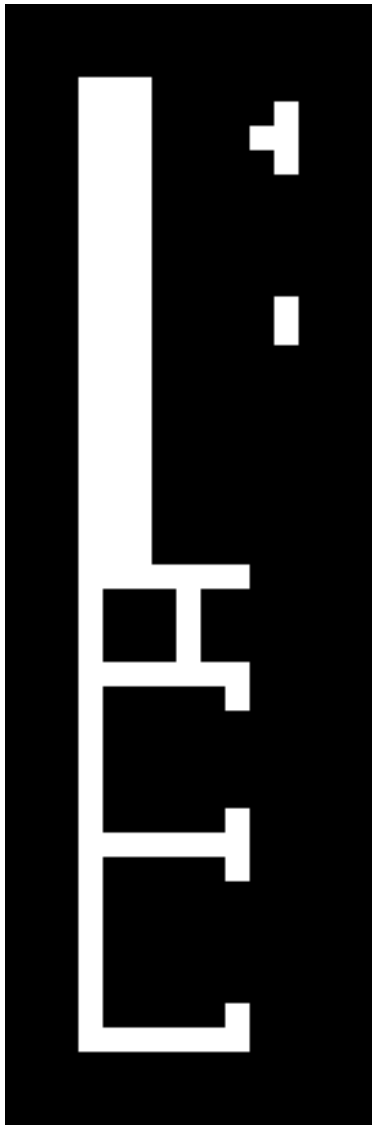
Dilation

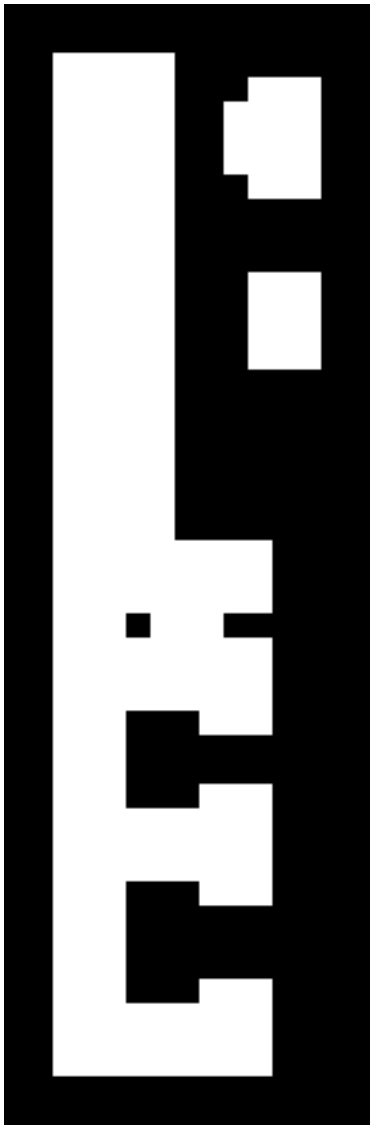


Morphological opening



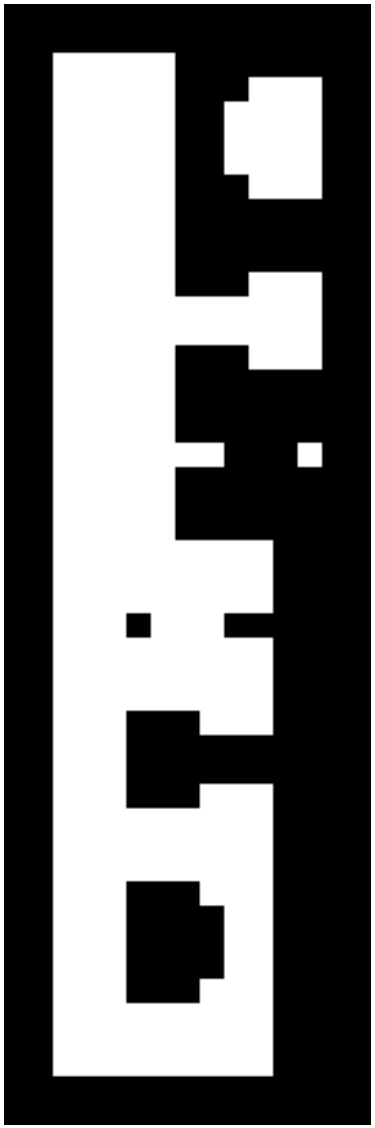
Original



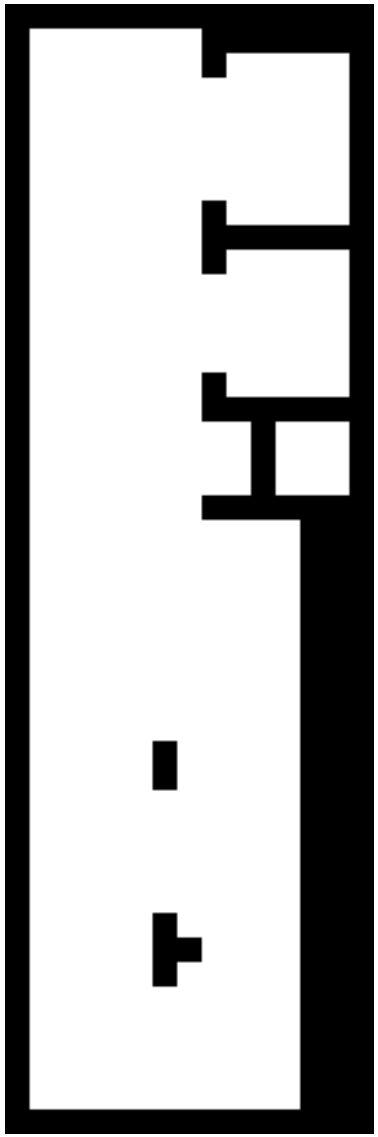


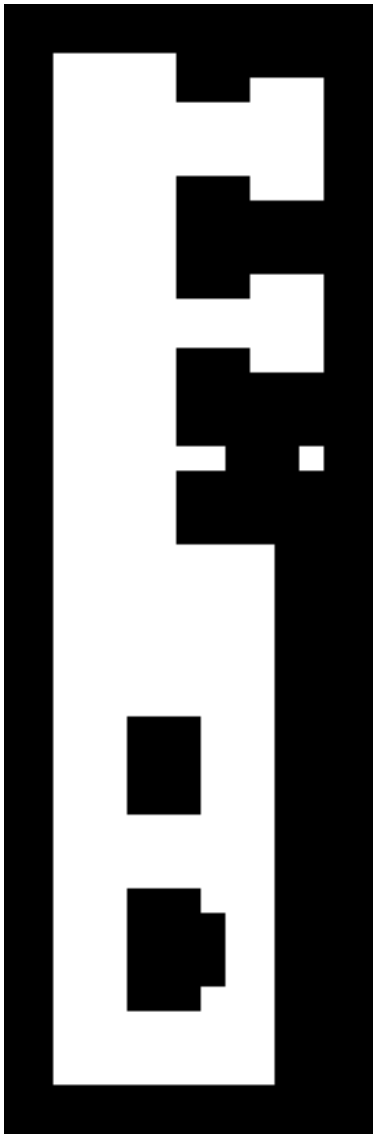
Erosion followed by dilation

Morphological closing



Original





Dilation followed by erosion

More formally

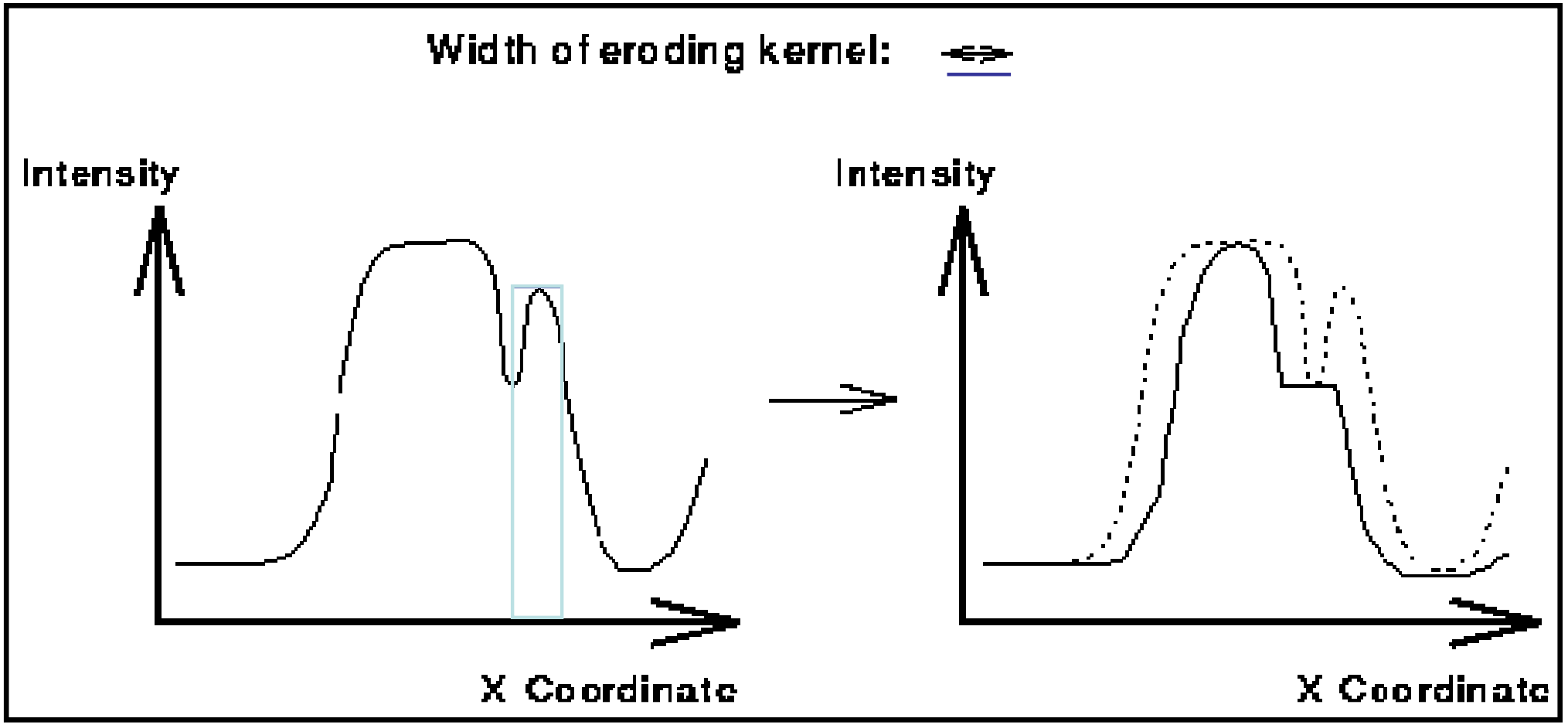
Erosion $$e(x, y) = \min_{\Delta x} \min_{\Delta y} h(x + \Delta x, y + \Delta y)$$

Dilation $$d(x, y) = \max_{\Delta x} \max_{\Delta y} h(x - \Delta x, y - \Delta y)$$

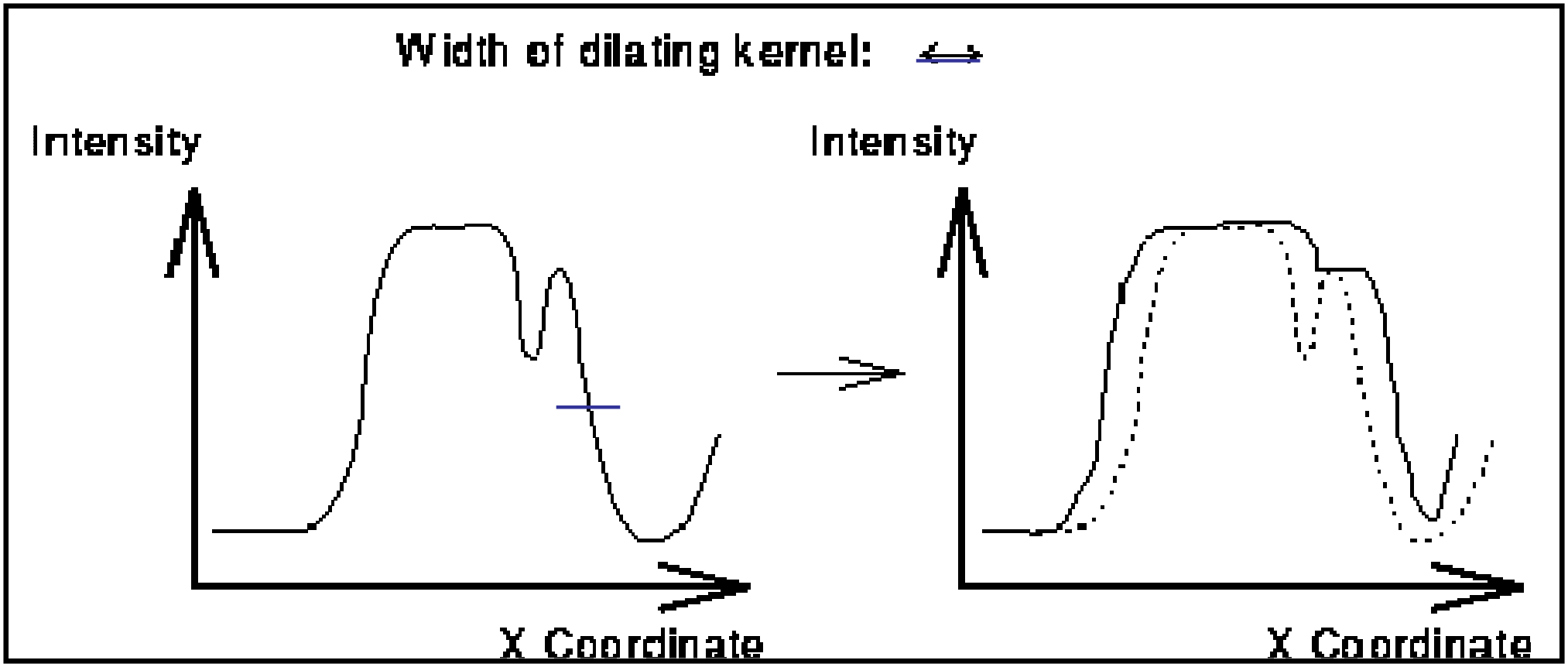
Δx, Δy - for all pixels inside structure element

Opening - Min/Max filter

Grey scale erosion



Grey scale dilation



Grey scale mathematical morphology

Kernel function $$k(\Delta x, \Delta y), \quad -\frac{K}{2} \le \Delta x, \Delta y \le \frac{K}{2}$$

Erosion $$e(x, y) = \min_{\Delta x} \min_{\Delta y} \left[h(x + \Delta x, y + \Delta y) - k(\Delta x, \Delta y) \right]$$

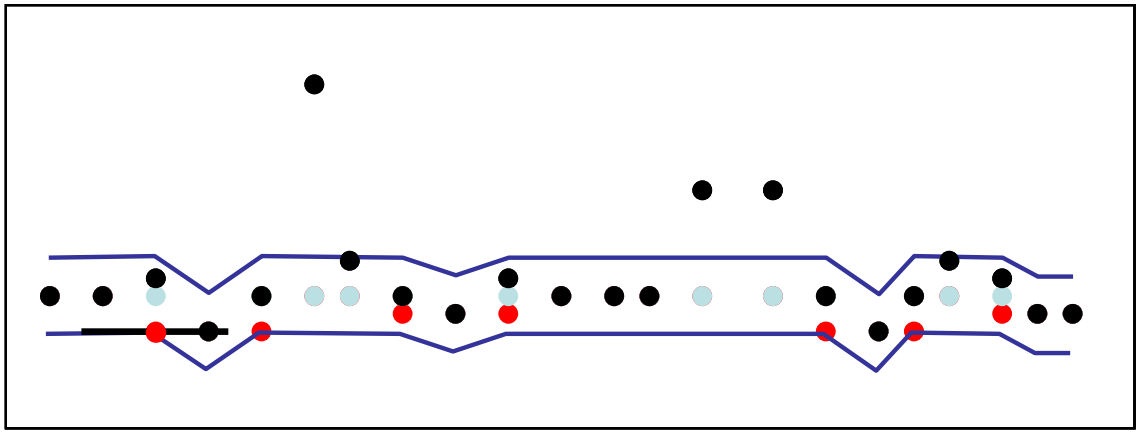
Dilation $$d(x, y) = \max_{\Delta x} \max_{\Delta y} \left[h(x - \Delta x, y - \Delta y) + k(\Delta x, \Delta y) \right]$$

Min/Max $$k(\Delta x, \Delta y) = 0, \quad -\frac{K}{2} \le \Delta x, \Delta y \le \frac{K}{2}$$

Filtering with mathematical morphology

Single opening (min/max)

- Selections
  - Window size
  - Height tolerance



Openings with multiple kernel sizes

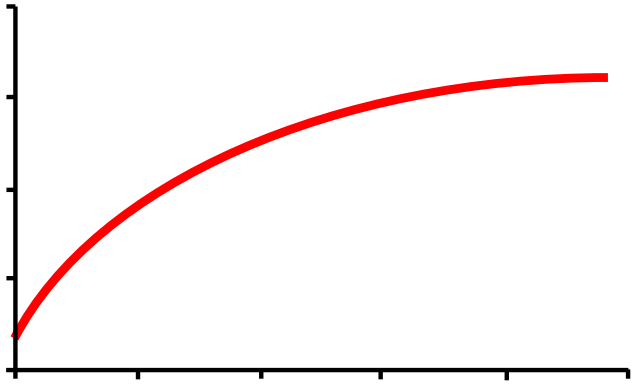
- Increasing height tolerance with increasing window size

Structure element

Slope based filtering

- Optimal filter depends on terrain type
- Reject large height jumps
- Take distance between points into account

Filter function: $\Delta h_{\max}(d)$



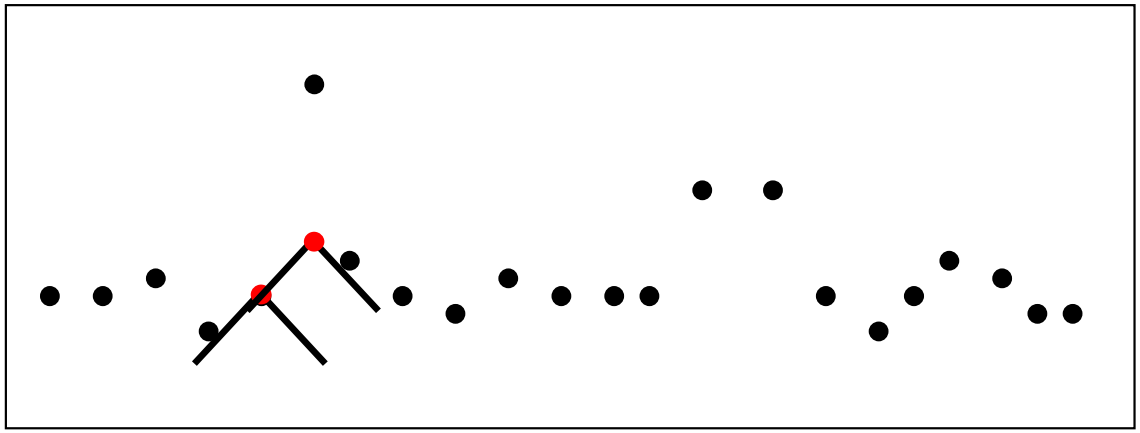
Let A be the set of all points. Define DEM* as

$$DEM = \left\{ p_i \in A \mid \forall p_j \in A : \Delta h_{ij} \leq \Delta h_{\max}(d_{ij}) \right\}$$

* DEM = ground point set

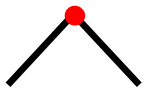
Erosion with a kernel function

Terrain properties encoded in structure element.



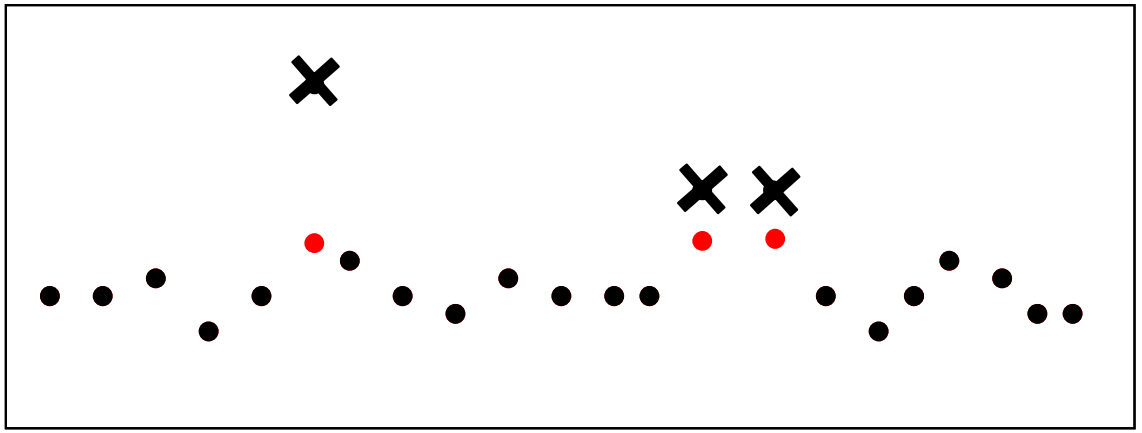
Example:

Maximum terrain slope

Structure element 

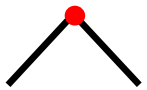
Erosion with a kernel function

Terrain properties encoded in structure element.



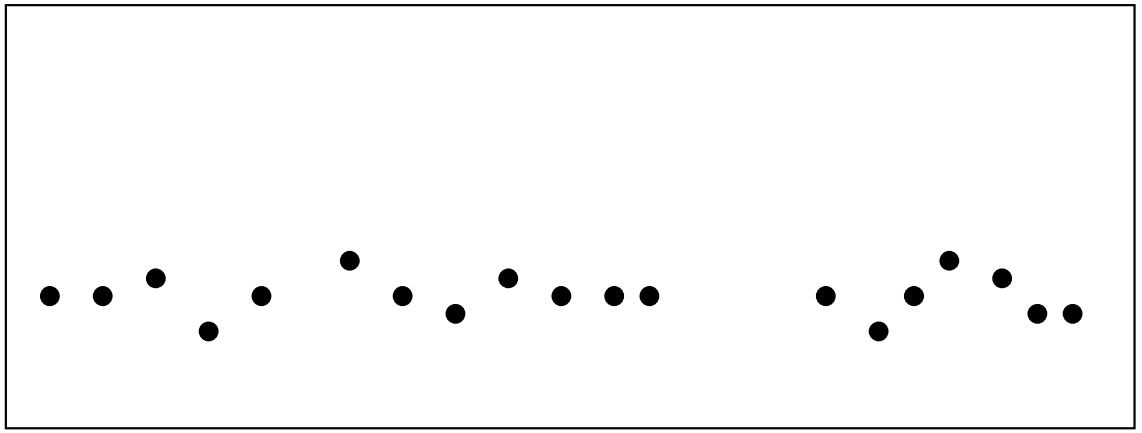
Example:

Maximum terrain slope

Structure element 

Erosion with a kernel function

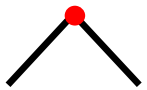
Terrain properties encoded in structure element.



Height ≤ eroded height

Example:

Maximum terrain slope

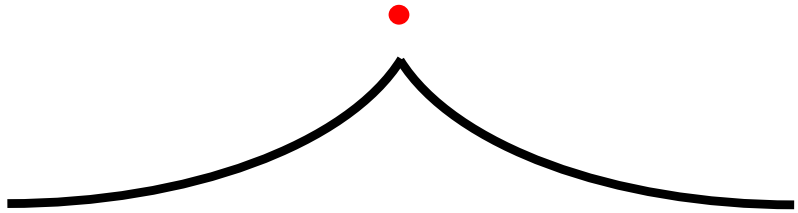
Structure element 

More formally

For images: $e(x,y) = \min_{\Delta x} \min_{\Delta y} \left[h(x+\Delta x, y+\Delta y) - k(\Delta x, \Delta y) \right]$

For sets: $e_{p_i} = \min_{p_j \in A} \left[h_{p_j} - k(\Delta x_{ij}, \Delta y_{ij}) \right]$

$$k(\Delta x, \Delta y) = -\Delta h_{\max} \left(\sqrt{\Delta x^2 + \Delta y^2} \right)$$



$$e_{p_i} = \min_{p_j \in A} \left[h_{p_j} + \Delta h_{\max} (d_{ij}) \right]$$

$$DEM = \left\{ p_i \in A \mid h_{p_i} \leq e_{p_i} \right\}$$

Filter functions

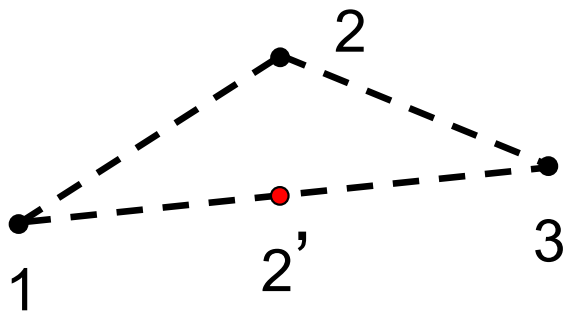
- Theoretical
  - Assume maximum slope, e.g. 30%
  - Assume standard deviation σ and a confidence interval, e.g. 95%.

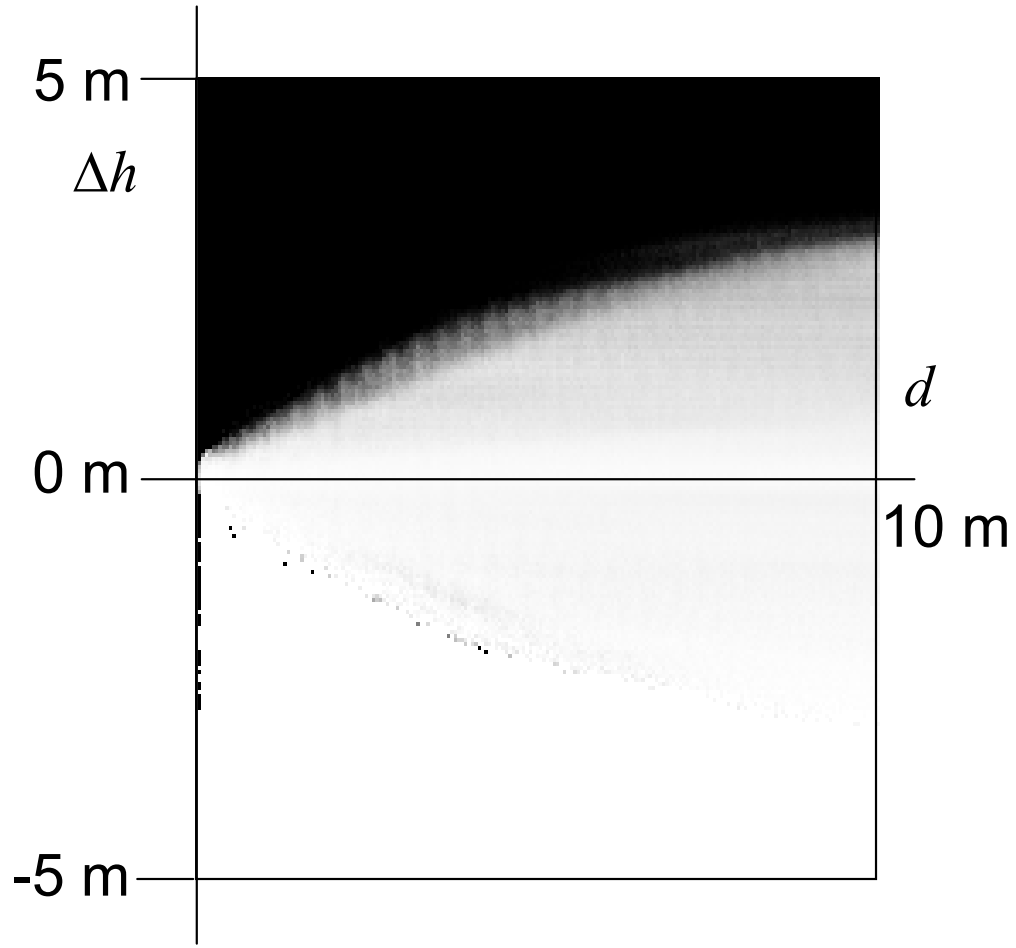
$$\Delta h_{\max}(d) = 0.3\, d + 1.65\sqrt{2}\sigma$$

- Preserving important terrain features
  - Training set with ground points only
  - For each distance interval d, determine max(Δh)

Filter functions (II)

- Minimising classification errors
  - Effect of type I error equals effect of type II error



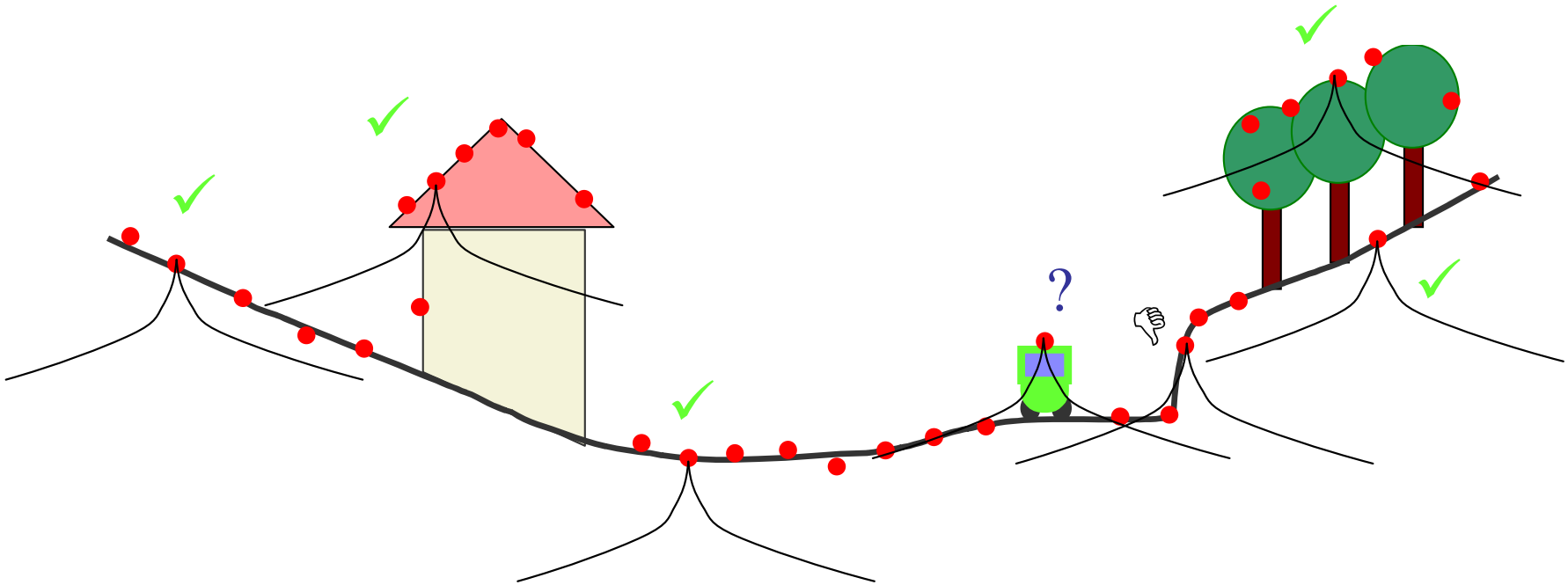


  - For each d, determine Δh for which

$$P(p_i \in DEM \mid \Delta h, d, p_j \in DEM) = 0.5$$

Filter functions (III)

morphological filtering



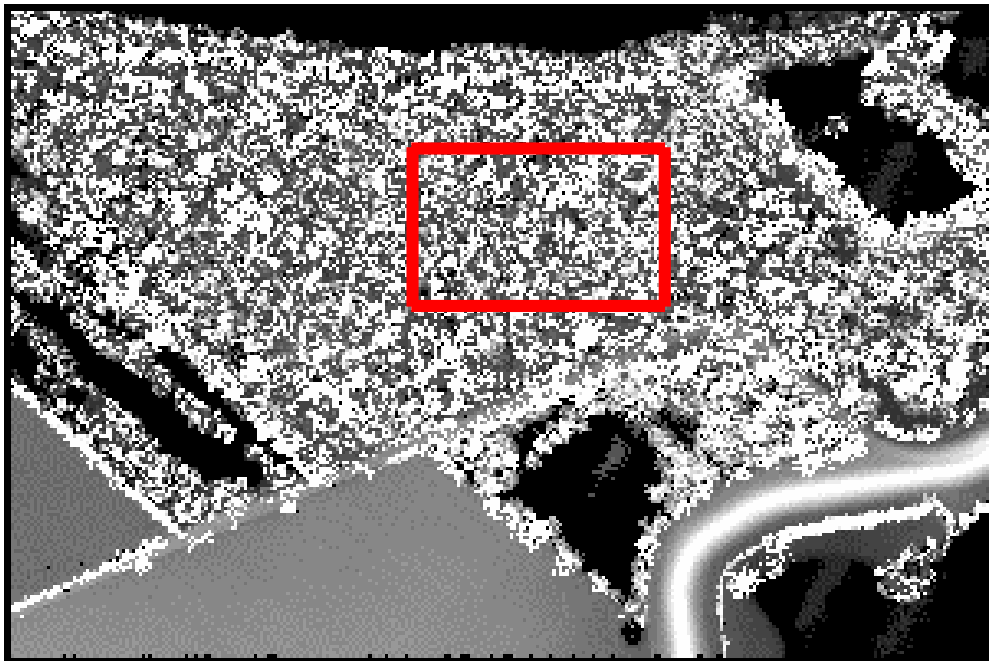
Example

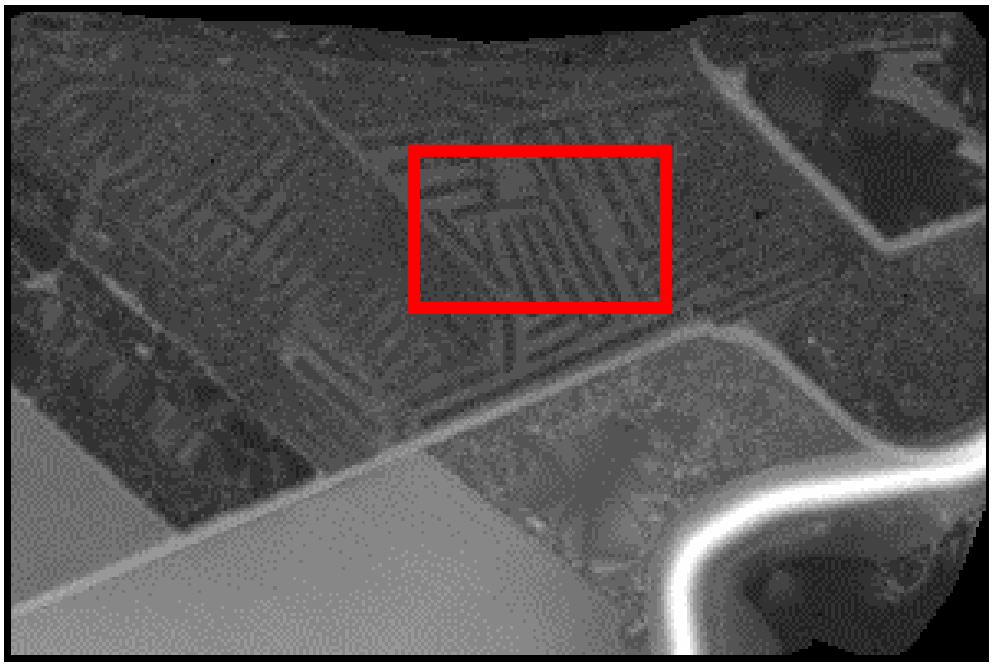
Area: partly open, wooded, with a dike

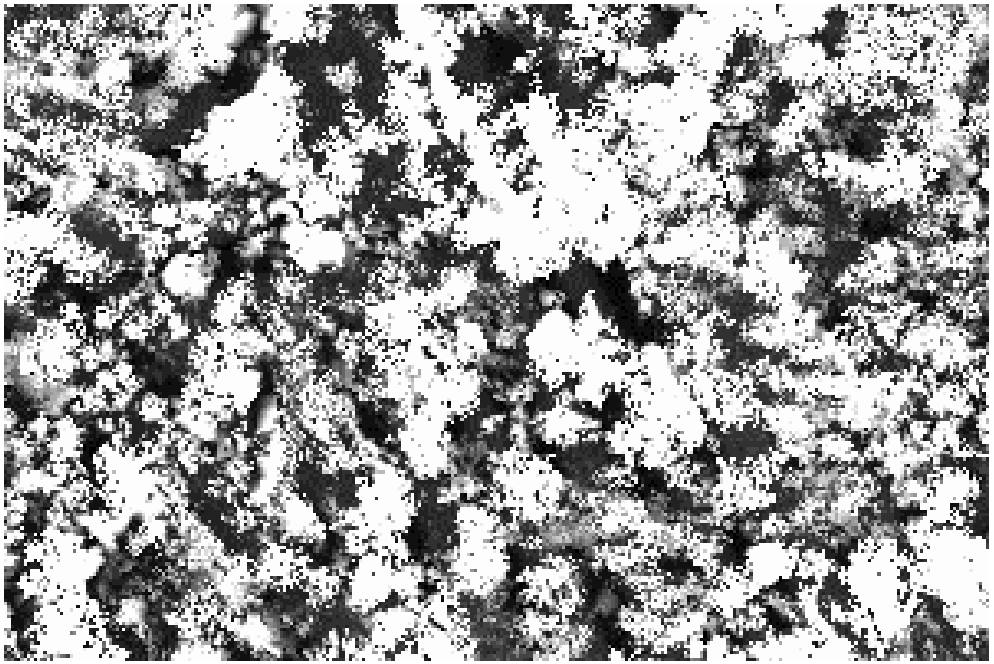
Filter kerner: use training data set

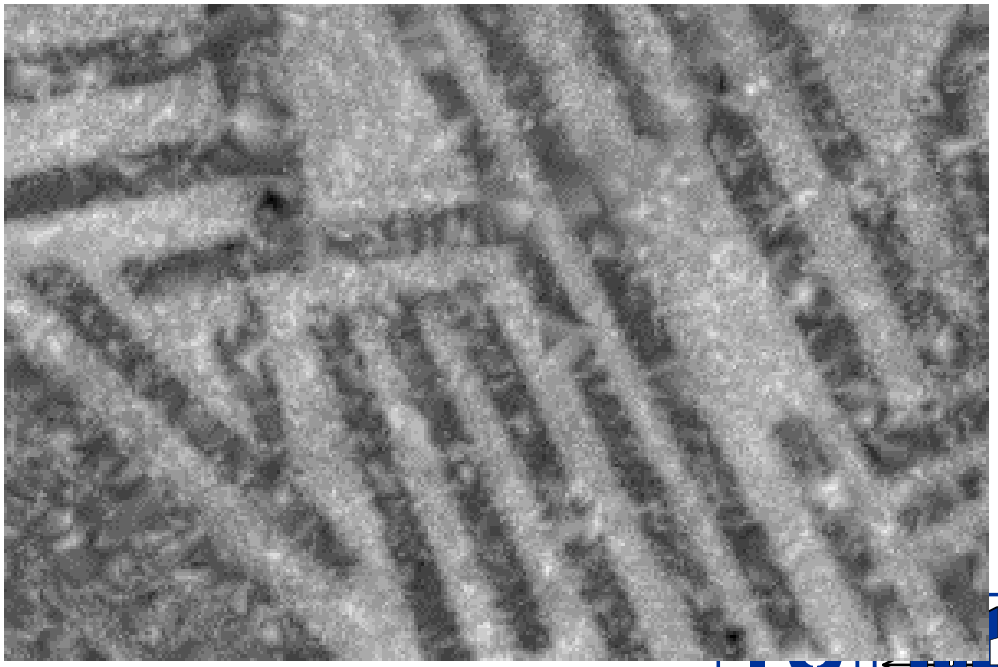
maximum filter (i.e. no ground points lost)

Tested also with reduced resolution









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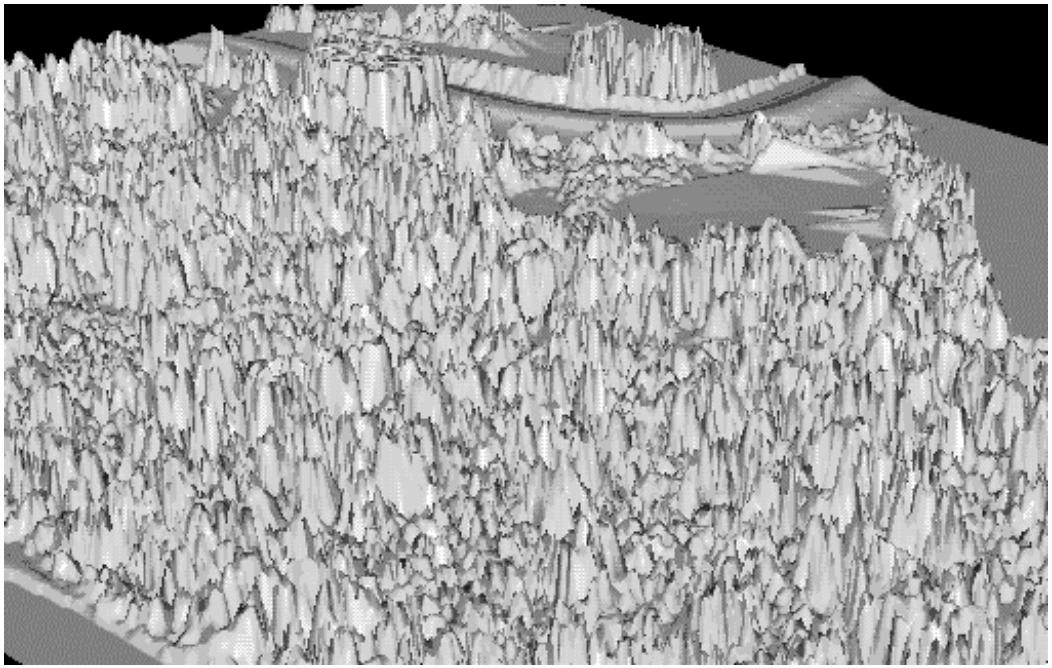

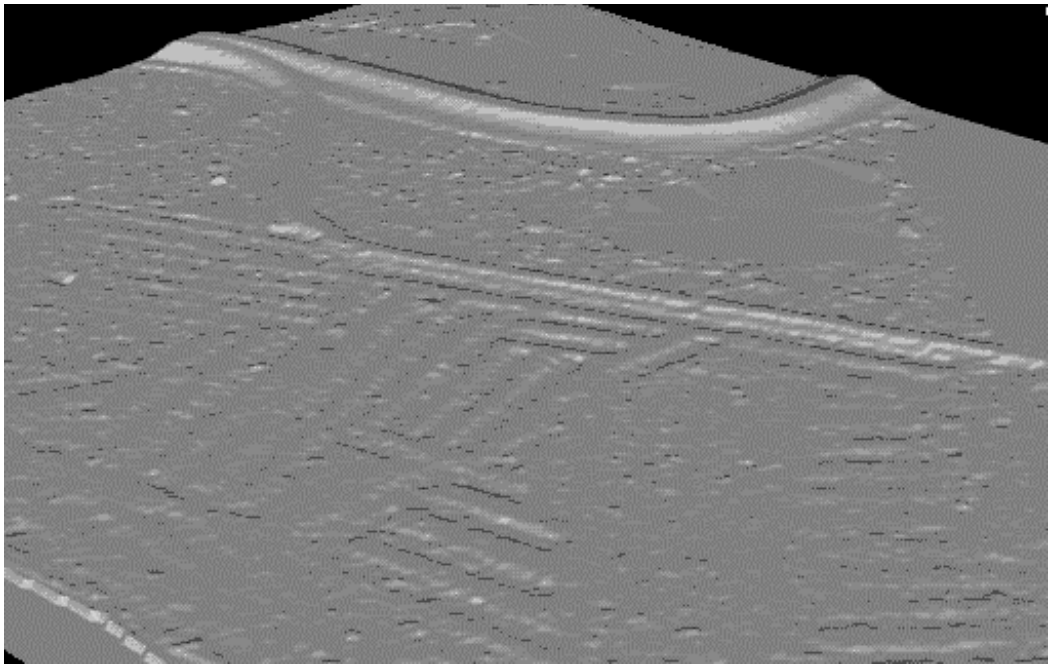

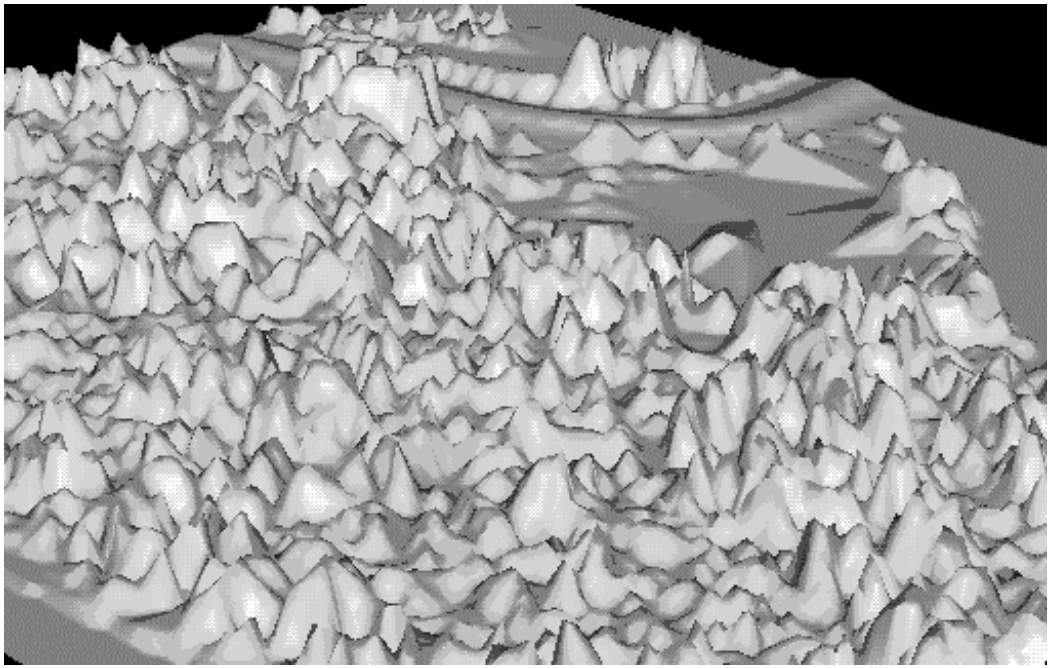

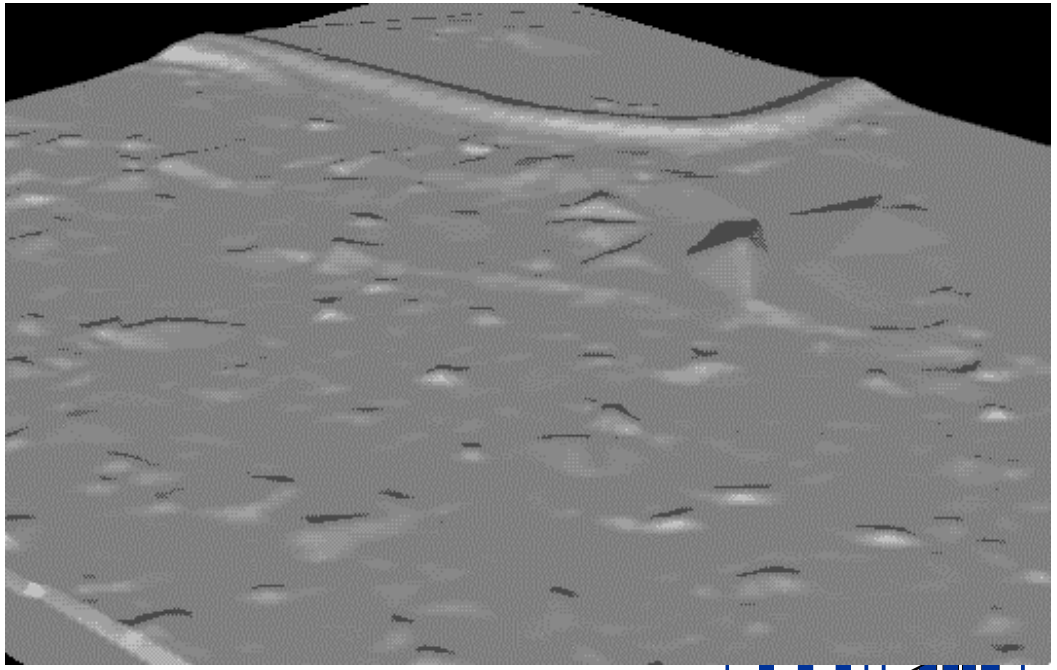

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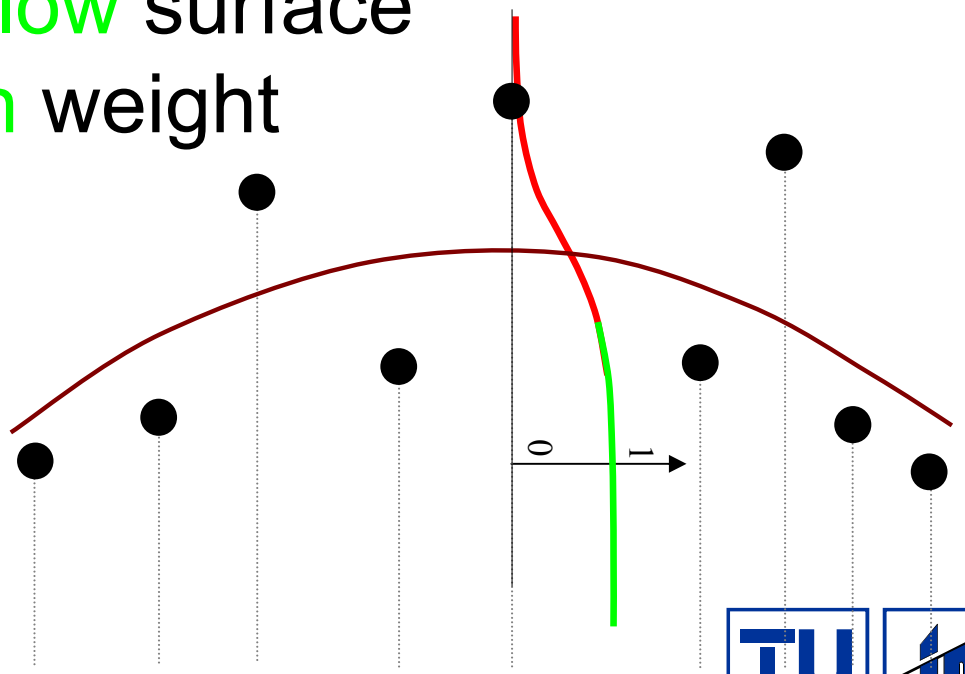
Approach 2
Robust interpolation

- Principle
- Mathematical description
- Hierarchic extension
- Example

Robust interpolation

- interpolation: surface $f(x,y)$ “through” points
  filtering of measurement errors
- robust: residuals (surface – laser point)
  weight function:
  points above/below surface
  ➲ small/high weight
- iterate
- General principle:
  weight function
  interpolation method



Mathematical formulation

$z(x,y) = \mathbf{c}^T\mathbf{C}^{-1}\mathbf{z}$

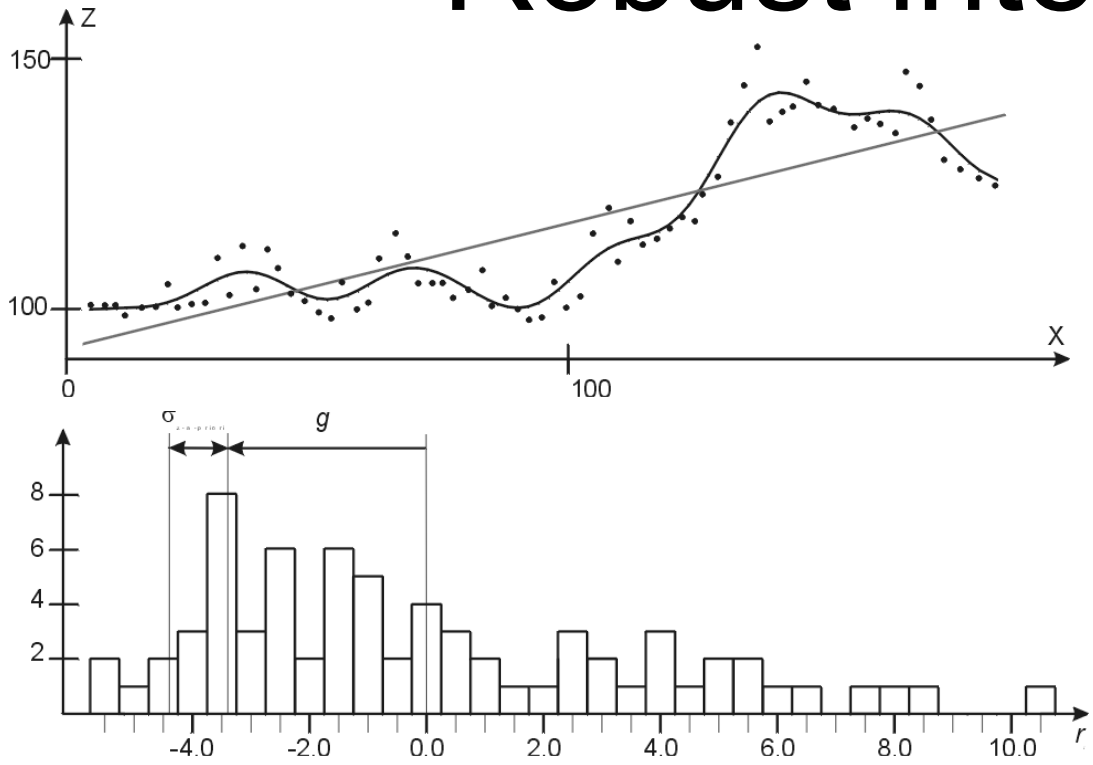
$\mathbf{c} = (C(p,p_1), \ldots C(p,p_n))^T , \quad \mathbf{z} = (z_1, \ldots z_n)^T$

$$\mathbf{C} = \begin{pmatrix} V_{zzp1} & C(p_1,p_2) & \cdots & C(p_1,p_n) \\ C(p_1,p_2) & V_{zzp2} & & C(p_2,p_n) \\ \vdots & & \ddots & \\ C(p_1,p_n) & C(p_2,p_n) & \cdots & V_{zzpn} \end{pmatrix}$$

$$V_{zzp_i} = \sigma_z{}^2 / \, w_i + C(0)$$

$$w(r) = \begin{cases} r < g & : \quad 1 \\ g \le r \le g + h & : \quad \dfrac{1}{1 + (a(r-g))^b} \\ r > g + h & : \quad 0 \end{cases}$$

Robust interpolation



Simple kriging (=lineare prediction)

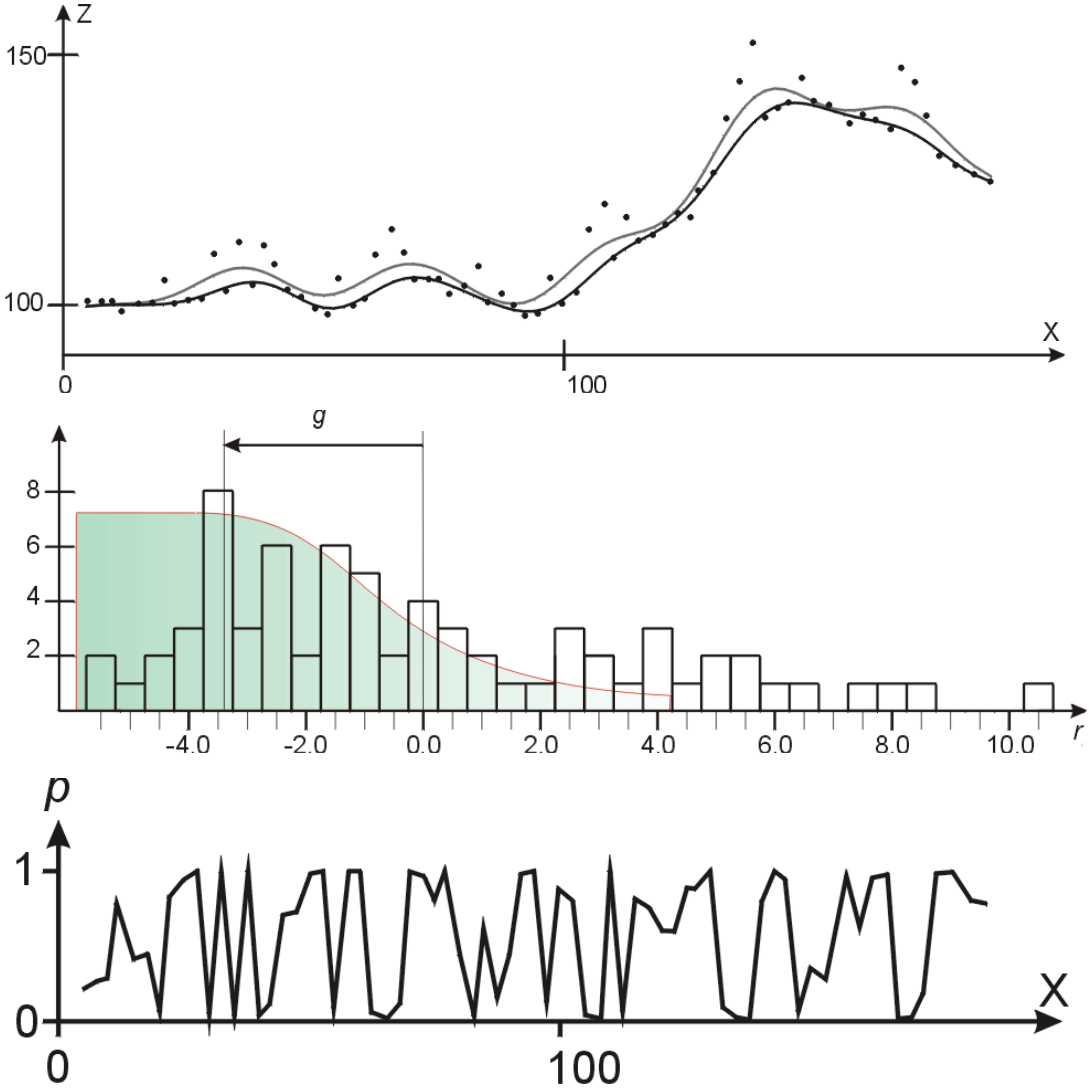
- random measurement errors

Histogram of residuals

Origin of the weight function

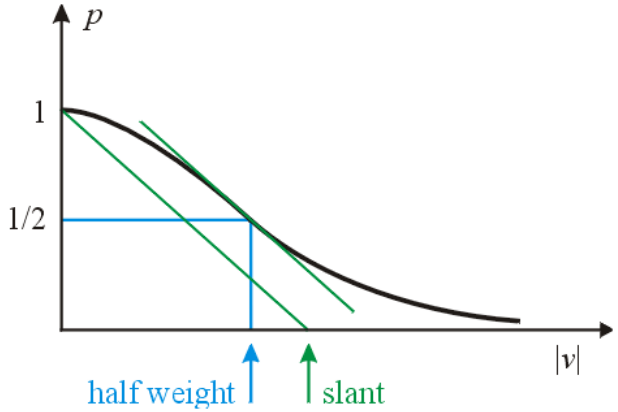
- statistical method
- penetration rate
- histogram analysis

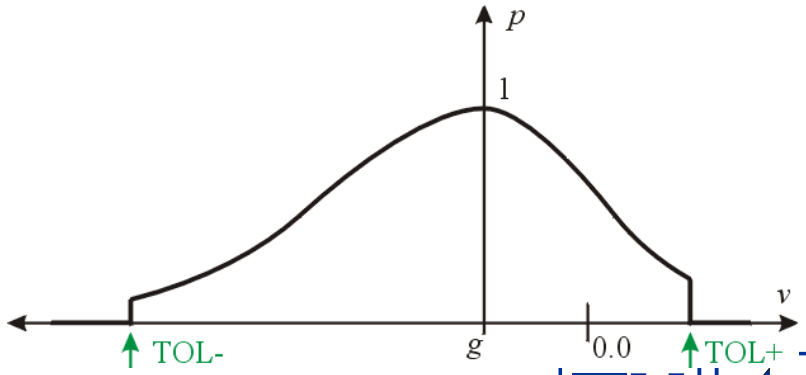
Robust interpolation



Weight funtion

- Half weight width
- Slant





Hierarchic filter strategy

- Robust interpolation requires
  good mixture of
  ground and off-terrain points
- Hierarchic approach guarantees mixture
- Hierarchic approach speeds up process

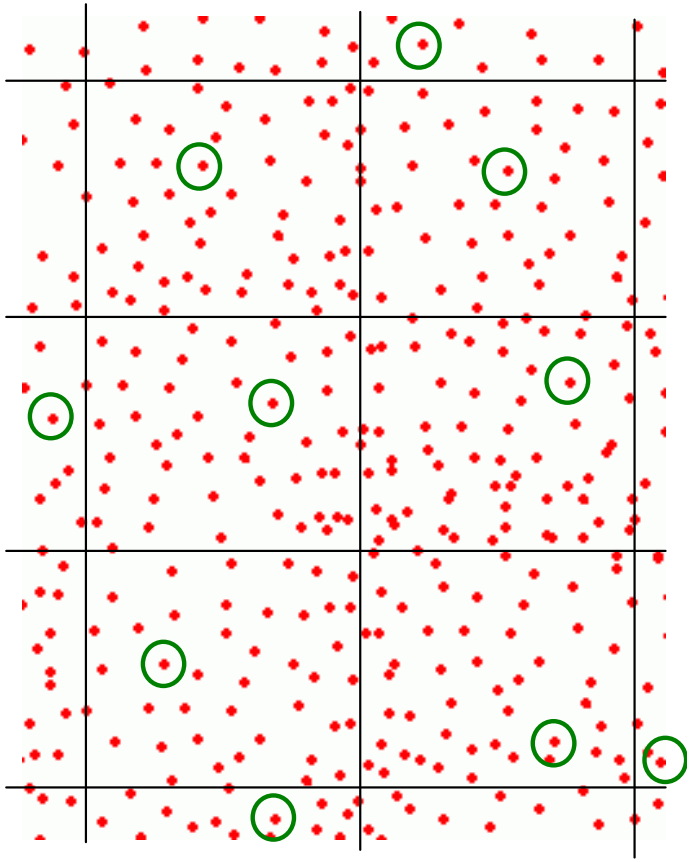
Hierarchic filter strategy I

- Compute data (point set) at different niveaus:

  Select

  – Lowest point or barycenter

  for each cell (define edge length)

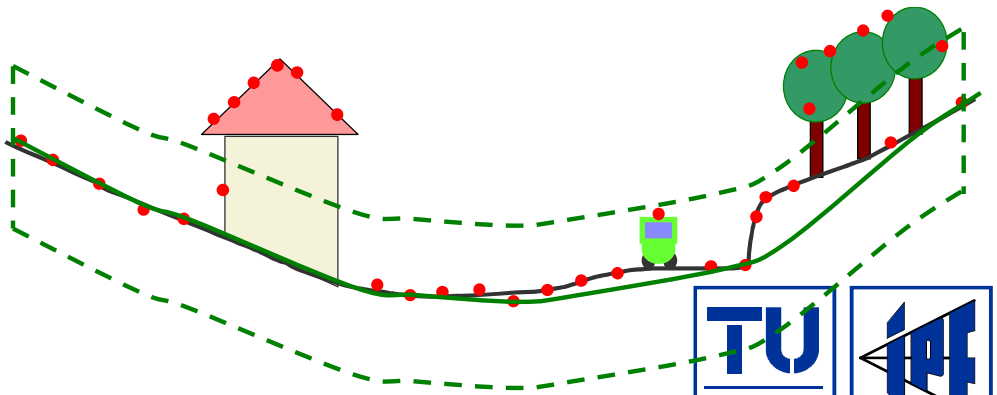


- Process (filter) different niveaus coarse to fine
  e.g.: 20m → 4m → original data

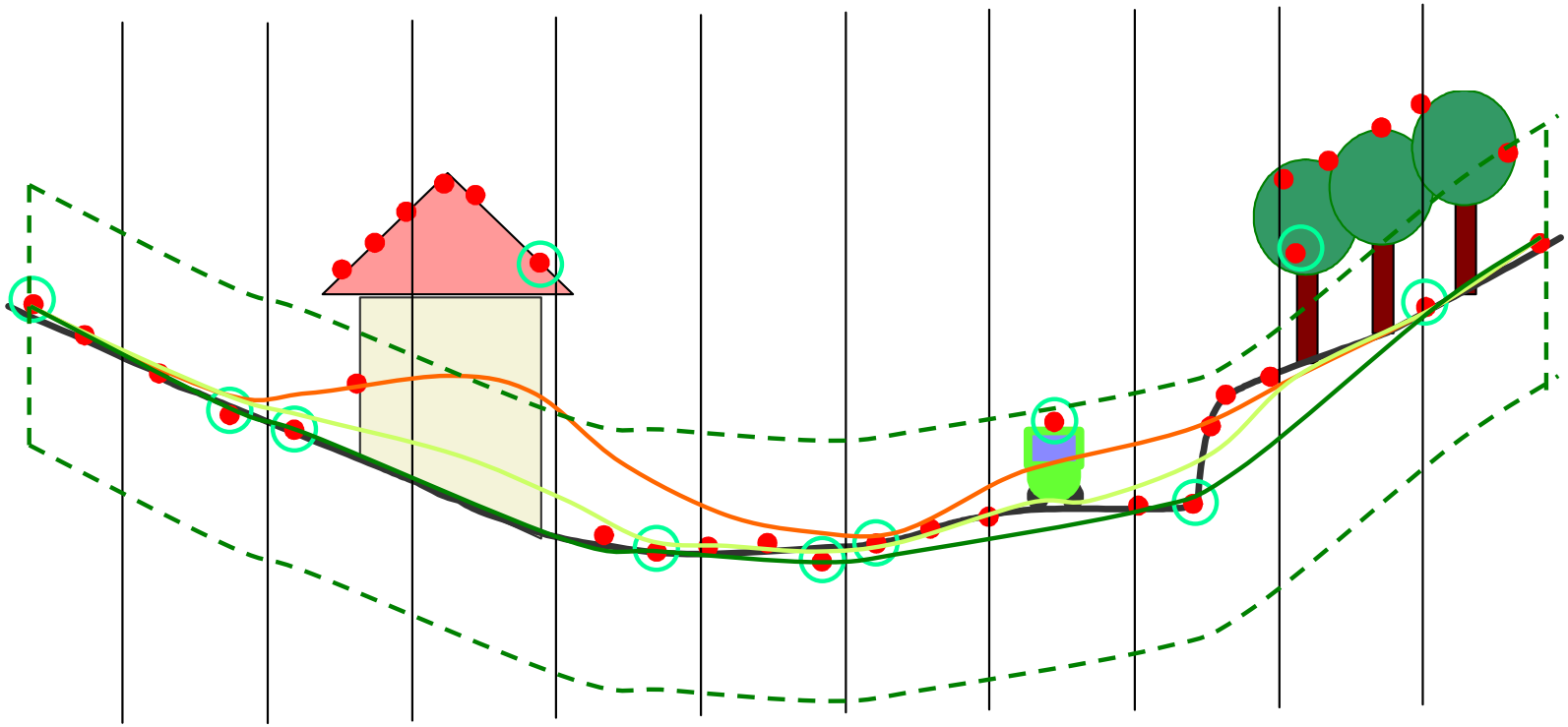
Hierarchic filter strategy II

Iteration

1. Robust interpolation for coarsest niveau
   → first DTM
2. Select points of next (finer) niveau within a tolerance band of DTM
3. Robust interpolation for selected points
4. Iterate from step 2

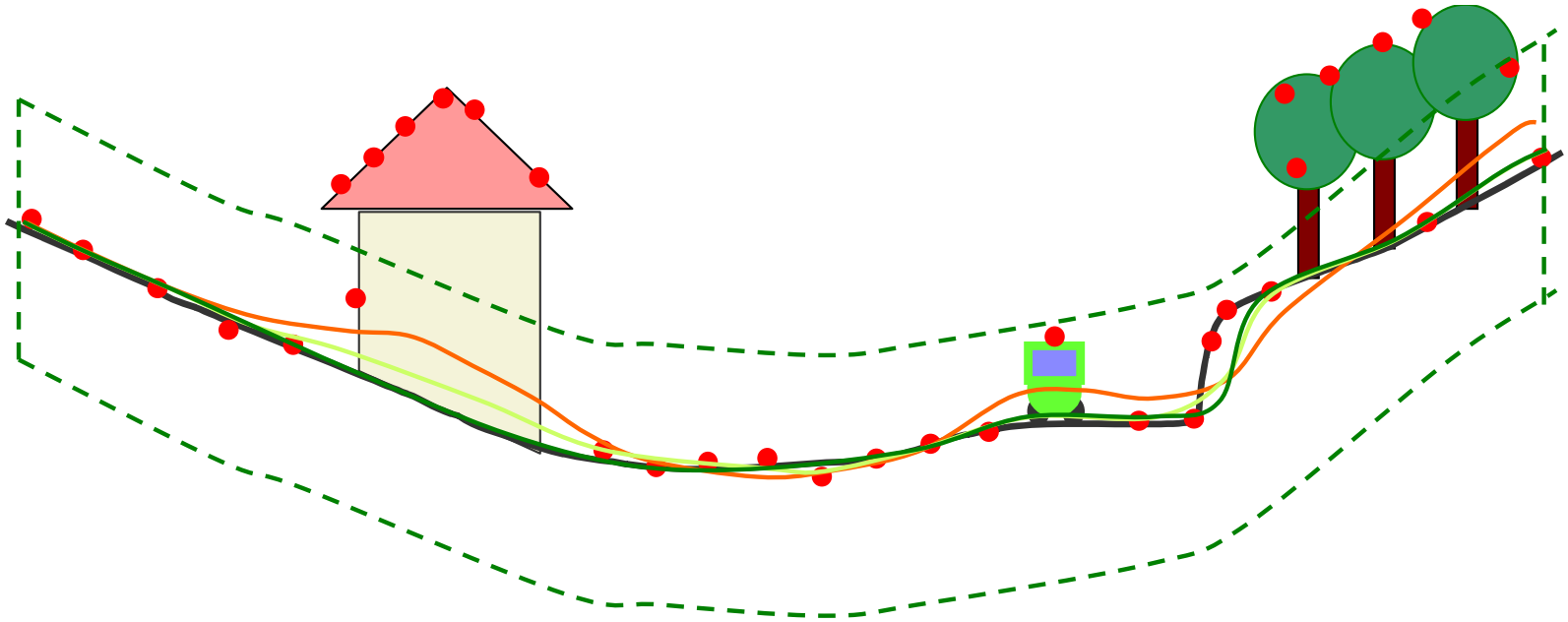


Hierarchic robust interpolation



Niveau 1

Hierarchic robust interpolation



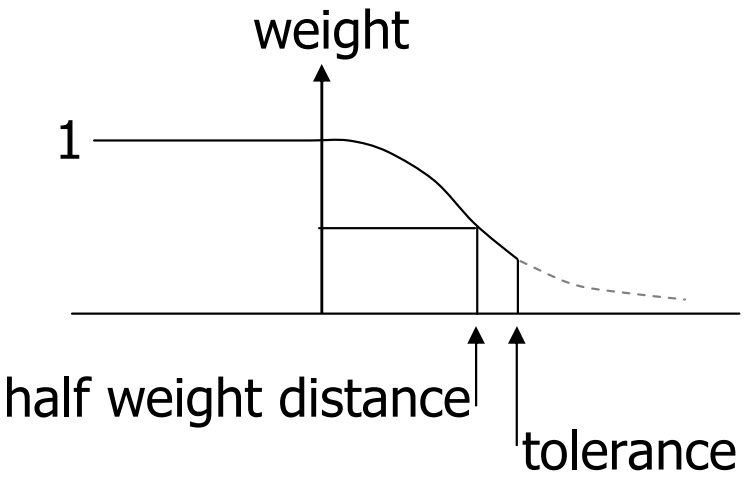
Niveau 2

Example

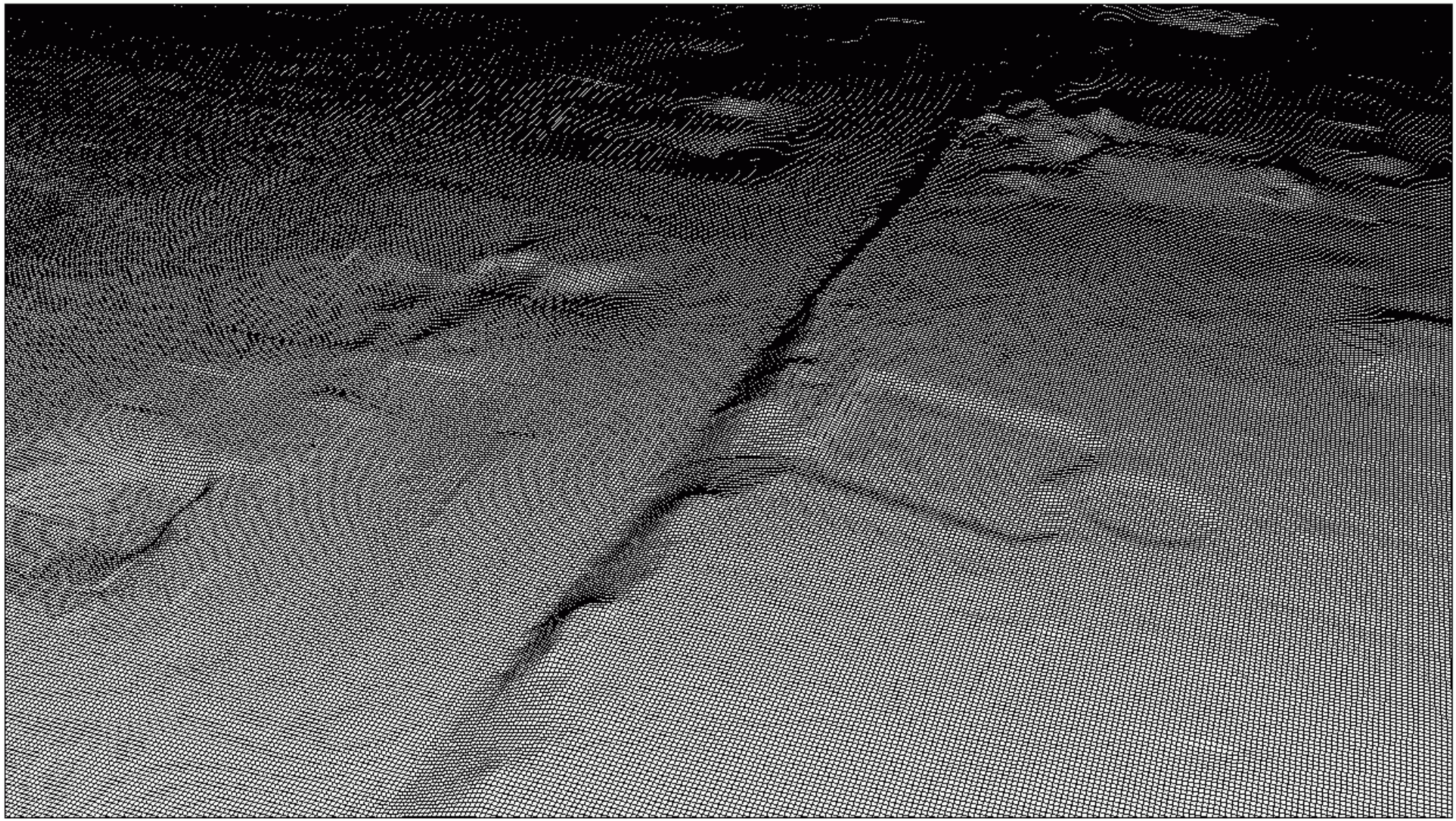
5m level
- select mean point in 5m x 5m cell
- robust filtering
  - weight function half weight @75cm
  - weight function tolerance 1m
- select Points ⌖3m of DTM

2m level
- select lowest point in 2m x 2m cell
- robust filtering
  - weight function half weight @30cm
  - weight function tolerance 60cm
- select Points ±2m of DTM

original (0.5m level)
- robust filtering
  - weight function half weight @20cm
  - weight function tolerance 30cm

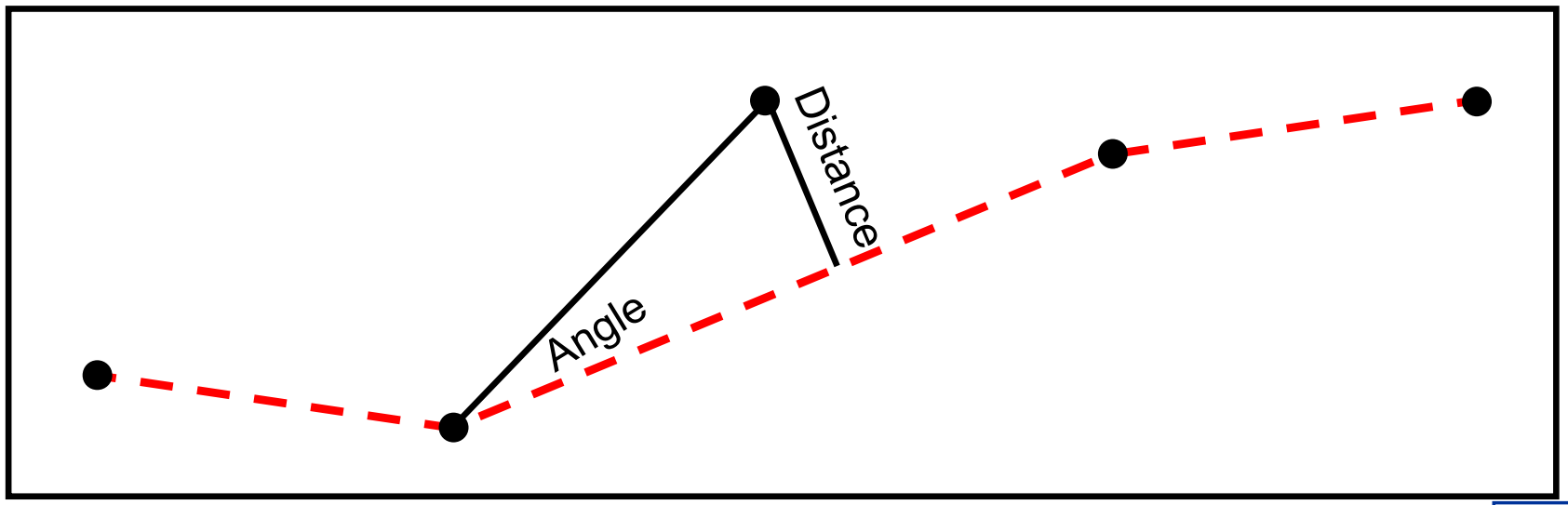


DTM - Stadtgebiet WEST - 0.5m Rasterweite



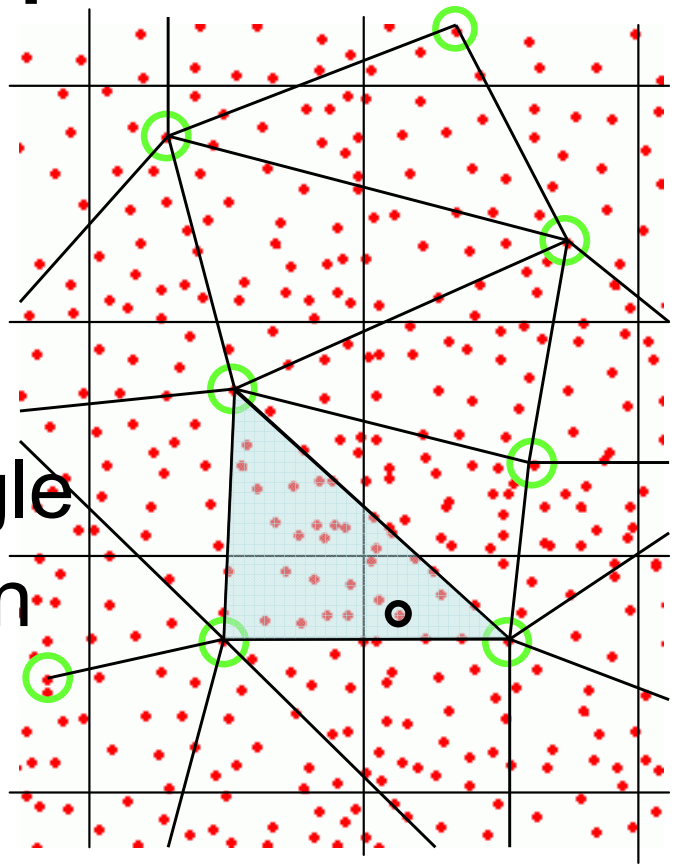
Approach 3
progressive TIN densification

- Select a few low points that are most likely terrain
- Build a TIN of the low points
- Add nearby points to TIN



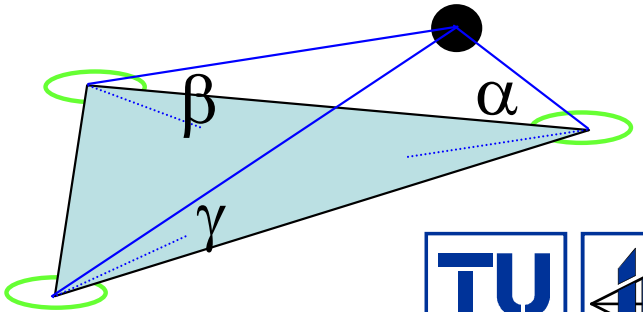
TIN densification

1. Select lowest points in big areas
2. Triangulate points
3. Test: single point ★ triangulation angle: (single point,vertex) to triangle
4. Add accepted points to triangulation
5. Iterate from step 3

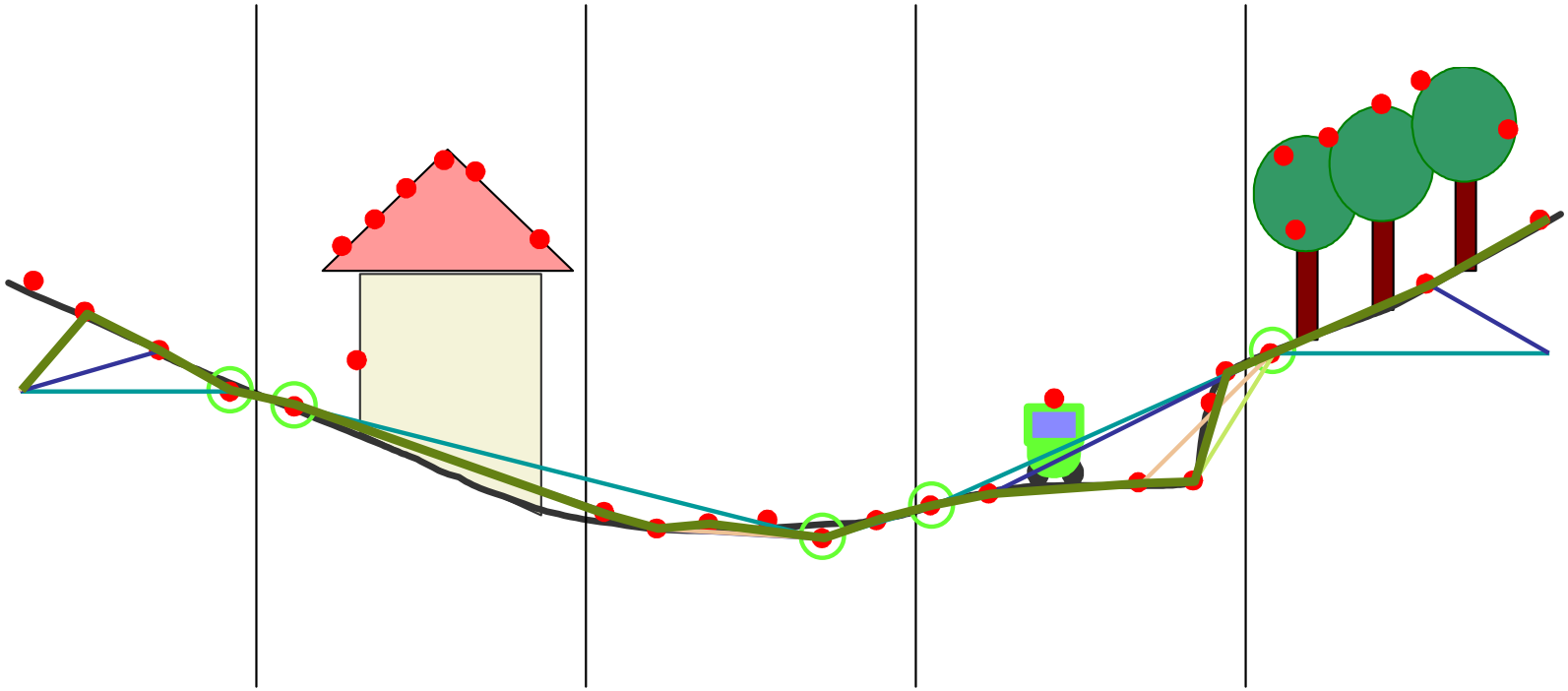


Variants:

- 1 point / more points per iteration
- criterion: angle, distance, ...



TIN densification



Approach 4
Segmentation Based Filters

What Is Segmentation?

- Partitioning of a data set R in object space (image, point cloud) into N disjoint, coherent subsets R_i.

1) $\cup R_i = R$

2) R_i is a connected region for all i

3) $R_i \cap R_j = \{\}$ for i # j

4) $P(R_i) = true$ for all i and a coherence predicate P

5) $P(R_i \cup R_j) = false$ for all adjacent regions R_i, R_j, i # j

What Is Segmentation?

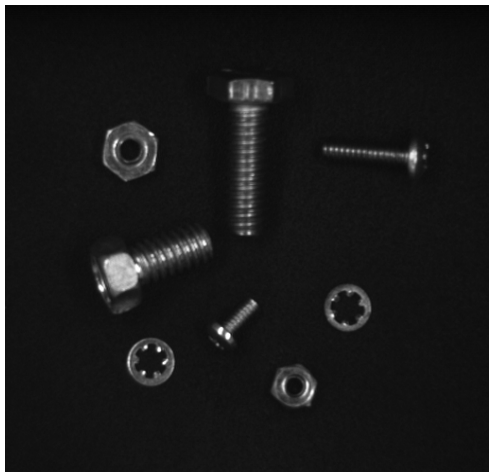
- Partition data into smaller, coherent and „meaningful“ subsets
  - Prerequisite for reconstruction (instantiation of geometric primitives)

- In the simplest case, segments correspond directly to objects of interest
  - Blob analysis in image processing

What Is Segmentation?

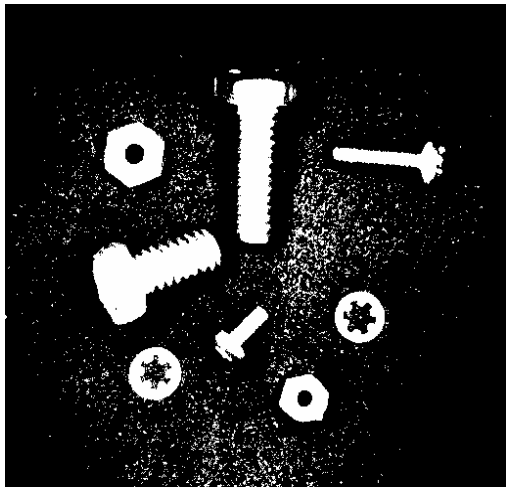
- Example: Image Segmentation + Blob Analysis

Grayscale Image



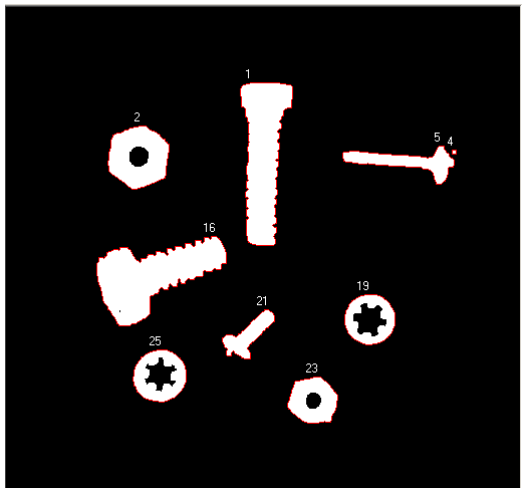
Thresholding

Binary Image



Postprocessing + Labeling

Detected Blobs (Objects)



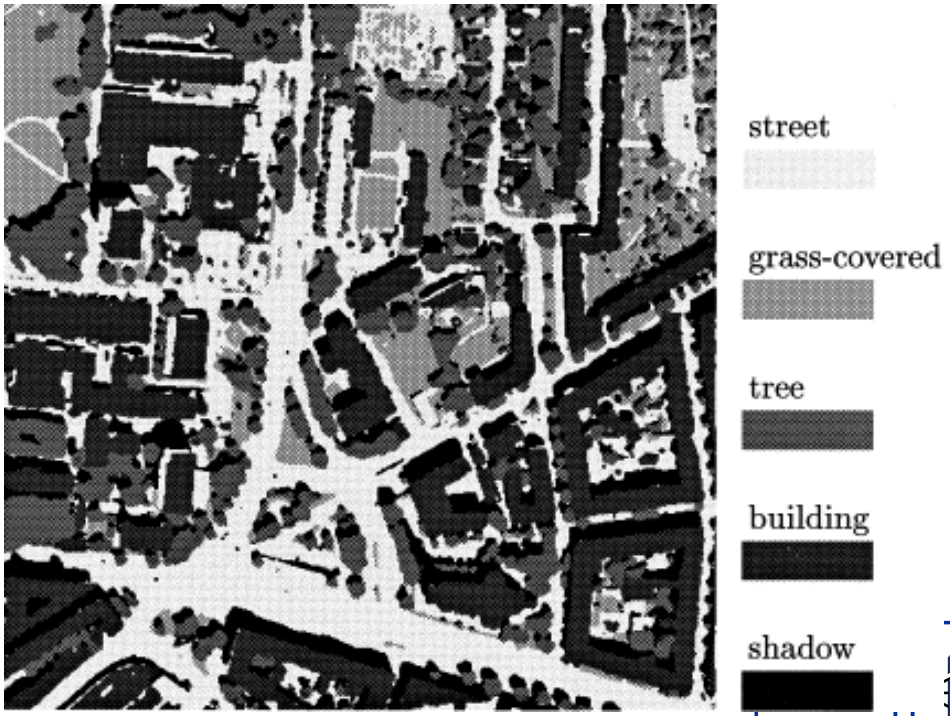
What is Segmentation?

- Classification vs. Segmentation
  - segmentation: assigment to (parts of) objects, e.g., roof plane #117
  - classification: assignment to thematic groups, e.g., vegetation, roof
  - segmentation ~ classification + connected components analysis

Classification example

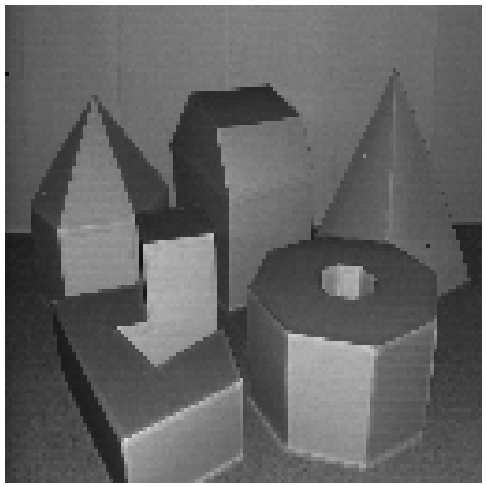
ISODATA clustering of height and intensity values + manual annotation of clusters

Hala & Brenner, ISPRS,1999

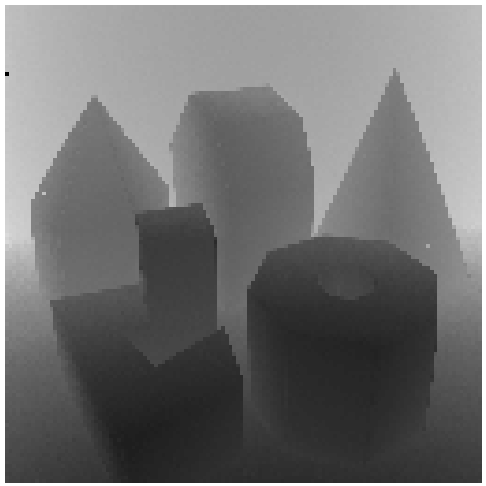


What is Segmentation?

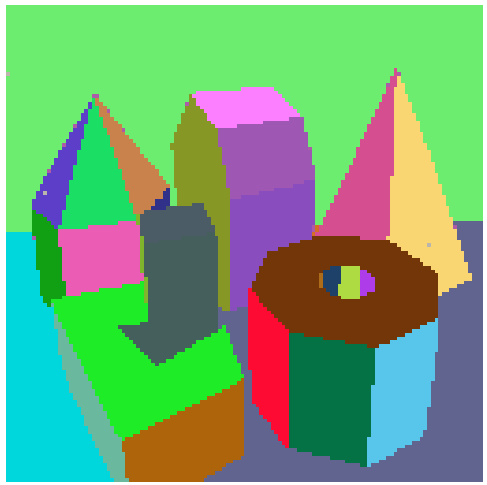
- Complex objects/scenes are broken down into simpler parts/subregions
  - Polynomial surface patches in 2.5 D range data segmentation
  - Example: 2.5 D segmentation of range data into planar patches (images taken from the USF database)



Intensity Image



Range Image



Ground Truth

Range Data Segmentation

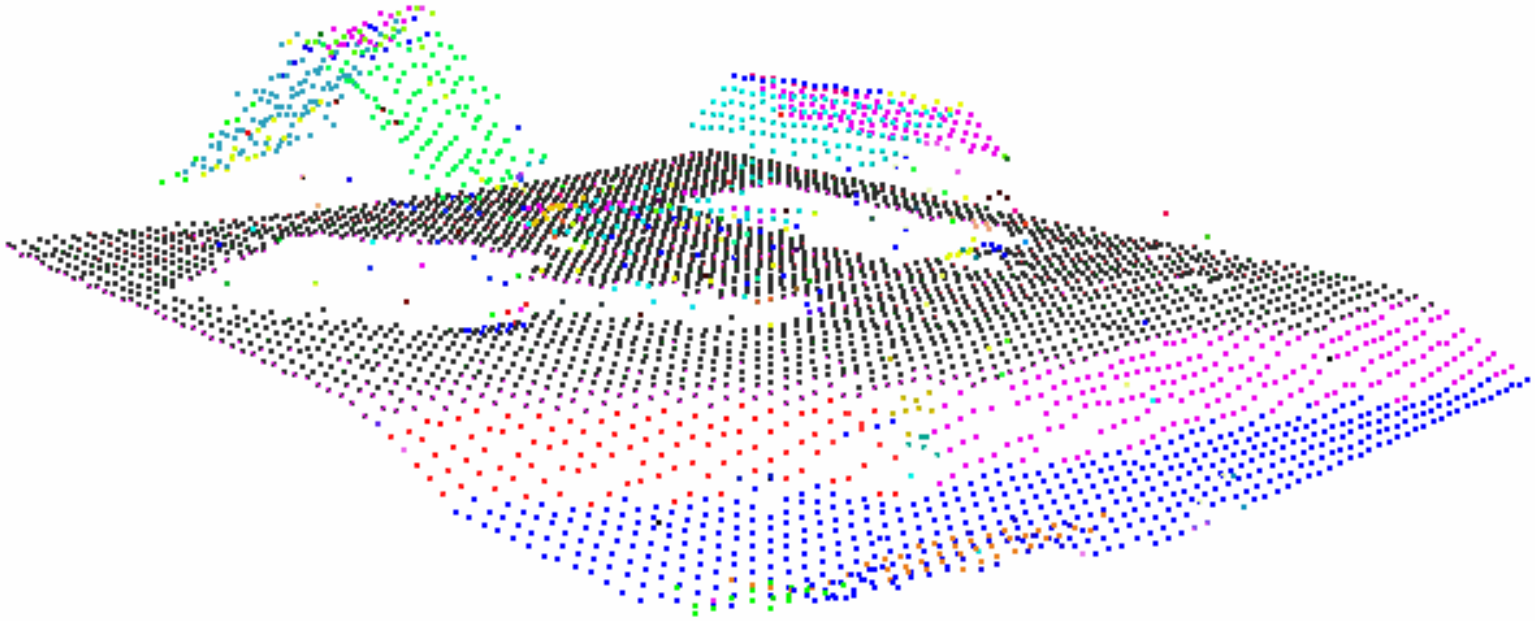
- Range image segmentation is a very active research area since the mid-1980ies.

- Seminal paper by Besl and Jain (1988, PAMI)
  "Segmentation Through Variable-Order Surface Fitting"

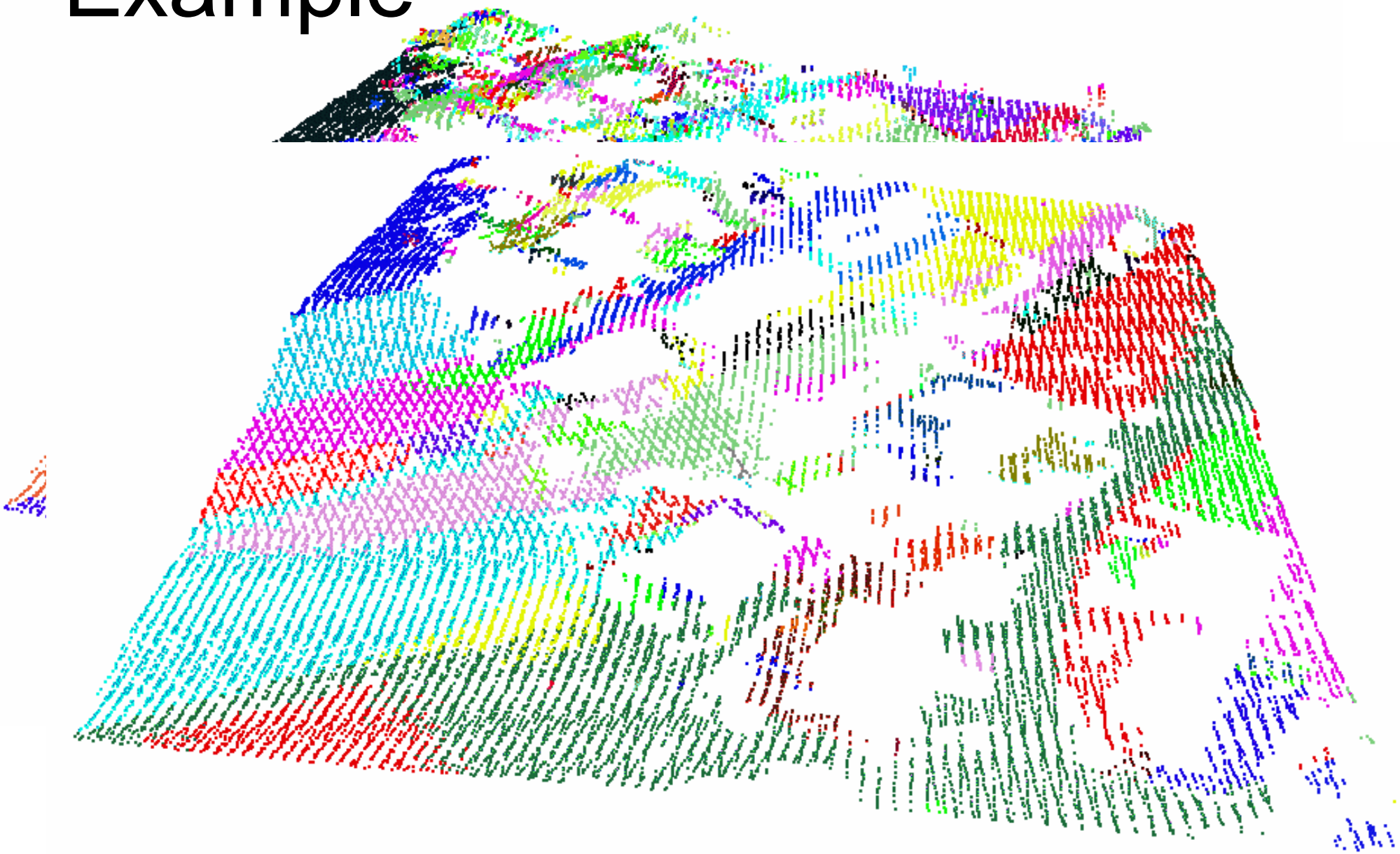
- Main idea
  - Surfaces are modeled locally by bivariate polynomial patches
  - Centers of individual surface patches (seed regions) are determined by Gaussian Mean/Curvature
  - Each patch is "grown" iteratively around its seed region
    - Region growing and model selection (polynomial degree) proceed according to the chi-square statistics of the residuals

Segmentation based filtering

What is a segmentation ?



Example



Comparison of Filtering Approaches

- Concept of surface

- Reducing / adding information

- Experimental comparison

  Sithole et al., 2004. Experimental comparison of filter algorithms for bare—Earth extraction from airborne laser scanning point clouds. ISPRS Journal of Photogrammetry and Remote Sensing

- What do we have now?
  Ground points …
- What do we want?
  Model of the terrain surface =
  = continuous function
  → Interpolation / Approximation
  - Consideration of measurement errors …
    … geostatistics
  - Special character of terrain surface
    - Lineaments
    - Varying variability

Lineaments in the terrain

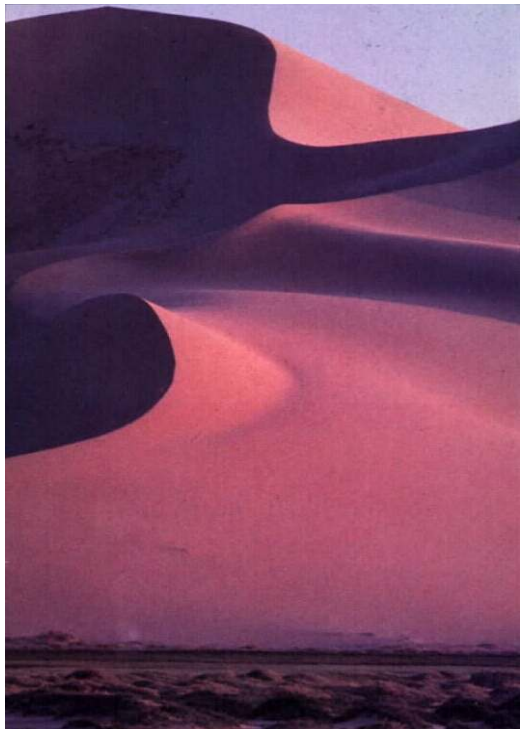
Extraction of break lines
from high resolution
laser scanning data

- Breakline **definition** + motivation
- Breakline **extraction** in **range** images
- Extension: extraction in **point** clouds

Examples for breaklines

http://www.niger-ue.net/minta/tourisme/DESERT/desert.htm

http://home.wanadoo.nl/e.dejong2003/landschap.htm



http://www.arch.mcgill.ca/prof/schoenauer/arch528/lect02/n02.htm

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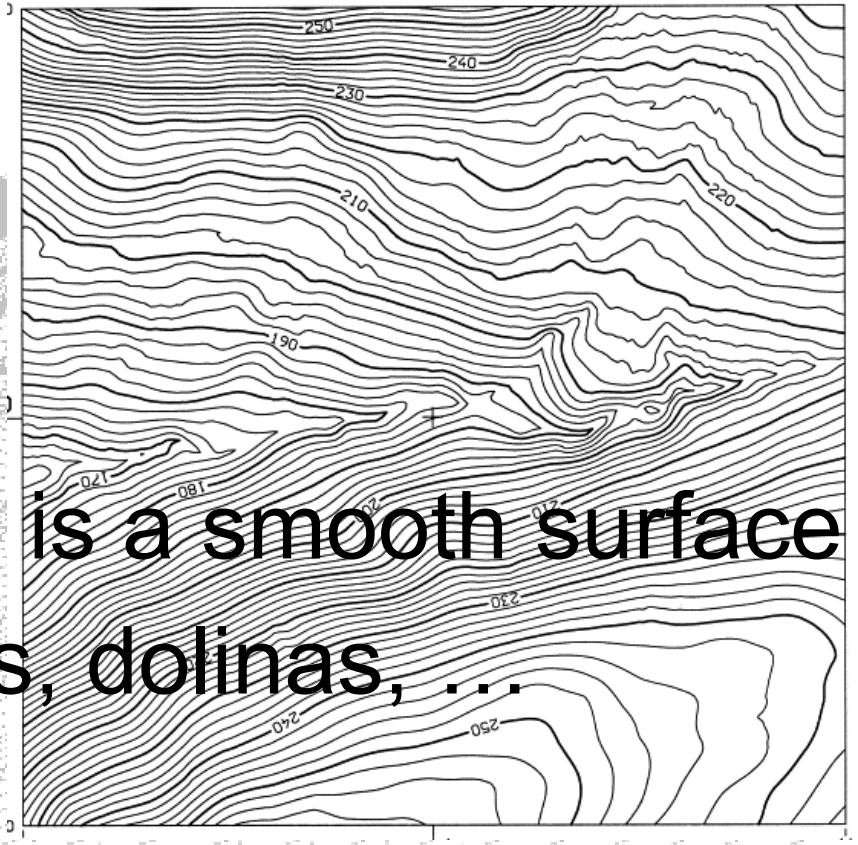
Jump Edge

Crease Edge

Curvature Edge

Breakline definition

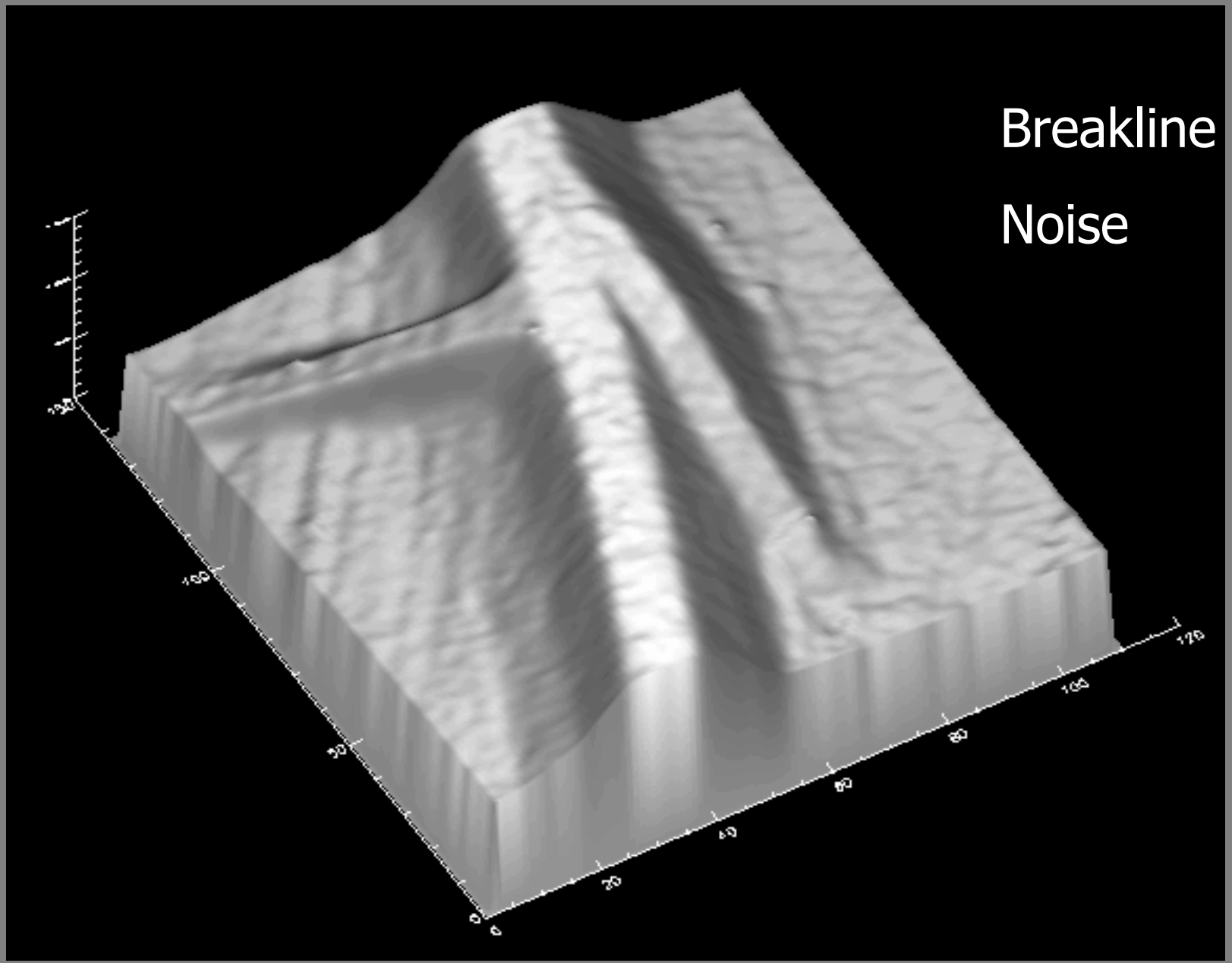


- General observation: terrain is a smooth surface
- Exception: breaklines, peaks, dolinas, …
- Linear feature (3D line)
- Found at curvature “maxima” (curvature not well defined!)
- Morphological terrain descriptors
- Appear often pair-wise (upper/lower or left/right)
- Most important morphological DTM information
- Contour lines turn sharply (high curvature or apex)

Purpose of breaklines

- Morphologically correct DTM
- Data reduction
  (high number of points required for implicit description)
- Data analysis
  - object recognition
  - terrain characterization (e.g. in geology)
- Water run-off modelling

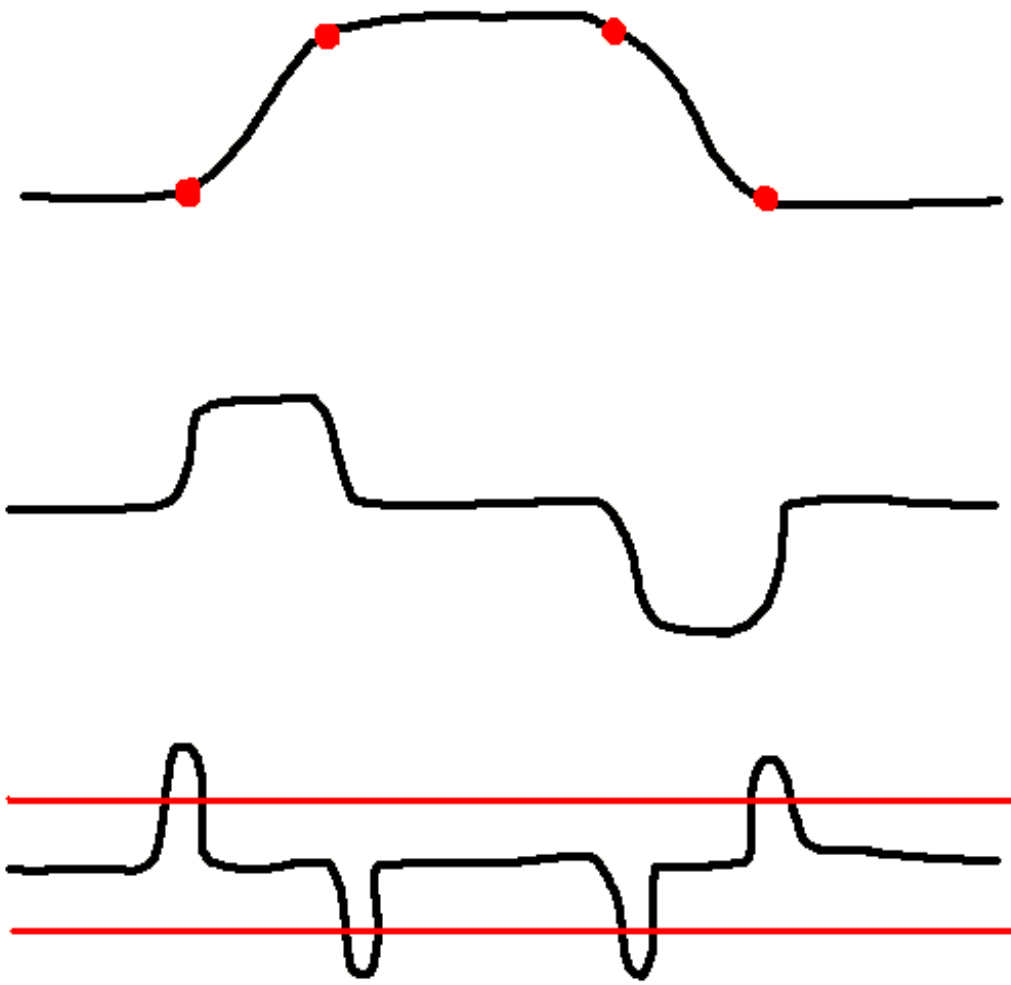
Breaklines in laser scanner data



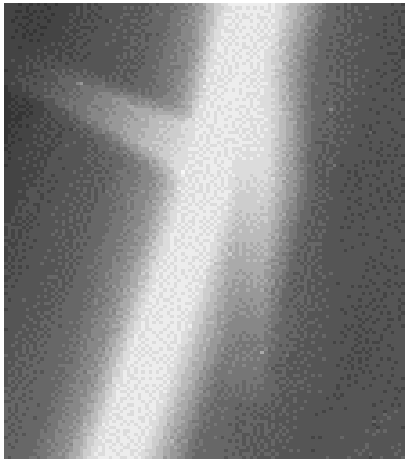
Breakline network

Noise

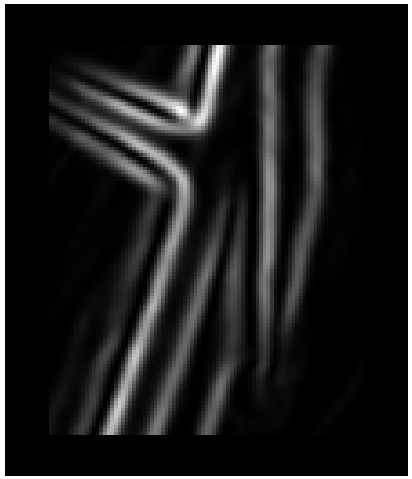
Extraction principle (approach of Brügelmann)



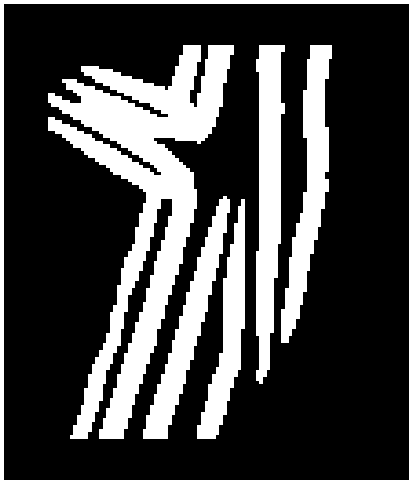
- Dike cross-section with breakline points
- 1st derivative
- 2nd derivate with threshold values



- Range image with dike
- Higher altitudes are shown brighter



- Curvature measure per pixel
- Filter operation: 2nd derivative with smoothing



- Statistical testing (threshold values)

$\Rightarrow$ possible breakline regions

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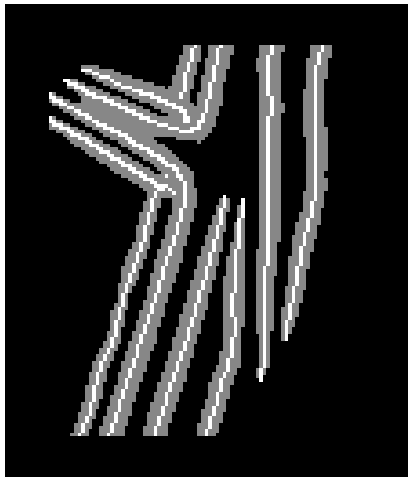
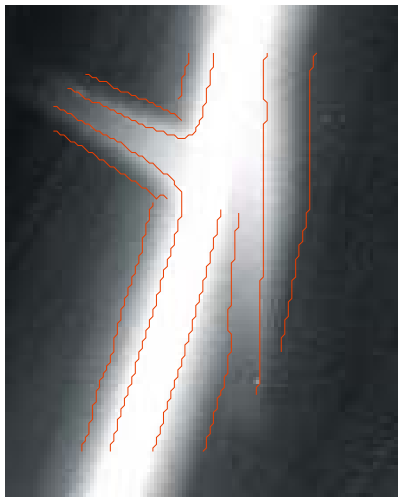


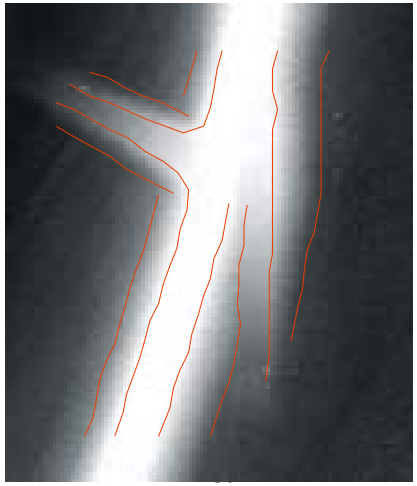
- Nonmaxima suppression
- Thinning

$\Rightarrow$ Raster breaklines



- Raster-vector conversion

$\Rightarrow$ raw vector breaklines



- Splines through x,y - coordinates
- z-coordinate from ‘smoothed surface’

$\Rightarrow$ ‘smooth’ vector breaklines

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Exact position and height

- Previous slide:

- Splines through x,y - coordinates
- z-coordinate from 'smoothed surface'

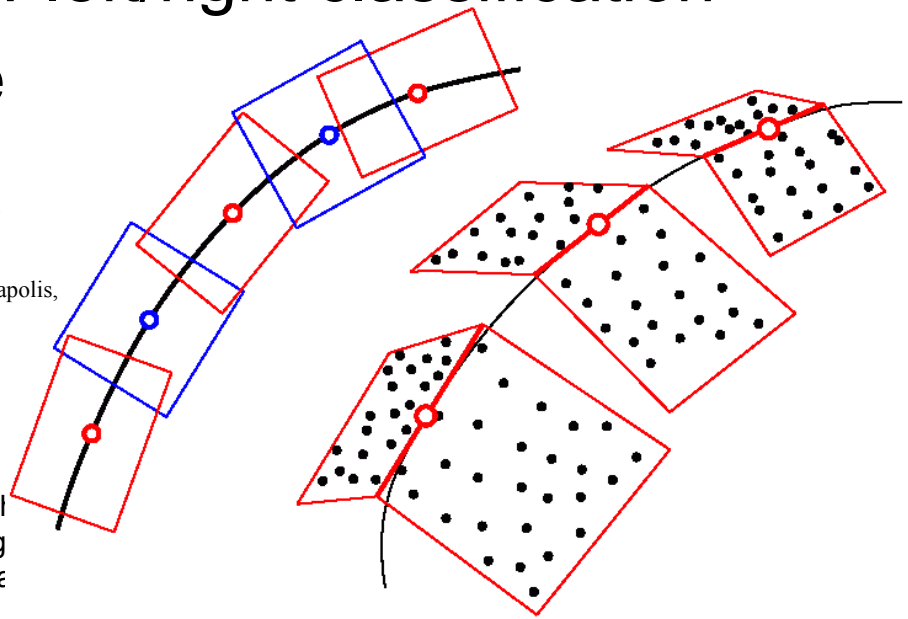
⇒ 'smooth' vector breaklines

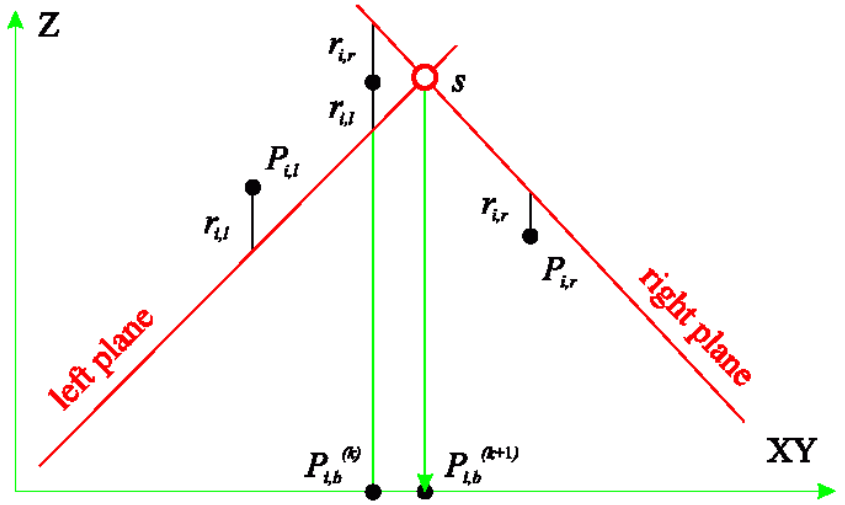
- Breakline point not measured by laser (only adjacent surfaces are measured)
- Improved location of breakline
- Improved elevation of breakline

Exact breakline determination (approach of Briese)

- Use previous result as 1st approximation
- Use model of breakline: intersection of 2 smooth surfaces
- Determine breakline patch-wise
- Current breakline defines left vs. right points
- Determine surface patches from left/right pts.
- Intersect in breakline
- Renew left/right classification
- Iterate

Advanced DTM generation from LIDAR data
by. K. Kraus, N. Pfeifer
IAPRS Vol XXXIV, 3/W4, Annapolis, Maryland, USA, 2001





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Lidar Technolog
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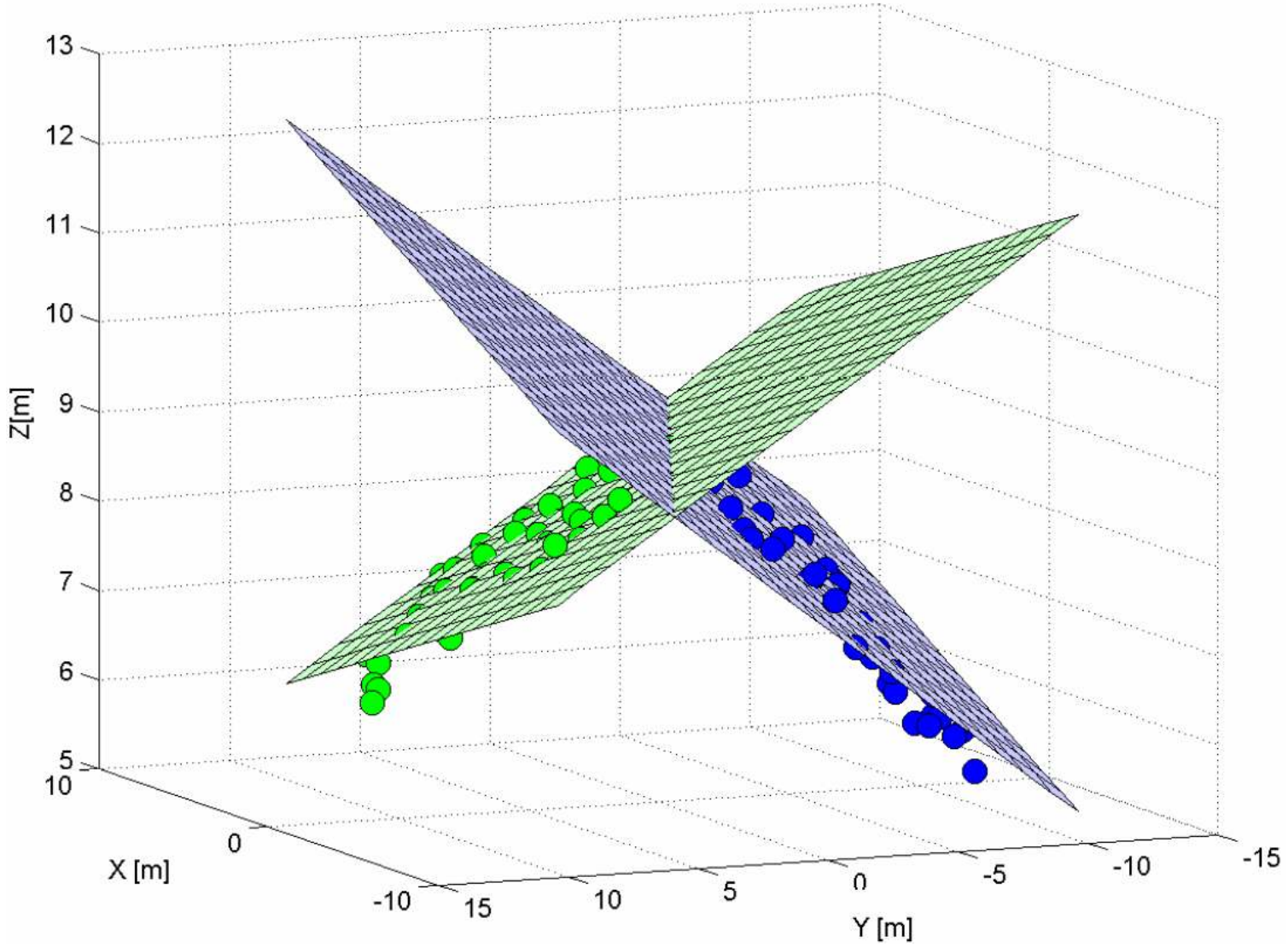
Modeling – plain pair I

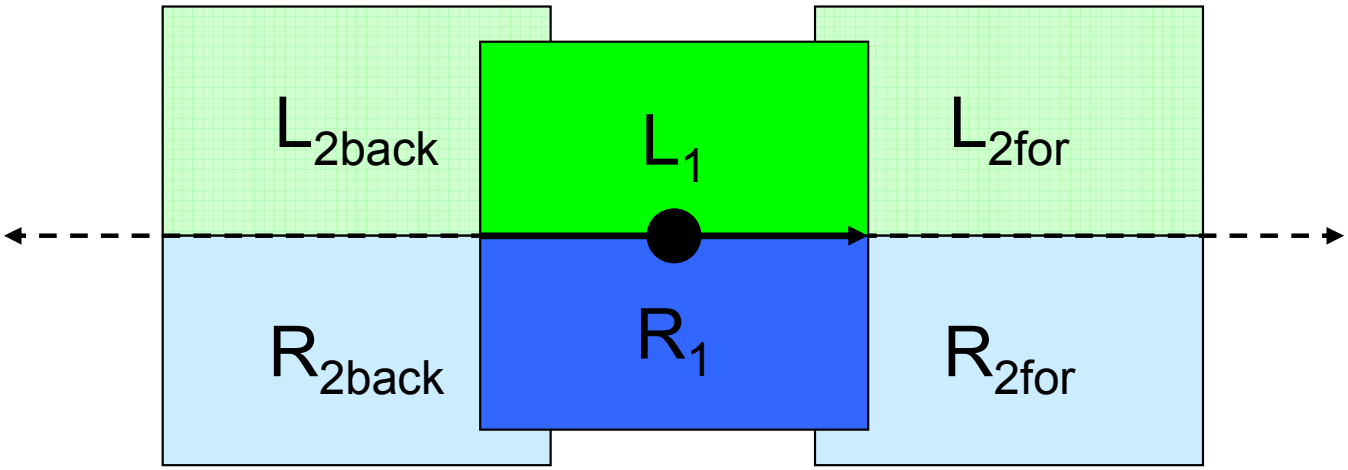


Results per break line

- One representative point per patch
- Edge direction per point
- Intersection angle of planes along the break line
- Adjustment information (precision, redundancy, …) along the break line

Automation – Growing of the edge

- **Growing on the basis of 1 start segment:**



PROCEDURE:

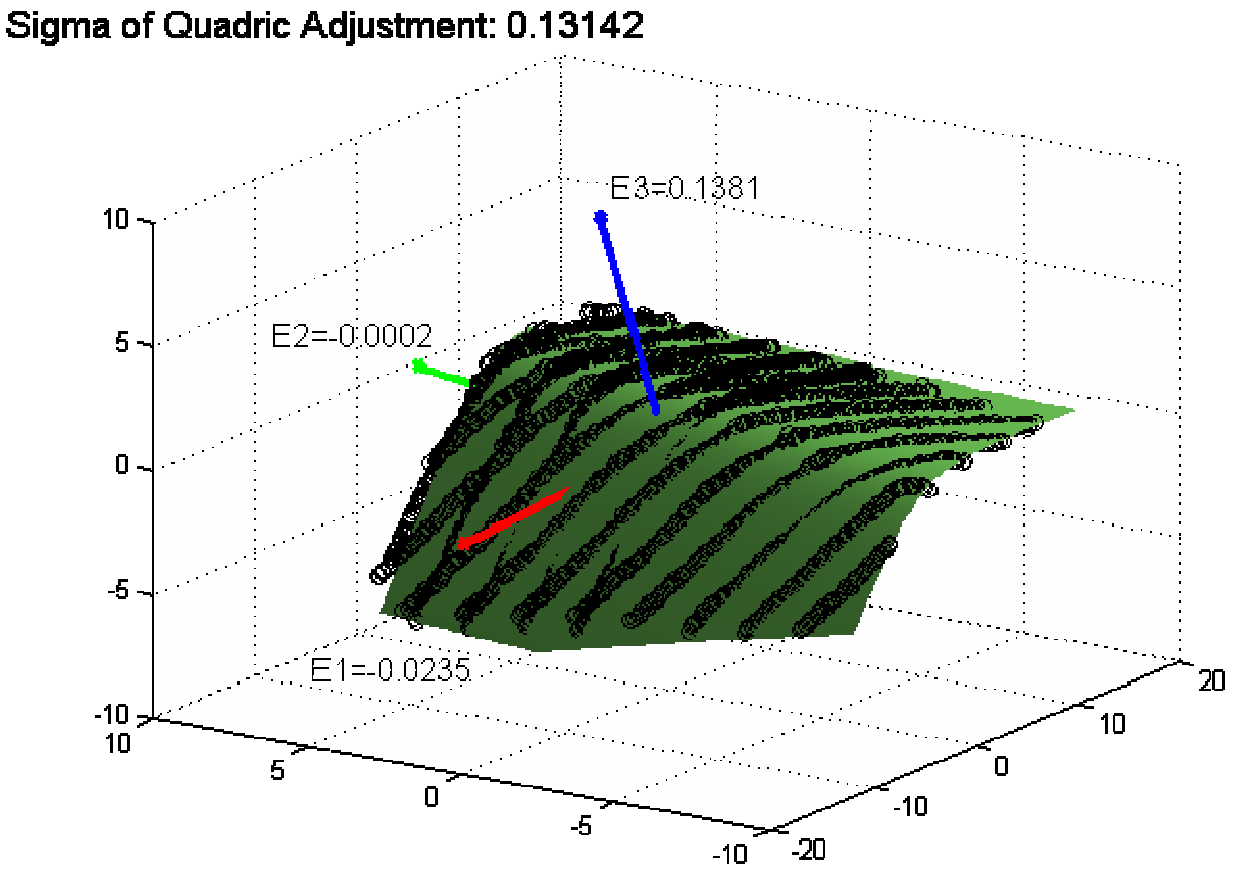
1. **Deterine patch/Break line edge with robust planar elements**
2. **Determine buffer zone for next/adjacent patch (Extrapolation)**
3. **Export (collect) unclassified ALS-point cloud within the buffer**

There steps are repreated until a certain criterion is reaches (e.g. intersection angle, precision, …)

Automation – Growing of the edge

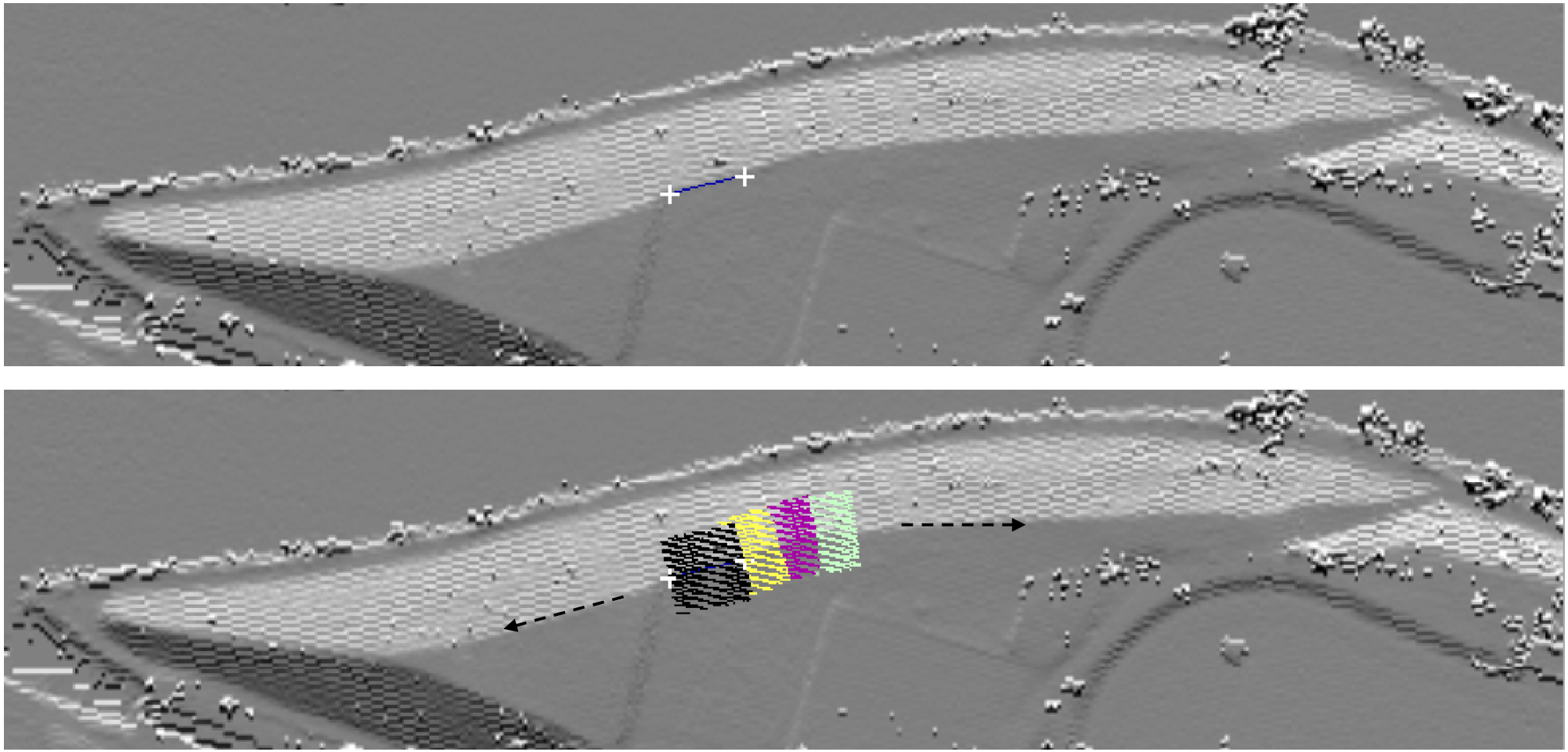
- **Growing on the basis of 1 Start-Point:**

  Adjusting Quadric:



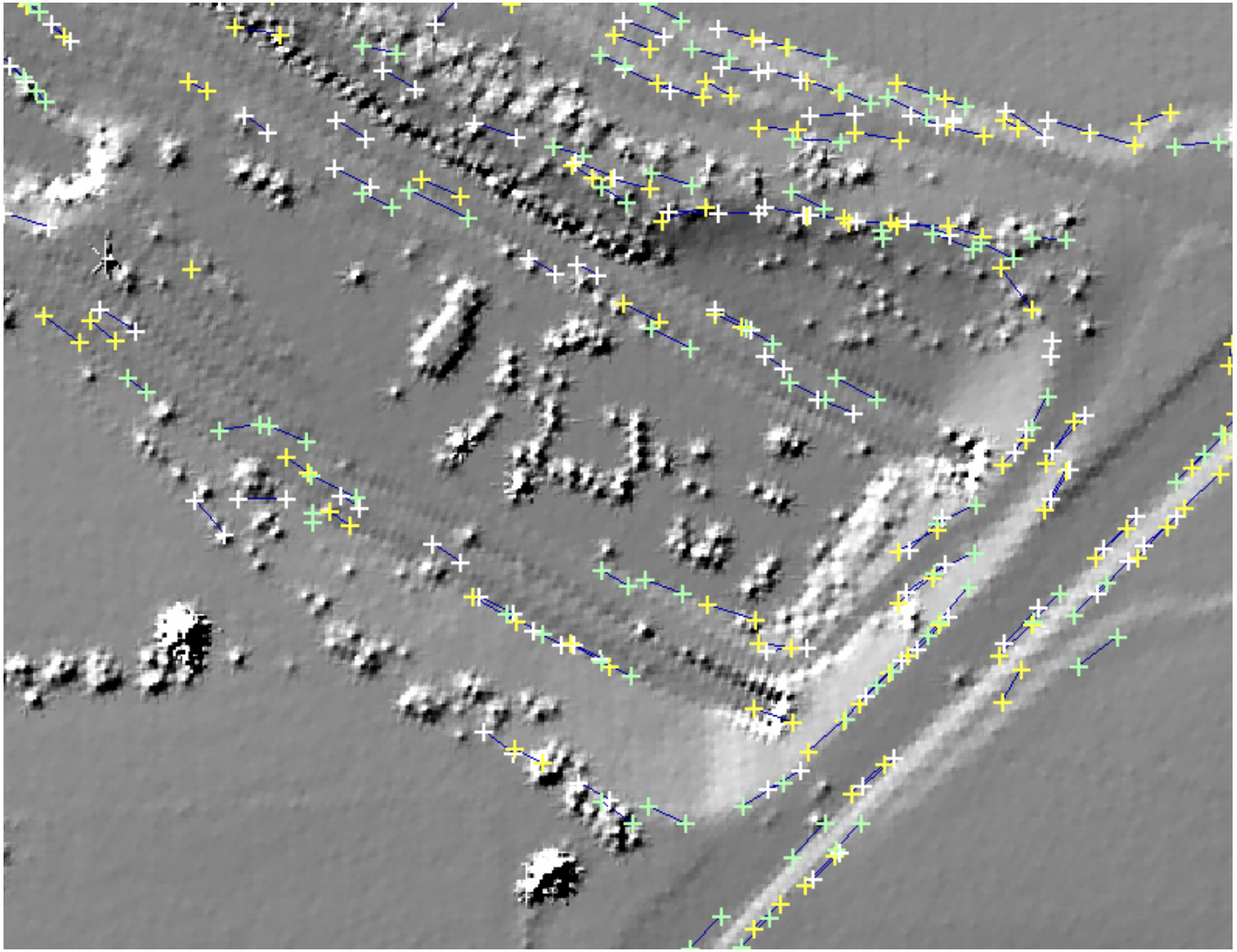
Edge direction: direction of the eigenvector of the smallest eigenvalue (after principle axis transformation)

Automation – Example



Full automation

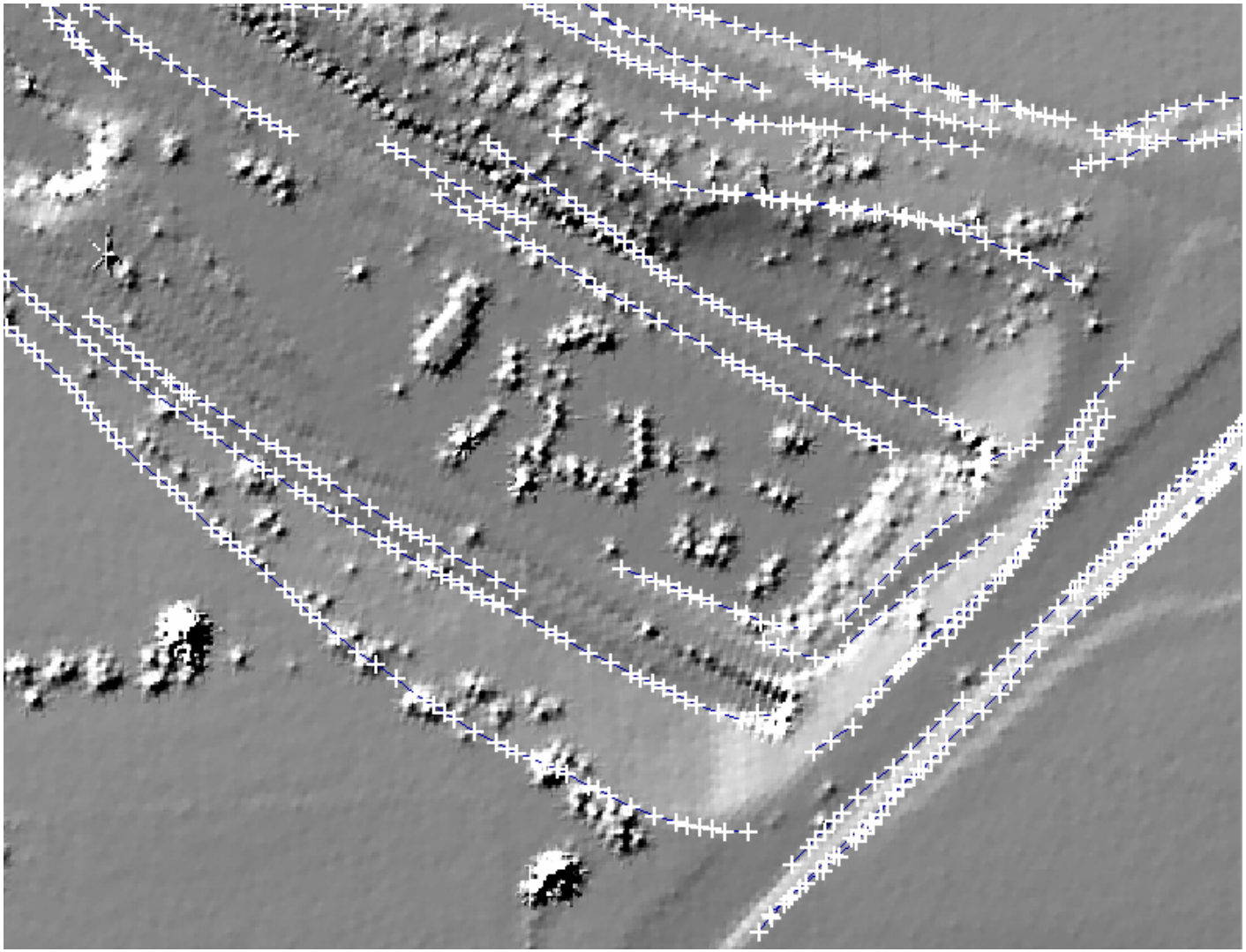
Start-Segments:



EuroSDR, Testdataset Vaihingen

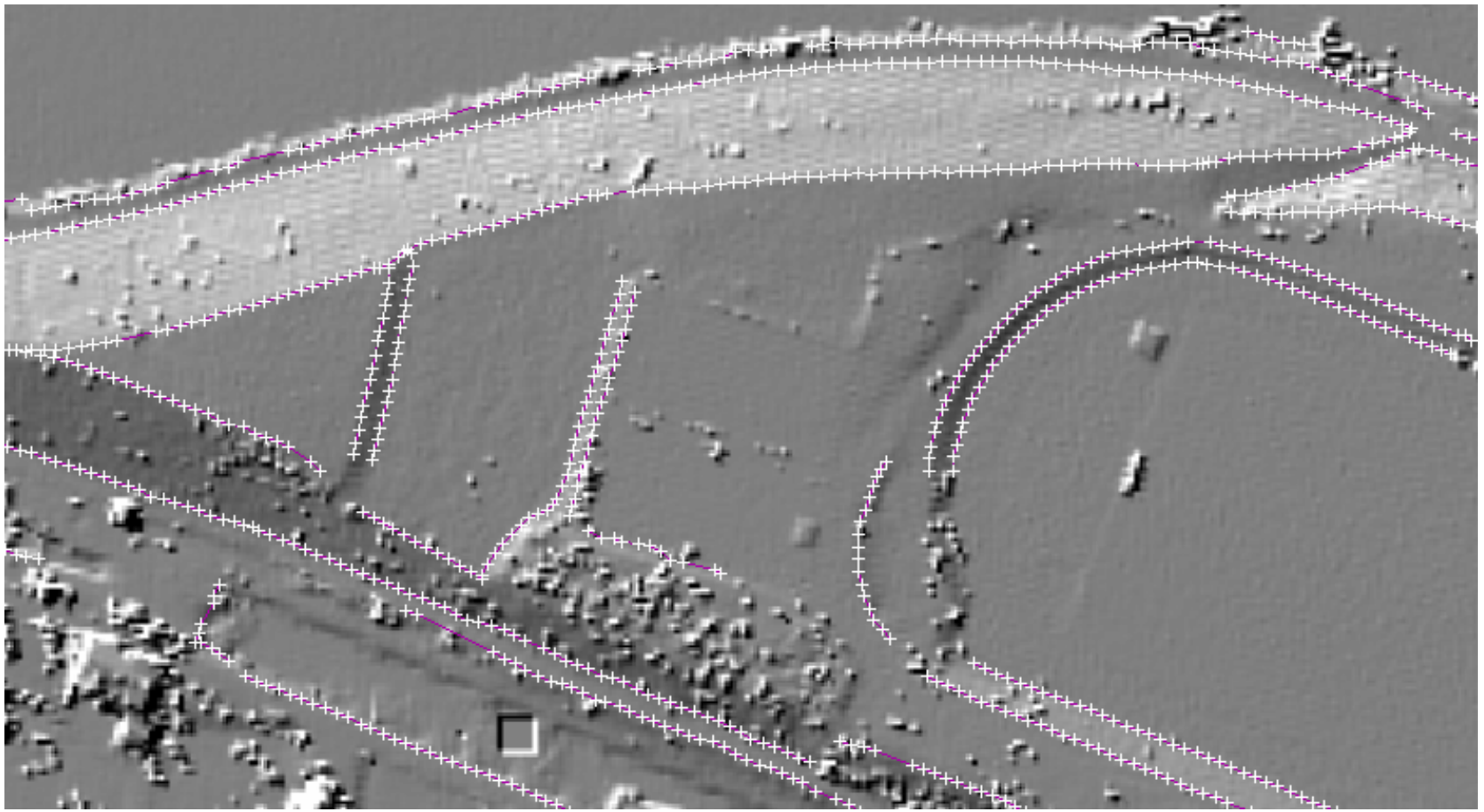
Full automation

Entirely automated derived break lines



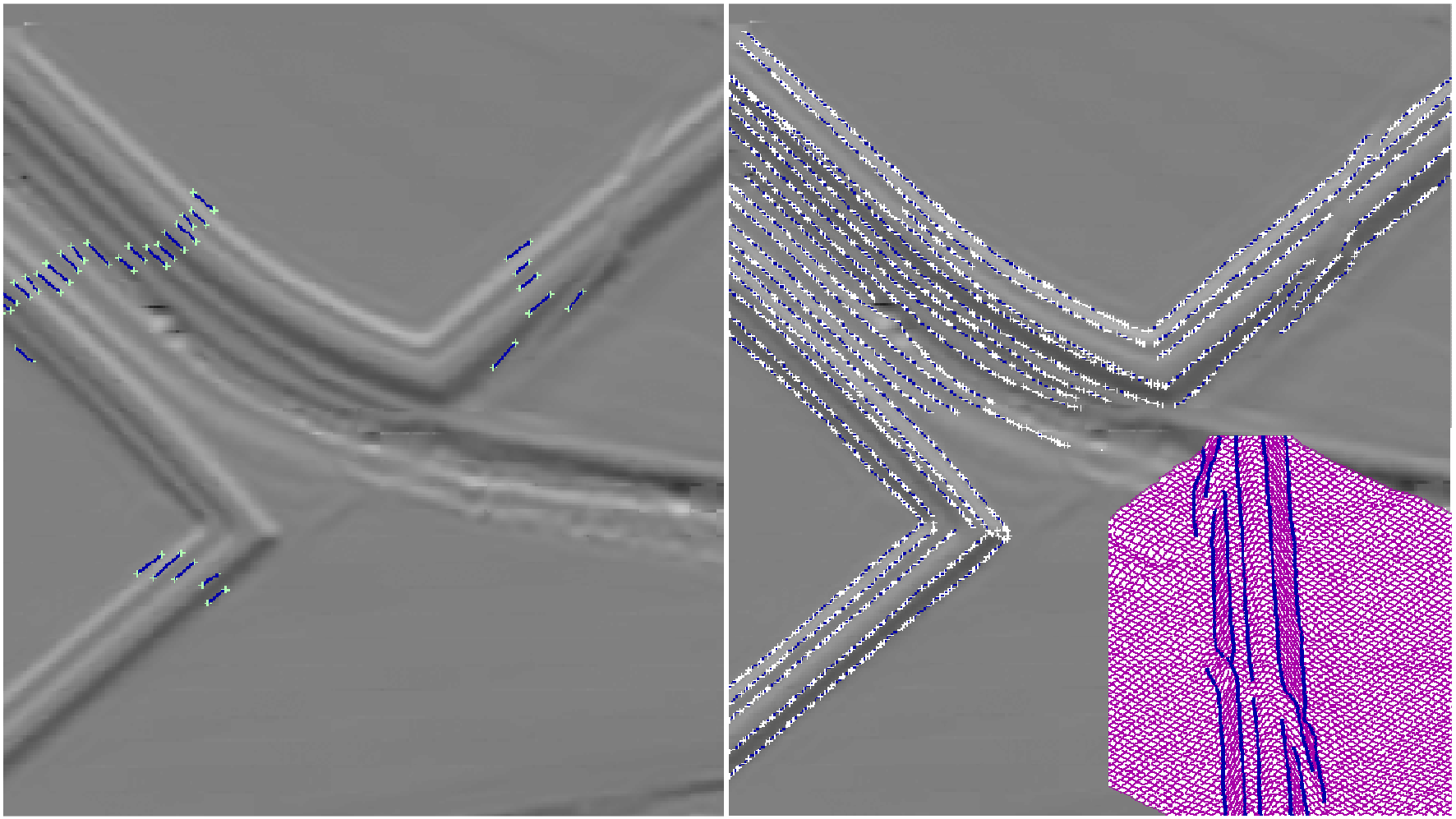
EuroSDR, Testdataset Vaihingen

Practical Example I



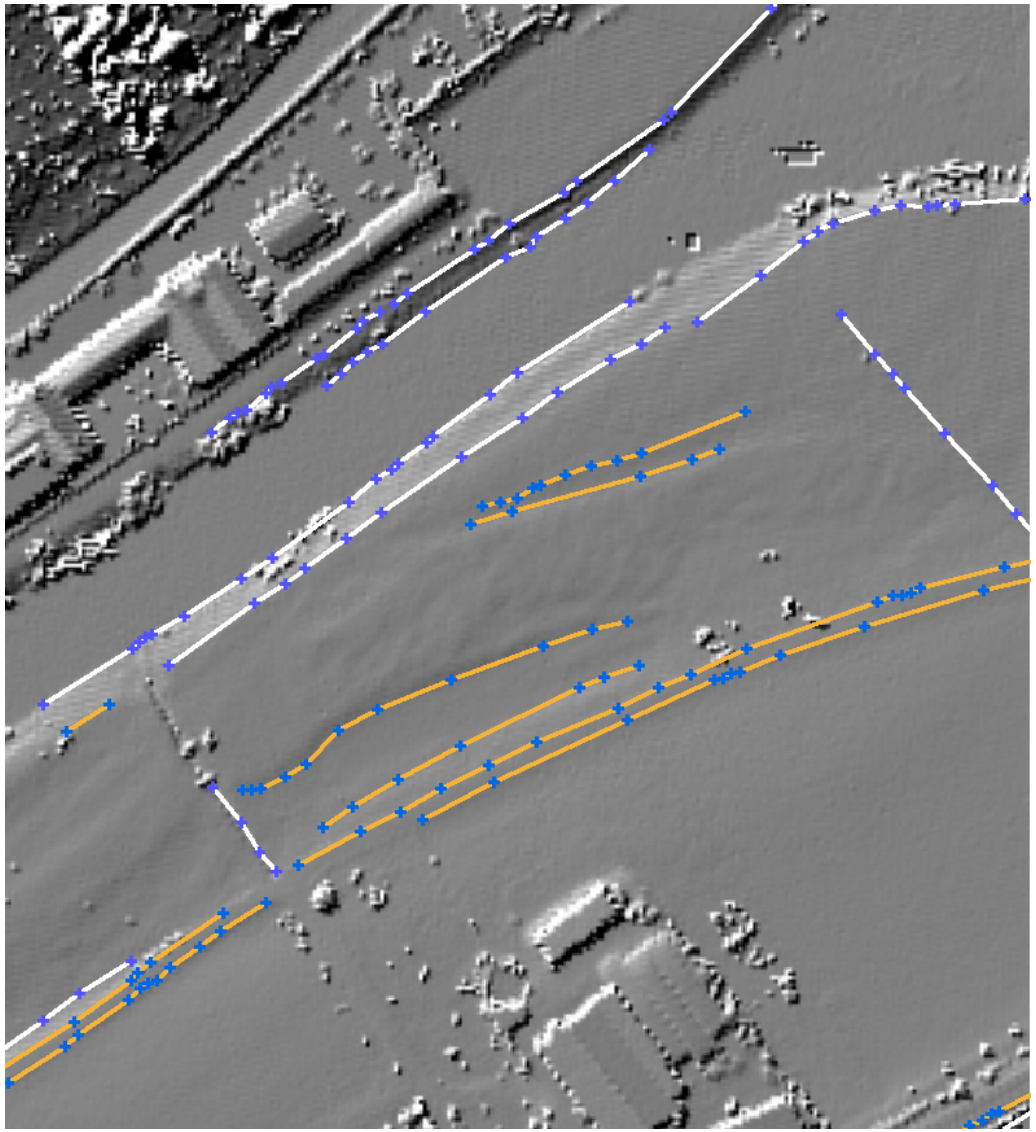
BfG (Bundesanstalt für Gewässerkunde, Federal Office of Water Ways, Germany), Testd ata Lahn

Practical Example II

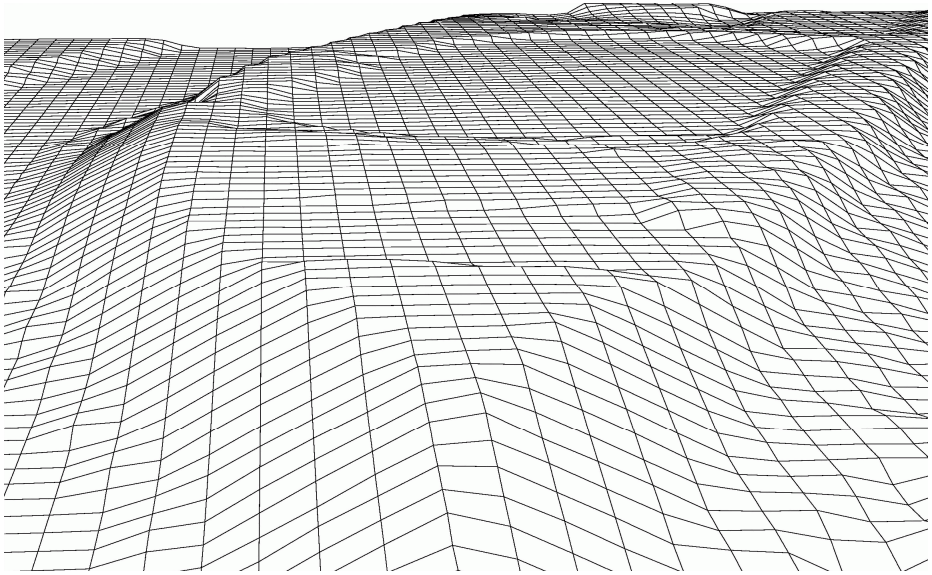


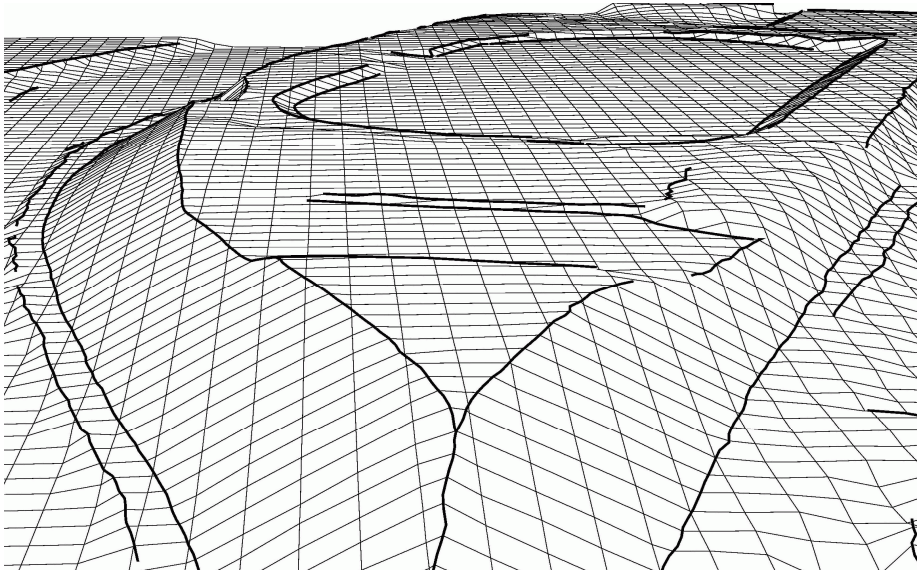
Österr. Wasserstraßendirektion, Hainburg

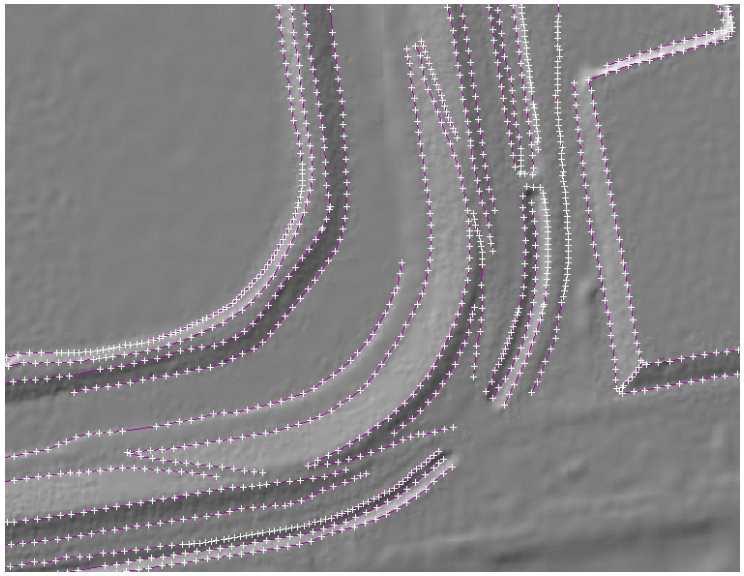
Classification on the basis of the intersection angle

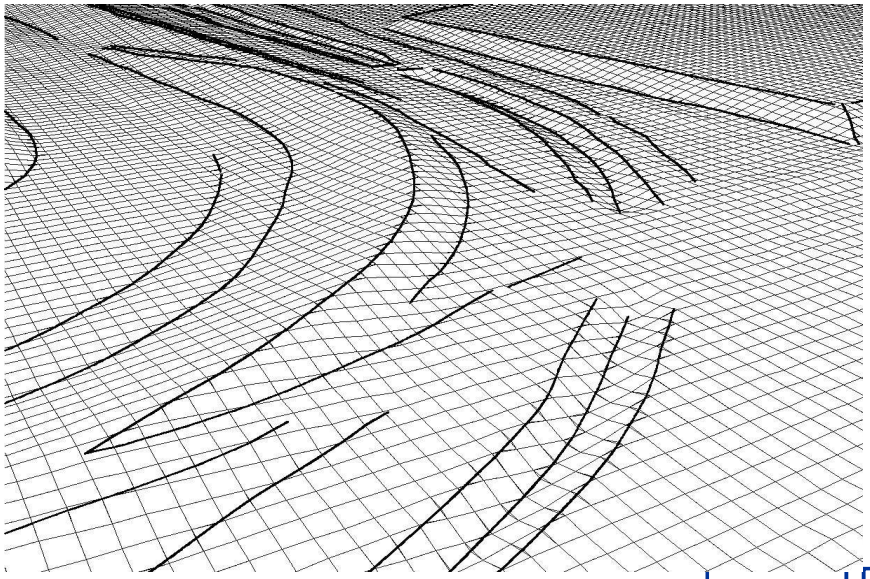


Practical Example – DTM after Filtering

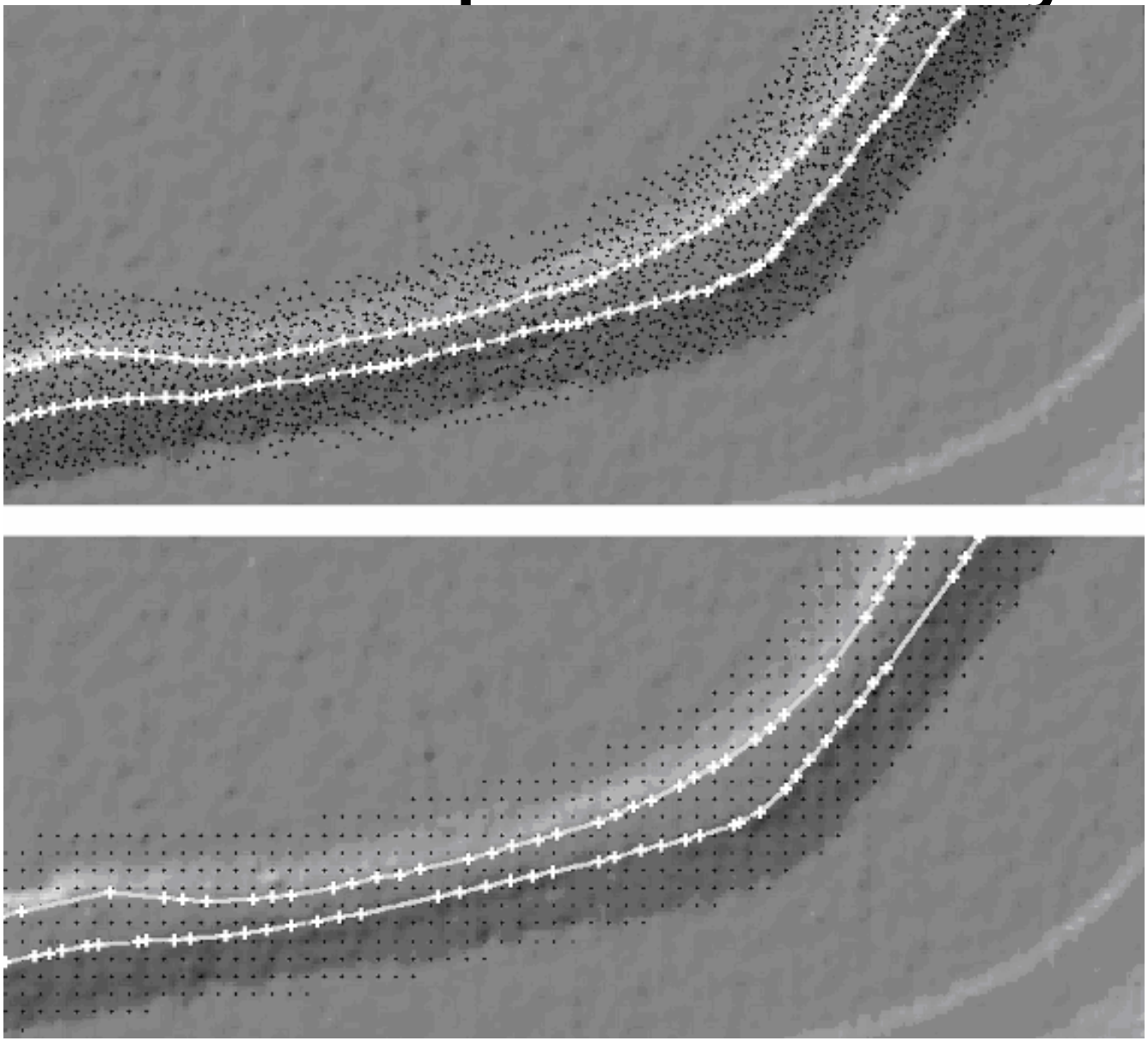




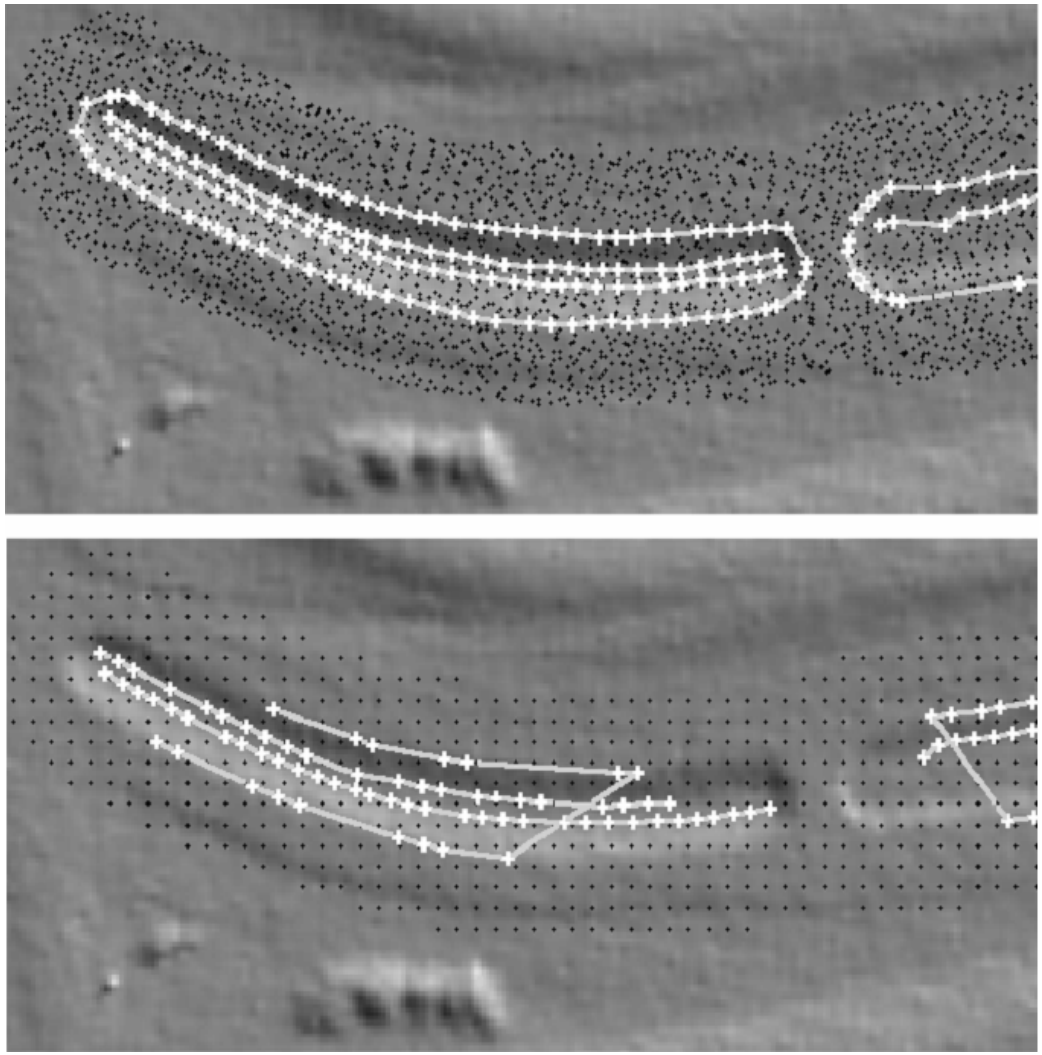




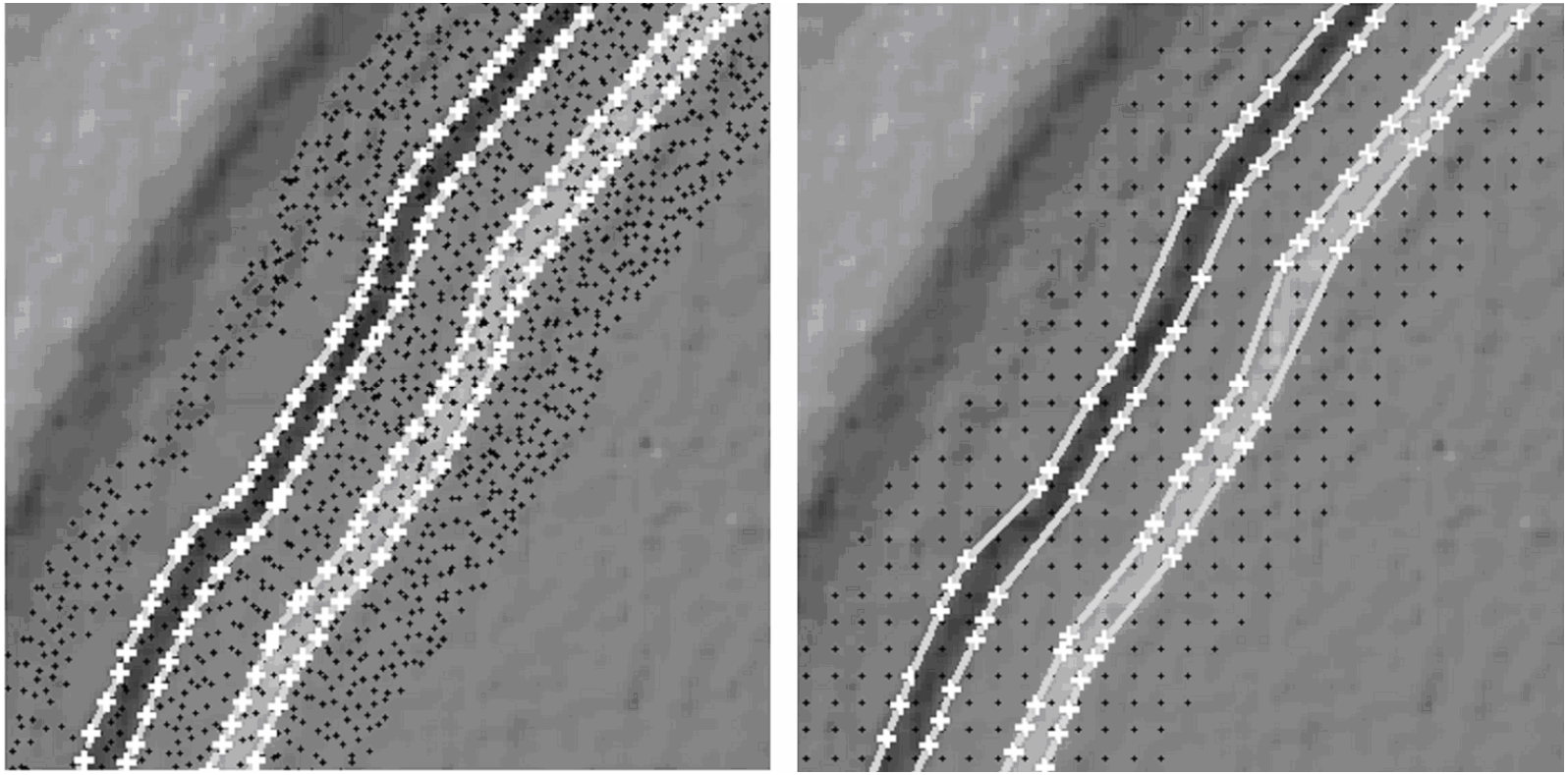
Different point density !



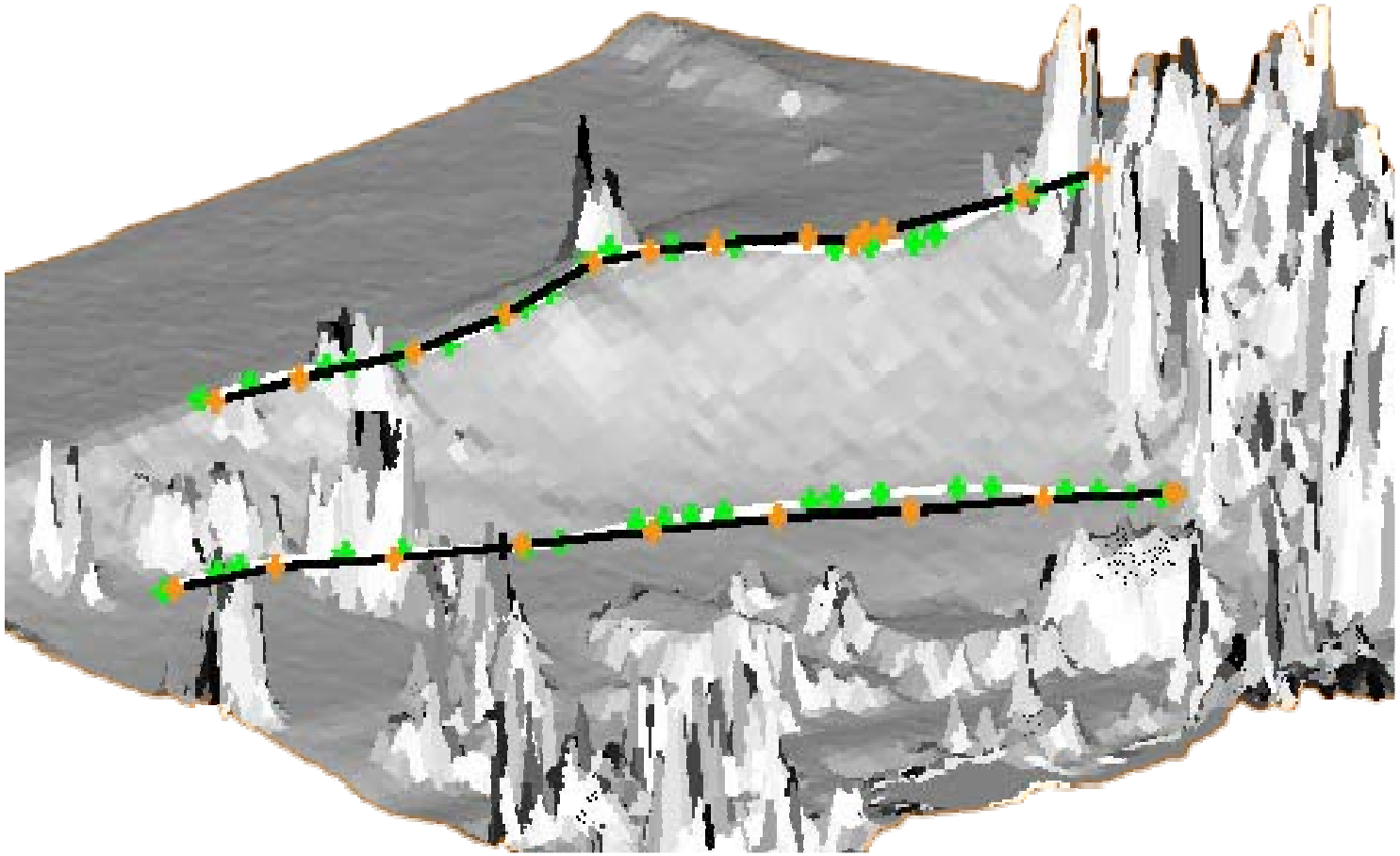
Different point density !



Different point density !



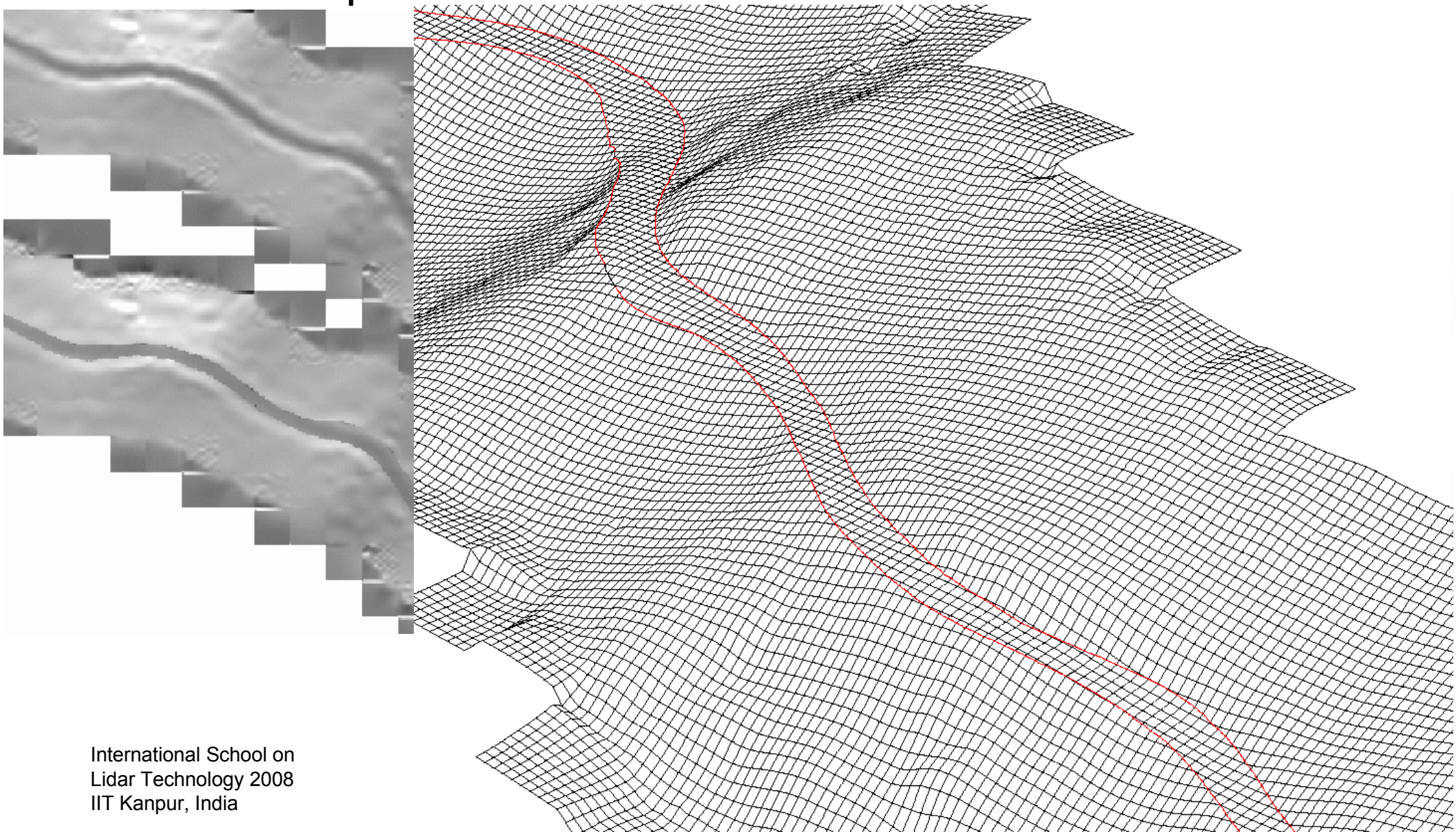
Accuracy assessment



Comparison to terrestrical determined break lines

Last Example

start with manual approximation of breakline
5m point distance, digitized in shading
use of filtered point cloud

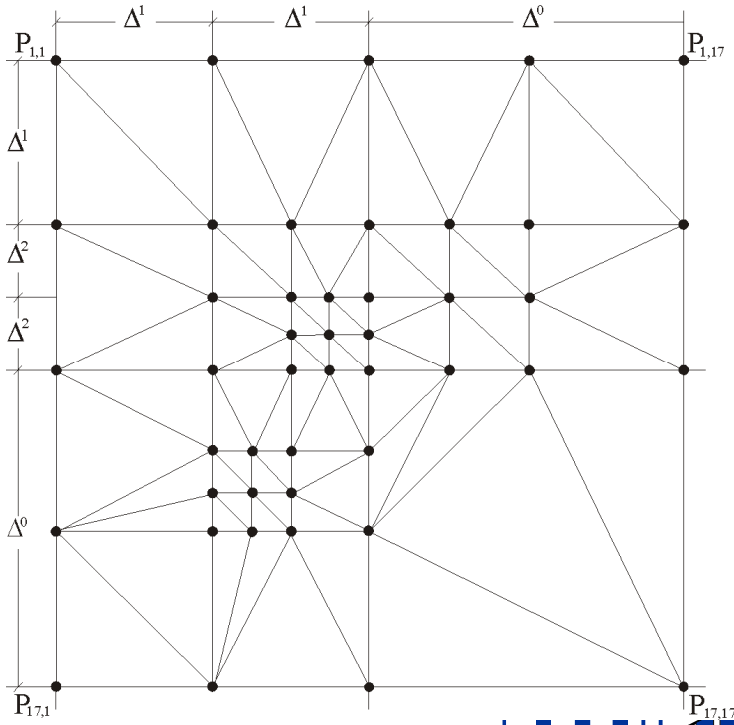


Break line Summary

- Automatic extraction of breaklines is possible
- Quality of breakline depends on density and accuracy of data (and pixel size)
- Improvement
  especially in geomorphologic DTM quality
- Regular grid becomes a hybrid grid
  … = grid with lines meshed into it

DTM data reduction – requirements

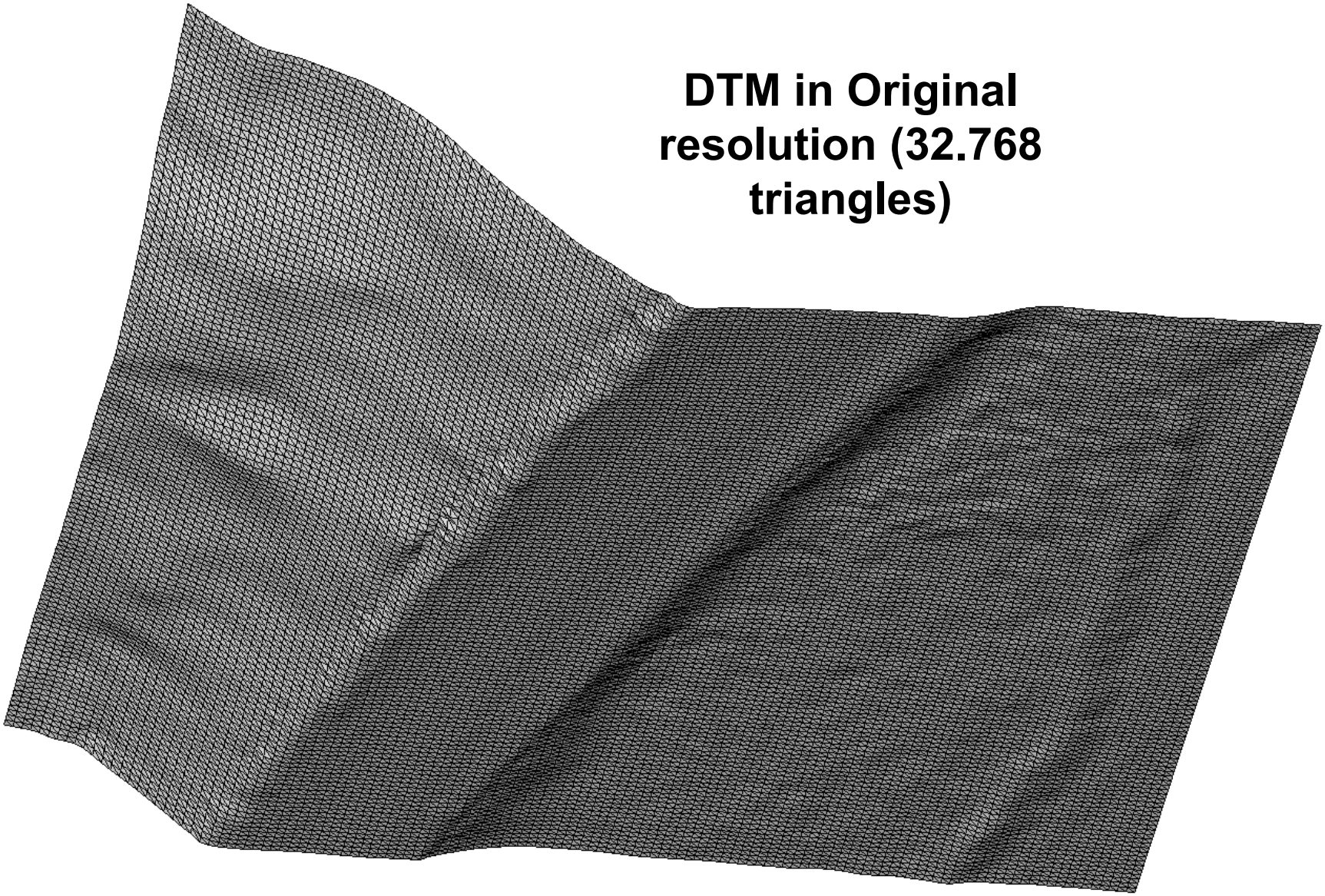
- Base data: DTM = set of elevations in a matrix strucutre
  possibly augemented by lines
- Height tolerance (L∞-Norm) vs. RMS approximation
- Maintaining a maximum point distance (Δ^0 niveau) [can be omitted]
- Splitting:
  - Hierarchic (quad tree, „inverses progressive sampling“)
  - Irregular
- Reduction criteria:
  - Curvature (in original DTM)
  - Slope (in original DTM)
  - Vertical distance
    (between original and reduces DTM)



Data reduction

- Basic ideas:
  - Surface approximation piecewise by linear surface patches (TIN)
  - Mesh refinement: coarse-to-fine
  - Mesh decimation: fine-to-coarse
  - Literature: Heckbert/Garland, 1997
- Reduction approach suggested [within Δ^0 niveau]:
  - Conceptual: dense terrain model → simplified TIN (fine-to-coarse)
  - Algorithm: refinement of a generalized DTM (coarse-to-fine)
- Reduction criteria:
  - Vertical distance of the DTM grid points to the TIN
  - Guaranteeing a maximum height tolerance ($L\infty$-Norm)

Datenreduction – original mesh



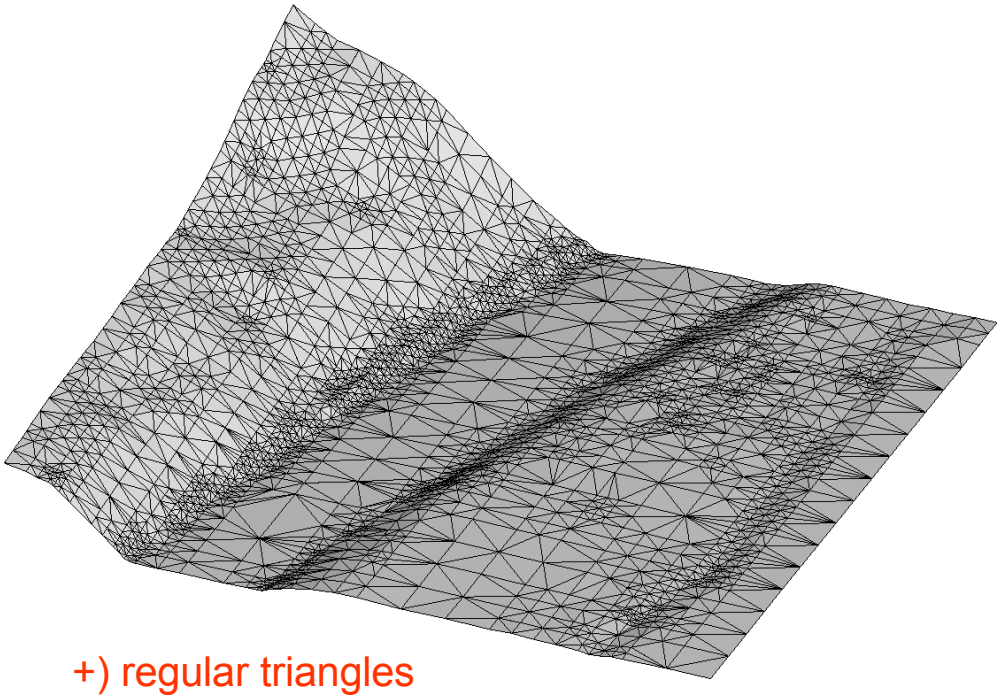
DTM in Original resolution (32.768 triangles)

Data: GeoConsult, Drau (Austria)

Datenreduktion – Mesh refinement

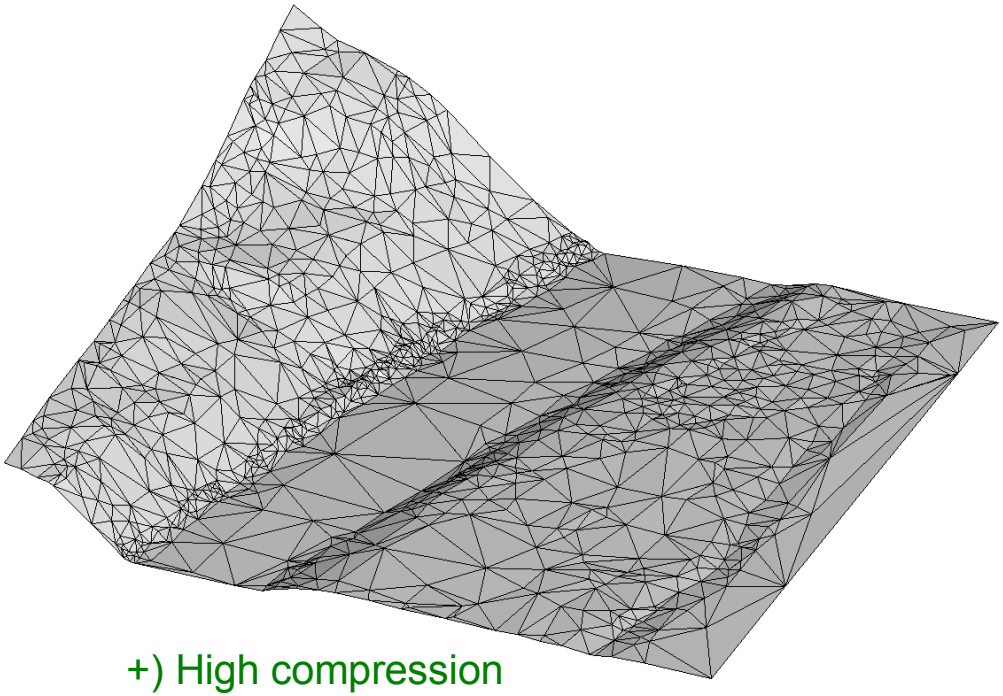
Reduced TIN
Maximum height tolerance = 25cm

Hierarchic splitting
5.496 Triangles (=17%)



+) regular triangles
-) Less compression

Irregular splitting
1.192 Triangles (=6%)



+) High compression
-) irregular triangle shapes

Summary on Filtering and DTM

- Filtering is operational
- Manual checking and improvement of filter results required for high quality
- Improvement options
  - FWF: other presentation in the Lidar Technology School 2008
  - Other sensors:
- Commercial implementations:
  SCOP++: hierarchic robust interpolation
  Terra Modeler: progressive densification
- Overview on filters
  Kobler et al., 2007. Repetitive interpolation: A robust algorithm for DTM generation from Aerial Laser Scanner Data in forested terrain. Remote Sensing of Environment.
  Pfeifer and Mandlburger, 2008. Lidar Data Filtering and DTM Generation. In (Shan and Toth, ed.) Topographic Laser Ranging and Scanning: Principles and Applications. CRC Press, to appear.
- Break lines for geomorphologically correct terrain representation
- Thinning for reducing data volume