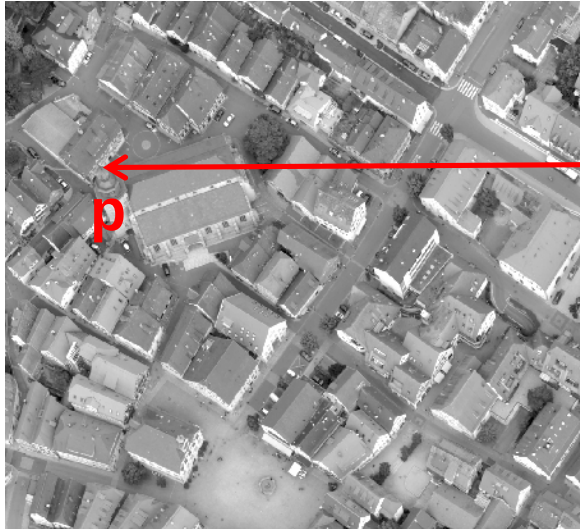


An aerial photograph of a town, likely in Europe, showing a dense cluster of buildings with red-tiled roofs. A prominent church tower with a blue dome is visible in the upper left. The town is surrounded by a white, irregular border, suggesting a 3D model or a specific geographic area. The text is overlaid on a semi-transparent rectangular area in the center of the image.

*Exploiting Multi-View Geometry for
Improvements in Reliability, Completeness,
and Accuracy*

Dense Image Matching - SGM

Exploiting Multi-View Geometry



Base image

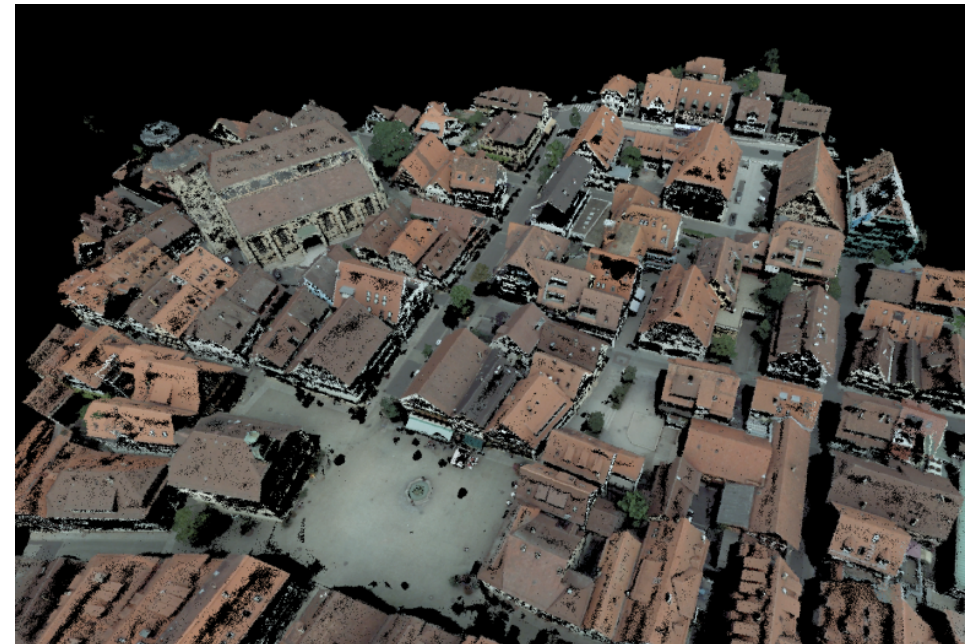


Match image



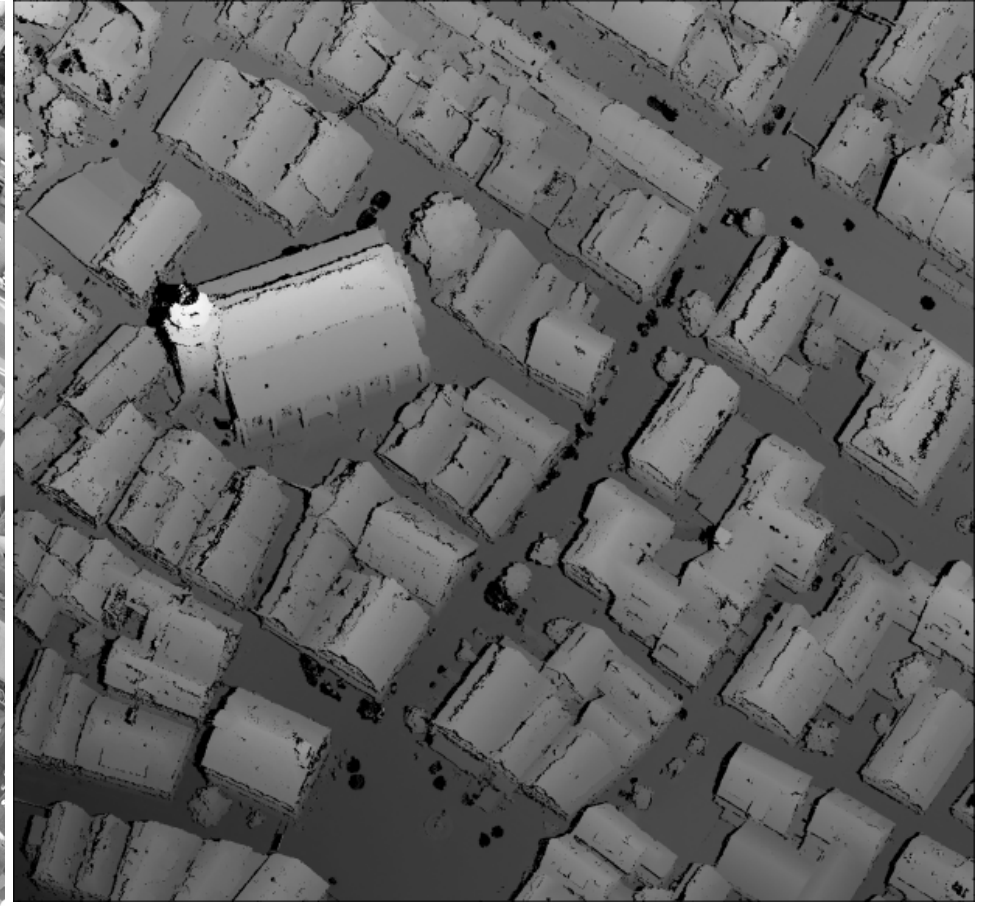
Parallax image

- § Stereo matching (1D) in epipolar image pairs
 - § Application of Semi-Global-Matching
- § Correspondences for each pixel
 - § Parallax/disparity images
- § 3D point cloud from spatial intersection



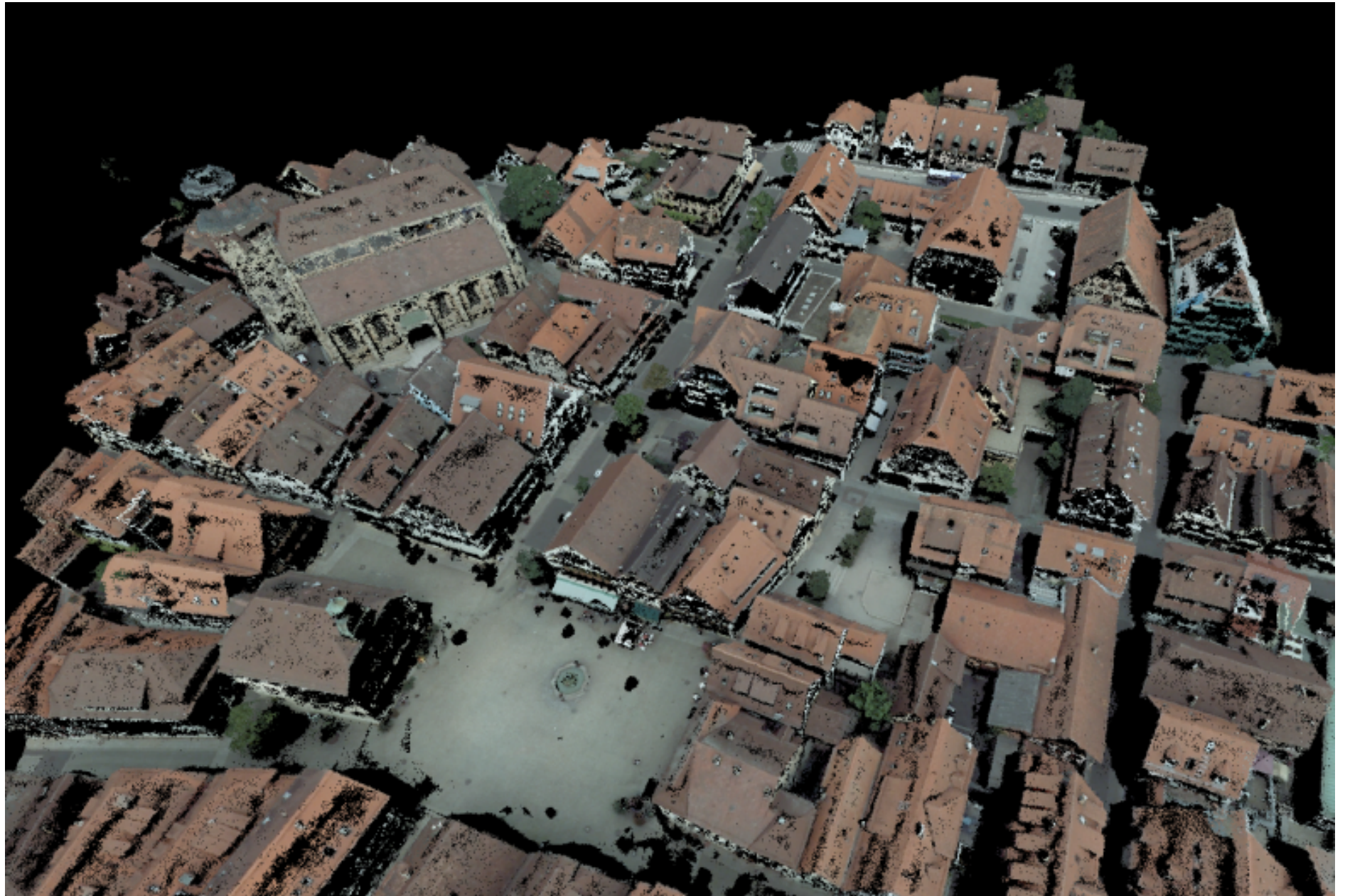
Exploiting Multi-View Geometry

Dense matching (I)



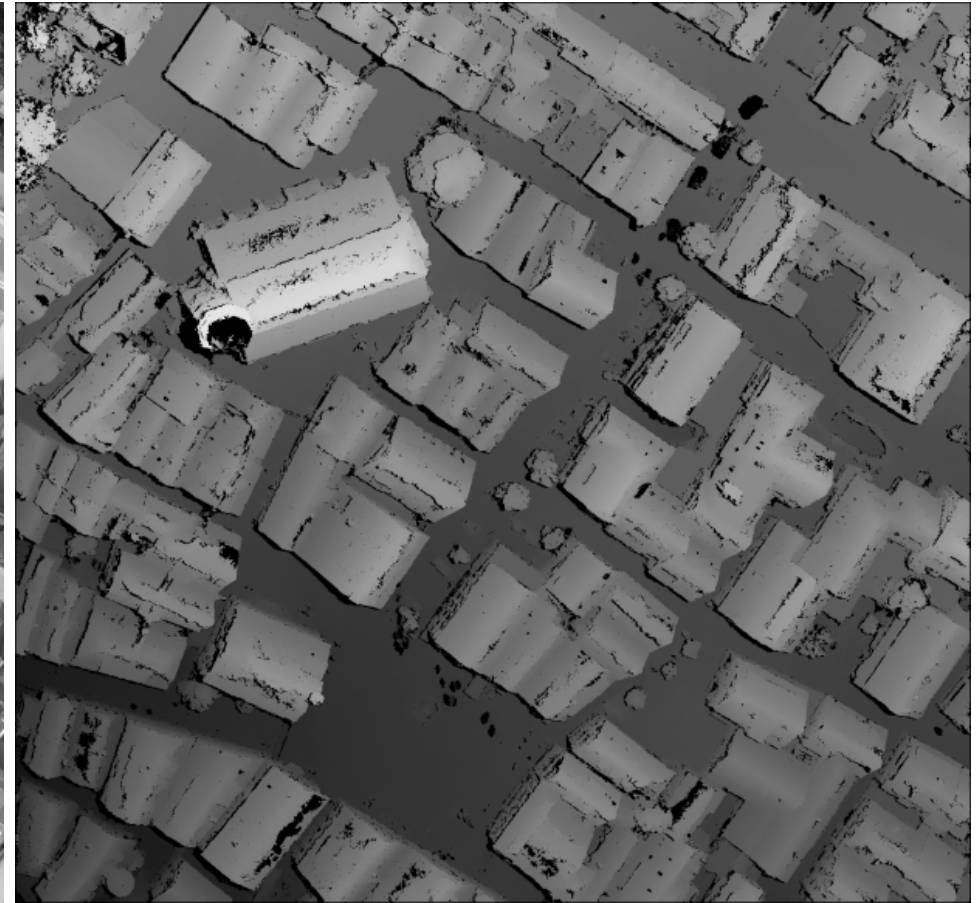
Exploiting Multi-View Geometry

3D Point Cloud from Spatial Intersection (I)



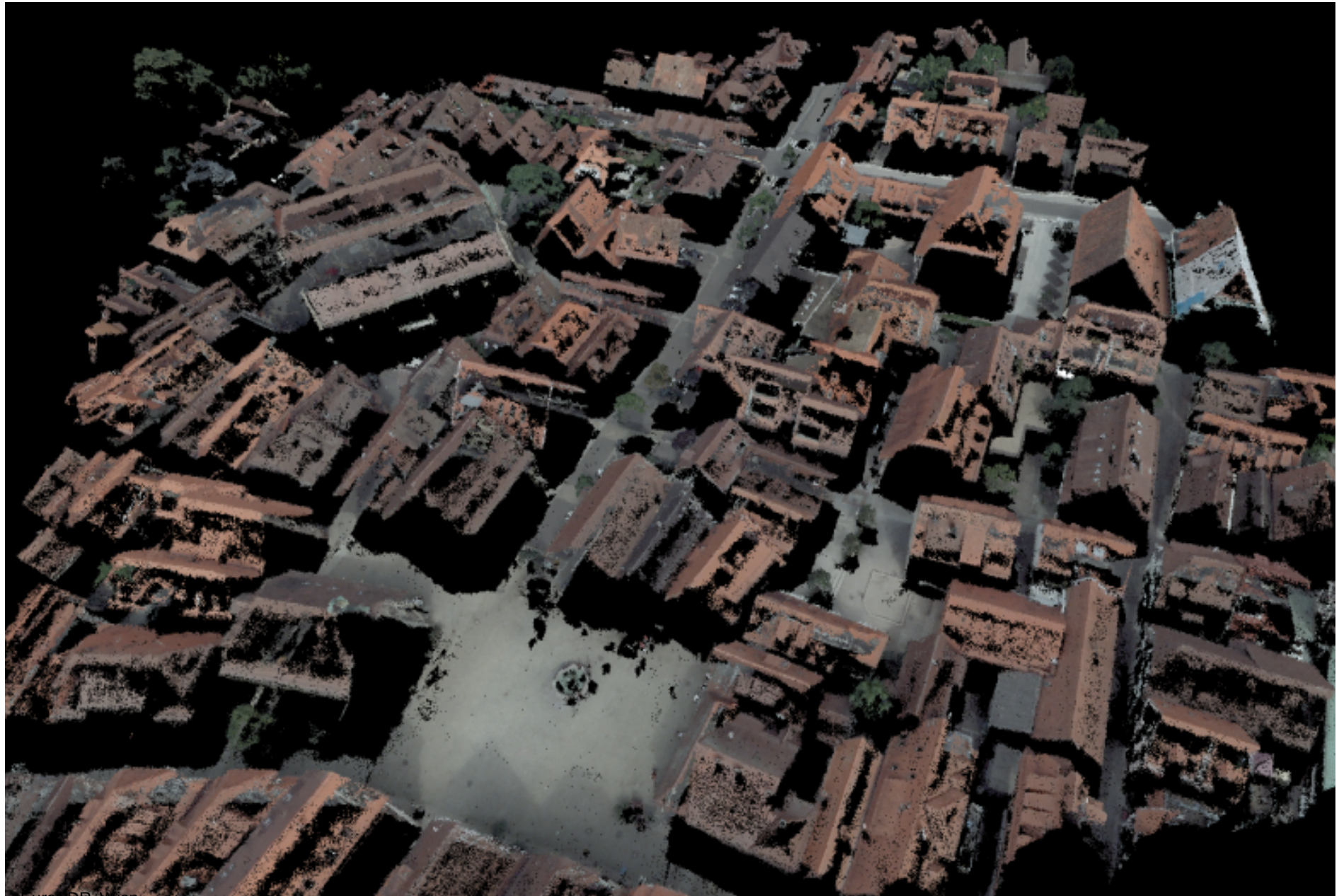
Exploiting Multi-View Geometry

Dense matching (II)



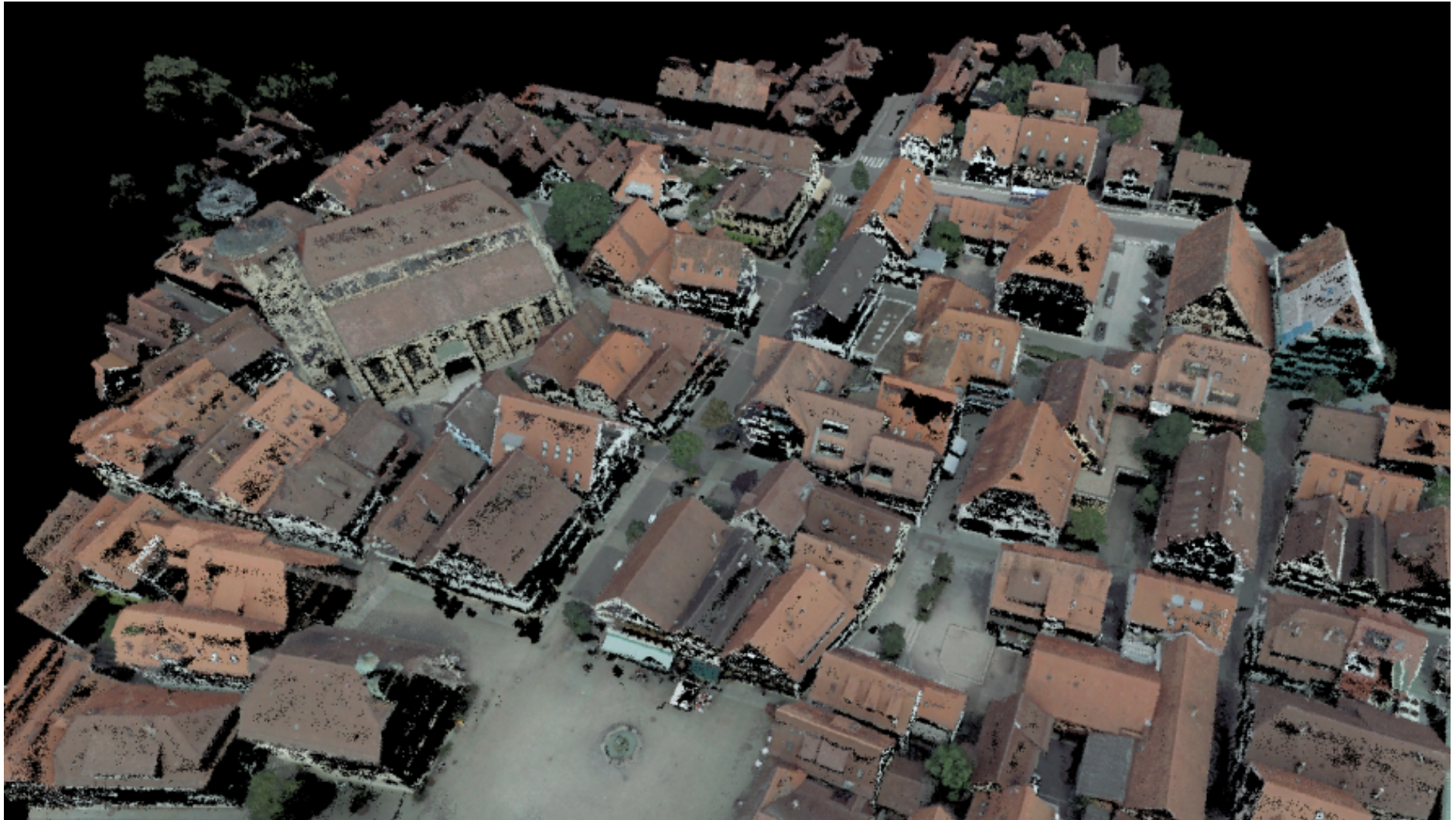
Exploiting Multi-View Geometry

3D Point Cloud from Spatial Intersection (II)



Exploiting Multi-View Geometry

Combination of 3D point clouds



- § Improved completeness by combination of 3D point clouds
- § Reliability and accuracy?

Exploiting Multi-View Geometry for Quality Improvement



- § Highly overlapping aerial image blocks
 - § Cost-free forward overlap for digital cameras
 - § Sideward overlap for true-ortho generation
- § 80% in-flight and 60% cross-flight
 - § Object visibility in 2 strips, 5 images each
- § Redundant matching for accurate and reliable point cloud generation



Flight direction

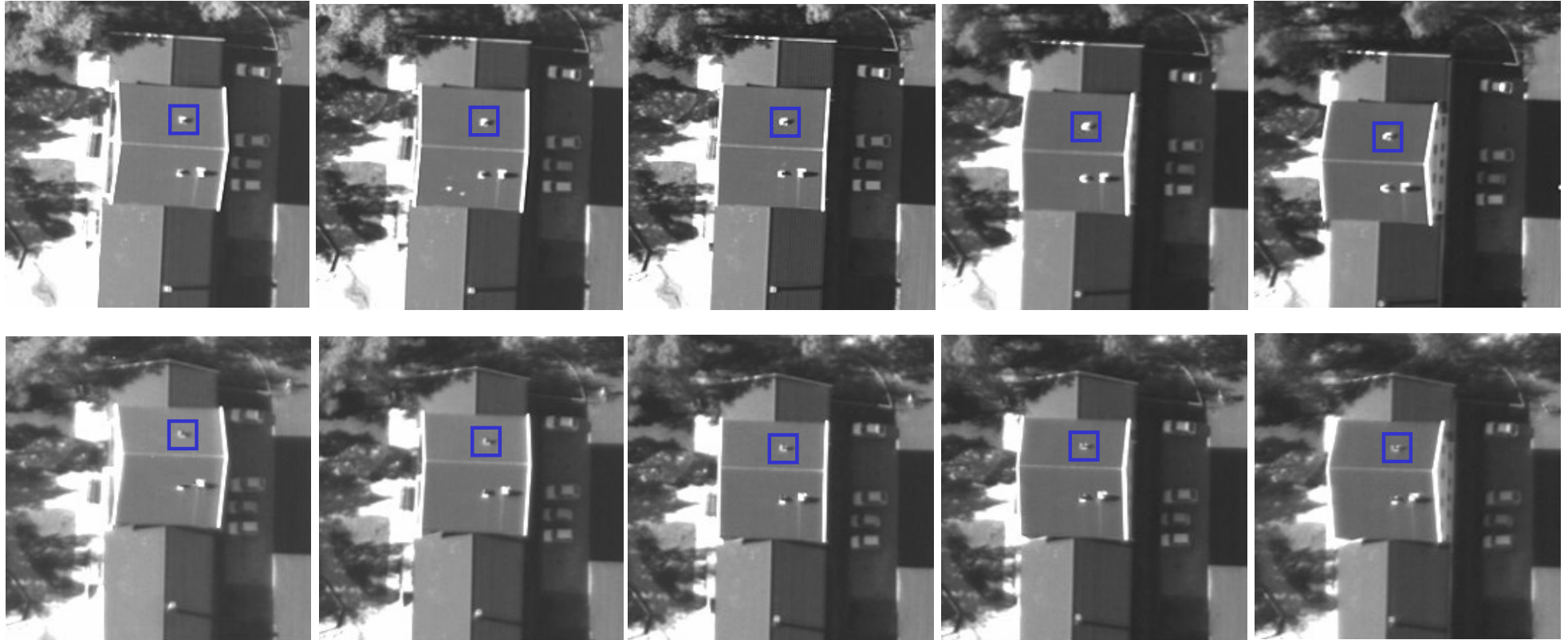


Strip 2

Strip 1



Potential Stereo Combinations for Highly Overlapping Blocks



§ 80% in-flight and 60% cross-flight overlap provides 45 potential stereo combinations

$$\binom{k}{r} = \frac{k!}{r!(k-r)!} = \binom{10}{2} = 45$$

§ Suitability of different stereo combinations for 3D point cloud generation?



Suitability of different stereo combinations for 3D point cloud generation



Image 1



Image 2



Image 5

§ Large stereo base

§ Advantageous geometric configuration for 3D point measurement

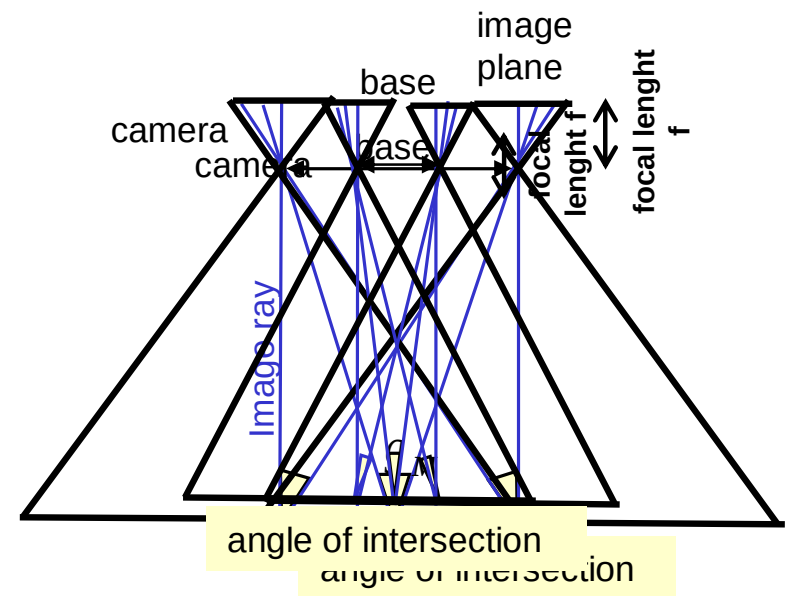
§ Stereo matching aggravated by occlusions

§ Short stereo base

§ Simplified automatic matching due to small image differences

§ Reduced accuracy for spatial intersection

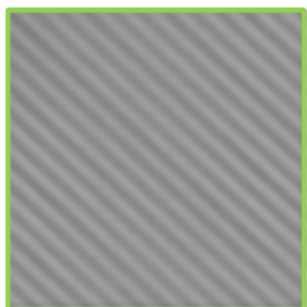
§ Influence of different combinations on accuracy, reliability, completeness of point measurement





Test area Gleisdorf

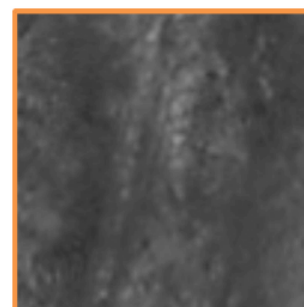
- § UltraCamXp
 - § flight height 1600m, GSD 0.1m
 - § 413 images, 43 control points,
 - § AAT by Match-AT
 - § RMS of tie points 0.07pix
- § Overlap 80% in-flight, 70% cross-flight
 - § 5 images in flight, 3 strips
- § Aim: Investigation of SGM matching quality for different configurations at potential problematic regions



High frequent periodic patterns



Small structures, shadows



Vegetation



Low texture
Planar area

Evaluation of stereo matching quality: Disparity differences



backward
> thresh

backward
< thresh

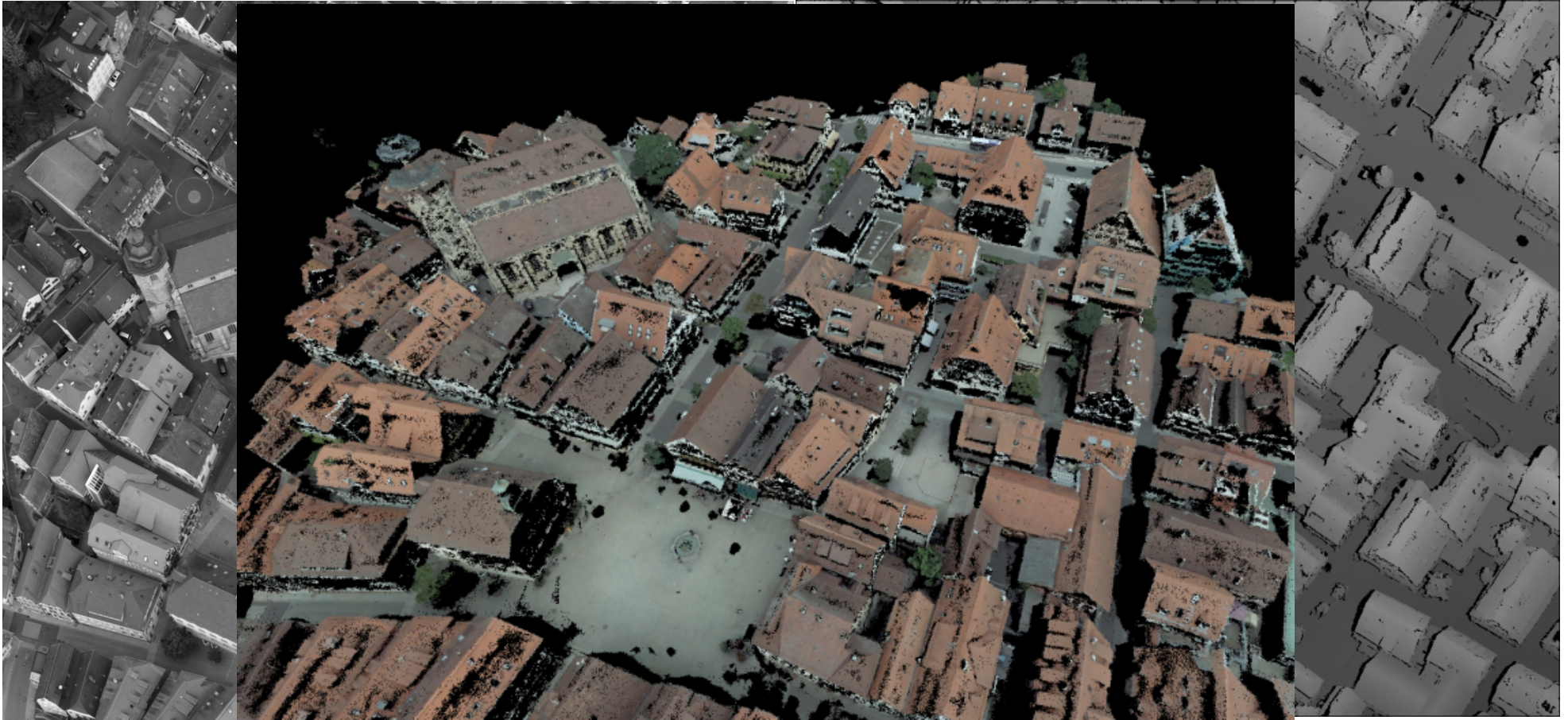


Forward match

- § Disparity differences forward-backward matching as measure of consistency
- § Filter out matches if difference exceeds certain threshold



Dense Stereo Image Matching



§ Parallax image after filtering disparity differences > 1 pixel

§ A priori filter for all subsequent tests



Disparity differences as filter and quality measure



backward-
transformation

backward-
transformation



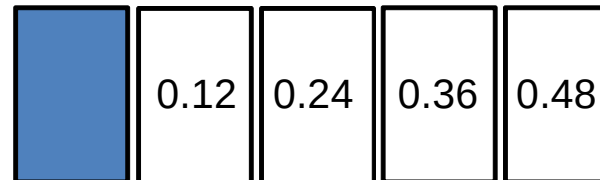
forward-
transformation

$$s_d = \frac{1}{\sqrt{2}} \sqrt{E[(d_{12i} + d_{21i} - E[d_{12i} + d_{21i}])^2]}$$

- § Disparity differences of all matched pixels to compute σ_{d_all}
- § Use $3\sigma_{d_all}$ as additional threshold to eliminate gross errors
- § Disparity differences of remaining parallaxes to measure matching accuracy σ_{d_3mv}



SGM performance from disparity differences



- § Test with 5 images of same strip
- § Stereo pairs with base-to-height-ratios from 0.12 to 0.48
 - § Base-lengths from 192m – 768m



SGM performance from disparity differences



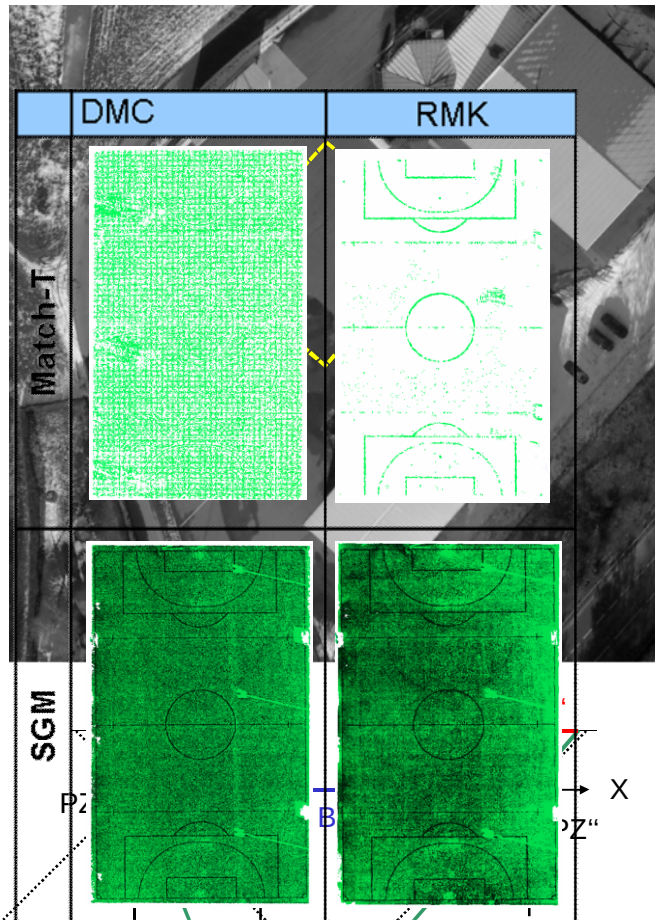
	0.12	0.24	0.36	0.48
--	------	------	------	------

Base-to-height ratios	0.12	0.24	0.36	0.48
Forward-backward matching $\sigma_{3mv}[\text{pix}]$	0.19	0.19	0.24	0.23
Completeness $n_{\text{Points}}[\%]$	86.2	82.5	65.6	53.7

- § Test with 5 images of same strip
- § Accuracy and completeness of SGM decreases for larger baselines
 - § Reliability of matching accuracy from forward-backward consistency?
- § Evaluation of generated 3D point cloud in object space



Evaluation in object space: Test at planar area



DGPF-Test 2009

Normal case of stereo photogrammetry
realized in epipolar images

- § Estimate polynomial at planar surface from generated 3D point cloud
- § Point accuracy from distances to estimated surface
- § Error propagation to provide accuracy in image space for comparison
 - § Spatial intersection from epipolar images as normal case of stereo photogrammetry

$$Z = \frac{c \cdot B}{x' - x''} = \frac{c \cdot B}{p_x}$$

$$\sigma_Z = \frac{Z}{c} \cdot \frac{Z}{B} \cdot \sigma_{p_x} = m_b \cdot \frac{Z}{B} \cdot \sigma_{p_x}$$

$$\sigma_{p_x} = \frac{1}{m_b} \cdot \frac{B}{Z} \cdot \sigma_Z$$



SGM performance at planar test area



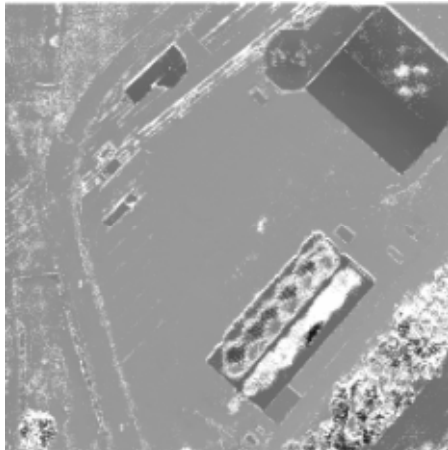
Base-to-height ratios	0.12	0.24	0.36	0.48
Forward-backward matching $\sigma_{3mv}[\text{pix}]$	0.09	0.10	0.16	0.16
Point cloud to reference surface $\sigma_{3mv}[\text{cm}]$	9.15	5.44	6.23	5.11
Transformation to image space $\sigma_{3mv}[\text{pix}]$	0.12	0.14	0.24	0.26
Completeness $n_{\text{Points}}[\%]$	97.79	98.05	96.63	97.31

- § Decreasing SGM accuracy for larger baselines is compensated by better geometric configuration for spatial intersection
- § Differences forward-backward matching and planar surface estimation provide similar accuracy values
- § Difference between values for complete and planar test area

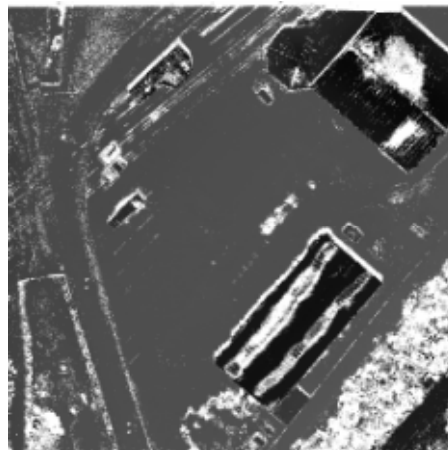


SGM performance

Completeness planar area vs. complete scene



Completeness 0.12



0.24



0.36



0.48

Base-to-height ratios	0.12	0.24	0.36	0.48
Plane area $n_{\text{Points}}[\%]$	97.8	98.0	96.6	97.3
Complete area $n_{\text{Points}}[\%]$	86.2	82.5	65.6	53.7

- § Planar area not representative for different surface types
- § Planar areas preferred by SGM smoothness constraints?
 - § Constrain solution by using large penalties for disparity changes of neighbouring pixels

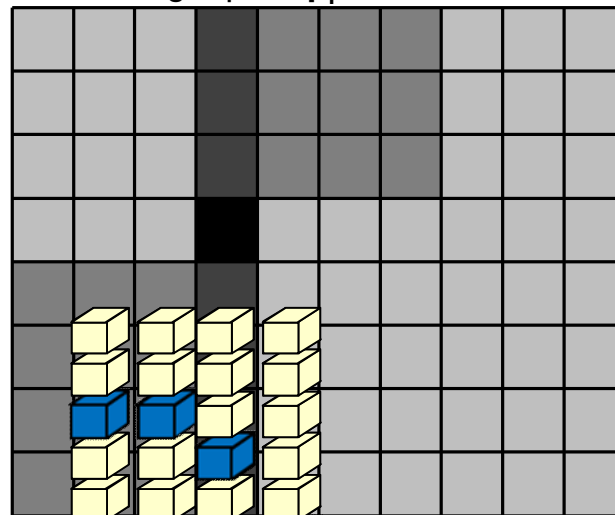


Semi Global Matching (SGM)



- § Ambiguities are avoided by additional continuity constraint
- § Add costs (Penalty) for disparity changes of neighbouring pixels
- § Constrain solution to planar areas by simply selecting large values for penalties P1 and P2 !!

Base Image, pixel $\mathbf{p}_i$



$$L_r(\mathbf{p}, d) = C(\mathbf{p}, d) + \min (\begin{aligned} &L_r(\mathbf{p} - \mathbf{r}, d), \\ &L_r(\mathbf{p} - \mathbf{r}, d - 1) + P_1, \\ &L_r(\mathbf{p} - \mathbf{r}, d + 1) + P_1, \\ &\min_i (L_r(\mathbf{p} - \mathbf{r}, i)) + P_2 \end{aligned}) - \min_k (L_r(\mathbf{p} - \mathbf{r}, k))$$



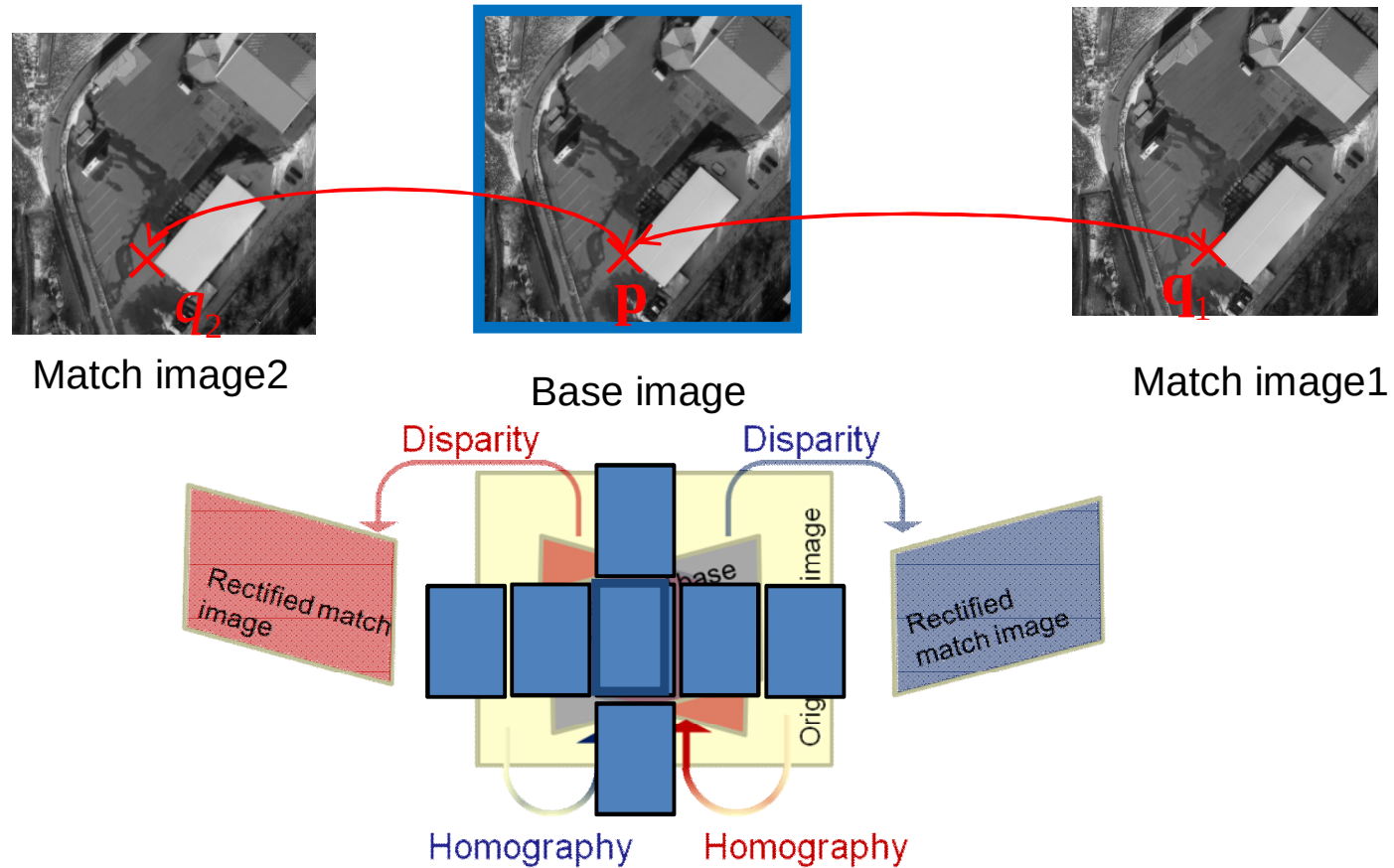
Costs $c(\mathbf{p}_i, \mathbf{q}_i)$



Minimal costs



Multi-View Geometry to improve reliability and accuracy



- § Multi-Stereo-Matching: Transfer each pixel of the base image to multiple match images
- § Redundant measures for each pixel in the match image to determine 3D object coordinates



Quality control by multi-ray photogrammetry



§ Aerial triangulation / bundle block adjustment

§ Feature based matching to generate tie points at overlapping image patches

§ Multiple rays to estimate camera parameters

§ Accuracy analysis

§ 3D coordinates of tie point as by-product

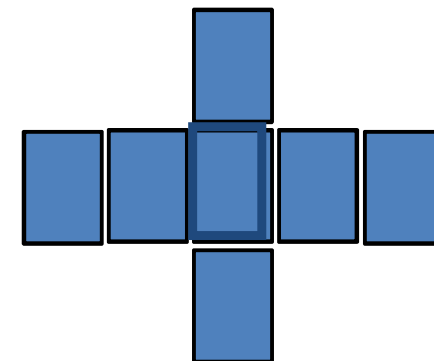
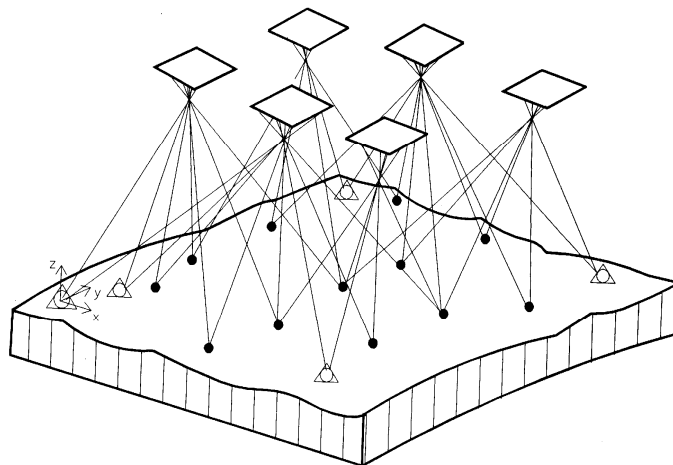
§ 3D point clouds / DSM generation

§ Dense stereo matching between base image and respective stereo images

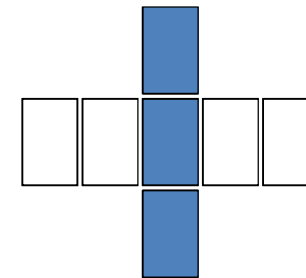
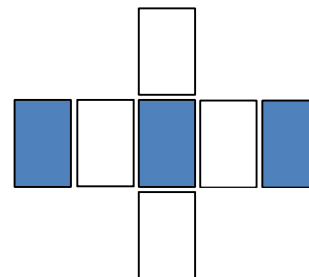
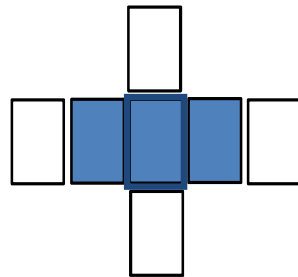
§ Spatial intersection of multiple rays to estimate 3D point coordinates

§ Accuracy analysis

§ Elimination of gross errors



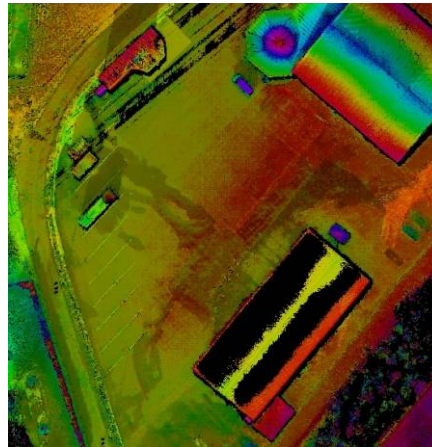
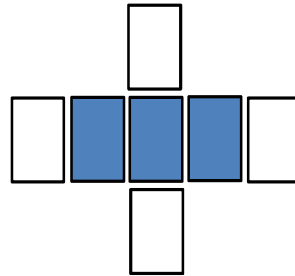
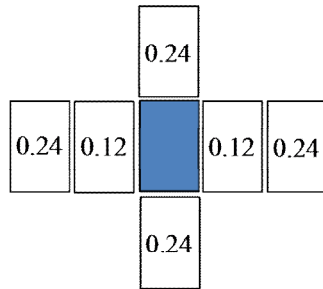
Combination of two stereo matches



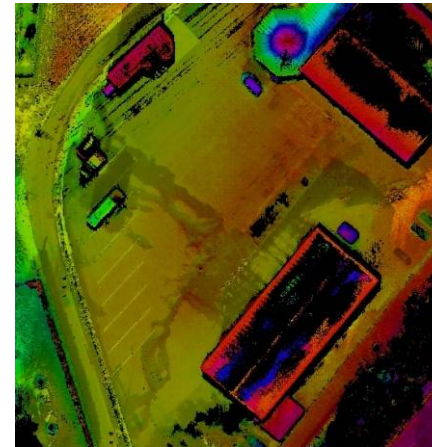
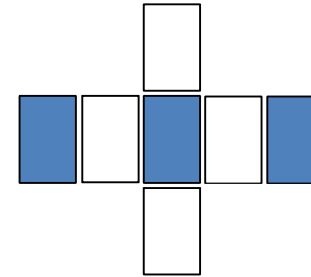
- § Match base image against two neighbors
- § Least squares spatial intersection of 3 image rays
 - § Estimate object coordinate and corresponding point error
 - § Determine σ_{Z_all} from all pixels i.e. points of match image
- § Eliminate gross errors $> \sigma_{Z_all}$
- § Determine accuracy of remaining points σ_{Z_3mv}



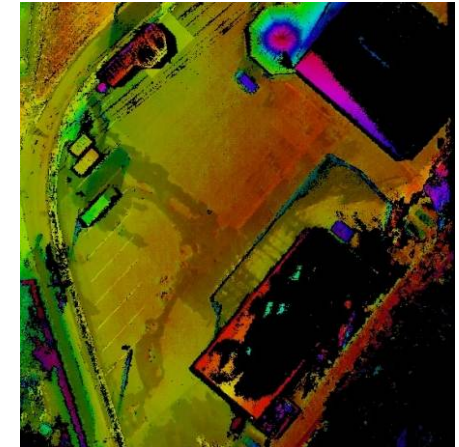
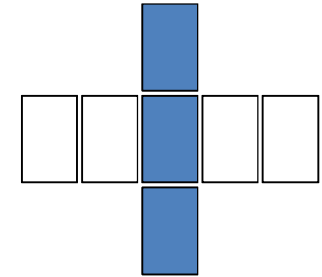
Point determination from double matches



$\sigma_7 = 4.85\text{cm}$
 $n_{\text{Pts}} = 81.6\%$



$\sigma_7 = 2.36\text{cm}$
 $n_{\text{Pts}} = 70.2\%$



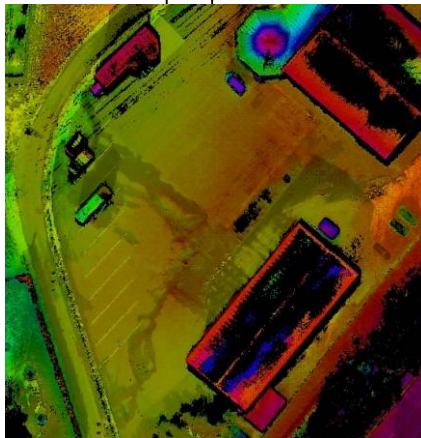
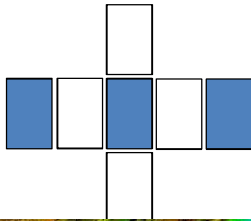
$\sigma_7 = 2.22\text{cm}$
 $n_{\text{Pts}} = 60.1\%$

- § Redundancy of 3 rays increases point accuracy and reliability
- § Larger baselines increase 3D point accuracy but reduces number of successful matches
- § Cross strip matching additionally reduces number of successful matches

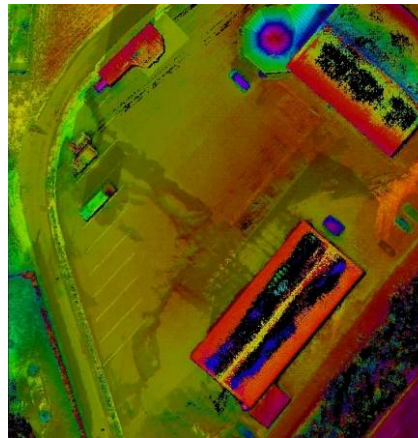
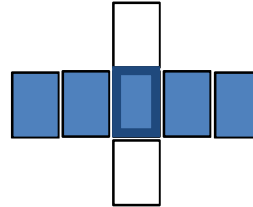


Point determination from multiple matches

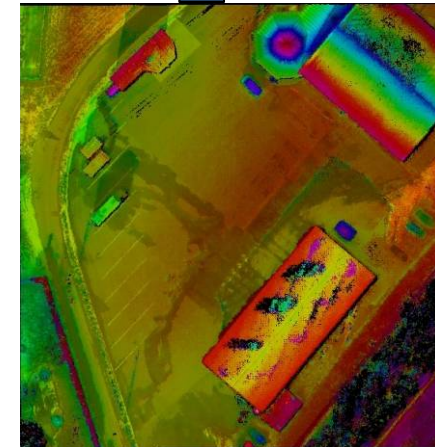
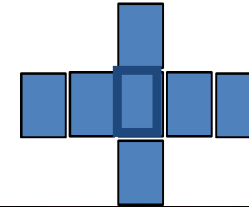
Increase to 5 or 7 image rays



$\sigma_7 = 2.36\text{cm}$
 $n_{\text{Pts}} = 70.2\%$



$\sigma_7 = 3.67\text{cm}$
 $n_{\text{Pts}} = 86.8\%$



$\sigma_7 = 2.78\text{cm}$
 $n_{\text{Pts}} = 91.6\%$

- § Use further increase of redundancy to eliminate single erroneous matches based on residuals in image space
- § Remaining matches for “error free” 3D point coordinates
- § Highest reliability and completeness



Multi-View Geometry to improve point cloud quality from dense matching



- § Performance of SGM stereo matching
 - § Accuracies of 0.14 - 0.25 pixel
 - § Increasing base-to-height ratio reduces accuracy and amount of matched pixels
 - § Reduced matching accuracy partly compensated by better geometric properties for ray intersections of 3D points
- § Multi-View and Multi-ray per pixel matching
 - § Transfers of base image pixels to multiple neighbours
 - § “Pixel-wise bundle block adjustment” for refined error analysis
 - § Improvement in accuracy, reliability and completeness for 3D point cloud
 - § Each 3D point provides
 - § Internal accuracy from spatial intersection
 - § Radiometric information from multiple images



Multi-View Geometry to improve point cloud quality from dense matching



- § SGM stereo matching @ accuracies of 0.14 - 0.25 pixel
- § Multi-View per pixel matching provides for each 3D point
 - § Internal accuracy from spatial intersection
 - § Radiometric information from multiple images
- § Large potential for further interpretation and analysis

