Norbert Haala
Institut für Photogrammetrie

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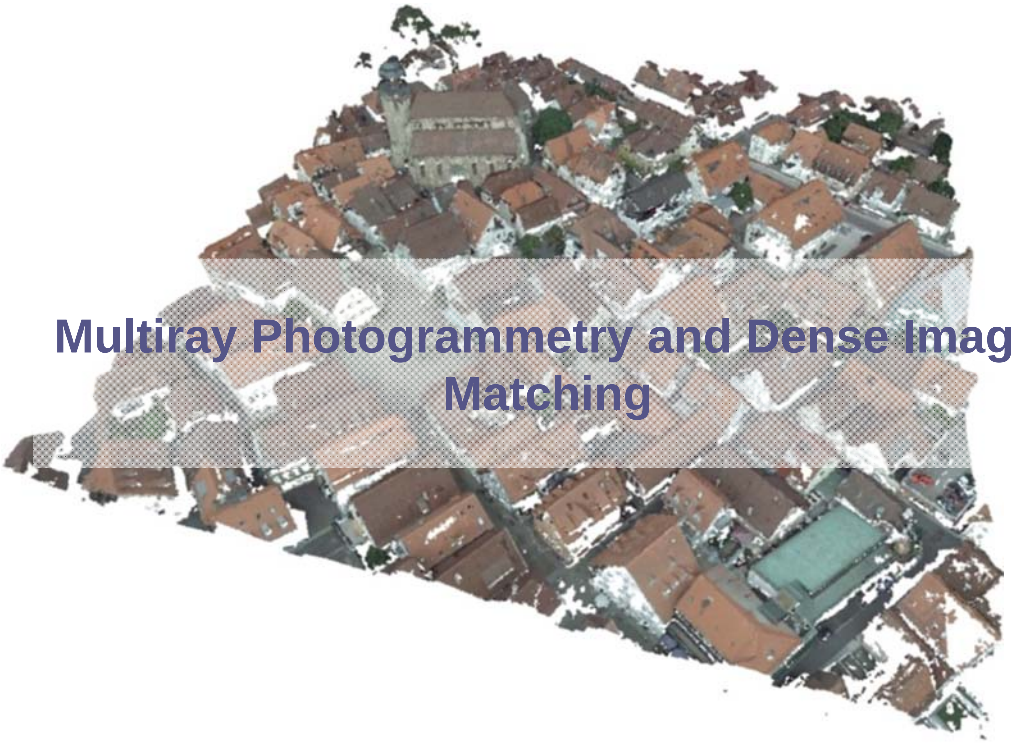
Universität Stuttgart

Multiray Photogrammetry and Dense Image Matching



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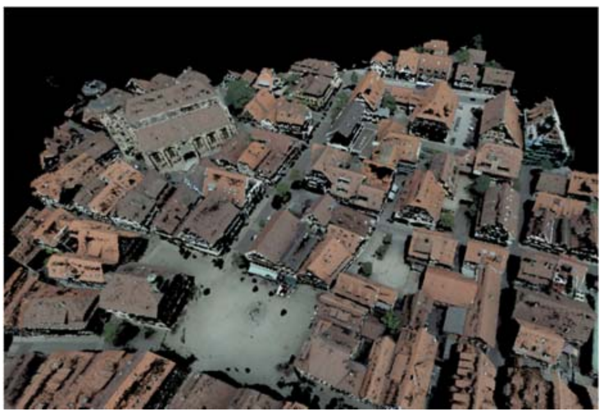
Dense Image Matching - Application of SGM

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



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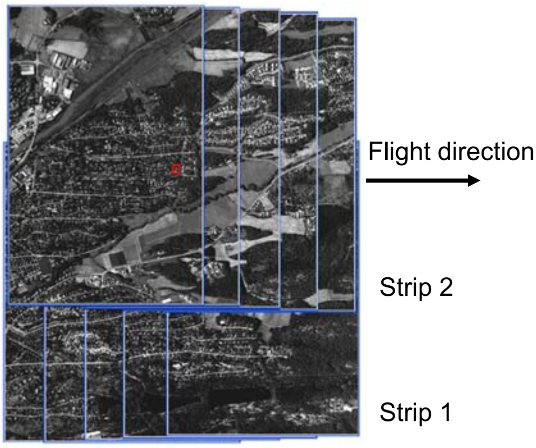
Multiray Photogrammetry and Dense Image Matching

- 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



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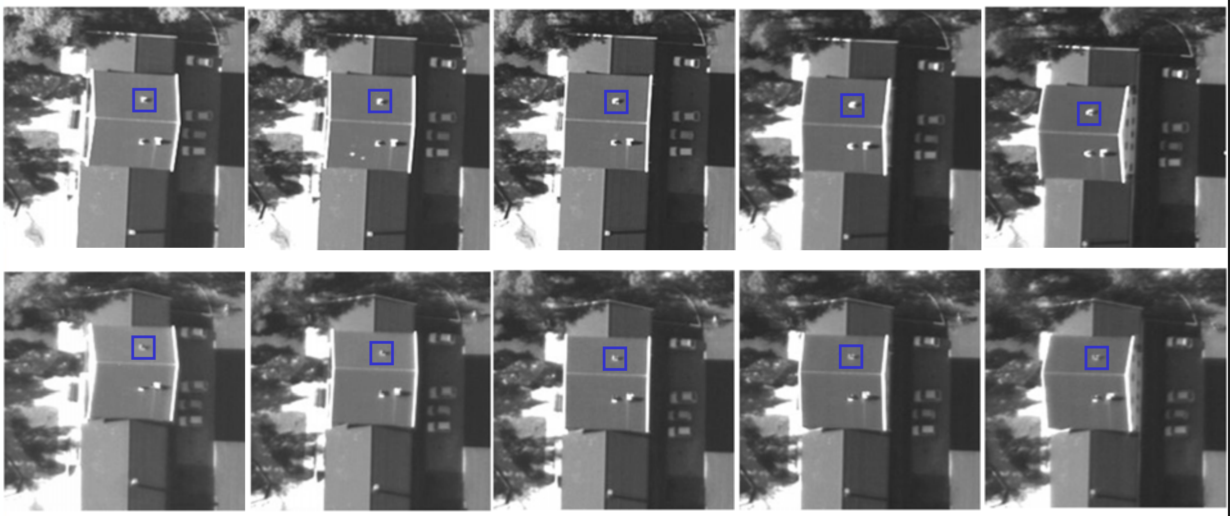
Dense matching using multiple-overlaps



- 80% in-flight and 60% cross-flight overlap provides 45 potential stereo combinations
- Suitability of different stereo combinations for 3D point cloud generation?

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

Suitability of different stereo combinations for 3D point cloud generation

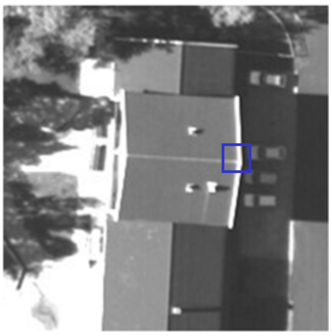


Image 1

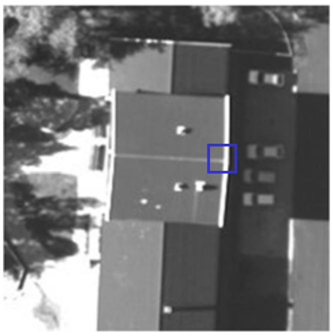


Image 2

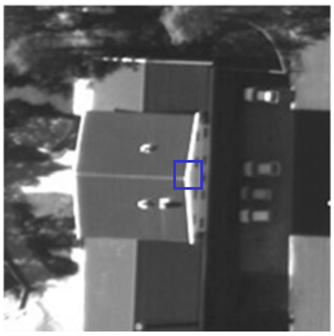
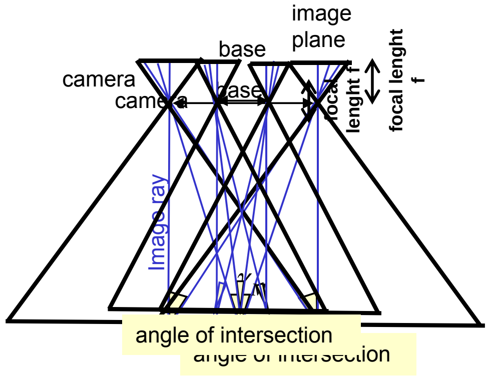


Image 5

- 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
- In-flight vs. cross-flight
- Influence of different combinations on accuracy, reliability, completeness of point measurement



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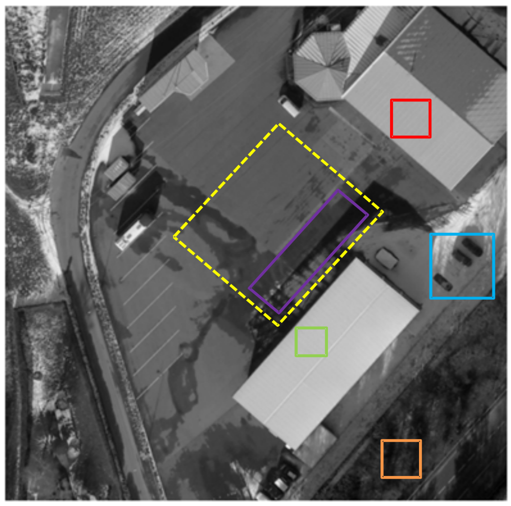
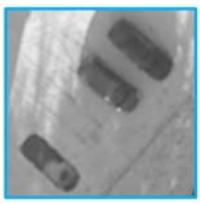
δ_{XY}

Test area Gleisdorf

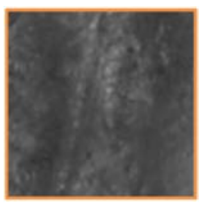
- UltraCamXp
  - flight height 1600m, GSD 0.1m
  - 413 images, 43 control points,
  - AAT by Match-AT
    - RMS of tie points 0.07pix
- Overlap 80% in-flight, 70% cross-flight
  - 5 images in flight, 3 strips
- Aim: Investigation of SGM matching quality for different configurations at potential problematic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



High frequent periodic patterns



Small structures, shadows



Vegetation

Low texture Planar area

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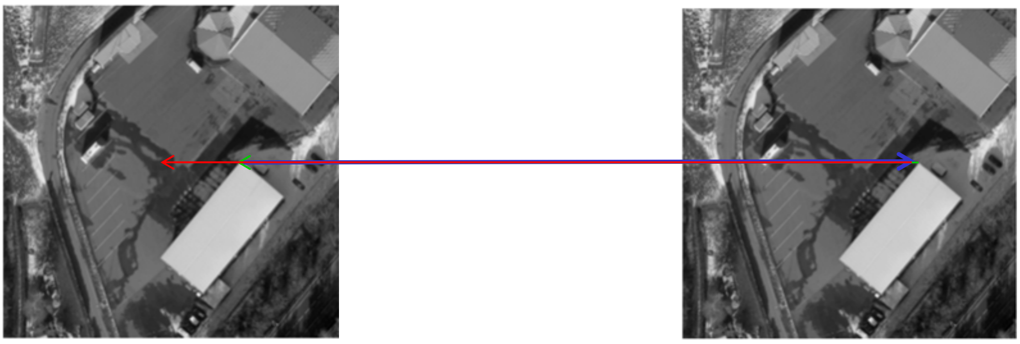
Evaluation of stereo matching quality: Disparity differences



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

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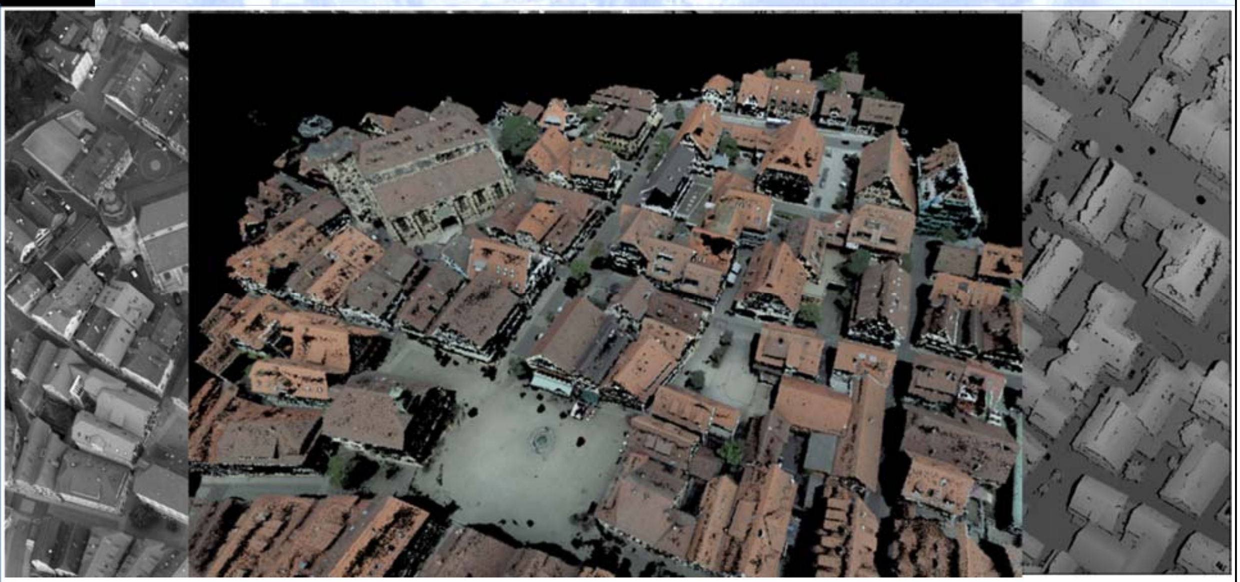
Dense Stereo Image Matching



- Parallax image after filtering disparity differences > 1 pixel
  - A priori filter for all subsequent tests

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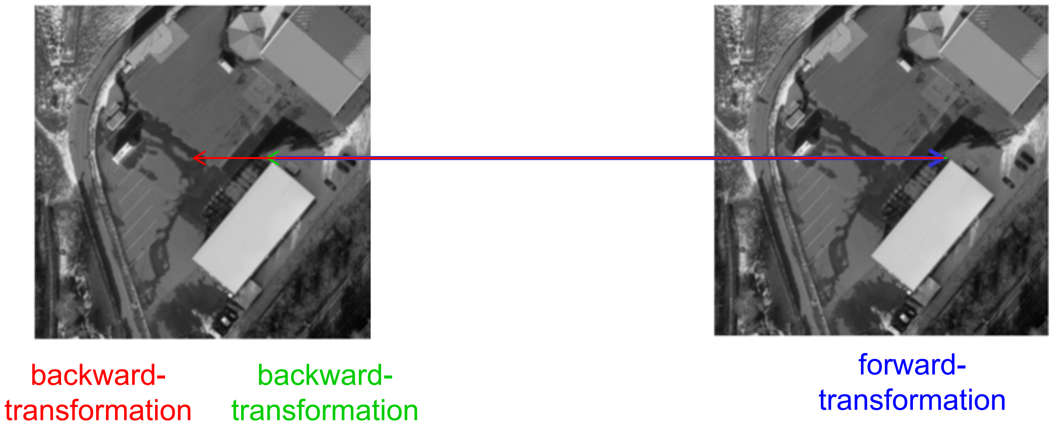
Disparity differences as filter and quality measure



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

- 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}

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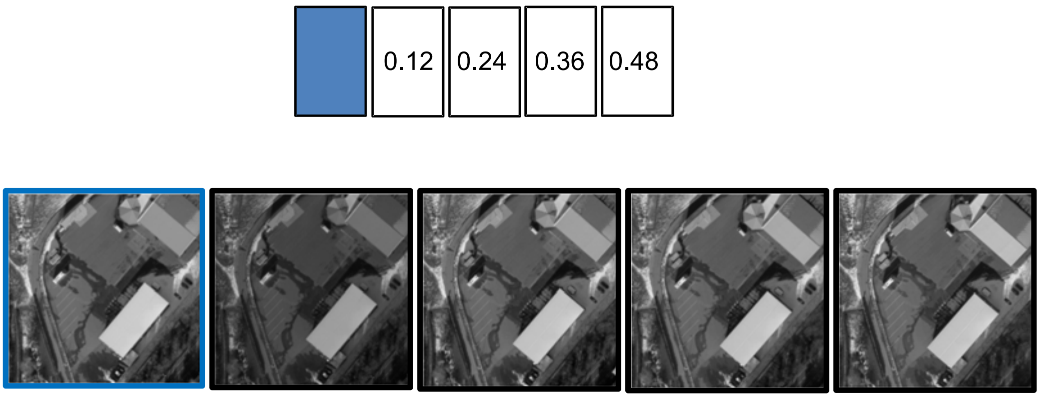
SGM performance from disparity differences



- 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

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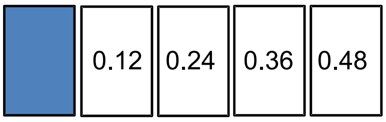
SGM performance from disparity differences



Base-to-height ratios	**0.12**	**0.24**	**0.36**	**0.48**
Forward-backward matching σ_{3mv}[pix]	0.19	0.19	0.24	0.23
Completeness n_{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

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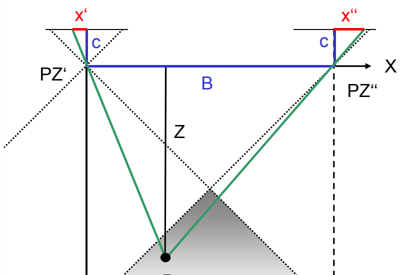
Evaluation in object space: Test at planar area

- 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



Normal case of stereo photogrammetry realized in epipolar images

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

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

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

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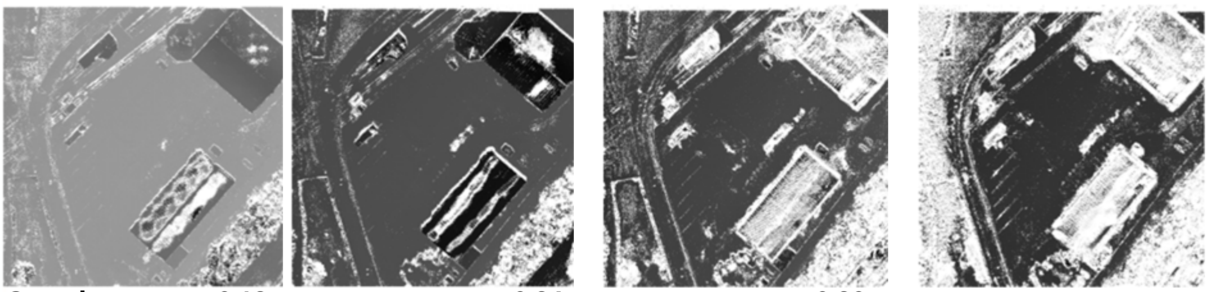
SGM performance at planar test area

Base-to-height ratios	**0.12**	**0.24**	**0.36**	**0.48**
Forward-backward matching σ_{3mv}[pix]	0.09	0.10	0.16	0.16
Point cloud to reference surface σ_{3mv}[cm]	9.15	5.44	6.23	5.11
Transformation to image space σ_{3mv}[pix]	0.12	0.14	0.24	0.26
Completeness n_{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



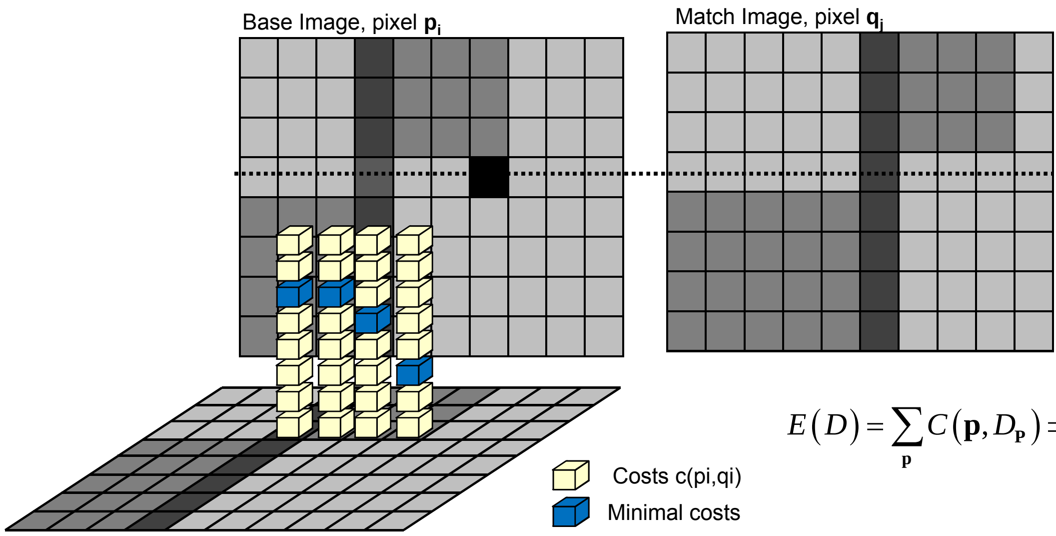
Completeness 0.12 0.24 0.36 0.48

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

- Restriction to planar area not representative for different surface types

Semi Global Matching (SGM)

- Semi-global Matching estimates disparities Dp which minimize costs (e.g. grey value “differences”) for complete stereo pair
  - Costs of potential matches (p,q) are assigned to 3d structure

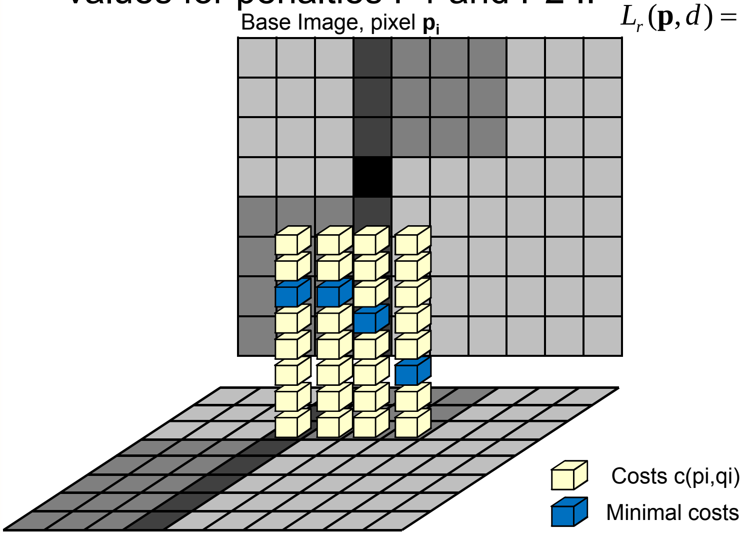


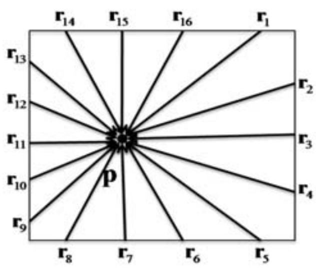
$$E(D)=\sum_{\mathbf{p}} C(\mathbf{p},D_{\mathbf{p}}) \Rightarrow \min$$

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 !!

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

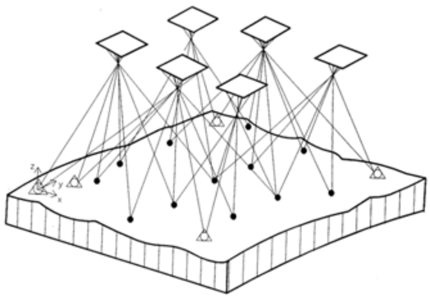


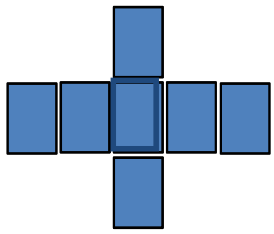


Quality control by multi-ray photogrammetry

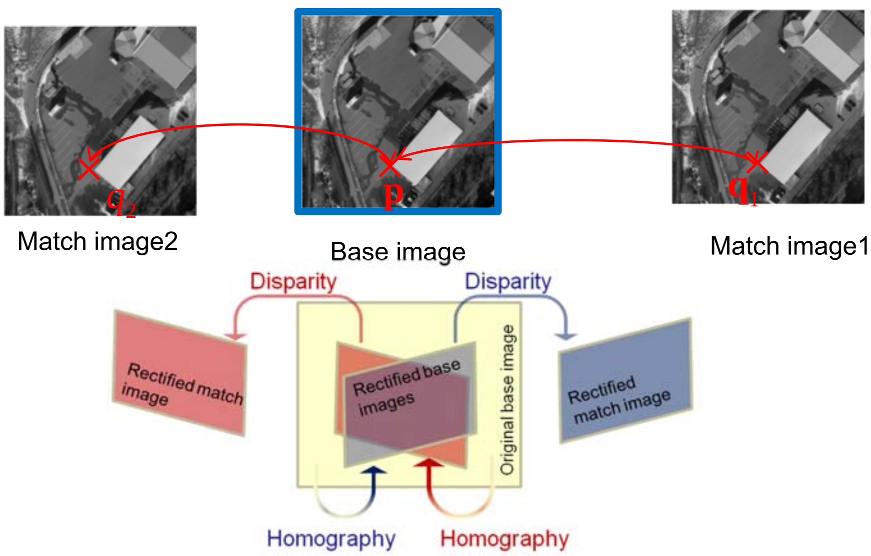
- Aerial triangulation / bundle block adjustment
  - Feature based matching to generate tie points at overlapping image patches
- Multiple rays to estimate camera parameters
  - Accuracy analysis
  - 3D coordinates of tie point as by-product

- 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



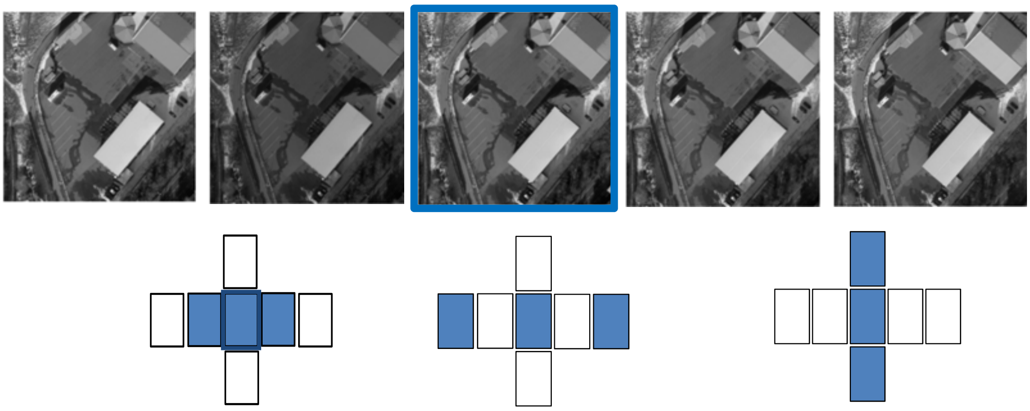


Multi-Stereo-Matching



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

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 > σ_{Z_all}
- Determine accuracy of remaining points σ_{Z_3mv}

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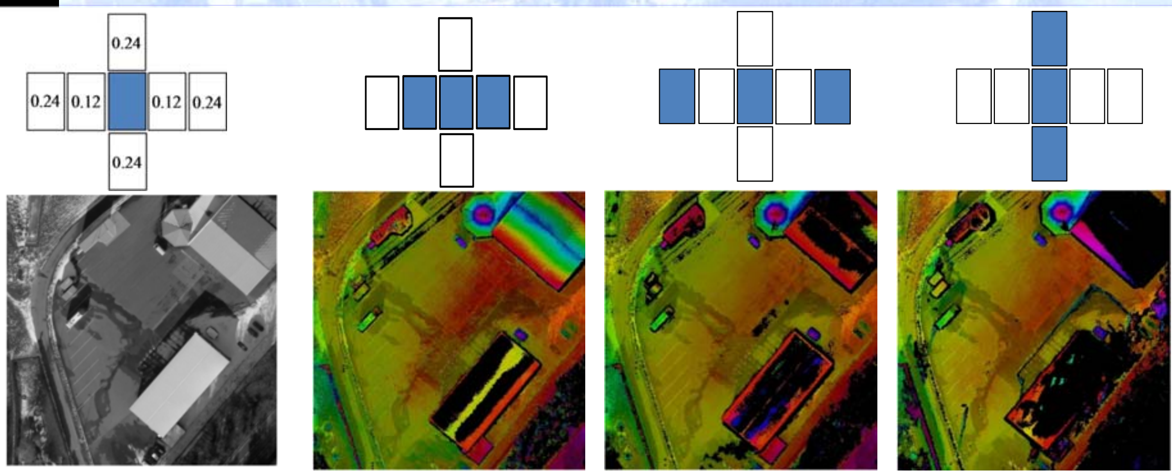
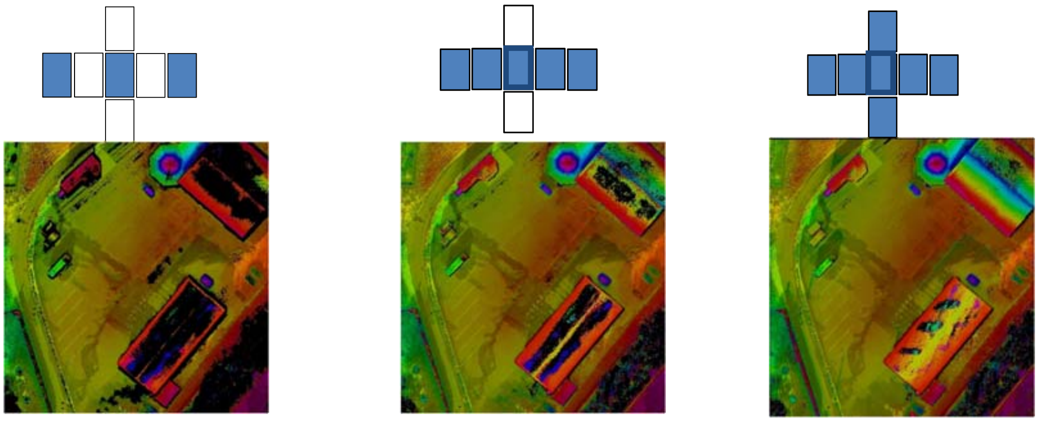
Point determination from double matches



σ_Z = 4.85cm	σ_Z = 2.36cm	σ_Z = 2.22cm
n_{Pts}= 81.6%	n_{Pts}= 70.2%	n_{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



σ_Z = 2.36cm
n_{Pts} = 70.2%

σ_Z = 3.67cm
n_{Pts} = 86.8%

σ_Z = 2.78cm
n_{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

Summary - Conclusions

- SGM stereo matching provides accuracies of 0.14 - 0.25 pixel
- Accuracy and number of successfully matched points decreases for larger base-to-height rations
- Better geometric properties for ray intersections of wide base lines partly compensate worse matching accuracy

- Multi-ray matching considerably improves accuracy, reliability and completeness of 3D point cloud generation
- “Pixel-wise bundle block adjustment” for refined error analysis

Comparison SGM – Feature Based Approaches

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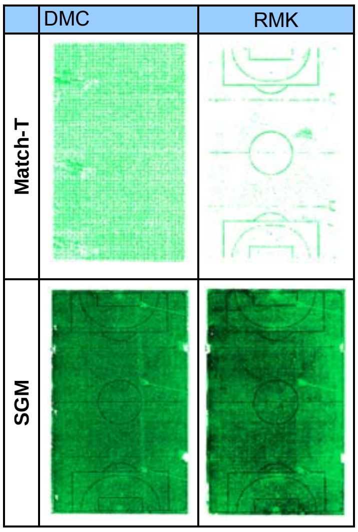
- Other data sets: DGPF Project on Digital Photogrammetric Camera Evaluation
- Comparison of results to commercial tool Match-T DSM (2009)
- In our tests SGM provided
  - Higher completeness
  - Better accuracy
- Planar test area prefers smoothness constraint

	Sensor	STD after filter [cm]	STD no filter [cm]	Density Pts/m^2
Match-T	DMC	3.4	5.2	23.39
	RMK	6.9	19.9	5.35
SGM	DMC	2.7	3.1	102.99
	RMK	4.6	25.7	103.06



Rothermel & Haala, 2011