HIGH ACCURACY 3D PROCESSING OF SATELLITE IMAGERY

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http://www.photogrammetry.ethz.ch
outline

• introduction
• sensor modeling of HRSI
• DTM/DSM generation from HRSI
• performance evaluation
• 3D city modeling with HRSI
• conclusions
• High-resolution PAN & MS imagery
  + Quickbird (0.7 m)
  + IKONOS (1.0 m)
  + SPOT (2.5-10 m)
  + ALOS / PRISM (2.5 m) …….
• More than 8-bit images, higher dynamic range
• Along- / cross-track stereo;
  Possibly multiple view terrain coverage

• Challenge:
  + Algorithmic redesign
  + Improvements
More than 8-bit images, higher dynamic range
• Along- / cross-track stereo;
  Possibly multiple view terrain coverage
SAT-PP (Satellite Image Precision Processing) -- High-Res Satellite Imagery (HRSI): $\leq 5$ m

+ New Processing Methods / Products for HRSI
+ Joint Sensor Model for IKONOS, QuickBird, SPOT, ALOS/RPISM and etc.
+ Specially Designed Image Matching Procedure for Linear Array Imagery

**Input**
Imagery with Supplementary Data
+ IKONOS
+ QuickBird
+ SPOT ......
GCPs

**SAT-PP**
+ Image Orientation
+ Image Matching
+ Feature Collection
+ 3D City Modeling
+ Image Pan-Sharpening
+ DTM & Ortho-Image Generation

**Products**
+ DSM / DTM
+ Ortho-Images
+ Pan-Sharpened Images
+ 3D Vector Data
+ Digital Image Maps
+ 3D City Models

......
Functionality of SAT-PP

- Project and data management tools, image format conversion and pre-processing, image display / roaming in mono and stereo modes
- Sensor models (RFM, affine and projective DLT model)
- Orientation of single stereo models
- On-line quality control and error analysis via interaction of graphics elements
- GCP and tie point measurement in manual and semi-automated modes
- Derivation of quasi-epipolar images for stereo mapping and feature collection
- Automated DSMs generation
- Generation of orthorectified images
- Mono-plotting functions with DTMs
- Manual and semi-automatic object extraction in mono/stereo
- 3D city modeling by using CyberCity Modeler™
- Pansharpening image generation. Fully automated sub-pixel image registration between multispectral and panchromatic imagery
Workflow of SAT-PP

INTRODUCTION

SENSOR MODELING

DSM GENERATION

CASE STUDIES

CONCLUSIONS

CITY MODELING
Sensor Modeling and Blockadjustment

- Rigorous sensor model
  + Physical imaging geometry (nearly parallel projection in along-track and perspective projection in cross-track); high accuracy; easier for statistic analysis
  - Mathematically more complicated; depends on type of sensors
- Sensor model based on RFM
  + Given (for IKONOS, Quickbird) and computed RFM parameters (RPCs)
    \[ px_n = \frac{f_1(X_n, Y_n, Z_n)}{f_2(X_n, Y_n, Z_n)} \]
    \[ py_n = \frac{f_3(X_n, Y_n, Z_n)}{f_4(X_n, Y_n, Z_n)} \]
- Blockadjustment model (Grodecki & Dial; 2003)
  + Calibrated system with a very narrow FOV; accurate a priori exterior orientation data (HRSI -- OK !)
    \[ x + \Delta x = x + a_0 + a_1x + a_2y = RPC_x(\varphi, \lambda, h) \]
    \[ y + \Delta y = y + b_0 + b_1x + b_2y = RPC_y(\varphi, \lambda, h) \]
- Other simpler sensor models
  + 3D affine; relief-corrected 2D affine; DLT ......
Sensor model based on RFM

For SPOT5 HRS / HRG
Fitting accuracy: 1/20 - 1/100 pixels
User interface for block adjustment
Ellipse fitting mode GCP measurement
Detailed DSM Generation

The approach uses a coarse-to-fine hierarchical solution with an effective combination of several image matching algorithms and automatic quality control.

The new characteristics provided by the IKONOS and Quickbird imaging systems, i.e. the multiple-view terrain coverage and the high quality image data, are also efficiently utilized.

It was originally developed for multi-image processing of the very high-resolution TLS/StarImager aerial Linear Array images. Now it has been extended and has the ability to process other linear array images as well.
Workflow of Automated DSM Generation

1. Images and Orientation Data
2. Image Pre-processing & Image Pyramid Generation
3. Initial DSM Generation (at Highest-level of Pyramid)
4. Feature Point Extraction & Matching
5. Grid Point Generation & Matching
6. Edge Extraction & Matching
7. Probability Relaxation Based Relational Matching
8. DSM Represented by TIN (Intermediate) Integration of Feature Points, Grid Points and Edges
9. Modified Multi-image Geometrically Constrained Matching (MPGC)
10. Final DSM
Automated DSM Generation Procedure

- Multiple image matching
  + Matching guided from object space
  + Simultaneously multiple images (≥ 2) with Geometrically Constrained Cross-Correlation
- Matching with multiple primitives --- points + edges
- Self-tuning matching parameters
- High matching redundancy
- Efficient surface modeling
  + TIN (from a constrained Delauney triangulation method)
- Coarse-to-fine Hierarchical strategy
Matching guided from object space
Self-tuning matching parameters

Strip-1: Forward Image  The Reference Image  Strip-1: Backward Image

## INTRODUCTION

### SENSOR MODELING

### DSM GENERATION

### CASE STUDIES

### CITY MODELING

### CONCLUSIONS

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**IKONOS Triplet, Hobart, Australia**

**RPC + 2 Translates**

<table>
<thead>
<tr>
<th>GCPs(CPs)</th>
<th>RMSE-X</th>
<th>RMSE-Y</th>
<th>RMSE-Z</th>
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<td>0.45</td>
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[Diagram showing control and check points with distances marked]
IKONOS Triplet, Hobart, Australia

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Automatic DTM/DSM Generation (IKONOS, Hobart, Australia)

- The strip encompassed buildings and suburban housing in central and southern Hobart; accuracy 0.25 m
- 111 GCPs as reference:
  - RMSE-Z: 0.9 m; Mean: -0.3 m; Absolute max.: 2.9 m
- LIDAR DSM as reference (ca. 252000 points):
  - RMSE-Z: 2.7 m; Mean: -0.2 m; Absolute max.: 29.6 m

**Raster DSM (5 m Spacing)**
### SPO T5-HRS, Bavaria, Germany

#### RPC + 2 Translates

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<td>4.63</td>
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SPO T5-HRS, Bavaria, Germany

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**SPO T5-HRS, Bavaria, Germany**
### RPC + 2 Translates

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**SPO T5-HRS, Bavaria, Germany**
Automatic DTM/DSM Generation (SPOT5-HRS, Bavaria, Germany)

Study area: Bavaria, Germany
+ Area: 120 × 60 Km²
+ Height range: ca. 1600 m

SPOT HRS stereo pair
+ Acquisition time: 1st October, 2002
+ 5m / 10m res. In along-/cross-track

Reference data:
+ 81 GPS GCPs (only 41 used)
+ 6 reference DTMs

<table>
<thead>
<tr>
<th>DTM Name</th>
<th>Location</th>
<th>DTM Spacing (m)</th>
<th>Source</th>
<th>DTM Size</th>
<th>Height Accuracy (m)</th>
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</thead>
<tbody>
<tr>
<td>DTM-1</td>
<td>Prien</td>
<td>5 × 5</td>
<td>Laser Scanner</td>
<td>5km × 5km</td>
<td>0.5</td>
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<tr>
<td>DTM-2</td>
<td>Gars</td>
<td>5 × 5</td>
<td>Laser Scanner</td>
<td>5km × 5km</td>
<td>0.5</td>
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<tr>
<td>DTM-3</td>
<td>Peterskirchen</td>
<td>5 × 5</td>
<td>Laser Scanner</td>
<td>5km × 5km</td>
<td>0.5</td>
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<tr>
<td>DTM-4</td>
<td>Taching</td>
<td>5 × 5</td>
<td>Laser Scanner</td>
<td>5km × 5km</td>
<td>0.5</td>
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<tr>
<td>DTM-5-1</td>
<td>Inzell-North</td>
<td>25 × 25</td>
<td>Laser Scanner</td>
<td>10km × 1.3km</td>
<td>0.5</td>
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<tr>
<td>DTM-5-2</td>
<td>Inzell-South</td>
<td>25 × 25</td>
<td>Contour lines</td>
<td>10km × 7.7km</td>
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<tr>
<td>DTM-6</td>
<td>Vilsbiburg</td>
<td>50 × 50</td>
<td>Photogrammetry</td>
<td>50km × 30km</td>
<td>2.0</td>
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</table>
Automatic DTM/DSM Generation (SPOT5-HRS, Bavaria, Germany)

Raster DSM (25 m Spacing, 120 × 60 km²)
Automatic DTM/DSM Generation (SPOT5-HRS, Bavaria, Germany)
Automatic DTM/DSM Generation (SPOT5-HRS, Bavaria, Germany)
### Automatic DTM/DSM Generation (SPOT5-HRS, Bavaria, Germany)

#### DSM Accuracy (All Reference Data)

<table>
<thead>
<tr>
<th>Ref. DTM</th>
<th>Terrain Characteristic</th>
<th>No. of Points</th>
<th>Max. Diff.</th>
<th>Min. Diff.</th>
<th>Average (m)</th>
<th>RMSE (m)</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>Matched</td>
<td>Reference</td>
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<tr>
<td>DTM-1</td>
<td>Smooth, weakly inclined</td>
<td>35448</td>
<td>1000000</td>
<td>25.1</td>
<td>-32.9</td>
<td>-2.6</td>
</tr>
<tr>
<td>DTM-2</td>
<td>Smooth, weakly inclined</td>
<td>32932</td>
<td>1000000</td>
<td>29.1</td>
<td>-37.1</td>
<td>-1.2</td>
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<tr>
<td>DTM-3</td>
<td>Smooth, weakly inclined</td>
<td>33450</td>
<td>1000000</td>
<td>20.7</td>
<td>-17.2</td>
<td>-0.5</td>
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<tr>
<td>DTM-4</td>
<td>Smooth, weakly inclined</td>
<td>32067</td>
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<td>13.6</td>
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<tr>
<td>DTM-5-1</td>
<td>Rough, strongly inclined</td>
<td>10327</td>
<td>21200</td>
<td>19.2</td>
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<td>-5.8</td>
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<tr>
<td>DTM-5-2</td>
<td>Rolling, strongly inclined</td>
<td>71795</td>
<td>139200</td>
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<td>600000</td>
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#### DSM Accuracy (Without Trees)

<table>
<thead>
<tr>
<th>Ref. DTM</th>
<th>Terrain Characteristic</th>
<th>Max. Diff.</th>
<th>Min. Diff.</th>
<th>Average (m)</th>
<th>RMSE (m)</th>
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<tbody>
<tr>
<td>DTM-1</td>
<td>Smooth, weakly inclined</td>
<td>15.4</td>
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<tr>
<td>DTM-2</td>
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<td>29.1</td>
<td>-31.7</td>
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<tr>
<td>DTM-3</td>
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<td>20.7</td>
<td>-13.6</td>
<td>0.1</td>
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<tr>
<td>DTM-4</td>
<td>Smooth, weakly inclined</td>
<td>10.5</td>
<td>-18.4</td>
<td>-1.2</td>
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<td>DTM-5-1</td>
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<td>19.1</td>
<td>-13.3</td>
<td>-1.7</td>
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<tr>
<td>DTM-5-2</td>
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<td>26.8</td>
<td>-25.9</td>
<td>2.1</td>
<td>4.4</td>
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</table>
### Comparison of sensor models for the IKONOS stereo pair. CPs are check points.

- **M_RPC1**: RPCs+2 translations
- **M_RPC2**: RPCs+6 affine parameters
- **M_3DAFF**: 3D affine transformation

<table>
<thead>
<tr>
<th>Sensor Model</th>
<th>GCPs</th>
<th>CPs</th>
<th>x-RMSE [m]</th>
<th>y-RMSE [m]</th>
<th>z-RMSE [m]</th>
<th>max. Δx [m]</th>
<th>max. Δy [m]</th>
<th>max. Δz [m]</th>
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<td>0.93</td>
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<td>1.01</td>
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<td>1.36</td>
<td>0.96</td>
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### Comparison between M_RPC1 and M_RPC2 using all five images with different numbers of GCPs.

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</table>
IKONOS Images, Thun, Switzerland

Decreasing number of GCPs doesn’t decreasing the accuracy significantly

Comparison of sensor models for the **IKONOS stereo pair** CPs are check points.

M_RPC1: RPCs+2 translations; M_RPC2: RPCs+6 affine parameters; M_3DAFF: 3D affine transformation

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Comparison of sensor models and number of GCPs for the **IKONOS triplet** CP are check points.

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Comparison between M_RPC1 and M_RPC2 using all five images with different numbers of GCPs.

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Even M_3DAFF could achieve similar results (for IKONOS imagery).

### Comparison of sensor models for the IKONOS stereo pair. CPs are check points.

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### Case Studies

#### Study area: town of Thun, Switzerland

- **Area:** $17 \times 20$ Km$^2$
- **Height Range:** 1600 m

#### IKONOS Geo Product

<table>
<thead>
<tr>
<th>IKONOS Image</th>
<th>Acquisition Date</th>
<th>Scanning Mode</th>
<th>Sensor-Azimuth [°]</th>
<th>Sensor-Elevation [°]</th>
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<td>128.17</td>
<td>82.62</td>
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#### Reference

- 2m spacing LIDAR DSM as reference
  - Accuracy: 0.5 m (1$\sigma$) for open areas;
- 1.5 m for vegetation & build-up areas
- 50 GPS GCPs (only 39 used)
Automatic DTM/DSM Generation (IKONOS, Thun, Switzerland)

Raster DSM (5 m Spacing) Generated from IKONOS Images
Automatic DTM/DSM Generation (IKONOS, Thun, Switzerland)
Automatic DTM/DSM Generation (IKONOS, Thun, Switzerland)
Automatic DTM/DSM Generation (IKONOS, Thun, Switzerland)
Z_diff = LIDAR_DSM_Z - Interpolation(IKONOS_DSM)

DSM accuracy evaluation results (triplet part of test area).
O-Open areas; C-City areas; T-Tree areas; A-Alpine areas.

<table>
<thead>
<tr>
<th>Area</th>
<th>No. of compared points</th>
<th>Mean (m)</th>
<th>RMSE (m)</th>
<th>&lt; 2.0 m</th>
<th>2.0-5.0 m</th>
<th>&gt; 5.0 m</th>
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<tbody>
<tr>
<td>O+C+T+A</td>
<td>29,210,494</td>
<td>-1.21</td>
<td>4.80</td>
<td>60.7%</td>
<td>16.8%</td>
<td>21.3%</td>
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<tr>
<td>O+C+A</td>
<td>17,610,588</td>
<td>-1.11</td>
<td>2.91</td>
<td>77.0%</td>
<td>13.9%</td>
<td>10.1%</td>
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<tr>
<td>O+A</td>
<td>14,891,390</td>
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<td>12.2%</td>
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<tr>
<td>O</td>
<td>11,795,795</td>
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<td>1.28</td>
<td>90.3%</td>
<td>8.5%</td>
<td>1.2%</td>
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DSM accuracy evaluation results (stereo part of test area).

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<tr>
<td>O+C+T</td>
<td>20,336,024</td>
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<td>4.78</td>
<td>57.7%</td>
<td>21.3%</td>
<td>20.9%</td>
</tr>
<tr>
<td>O+C</td>
<td>13,496,226</td>
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</tr>
<tr>
<td>O</td>
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<td>1.54</td>
<td>83.0%</td>
<td>15.0%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

Z_diff = Matched_POINT_Z - Interpolation(LIDAR_DSM)
(dense LIDAR points --> Less surface modeling errors)

+ Point number: ca. 14,327,000

+ RMSE: 3.30 m

+ Mean: -0.32 m
Semi-automated Feature Extraction with SAT-PP

- Currently available for some kind of objects, such as points, lines and polygons
- The user only needs to measure, for example, the outlines of buildings in one image. The correspondences of building outlines in other images are computed automatically.
- User intervention is possible for editing the polygon/line nodes when mismatching occurs

An extracted building from an IKONOS stereopair. The left building is measured manually and the right one is matched automatically.
CyberCity Modeler approach, from stereo images and laser data
Point Cloud Coding System
- Independence regarding used DPS
- Reduction of manual labour

CyberCity-MODELER™

Digital Photogrammetric Station

Point cloud (x, y, z)
+ DTM

Roof modeling
Wall generation

Geometry improvement

3D City Model

Quality Control

CAD Systems
(Formats: DXF etc.)

Visualization
(Formats: FLT, VT etc.)

ArcGIS 9
(Shape, PGDB, ArcSDE)

Roof texturing
Facade texturing
TEXTURING

Generic Texturing
- Texture library
- Not realistic
- Regional texture types
- Automatic

Automatic Texturing
- (Oblique-) Aerial Imagery
- Realistic
- Automatic

Terrestrial Texturing
- Digital Photographs
- Realistic / High resolution
- Manually applied
3D Object Extraction From IKONOS Imagery

Input & Data Pre-processing

**IKONOS Melbourne Stereopair**

7x7 km area

elevation range of less than 100 m

32 GPS-surveyed ground measured semi-automatically by ellipse-fitting method

<table>
<thead>
<tr>
<th></th>
<th>Left stereo</th>
<th>Right stereo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date, time (local)</td>
<td>16/7/2000, 09:53</td>
<td>16/7/2000, 09:53</td>
</tr>
<tr>
<td>Sensor azimuth (°)</td>
<td>136.7</td>
<td>71.9</td>
</tr>
<tr>
<td>Sensor elevation (°)</td>
<td>61.4</td>
<td>60.7</td>
</tr>
<tr>
<td>Sun azimuth (°)</td>
<td>38.2</td>
<td>38.3</td>
</tr>
<tr>
<td>Sun elevation (°)</td>
<td>21.1</td>
<td>21.0</td>
</tr>
</tbody>
</table>

Orientation was based on the supplied RPCs parameters (from Space Imaging) plus additional 6 affine transformation parameters in image space. The RMSEs of orientation are 0.4 meters in planimetry and 0.9 meters in height.
3D Object Extraction From IKONOS Imagery

INTRODUCTION
SENSOR MODELING
DSM GENERATION
CASE STUDIES
CITY MODELING
CONCLUSIONS
3D Object Extraction From IKONOS Imagery

Measurement area overview
3D Object Extraction From IKONOS Imagery

Generated 3D city model
3D City Modeling from Quickbird

- Quickbird stereo images over Phoenix, USA
  - Acquired on 9 April 2004
  - Along track stereo images
  - GSD: 75cm (mean)
  - Viewing angles: 29°, -27°

• Detail in Quickbird images
3D City Modeling from Quickbird
Facade textures from library
3D City Modeling from Quickbird
3D City Modeling from Quickbird
Conclusions

**SAT-PP:** sophisticated image pre-processing algorithms, a set of sensor models, an image matching approach for DSM generation and feature extraction from HRSI.

**Sensor modeling and block adjustment:**

Basically three types of sensor-model orientation concepts at our disposal:

a) rigorous/physical sensor model

b) Rational Functional Model (RFM) with given RPCs

c) 2D affine model, possibly with added parameters

d) 3D affine and DLT models

Precise (sub-pixel) GCP / tie point collection (LSM) in semi-automatic model

Sub-pixel orientation accuracy can be achieved for all models
Conclusions

**Automatic DSM/DTM generation:**

Reproduces not only general features, but also detailed features of the terrain relief

Height accuracy of around 1 pixel in cooperative terrain

- RMSE values of 1.3-1.5 m (1.0-2.0 pixels) for IKONOS
- RMSE values of 2.9-4.6 m (0.5-1.0 pixels) for SPOT5 HRS

**3D city modeling:**

The manual and semi-automatic feature extraction capability of SAT-PP provides a good basis also for 3D city modeling applications with CyberCity-Modeler™ (CCM).

The tools of SAT-PP allowed the stereo-measurements of points on the roofs in order to generate a 3D city model with CCM. Additional features of CCM allow roof and facade texturing.

The results show that building models with main roof structures can be successfully extracted by HRSI. As expected, with Quickbird more details are visible.
Acknowledgements

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➢ NPOC (National Point of Contact) - swisstopo, Bern