DSM GENERATION FROM OPTICAL AND SAR HIGH RESOLUTION SATELLITE IMAGERY:
METHODOLOGY, PROBLEMS AND POTENTIALITIES

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*** Vermessung AVT ZT- GmbH, Austria

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Aim of the work

Evaluate the performances of high resolution optical and SAR imagery (with radargrammetric approach) for DSMs generation

The image processing and DSMs generation are carried out with the software packages SISAR (Software Immagini Satellitari ad Alta Risoluzione), SAT-PP (SATellite image Precision Processing) and OrthoEngine

- **SISAR** is a scientific software developed by the research group of Geodesy and Geomatic Institute - University of Rome “La Sapienza”
- **SAT-PP** is a commercial software developed by the ETH Zurich and sold by 4DiXplorer AG
- **OrthoEngine** is a tool of the commercial software PCI Geomatica 2012

- **Tests** on one optical GeoEye-1 and two TerraSAR-X SpotLight stereo pairs acquired over Trento area (Northern Italy)
**GeoEye-1 and TerraSAR-X sensors**

**GeoEye-1**

**Optical sensor**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>Panchromatic Sensor</td>
<td>0.41 m x 0.41 m</td>
</tr>
<tr>
<td>Multispectral Sensor</td>
<td>1.65 m x 1.65 m</td>
</tr>
<tr>
<td>Swath Width</td>
<td>15.2 km</td>
</tr>
<tr>
<td>Off-Nadir Imaging</td>
<td>Up to 60 degrees</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>11 bits per pixel</td>
</tr>
<tr>
<td>Mission Life Expected</td>
<td>&gt; 10 years</td>
</tr>
<tr>
<td>Revisit Time</td>
<td>Less than 3 days</td>
</tr>
<tr>
<td>Orbital Altitude</td>
<td>681 km</td>
</tr>
</tbody>
</table>

**TerraSAR-X**

**X-band Radar sensor**

<table>
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<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar frequency</td>
<td>9.65 GHz</td>
</tr>
<tr>
<td>Resolution</td>
<td>1 m, 3 m, or 16 m</td>
</tr>
<tr>
<td>Orbital altitude</td>
<td>514 km</td>
</tr>
<tr>
<td>Angle of inclination</td>
<td>97.4 °</td>
</tr>
<tr>
<td>Mission Life Expected</td>
<td>at least 5 years</td>
</tr>
</tbody>
</table>
The two main steps for DSMs generation from satellite imagery according to the stereoscopic approach are:

- the stereo pair orientation
- the image matching
Project schedule

GeoEye-1 stereopair

SISAR -> SAT-PP -> OrthoEngine

RPCs model orientation

GeoEye-1 stereopair

SISAR-DSM -> SAT-PP DSM -> OE-DSM

TerraSAR-X stereopairs

SISAR -> Radargrammetric model orientation

TerraSAR-X stereopairs

SISAR -> Image Matching -> DSM
The Rational Polynomial Functions - RPFs relate object point coordinates (Latitude $\phi$, Longitude $\lambda$ and Height $h$) to pixel coordinates ($I$, $J$) in the form of polynomial ratios:

$$J = \frac{P_1(\phi, \lambda, h)}{P_2(\phi, \lambda, h)} \quad I = \frac{P_3(\phi, \lambda, h)}{P_4(\phi, \lambda, h)}$$

Each polynomial has the generic form:

$$P_n = \sum_{i=0}^{m_1} \sum_{j=0}^{m_2} \sum_{k=0}^{m_3} r_{ijk} \phi^i \lambda^j h^k$$

$r_{ijk}$ are the RPCs

**Bias correction for RPFs**

$$J = A_0 + J \cdot A_1 + I \cdot A_2 + \frac{P_1(\phi, \lambda, h)}{P_2(\phi, \lambda, h)}$$

$$I = B_0 + J \cdot B_1 + I \cdot B_2 + \frac{P_3(\phi, \lambda, h)}{P_4(\phi, \lambda, h)}$$

- $A_0, A_1, A_2, B_0, B_1, B_2$ model a 2D affine transformation
- $A_0, B_0$ model a 2D coordinate shift

<table>
<thead>
<tr>
<th>polynomial order</th>
<th>RPCs #</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
</tr>
<tr>
<td>3</td>
<td>78</td>
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</table>
Radargrammetric technique

**Radargrammetry**: technique similar to photogrammetry but based on distances instead of angles; allows a 3D reconstruction starting from a stereo model.

Optimal geometric configurations:

- **B/H ratio** ranging from 0.25 to 2 is recommended to have a good stereo geometry.
- Opposite-side view cause large geometric and radiometric disparities, hindering the image matching process.
- A good compromise is to use a **Same-side** to enable an easier image matching.
Radargrammetric model

\[
\begin{align*}
\vec{v}_S \cdot (\vec{P} - \vec{S}) &= 0 \quad \rightarrow \text{zero-Doppler constrain} \\
|\vec{P} - \vec{S}| &= D_S + CS \cdot I \quad \rightarrow \text{slant range constrain}
\end{align*}
\]

- \(\vec{P}\) position of a ground point \(P\)
- \(\vec{S}\) satellite position corresponding to the point \(P\)
- \(\vec{v}_S\) satellite velocity
- \(D_S\) near range
- \(CS\) slant range resolution (column spacing)
- \(I\) column coordinate of the point \(P\) on the image

✓ A **Lagrange Polynomial Interpolation** has been used in order to retrieve the satellite position and velocity at the corresponding row

✓ start-time, PRF: linear function that relates the time of acquisition \(t_p\) of each GP (Ground Point) to its line number \(J_p\)

\[
t_p = \text{start-time} + \frac{1}{\text{PRF}} \cdot J_p
\]
Image matching

Automatic detection of homologous points
Define a matching primitive

The first step of image matching process is to define the matching entity, that is a primitive (in the master image) to be compared with a portion of other (slave) images, in order to identify correspondences among different images.

Area Based Matching (ABM): a small image window represents the matching primitive and the methods to assess similarity are cross-correlation and Least Squares Matching (LSM)

Feature Based Matching (FBM): basic features, that are typically the easily distinguishable primitives in the input images, like corners, edges, lines, are used as main class of matching

Example of two windows primitives

Left: extracted points with Harris operator.
Right: Extracted edges with Canny operator.
Matching strategies

**SISAR** matching algorithm:
• based on a coarse-to-fine hierarchical solution with an effective combination of geometrical constrains and an Area Based Matching (ABM) algorithm
• homologous points are looked for by cross-correlation and signal to noise ratio threshold

**SAT-PP** matching algorithm:
• based on a coarse-to-fine hierarchical solution with an effective combination of geometrical constrains and an Area Based Matching (ABM) algorithm
• Feature Based Matching (points, edges, grid points)
• homologous points are looked for by cross-correlation and signal to noise ratio threshold
• Epipolar images

**OrthoEngine** matching algorithm:
• homologous points are looked for by cross-correlation
• Epipolar images
For all the tests performed has been used the same validation procedure:

- The regular DSMs or the points clouds have been compared with the reference DSM\DTM through DEMANAL software, developed by Prof. K. Jacobsen - Leibniz University Hannover

- The accuracy, in terms of Root Mean Square Error (RMSE) was computed at the 95% probability level, so that the LE95 was evaluated, in order to leave out the outliers from the statistical evaluation
The reference DSM was acquired with LiDAR technology
- horizontal grid spacing: 1.0 x 1.0 m
- vertical accuracy: 0.25 m
- made available by the Provincia Autonoma di Trento
Data Set GeoEye-1 – Trento

<table>
<thead>
<tr>
<th>Area</th>
<th>Acquisition data</th>
<th>Coverage (Km²)</th>
<th>Mean incidence angles (degrees)</th>
<th>Orbit</th>
<th>Look side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trento</td>
<td>28/09/2011</td>
<td>10 x 10</td>
<td>14.4 °</td>
<td>Desc</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>28/09/2011</td>
<td>10 x 10</td>
<td>19.6 °</td>
<td>Desc</td>
<td>-</td>
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</table>

60 Ground Points (GPs):
- acquired with a double frequency GNSS receiver (accuracy 0.1 m)

Provided by FBK with funding of Provincia Autonoma di Trento
GeoEye-1 DSMs accuracy assessment

Tile 1

Tile 2

1 Km

0.3 Km
GeoEye-1 DSM accuracy assessment: Tile1

- **RMSE** around 2.5 m
- No significant systematic errors (slightly higher for SISAR)
- **SAT-PP** gives slightly better results

<table>
<thead>
<tr>
<th></th>
<th>BIAS [m]</th>
<th>ST.DEV. [m]</th>
<th>RMSE LE95 [m]</th>
<th>LE95 [m]</th>
<th># Points</th>
<th>MAX [m]</th>
<th>MIN [m]</th>
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<tbody>
<tr>
<td>PCI</td>
<td>0.11</td>
<td>2.63</td>
<td>2.63</td>
<td>10.50</td>
<td>540218</td>
<td>29.84</td>
<td>-31.72</td>
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<tr>
<td>SISAR</td>
<td>0.92</td>
<td>2.47</td>
<td>2.63</td>
<td>8.92</td>
<td>540193</td>
<td>32.74</td>
<td>-34.19</td>
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<tr>
<td>SAT-PP</td>
<td>0.29</td>
<td>2.34</td>
<td>2.35</td>
<td>8.34</td>
<td>540218</td>
<td>27.58</td>
<td>-27.85</td>
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</table>

- **LE95**:
  - PCI: 2.63
  - SISAR: 2.63
  - SAT-PP: 2.35

- **All points**
GeoEye-1 DSMs Error Maps: Tile 1

PCI Geomatica

SISAR

SAT-PP

✓ Feature-based approach in SAT-PP preferable for tall building reconstruction

✓ Positive errors due to presence of trees
Trento DSMs profile: Tile 01

✓ Errors due to occlusions (narrow streets) and low texture (shadows)
**GeoEye-1 DSM accuracy assessment: Tile2**

- **RMSE around 4.3 m**

<table>
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<tr>
<th>BIAS [m]</th>
<th>ST.DEV. [m]</th>
<th>RMSE LE95 [m]</th>
<th>LE95 [m]</th>
<th># Points</th>
<th>MAX [m]</th>
<th>MIN [m]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PCI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.09</td>
<td>4.54</td>
<td>4.54</td>
<td>13.70</td>
<td>154996</td>
<td>38.18</td>
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<td>SISAR</td>
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<td></td>
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<tr>
<td>1.40</td>
<td>4.06</td>
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<td></td>
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<tr>
<td>1.35</td>
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<td>4.23</td>
<td>11.82</td>
<td>154996</td>
<td>35.38</td>
<td>-28.29</td>
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</tbody>
</table>

**LE95**

**All points**
In case of small buildings, SISAR and SAT-PP estimate the height correctly.
## Data Set TerraSAR-X – Trento

<table>
<thead>
<tr>
<th>Area</th>
<th>Acquisition data</th>
<th>Coverage (Km²)</th>
<th>Mean incidence angles (degrees)</th>
<th>Orbit</th>
<th>Look side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trento</td>
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<td>24.1°</td>
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<tr>
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<td>14/01/2011</td>
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<td>38.9°</td>
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<td>31.1°</td>
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<tr>
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<td>5 x 10</td>
<td>44.2°</td>
<td>Asc</td>
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### 60 Ground Points (GPs):
- acquired with a double frequency GNSS receiver (accuracy 0.1 m)

Provided by DLR in the framework of ISPRS project working group VII/2 “SAR Interferometry”
TerraSAR-X DSMs accuracy assessment

Larger tiles have been selected for SAR DSM in order to evaluate TerraSAR-X capabilities also in vegetated areas

GeoEye-1 Tile

TerraSAR-X Tile

Remarks:

- the orientation and DSM generation were performed **without** GCPs
- **SRTM DSM is not needed** to drive the generation of TerraSAR-X DSM in SISAR
TerraSAR-X DSM accuracy assessment: Tile1

- **RMSE** around 4.7 m
- Some problems related to the strong geometrical deformations typical of these images especially in built up areas

<table>
<thead>
<tr>
<th></th>
<th>BIAS [m]</th>
<th>ST.DEV. [m]</th>
<th>RMSE LE95 [m]</th>
<th>LE95 [m]</th>
<th># Points</th>
<th>MAX [m]</th>
<th>MIN [m]</th>
</tr>
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<tbody>
<tr>
<td><strong>ASC</strong></td>
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<td></td>
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<td></td>
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<td></td>
<td>-0.89</td>
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<td>290538</td>
<td>90.32</td>
<td>6.92</td>
<td></td>
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</tbody>
</table>

**LE95**

**All points**
In the merged DSM:

- the bias is reduced
- the overall accuracy is approximately the same as the best single (descending) DSM
# TerraSAR-X DSM accuracy assessment: Tile2

Overall results appear remarkably worse than for Tile 1

<table>
<thead>
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<th>ST.DEV. [m]</th>
<th>RMSE LE95 [m]</th>
<th>LE95 [m]</th>
<th># Points</th>
<th>MAX [m]</th>
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<td>100.38</td>
<td>-100.38</td>
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</table>

**LE95**

All points
The bias is reduced in the merged product.

Larger errors occur in green highlighted area, due to:

- **Tree height** probably different in SAR images and LiDAR DSM
- **Complex** terrain morphology
TerraSAR-X DSMs Tile 2 analysis

<table>
<thead>
<tr>
<th></th>
<th>BIAS [m]</th>
<th>ST.DEV. [m]</th>
<th>RMSE LE95 [m]</th>
<th>LE95 [m]</th>
<th># Points</th>
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<th>MIN [m]</th>
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<tbody>
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<td></td>
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<td>5.65</td>
<td>15.13</td>
<td>32142</td>
<td>71.08</td>
<td>10.64</td>
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</tbody>
</table>

**Urban area**  **Rural area**  **LE95**  **All points**

- **Better results** achievable with rural and wooded land cover, where the **radargrammetry** represents an effective approach in comparison with the classical SAR **interferometry**, suffering for lack of coherence.
Conclusions

• A comparison between different software (SISAR, SAT-PP, PCI Geomatica 2012) for automatic optical DSM generation has been carried out

• The achieved accuracy level is similar for the three software using the optical GeoEye-1 data, and it is around 2.5 m for tile 1 and 4.5 m for tile 2

• The geometric constraints in SAT-PP and SISAR matching allow for building reconstruction; the feature-based detection in SAT-PP provides good results for tall buildings too

• SAR DSM has been generated using only SISAR software, in which a radargrammetric tool is implemented. Results are worse than the optical ones, around 4.5 m for tile 1 and 7.5 m for tile 2, that present more complex terrain morphology

• Deeper analysis of SAR DSM Tile 2 shows that better results are achievable in rural and vegetated areas in comparison to urban area (about 1 m difference in RMSE)

• Better results are achievable with rural and wooded ground coverage, where the classical SAR interferometry suffers lack of coherence

• As future prospects, multiple images could be used to avoid the occlusion effects in optical imagery and to reduce the errors due to SAR distortions
Thank you for your kind attention