Deformation Monitoring of Urban Infrastructure by Tomographic SAR Using Multi-View TerraSAR-X Data Stacks

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TomoSAR Urban Imaging

- Multi-baseline InSAR approach
- Layover separation capability
- Up to $10^6$ points/km$^2$ achievable with meter-resolution SAR data
- Non-linear and multi-component motion (e.g. linear subsidence and thermal seasonal deformation) can be accounted for → LOS deformation

Source: Zhu, 2011
InSAR LOS Deformation

- InSAR provides deformation estimates projected onto the LOS of the satellite
  (One-dimensional deformation)

\[ d_{\text{LOS}} = d_u \cos(\theta_{\text{inc}}) - d_e \cos(\alpha_h) \sin(\theta_{\text{inc}}) + d_n \sin(\alpha_h) \sin(\theta_{\text{inc}}) \]

- \( d_{\text{LOS}} \): LOS deformation
- \( d_u \): Motion component in vertical direction
- \( d_e \): Motion component in east-west direction
- \( d_n \): Motion component in north-south direction
- \( \theta_{\text{inc}} \): Local incidence angle of satellite beam
- \( \alpha_h \): Azimuth angle of the satellite

LOS deformation estimates from, at least, three geometries \( \rightarrow \) Retrieval of \( d_u, d_e, d_n \)
InSAR LOS Deformation

- Considering near-polar orbits of TerraSAR-X, for instance:
  - Heading angle ($\alpha_h = 190.6^\circ$)
  - Incidence angle ($\theta_{inc} = 36.1^\circ$)

\[
\begin{bmatrix}
0.8 & 0.58 & -0.1
\end{bmatrix}
\begin{bmatrix}
u \\
e \\
n
\end{bmatrix}^\top
\]

- Should not lead to ignorance of $d_n$ in the functional model of 3D motion retrieval

\[
\Delta_e = d_n \cdot \tan(\alpha_h) \approx 18 \% d_n
\]
Why motion decomposition?

Tomographic data available from **one** viewing geometry:

- One-dimensional LOS deformation
- No information on the shadowed part

Tomographic data available from **multiple** viewing geometries:

- Decomposed horizontal and vertical motion
- Shadow-free deformation monitoring
- Higher number of scatterers on each building
Workflow

- Required data: Stacks available from cross-heading tracks

- TomoSAR processing of each SAR image stack and geocoding

- Geodetic point cloud fusion

- Motion decomposition from the available LOS measurements
Tomo-GENESIS Processing System

New features:
- SL1MMER for SR
- Time Warp method
- Integrated solution
- Point clouds fusion
Point Cloud Fusion

- TomoSAR point clouds from different acquisition geometries cannot be directly merged:
  - Unknown height of the reference point in each stack

- Available *geometrical* fusion algorithms
  - Least squares identical point matching (Gernhardt et al., 2012)
  - Feature-based building end-point matching (Wang and Zhu, 2014)

*How about geodetic point cloud fusion?*
Geodetic Point Cloud Fusion

- Based on an **absolutely localized identical reference point** for all the TomoSAR stacks

**Corrections**: Atmospheric and geodynamic effects

**Stereo-SAR**: Combination of absolute SAR measurements

Elevation and deformation estimates of all the stacks are w.r.t this point
Motion Decomposition

\[ d_{LOS} = d_u \cos(\theta_{inc}) - d_e \cos(\alpha_h) \sin(\theta_{inc}) + d_n \sin(\alpha_h) \sin(\theta_{inc}) \]

- \( m \): Number of points inside the cube
- \( x \): Unknown vector consist of \((d_u, d_e, d_n)\)
- \( b \): Observation vector consist of TomoSAR LOS deformations
- \( A \): Design matrix based on \((\theta_{inc}, \alpha_h)\)
- \( W \): Weight matrix proportional to inversed squared distances
- \( v \): Vector of residuals
- \( w \): Vector consists of diagonal elements of \( W \)

Fused point cloud

Volume of 5m x 5m x 5m

For each point

Overdetermined system

\[ \text{Setup } b + v = Ax \]

\[ w^T |v| = \sum_{i=1}^{m} w_i |v_i| \rightarrow \min \]

Retrieved motion components

\( m \geq 3? \)

No

Yes

\( m \geq 3? \)
Why L1 Norm Instead of L2?

- L2 norm minimization (Least squares):
  \[ \mathbf{v}^T \mathbf{W} \mathbf{v} = \sum_{i=1}^{m} v_i \ W_{i,i} \ v_i^T \rightarrow \min \]

- L1 norm minimization
  \[ \mathbf{w}^T |\mathbf{v}| = \sum_{i=1}^{m} w_i \ |v_i| \rightarrow \min \]
  Robust against outliers
Experimental Results
Dataset and Test Area

- Central area of Berlin, Germany
- Four stacks of TerraSAR-X VHR spotlight images (300MHz)
- Period: March 2008 to March 2013

Scene coverage

SAR data

<table>
<thead>
<tr>
<th>Beam</th>
<th>Incidence angle</th>
<th>Heading angle</th>
<th>Track type</th>
<th>Nr. of Images</th>
</tr>
</thead>
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<td>57</td>
<td>41.9°</td>
<td>350.3°</td>
<td>Ascending</td>
<td>102</td>
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<tr>
<td>85</td>
<td>51.1°</td>
<td>352°</td>
<td>Ascending</td>
<td>111</td>
</tr>
<tr>
<td>42</td>
<td>36.1°</td>
<td>190.6°</td>
<td>Descending</td>
<td>109</td>
</tr>
<tr>
<td>99</td>
<td>54.7°</td>
<td>187.2°</td>
<td>Descending</td>
<td>138</td>
</tr>
</tbody>
</table>
TomoSAR Deformation Results
Seasonal deformation map (Descending)

Processed by Tomo-GENESIS, DLR
Linear deformation map (Descending)

Processed by Tomo-GENESIS, DLR
Seasonal deformation map (Ascending)

Processed by Tomo-GENESIS, DLR
Linear deformation map (Ascending)

Processed by Tomo-GENESIS, DLR
Geodetic Point Cloud Fusion
Geodetic Point Cloud Fusion

Selected reference point: Base of a lamp post near central railway station

ITRF 2008:

\[ X = 3783630.014 \pm 0.010 \, \text{m} \]
\[ Y = 899035.0040 \pm 0.010 \, \text{m} \]
\[ Z = 5038487.589 \pm 0.011 \, \text{m} \]

We expect a bias of approximately 20 cm due to the diameter of the lamp post
Geodetic Point Cloud Fusion

\[ D \approx 20 \text{ cm} \]

\[ \theta_{\text{Asc}} \quad \theta_{\text{Dsc}} \]

\[ d_I = D \cdot \tan(\theta_{\text{Asc}}) \cdot \tan(\theta_{\text{Dsc}}) \]

\[ dx_{\text{Asc}} = d_I \cdot \cos(\alpha_{\text{Asc}}) \]

\[ dy_{\text{Asc}} = -d_I \cdot \sin(\alpha_{\text{Asc}}) \]

\[ dx_{\text{Dsc}} = d_I \cdot \cos(\alpha_{\text{Dsc}}) \]

\[ dy_{\text{Dsc}} = -d_I \cdot \sin(\alpha_{\text{Dsc}}) \]
Geodetically Fused TomoSAR point cloud of Berlin
Berlin in 3D

- 63 Million scatterers (10km x 5km)
- Accuracy w.r.t LiDAR DSM: approx 20 cm

Processed by Tomo-GENESIS, DLR
Motion Decomposition
Motion Decomposition (Geometry Assessment)

- Assuming a single scatterer is visible in all the four stacks

- A concept similar to Dilution of Precision (DOP) in GPS:
  - \( A \): Design matrix (based on \( \alpha_h, \theta_{inc} \))
  - \( \sigma = 1 \)

\[
G = \sigma^2 \cdot (A^T A)^{-1}
\]

\[
\begin{bmatrix}
43.3 & -0.8 & 277.8 \\
-0.8 & 0.51 & -5.4 \\
277.8 & -5.4 & 1801.7
\end{bmatrix}
\]

- \([6.6 \ 0.7 \ 42.5]\)
- Correlation between components
Seasonal Motion Decomposition (Berlin Central Station)

With L2 norm minimization

With L1 norm minimization

East-West
Linear Motion Decomposition (Berlin Central station)
Seasonal Motion Decomposition (Eisenbahn Bridge)

D 42
A 57
A 85
D 99

Up
East-West

[mm]

-10 -5 0 5 10
Conclusions and Outlook

- Motion decomposition based on multiple-viewing angles:
  - The functional model of deformation should contain the three components in order to prevent biased deformation estimates.
  - In urban area monitoring using X-band data the seasonal deformation should be considered.
  - Seasonal deformation in the order of 12 mm (between summer and winter 24 mm) in the east-west direction were observed in Berlin central station.
- Retrieval of the motion components by L1 norm preserves more information than L2.
- GPS deformation observations can be incorporated to provide absolute deformations.
Thank you for your attention!