Towards Absolute Positioning of InSAR Point Clouds

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Automatic Generation of SAR-based GCPs with TerraSAR-X

→ Improve the geocoding of InSAR point clouds


### Imaging Geodesy

**absolute 2-D measurements in space and time**

- For a 1.5 m CR:
  - $\sigma_{rg} = 1.16 \text{ cm}$
  - $\sigma_{az} = 1.85 \text{ cm}$

\[
\tau_{rg} = 2 \times \frac{R}{c} + \delta\tau_{SD} + \delta\tau_{O} + \delta\tau_{I} + \delta\tau_{T} + \delta\tau_{G} - \tau_{r,0}
\]

\[
t_{az} = t + \delta t_{SD} + \delta t_{O} + \delta t_{G} - t_{az,0}
\]

- Highly precise orbit determination
- Precise calibration of SAR instrument timings
- Geometrically accurate processing of SAR data
- Compensation of signal propagation delays by GNSS measurements or models
- Compensation of Earth dynamics

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**Geodetic Stereo SAR**

- Combination of two or more SAR observations for 3-D positioning
- Non-linear LS plus variance component estimation
- **Output**: coordinates, estimated precision and observation quality

\[
|X_s - X_t| - c \cdot \tau_{rg} = 0
\]

\[
\frac{\dot{X}_s (X_t - X_s)}{|\dot{X}_s| |X_t - X_s|} = 0
\]

\[
x_s = a_0 + a_1 t_{az} + a_2 t_{az}^2 + \cdots + a_6 t_{az}^6
\]

\[
y_s = b_0 + b_1 t_{az} + b_2 t_{az}^2 + \cdots + b_6 t_{az}^6
\]

\[
z_s = c_1 + 2 c_2 t_{az} + \cdots + 6 c_6 t_{az}^5
\]

For a 1.5 m CR
- 3-D precision \(\approx 4 \text{ cm}\)
- Absolute accuracy \(\approx 3 \text{ cm}\)

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Geocoding of InSAR Point Clouds

• Solving range-Doppler-ellipsoid equations for each pixel

\[ |X_s - X_t| - c \cdot \tau_{rg} = 0 \]

\[ \frac{\dot{X}_s (X_t - X_s)}{|X_s| |X_t - X_s|} = 0 \]

\[ \frac{x_t^2}{(a + H_t)^2} + \frac{y_t^2}{(a + H_t)^2} + \frac{z_t^2}{(b + H_t)^2} - 1 = 0 \]

• Remarks:
  • The ellipsoid height \( H_t \) is relative w.r.t one reference point \( H_0 \)
  • Unknown DEM error in \( H_0 \) is propagated to all points

All geocoded points have offsets w.r.t true positions in horizontal and vertical directions

The height offset of the reference point is constant and affects all PS
Motivation

**Geodetic Stereo SAR**

- **Goal:** Generation of large number of GCPs
- Rare occurrences of identical PS
- Difficult identification solely based on SAR images

**Geocoding of InSAR point clouds**

- Use GCP heights to correct for the height bias of reference point
- Improve geocoding by corrected heights
- For now no direct modification in InSAR stacking (PSI/TomoSAR) processing chain
Automatic Generation of SAR-based Ground Control Points
SAR GCP Generation

- Focus is on urban areas captured from TerraSAR-X HR spotlight products

Identification of common PS in multi-aspect SAR images

Precise extraction of PS azimuth and range timings

Initial outlier removal based on phase noise time series

Geodetic Stereo SAR for 3-D absolute positioning plus stochastics
Data description and PSI processing

- City of Oulu, Finland
- Four stacks of TS-X HR spotlight images (171 images)
- PSI processing by PSI-GENESIS (IWAP) of DLR
  - PS detection
  - PS reference network computation
  - Height update + deformation

31° Asc (44)  46° Asc (37)
41° Dsc (42)  54° Dsc (48)

PSI-31° Asc.: Elevation map of ~700 000 PS

[m]
Identification of common PS in multi-aspect SAR images (Same-heading)

• Search PS in fused PSI results
  • PSI processing and geocoding for each stack
  • Fusion → minimize global distance
  • Apply threshold → common PS → PSC

• Remarks:
  • PS on buildings
  • Complete PSI processing is required
  • PSI localization limit → wrong PSC
  • Only same-heading tracks → large cross-range error
Identification of common PS in multi-aspect SAR images (Cross-heading)

- Search PS close to roads
  - Targets visible in cross-heading → lamp poles, traffic lights, …
  - Radar-coding of road network data on SAR images
  - PS with min. ADI in neighborhood
- Geocode results → apply threshold → PSC → radar-coding
Initial outlier removal based on phase noise time series

- Phase noise time series of PSC:
  - PTA on each data-take $\rightarrow$ Oversampling and kernel interpolation
  - SCR estimation $\rightarrow$ phase noise: $\sigma_{\phi_i} \approx \frac{1}{\sqrt{2 \cdot SCR_i}}$ $\rightarrow$ skewed distribution
- Outlier removal $\rightarrow$ adjusted-boxplot:
  - Exclude $\sigma_{\phi} \geq 0.5 \text{ [rad]}$
Absolute 3-D positioning

- Corrections (No GNSS data available)
  - Global ionospheric maps
  - Integration of weather models
  - IERS conventions

- Iterative geodetic stereo SAR processing
  - Raw result: solution from the input timings
  - Gross outlier removal → R > 0.6 m or A > 1.1 m
  - 3sigma test
  - Best PS selection: $S_{az} < 0.2$ m (objective!)

- Output:
  - Coordinates and Full VC matrix
  - Timing observation quality

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**Bad candidate!**

**Good candidate!**
Positioning results

• Positioning of 2049 Ground Control Points (GCPs) → on average 40 per km²
Positioning statistics

- All precision values in 95% confidence interval in **East**, **North**, **Height**
- The effect of geometry → larger intersection angle → higher height precision
- **Remarks:**
  - For cross-heading: the diameter of the lamp pole

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<th>Geometry</th>
<th>Nr. Scatterers</th>
<th>$\mu_{SE}$ [cm]</th>
<th>$\mu_{SN}$ [cm]</th>
<th>$\mu_{SH}$ [cm]</th>
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<td><strong>1.12</strong></td>
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<td>0.55</td>
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Improve the geocoding of InSAR point clouds
Height correction

• Improve geocoding by using GCP heights
  • The differences between $h_{GCP}$ and $h_{PSI}$ → $\delta h = h_{GCP} - h_{PSI}$
  • Removing outliers → adjusted boxplot
  • Weighting of observations
    • $\sigma_{h_{GCP}}$: stereo SAR results
    • $\sigma_{h_{PSI}}$: coherence of PS
  • Estimation of a constant height offset $\tilde{\delta h}$ by WLS
  • Add the height offset to all PS heights → $h_{PSI} + \tilde{\delta h}$
  • Perform geocoding with correct height for each stack
Preliminary results

• No GNSS or absolute reference available
  • Check improvement of geocoding visually (in 2-D)
  • Check the L-shape matching in three scenarios
    • Fusion with no height correction (PSI raw results)
    • Fusion with height correction from same-heading tracks
    • Fusion with height correction from cross-heading tracks

\[ \checkmark \quad \times \quad \times \]
Preliminary results

PSI raw results

Height from same-heading

Height from cross-heading
Preliminary results
Conclusions and outlook

• **GCP generation**
  • Large number of GCP generation based on SAR data
    • Tie point for registration of optical images
    • Reference network for PSI/TomoSAR techniques
    • Large magnitude deformation (e.g. plate tectonics)

• **Absolute InSAR point clouds**
  • Improved geocoding with GCP heights
  • Fused PSI point clouds from cross-heading tracks
    • Detailed urban mapping
    • Motion decomposition

• **Future work**
  • Timing error correction before geocoding
  • Assess the absolute accuracy of GCP with GNSS/LiDAR data
  • Systematic Quantitative analysis of the absolute accuracy of point clouds
  • Integration of GCPs in the PSI/TomoSAR processing chain
Thank you for your attention!