Ground Deformation Monitoring at Natural Gas Production Sites using Interferometric SAR

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Introduction
Motivation

- Natural gas production has increased significantly to meet energy demands.
- Extraction leads to decreased reservoir pressure and may cause subsidence.
- Monitoring this subsidence important for geological and hazard analysis.
Small volumes produced as compared internationally

In 2007, 17% domestic consumption from domestic production

Lower-Saxony accounted for 93% of German natural gas production

BGR, Germany, collaborating with DLR for monitoring subsidence due to natural gas extraction

Source: BGR, Germany
Interferometric SAR (InSAR)

- Powerful remote sensing technique for detecting ground deformation

- Deformation estimation using 2 SAR images and Digital Elevation Model (DEM)

- Interferogram phase contributions:

\[ \Phi_{\text{InSAR}} = \Phi_{\text{defo}} + \Phi_{\text{topo}} + \Phi_{\text{atmo}} + \Phi_{\text{noise}} \]
C-Band SAR

- Medium resolution of 25 m
- 5.6 cm wavelength
- 100 km swath width
X-Band SAR

- High resolution of up to 1 m
- 3.1 cm wavelength
- High sensitivity to even millimetric displacements

TerraSAR-X (TSX)
Methodology
Persistent Scatterer Interferometry (PSI)

- Coherent InSAR stacking technique
- Permanently coherent PSs exploited
- Differential interferograms wrt a single master image used
- Model-based deformation estimation
DLR’s Integrated Wide Area Processor (IWAP)

- Highly automated, efficient and robust multi-sensor PSI-GENESIS software
- Successful demonstration and validation during ESA's Terrafirma project

Source: Rodriguez Gonzalez et al., 2013
PSI Algorithm

1. PSs Detection
2. PSs Reference Network Estimation
3. Atmospheric Phase Screen (APS) Estimation and Removal
4. PSs Final Network Estimation
PSs Reference Network Estimation - Block Processing

- Division of scene into overlapping blocks
- Blockwise creation of reference network (arcs connecting the PSs)
- Blockwise estimation of relative deformation and residual DEM for the arcs using LAMBDA estimator
- Blockwise network inversion to estimate deformation and residual DEM for the PSs using least squares
- Merging of independently estimated blocks via least squares adjustment

Illustration of block adjustment network
Developed by: Werner Liebhart
PSs Reference Network Estimation - Single Network

- Creation of reference network (arcs connecting the PSs)
- Estimation of relative deformation and residual DEM for the arcs using LAMBDA estimator
- Single network inversion to estimate deformation and residual DEM for the PSs using least squares

- Mitigates error propagation
- High computational load and memory consumption
Single network inversion - Strategies:

- Solve $A x = B \Rightarrow A^T A x = A^T B$
- $A^T A$ is symmetric positive definite square matrix
- Exploit sparsity of $A \Rightarrow A^T A$
- Use QR or LU decomposition for fast inversion, instead of SVD decomposition
- Use a parallelizable solver
- Estimate deformation, residual DEM and standard deviation of estimates
Example matrix A dimensions:

- TerraSAR-X Stripmap:
  Size(A) = (30000, 600000)

- ERS:
  Size(A) = (90000, 1800000)

- Sentinel-1:
  Size(A) = (450000, 9000000)
PSs Reference Network Estimation - Single Network

Example matrix $A$ dimensions:

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Example matrix $A^T A$ dimensions:

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- Sentinel-1:
  \[ \text{Size}(A^T A) = (450000, 450000) \]
Application Test Case and Results
TSX Data - Ascending Stripmap Stack

35 Scenes, 23.01.2008 – 18.04.2009
Time – Baseline Plot

![Time vs. Effective Baseline Plot](image-url)

- **Effective baseline [m]**
- **Temporal baseline [days] (Reference: 2008-09-10T17:09:47.210753Z)**
Master Amplitude Image
Interferogram Examples
Deformation Estimation Results
Deformation Time Series Example
PSs Reference Network Estimation - Block Processing

Set of Blocks network generated by merging of network of blocks
PSs Reference Network Estimation - Block Processing
PSs Reference Network Estimation - Block Processing

Residual topography
-20 mm +20 mm

Deformation
-5 mm/yr +5 mm/yr
PSs Reference Network Estimation - Difference

Residual topography

Deformation

-20 mm - 20 mm

-5 mm/yr - 5 mm/yr
Summary
Conclusion and Outlook

- **PSI** powerful and cost-effective tool for monitoring the **impact of hydrocarbon reservoirs**

- **Single reference network inversion** has potential to improve the deformation velocity maps

- Comparison with GPS data would be performed in the future to **validate the pilot study**

- **Sentinel-1** data would be acquired for large area monitoring
Thank you…

Any questions?
PSs Reference Network Estimation - Scatter Plot

- Residual topography
- Deformation

- Block processing
- Single Network
PSs Reference Network Estimation - Scatter Plot

- Residual topography
- Deformation

Block processing
Single Network

Block processing