Towards the Integration of SAR Tomography and PSI for Improved Deformation Assessment in Urban Areas

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Introduction

- Persistent scatterer interferometry (PSI):
  - **Advanced DInSAR** approach
  - Used to estimate the **deformation** (time-series) on scatterers exhibiting point-like behavior, i.e., relative stability of the backscattering over time, and also low spectral diversity.
  - Assumes a single temporally coherent scatterer inside a range-azimuth resolution cell; **layovers are rejected in principle**.

- SAR tomography:
  - An **aperture synthesis** technique
  - Conventionally used to estimate the **location of scatterer(s)** in perpendicular LOS (elevation), 3D reconstruction
  - Has the potential to **resolve layovers** (typical in urban areas)
Motivation / Goals

Integration of SAR tomography into a PSI processing framework to potentially extend deformation analysis into layover-affected areas:

- enhance the level of detail and/or
- increasing the density of points in the PSI processing.

In this investigation:

- We extend a preliminary PSI analysis with tomography, and discuss the impact of using extended tomographic phase models for spatio-temporal inversion.
- We study a particular example of a layover scenario cast by a high-rise building where potentially deformation and thermal expansion are to be expected.
SAR Tomography (3D SAR)

Considering stable target(s) along the elevation, $s$

$$y_n = \int_{\Delta s} \gamma(s) \exp[-j \varphi_n(s)] \, ds$$

$n = 0, 1, \ldots, N - 1$

$y_n$: $n^{th}$ SLC value in the coregistered stack

$\gamma(s)$: Reflectivity along elevation

$\varphi_n(s)$: interferometric phase (due to sensor-to-target geometry)

$\varphi_n(s) = 2k \Delta r_n(s)$

$\Delta r_n(s) = r_n(s) - r_0(s)$

$$\approx \frac{s^2}{2 \left( r_0 - b^\parallel_n \right)} - \frac{b^\perp_n s}{r_0 - b^\parallel_n}$$

$k$: central wavenumber

$n = 0$ is the master acquisition

$b^\parallel_n$: $n^{th}$ parallel baseline

$b^\perp_n$: $n^{th}$ perpendicular baseline

Considering $L$ discrete locations along the elevation, $s$

$$y = A \gamma$$

$$A = \begin{bmatrix} a_1 & a_2 & \ldots & a_L \end{bmatrix}$$

$A$: steering matrix
Data

- Interferometric data stack of 50 TerraSAR-X stripmap SLCs

- Acquired between Dec. 2007 – Oct. 2012 (Barcelona city)

- Orthogonal Baseline (total): 503 m

- The distribution of the spatial and temporal baselines is as shown on the right; the red circle marks the reference SLC.
Average backscatter image over 50 scenes

Incidence angle: 35.3 deg
Range pixel spacing: 0.455 m
Azimuth pixel spacing: 1.89 m
Average backscatter image over 50 scenes

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Prior to tomographic inversion, the interferometric stack is phase calibrated:

- Atmospheric phase screen (APS) has to be isolated in each layer.
- A preliminary PSI solution obtained with the Interferometric Point Target Analysis (IPTA) PSI framework from GAMMA has been used.
Tomographic inversion

- Prior to tomographic inversion, the interferometric stack is phase calibrated:
  - Atmospheric phase screen (APS) has to be isolated in each layer.
  - A preliminary PSI solution obtained with the Interferometric Point Target Analysis (IPTA) PSI framework from GAMMA has been used.

- We implement **tomographic inversion with three different phase models**:
  - **P1** (elevation only)
    \[
    \varphi_n (s) = 2k \Delta r_n (s) , \quad y_n = \int \gamma (s) \exp [-j \varphi_n (s)] \, ds
    \]
  - **P2** (elevation and deformation)
    \[
    \varphi_n (s, \nu) = 2k [\Delta r_n (s) + \nu t_n] , \quad y_n = \iint \gamma (s, \nu) \exp [-j \varphi_n (s, \nu)] \, dsd\nu
    \]
  - **P3** (elevation, deformation & thermal expansion)
    \[
    \varphi_n (s, \nu, \kappa) = 2k \left[\Delta r_n (s) + \nu t_n + \frac{1}{2k} \kappa \tau_n \right] , \quad y_n = \int \gamma (\mathbf{p}) \exp [-j \varphi_n (\mathbf{p})] \, d\mathbf{p} , \quad \mathbf{p} = [s, \nu, \kappa]
    \]
The tomogram above is obtained with conventional SAR tomography, with the following phase model (P1):

\[ \varphi_n(s) = 2k \Delta r_n(s) , \quad y_n = \int_\Delta s \gamma(s) \exp[-j \varphi_n(s)] \, ds \]

Only the sensor-to-target geometry based interferometric phase is modeled; a stationary scatterer is assumed.
The tomogram above is obtained with conventional SAR tomography, with the following phase model (P1):

\[ \varphi_n(s) = 2k \triangle r_n(s) \quad , \quad y_n = \int_\triangle s \gamma(s) \exp[-j\varphi_n(s)] \, ds \]

Only the sensor-to-target geometry based interferometric phase is modeled; a stationary scatterer is assumed.
Assuming the scatterer is subject to a linear deformation over time, the phase model is next extended as follows (P2):

\[
\varphi_n(s, \nu) = 2k [\Delta r_n(s) + \nu t_n], \quad y_n = \iint_{\Delta s, \Delta \nu} \gamma(s, \nu) \exp[-j\varphi_n(s, \nu)] \, ds \, d\nu
\]

- The model considers both the elevation and (linear) deformation of the scatterer. \( t_n \) refers to the temporal baselines.
The phase model is now further extended to include a thermal expansion induced phase variation (P3):

\[ \varphi_n(s, \nu, \kappa) = 2k \left[ \Delta r_n(s) + \nu \tau_n + \frac{1}{2k} \kappa \tau_n \right], \quad y_n = \int_{\Delta p} \gamma(p) \exp \left[ -j \varphi_n(p) \right] \, dp, \quad p = [s, \nu, \kappa] \]

The model now considers elevation, deformation as well as thermal expansion of the scatterer. \( \kappa \) and \( \tau_n \) refer to the phase-to-temperature sensitivity and local temperatures, respectively.
Comparison between the phase models (1)

The estimated elevation profiles, corresponding to the transect shown in white dashed line in the tomograms above. The red line shows the extent of the echo corresponding to the above tomograms.
Comparison between the phase models (2)

A point (non-PS) at the tip of the Torre Agbar, marked with a green cross, is analyzed in detail.
Comparison between the phase models

A point (non-PS) at the tip of the Torre Agbar, marked with a green cross, is analyzed in detail.

Since the actual tower height is ~ 150 m (corresponding to 260 m in PLOS), the elevation of the tower is better estimated when using the extended tomographic phase model.
Scatterer Detection & Parameter Estimation

- Single-look conventional beamforming has been used for tomographic inversions for each phase model:

\[ \hat{\gamma}(p) = a^H(p)y \]

where \( y \) is the vector of SLC values, and \( a \) is the steering vector.

- The unknown parameter vector \( p \) is estimated using the following maximization:

\[ \hat{p} = \arg\max_p \left( \frac{\hat{\gamma}(p)}{||a(p)|| ||y||} \right) \]

- For scatterer detection, we use the Generalized Likelihood Ratio Test (GLRT)*, for two hypothesis:

\[ H_0 : y = w \]
\[ H_1 : y = \gamma(p_1)a(p_1) + w \]

\[ \arg\max_p \left( \frac{\hat{\gamma}(p)}{||a(p)|| ||y||} \right)_{H_0 \lesssim H_1}^T \]

- The threshold can be empirically selected between 0 and 1.

Scatterer Detection & Parameter Estimation

Average deformation velocity

Phase-to-temperature sensitivity

Reflectivity (normalized) at the peak location
Scatterer Detection & Parameter Estimation

- Low backscatter
- Shadow / Noisy
Comparison of Estimates | IPTA & Tomography

- Average deformation velocity
- Phase-to-temperature sensitivity
- Reflectivity (normalized) at the peak location

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Swiss Federal Institute of Technology Zurich

Earth Observation and Remote Sensing

GAMMA REMOTE SENSING
Comparison of Estimates | IPTA & Tomography

Average deformation velocity

Phase-to-temperature sensitivity

Reflectivity (normalized) at the peak location
The estimates are fairly consistent! And higher density!
3D plot of detected scatterers

- Height (m) Referenced above SRTM
- Average deformation velocity (mm/yr)
- Phase-to-temperature Sensitivity (rad/K)

Background images are © Google Earth. A very few scatterers (< 1%) have estimates that fall outside the given ranges on the color scale; they are marked in black.
3D plot of detected scatterers

Height (m)  
Referenced above SRTM

Average deformation velocity (mm/yr)

Phase-to-temperature Sensitivity (rad/K)

Background images are © Google Earth. A very few scatterers (< 1%) have estimates that fall outside the given ranges on the color scale; they are marked in black.
The tomographic inversion of a layover scenario caused by a high-rise building (Torre Agbar) was analyzed in detail with three different tomographic phase models.

- The results show that for successful spatio-temporal inversion of the scatterers in the upper parts of the building, we need to include an extended tomographic phase model.

- It has been highlighted that SAR tomography has the potential to provide value-addition to PSI in terms of simultaneous estimation of spatio-temporal parameters.

- Using the extended phase model, the estimated deformation estimates showed consistency with PSI. We also observed a higher density of the scatterers detected with tomographic inversion compared to the PSs.

- Further efforts are targeted towards the detection of double-scatterers in layover-affected areas, and to perform a more comprehensive consistency analysis between PSI and tomographic inversions.
Thank You!

Questions/Comments are welcome.

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- TerraSAR-X data © German Aerospace Center – DLR, data access granted through proposal MTH1717.

- SRTM © USGS
… a few remarks

- Regarding the computation ...
  - The parameter search space may become huge.
  - A possible way is to compute the parameters over the entire search space, and apply a peak-detector.
  - Or using an optimization algorithm:
    - Constrained minimization (constrained with bounds on parameters)
    - 'Interior-point' algorithm, Global search (MATLAB implementation)
SAR Tomographic Inversion | Methods (2)

**Uniform Baselines**

1. Single Target
2. Double Scatterer, 50 m separation, Uniform Baselines
3. Double Scatterer, 30 m separation, Uniform Baselines

**Non-uniform Baselines**

1. Single Target, Non-uniform Baselines
2. Double Scatterer, 50 m separation, Non-uniform Baselines
3. Double Scatterer, 30 m separation, Non-uniform Baselines
If the baselines were uniform, the elevation resolution would be \( \sim 19 \text{ m} \).

To keep range migration smaller than range resolution (1.2 m):

\[
\Delta s \leq \frac{\rho_r r}{B} = 1483.8 \text{ m}
\]

Irregular baselines tend to prevent elevation ambiguities.
... a few remarks

- Thermal expansion modeling with the IPTA framework

**With** thermal expansion modeling

**Without** thermal expansion modeling

![Diagram showing average deformation velocity (mm/yr) with and without thermal expansion modeling.](image)
Local temperature refinement with a least-squares fit on the residual
SAR Tomographic Inversion | Simulated on real baselines

... in the absence of noise