EXPERIMENTS AND ADVANCES OF TOMO AND DIFF-TOMO TECHNIQUES FOR COMPLEX NON-STATIONARY SCENARIOS

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Outline

- Introduction

- 3D SAR Tomography (Tomo-SAR)
  - Issues & proposed solutions
  - Experimental results

- Differential SAR Tomography (Diff-Tomo)
  - Diff-Tomo potentials
  - Advances of Diff-Tomo: analysis of volumetric non-stationary scenarios
  - Simulated and experimental results

- Conclusions
**Introduction**

**InSAR and D-InSAR**

- Mature operational techniques are available (PS, SBAS, …)
- Based typically on **phase-only** data, **single scattering** mechanism

**Coherent SLC SAR data combination techniques**

- Extraction of information about the **full 3D characteristics** and the **temporal variations** of complex scenarios, producing **new and/or more accurate measures** with respect to conventional interferometric processing with phase-only data
- Full exploitation of existing SAR data archives, experimented multi-antenna airborne systems, and incoming multistatic satellite clusters
- **3D SAR Tomography** (Tomo-SAR) and **Differential SAR Tomography** (Diff-Tomo) are two experimental coherent data combination modes for the analysis of **complex** and/or **non-stationary scenarios**

*Review of recent research at University of Pisa and advances of Tomo-SAR and Diff-Tomo based techniques…*
Tomo-SAR is a multibaseline technique for direct imaging (profiling) of elevation-distributed scatterers (semitransparent volume scattering layers, multiple layover scatterers)

Define an elevation-dependent spatial frequency: \( \omega_s = \frac{4\pi s}{\lambda R} \)

\[ y(b_n) \Rightarrow \gamma(\omega_s) \] 1-D Fourier relation

Tomo-SAR can identify the multiple scatterers through spatial spectral estimation (i.e. elevation beamforming)

Applications:
- solving InSAR layover heights and reflectivity misinterpretation in urban areas
- estimation of forest height and biomass
- sub-canopy topography
- (soil humidity, arid zones, ice thickness monitoring)

[Reigber-Moreira, IEEE-TGARS '00]
Issues, Solutions and Experiments

Irregular baselines

- **High-contrast tomography (adaptive)**
  Identified double scatterers over the Cinecittà area of the city of Rome (ERS-1/2 data) through Capon Tomo-SAR

- **Knowledge-based tomography**
  Baseline interpolation with an a-priori information about the height sector containing the scatterers

- **Model-based super-resolution tomography (MUSIC)**

Low bandwidth data

- **Common-band tomography**
  Multibaseline spectral shift filtering

Coarse range resolution (e.g. possible future P-band spaceborne missions): the perspective effects impair the Tomo-SAR imaging
The Diff-Tomo Concept

- D-InSAR concept
- Tomo-SAR concept
- Conv. acquisition
- New processing

“Differential Tomography”

It “opens” the SAR pixel extracting joint height and dynamical information of superimposed non-stationary scatterers

Define a velocity-dependent temporal frequency: \[ \omega_T = \frac{4\pi v}{\lambda} \]

\[ y(b_n, t_n) \Rightarrow \gamma(\omega_S, \omega_T) \]

2-D Fourier relation

Spatial-temporal spectral estimation

- 2D support in 2D baseline-time plane deeply exploited
- the hybrid baseline-time correlation matrix codes all the information

Irregular baseline-time sampling to be counteracted (e.g. adaptive Diff-Tomo)
Diff-Tomo Potentials and Experiments

Moving layover scatterers
Urban structures subsidence monitoring

Motion-robust Tomo-SAR
Better than Tomo-SAR, affected by the presence of (residual) motions

Single-look Diff-Tomo
Full resolution, knowledge-based baseline-time interpolation

Non-rigid volumes
Monitoring e.g. of internal glacier dynamics

Buried scatterer motion
Monitoring e.g. of subsurface ground water level, subcanopy subsidence...

Decorrelation-robust Tomo-SAR
...
Tomography of temporal decorrelating volumes

Temporal signal variation from scatterers motion and temporal decorrelation: which is the effect on the Tomo-SAR imaging of volumes?

Analysis of Tomo MUSIC, useful for critical resolutions (better than adaptive BF in ideal conditions)

Main blurring effects:
- Heavy loss of resolution
- Loss of height accuracy

Temporal decorrelation is recognized as a possible Tomo-SAR limiting factor for forest scatterers and spaceborne acquisitions (NASA-JPL, ESA)

Temporal signal histories are equivocated with spatial histories
Temporal decorrelation of a scattering component

**Diff-Tomo processing**

Continuos spectrum in which temporal frequencies are signatures of the temporal decorrelation!

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In the sample scenario:
- A 1 Fourier r.u. temporal bandwidth corresponds to $\tau_c = 2.8$ revisit times
- A 0.2 Rayleigh r.u. bandwidth in height corresponds to the volume height extension

Temporal signal histories can be “decoupled” from baseline signal histories

Elevations extraction by discriminating temporal frequencies effects in the spatial frequencies estimation

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**Diff-Tomo MUSIC**

- Matched to 2-D spectral lines (approximated model)

**Diff-Tomo generalized MUSIC**

- Extension in the 2-D domain of 1-D distribution-matched MUSIC
- Continuous spectral components equivalent to a distribution of elementary lines
- Elevations are estimated by picking the highest peaks of functional $f(\omega_\gamma, \omega_f, B)$ nuisence parameters
Real data analysis

Remningstorp forest site, Sweden
Volumetric forest scattering with mild temporal decorrelation
- DLR’s E-SAR (ESA project BIOSAR), P-band, 9 tracks (quasi-multistatic)
- Baseline span: 80 m, height Rayleigh resolution 28 m
- Time span: 2 months, temp. freq. resolution 0.5 phase cycles/month

Diff-tomo analysis of a forested cell

Resolution capability can be restored!

Profiles extracted in other cells
New possible Diff-Tomo functionalities

Nuisance temporal frequency estimates also exploited

The Diff-Tomo approach for identifying temporal harmonic deriving from subcanopy scatterer motion

Sample forest scenario with subsidence motion

- Quick ground subsidence of -0.22 Fourier res.unit

Sub-canopy subsidence motion can be revealed!

Nuisance bandwidth estimates also exploited

Possibility of recovering information about temporal decorrelation mechanisms of overlayed scatterers exploiting bandwidth estimates.

Different temporal decorrelation processes may be revealed inside the same resolution cell!
Conclusions

- **Tomo-SAR** and **Diff-Tomo** are two promising coherent SAR data combination modes.

- In the Tomo-SAR framework, **solutions** have been successfully experimented against the irregular baseline distribution and low bandwidth acquisitions.

- The potential of Diff-Tomo has been shown of **extracting height and dynamical information** of multiple superimposed non stationary scatterers in the same pixels.

- **Advances** have been presented regarding the application of the Diff-Tomo processing to **temporal decorrelating volumes**. In particular:
  - Diff-tomo, accounting for the temporal dimension, can improve the MB Tomo-SAR functionality (**robust Tomo-SAR**).
  - Diff-Tomo may also furnish **novel Tomo SAR functionalities** (subcanopy ground motions, volume relative motions, discrimination of overlayed temporal decorrelation sources).

- Simulations and first real data tests proved the concept of the new functionalities.

*These new Diff-Tomo concepts might be fruitfully further investigated in the framework of studies such as the ESA BIOMASS, the DLR TanDEM-L, the Argentinean SAOCOM, and the NASA-JPL DESDynI missions*
Identification of scatterers in urban scenarios

ERS-1/2 dataset around the S. Paolo Stadium (Naples)
Calibrated dataset from IREA-CNR

30 tracks, acquired between 1992 and 1998
Total baseline 1066 m
Height resolution Rayleigh limit: 8.8 m

- Three/four-floor buildings (typical)
- Industrial buildings/infrastructure
- Vegetated areas

Example of ABF tomo slice (San Paolo stadium)

- Layover areas are visible
Identification of scatterers in urban scenarios

Estimated deformation velocities of the identified scatterers through adaptive Diff-tomo

- 5 az. looks processing
- Velocities coded with colors and superimposed to the radar image
- Known subsidence phenomena recognized in the top-right area
- The number of velocity measures of double scatterers amounts to the 60% of single scatterers

Analysis of the results in [Lombardini-Pardini, submitted to IEEE-TGARS, 2009]

Results obtained with a more extended dataset (same tracks)
Simulated analysis

**Forest scenario**
- Compact scatterer (ground) + volumetric scatterer (canopy)
- Height distance: 0.7 Rayleigh res. units
- g/v = 1/5 (L-band acquisition)
- Total SNR = 15dB
- 16 looks
- Different temporal decorrelation processes

**BioSAR-1 acquisitions**
- Compact scatterer (ground) + volumetric scatterer (canopy)
- Height distance: 0.7 Rayleigh res. units
- g/v = 3 (P-band acquisition)
- 3 pass, 3 pass per tracks

<table>
<thead>
<tr>
<th><strong>Δh accuracy</strong></th>
<th>RMSE (r.u.)</th>
<th>% res.</th>
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<tbody>
<tr>
<td>Tomo MUSIC</td>
<td>0.25</td>
<td>4%</td>
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<td>Tomo Adaptive BF</td>
<td>0.15</td>
<td>42%</td>
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**Baseline-time acquisition pattern**

**Estimated temporal bandwidth**
- Same scenario as before
- Decorrelating volume revealed with higher temporal bandwidth than steady ground

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<th><strong>B_{ω_T} mean values (Fourier r. u.)</strong></th>
<th>Canopy</th>
<th>Ground</th>
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<td>L-band acquisition (g/v=1/5)</td>
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Real data analysis

Profiles extracted in other cells
Knowledge-based tomography
Baseline interpolation with an a-priori information about the height sector containing the scatterers
Temporal decorrelation of a scattering component (temporal harmonic distribution) \( \rightarrow \) **Diff-Tomo processing** \( \rightarrow \) Continuous spectrum in which temporal frequencies are signatures of the temporal decorrelation!

\[
\begin{align*}
\text{In the reference scenario:} \\
\text{a 1 Fourier r.u. temporal bandwidth corresponds to } t_c = 2.8 \text{ revisit times} \\
\text{a 0.2 Rayleigh r.u. bandwidth in height corresponds to the volume height extension}
\end{align*}
\]

Temporal signal histories can be “decoupled” from baseline signal histories

*Elevations extraction by discriminating temporal frequencies effects in the spatial frequencies estimation*

**Diff-Tomo MUSIC**
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**Diff-tomo generalized MUSIC**
- Extension in the 2-D domain of [Meng-Stoica-Wong, IEE-RSN '96]
- Continuous spectral components equivalent to a distribution of elementary lines

\[
\left\| P_{\text{Noise}}(a_i) \right\| = 0 \quad \Rightarrow \left\| \int_{\alpha_i} P_{\text{Noise}}(a) \, d\omega_T \right\| = 0
\]

- Elevations are estimated by picking the highest peaks of functional \( f(\omega_S, \omega_T, B) \) nuisance parameters
Simulated and Real data analysis

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Diff-Tomo MUSIC

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Diff-Tomo Gen. MUSIC: accuracies from simulation