Multidimensional SAR Imaging: Studies in the Framework of LIMES Project

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Overview

- The LIMES project
- Motivation
- 3D tomographic imaging, ERS results
- 4D differential tomography, ERS results
- Performance evaluation, satellite clusters
- Conclusions
In the framework of LIMES project, SAR 3D/4D Tomography is experimented for supporting Critical Infrastructure Surveillance. Critical regasification plants and pipelines in Spain considered as test areas.
**Motivation**

- Accurate determination of scatterer locations
- Precise tracking of their movement

- Surface penetration
- Steep ground topography (layover)
- High spatial density of strong scatterers

Superposition of responses from multiple scatterers in the same pixel

Need for more sophisticated techniques

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**3D SAR Tomography**

- Multibaseline data
- Separation in elevation of scattering contribution within a single pixel
- Full 3D Imaging

[Pasquali-Prati-Rocca et al., IGARSS ’95]
[Reigber-Moreira, IEEE-TGARS ’00]

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**4D SAR Imaging (differential tomography)**

- Multibaseline multitemporal data
- Joint elevation-velocity reconstruction

[Lombardini, IEEE-TGARS ’05]
3D Imaging: SAR Tomography

Data acquired at the n\textsuperscript{th} antenna (pass):

\[
g_n = \int_{-s_{\text{max}}}^{s_{\text{max}}} \gamma(s) \exp \left[ j2\pi \frac{2b_{\perp n}}{\lambda r} s \right] ds
\]

Need for data calibration (removal of atmospheric variations, scene deformations, ...)

After collecting all data, the problem is the inversion of a simple semi-discrete linear operator:

\[
g = L\gamma(s)
\]

The inversion can be afforded with different algorithms (linear, regularized, adaptive, parametric, ...)

- Beamforming
- SVD
- Adaptive beam
- MUSIC
- ......
3D: Real data experiments

- San Paolo stadium, Naples

ERS-1/2 data, 63 images
Baseline span: 1700 m, height resolution 5.5 m
Temporal span: ~10 years

- Singular Value Decomposition (single look)
- SVD (5 azimuth looks)
- Adaptive beamforming (5 azimuth looks)
- SAR image
Multistatic system: data acquired at the $n^{th}$ track and the $m^{th}$ pass:

$$g_{n,m} = \int_{-v_{\text{max}}}^{v_{\text{max}}} \int_{-s_{\text{max}}}^{s_{\text{max}}} \gamma(s, v) e^{j2\pi \left( \frac{s}{\lambda_T b_{\perp}} + \frac{s^2}{2v t_m} \right)} ds dv$$

Elevation-velocity backscattering profile  
$n$-th orthogonal baseline  
$m$-th pass

**SPATIO-TEMPORAL COMPLEX AMPLITUDE SPECTRUM**

After collecting all data, we have again:

$$g = L \gamma(s, v)$$

- 2D Beamforming
- 2D SVD
- 2D Adaptive beamforming
- ......
4D: Experimental results (1)

"Mergellina", Naples
Single scattering mechanism

30 tracks
Baseline span: 1066 m, height resolution 8.8 m
Time span: ~ 6 years
- Scatterers well resolved in height
- Estimation of deformation velocity consistent with independent measures
- Reduced SLL w.r.t. 2D Fourier beamforming, but higher sensitivity to miscalibration residuals
- No equal velocity constraints (equal velocity case: [Ferretti-Bianchi-Prati-Rocca, EURASIP JASP ’05])
"Vomero", Naples
ERS-1/2, 58 passes, ~10 years temporal span

SVD single look

- Single scatterers -
  - Scattering mechanisms can be separated
  - Automatic single/double scatterer identification also tested

- Double scatterers -
4D: Experimental results (4)

San Paolo Stadium, Naples

SVD single look

- Single scatterers -

- Double scatterers -
Imaging Capabilities and Satellite Clusters (1)

Typical poor and irregular baseline/time sampling

High sidelobes in the 3D/4D reconstructed profile

3 tracks per pass

Double speckled compact scatterers
SNR = 15, 12 dB
32 looks
2 antennas per pass

Acquisition grid (baseline/time)
58 passes, orth. baseline separation 150 m

Singular value (SV) distribution

Larger SV dynamic
Accuracy Bounds Evaluation

- Algorithm performance judgement
- Characterization of precision limits

**Tools from information theory:**

- **3D Cramér-Rao Lower Bound (CRLB)**
  [Gini-Lombardini-Montanari, IEEE-Tr. on AES ’02]

- **3D Hybrid CRLB (HCRLB)**
  *takes into account possible miscalibration residuals*
  [Pardini-Lombardini-Gini, IEEE-TSP, accepted for publication]

**Given a statistical model for the data vector \( g \), bounds can be evaluated for the 4D estimation of scatterer elevations and line of sight velocities**

- ERS-1/2, 58 passes
- 10 looks
- Double speckled scatterers, large critical baseline
  \( (b_{\perp}^{\text{TOT}}/b_c = 0.05, \text{classical triangular-shaped spatial decorrelation}) \)
- Possible temporal decorrelation, \( \tau_c = 2 \text{ months (exponential decorrelation model)} \)
  [Rocca-De Zan-Monti Guarnieri-Tebaldini, ENVISAT Symp. ’07]
CRLB Sample Curves

Double scatterer distance in height: 2 resolution units
Relative motion: 0.7 mm/yr

Single track per pass

4D: height

4D: l.o.s. velocity

[Fully ideal]

4D: height

2 antennas per pass
Baseline separation: 150 m

Limited advantage in the height precision limit, but gain in the SLL
High gain expected in real cases with miscalibration residuals (atmosphere)

HCRLB for 4D: work in progress
Conclusions

- In this work, we have summarize the achievements of 3D/4D SAR imaging with satellite long-term data.
- The presented results demonstrate that urban scatterers can be separated in the elevation/velocity domain by multi-dimensional imaging.
- By means of numerical tests and analytical bounds we have investigated the potentialities of SAR tomography with satellite clusters.

Future systems (e.g. COSMO-Skymed) or cooperative satellite formations (CartWheel, Pendulum, e.g. Tandem-X, ASI Sabrina) are expected in the future to collect high resolution data with lower temporal separation, or simultaneously. Thus, the accuracy and performance are expected to increase.