INFORMATION EXTRACTION IN DECORRELATING FOREST LAYERS: GENERALIZED-CAPON DIFF-TOMO

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Outline

- Research framework
- 3D SAR Tomography resolution and decorrelation issues
- Decorrelation-robust Tomography through 4D Diff-Tomo
- Tech and application extension: Generalized-Capon Diff-Tomo method
- Application sample: decorrelation-robust forest Tomography
- Application: forest decorrelation mechanisms separation
- Conclusions and future work
Some tech achievements at UniPi

- first principle of ML Coherent SAR Data Combination for MB SAR Interferometry, ‘96
- introduction of Superres. Capon & MUSIC Tomo, ‘01
- introduction of the 4D Diff-Tomo (MD SAR Imaging) framework, ‘03
- introduction of Sector Baseline Interpolation, ‘06
- extension of the 4D SAR concepts to Natural Scenes (S-T Signatures of Decorrelation, Decorrelation-Robust Tomo), ‘08
- extension of Superres. Tomo (3D/4D/5D to Single-Look (urban) Light-Burden processing, ‘11
- first 4D Superres. ERS (urban) Experiments, ‘05
- first BioSAR-1 Capon Forest Tomo Experiments, ‘08
- contrib. to first UAVSAR Forest Tomo Experiments, ‘11
- first 4D Superres. Cosmo-SKYMED (urban) Results, ‘12
- first Height-Varying Short-Term GB Coherence Analyses (for companion satellites), ‘15

3D SAR Tomography issues

- Multibaseline 3D SAR Tomography well suited for (urban) layover solution and (forest) volumetric structure sensing; core is spatial (baseline) spectral estimation

- Resolution/sidelobes issue controllable by superresolution (adaptive Capon, model-based MUSIC); Capon very used for forest applications despite radiometric drawbacks

- Temporal decorrelation impacts any Tomographic method using repeat-pass acquisitions (yet also Tandem mission concepts affected, by short-term decorrelation)

- Big issue of temporal decorrelation first tackled from processing viewpoint (not by system/mission optimization) exploiting higher-order (4D) Differential Tomography

- 4D Diff-Tomo allows joint elevation-velocity (space-temporal freq.) resolution, originally exploited for layover discrete (urban) slow-moving scatterers; advanced application to natural decorrelating scatterers
Decorrelation-robust Tomography

- **Advanced concept of space-time signatures of temporal decorrelation exploited**
  
  temporal perturbations of a scattering component originate temporal-frequency harmonics, associated to spatial-frequency harmonic for the height component

- **Diff-Tomo processing based on space-time generalization of MUSIC**

  Diff-Tomo can identify such space-time distributions, avoiding misinterpretation of spatial signal histories and temporal histories

  fully parametric model-based method matched to height-discrete continuous temporal-frequency distributions (spatio-temporal ridges)

- **Effective! Limitations: compact scatterers model, no reflectivity info extracted**

Gen-Capon Diff-Tomo

- To extend tech capabilities
  distributed volumetric scatterers, higher flexibility; reflectivity info extraction, richer output

- To extend application
  decorrelation-robust heights plus reflectivities extraction for significantly distributed scatterers;
  (more) accurate and flexible temporal decorrelation mechanisms extraction

- Diff-Tomo processing based on space-time generalization of non-parametric Capon
  semi-parametric adaptive method for general (continuous) height-distributed continuous temporal-frequency distributions (continuum of spatio-temporal ridges)
  spectral model of temporal decorrelation still exploited
  \[ P_{GC}(f_S, \bar{f}_T, B_T) \]
  non-parametric adaptive in height, temporal-parametric only

- Early concept (UniPi ’13); tested; characterization, tuning, and exploitation phase

Robust Gen-Capon reflectivity profiling

- Controlled simulated scenario
  - multipass multistatic data
    (10 passes, 3 tracks each)
    irregular baselines,
    looks 128
  - volumetric scatterer,
    1 Rayleigh res. unit thick
    (Gaussian tapering), SNR 15dB,
    $B_T=0.25\div1.75$ Fourier res. units
    ($\tau_C=11.5\div1.6$ revisit time units)

- reflectivity outputted
- blurred reflectivity restored
- operation for non-compact scatterers
- higher height accuracy
Gen-Capon decorrelation profiling

- Controlled simulated scenario
- multipass multistatic data
- volumetric scatterer,  
  1 Rayleigh res. unit thick

$B_T = 0.25 \div 1.75$ Fourier res. units  
($\tau_C = 11.5 \div 1.6$ revisit time units)

- accurate separation of temporal decorrelation mechanisms 
  (with some bias)
- operation for non-compact scatterers
Gen-Capon P-band experiments

- Real (boreal) forest scenario

- BioSAR-1 multipass HV P-band data
  (9 passes, 2 months span), uniform baselines
  Rayleigh res. 25m, looks $17 \times 71$

- real decorrelation-robust reflectivity superresolution achieved
- real decorrelation mechanisms separation achieved
- consistent results
Gen-Capon P-band large-scale experiments

- Real (boreal) forest scenario
- BioSAR-1 multipass HV P-band data
- temporal decorrelation mechanisms separation possible in large-scale airborne data

<table>
<thead>
<tr>
<th>Decorrelation separation</th>
<th>Canopy</th>
<th>Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. temporal bandwidths</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>(phase-cycles/month)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg. coherence times</td>
<td>9.1</td>
<td>16.8</td>
</tr>
<tr>
<td>(months)</td>
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>200 hectares analyzed! >> than TropiScat and AfriScat towers
Conclusions

- 3D Tomography emerged for spaceborne forest biomass monitoring, beyond urban app
- Temporal decorrelation still an issue
- Advanced temporal-decorrelation robust 3D through special 4D Diff-Tomo methods
- Gen-MUSIC method extended for technical performance and application capability
- Semi-parametric adaptive Gen-Capon Diff-Tomo solution gets decorrelation-robust superresolution Tomo for distributed volumes, outputting reflectivity profiles!
- Height-varying (long-term) temporal decorrelation level can be also flexibly profiled!
- Characterization and real data application is being expanded
- Short-term decorrelation profiling also ongoing (special quick HW solution)
- Solutions can be useful for ESA BIOMASS (and Companion Satellites) programs
THANKS FOR YOUR ATTENTION!

ESA–MOST Dragon Cooperation

2019 DRAGON 4 SYMPOSIUM

24–28 June 2019 | Ljubljana, Slovenia
\[
\min_w w^H \hat{R} w \quad \text{subject to} \quad w^H R_M (f_S, \bar{f}_T, B_T) w = 1
\]
Some tech achievements at UniPi:

• 1996 Development of the principle of Optimal (ML) Coherent SAR Data Combination for MB SAR Interferometry
• 2001 Fertilization of 3D MB SAR Tomography with Superresolution Array Processing techniques (Capon)
• 2003 Origination of the MD SAR Imaging (“4D” Differential SAR Tomography) Framework
• 2004 Participation in the ASI Cosmo-Skymed 2nd Generation Feasibility Study (ocean ATI)
• 2005 First 4D SAR Experiments with ERS
• 2007 Participation in the Cosmo-Skymed SABRINA Mission Feasibility Study (ocean bistatic ATI)
• 2008 Participation in the 1st ESA Campaign in support of the BIOMASS Program (BioSAR-1 3D forest tomography)
• 2008 First Extension of the new 4D SAR Concepts to Natural Scenes (Robustness to temporal decorrelation)
• 2011 Contribution to first UAVSAR tomographic experiments of JPL
• 2011 Development of Single-Look (urban) Light-burden Superresolution Tomography techniques (3D/4D/5D)
• 2012 First 4D Superresolution Cosmo-Skymed Results …
Robust extraction of forest height in decorrelating scenarios through Diff-Tomo (4/5D)

Model-based 3D Tomo-SAR

Gen-MUSIC decorrelation-robust Tomo

- Several canopy layer portions blurred/missed
- Height resolution significantly restored, sidelobes better cleaned, both canopy and ground scatterers neatly located

5D processing here “absorbs” nuisance temporal harmonics from decorrelation

Capon self-cancellation

- Capon filter tailored to reject interference (from non-targeted heights)
  Tomo spatial harmonic coded in steering vector
  Capon vector projection interpretation:

  - large filter vector norm, critical rejection job

  - Multibaseline array steering vector mismatch from nominal one -> misinterpreted as interference -> self-cancellation
    tuning on signal component, \( \mathbf{a} = \mathbf{a}_s \) (nominal steering vector), no cancellation effective steering vector/signal component \( \tilde{\mathbf{a}}_s \neq \mathbf{a}_s = \mathbf{a} \)

  - Imperfections in array correlation matrix estimates analogous effect, in addition to the residual miscalibration

  “close” tuned and interference components (array steering vectors)
Self-cancellation real data example

ERS-1/2 ESA
C-band, VV
(UniPi processing)

BIOSAR-1 ESA
P-band, HH
(DLR data, UniPi processing)

- Power losses vary with scattering power -> both absolute and relative non-linear radiometric sensitivity
Capon loading

- Filter vector sq. norm = amplification of thermal noise
- Noise brakes adaptivity:
- Cross-talk reduction and superresolution depends on noise level; Capon self-cancellation criticality depends on noise level
- Diagonal loading of array correlation matrix estimate (virtual noise) powerful Capon robustification tool (at the cost of original full superresolution properties)
- Neither definite recipe nor single optimal value of loading, classical loading only partially controls the radiometric issues

“close” tuned and interference components (array steering vectors)
(Absolute) radiometric analysis

- irregular passes, miscalibration \( \lambda/100 \), looks 32
- 2 speckled height-compact scatterers, equi-power, unit power noise (scatterer power=SNR), over-Rayleigh delta h
- very strong non-linearity for urban case; forest case less extreme effects, yet radiometry more important
- loading is not ultimate solution
Radiometrically improved adaptive method

- Preconditioning of the data for the adaptive filter calculation
- Height-varying

\[ y(n) \rightarrow \hat{R}(z) \rightarrow \hat{P}_a(z) \]

- Method is double adaptive
- Expected to better trade off superresolution with reduced radiometric losses
- What about accuracy? Partialization also introduced
**3D imaging quality analysis**

- **Controlled simulated scenario**
  - 6 passes, uniform (BIOMASS), miscalibration $\lambda/100$, looks 32
  - 1 speckled height-compact scatterer, SNR 10dB, unit power noise (scatterer power=SNR)

- **flat roof, peak splitting**
- **partialization beneficial**
6 passes (uniform), miscalibration $\lambda/100$, looks 32

2 speckled height-compact scatterers, equi-power, total SNR 13dB, unit power noise (scatterer power=SNR), sub-Rayleigh delta $h$
- canopy scatterer weaker than ground, delta SNR 4dB (P-band)
3D imaging quality analysis

- higher multilooking degree, looks 64 (biomass estimation)
- equi-power scatterers
Capon trade-offs

- resolution/radiometry/accuracy

- quickly degraded superresolution
- residual radiometric loss
Double adaptive method trade-offs

- resolution/radiometry/accuracy

- knee point

- splitting and accuracy stabilized
- very low radiometric loss, and good superresolution
ERS-1/2 ESA C-band, VV

Self-cancellation real data example

Radiometrically improved adaptive method 2

- Variable loading for the adaptive filter calculation

Both methods are double adaptive

- Expected to trade off superresolution with reduced radiometric losses and enhanced linearity
Absolute radiometric analysis

- equi-power scatterers
Relative (differential) radiometric analysis

- different-power scatterers
A real data test

- Real airborne data boreal forest scenario

- BioSAR-1 data,
  9 passes (uniform), 2 months time span, 
  emulated satellite resolution (SAR data filtering), 
  HV pol.
3D imaging quality analysis

- larger number of passes (irregular), miscalibration \( \lambda/100 \), looks 32

- 2 speckled height-compact scatterers, equi-power, over-Rayleigh delta h
3D imaging quality analysis

- canopy scatterer weaker than ground
- h
- e
\[ h \]

\[ e \]
Double adaptive method

Radiometric loss (dB)

Partialization factor
- h
- e
- h
- e