On phase calibration of BIOMASS data stacks for InSAR and TomoSAR applications

Stefano Tebaldini, Fabio Rocca

Dipartimento di Elettronica, Informazione e Bioingegneria

Politecnico di Milano
Mission Objectives
- to determine the distribution of aboveground biomass in the world’s forests
- to measure annual changes in this stock over the period of the mission.
BIOMASS Tomography - motivation

Multi-baseline SAR Tomography ⇔ Direct imaging of the vertical structure of Radar scattering

- investigate the **phenomenology** of Radar scattering from forested areas
- **help** physical modeling to be used with non-interferometric and single baseline data
The BIOMASS Tomographic phase

Features:

- One year duration
- Global coverage
- 7 passes per illuminated sites
- 3 day repeat pass time
- About 20 m vertical resolution

Main goal:
Help improve forest biomass and height retrieval methods by addressing three questions:

- What are the main scattering mechanisms (SMs) at forest and ground level
- How do the SMs vary as a function of polarization
- How do the SMs vary over the global forest biomes

Products:

- Tomographic cubes \( \Leftrightarrow \) 3D representation of Radar scattering
- Sub-canopy Digital Terrain Model
TomoSAR provides resolution in elevation by jointly focusing data from multiple baselines

- Resolution $\Leftrightarrow$ total baseline span
- Vertical Ambiguity $\Leftrightarrow$ baseline spacing

➢ Phase jitters result in signal defocusing
  - Spaceborne: orbit uncertainty, troposphere, ionosphere
  - Airborne: uncompensated platform motions
Permanent Scatterers Interferometry (PS-InSAR) is based upon the assumption of a number of stable targets within the data-stacks

⇒ Accurate phase estimation on a sparse grid

BioSAR 2007:
• P-Band, semi-boreal forest, flat terrain
• Stable targets were found to correspond to double bounce scattering from trunk-ground interactions
Phase Calibration via PS-InSAR

Tomographic reconstruction of an azimuth cut:

Reflectivity (HH) – Average on 9 tracks

The analyzed profile is almost totally forested, except for the dark areas

HH:
- Dominant phase center is ground locked
- Vegetation is barely visible

Similar conclusions for VV

HV:
- Dominant phase center is ground locked
- Vegetation is more visible

=> Double bounces from ground/trunk interactions serve as PSs
Sum of Kronecker Product (SKP) Decomposition = tool for decomposing multi-baseline multi-polarimetric data into ground-only and volume-only contributions

⇒ Direct estimation of the ground phase

Phase Calibration via SKP Decomposition
Structure model for the data covariance matrix: Sum of Kronecker Products (SKP)

\[ W = E[yy^H] = \sum_{k=1}^{K} C_k \otimes R_k \]

Each SM is represented by a Kronecker Product (KP) of two matrices:

**Polarimetric Signature,** \( C_k : \)
- polarimetric covariance matrix of the \( k\)-th SM alone [3 x 3]
- \( \Leftrightarrow \) Electromagnetic properties of the \( k\)-th SM

\[ C_k = \begin{bmatrix}
    c_k(w_1 , w_1) & c_k(w_1 , w_2) & c_k(w_1 , w_3) \\
    c_k(w_2 , w_1) & c_k(w_2 , w_2) & c_k(w_2 , w_3) \\
    c_k(w_3 , w_1) & c_k(w_3 , w_2) & c_k(w_3 , w_3)
\end{bmatrix} \]

**Structure Matrix,** \( R_k : \)
- matrix of the interferometric coherences of the \( k\)-th SM alone [N x N]
- \( \Leftrightarrow \) Backscattered power distribution of the \( k\)-th SM

\[ R_k = \begin{bmatrix}
    \gamma_{k}(1,1) & \gamma_{k}(1,2) & \cdots & \gamma_{k}(1,N) \\
    \gamma_{k}(2,1) & \gamma_{k}(2,2) & \cdots & \gamma_{k}(2,N) \\
    \vdots & \ddots & \vdots & \vdots \\
    \gamma_{k}(N,1) & \gamma_{k}(N,2) & \cdots & \gamma_{k}(N,N)
\end{bmatrix} \]

\( R_k, C_k \) are (semi)positive definite by definition
Structured model for forest scattering

\[
W = C_g \otimes R_g + C_v \otimes R_v
\]

**SKP Decomposition**

\[
\begin{align*}
W \Rightarrow & \quad U_1, U_2 \quad \Rightarrow \quad V_1, V_2 \\
& \Rightarrow \quad C_g = (a - b)^{-1}((1 - b)U_1 - bU_2) \\
& \Rightarrow \quad C_v = (a - b)^{-1}(- (1 - a)U_1 + aU_2)
\end{align*}
\]

Find (a, b)

\[
R_g = aV_1 + (1 - a)V_2 \\
R_v = bV_1 + (1 - b)V_2
\]

**Separation of ground-only and volume-only InSAR coherences!!!**

**HV**

**Ground-only**

**Volume-only**
Phase Calibration via SKP Decomposition

BIOMASS data-set derived by DLR from the airborne data-set BIOSAR 2008

Campaign: BIOSAR 2008 (ESA/DLR) - Test-site: Krycklan, Northern Sweden; Boreal forest

![Graphs showing E-SAR - HV and BIOMASS– HV data comparison]

Forest height retrieval
- based on a direct investigation of the shape of the retrieved tomographic profiles
- Good match with LIDAR
  - Standard Deviation < 4 m w.r.t. LIDAR
Phase Calibration via SKP Decomposition

BIOMASS data-set derived by PoliMi from the airborne data-set TropiSAR 2009
Campaign: TropiSAR 2009 (ESA/ONERA) - Test-site: Paracou, French Guiana; Tropical forest
Phase Calibration via Phase Center Double Localization

Phase calibration recast in terms of a **double localization problem**

\[ \Leftrightarrow \text{joint estimation of target and aircraft positions} \]

- No need for PSs
- No need for ground visibility
- Works on single-pol data
- Tailored for airborne data
  (atmosphere is not considered)

**Key concepts:**

- Multiple baselines provide equations enough to jointly estimate aircraft positions and target phase center height at each along track position, up to a roto-translation of the coordinate system (**Double localization**)

- Volumetric targets can be represented as equivalent phase centers by means of a suitable phase model (**Equivalent phase center representation**)

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CEOS 2015, ESA-ESTEC, Noordwijk, The Netherlands
Double Localization

**Problem statement:**

Find the position of $N$ sensors and $P$ targets given the set of all sensor-to-target distances (for every along-track location)

- No solutions other than roto-translations exist that are consistent with the given distance-set provided that **at least 3 passes are available ($N>2$)**

$\Rightarrow$ The double localization problem becomes treatable in the multi-baseline case
Equivalent Phase Center Representation

**Idea:**

represent volumetric targets in terms of equivalent phase centers by finding the $N-1$ phases that best fit the data covariance matrix

Data covariance matrix (NxN)

$$\hat{\phi}_n^p = \frac{4\pi}{\lambda} (\hat{r}_n^p - r_{ref}^p)$$

Estimation criterion:

$$\{\hat{\phi}_n\}_{n=1}^{N-1} = \arg\max\left\{\text{real}\left(\sum_{nm} d_n^* d_m w_{nm} e^{i(\phi_n - \phi_m)}\right)\right\}$$

**Resolving algorithm:** Phase Linking (Tebaldini and Monti Guarnieri, IGARSS 2007, TGRS 2008)

- **Maximum Likelihood phase estimator** under the constraint of triangularity
- Accounts for target statistics based on the estimated coherence magnitudes
- Easily parallelized to run on large areas $\Leftrightarrow$ limited computational burden
Trajectory retrieval accuracy

Retrieval accuracy assessment from TropiSAR 2009 (Onera)

- Simultaneous P-Band and L-Band data over a tropical forest (Paracou, French Guiana)
- Independent processing of P- and L-Band data
- A cross-check of the results indicates that the dispersion of the retrieved flight trajectories is limited to a few millimeters
Trajectory retrieval accuracy

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InSAR analysis of 15 x 15 interferometric pairs
Data from the airborne campaign AlpTomoSAR 2014 (ESA)
Phase Calibration via Phase Center Double Localization

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Phase Calibration via Phase Center Double Localization

TomoSAR Vertical Section Before Calibration - Direction 1

TomoSAR Vertical Section Before Calibration - Direction 2
Phase Calibration via Phase Center Double Localization

TomoSAR Vertical Section After Calibration - Direction 1

TomoSAR Vertical Section After Calibration - Direction 2

On phase calibration of BIOMASS data stacks for InSAR and TomoSAR applications
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Fast-varying phase screens

Phase screen variations within an aperture time in excess of $\approx 1$ rad prevent along-track focusing

Phase screen compensation methods include:

- Measurements of the phase screen gradient by sub-look processing
  - Good results in presence of point scatterers (PS)
  - In the absence of PS it is necessary to resort to incoherent processing, which may fail in a distributed scatterer scenario due to texture loss (i.e.: forests)

- Phase Gradient Autofocus
  - Needs good points to initialize the algorithm $\Leftrightarrow$ not robust to texture loss
  - Assumption of range-independent phase screen $\Leftrightarrow$ large bandwidth

- Range dispersion based methods
  - Peculiar to the case of Ionosphere, requires large bandwidth

- Polarimetric methods
  - Peculiar to the case of Ionosphere, do not perform in areas close to the magnetic equator
Fast-varying phase screens

Phase screen variations within an aperture time in excess of $\approx 1 \text{ rad}$ prevent along-track focusing

Phase screens [rad]

As a backup strategy, we resort to Multi-Squint Differential InSAR, i.e.:

- Measurements of the phase screen difference between different passes at multiple squint angles
  
  - Phase measurements from coherent sub-looks $\Leftrightarrow$ accurate phase screen estimation
  
  - Need to find one phase screen free acquisition to allow absolute calibration
    $\Rightarrow$ Suitable for systems providing frequent observations of the same area

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Simulated system: BIOMASS

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture length</td>
<td>20 Km</td>
</tr>
<tr>
<td>Ionospheric height</td>
<td>350 Km</td>
</tr>
<tr>
<td>Azimuth resolution</td>
<td>12.5 m</td>
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<tr>
<td>Orbit height</td>
<td>650 Km</td>
</tr>
<tr>
<td>Scenario</td>
<td>Distributed targets</td>
</tr>
<tr>
<td>Number of looks for phase estimation</td>
<td>1</td>
</tr>
</tbody>
</table>

Ionospheric phase screens provided by the University of Sheffield in the frame of BIOMASS phase-A studies

The employed phase screens are intended to represent a severe case of ionospheric scintillations, typical of boreal latitudes

\[ A_{opt} = \sqrt{\frac{H_0 - H_i}{vH_i \cdot K}} \approx 460 \text{ m} \]

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Phase Calibration via MS InSAR
Phase Calibration via MS InSAR

Phase screen estimation (1 look)

Rms estimation error $\approx 0.5$ rad

$\Rightarrow$ Consistent with dispersion of 1-look interferometric phase estimates

$\gamma = 0.96 \Rightarrow \sigma \approx 0.47$ rad

$\Rightarrow$ Phase error is due to non-visible high-frequency components

Phase screen compensation

Method: Time Domain Backprojection

- Full resolution is recovered
- Interferometric coherence after compensation $\gamma = 0.95$
Discussion – what we know

BIOMASS data stacks will need to be compensated for residual phase screens due to:
- Orbit accuracy – 360° every half a wavelength, yet easy to model
- Troposphere – some 10° expected...
- Ionosphere – largest contributions to phase screens – fast varying components at least partly compensated by L1 correction algorithms

Phase calibration via SKP
- Ground/volume decomposition provides a continuous phase reference
- Feasible in dense forest environments – tested using simulated BIOMASS data
- Ground signal may tend to vanish in presence of steep topographic slopes

Phase calibration via PSInSAR
- Possibility to reuse methods from a huge literature
- Feasibility in dense forests is dubious

Phase calibration via Phase center double localization
- No need for ground visibility
- Single pol
- Needs to be adapted to treat stochastic phase screens (ionosphere)

Phase calibration of fast varying phase screens
- Needed if L1 correction fails
- Enhanced performance – relative to one reference pass
Discussion – what we don’t know

Occurrence of L1 correction failures
- Ionospheric scintillations
- Radio Frequency Interferences

Requirement about minimum coherence value
- Statement of minimum coherence value to phase calibrate BIOMASS data-stack
- Multi-baseline InSAR allows to handle some decorrelation sources (spatial, progressive temporal decorrelation)
- The impact of rain events need to be clarified

Calibration algorithm
- De-focusing vs. Sub.look processing – the best option should consider simultaneous presence of phase screens associated with different heights (orbit, ionosphere, topography)

Performance optimization might require to operate with more and better correlated data-stacks
- Reduce incremental baseline