SARSIM and SARSIM+: data-bases for the development of SAR Tomography in forestry applications

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Klaus Scipal, Clément Albinet, ESA
Key features:

- Microwaves penetrate through rain and clouds  \(\Leftrightarrow\) visibility in all weather conditions
- Aperture Synthesis  \(\Leftrightarrow\) fine spatial resolution
- Phase preserving  \(\Leftrightarrow\) millimeter accuracy about distance variations

Spaceborne SARs provide accurate and continuous information about the Earth’s surface and its evolution over time.
Another key feature:

- Microwaves **penetrate** into natural media, like forests, snow, ice, sand ⇔ sensitivity to the three-dimensional structure of illuminated media

  Tomographic SAR imaging ⇔ access to the 3D structure of the illuminated media

**Measurement principle:**
- **Two dimensional synthetic aperture** ⇔ targets are resolved in three dimensions
**Forest scenarios:** separation of backscatter from different heights within the vegetation

$\Rightarrow$ Improved forest biomass retrieval

$\Rightarrow$ Sub-canopy terrain topography

$\Rightarrow$ Forest height
Glaciers: inside view of the glacier volume

⇒ Bedrock detection up to 50 m below the ice surface

⇒ Detection of internal structures (crevasses, firn layering)

Tebaldini et al., TGRS, 2016

SAR Tomography (TomoSAR)
**Snow**: fine structure of snowpack layering

- Total Snow depth
- Refractive index
- Internal layering
SAR Tomography can be formulated according to one simple principle:

Each focused SLC SAR image is obtained as the Fourier Transform of the scene complex reflectivity along the cross-range coordinate

$$I_n(r, x) = \int_C s(r, x, v) \cdot \exp \left\{ -j \frac{4\pi b_n}{\lambda} \frac{r}{v} \right\} dv$$

$I_n(r, x)$: SLC pixel in the $n$-th image
$s(r, x, v)$: cross-range projection of target reflectivity within the SAR resolution cell at $(r, x)$
$b_n$: normal baseline for the $n$-th image
$\lambda$: carrier wavelength
TomoSAR provides resolution in elevation by jointly focusing data from multiple baselines

- Phase jitters result in signal defocusing
  - Spaceborne: tropospheric and ionospheric phase screens
  - Airborne: uncompensated platform motions on the order of a fraction of a wavelength

Phase screens

![Diagram of phase screens and TomoSAR resolution](image-url)
Each focused SLC SAR image is obtained as the Fourier Transform of the scene complex reflectivity along the cross-range coordinate,

**Phase rotated by an (often unknown) phase screen** \(\alpha_n(r, x)\)

\[
I_n(r, x) = \exp\{-j\alpha_n(r, x)\} \int_C s(r, x, v) \cdot \exp\left\{-j \frac{4\pi b_n}{\lambda} v\right\} dv
\]

\(I_n(r, x)\): SLC pixel in the \(n\)-th image
\(s(r, x, v)\): cross-range projection of target reflectivity within the SAR resolution cell at \((r, x)\)
\(b_n\): normal baseline for the \(n\)-th image
\(\lambda\): carrier wavelength
\(\alpha_n(r, x)\): *phase screen for the \(n\)-th pass*
Phase calibration = phase screen removal

\[ I_n(r, x) = \exp\{-j\alpha_n(r, x)\} \int_C s(r, x, v) \cdot \exp\left\{-j \frac{4\pi b_n}{\lambda} \frac{v}{r}\right\} dv \]
**BIOSAR 2007 – P-Band**

<table>
<thead>
<tr>
<th>Site</th>
<th>Remningstorp, Southern Sweden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>Spring 2007</td>
</tr>
<tr>
<td>Scene</td>
<td>Semi-boreal forest</td>
</tr>
<tr>
<td>Topography</td>
<td>Flat</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>P-Band</td>
</tr>
<tr>
<td>Number of passes</td>
<td>9</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>≈ 10 m (near range) to ≈ 40 m (far range)</td>
</tr>
</tbody>
</table>

**IceSAR 2012 – P-Band**

<table>
<thead>
<tr>
<th>Site</th>
<th>K-transect, Southwest Greenland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>May 2012</td>
</tr>
<tr>
<td>Scene</td>
<td>Ice</td>
</tr>
<tr>
<td>Topography</td>
<td>Flat</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>P-Band</td>
</tr>
<tr>
<td>Number of passes</td>
<td>8</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>&gt; 50 m</td>
</tr>
</tbody>
</table>
AlpTomoSAR 2014 –L-Band

TomoSAR Vertical Section Before Calibration

TomoSAR Vertical Section After Calibration
\[ I_n(r, x) = \exp \left\{-j \frac{4\pi}{\lambda} R_n(\text{ref}) \right\} \cdot \int_C s(r, x, v) \cdot \exp \left\{-j \frac{4\pi b_n}{\lambda} \frac{v}{r} \right\} dv \]

**Phase offset to be removed based on knowledge of the acquisition geometry (terrain flattening)**

**Red = Reference terrain elevation**

**Orange = True terrain elevation**
$I_n(r, x) = \exp \left\{ -j \frac{4\pi}{\lambda} R_n(\text{ref}) \right\} \cdot \int_C s(r, x, v) \cdot \exp \left\{ -j \frac{4\pi b_n}{\lambda} \frac{v}{r} \right\} dv$

Phase offset to be removed based on knowledge of the acquisition geometry (terrain flattening)

Orange = Reference terrain elevation = True terrain elevation
Multiple flight tracks are usually collected by flying multiple passes. The illuminated scene is required to be stable over time to enable Tomographic imaging.

⇒ **Spaceborne Tomography of natural media is in most cases prevented by temporal decorrelation**

<table>
<thead>
<tr>
<th>Revisit time</th>
<th>Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne P- and L-Band</td>
<td>minutes</td>
</tr>
<tr>
<td>Spaceborne P-Band</td>
<td>days</td>
</tr>
<tr>
<td>Spaceborne L-Band and higher frequencies</td>
<td>days</td>
</tr>
</tbody>
</table>

**P-Band Spaceborne simulation derived from ground-based Radar**

Revisit time ≈ seconds

Revisit time = 3 days

*Bai Yu et al., 2018*
Correlation tomography by Bistatic SAR
Single pass InSAR: a way out of temporal decorrelation

- **Cartwheel**
- **Tandem-X**
- **Tandem-L**
- **SAOCOM-CS**
- **PARSIFAL**

Processing:

\[
\mathbf{y} = \begin{bmatrix}
\gamma_1 \\
\gamma_2 \\
\vdots \\
\gamma_N
\end{bmatrix}
\]

**TomoSAR processing**

Intrinsically robust to temporal decorrelation, since the images forming each interferometric pair are acquired nearly simultaneously.

**Note:** no coherent combination of data different passes ↔ **Correlation Tomography**
SARSIM and SARSIM+

The SARSIM and SARSIM+ data-bases have been created in the frame of the ESA study “L- and P-band SAR Tomography Synergies Consolidation Study”

**Study team:** PoliMi, Chalmers, Rennes 1, DLR, ONERA

**Goal:** build a reference data-set for current and future researches on the application of SAR Tomography for the remote sensing of boreal, temperate, and tropical forests at P- and L-Band.

- SARSIM includes L1 SLC images from airborne campaign, simulated spaceborne SLCs, and ancillary information
- SARSIM+ includes processed tomographic voxels as obtained in airborne and spaceborne configuration

**Note:** the two data-bases are provided are unified in a single deliverable item
The intended users of SARSIM and SARSIM+ are:

- Signal processing researchers interested in developing new tomographic processing approaches without having to implement any pre-processing operation
- Remote sensing and ecology researchers interested in using tomographic data for the retrieval of forest parameters
- Researchers interested in developing 3D forest scattering models
- Graduate and Ph.D. students willing to learn SAR tomographic processing and/or experiment with tomographic data.

*Official release to ESA in February 2019!*
Relevant features of SARSIM and SARSIM+ are:

- The inclusion of campaign data from boreal, temperate, and tropical forests
- The inclusion of both P-Band and L-Band polarimetric SAR data
- All data have been accurately phase calibrated
- An accurate Digital Terrain Model (DTM), either derived from Lidar or directly from SAR data, is provided along with each data-set
- Simulated spaceborne data derived from campaign data are provided along with each data-set
- 3D Tomographic voxels are provided along with each data-set
- All data are provided in TIFF format to ensure compatibility with different platforms.
- DEMO Matlab codes are provided for educational purposes to show how to load the data, visualize them, and implement basic tomographic processing.
Spaceborne data were derived from airborne data to mimic future spaceborne acquisitions at P- and L-Band will be like at the campaign sites.

P-Band spaceborne data were produced with reference to BIOMASS:
- 6 MHz pulse bandwidth
- 12 m azimuth resolution
- Tomographic cubes produced by coherent tomography

L-Band spaceborne data were produced with reference to SAOCOM-CS:
- 40 MHz pulse bandwidth
- 7.5 m azimuth resolution
- Tomographic cubes produced by correlation tomography
<table>
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<tr>
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<th>Campaign</th>
<th>Site</th>
<th>Forest type</th>
<th>Operator</th>
<th>Band</th>
<th>Sensor</th>
<th>Data processing</th>
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## SARSIM and SARSIM+: data-sets

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### ACKNOWLEDGMENT

The AfriSAR data-set acquired by JPL’s UAVSAR was included in SARSIM and SARSIM+ in the frame of a friendly collaboration with JPL, for which we wish to warmly thank Dr. Marco La Valle and Dr. Scott Hensley.
Table of contents:
1 INTRODUCTION 3
2 SAR TOMOGRAPHY 3
  2.1 Signal models 5
  2.2 Tomographic focusing 6
  2.3 Correlation tomography 7
  2.4 Phase calibration 9
3 SPACEBORNE DATA SIMULATION 10
4 DATA 11
  4.1 Data-set information: 12
    4.1.1 AFRISAR ONERA DATA-SETS 12
    4.1.2 AFRISAR DLR DATA-SETS 13
    4.1.3 AFRISAR JPL DATA-SETS 14
    4.1.4 BIOSAR DATA-SETS 14
    4.1.5 BIOSAR 2008 DATA-SETS 15
    4.1.6 TRAUNSTEIN DATA-SETS 15
  4.2 Naming System 16
    4.2.1 Fields: 16
    4.2.2 File names: 16
5 DEMO CODES AND UTILITIES 17
  5.1 DEMO scripts 18
    5.1.1 DEMO_SARSIM.m 18
    5.1.2 DEMO_SARSIM_PLUS.m 18
    5.1.3 SAR_TOMOGRAPHY_DEMO.m 18
  5.2 Utilities 18
    5.2.1 SARSIM_DATA_SELECTION.m 18
    5.2.2 SARSIM_PLUS_DATA_SELECTION.m 18
    5.2.3 SARSIM_PARAM.m 19
    5.2.4 SARSIM_PLUS_PARAM.m 19
    5.2.5 LOAD_SLC.m 19
    5.2.6 LOAD_Kz.m 19
    5.2.7 LOAD_DTM.m 19
    5.2.8 LOAD_TOMOGRAPHIC_SECTION.m 19
    5.2.9 LOAD_ALL_TOMOGRAPHIC_SECTIONS.m 19
  5.3 Signal processing utilities 19
    5.3.1 Correlation_Tomography.m 19
    5.3.2 Generate_Interferograms.m 19
    5.3.3 Filter_Matrix.m 19
    5.3.4 Display_Interferograms.m 19
6 ACKNOWLEDGMENT 20
7 REFERENCES 20
## Table of contents:

1. **INTRODUCTION** 3

2. **SAR TOMOGRAPHY** 3

   2.1 Signal models 5

   2.2 Tomographic focusing 6

   2.3 Correlation tomography 7

   2.4 Phase calibration 9

3. **SPACEBORNE DATA SIMULATION** 10

4. **DATA** 11

   4.1 Data-set information: 12

   4.1.1 AFRISAR ONERA DATA-SETS 12

   4.1.2 AFRISAR DLR DATA-SETS 13

   4.1.3 AFRISAR JPL DATA-SETS 14

   4.1.4 BIOSAR DATA-SETS 14

   4.1.5 BIOSAR 2008 DATA-SETS 15

   4.1.6 TRAUNSTEIN DATA-SETS 15

4.2 **Naming System** 16

   4.2.1 Fields: 16

   4.2.2 File names: 16

5. **DEMO CODES AND UTILITIES** 17

   5.1 **DEMO scripts** 18

   5.1.1 DEMO_SARSIM.m 18

   5.1.2 DEMO_SARSIM_PLUS.m 18

   5.1.3 SAR_TOMOGRAPHY_DEMO.m 18

   5.2 **Utilities** 18

   5.2.1 SARSIM_DATA_SELECTION.m 18

   5.2.2 SARSIM_PLUS_DATA_SELECTION.m 18

   5.2.3 SARSIM_PARAM.m 19

   5.2.4 SARSIM_PLUS_PARAM.m 19

   5.2.5 LOAD_SLC.m 19

   5.2.6 LOAD_Kz.m 19

   5.2.7 LOAD_DTM.m 19

   5.2.8 LOAD_TOMOGRAPHIC_SECTION.m 19

   5.2.9 LOAD_ALL_TOMOGRAPHIC_SECTIONS.m 19

   5.3 **Signal processing utilities** 19

   5.3.1 Correlation_Tomography.m 19

   5.3.2 Generate_Interferograms.m 19

   5.3.3 Filter_Matrix.m 19

   5.3.4 Display_Interferograms.m 19

6. **ACKNOWLEDGMENT** 20

7. **REFERENCES** 20
Mathematical models

\[ I_n = \int s(y, z) \cdot \exp \left( j \frac{4\pi}{\lambda} R_n(y, z) \right) dy dz \]

\[ I_n \approx \int P(e) \cdot \exp \left( j \frac{4\pi b_n}{\lambda} \frac{1}{R} \cdot e \right) de \]
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Tomographic focusing
- 3D Backprojection
- 2D Backprojection
- Beamforming

\[ T(x, y, z) = \sum_n d_n \left( t = \frac{2}{c} R_n(x, y, z, \tau) \cdot \exp \left( -j \frac{4\pi}{\lambda} R_n(x, y, z, \tau) \right) \right) d\tau \]

\[ T(x, r, z) = \sum_n I_n(r, x) \cdot \exp(-jK_z(n) \cdot z) \]
Correlation tomography

\[ \hat{P}(x, r, z) = 1 + 2Re \left( \sum_{n=1}^{N} \left( \frac{N + 1 - n}{N + 1} \right) C_n(x, r)e^{-j\kappa_n z} \right) \]
Phase calibration: Basic information about the need for phase cal
Spaceborne simulation:
- P-Band: geometrical simulation (spaceborne geometry)
- L-Band: filtering (airborne geometry)
4.1.2 AFRISAR DLR DATA-SETS

Tomographic processing:
- P-Band Airborne data: 2D Time Domain Back Projection, see equation 10
- L-Band Airborne data: Beamforming, see equation 11
- P-Band Spaceborne data: 2D Time Domain Back Projection, see equation 10
- L-Band Spaceborne data: Correlation Tomography, see equation 14

Approach for simulating spaceborne data:
- P-Band: Spaceborne Geometry Simulator
- L-Band: Airborne Geometry Simulator

Vertical resolution
- P-Band Airborne data: 15 m to 20 m (near range – far range)
- P-Band Spaceborne data: 23.6 m (mid-range)
- L-Band Airborne data: 5 m to 7.5 m (near range – far range)
- L-Band Spaceborne data: 5 m to 7.5 m (near range – far range)

References to be added in publications using these data-sets:

Suggested format: “… DLR data from the AfriSAR campaign [1]. Phase calibration was carried out according to the procedure described in [2].”
Examples
**SARSIM example**

<table>
<thead>
<tr>
<th>9</th>
<th>AfriSAR</th>
<th>Lopé</th>
<th>Tropical</th>
<th>JPL</th>
<th>L-Band</th>
<th>Airborne</th>
<th>JPL &amp; POLIMI</th>
</tr>
</thead>
</table>

% DATA SELECTION
ID = SARSIM_DATA_SELECTION('JPL','Lope','HH','L','Airborne');

**DEMO_SARSIM.m**

*Implemented functions:*

- Data-set selection, e.g.: operator, site, polarization, etc.
- Data loading (SLC, DTM, Kz, range and azimuth coordinates)
- Display SAR Intensity
- Interferogram generation
- Display interferogram phase
- Evaluate and display vertical resolution
SARSIM example

% DATA SELECTION
ID = SARSIM_DATA_SELECTION('JPL','Lope','HH','L','Airborne');

DEMO_SARSIM.m

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- Evaluate and display vertical resolution
% DATA SELECTION
ID = SARSIM_DATA_SELECTION('JPL','Lope','HH','L','Airborne');

DEMO_SARSIM.m

Implemented functions:

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- Data loading (SLC, DTM, Kz, range and azimuth coordinates)
- Display SAR Intensity
- Interferogram generation
- Display interferogram phase
- Evaluate and display vertical resolution
**SAR_TOMOGRAPHY_DEMO.m**

**Implemented functions:**

- Data-set selection, e.g.: operator, site, polarization, etc
  - Interferogram generation
  - Display intensities, coherence magnitude, and phase
  - Tomographic processing via Beamforming (see equation 11) or via Correlation Tomography (see equation 14) to obtain a vertical section in the height, range plane
  - Display the obtained vertical section
### SAR_TOMOGRAPHY_DEMO.m

*Implemented functions:*

Data-set selection, e.g.: operator, site, polarization, etc
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- Display the obtained vertical section
SARSIM_PLUS_DEMO.m

Implemented functions:

- Data-set selection, e.g.: operator, site, polarization, etc.
- Load a tomographic at user-specified height
- Load section coordinates (ground-range, azimuth)
- Display Tomographic Intensity or Tomographic coherence
- Load all tomographic sections
- Extract and display vertical sections
**SARSIM_PLUS_DEMO.m**

*Implemented functions:

- Data-set selection, e.g.: operator, site, polarization, etc.
- Load a tomographic at user-specified height
- Load section coordinates (ground-range, azimuth)
- Display Tomographic Intensity or Tomographic coherence
- Load all tomographic sections
- Extract and display vertical sections

---

**Diagram:**

*Average Intensity [dB] JPL Lope HHHH L Airborne*

<table>
<thead>
<tr>
<th>Azimuth [m]</th>
<th>Range [m]</th>
</tr>
</thead>
<tbody>
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<td>-35</td>
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<tr>
<td>1000</td>
<td>-30</td>
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<tr>
<td>2000</td>
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<tr>
<td>4000</td>
<td>-15</td>
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<tr>
<td>5000</td>
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<td>-5</td>
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<tr>
<td>7000</td>
<td>0</td>
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<td>8000</td>
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</tr>
<tr>
<td>9000</td>
<td>10</td>
</tr>
<tr>
<td>10000</td>
<td>15</td>
</tr>
</tbody>
</table>

---
SARSIM_PLUS_DEMO.m

Implemented functions:

- Data-set selection, e.g.: operator, site, polarization, etc.
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- Load section coordinates (ground-range, azimuth)
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- Extract and display vertical sections
The SARSIM and SARSIM+ data-bases have been created to build a reference data-set for current and future researches on the application of SAR Tomography for the remote sensing of boreal, temperate, and tropical forests at P- and L-Band.

- SARSIM = Coregistered and phase calibrated SLC data
  \[\Rightarrow\text{Ready for tomography}\]

- SARSIM+ = processed tomographic voxels
  \[\Rightarrow\text{Ready for scientific analysis on 3D scattering}\]

- All data saved as Tiff

- Educational codes & user manual attached