Module 2201: SAR Interferometry Basics

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Further Reading

Books


Papers


Structure

- Interferogram formation
- Techniques
- InSAR data processing sequence
- Phase unwrapping
- InSAR satellites and examples
Structure

- First milestones of SAR interferometry
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Phase of a Pixel in a SAR Image

Phase is cyclic, $n$ is unknown!

$$\text{phase: } \phi = -\frac{4\pi}{\lambda} R + \phi_{\text{scatt}} - n \cdot 2\pi$$

**X-band:** $\lambda = 3.1 \text{ cm}$

Fig.: © DLR
A complex SAR image can be decomposed into ...

Intensity and Phase

TerraSAR-X ©DLR

© DLR
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Across-Track Interferometry - Digital Elevation Models

Phase of a Pixel in ...

... SAR-Image #1: \( \phi_1 = -\frac{4\pi}{\lambda} R + \phi_{\text{scatt,1}} \)

... SAR-Image #2: \( \phi_2 = -\frac{4\pi}{\lambda} (R + \Delta R) + \phi_{\text{scatt,2}} \)

... Interferogram: \( \phi = \phi_1 - \phi_2 = \frac{4\pi}{\lambda} \Delta R \)

(if \( \phi_{\text{scatt,1}} = \phi_{\text{scatt,2}} \) !)

X-band: \( \lambda = 3.1 \text{ cm} \)

Fig.: © DLR
Phase Difference of Two SAR Images

Phase in one SAR image looks random (→ speckle effect!). Only after accurate co-registration the phase difference reveals the interferogram.

\[ \text{Interferogram Formtion} \]

\[ \text{Int} = E_{u1}E_{u2}^* \]

(Video Animation)
ERS SAR Image

Bachu, China

approx. 100 km × 80 km
Interferometric Phase

Bachu, China

approx. 100 km × 80 km
InSAR DEM (ERS-1/2)

Bachu, China

approx. 100 km × 80 km
Interferometric Sensitivity as a Function of Wavelength

$$\phi = \phi_1 - \phi_2 = \frac{4\pi}{\lambda} \Delta R$$

X-band

C-band

L-band

Fig.: Mt. Etna
data: SRL-2 (© DLR)
Differential Interferometry

\[ t = t_1 \]

\[ t = t_2 \]

\[ B \]

\[ \Delta R \]

\[ R' = R + \Delta R \]

\[ \phi = \phi_{\text{topo}}(z; B) + \phi_{\text{diff}} \]

\[ \phi_{\text{diff}} = \frac{4\pi}{\lambda} \Delta R_{\text{diff}} \]

Interferometric phase:

\[ \Delta R_{\text{diff}} \]

terrain motion or subsidence

Fig.: © DLR
Sensitivity for Displacement

\[ \Delta R = \Delta y \sin \theta - \Delta z \cos \theta \]

for ERS:

1 fringe (\(2\pi\)) corresponds to

- 2.8 cm in R
- 3.0 cm in z (e.g. subsidence)
- 7.2 cm in y (motion)

Fig.: © DLR
Coseismic Deformation of Bam Earthquake 26 Dec 2003

Monitoring of Landslides by D-InSAR

La Valette/South France

Interferogram

Motion map after removal of topographic phase

(Vietmeier, 2000)
Data: ERS-1/2, ©ESA
Glacier Flow Field Derived from D-InSAR

Antarctic Thwaites glacier Data: ERS-1/2, ©ESA

approx. 500 km x 500 km

(Lang et al., 2004)

Module 3430 Cryosphere – Glaciers & Ice Sheets
Along Track Interferometry (ATI)

- Use of two antennas at different along track positions
  - images taken at different times $\Delta t = \Delta x / (2v)$
  - range component $v_r$ of ground motion causes phase difference between antennas: $\Delta \phi = \frac{2\pi \Delta t^* v_r^*}{\lambda}$

- Examples: SRTM antenna displacement or TerraSAR-X in Dual Receive Mode

SRTM

$\Delta x = 7 \text{ m}$

$60 \text{ m}$

TerraSAR-X

$\Delta x = 2.4 \text{ m}$

Transmit: with whole antenna

Receive: With two antenna halves and two receiver chains

Fig.: © DLR
Tidal Currents Measured by SRTM/X-SAR ATI

Dutch Wadden Sea
3:16 hours before high tide

radial velocity
-0.8 m/s + 1.2 m/s

(Romeiser et al., 2003)
Along Track Interferometry (ATI) ($\Delta t=\text{ms}$)

Vehicle velocity estimation using along track phase difference and azimuth displacement („train off the track effect“).
Example: Autostrada del Sole south of Rome (Suchandt, 2008). Data: TerraSAR-X.
Summary: SAR Interferometry ...

... combines two or more complex-valued SAR images to derive geometric information about the imaged objects (compared to using a single image) by exploiting phase differences.

⇒ Images must differ in at least one aspect (= “baseline”)

<table>
<thead>
<tr>
<th>baseline type</th>
<th>known as ...</th>
<th>applications: measurement of ...</th>
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<td>$\Delta \theta$</td>
<td>across-track</td>
<td>topography, DEMs</td>
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<td>$\Delta t = \text{days}$</td>
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<td>coherence estimator</td>
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- First milestones of SAR interferometry
- Interferogram formation
- Techniques
- InSAR data processing sequence
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InSAR Processing - Data Selection (I)

- Select two (or more) single-look complex SAR images according to application:
  - Usually repeat pass, i.e.
    - Same orbital track, same incidence angle, same mode, same polarization
    - Different time, different position (baseline)
  - Apply spectral (wavenumber) shift filtering (see later)
InSAR Processing - Coregistration (II)

reasons for misregistration:

- Parallel baseline $B_\parallel \rightarrow$ relative image shift
- Divergent orbits $\rightarrow$ image rotation (mostly negligible)
- Orthogonal baseline $B_\perp \rightarrow$ range stretch due to flat Earth and topography

Fig.: © DLR
InSAR Processing - Coregistration (III)

- Determine co-registration parameters:
  - Cross-correlate >100 image chips spread over image
  - A-priori shift parameters can be calculated from annotation (orbit, timing) and a DEM
  - Use over-sampling and interpolation to locate correlation peaks
  - Apply regression to parameterize co-registration (e.g. affine transform)

Fig.: © DLR
InSAR Processing - Resampling (IV)

- **Co-register images:**
  - Resample slave image(s) to match master image
  - Required accuracy: $\ll 1/10$ resolution element for low squint-case
  - 4 point cubic (or better) to minimize interpolation errors
  - Interpolation in azimuth requires *band-pass* interpolator in case of non-zero Doppler centroid frequency
  - Effect of mis-registration $\delta R, \delta t$: $\delta \phi = 2\pi f_{DC} \delta t$
    - loss of coherence
    - phase bias in high squint case:
InSAR Processing – Interferogram Formation

Phase in one SAR image looks random (→ speckle effect!). Only after accurate co-registration the phase difference reveals the interferogram.

\[ \text{Int} = E_{u1}E_{u2}^* \]

(Video Animation)
Coherence - A Measure of Interferogram Quality

Normalized Correlation coefficient between the two complex SAR images $u_1, u_2$

$$\gamma = \frac{E\{u_1 u_2^*\}}{\sqrt{E\{|u_1|^2\} E\{|u_2|^2\}}}$$

Coherence estimate:

$$|\hat{\gamma}[i,k]| = \frac{\left| \sum_w u_1[i,k] u_2^*[i,k] \right|}{\sqrt{\sum_w |u_1[i,k]|^2 \sum_w |u_2[i,k]|^2}}$$

$W$: small window centered around pixel $[i,k]$

Typical window size: 5 – 100 pixels
Stationarity within window assumed!
Loss in coherence (decorrelation)

Some causes of loss in coherence:

- **System**
  - Baseline decorrelation
  - Thermal decorrelation

- **Object**
  - Temporal decorrelation
  - Volume decorrelation
Temporal Decorrelation
Volume Decorrelation
Interferogram flattening
Phase Unwrapping

\[
\begin{align*}
\pi \quad \text{Absolute Phase} \\
-\pi \\
\pi \quad \text{Wrapped Phase} \\
-\pi
\end{align*}
\]
Phase Unwrapping
Interferometric Phase is Ambiguous

good fringe quality
ERS-1/2, 13/14 Jan. 1996

bad fringe quality
ERS-1/2, 23/24 March 1996
Intro: 2D Wrapping Problem (I)

Contour plot of heights

Reality: a Half-Dome Mountain

Fig.: © DLR
Phase to height conversion and geometric correction
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Satellites for SAR Interferometry: ERS-1

- Operated by ESA
- C-Band (5.6 cm)
- 15.5 MHz bandwidth
- 35 day repeat polar orbit,
  - 3 day repeat ice phase
- Highly successful mission
- Initiated cross track and along track SAR interferometry

ERS-1 fully deployed inside the Interspace Test facility, Toulouse, France.

http://earth.esa.int/ers/satconc/satconc.html
ERS-1 Highlight

Fig.: The displacement field of the Landers earthquake mapped by radar interferometry (Massonnet et al., 1993)
Satellites for SAR Interferometry: ERS-2

- Operated by ESA
- Launched 1995
- SAR instrument and orbit identical to ERS-1
  - 1 day time delay
- ERS-1/2 tandem operation 1995-1998
  - controlled baseline
- 1 day time lag → low decorrelation → DEM generation

ERS-1
Operated by ESA
Launched 1995
SAR instrument and orbit identical to ERS-1
1 day time delay
ERS-1/2 tandem operation 1995-1998
controlled baseline
1 day time lag → low decorrelation → DEM generation

http://earth.esa.int/rootcollection/eeo/_foto21b.gif
ERS-1/2 Tandem Mission Result: DEM of Europe processed at DLR

- Acquisition time: 1995-2000
- Size of area: 610,000 km²
- Projection: UTM zone 32, ellipsoid & datum: WGS84
- Pixel size: 25 m x 25 m
- Height error (1σ):
  - flatlands: 4-8 m
  - moderate relief: 8-30 m
  - alpine relief: >>30 m

© DLR
Persistent Scatterer Interferometry with ERS-1/ERS-2

Area: Las Vegas

subsidence of point 81491: $-18.5 \pm 0.1 \text{ mm/a}$

subsidence of point 167088: $-4.1 \pm 0.2 \text{ mm/a}$

Fig.: © DLR
Satellites for Interferometry: ENVISAT/ASAR

- ESA, Launch 2002
- Orbit like ERS-1/2
- More imaging modes
  - ScanSAR (!)
  - Polarimetric
- C-Band, but 30 MHz shifted w.r.t. ERS-1/2
- Not directly InSAR compatible with ERS
- Out of InSAR orbit since Oct. 2010

© http://www.esa.int/export/esaSA/ESAJZA8VTTC_earth_1.html
© ESA
ENVISAT Wide Swath Mode / Wide Swath Mode

Wide swath interferogram of Bam earthquake Dec 2003

Small et al., 2005
Satellites for Interferometry: RADARSAT-1

- Canada, launched 1995
- C-Band
  - Incompatible with ERS, ASAR
- Many modes
  - ScanSAR
  - Higher resolution (30 MHz)
- Interferometry more difficult due to
  - Weak orbit control
  - Lower orbit precision
Satellites for Interferometry: JERS-1, ALOS / PALSAR

- **JERS-1**
  - Japan, 1992
  - L-Band
  - Initially little support for interferometry
  - Increasingly being used with good coherence

- **ALOS/PALSAR**
  - Launched 2006
  - Polarimetry
  - DInSAR-Mission
  - Long term coherence
  - Failed 2011
ALOS Interferogram

Bn ~ 530 m
(Processed at DLR)
Satellites for Interferometry: TerraSAR-X

- Germany, launched 2007
- X-Band
- Many modes
  - Spotlight, ATI
- Polarimetric
- 11 day repeat
- High resolution (150 MHz, 1 m class)
  - Large baselines
- Fast decorrelation on vegetation

© DLR
TerraSAR-X: Tokyo @ 300 MHz High Resolution Spotlight
B=158 m, 43.8 m/fringe
Single Pass Missions

SRTM
- USA/Germany/Italy, 11 days in 2000
- X+C-Band,
- Dedicated single pass interferometer
- Global DEM between +-60°
SRTM Imaging Geometry

Geometry parameters
- Orbit height: 233 km
- Orbit inclination: 57 °
- Nominal baseline: 60.69 m
- Nominal baseline tilt angle: 45 °
- Look angle at swath center: 52 °

X-SAR instrument parameters
- Wavelength: 3.1 cm
- Pulse repetition frequency: 1674 Hz
- Range sampling frequency: 11.25 MHz
- Chirp bandwidth: 9.5 MHz
- Proc. azimuth bandwidth: 1180 Hz

Fig.: © NASA
Nanga Parbat (8125m) as seen by SRTM-X

SAR intensity - perspective
SRTM/X-SAR Image

Volcano Cotopaxi
Ecuador
SRTM/X-SAR Interferometric Phase

Volcano Cotopaxi
Ecuador
SRTM/X-SAR Digital Elevation Model

Volcano Cotopaxi
Ecuador

geocoded
GLOBE
resolution
1 km x 1 km

SRTM
InSAR
resolution
25 m x 25 m

GLOBE © DLR
SRTM © DLR
TanDEM-X

Germany’s current Earth Observation Mission

- Two satellites in close constellation
- Variable across track baseline -> DEMs
- Variable along track baseline -> ATI
- Main mission goal: global HRTI-3 DEM

© DLR
TanDEM-X Applications: open pit mining

Hambach, Germany
12/2010
TanDEM-X Raw-DEM
TanDEM-X DEM and Changes since SRTM 2000

Volume transport: $2.5 \times 10^9$ m$^3$

Volume decrease: $8.9 \times 10^8$ m$^3$
Sentinel-1 TOPS Mode (2014)

TOPS: Reduce aperture time by steering the antenna electronically **forward** in azimuth
- More azimuth distance, less illumination time per target
- Saved time can be used to electronically steer the antenna to other elevation directions

→ increased swath width (e.g. S1: 3 x = 250 km)
→ reduced resolution (e.g. S1: 17 m)

Italy – 1200 Km Seamless TOPS Interferogram
Some SAR/InSAR Processing Software

Commercial

- GAMMA software (Switzerland)  
  http://www.gamma-rs.ch/
- EarthView® InSAR (PCI Geomatics, Canada)  
  http://www.pcigeomatics.com/
- SARscape for ENVI (Exelis, USA)  
  http://www.exelisvis.com/ProductsServices/ENVI/ENVISARscape.aspx  
  http://www.geosystems.de/
- ERDAS IMAGINE

Public Domain

- SNAP (Sentinels Application Platform, ESA)  
  http://step.esa.int/main/toolboxes/snap/
- Alaska SAR facility (ASF, USA)  
  http://www.asf.alaska.edu/
- ROI_PAC (NASA/JPL, USA)  
  https://www.openchannelsoftware.com/
- Doris (Delft University, The Netherlands)  
  http://doris.tudelft.nl/
- StaMPS/MTI (Delft University, The Netherlands)  
  http://radar.tudelft.nl/~ahooper/stamps/
SAR-EDU – SAR Remote Sensing Educational Initiative

https://saredu.dlr.de/

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