Lecture 12: Concepts of InSAR and Its Application to Mapping Topography
THE GENERAL CONCEPTS OF INTERFEROMETRIC SAR (InSAR)
InSAR, a differential technique (or, interference & coherence is back ... again):

- InSAR makes analyzes the phase difference between two or more SAR images in order to map surface topography and monitor surface deformation.

  - **Q1**: We have to rely on phase differences as the phase of a single SAR image appears spatially random and does not allow access to information. Use the concept of interference to explain why that is.

  - **Q2**: We calculate phase differences between SAR images to extract information about surface topography and/or deformation. For this approach to be successful, we require the data to have sufficient coherence. From your knowledge about coherence, explain how coherence affects this process.
SAR Interferometry ....

... combines two or more complex-valued SAR images to derive more 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>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \theta$</td>
<td>across-track</td>
<td>topography, DEMs</td>
</tr>
<tr>
<td>$\Delta t = \text{ms to s}$</td>
<td>along-track</td>
<td>ocean currents, moving object detection, MTI</td>
</tr>
<tr>
<td>$\Delta t = \text{days}$</td>
<td>differential</td>
<td>glacier/ice fields/lava flows, SWE, hydrology</td>
</tr>
<tr>
<td>$\Delta t = \text{days to years}$</td>
<td>differential</td>
<td>subsidence, seismic events, volcanic activities, crustal displacements</td>
</tr>
<tr>
<td>$\Delta t = \text{ms to years}$</td>
<td>coherence estimator</td>
<td>sea surface decorrelation times, land cover classification</td>
</tr>
</tbody>
</table>
What is the Phase of a Radar Signal

- A radar transmits electromagnetic waves in the radar spectrum
- The following schematic sketch illustrates a propagating radar wave

Distance = 3 full periods + a fraction of a period

The length of the fractional period is described by the term “Phase”
Phase Representation

Phase is always ambiguous w.r.t. integer multiples of $2\pi$

pictorial representation of phase:

grey value

0 $\pi$ $2\pi$

$0 = 2\pi$

$\pi$

$\pi/2$

$3\pi/2$

$\color{white}{\pi}$

$\color{white}{\pi/2}$
Interferometric SAR Measures Phase Differences Between Repeated Observations to Measure Topography and Deformation

Source: Jet Propulsion Laboratory (JPL)
The Concept of Interferometric SAR (InSAR)

- Calculation of Phase Difference between Pairs of Radar Remote Sensing Images acquired from similar vantage points

Phase difference measurement (interferometric phase $\phi$) is sensitive to:

**Surface Topography** $\phi(h, B, R, \theta)$
The Concept of Interferometric SAR (InSAR)

• Calculation of Phase Difference between Pairs of Radar Remote Sensing Images acquired from similar vantage points

Phase difference measurement (interferometric phase $\phi$) is sensitive to:

$Surface Topography$ $\phi(h, B, R, \theta)$
Cotopaxi Volcano
Ecuador

Spaceborne SAR Image

Data: SRTM ©DLR
Interferometric Phase Image

Cotopaxi Volcano
Ecuador
InSAR-derived DEM, Cotopaxi Volcano, Ecuador
How InSAR Really Works:
1. What is Contained in a SAR Image’s Phase Signal

- Phase in a pixel of a SAR image is sum of two components:
  1. A **deterministic** component that is a function of the distance $R$ between satellite and pixel on ground ($\psi(R)$)
  2. A **random** phase change $\psi_{\text{scatt}}$ caused by how all scattered signals from one pixel combine together

- Therefore, the phase signal measured in a SAR pixel is:
  $$\psi = \psi(R) + \psi_{\text{scatt}}$$

- As $\psi_{\text{scatt}}$ is different for every pixel (every pixel contains different combination of scatterers), the phase in a single SAR image $\psi$ looks random
**Example:** Amplitude and Phase of a SAR Image of Mount Etna

Amplitude of a segment of an ERS-1 image over Mount Etna, Italy

Phase $\psi$ of a segment of an ERS-1 image over Mount Etna, Italy

$$\psi = \psi(R) + \psi_{scatt}$$
How InSAR Really Works:
2. Form Interferogram to Remove Random Phase $\psi_{scatt}$

Note:
Accurate Image co-registration is needed to successfully remove random phase $\psi_{scatt}$
More about that later!

phase of complex pixel in ...

... SAR image #1: $\psi_1 = -\psi(R) + \psi_{scatt,1}$

... SAR image #2: $\psi_2 = -\psi(R + \Delta R) + \psi_{scatt,2}$

... interferogram: $\phi = \psi_1 - \psi_2 = \phi(R)$

(if $\psi_{scatt,1} = \psi_{scatt,2}$!)

$\psi(R)$
Example: Form Interferogram to Remove Random Phase Component $\psi_{scatt}$

- To form interferogram, we calculate: $I = u_1 \cdot u_2^*$ ($^*$ is complex conjugate)
How InSAR Really Works:

3. Interferometric Phase $\phi$ as a Measurement of Angle

Note: Even for flat terrain: phase varies from near-range to far-range
How InSAR Really Works:
5. Subtraction of Flat Earth Phase

• Example:
  - ALOS PALSAR Interferogram near of Drift River Valley, AK (Baseline ~ 400m)
How InSAR Really Works:

6. Coherence: A Phase Quality Descriptor

- Contributions to Phase Noise:
  - receiver noise
  - processor errors
  - propagation effects
  - temporal changes of surface scattering conditions

Coherence:
- Quality measure describing noise level of InSAR phase

Useful for:
- How accurate is a topography or deformation estimate from InSAR
6. Coherence: A Phase Quality Descriptor

- We can calculate coherence using the following approach:

\[
|\hat{\gamma}[i, k]| = \frac{|\sum_W u_1[i, k] \cdot u_2^*[i, k]|}{\sqrt{\sum_W |u_1[i, k]|^2 \cdot \sum_W |u_2[i, k]|^2}}
\]

\(W\): small window centered around pixel \([i, k]\)

- **Coherence** is an indicator for the level of noise in phase \(\phi[i, k]\) of interferogram pixel \([i, k]\)

- Coherence is defined between 0 (high phase noise) and 1 (low phase noise)

- Coherence can be converted to a phase standard deviation \(\sigma_\phi[i, k]\)
Coherence and Phase Noise - Theory

- How Coherence $\gamma$ converts into phase standard deviation $\sigma_\phi$ depends on the number of looks $N_L$ (how much we average)

$$N_L = 1$$

$\sigma_\phi [\text{deg}]$

$\gamma = 0.6 \rightarrow$ higher phase noise

$\gamma = 0.9 \rightarrow$ low phase noise

$N_L = 16$, $8$, $4$, $2$
Interferometric Coherence - Example

- This example compares interferometric phase quality and coherence side-by-side.

Interferometric phase:
- High coherence → Low phase noise
- Low coherence → High phase noise

Coherence:
INSAR FOR TOPOGRAPHIC MAPPING
Across-Track InSAR Geometry To Enable Topographic Mapping

- For sensitivity to topography: Images from two slightly different vantage points are required.

- Sensitivity to topography depends on these acquisition parameters:
  - The separation of the acquisition locations perpendicular to the sensor look direction $B_{\perp}$
  - The sensor’s wavelength $\lambda$
  - The distance between satellite and ground $R$
  - The sensor look angle $\theta$
## Measuring Topography using InSAR

How to measure topographic height from the InSAR phase:

\[
\phi_{\text{topo}} = \frac{4 \pi}{\lambda} \frac{B_\perp}{R \sin \theta} h
\]

How well can we measure height:

\[
\sigma_h = \frac{\lambda}{4 \pi} \frac{R \sin \theta}{B_\perp} \cdot \sigma_\phi
\]

**example ALOS PALSAR:** \( \lambda \approx 25 \text{ cm} \)

\( R \approx 800 \text{ km} \)

\( \theta = 30^\circ \rightarrow \sin \theta = 0.5 \)

<table>
<thead>
<tr>
<th>baseline</th>
<th>height for 1 phase cycle (2\pi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 m</td>
<td>\approx 1000 m</td>
</tr>
<tr>
<td>100 m</td>
<td>\approx 500 m</td>
</tr>
<tr>
<td>200 m</td>
<td>\approx 250 m</td>
</tr>
</tbody>
</table>
Interferometric Sensitivity as a Function of Wavelength

Three simultaneously acquired Interferograms with identical $B$, $R$, and $\theta$ but varying $\lambda$

- **X-band**
  - $\lambda \approx 3.1 cm$

- **C-band**
  - $\lambda \approx 5.6 cm$

- **L-band**
  - $\lambda \approx 24.0 cm$

Mt. Etna data: SRL-2
Topographic Mapping with InSAR - Example

• Example:
  – ALOS PALSAR Interferogram near of Drift River Valley, AK (Baseline ~ 400m)

What is the altitude of the highlighted peak?

Height per phase cycle (fringe):

\[ h_{2\pi} = \frac{\lambda}{2} \frac{R \sin \theta}{B_\perp} \]

Parameters:

- \( B \) = 400m
- \( R \) = 800,000m
- \( \sin \theta \) = 0.5
- \( \lambda \) = 0.25m

Height per fringe:

\[ h_{2\pi} = 125m \]

About 4 fringes \( \rightarrow \)

\[ h_{\text{peak}} \approx 125m \cdot 4 = 500m \]
Problem of InSAR: Interferometric Phase is Ambiguous

A specific interferometric phase value matches several topographic height values!
Phase Unwrapping: Find “Most Likely” Absolute Phase Given Measured Ambiguous Phase

- Phase Unwrapping algorithms find mathematical ways of describing that ... this is much more likely ...
- ... than this
Shuttle Radar Topography Mission

A Global 30 Meter Digital Elevation Model in 11 Days

February 11 - 22, 2000
SRTM – A Dedicated Topographic Mapping Mission

**2 Single-Pass Interferometers:**

**C-band (NASA/NIMA):**
ScanSAR mode, 225 km swath
⇒ full coverage (± 60° lat.)
< **10 m** vertical relative accuracy

**X-band (DLR/ASI):**
50 km swath
⇒ partial coverage, but higher accuracy
< **6 m** vertical relative accuracy
SRTM – Deployment of Mast
SRTM Coverage
SRTM Example, Cotopaxi Volcano, Ecuador

Cotopaxi Volcano
Ecuador

SRTM/X-SAR

Digital Elevation Model (DEM)
geocoded
TanDEM-X
An X-Band Mission for Global Topographic Mapping

• Mission Goals:
  – Acquisition of a global DEM according to HRTI-3 standard
  – Generation of Local DEMs with HRTI-4 quality
  – Demonstration of innovative bistatic imaging techniques and applications
Helix Orbit of TanDEM-X

vertical baseline

horizontal baseline

NH (desc.)

SH (asc.)
## TanDEM-X

### DEM Vertical Accuracy

<table>
<thead>
<tr>
<th>Spatial Resolution</th>
<th>Absolute Vertical Accuracy (90%)</th>
<th>Relative Vertical Accuracy (point-to-point in 1° cell, 90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTED-1</td>
<td>&lt; 30 m</td>
<td>&lt; 20 m</td>
</tr>
<tr>
<td>DTED-2</td>
<td>&lt; 18 m</td>
<td>&lt; 12 m</td>
</tr>
<tr>
<td>TanDEM-X</td>
<td>&lt; 10 m</td>
<td>&lt; 2 m</td>
</tr>
<tr>
<td>Level-4</td>
<td>&lt; 5 m</td>
<td>&lt; 0.8 m</td>
</tr>
</tbody>
</table>

### Visualization of improved DEM quality:

TanDEM-X vs. SRTM DEMs
Global TanDEM-X DEM
Global TanDEM-X DEM

Absolute Height Error


cumulated absolute height error: 1.3 m
What if the InSAR Partner Images Are Acquired at Different Times?

**Interferometric Phase:**

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

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

**d-InSAR Goal:**

extraction of deformation signal from interferometric phase
Repeat-Pass vs. Single-Pass Interferometry

- **Best for Deformation Mapping (Next Lecture)**
  - atmospheric delay variations
  - temporal decorrelation ($\phi_{scat,1} \neq \phi_{scat,2}$)
  - reduced & variable quality
  - sensitive to surface deformation

- **Best for Topographic Mapping**
  - $B_{effective} = \frac{1}{2} B_{physical}$
  - e.g.: SRTM, TanDEM-X, airborne InSAR
  - high and constant quality DEMs
  - not sensitive to surface deformation

- e.g.: ERS-1/2, Radarsat, Radarsat-2, ENVISAT, ALOS
What’s Next?

- This is what awaits next week:
  - **Tuesday March 05** we will talk more about d-InSAR
  - **Thursday March 07**: Project Concept Presentations