Lecturer:
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Lecture 9: Geometric & Radiometric Properties of SAR Data; Geocoding, Geometric & Radiometric Correction
Problems to Solve when Trying to Use SAR Data for Geophysical Analysis

- **Problem 1:** SAR data suffers from geometric distortions owing to the side-looking observation geometry
  - **Solution:** We will identify the distortions and look for ways to remove them

- **Problem 2:** SAR images appear very noisy, making interpretation harder
  - **Solution:** We will describe the noise and talk about filtering methods

- **Problem 3:** SAR data is in the acquisition coordinate system defined by the Azimuth & Slant Range directions
  - **Solution:** We will talk about Geocoding
Example of a Geometric and Radiometric Distortions in SAR Imagery

- **Evident Geometric Distortion:**
  - One side of the mountain seems shorter than the other

- **Evident Radiometric Distortion:**
  - One side of the mountain seems much brighter
GEOMETRIC PROPERTIES OF SAR IMAGERY
Geometric Distortions are CAUSED by the Slant Observation Geometry of SAR Systems

For SAR images processed to ‘zero-Doppler’ geometry:

\[
\begin{pmatrix}
    x \\
    y \\
    z
\end{pmatrix}
\rightarrow
\begin{pmatrix}
    x \\
    R
\end{pmatrix}
\]

where

\[R = \sqrt{(y_0 + y)^2 + (H - z)^2}\]
Three Types of Geometric Distortions Occur As a Consequence of Oblique Look Angle

- **Foreshortening**
  - Sensor-facing slope forshortened in image
  - Foreshortening effects *decrease* with increasing look angle

- **Layover**
  - Mountain top overlain on ground ahead of mountain
  - Layover effects *decrease* with increasing look angle

- **Shadow**
  - Area behind mountain cannot be seen by sensor
  - Shadow effects *increase* with increasing look angle
Geometric Distortions of SAR Images

1. Foreshortening

![Diagram showing foreshortening in SAR images]

ERS-1

$\theta = 23$ deg
data © ESA
Geometric Distortions of SAR Images

2. Layover

ERS-1

\[ \theta = 23 \text{ deg} \]

data © ESA
Geometric Distortions of SAR Images

3. Shadow

SRTM/X-SAR

\( \theta = 54 \text{ deg} \)
Example of a Geometric and Radiometric Distortions in SAR Imagery

- Questions:
  - Which direction is range and which is azimuth?
  - Where (if at all) do you see foreshortening?
  - Where (if at all) do you see layover?
  - Where (if at all) do you see radar shadow?

McKinley National Park Airport

ALOS PALSAR (L-band) data © JAXA (2007)
Look angle of image: ~35°
Analysis of Complex Structures

Simulation of SAR Signatures (Dr. H. Hammer, S. Kuny)

TerraSAR-X image (Giza, Egypt)

Courtesy A. Thiele, KIT & Fraunhofer IOSB, DE
Contact author @: https://www.ipf.kit.edu/mitarbeiter_thiele_antje.php
Analysis of Complex Structures

Simulation of SAR Signatures (Dr. H. Hammer, S. Kuny)

TerraSAR-X image (Giza, Egypt)

Optical images © Berthold Werner, Jon Bodsworth (Wikipedia)

Range

Courtesy A. Thiele, KIT & Fraunhofer IOSB, DE
Contact author @:
https://www.ipf.kit.edu/mitarbeiter_thiele_antje.php
Analysis of Complex Structures

Simulation of SAR Signatures (Dr. H. Hammer, S. Kuny)

TerraSAR-X image (Giza, Egypt)

stepped pyramid

Range

Range

Courtesy A. Thiele, KIT & Fraunhofer IOSB, DE
Contact author @:
https://www.ipf.kit.edu/mitarbeiter_thiele_antje.php
Another Cool Example of Geometric Distortions
RADIOMETRIC PROPERTIES OF SAR IMAGERY
Think – Pair – Share

• Geometric Distortions can be challenging...
  – Try to explain this scene. What object are you seeing? What is the observation direction in this scene. What causes all the different bright spots?

• Speckle is not noise, he says ...
  – I am claiming that Speckle is not noise in the traditional sense but rather a consequence of the imaging process resulting from the big two principles in SAR, Interference & Coherence. Try to discuss how interference effects in coherent imaging systems may naturally cause speckle?
  – Can you think of other sensors (other than SAR) that also may suffer from Speckle?
SAR Images Often Appear a Bit Noisy

- Do you see the noise?

- This noise is caused “Speckle” and is an inherent property of all coherent imaging systems

- Technically speaking, it is not noise but an interference pattern

http://www.astronomy.com/news/2015/02/a-new-way-to-view-titan-despeckle-it
Coherent Waves and Speckle

\[ \phi(t) \]

\[ \text{Re}\{u(t)\} \]

\[ \text{Im}\{u(t)\} \]

\[ \lambda \]

\( \frac{\pi}{2}, \pi, \frac{3\pi}{2}, 2\pi \)
Coherent Waves and Speckle

Summing contributions within a pixel
Speckle

- Random positive and negative interference of wave contributions from the many individual scatterers within one resolution cell
  - varying brightness from pixel to pixel even for constant $\sigma^0$
  - granular appearance
**Speckle Statistics**

<table>
<thead>
<tr>
<th>quantity</th>
<th>$\sqrt{u_i^2 + u_Q^2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>probability</td>
<td>Rayleigh</td>
</tr>
<tr>
<td>distribution</td>
<td>exponential</td>
</tr>
</tbody>
</table>

**Important:**

1. Noise level depends on radar cross section $\sigma^0 \rightarrow$ higher $\sigma^0$ causes more noise!

2. Noise is highly non-Gaussian!

\[
pdf_f(I|\sigma^0) = \frac{1}{\sigma^0} \exp\left\{-\frac{I}{\sigma^0}\right\}
\]
### Speckle Statistics

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Amplitude</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sqrt{u_i^2 + u_Q^2}$</td>
<td>$I = u_i^2 + u_Q^2$</td>
</tr>
<tr>
<td>Probability Distribution</td>
<td>Rayleigh</td>
<td>Exponential</td>
</tr>
</tbody>
</table>

**Important:**

1. Noise level depends on radar cross section $\sigma^0 \rightarrow$ higher $\sigma^0$ causes more noise!

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\[
pdf(I|\sigma^0) = \frac{1}{\sigma^0} \exp\left\{-\frac{I}{\sigma^0}\right\}
\]

3. Averaging of $N_L$ independent samples (looks) $\rightarrow$ more Gaussian

\[
pdf(I|\sigma^0, N_L) = \frac{I^{N_L-1} N_L^{-N_L} \exp\left\{-\frac{I N_L}{\sigma^0}\right\}}{\Gamma(N_L) \sigma^0^{N_L}}
\]
Speckle Example
Time Series of SAR Images

- Right image: shows how speckle can vary over time and in space
- Left image: shows that on average, the backscatter from an area is equal to its radar cross section $\sigma^0$
Speckle Reduction

• **SPECKLE is a scattering phenomenon and not noise. However, speckle can be modeled as multiplicative noise for distributed targets (Lee, IGARSS-98)**

• Speckle “masks” underlying image

• **Speckle filtering:**
  – GOAL: Reduction of the speckle noise without sacrificing information content (including the spatial resolution)
  – PRINCIPLE: *Select homogeneous neighboring pixels and then average*

• **Simplest form of speckle reduction:** averaging of adjacent pixels (box filter) or multi-looking \(\rightarrow\) loss of resolution

• More complex models (try to limit resolution degradation)
Speckle Reduction
Example

Original
4-look amplitude

5x5 Median

5x5 Boxcar

Lee refined
(7x7)
Example for Bayesian Speckle Reduction

Original SAR Image
SAR data © AeroSensing GmbH

Speckle Filtered
Bayesian Algorithm
## Selected Speckle Filters

<table>
<thead>
<tr>
<th>SPECKLE FILTERS</th>
<th>DESCRIPTION</th>
<th>RELATED PUBLICATION(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change-preserving multi-temporal Speckle filter</td>
<td>Filter for stacks of SAR images; reduces speckle while preserving changes in the time series (e.g., related to deforestation)</td>
<td>Quegan and Yu, 2001</td>
</tr>
<tr>
<td>Lee filter</td>
<td>Standard deviation-based (sigma) filter, filtering data based on statistics calculated from the data. Unlike a Gaussian or boxcar filter, the Lee filter and other similar sigma filters preserve image sharpness and detail while suppressing noise.</td>
<td>Lee, 1980</td>
</tr>
<tr>
<td>Enhanced Lee filter</td>
<td>The enhanced Lee filter is an adaptation of the Lee filter. Each pixel is put into one of three classes, which are treated as follows:</td>
<td>Lopes et al., 1990</td>
</tr>
<tr>
<td></td>
<td>- <strong>Homogeneous</strong>: The pixel value is replaced by the average of the filter window.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- <strong>Heterogeneous</strong>: The pixel value is replaced by a weighted average.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- <strong>Point target</strong>: The pixel value is not changed.</td>
<td></td>
</tr>
<tr>
<td>Frost and enhanced Frost filters</td>
<td>The Frost filter is an exponentially damped circularly symmetric filter that uses local statistics. The Enhanced Frost filter is an adaptation of the Frost filter. It classifies and filters pixels according to the logic explained in the row above.</td>
<td>Frost et al., 1982; Lopes et al., 1990</td>
</tr>
<tr>
<td>Non-local means filters</td>
<td>The basic idea behind non-local means filters is to provide an estimate of the clean image via a proper averaging of similar pixels or patches, found in the image. Essentially, the algorithm searches for image patches that resemble the area around the pixel to be filtered. Using some similarity criterion, these patches are found and averaged together to de-noise the image without losing resolution.</td>
<td>Buades et al., 2005; Chen et al., 2014; Di Martino et al., 2016; Martino et al., 2015</td>
</tr>
</tbody>
</table>
GEOCODING, GEOMETRIC & RADIOMETRIC CORRECTION
Definitions

• Geocoding
  – geometric transformation of an image into a cartographic map projection

• Georeferencing
  – relating image coordinates to map coordinates by defining control points (usually image corners); image remains in native image geometry
Geocoding Using a Sensor Model

• Sensor model
  – sensor specific
  – analytical reconstruction of image formation using orbit and sensor parameters
  – Digital Elevation Model (DEM) required to correct image globally
Geocoding Steps

1. **Relation between image coordinates and geographic coordinates using image and sensor geometry and DEM information**
   - line / sample $\rightarrow$ latitude / longitude

2. **Conversion of geographic coordinates into map-projected coordinates**
   - latitude / longitude $\rightarrow x_{\text{map}} / y_{\text{map}}$
   - choice of map projection and datum

3. **Determination of a transformation function to map image coordinates into projection coordinates**

4. **Resampling using mapping function**
   - determination of pixel value in the map projected using one of the interpolation methods
Example: Original Image
Example: Transformed Image
(After Steps 1-3)
Example: Transformed Image
(After Steps 1-4)
Geometric Terrain Correction

• Geometric terrain correction (GTC) describes how to remove geometric distortions by using a DEM in the geocoding process:
  – To make sure that ALL pixels appear at their proper geographic location.
  – To allow for overlaying SAR data onto remote-sensing data from different sensors

• **GTC problem:** What are the image gray values in every pixel of the output (geocoded) image given the input image and the DEM?

• **Two main approaches for geocoding **including GTC** are shown in the following:**
  – Backward Geocoding
  – Forward Geocoding
Forward Geocoding

Forward geocoding

- Forward geocoding starts from a pixel in the slant-range image for which the location on ground is determined.
- This results in an irregularly distributed point cloud on ground and a subsequent resampling step is necessary.
- Terrain correction is done in image space.
Backward Geocoding

“painting the DEM in map-projection space”

- Starting from a predefined pixel location in the geocoded output image, the corresponding column and line in the slant-range image are calculated using the DEM information.
- The grey value for the output pixel is calculated through interpolation in the slant-range image.
A Second Look At **Forward Geocoding**

1. **Forward Geocoding:**
   - **Step 1:** Project pixels \((x_i, y_i)\) into output image \(g_o\) using DEM
   - **Step 2:** Determine gray values in output image by interpolation between projected pixels

![Diagram of input and output images showing the steps of forward geocoding.](image)
A Second Look At **Backward Geocoding**

2. **Backward Geocoding:**
   - **Step 1:** Project output image pixels \((x_o, y_o)\) into input image \(g_i\) using DEM
   - **Step 2:** Step 2: calculated gray value of projected pixel by interpolation and assign to \((x_o, y_o)\) in output image

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Only Inverse Mapping guarantees that ALL pixels in the output image receives a gray value (no holes) \(\rightarrow\) inverse mapping is standard approach
Geometric Terrain Correction Example (I)

Original Image

ALOS PALSAR (L-band) data © JAXA (2007)
Geometric Terrain Correction Example (II)

Geometrically Terrain Corrected Image

McKinley National Park Airport

ALOS PALSAR (L-band) data © JAXA (2007)
Radiometric Terrain Correction (RTC)

• Problem: Sensor facing slopes appear overly bright in radar images.
• Cause: Pixel Size on sensor-facing slopes is larger → more ground is integrated into pixel → brightness goes up

• Solution: Radiometric Terrain Correction (RTC)
  1. Using DEM and observation geometry, calculate exact equivalent area $A_\sigma$ covered by each pixel
  2. Normalize radar cross section by $A_\sigma$ to arrive at terrain normalized data $\sigma_T^0$
Radiometric Terrain Correction Example (I)
Radiometric Terrain Correction Example (II)

Image after RTC

McKinley National Park Airport
Example of RTC Normalization for an Area in Arkansas, USA

VV/VH/Ratio RGB composite after pixel scattering area normalization.

Google Earth Image of a 85 x 85 km region in Western Arkansas
Pixel scattering area calibration factors derived from SRTM digital elevation data.
RTC Example
Comparison of Processing Techniques
RTC Example
Comparison of Processing Techniques

RTC Image
[Processed with GAMMA RS]
Sentinel-1 RTC images over El Salvador and Honduras
Sentinel-1 RTC images over El Salvador and Honduras
Environmental Monitoring using RTC Images
Example: Dynamics of Areas near Galena, AK

- Radar brightness times series of locations near Galena, AK

1. Time Series Profiles of Sentinel-1 SAR Backscatter
   Sentinel-1 Backscatter
   River Water

2. Time Series Profiles of Sentinel-1 SAR Backscatter
   Sentinel-1 Backscatter
   Tundra [high(er) moisture]

3. Time Series Profiles of Sentinel-1 SAR Backscatter
   Sentinel-1 Backscatter
   Tundra [low(er) moisture]

4. Time Series Profiles of Sentinel-1 SAR Backscatter
   Sentinel-1 Backscatter
   Lake Water

SAR Backscatter Time Series Information

Sentinel-1 SAR Time Series Yukon River, Alaska

2017-01-21
What’s Next?

• Lab week:
  – Labs on SAR image focusing and geocoding
  – Labs on SAR image time series visualization and analysis

• After that, we will start talking about InSAR, a method for topographic mapping and deformation analysis

• In preparation for next week, please read the following information in the SAR Handbook:
  – Chapters 2.1, 2.2, 2.5 & 2.6.1