HYDROSAR – WEATHER-RELATED HAZARD INFORMATION FROM SAR

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Lecture 1: An intro to Synthetic Aperture Radar (SAR) with a Focus on Its Applications for Flood Mapping
HydroSAR is an SERVIR-AST-Funded Project to Develop Products, Tools & Services to Support Monitoring Hydrological Hazards in the HKH Region

SAR-based value-added products

- RTC Image Time Series
- RGB Composites
- Flood Extent Maps
- Change Detection Maps
- Active Agriculture Maps

Cloud-based Computational Resources

Automatic Cloud-based Production Pipelines

Exercising mature algorithm large scale using cloud-based workflows

The OpenSARLab

Cloud-based Application Development Platform
The HydroSAR Team

HydroSAR Development Team

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HydroSAR Partners

SERVIR
Connecting Space to Village

ICIMOD
HydroSAR Training Syllabus

• The Syllabus and all lecture materials can be found here:
  – https://drive.google.com/drive/folders/1QOdS5P3kv52pkkjidsY8Jkil-3IsSBn?usp=sharing

HydroSAR Training: Extracting Flood Information from SAR

1. Course Information:
   • Title: Extracting Flood Information from SAR Time Series Data
   • Course Type: Synchronous Remote Training
   • Format and Duration: Four-session training three-hours each
   • Dates and Times: U.S. Jan 25 - 28, 2021
     Nepal: Jan 26 - 29, 2021
   • Prerequisites:
     ● ARSET Fundamentals of Radar Remote Sensing training:
       https://appliedsciences.nasa.gov/join-mission/training/english/introduction.synthetic-aperture-radar
     ● Basic knowledge of Python (for help with Python please see):
       ○ https://www.w3schools.com/quiztest/quiztest.asp?qtest=PYTHON
       ○ https://pynative.com/basic-python-quiz-for-beginners/
BENEFITS OF RADAR REMOTE SENSING
**Wavelength Discriminates Radar from Optical Data**

- Radar has excellent capabilities for routine global change monitoring
  - 24/7 imaging capabilities: due to weather and illumination independence
  - Advanced change detection performance: due to stable image geometry and own signal source
  - Complementary to optical sensors: provides independent information about surface
Weather Independence Provides Advantages Especially For Weather-Related Events such as Flooding and Rain-Triggered Landslide Activity

Animation of the use of SAR during Flooding events (credit: DLR TerraSAR-X team)
Modern SAR Sensors provide regularly-sampled, high-resolution & weather-independent earth observation data from Space

ESA Sentinel-1 SAR
Preparation for NASA-ISRO SAR (NISAR) Radar Earth Observation Satellite Project

**Launch Spring 2023**

First spaceborne L- and S-band SAR

Full global coverage in 12 days

150 Petabyte of Earth Observation data / year

**All Data Free and Open!**

NISAR Data Center

NISAR Ground Station

NISAR Science Team Member

NISAR L2 Algorithm Development
The Microwave Spectrum

(approximate)

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency $f_0$</th>
<th>Wavelength $\lambda = c/f_0$</th>
<th>Typical Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ka</td>
<td>27 – 40 GHz</td>
<td>1.1 – 0.8 cm</td>
<td>Rarely used for SAR (airport surveillance)</td>
</tr>
<tr>
<td>K</td>
<td>18 – 27 GHz</td>
<td>1.7 – 1.1 cm</td>
<td>Rarely used for SAR (H$_2$O absorption)</td>
</tr>
<tr>
<td>Ku</td>
<td>12 – 18 GHz</td>
<td>2.4 – 1.7 cm</td>
<td>Rarely used for SAR (satellite altimetry)</td>
</tr>
<tr>
<td>X</td>
<td>8 – 12 GHz</td>
<td>3.8 – 2.4 cm</td>
<td><strong>High-resolution SAR</strong> (urban monitoring; ice and snow; little penetration into vegetation cover; fast coherence decay in vegetated areas)</td>
</tr>
<tr>
<td>C</td>
<td>4 – 8 GHz</td>
<td>7.5 – 3.8 cm</td>
<td><strong>SAR workhorse</strong> (global mapping; change detection; monitoring areas with low to moderate vegetation; improved penetration; higher coherence)</td>
</tr>
<tr>
<td>S</td>
<td>2 – 4 GHz</td>
<td>15 – 7.5 cm</td>
<td><strong>Little but increasing use for SAR-based Earth obs.</strong>; agriculture monitoring (NISAR will carry S-band; expands C-band applications to higher vegetation density)</td>
</tr>
<tr>
<td>L</td>
<td>1 – 2 GHz</td>
<td>30 – 15 cm</td>
<td><strong>Medium resolution SAR</strong> (Geophysical monitoring; biomass and vegetation mapping; high penetration; InSAR)</td>
</tr>
<tr>
<td>P</td>
<td>0.3 – 1 GHz</td>
<td>100 – 30 cm</td>
<td><strong>Biomass estimation.</strong> First P-band spaceborne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR.</td>
</tr>
</tbody>
</table>
Atmosphere almost Transparent at Microwave Window

From Woodhouse (2006)
Depending on Signal Wavelength, SAR can Penetrate Into Vegetation and Soils

- **Example**: X-band vs P-band penetration into Forest Canopies

<table>
<thead>
<tr>
<th>Wavelength-Dependent Penetration into Top Surface Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation</td>
</tr>
<tr>
<td>X-Band ~ 3 cm</td>
</tr>
<tr>
<td>C-Band ~ 6 cm</td>
</tr>
<tr>
<td>L-Band ~ 23 cm</td>
</tr>
<tr>
<td>Dry Alluvium</td>
</tr>
<tr>
<td>Glacier Ice</td>
</tr>
</tbody>
</table>

**P-band** radar image of forested area
Radar like Optical EM Signals are Transverse Oscillating Waves

Longitudinal oscillating waves (sound waves, waves on oceans)

Transverse oscillating waves (e.g., EM waves)

Traverse oscillating waves (like EM waves) have one additional degree of freedom: Direction in which oscillation takes place, called Polarization
In Radar, we can Control the Polarization of the Transverse Oscillating Signal \rightarrow Its Polarization

- Polarization planes are perpendicular – orientation technically arbitrary
- Usually, horizontal and vertical planes are chosen
- The terms horizontal and vertical then refer to either the earth or the antenna surface
Example of Multiple Polarizations for Vegetation Studies - Pacaya-Samiria Forest Reserve in Peru

- L-band SAR images from UAVSAR (HH, HV, VV)

RGB Combination of Polarizations
WHAT IS SYNTHETIC APERTURE RADAR (SAR)?
Radar Principle

Range $R$

Light velocity

Scattering object

Transmit

Received echo:

$2 \frac{R}{c}$

Time $\tau$
How to Form a Radar Image

Radar transmits pulses and receives echoes at the rate of the pulse-repetition frequency (PRF):

$$PRF \approx 1000 - 4000 \text{ Hz}$$

**Range pixels:** pixel size defined by pulse width (radar principle)

**Azimuth pixels:** scanning in flight direction at $V_{S/C}$
Imaging the Surface with SLARs

Scanning Ground-based Radar System as a SLAR Example

- Resolution defined by pulse length & length of antenna
Example of Scanning Ground-Based Radar Acquisition

- 180 degrees scan angle – location: Fairbanks, Alaska
The Problem of SLARs – Azimuth Resolution Degrades with Distance

Antenna Size vs. Beam Width

short antenna

\[ L = 10 \text{ m} \]

\[ \beta \approx \frac{\lambda}{L} \]

\[ R \approx 850 \text{ km} \]

wide beam

\[ R \frac{\lambda}{L} \approx 5 \text{ km} \]

long antenna

\[ L = 5 \text{ km} \]

\[ \approx 10 \text{ m} \]

narrow beam

ERS-1/2 parameters
Formation of a Synthetic Aperture — SAR Principle

Combination of overlapping acquisitions

High resolution

Antenna footprint

Flight direction of sensor

L

Combination of overlapping acquisitions
Modern Radars (so called SAR’s) Enable Meter-Resolution Imaging from Space

Guelb er Richat, Mauritania
Shallow ring structures of limestone, dolomites, and breccias (TerraSAR-X image, July 8, 2007, courtesy: DLR)
## Satellite SAR Sensors: L-Band

<table>
<thead>
<tr>
<th></th>
<th>SEASAT</th>
<th>JERS-1 Japan</th>
<th>ALOS PALSAR Japan</th>
<th>ALOS-2 PALSAR Japan</th>
<th>ALOS-4 PALSAR Japan</th>
<th>SAOCOM, 1A / 1B Argentina</th>
<th>NISAR USA/India</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Band</strong></td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>HH</td>
<td>HH</td>
<td>Polarimetric</td>
<td>Polarimetric</td>
<td>Polarimetric</td>
<td>Dual</td>
<td>Dual</td>
</tr>
<tr>
<td><strong>Spatial Resolution [m]</strong></td>
<td>20</td>
<td>18</td>
<td>10, 20, 100</td>
<td>3 - 100</td>
<td>3 - 100</td>
<td>10-100</td>
<td>10</td>
</tr>
<tr>
<td><strong>Repeat Cycle [days]</strong></td>
<td>17</td>
<td>44</td>
<td>46</td>
<td>14</td>
<td>14</td>
<td>16/8</td>
<td>12</td>
</tr>
</tbody>
</table>
### Satellite SAR Sensors: C-Band

<table>
<thead>
<tr>
<th></th>
<th>RADARSAT-1 Canada</th>
<th>RADARSAT-2 Canada</th>
<th>RADARSAT Constellation Mission Canada</th>
<th>ERS-1/2 Europe</th>
<th>Envisat Europe</th>
<th>Sentinel-1 ESA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Band</strong></td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>HH</td>
<td>Quad-pol</td>
<td>Quad-pol</td>
<td>VV</td>
<td>HH, VV, HV</td>
<td></td>
</tr>
<tr>
<td><strong>Spatial Resolution [m]</strong></td>
<td>10-100</td>
<td>3-100</td>
<td>3-100</td>
<td>30</td>
<td>10-100</td>
<td>5-100</td>
</tr>
<tr>
<td><strong>Repeat Cycle [days]</strong></td>
<td>24</td>
<td>24</td>
<td>1</td>
<td>3/75/176</td>
<td>35</td>
<td>12/6</td>
</tr>
<tr>
<td><strong>Sentinel-1 C/D approved for operations until 2030</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sentinel-1 C/D approved for operations until 2030</td>
</tr>
</tbody>
</table>
## Satellite SAR Sensors: X-Band

<table>
<thead>
<tr>
<th></th>
<th>TerraSAR-X Tandem-X DLR/InfoTerra</th>
<th>Cosmo SKYMED Constellation, ASI, eGeos</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operation Date</strong></td>
<td>4/2007 2009 Tandem-X</td>
<td>2007</td>
</tr>
<tr>
<td><strong>Frequency Band</strong></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>Polarimetric Interferometric</td>
<td>Polarimetric Interferometric</td>
</tr>
<tr>
<td><strong>Spatial Resolution [m]</strong></td>
<td>Up to 1</td>
<td>Up to 1</td>
</tr>
<tr>
<td><strong>Repeat Cycle [days]</strong></td>
<td>11</td>
<td>16</td>
</tr>
</tbody>
</table>
Satellite SAR Sensors: Other Bands

<table>
<thead>
<tr>
<th></th>
<th>ESA Biomass Mission Europe</th>
<th>NISAR USA/India</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operation Date</strong></td>
<td>2018</td>
<td>2020</td>
</tr>
<tr>
<td><strong>Frequency Band</strong></td>
<td>P</td>
<td>S</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>Polarimetric Interferometric</td>
<td>Polarimetric Interferometric</td>
</tr>
<tr>
<td><strong>Spatial Resolution [m]</strong></td>
<td>50-200</td>
<td>~3</td>
</tr>
<tr>
<td><strong>Repeat Cycle [days]</strong></td>
<td>25</td>
<td>12</td>
</tr>
</tbody>
</table>
GEOMETRIC PROPERTIES OF SAR
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
Examples of 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°
CORRECTING GEOMETRIC PROPERTIES OF SAR
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?

• **Geocoding including GTC** uses a Digital Elevation Model to project every image pixel onto its right location on the earth surface
Geometric Terrain Correction Example (I)

Original Image

McKinley National Park Airport

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

Geometrically Terrain Corrected Image
Radiometric Terrain Correction

• **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)

Image after GTC

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

Image after RTC

McKinley National Park Airport

ALOS PALSAR (L-band) data © JAXA (2007)
Sentinel-1 RTC images over El Salvador and Honduras
HOW SAR SEES THE WORLD
SAR Characteristics Relevant for Ecosystems Monitoring

- SAR backscatter values are determined by both sensor and target characteristics

**Sensor Characteristics:**
- frequency/wavelength of the SAR,
- polarization of the transmitted and received SAR signal,
- incidence angle of the radar beam interacting with the ground,
- and look direction of the sensor

**Target Characteristics:**
- Surface roughness and vegetation structure → more roughness and more structure increase SAR backscatter
- Increased moisture in soils and vegetation → increase SAR backscatter
- Standing open water → typically very dark - However, wind and currents can rough up water and increase brightness especially for short wavelength (X- and C-band) observations
- At longer wavelengths, double-bounce effect under canopies can have strong backscatter signal (see Slide 9)

Especially for time series analysis:
Use data with same sensor characteristics → avoid misinterpretation of sensor characteristics as change
Radar Interaction with Objects on the Surface

- At Radar wavelength, scattering is very physical and can be described as a series of bounces on scattering interfaces.

- Three main scattering mechanisms dominate:
  - **Scattering on (rough) surfaces**: Water, bare soils, roads – Scattering strongly dependent on surface roughness and sensor wavelength (see Slide #6).
  - **Double-bounce scattering**: Buildings, tree trunks, light poles – little wavelength dependence.
  - **Volume Scattering**: Vegetation; dry soils with high penetration – strongly dependent on sensor wavelength and dielectric properties of medium.
Examples of Radar Interaction
Smooth Surface Reflection (Specular Reflection)

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)

Pixel Color

Smooth, level surface
(open water, road)
Examples of Radar Interaction
Rough Surface Scattering

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)

Pixel Color

rough bare surface
(deforested areas, tilled agricultural fields)
Examples of Radar Interaction
Volume Scattering by Vegetation

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)
Examples of Radar Interaction

Double Bounce Scattering

Inundated Vegetation

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)

Pixel Color
Influence of Wavelength on Signal Penetration

- Penetration into vegetation and soils increases with sensor wavelength
  - L-band penetration > C-band > X-band

- For vegetated areas:
  - X-band SAR mostly scatters at the tops of tree canopies
  - C- and L-band signals penetrate increasingly \(\rightarrow\) more volume scattering & better for vegetation characterization
  - Longer wavelength \(\rightarrow\) improved mapping of inundation under forest canopies

- Penetration into soils also strongly dependent on soil moisture content (see slide 21)
Inundation under Vegetation at L-band Frequencies

- Increased double-bounce effect from bellow-canopy flooding at L-HH polarization from ALOS-1:
  - **Left:** Low-water season and
  - **Right:** High-water season
  - Note the brightening of the forests during inundation
Annual Maximum Inundation in the Amazon derived from L-band HH and HV ALOS PALSAR-2 Data

Legend:
- Inundated Veg.
- Submerged Veg.
- Open Water
- Areas Not Flooded
Different SAR Polarizations See Different Things

- Horizontal Transmit, Horizontal Receive: HH
- Horizontal Transmit, Vertical Receive: HV
- Vertical Transmit, Vertical Receive: VV
- Vertical Transmit, Horizontal Receive: VH

Legend:
- H: Horizontal polarization
- V: Vertical polarization
Polarimetric Dependence of Scattering Principles

Relative scattering strength by polarization:

- Pure Surface Scattering: \(|S_{VV}| > |S_{HH}| > |S_{HV}|\) or \(|S_{VH}|\)
- Double Bounce Scattering: \(|S_{HH}| > |S_{VV}| > |S_{HV}|\) or \(|S_{VH}|\)
- Volume Scattering: main source of \(|S_{HV}|\) and \(|S_{VH}|\)

Legend

Low Radar Brightness (\(|S|\)) | High Radar Brightness (\(|S|\))
Example of Multiple Polarizations for Vegetation Studies - Pacaya-Samiria Forest Reserve in Peru

- L-band SAR images from UAVSAR (HH, HV, VV)

RGB Combination of Polarizations
Selected Additional SAR Training Resources

**SAR-CBC is Funded by NASA Applied Sciences**
Information on project partners and activities

**Online SAR Course on “Synthetic Aperture Radar: Hazards” on edX**
Fully remote accessible

**NASA Applied Remote Sensing Training**
Virtual trainings on all things remote sensing

**The SAR Handbook**
Free-and-open book on SAR Remote Sensing

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Franz J Meyer, UAF
HydroSAR Training, 01/2021
QUESTIONS?

UP NEXT: INTRODUCTION TO THE OPENSARLAB