INTRODUCTION TO SAR REMOTE SENSING

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Introduction to SAR remote sensing

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1. Introduction to SAR remote sensing

2. Statistical properties of SAR images

3. Physical content of SAR data

4. Application to agriculture

4. Application to forests – Biomass estimation
The electromagnetic spectrum

Synthetic Aperture Radar (SAR)
The electromagnetic spectrum

Visible (VIS) + Near Infrared (NIR) = Optical

Thermal Infrared (TIR)

Synthetic Aperture Radar (SAR)
SAR: all-weather observing system

Forest loss in Cameroon

Sentinel-1

Sentinel-2
Marginal atmospheric effects

Very low attenuation by atmospheric constituents for $\lambda > \sim 5\, \text{cm}$
Active system:
day and night operations
Side Looking Radar

Azimuth direction

Range direction

Pulses

Linear displacement of the antenna along the track

The range information comes from the time needed by the pulse to travel way and back
Why side looking?
The larger the antenna, the narrower the aperture (finer resolution).

Resolution = \( \frac{\lambda R}{L} \)

Numerical example:

\( L \approx 10m, R \approx 1000 \text{ km (spaceborne radar)}, \lambda \approx 5 \text{ cm (C band)} \rightarrow \text{resolution} \approx 5 \text{ km} \)
Synthetic aperture technique

An array of antennas is equivalent to a single antenna moving along the flight line $L_S$ if the received signals are coherently recorded and added, and the target assumed to be static during the period.

The echoes from $X_1$, $X_2$, ..,$X_n$ are recorded coherently (amplitude and phase as a function of time).

Azimuth resolution

$$R_a = \frac{\lambda R}{L_S}$$
The SAR image

Satellite orbit

Look angle
Off nadir

Slant range

Azimuth

Ground range
What does the SAR measure?

1. **Amplitude** which depends on the target properties (dielectric and geometric properties)

2. **Phase** which is function of the sensor-target distance and target properties
SAR measurement modes - BIOMASS

PolSAR

Pol-InSAR

TomoSAR
Polarimetric Interferometry (PolinSAR)

Tree height inversion

Garestier, 2006
Radar Interferometry

**Relief**
- Etna iso-altitude curves

**Terrain displacement**
- Landers iso-displacement curves

Accurate range measurement

Digital elevation models

Cartography of terrain displacements
Impact of a geothermal plant on the environment. Interferogram processed from two ERS images, acquired at two years interval. The fringes characterize the ground subsidence around the plant. One observe a subsidence of about 6 cm (2 fringes) which covers 17km x 8km.
## Principal available SAR data

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Life-time</th>
<th>Frequency</th>
<th>Polarisation</th>
<th>Resolution</th>
<th>Frame</th>
<th>Repeat cycle</th>
<th>Access</th>
</tr>
</thead>
<tbody>
<tr>
<td>TerraSAR-X</td>
<td>2007-2010-</td>
<td>X-band</td>
<td>Single HH, VV</td>
<td>Spotlight: &lt;1m, 1.7x3.5m Stripmap: 3x3m</td>
<td>Spotlight: 3x10km ScanSAR:150x100, 200x200km</td>
<td>11days</td>
<td>Restrained Scientific, Commercial</td>
</tr>
<tr>
<td>TanDEM-X</td>
<td></td>
<td>λ = 3.5cm</td>
<td>Dual: HH/VV, HH/HV</td>
<td>Stripmap: 5x20m Extra Wide Swath (EW): 20x40m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COSMO-Skymed</td>
<td>2007-</td>
<td>X-band</td>
<td>Single: HH, VV,</td>
<td>Spotlight: &lt;1m Stripmap: 3x15m</td>
<td>Spotlight: 10x10km ScanSAR:100x100, 200x200km</td>
<td>Sat: 16 d</td>
<td>Commercial Limited scientific.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>λ = 3.5cm</td>
<td>HV, VH Dual</td>
<td>Stripmap: 3x10m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radarsat-2</td>
<td>2007-</td>
<td>C-band</td>
<td>Single: HH, VV,</td>
<td>Spotlight: 1.5m Stripmap: 3x3m 25x25m</td>
<td>Spotlight: 18x8km Stripmap: 20x170km ScanSAR:300x300, 500x500km</td>
<td>24 days</td>
<td>Commercial</td>
</tr>
<tr>
<td></td>
<td></td>
<td>λ = 5.6cm</td>
<td>HV, VH Dual</td>
<td>Stripmap: 35x35m 100x100 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dual: HH/HV, HV/VH</td>
<td>ScanSAR: 5x5m Interferometric Wide Swath (IW):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Quad</td>
<td>5x20m Extra Wide Swath (EW): 20x40m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PALSAR-2</td>
<td></td>
<td>λ = 24.6cm</td>
<td>HV, VH Dual</td>
<td>Stripmap: 70x70km ScanSAR: 355x355km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dual: HH/HV, HV/VH</td>
<td>ScanSAR: 25x10m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Quad</td>
<td>Stripmap: 3x10m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>λ = 5.6cm</td>
<td>Dual: HH/HV, HV/VH</td>
<td>EW:400 km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Stripmap: 3x10m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The available SAR data for each satellite is described in terms of frequency, resolution, and specific modes, including spotlight, stripmap, and ScanSAR. The repeat cycle varies depending on the satellite and mission requirements, ranging from 11 days to 14 days, with some offering free and open access.
## Radar frequency bands

<table>
<thead>
<tr>
<th>Frequency band</th>
<th>Wavelength (cm)</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ka</td>
<td>0.8-1.1</td>
<td>40 - 26.5</td>
</tr>
<tr>
<td>K</td>
<td>1.1-1.7</td>
<td>26.5 - 18</td>
</tr>
<tr>
<td>Ku</td>
<td>1.7-2.4</td>
<td>18 - 12.5</td>
</tr>
<tr>
<td>X</td>
<td>2.4-3.8</td>
<td>12.5 - 8</td>
</tr>
<tr>
<td>C</td>
<td>3.8-7.5</td>
<td>8 - 4</td>
</tr>
<tr>
<td>S</td>
<td>7.5-15</td>
<td>4 - 2</td>
</tr>
<tr>
<td>L</td>
<td>15 -30</td>
<td>2 - 1</td>
</tr>
<tr>
<td>P</td>
<td>30 -100</td>
<td>1 - 0.3</td>
</tr>
</tbody>
</table>

\[ f \text{ (in Hertz)} = \frac{C}{\lambda} \]

\[ C = 3.10^8 \text{ m} \]

\[ \lambda = \text{wavelength in m} \]
Polarisation

Magnetic field

Electric field

Trajectory of the electric field

Propagation direction

Transverse plane
Polarisation

- Electric field
- Plane orthogonal to the propagation direction
- Propagation direction

Horizontal polarisation
Vertical polarisation
Polarisation

- **VV**
  - Radar antenna transmits vertically polarized energy toward the earth
  - Vertical send
  - Vertical receive
  - Vertical filter
  - Backscattered vertically polarized energy from earth is received by the antenna

- **HH**
  - Radar antenna transmits horizontally polarized energy toward the earth
  - Horizontal send
  - Horizontal receive
  - Horizontal filter
The radar scattering

the amplitude, phase and polarisation of $E_s$ are modified with respect to $E_i$
The basic measurement made by a SAR is called $S$ (amplitude and phase). This is the complex image.

Main types of images:

$A$ is the **amplitude image**.

$I = A^2$ is the **intensity image**.

(the phase of a single image is not exploitable)
The radar cross-section (RCS) is defined as

\[ \sigma_{pq} = 4\pi \left| S_{pq} \right|^2 = 4\pi R^2 \frac{P_s}{P_i} \quad \left[ \text{m}^2 \right] \]

*R is the radar-target distance*

*\(P_i\) is the incident power,*

*\(P_s\) is the power scattered by the target.*
For **distributed targets** each resolution cell contains many scatterers and the phase varies rapidly with position.

The **differential backscattering coefficient**, \(\sigma^o\), is

\[
\sigma^o = \frac{4\pi R^2}{\Delta A} \frac{P_s}{P_i} \quad [m^2/m^2]
\]

where \(\Delta A\) is the area of the illuminated surface over which the phase can be considered constant.
Slant and ground range

Source: CCRS tutorials
1. Introduction to SAR remote sensing
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4. Application to forests – Biomass estimation
What is a SAR image?

The image is seen as a picture.

Pixels are numbers.

Image is affected by speckle noise

Example of an intensity image
APP HH image 400 x 400 pixels (of 12.5m)
Gaoyou, Jiangsu province, China, 2004 05 24
Same image, after speckle filtering
HH (magenta) and VV (green) images
400 x 400 pixels
Gaoyou, Jiangsu province, 2004 09 06
Origin of speckle noise
Speckle noise must be reduced...

Before speckle filtering

After speckle filtering
...to start analysing SAR images content
Probability density distribution of speckle:
- **Intensity** image: **Gamma** distribution
- **Amplitude** image: **Rayleigh** distribution

\[ \text{var}(I) = \frac{\sigma^2}{L} \]
Multilooking reduces the effect of speckle. The distribution tends to normality as $L$ increases.

\[ \text{var}(I) = \frac{\sigma^2}{L} \]
Speckle filtering reduces variance and preserves radiometry.

Non filtered – 4 looks

Filtered – 20 looks

\[ \gamma^o_{HV} \]

-8 dB

-20 dB

Yellow area

Blue area

ENL=20
Mean = -14.70 dB
SD = 1.58 dB

ENL=4
Mean = -14.70 dB
SD = 2.47 dB

ENL=20
Mean = -11.89 dB
SD = 1.21 dB

ENL=4
Mean = -11.89 dB
SD = 2.31 dB

Mermoz et al., 2016
Speckle filtering

\[ I = \sigma \cdot v \]

\( I \): measured intensity
\( \sigma \): scene reflectivity (what we want to measure)
\( v \): speckle noise
\( L \): number of looks

\[
\bar{I} = \sigma \quad \text{and} \quad \text{var}(I) = \frac{\sigma^2}{L}
\]

Speckle filtering consists in assessing \( \sigma \) from \( I \) by reducing the variance of \( I \) (and therefore increasing the Equivalent Number of Looks).

1. **Frequency filtering**: spectral filtering during SAR processing (production of multi-look images)

2. **Spatial filtering**: local estimations using moving kernels
   Filters of Lee, Kuan, Frost, MAP widely available

3. **Multi channel filtering**: applied on multiple images of the same scene
   Multi polarisation, multi temporal, and multi frequency
Multi-image intensity filtering (temporal and polarisation)

Purpose of filter:

1. Preserve radiometry ⇒ unbiased
   \[
   \langle I_k(x, y) \rangle = \langle J_k(x, y) \rangle \quad 1 \leq k \leq M
   \]

2. Minimise the variance of \( J_k \)
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Scattering Mechanisms

- The backscattered signal results from:
  - surface scattering
  - volume scattering
  - multiple volume-surface scattering

- The relative importance of these contributions depends on geometric and dielectric properties of the medium (surface and volume)

- All of these factors depend on
  - the radar frequency
  - the polarisation
  - the incidence angle

Thuy Le Toan, CESBIO, Toulouse, France
Scattering mechanisms

- **Surface scattering**
  - Water
  - Vegetation

- **Volume scattering**
  - Soil, rock
  - Snow

- **Volume-surface scattering**
  - Vegetation
Interactions between radar wave and vegetation cover

**Geometric, structural properties**

- Scatterers size
- Scatterers orientation
- Scatterers density
- Soil roughness

**Dielectric properties**

- Scatterers water content
- Soil moisture
Surface scattering

The roughness of the surface (wrt to the wavelength) governs the scattering pattern.

\[ \varepsilon_{r1} \]

Smooth surface

\[ \varepsilon_{r2} > \varepsilon_{r1} \text{ medium 2 is wetter than medium 1} \]

Wetter media

The dielectric constant (moisture content) of the medium governs the strength of the backscatter.

\[ \varepsilon_{r2} \]

Rough surface
Contents

1. Introduction to SAR remote sensing
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Radar backscatter depends on the dielectric and geometry of the target, and on the frequency, polarisation and incidence angle of the wave e.g. Small Perturbation Method for surface scattering

\[
\sigma_{pp}^0 = 4 (ks)^2 (kl)^2 \cos^4 \theta \left| \alpha_{pp} \right|^2 \left[ 1 + 2 (kl \sin \theta)^2 \right]^{3/2}
\]

Here

- \( k = \frac{2\pi}{\lambda} \) (Wave number)
- \( pp = \) HH or VV
- \( \theta = \) incidence angle
- \( s = \) surface RMS height
- \( l = \) surface autocorrelation length

\[
\alpha_{hh} = \frac{\cos \theta - \sqrt{\varepsilon - \sin^2 \theta}}{\cos \theta + \sqrt{\varepsilon - \sin^2 \theta}} \quad \alpha_{vv} = (\varepsilon - 1) \frac{\sin^2 \theta - \varepsilon (1 + \sin^2 \theta)}{(\varepsilon \cos \theta + \sqrt{\varepsilon - \sin^2 \theta})}
\]

- \( \varepsilon = \) dielectric constant

\( \sigma^0 \) is the backscattering coefficient
### Agricultural surface roughness statistics

<table>
<thead>
<tr>
<th>Tillage</th>
<th>Rms (mean)</th>
<th>Rms (std)</th>
<th>Corr. Length (mean)</th>
<th>Corr. Length (std.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seedbed</td>
<td>0.6</td>
<td>0.3</td>
<td>3.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Harrowed</td>
<td>1.6</td>
<td>0.7</td>
<td>3.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Ploughed</td>
<td>2.7</td>
<td>1.0</td>
<td>6.9</td>
<td>2.7</td>
</tr>
</tbody>
</table>

RMS heights $s$ and correlation length $l$ (mean and std in cm)
Dielectric constant as a function of soil volumetric water content

![Graph showing dielectric constant as a function of soil volumetric water content.](image)

**Fig. 6.** A comparison between the calculated dielectric constants from the empirical model and the measured values at 5 GHz.
Sensitivity to soil moisture and surface roughness

Low backscatter ➔ dry soil

High backscatter ➔ Wet soil

BUT:

Low backscatter ➔ Smooth surface

High backscatter ➔ rough surface

For constant roughness

For constant moisture

Simultaneous effect of roughness and moisture on the radar signal
Our first ERS experiment in 1992 on irrigated area in Gharb, Morocco

We mapped irrigated fields, but to retrieve soil moisture was found hard with a single ERS data!

Le Toan, T, J.C. Souyris and P. Macchia,
Polarisation in surface scattering

Smooth surface

- no depolarisation
- no HV or VH backscatter
- Fresnel Reflectivity $R_H > R_V$

Rough surface

- some depolarisation
- HV or VH backscatter $> 0$
- Fresnel Reflectivity $R_H = R_V$
* Order 0

Order 0 represents **Attenuated surface scattering**.

* Order 1: Simple scattering

- **Volume scattering**
- **Surface-volume scattering**

\[
\sigma^0 = \sigma_{soil}^0 + \sigma_{veg.}^0 + \sigma_{soil−veg.}^0
\]
Volume scattering

Single and multiple scattering
Polarisation in volume scattering

Point scatterer

-\( V \)\(^\rightarrow\) no depolarisation

Anisotropic scatterer

-\( H \)\(^\rightarrow\) depolarisation

Multiple scattering

-\( H \)\(^\rightarrow\) depolarisation

HV or VH: high backscatter of vegetation canopy
Optical image
Sentinel-2

Radar image
Sentinel-1
Contents

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How do the radars see the trees?

Austrian pine

- X band: $\lambda = 3$ cm
- C band: $\lambda = 6$ cm
- L band: $\lambda = 27$ cm
- P band: $\lambda = 70$ cm
- VHF: $\lambda > 3$ m
Interaction mechanisms in a forest

Scatterers contribution

1) Direct Crown scattering
2) Direct trunk-ground
3) Trunk scattering
4) Multiple trunk-ground
5) Attenuated ground
6) Direct ground scattering

Leaves, Needles
Primary Branches
Secondary branches
Higher order branches
Trunk

1) Direct Crown scattering
2) Direct trunk-ground
3) Trunk scattering
Interactions mechanisms in a forest – C-band

Scatterers contribution

1) Direct Crown scattering

Leaves, Needles

5) Attenuated ground

6) Direct ground scattering
Scattering mechanisms simulated by a R.T. model


Change in dominant mechanism

Varzea Dry

Varzea Wet Season

SAR image (L-HH)

SAR image (L-HH)
Forest structure - Boreal vs Tropical rain forest
Yu & Saatchi S., 2016
Dielectric constant of wood material

Francois Demontoux, Wood Sci Technol, DOI 10.1007/s00226-017-0935-4, 2017

Fig. 1. \(\varepsilon'\) (a) and \(\varepsilon''\) (b) versus gravimetric moisture content for spruce, pine and beech for \(E_{\text{total}}\) parallel to fiber direction and frequency of 1.26 GHz.

Fig. 2. \(\varepsilon'\) (a) and \(\varepsilon''\) (b) versus gravimetric moisture content for spruce, pine and beech for \(E_{\text{total}}\) perpendicular to fiber direction and frequency of 1.26 GHz. Linear behavior of permittivity versus MCg is indicated by straight lines which are shown before (plain) and after (dashed) the fiber saturation point for beech data, indicating changes of slopes for \(\varepsilon'\) (a) and \(\varepsilon''\) (b).
Dielectric constant of living wood

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 40, NO. 9, SEPTEMBER 2002

Diurnal and Spatial Variation of Xylem Dielectric Constant in Norway Spruce (Picea abies[L.] Karst.) as Related to Microclimate, Xylem Sap Flow, and Xylem Chemistry, Kyle C. McDonald,, Reiner Zimmermann, and John S. Kimball
A ground-based radar observing a tropical forest
- Located in French Guyana – same site as TropiSAR
- Team members from ONERA, CNES, CESBIO, POLIMI
- 20 antennas installed on top of the Guyaflux tower (55 m)
- Fully polarimetric (HH, HV, VH and VV)
- Vertical resolution capabilities
- One image every 15 minutes over a time span of one year

⇒ **Access to the vertical structure of temporal decorrelation**
Diurnal variation of Radar center of mass
The center of mass is going down, from 7am, with minimum at 13-15 pm and up again to original height at 22-23 h. The amplitude is about 1.5 m inside the forest.

Average of 10 dry days (without rain) during the period from 8 to 31 December 2011.
Diurnal cycle of radar intensity

Hamadi et al., 2013

Tour Guyaflux
Equipe Guyafor
Borealscat at Remningstorp, Sweden

Research infrastructure:

- A 50-m high radar tower in a hemi-boreal forest site in southern Sweden.
- Acquires tomographic P/L/C-band radar data
- On-site weather station and moisture sensors: dendrometers, sap flow, and soil moisture
- More details at www.borealscat.se

L. Ulander, A. Monteilh, 2020
Backscatter variability caused by freeze/thaw in boreal forest

Backscatter Jun 2017- Jun 2019: Canopy, Ground and Full forest

Monthly range of canopy backscatter

Backscatter varies 2-4 dB during summer, whereas much larger variability during winter (freeze/thaw).

L. Ulander, A. Monteilh, 2020
Biomass is an ECV (Essential Climate Variable) of the ESA CCI (Climate Change Initiative)

1. Biomass consists of approximately 50% carbon

2. Forests account for 70-90% of the terrestrial above-ground biomass, and the majority are located in the tropics

3. The forest biomass stocks and their change remain poorly quantified

Biomass = dry weight of woody matter (in tons/ha)
Forests are a major carbon sinks, but can be C sources

International Conventions and National Determination on the forests aim at:

- Increase C sequestration
- Reduce the emissions

→ need to quantify C losses and gains for the carbon cycle
SAR intensity increases with biomass

L band ($\lambda=25\text{cm}$)

P band ($\lambda=70\text{cm}$)
SAR intensity increases with biomass

Figure 5.22 Sensitivity of radar backscatter measurement at L-band and P-band frequencies and HV polarization to forest AGB over sites distributed in boreal, temperate, and tropical ecosystems (Shugart et al. 2010).
Scattering mechanisms simulated by a R.T. model


Crucial point: for biomass inversion to perform well, data must be processed to retain only the volume component of the forest canopy.
SAR measurement modes-BIOMASS

PoISAR

Pol-InSAR

TomoSAR
SAR tomography, a new concept to explore 3D forest structure

Generates images of different forest layers from multi-orbit SAR images

Guyafux tower (Tropiscat experiment)

Tomographic Processing

Normalised backscatter intensity
Tomography to understand scattering mechanisms

Provides the most complete description of all contributions to the radar signal through 3D reconstruction of forest backscatter.
Scattering mechanisms in tropical forests

Capon spectrum - HH channel

Capon spectrum - HV channel

Capon spectrum - VV channel

Normalised backscatter intensity

Slant range [m]
Tomography to understand scattering mechanisms

Provides the most complete description of all contributions to the radar signal through 3D reconstruction of forest backscatter.

Boreal forest

Tropical forest
Isolate the layer not containing ground scattering

.. Whose biomass related to AGB


Ho Tong Minh Dinh et al., 2013, 14
La biomasse des forêts tropicales (≥ 500 t/ha) mesurable par le SAR bande P de Biomass.
Tomography techniques allow AGB up to 500t/ha
Isolating the volume by ground cancellation

HH-VV phase difference:

30 m height

Tomographic section at terrain height

More by: S. Tebaldini

Ground level
1. Strong evidence that the volume layer 25-35 m above the ground in tropical forest is strongly correlated with the total AGB.
2. Development of methods for ground cancellation using tomography or Pol-InSAR to isolate volume scattering.
3. Development of an approach to solve the volume scattering equation that minimizes the need for reference data.
1. An introduction on radar remote sensing has been given, with focus on agriculture and forests.

2. It is essential to understand the statistical properties of SAR images, and the physical content of the SAR data, to interpret and to analyse the images, and to develop retrieval and mapping algorithms.

3. Lectures and training on advanced SAR polarimetry, Pol-InSAR and TomoSAR will be provided in the following sessions.