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Theme Leader, Geospatial Solutions
Science and Data Lead, SERVIR-HKH

Concept of microwave remote sensing
Dr. Thapa works at ICIMOD and provides scientific leadership to the Geospatial Solutions Theme and is the Science and Data Lead for SERVIR-HKH (a joint NASA and USAID partnership) Initiative within MENRIS Program. His research focusses on monitoring and assessment of terrestrial environments including forest, agriculture, urban, and disasters thematic areas and capacity development. He empowers people to use emerging Earth observation and geospatial technologies for making evidence-based decisions to protect the pulse of the planet.

He is an active member of Group on Earth Observations (GEO) Capacity Development Working Group and has over twenty years work experience across various Asian countries including Japan, Thailand, and the HKH region. Prior to joining ICIMOD, he served at the Japan Aerospace Exploration Agency (JAXA). He was also a visiting professor at the University of Tsukuba, Japan. He holds a PhD in Geoenvironmental Science, MSc in Remote Sensing and GIS, and Master Degree in Geography. Recently, SERVIR Global recognized his remarkable contributions and unwavering commitment to capacity development for connecting space to village mission and awarded prestigious SERVIR Award of Excellence.

https://www.icimod.org/team/rajesh-bahadur-thapa/
Why radar?
Why radar?
Why radar?

same satellite, time & location but different sensors

ALOS AVNIR-2: optical, passive
ALOS PALSAR: radar, active

JAXA –Advanced Land Observing Satellite (ALOS)
Why radar?

Safsaf Oasis, Egypt

... Landsat Thematic Mapper (left) and SIR-C/X-SAR (right). Visible and infrared wavelengths of Landsat are only sensitive to the materials on the surface, while the radar wavelengths of SIR-C/X-SAR can penetrate the thin sand cover in this arid region to reveal details hidden below the surface.

Field studies in this area indicate that the L-band radar can penetrate as much as 2 meter (of very dry sand) to image buried rock structures. Ancient drainage channels, shown at the bottom of this image, are filled with sand more than 2 meter thick and therefore appear dark because the radar waves cannot penetrate them.

http://www.jpl.nasa.gov/radar/sircxsar/safsaf2.html
P-49668 March 26, 1998
Which one is radar system?

RADAR satellite: Sentinel-1 A, B, ALOS-2, RADARSAT, TanDEM-X, TerraSAR-X, etc.

There are also some airborne sensor, such as PiSAR, PiSAR-L2, LiDAR, etc. Recently UAVs based small sensors are also getting popular.

Satellite height: 300~36000 km; Airborne: ~12 km
What is radar?

Radio detection and ranging (radar) refers to a technique as well as an instrument.

The radar instrument emits electromagnetic pulses in the radio and microwave regime and detects the reflections of these pulses from objects in its line of sight.

The radar technique uses the two-way travel time of the pulse to determine the range to the detected object and its backscatter intensity to infer physical quantities such as size or surface roughness.

Unlike optical, radar systems consists of all-weather and all-day capabilities allowing regular mapping of areas affected by heavy cloud cover, persistent rain, or extended darkness.

Radar systems are side looking! The signals interact differently with the surface than most other sensing systems, providing interesting new information about the observed environment.
How radar system works?

1. Stepper Motor, Computer, Power, and Storage
2. Transmit-Receive Unit, A/D Converter, and Signal Generator
3. Radar Antenna(s) (Sensor)

One transmit and two receive antennas

Positioner: Allowing for precision orientation and rotation of antennas

Courtesy: F. Meyer, UofAF
How radar system works?
Describing microwave signals

Electromagnetic (EM) radiation can be described by wave theory:

- Wavelength – lambda ($\lambda$)
- Frequency – ($f = \frac{c}{\lambda}$)
- Period – Pulse length ($\tau$)
- Amplitude ($A$)
- Energy ($E$)

These descriptors provide fundamental information about how EM waves interact with object and hence can be utilized (inversely) to yield information about the object of study.
How radar system works?
Radar signals are transverse oscillating waves

Longitudinal oscillating waves (sound waves, waves on oceans)

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

In transverse oscillating waves, the direction in which oscillation takes place, called Polarization
Electromagnetic radiation

Energy from any sources comes in the form of electromagnetic radiation.

ER consists of Electrical field (E) and Magnetic field (M), travel at the speed of light (C).

Wavelength and Frequency. The wavelength is the length of one wave cycle, which can be measured as the distance (in m, cm, mm, and nm) between successive wave crests.

Frequency refers to the number of cycles of a wave passing a fixed point per unit of time. Frequency is normally measured in hertz (Hz), equivalent to one cycle per second, and various multiples of hertz. These two are inversely related to each other. The shorter the wavelength, the higher the frequency and vice-verse.
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

![Diagram showing wavelength discrimination between radar and optical signals](image)
The microwave region of the spectrum is quite large, relative to the visible and infrared, and there are several wavelength ranges from 0.1cm to 100cm (300GHz to 0.3GHz in frequency) with unique code band. Microwaves with longer wavelengths than Ka-band (7.5mm) are generally used as radar. Currently, X-band, C-band, and L-band are in operation in Earth observation satellites, i.e., TerraSAR-X, Sentinel-1, ALOS-2, respectively.
## Spectrum of Microwave Region

<table>
<thead>
<tr>
<th>SAR Band</th>
<th>Frequency</th>
<th>Wavelength</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 (H₂O 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>High resolution SAR (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>SAR workhorse (global mapping; change detection; monitoring of areas with low to moderate vegetation; improved penetration; higher coherence); Ice, ocean, maritime navigation</td>
</tr>
<tr>
<td>S</td>
<td>2 – 4 GHz</td>
<td>15 – 7.5 cm</td>
<td>Little but increasing use for SAR-based Earth observation; agriculture monitoring (NISAR will carry an S-band channel; 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>Medium resolution SAR (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>Biomass. First P-band spaceborne SAR will be launched around 2020; vegetation mapping and assessment. Experimental SAR.</td>
</tr>
</tbody>
</table>

Source: *The SAR Handbook 2019*
Advantages of Microwave Signals

This figure provides a conceptual overview of the influence of sensor wavelength $\lambda$ on signal penetration into a variety of surface types. The radar signals penetrate deeper as sensor wavelength increases. This is related to the dependence of the dielectric constant $\varepsilon_r$ on the incident wavelength, allowing for higher penetration at L-band than at C- or X-band.
Measuring Biomass from Space with Radar Needs the Longest Possible Wavelength

Mapping forest biomass needs a radar sensor that

- penetrates the canopy in all forest biomes
- interacts with woody vegetation elements
- allows forest height to be estimated with a single satellite (affordability)
Effects of different bands in surface penetration

X-band radar image of forested area
Effects of different bands in surface penetration

P-band radar image of forested area
Observation Geometry of Imaging Radars

The figure is a schematic diagram of a radar observation geometry where a platform is moving along a straight path at altitude $H$. Unlike most optical imaging systems, which point their sensors towards nadir, the antenna of imaging radar is pointed away from nadir by a look angle.

Adapted from: Lee and Pottier, 2009
Synthetic Aperture Radar (SAR)

A radar antenna (indicated by a gray rectangle) of reasonably short length is moving at a velocity $V$ along its flight path from the right to the left. While moving, it is constantly transmitting short radar pulses and is receiving echoes returned from objects on the ground. Each radar pulse illuminates an instantaneous footprint of size $S$ on the Earth surface.

SAR is an active sensor transmitting a microwave signal towards a target and receive a reflection called backscatter.
How imaging radar works?

Identify the directions for Azimuth and Range

Tips: Imaging radars are side-looking!
How imaging radar works?

- Radars actively transmit microwave signals (usually a radar pulse)
- Radar antenna provides directivity for transmitted signal
- A radar sensor records two different parameters: Amplitude and Phase of the reflected microwave signals

Detected amplitude measures surface radar cross section (RCS)

Timing of transmitted signal (radar pulse) provides information about distance between satellite and ground
SAR image processing flow

SAR image is constructed from the many pulses reflected by each single target and received by the antenna and registered at all position along the flight path. Then image processing algorithm performs range and azimuth compressions to create 2-D SAR image.
SAR satellite imaging mode

- **Available Image Modes:**
  - **Stripmap Mode**
    - Intermediate resolution
  - **Spotlight Mode**
    - Highest resolution – limited coverage
  - **ScanSAR Mode**
    - Lowest resolution – largest coverage
SAR satellite imaging mode

Mode 1: Stripmap mode

• Stripmap Mode
  Observation Geometry:
  – Radar images a strip-like swath parallel to satellite orbit
  – Standard operational mode

• Properties:
  – Intermediate resolution (~10m)
  – Continuous mode → complete areal coverage
  – Main application: continuous monitoring of signals of intermediate scale (e.g. sinkholes; road network; surface subsidence)
Mode 2: Spotlight mode

• To increase resolution, synthetic aperture length is increased by beam steering to selected area

• Properties:
  – Highest spatial resolution (1m-scale)
  – Non-continuous imaging
  – Best equipped for high-resolution monitoring of high-priority objects (e.g., bridges, dams, ...)

Summary: higher resolution at the expense of spatial coverage
SAR satellite imaging mode

Mode 3: ScanSAR mode

- To achieve wider swaths, synthetic aperture is divided into short pieces (bursts)

⇒ successive illumination of several parallel swaths for **increased swath width** (100 to 500km)

- Properties:
  - Lowest resolution mode (10s of meters)
  - **Highest spatial coverage**
  - Best suited for quick mapping of large areas ⇒ analysis of large-scale signals such as tectonic motion or flooding extent
How SAR sees the world

- At Radar wavelength, scattering is very physical and can be described as a series of bounces on scattering interfaces
- Three main scattering mechanisms dominate:
  - **Surface scattering**: Water, bare soils, roads – scattering strongly dependent on surface roughness and sensor wavelength
  - **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
How SAR sees the world

The apparent roughness of a surface is strongly wavelength dependent.

- **When is a surface rough?** The Fraunhofer criterion (a strict criterion) states:
  \[ h_{\text{rough}} > \frac{\lambda}{32\cos\theta_i} \]
  Wavelength Dependence of Roughness

- **Wavelength dependence of radar brightness for given surface roughness** \( h_{\text{rough}} \):

<table>
<thead>
<tr>
<th>Sensor Wavelength</th>
<th>X-band ([\lambda \approx 3.5cm])</th>
<th>C-band ([\lambda \approx 5.6cm])</th>
<th>L-band ([\lambda \approx 25cm])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar Brightness</td>
<td>Light</td>
<td>Medium</td>
<td>Dark</td>
</tr>
</tbody>
</table>
How SAR sees the world
Role of soil moisture

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3681152/

Sample collection depth
s=0.4 cm, s=0.6 cm, s=0.8 cm, s=1 cm
How SAR sees the world – SAR data

Spatial resolution 3 meters
Color composite
R: HH, G: HV, B: VV
Distortions

- Geometric distortion:
  - One side of the mountain seems shorter than the other

- Radiometric distortion:
  - One side of the mountain seems much brighter

Source: The SAR Handbook 2019
**Distortions – Geometric**

Main geometric distortions on SAR images with their dependence on acquisition geometry.

- **Foreshortening**
  - Sensor-facing slope foreshortened 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

*Source: The SAR Handbook 2019* (Chapter 2. F. Meyer)
**Distortions – Geometric**

Foreshortening occurs when the radar beam reaches the base of a tall feature tilted away from the radar before it reaches the top. Small incidence angle produces large influence from this distortion. The foreshortened slopes appear as bright features on the image.

Layover occurs when the radar beam reaches the top of a tall feature before it reaches the base. This effect on a radar image looks similar to that due to the foreshortening. Small incidence angle also produces large influence from this distortion.

Shadow occurs when the radar beam is not able to illuminate the ground surface behind tall features or slopes. Large incidence angle produces large shadowed area.
Distortions
How SAR sees the world?

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 \(\rightarrow\) \(x_{map}\) / \(y_{map}\)
   - 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

Source: The SAR Handbook 2019
Distortions
How SAR sees the world – Geometric correction

Geocoding steps

Geocoded image after steps 1-4

Original image

Transformed image after steps 1-3
Distortions - geometric

Geometric terrain correction (GTC)

- 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
Distortions

- Geometric distortion:
  - One side of the mountain seems shorter than the other
- Radiometric distortion:
  - One side of the mountain seems much brighter

Source: The SAR Handbook 2019
Distortions

Geometrically Terrain Corrected Image

Source: The SAR Handbook 2019
Distortions – Radiometric

How SAR sees the world?

• Noise caused “Speckle” which is an inherent property of all coherent imaging systems

• Technically, it looks noise but it is not, it is an interference pattern
Distortions – Radiometric
How SAR sees the world?

Random positive and negative interference of wave contributions from many individual scatters within one resolution cell.

Summing contributions within a pixel.
Distortions – Radiometric

How SAR sees the world?

Speckle reduction

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

Original SAR Image
SAR data © AeroSensing GmbH

Speckle Filtered
Bayesian Algorithm

Speckle reduction
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* $A_{\beta}$ covered by each pixel
  2. Normalize radar cross section by $A_{\beta}$ to arrive at terrain normalized data $\beta_T^0$
Distortions

- Geometric distortion:
  - One side of the mountain seems shorter than the other

- Radiometric distortion:
  - One side of the mountain seems much brighter

Source: The SAR Handbook 2019
Distortions

Image after Radiometric Terrain Corrections

Source: The SAR Handbook 2019
SAR Missions and data availability

Past:
- SEASAT 1978
- ERS-1/2 '91-2011
- ENVISAT '02-2012
- JERS/ALOS '92-2011
- Radarsat-1 '95-2013

Present:
- TanDEM-X 2007
- Radarsat-2 2007
- COSMO-SkyMed 2007
- ALOS-2 2014
- Sentinel-1 2014

Future:
- SAOCOM 2018
- PAZ SAR 2018
- RCM 2019
- BIOMASS 2018
- NISAR 2023
- PAZ SAR 2024
- ALOS-4 2023
- ICEYE - 2020
- Capella Space – Denali 2018, Sequoia, 2020
# SAR Data Access

<table>
<thead>
<tr>
<th>Mission(s)</th>
<th>Region</th>
<th>Costs</th>
<th>Data Access</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS-1/2, Envisat</td>
<td>USA</td>
<td>Free and open</td>
<td>ASF</td>
<td>User Registration</td>
</tr>
<tr>
<td></td>
<td>Worldwide</td>
<td>Free and open</td>
<td>ESA Earthnet</td>
<td>Online data: Open Restrained data: Proposal to ESA</td>
</tr>
<tr>
<td>Sentinel-1A/B</td>
<td>Worldwide</td>
<td>Free and open</td>
<td>ESA &amp; ASF</td>
<td>User registration</td>
</tr>
<tr>
<td>ALOS PALSAR</td>
<td>Americas/Antarctic</td>
<td>Free and open</td>
<td>ASF</td>
<td>User registration</td>
</tr>
<tr>
<td></td>
<td>Europe, Africa, Greenland</td>
<td></td>
<td>ESA Earthnet</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Asia</td>
<td></td>
<td>PASCO, JP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Australia</td>
<td></td>
<td>PASCO, JP</td>
<td></td>
</tr>
<tr>
<td>ALOS-2</td>
<td>Worldwide</td>
<td>Science users: free</td>
<td>Science: AUSG</td>
<td>Science: Proposal to JAXA (look here)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Commercial users: $$$</td>
<td>Commercial: PASCO</td>
<td></td>
</tr>
<tr>
<td>TerraSAR-X,</td>
<td>Worldwide</td>
<td>Archived: free</td>
<td>Science: TS-X / TD-X</td>
<td>TSX or TDX Proposal to DLR</td>
</tr>
<tr>
<td>TanDEM-X</td>
<td></td>
<td>New science: $100 – 200</td>
<td>science server</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Commercial: $$$</td>
<td>Commercial: Airbus</td>
<td></td>
</tr>
<tr>
<td>COSMO-SkyMed</td>
<td>Worldwide</td>
<td>Archive free (science use)</td>
<td>Science: ASI</td>
<td>Science: Proposal to ASI</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Commercial: $$$</td>
<td>Commercial: e-GEOS</td>
<td></td>
</tr>
<tr>
<td>Radarsat-1/2</td>
<td>USA/Canada</td>
<td>Free R-1 until 2009</td>
<td>ASF</td>
<td>Proposal to NASA</td>
</tr>
<tr>
<td></td>
<td>Worldwide</td>
<td>$$$ (R2 &amp; R1 after 2009)</td>
<td>McDonald Dettwiler</td>
<td>If lucky check for free data here</td>
</tr>
</tbody>
</table>

Excellent additional resource for information on current and future SAR sensors: [eoPortal Directory](#)
### SAR Data Processing Software...

<table>
<thead>
<tr>
<th>Freely Available</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-Expert User</strong></td>
<td><strong>Commercial</strong></td>
</tr>
<tr>
<td>MapReady (ASF)</td>
<td>GlobalSAR</td>
</tr>
<tr>
<td>SNAP (ESA)</td>
<td>SARscape</td>
</tr>
<tr>
<td>PolSAR Pro (ESA)</td>
<td>Photomod Radar</td>
</tr>
<tr>
<td><strong>Expert User</strong></td>
<td><strong>Expert User</strong></td>
</tr>
<tr>
<td>ISCE (JPL/Stanford)</td>
<td>GAMMA RS</td>
</tr>
<tr>
<td>GIAnt (JPL/Stanford)</td>
<td></td>
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<tr>
<td>ROI_PAC (JPL)</td>
<td></td>
</tr>
<tr>
<td>DORIS (U Delft, NL)</td>
<td></td>
</tr>
<tr>
<td>GMTSAR (Scripps)</td>
<td></td>
</tr>
</tbody>
</table>

- **SAR Focusing**
- **SAR Filtering**
- **SAR Geocoding/GTC/RTC**
- **Polarimetric SAR**
- **Interferometric SAR**
There are many applications …our recent book on applications…

SAR Handbook: Comprehensive Methodologies for Forest Monitoring and Biomass Estimation
Editors: Africa F. Anderson, Kelsey E. Herndon, Rajesh B. Thapa, Emil Cherrington

▷ Freely-available eBook, interactive pdfs, and training modules; result of a 2-year joint collaboration between NASA SERVIR & SilvaCarbon

▷ Applied content, hands-on trainings to get started using Synthetic Aperture Radar (SAR) for forest monitoring, biomass estimation, mangrove extent, time-series analysis

▷ Authored by world-renowned SAR experts from the NISAR Science Team, US Forest Service, academia

▷ Reviewed and tested by the SERVIR-Global network

▷ Downloadable open-source scripts and sample datasets for a variety of forestry applications; useful for beginners to experts

For more information, visit the SERVIR website @ SERVIRglobal.net

Downloadable open-source scripts and sample datasets for a variety of forestry applications; useful for beginners to experts.

Selected pages from Chp 6: Radar Remote Sensing of Mangrove Forests (by Dr. Marc Simard, Sr. Scientist & mangrove specialist, NASA Jet Propulsion Laboratory)
Integration of RS&GIS, many applications …our book, our region

https://lib.icimod.org/record/35312

Major highlights

• This open access book is a consolidation of lessons learnt and experiences gathered in 19 chapters from its decade long efforts on applications of Earth observation science and geospatial information technologies to address regional and local needs in the Hindu Kush Himalayan region.

• The book highlights SERVIR’s approaches to innovative applications in – agriculture and food security; land cover and land use change, and ecosystems; water resources and hydro-climatic disasters; and weather and climate services.

• It offers a collection of multi-disciplinary topics with practically tested applications in the region.

• The book is a complete package of knowledge and learnings on project cycle including service area planning, stakeholder consultation, user engagement, capacity building, monitoring and evaluation, gender integration, and communications.

DOI: 10.1007/978-3-030-73569-2
You are amazing!

Let’s protect the pulse.