Introduction to Geoinformation Science

Marco Heinzen
Deputy Head Software & Integration C5I

Data Engineering – Data Science - Geoinformatics

Introduction to Remote Sensing Imagery & Principles

Figure 1: Sentinel-2 Satellite, Source: ESA

Sentinel-2 Satellite, Source: ESA

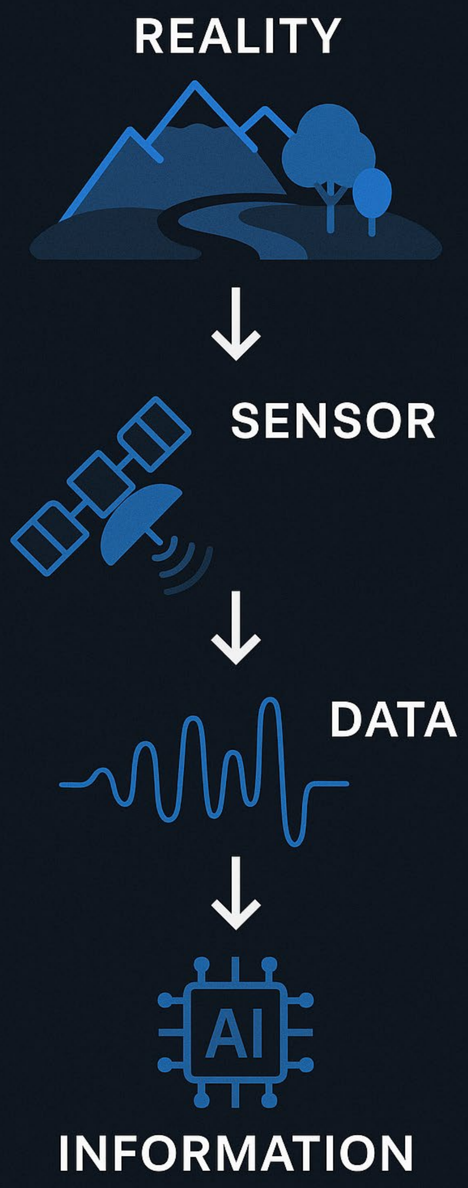
Marco Heinzen

Deputy Head Software & Integration C5I: Data Engineering – Data Science - Geoinformatics

Marco Heinzen has been working for years at the intersection of geoinformatics, remote sensing, and data science - with the ambition of transforming data into decision-relevant insights. He works in the defense industry and is Deputy Head of Software & Integration C5I at RUAG AG, where he is responsible for data engineering, data science, and geoinformatics.

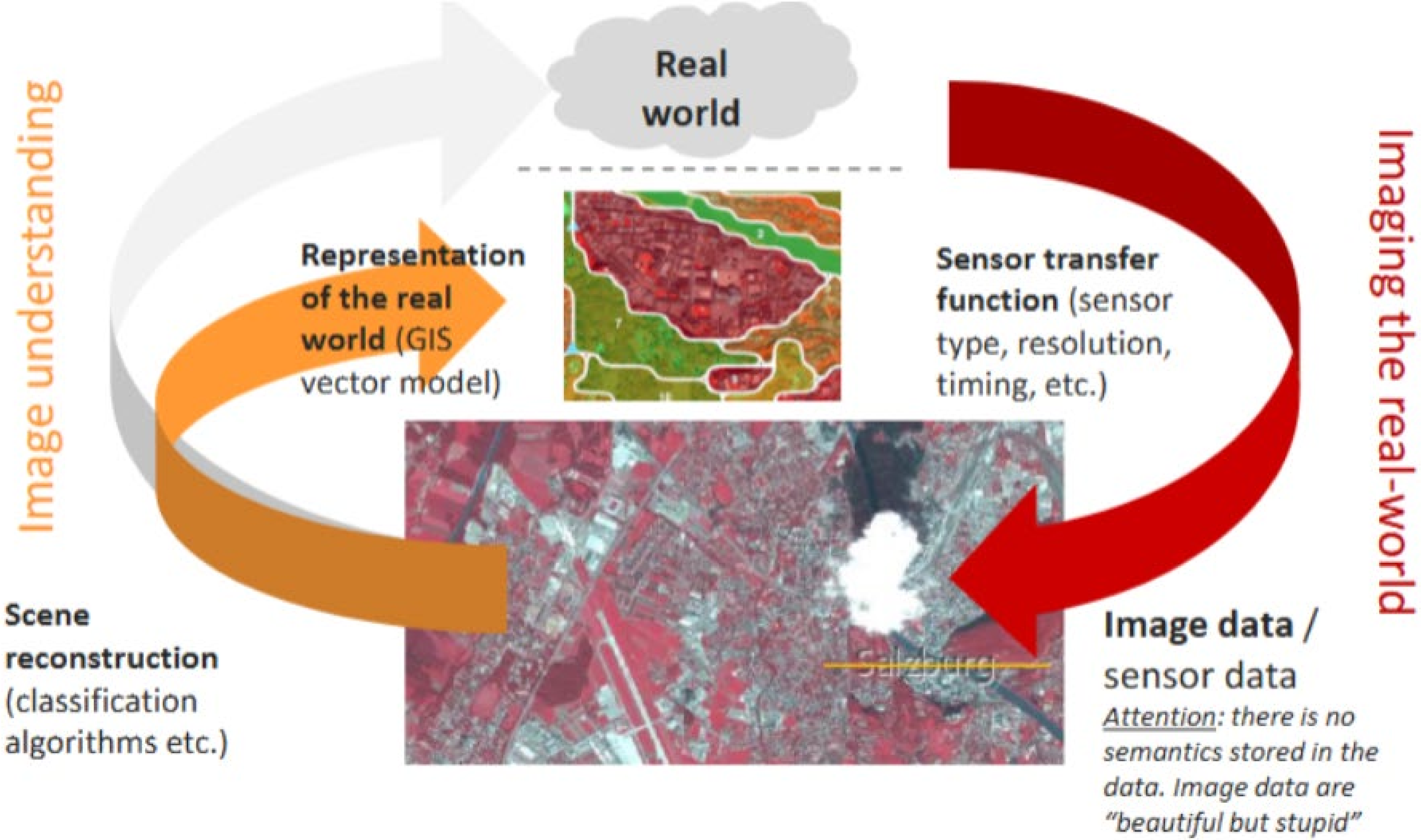
His focus is on defense-relevant data pipelines, scalable geoinfrastructure, and AI-supported situational awareness.

His academic background includes, among others, a CAS at ETH Zurich and an MSc program in Geoinformation Sciences & Systems at the Paris Lodron University of Salzburg



Chapter 1: From Reality to Information

- Physical world → energy → sensor → pixels
- Data processing + correction
- Analysis & domain knowledge → decision support

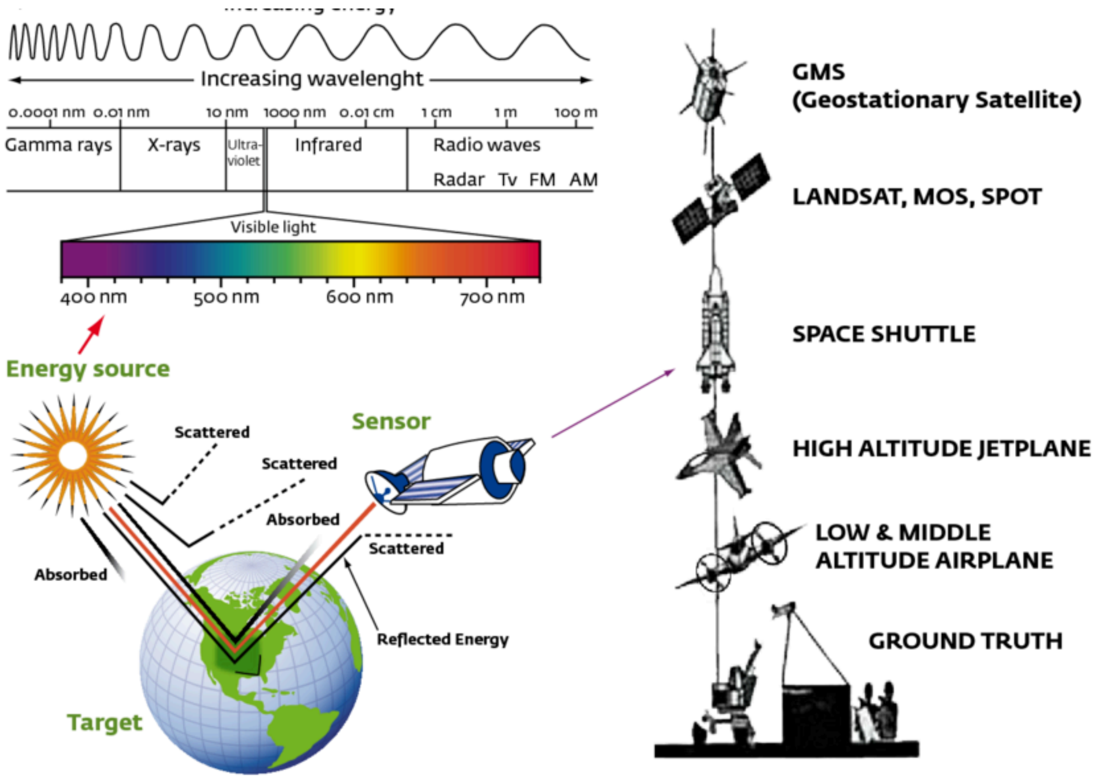


From the real world to sensor data to scene reconstruction. Image from UNIGIS Salzburg based on (Blaschke, 2010)

From Sensor Data to Information

- **Sensor transfer function: conceptual model linking real world → image**
  - Attributes: spectral range, spatial resolution, temporal repeat, atmospheric sensitivity
  - Determines which features are captured vs. ignored (Richards, 2022)
- **Process is selective and lossy** → only certain scene characteristics preserved
- **Scene reconstruction = interpretation of sensor data**
  - Combines raw data + context + prior knowledge
  - Transforms pixels → semantic info (land cover classes, objects) (Blaschke, 2010)

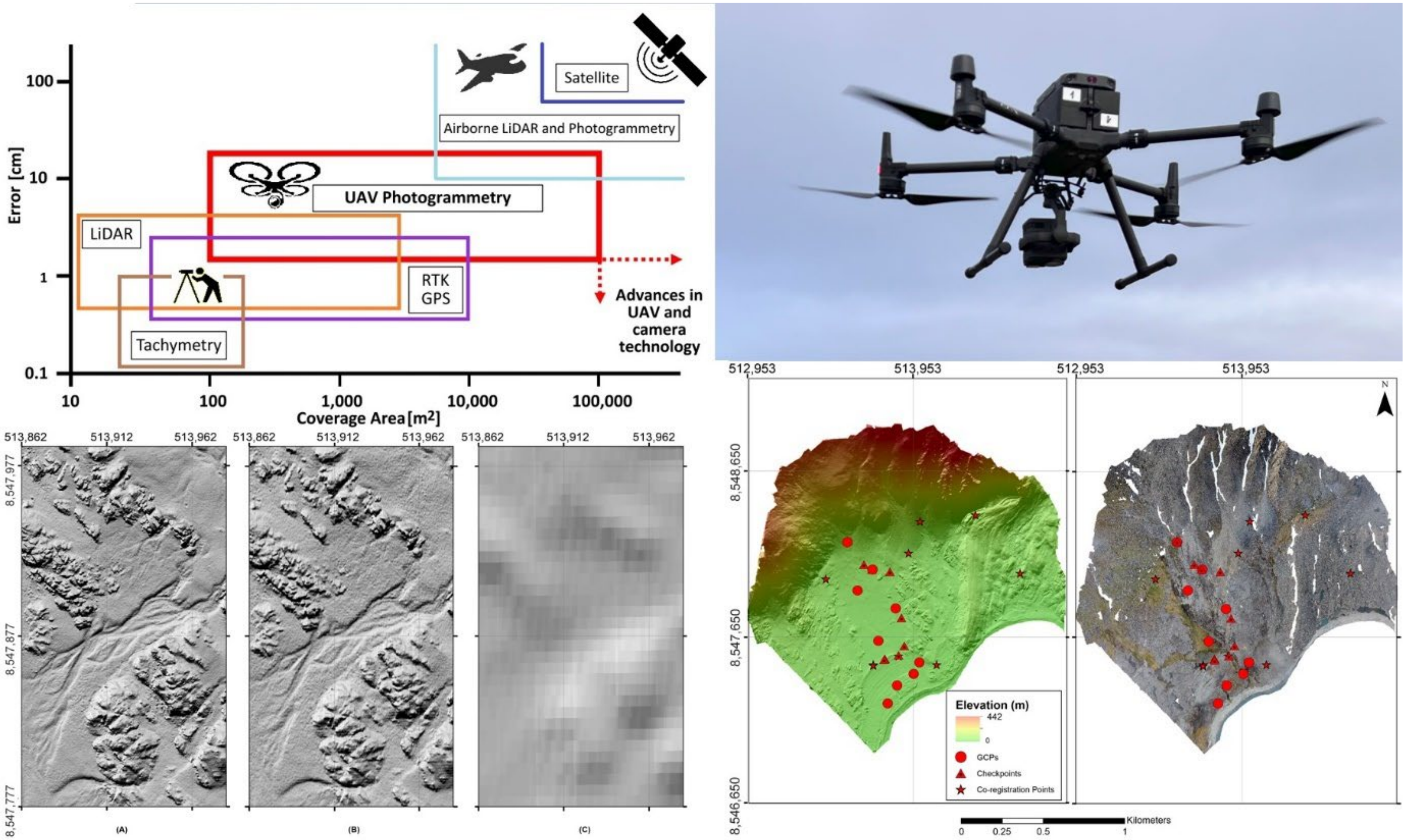
Introduction to Remote Sensing



Theory of remote sensing of the earth Electromagnetic spectrum of energy radiations
Remote sensing platforms with Sensors on board (Omuto et al., 2012)

- Remote sensing = acquisition of Earth surface/atmosphere information without direct contact
- Platforms: satellites, aircraft, drones
- Principle: detection of electromagnetic radiation
- Naturally emitted or reflected (passive)
- Artificially transmitted and scattered back (active)

Different Carriers – Same Goal



Graphical Abstract (Alphonse et al., 2023)

- Ground
- UAVs
- Airplanes & Helicopters
- Satellites

Goal:
- Getting Data through Sensors without touching the Object

Ground

(a)

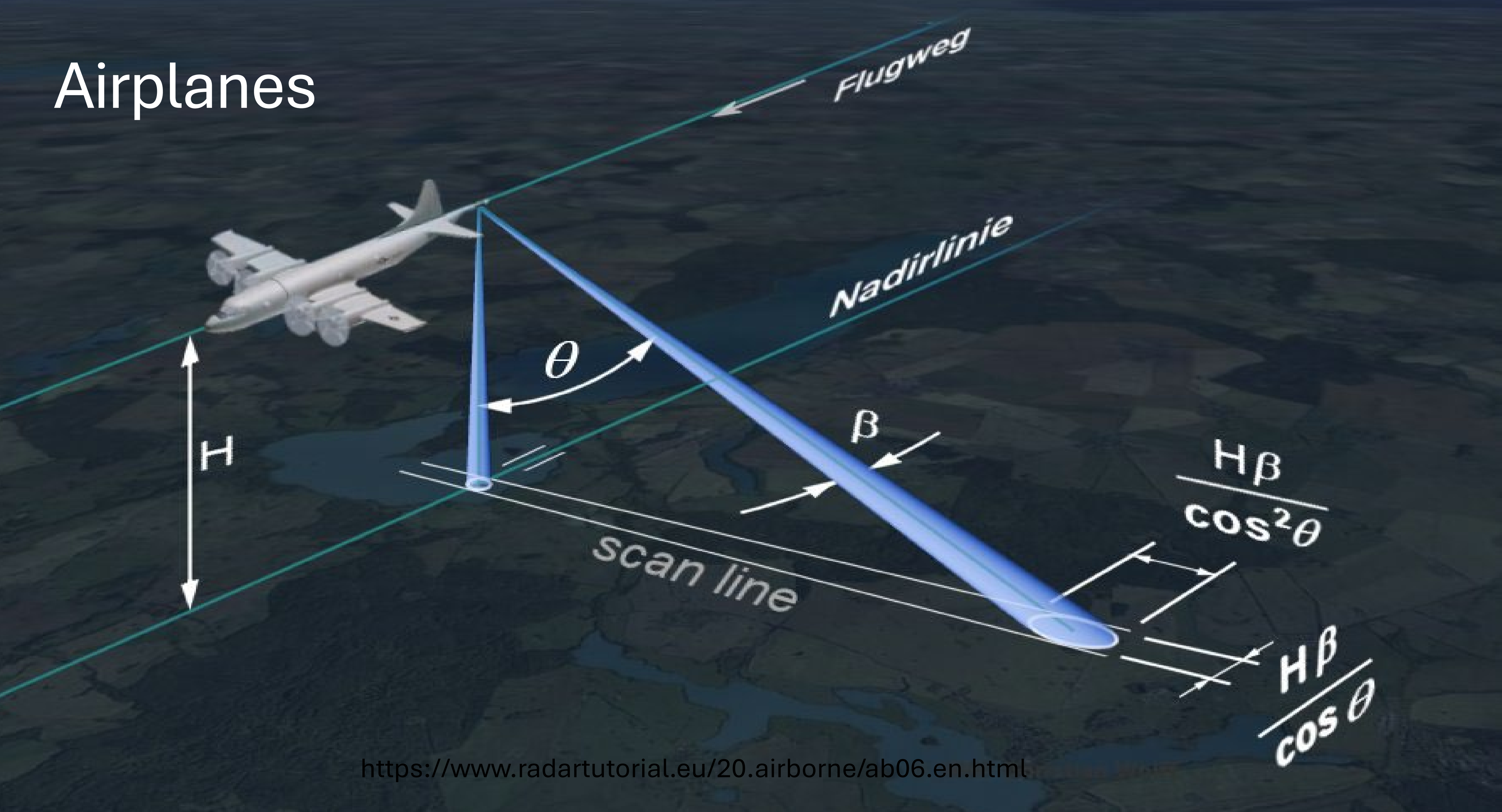
(b)

https://www.mdpi.com/1424-8220/21/8/2632

UAVs

DJI Matrice 300 RTK Drone equipped with Zenmuse P1 camera during the mission at Fuglebekken catchment. (Alphonse et al., 2023)

Airplanes



https://www.radartutorial.eu/20.airborne/ab06.en.html

Satellites

https://sentiwiki.copernicus.eu/web/sentinel-2

Important Notice

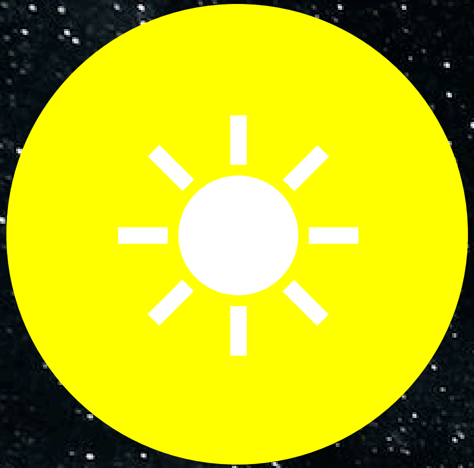
Ante Elon: Satellites were launched by governments

Post Elon: Satellites became commercial products

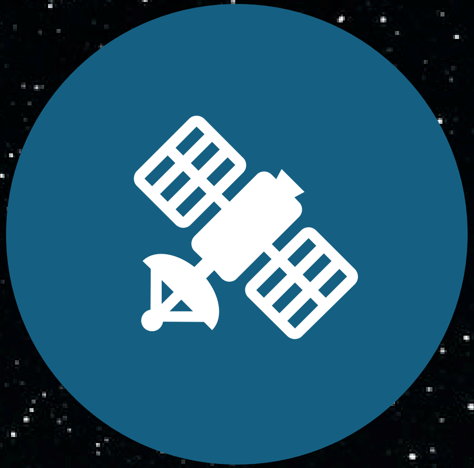
BUT:
Practically all Satellites are Dual-Use

- Science
- Military

Chapter 2: Active & Passive Sensors

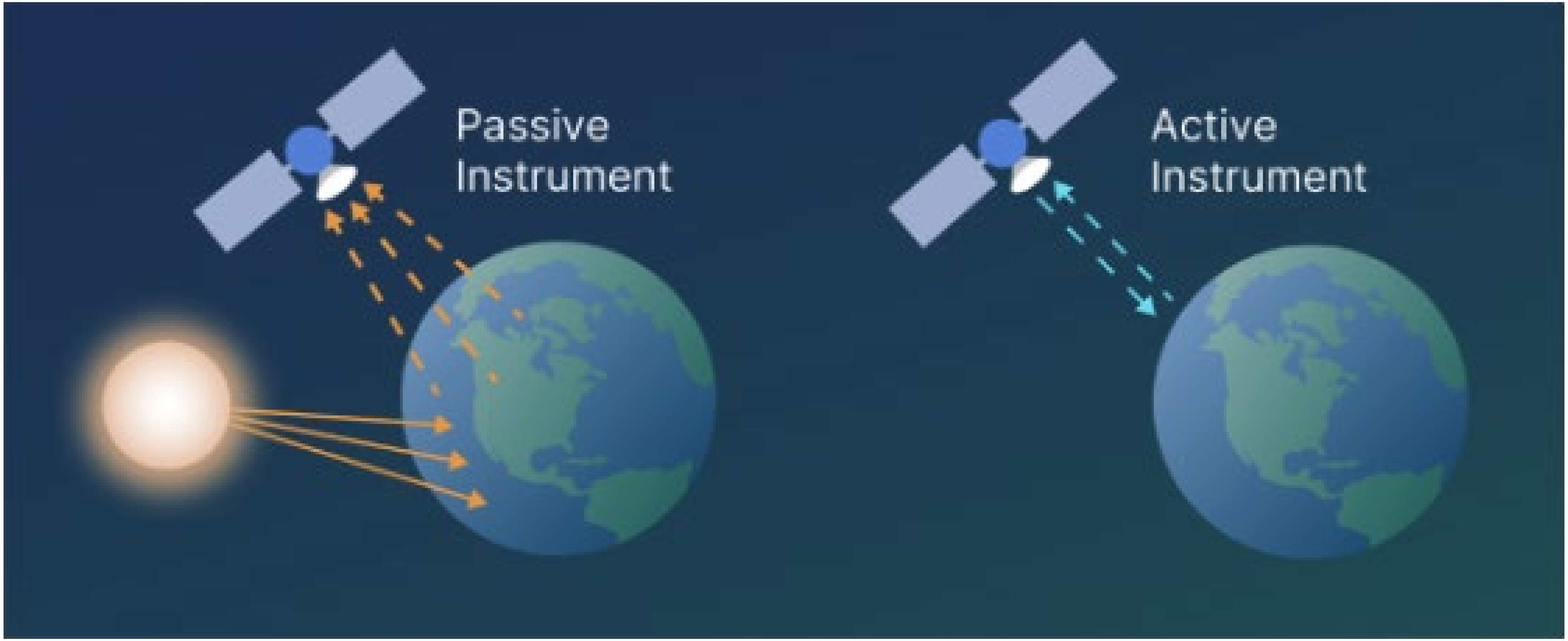


PASSIVE: SUNLIGHT, THERMAL
→ CLOUD-SENSITIVE



ACTIVE: RADAR, LIDAR →
DAY/NIGHT, ALL-WEATHER

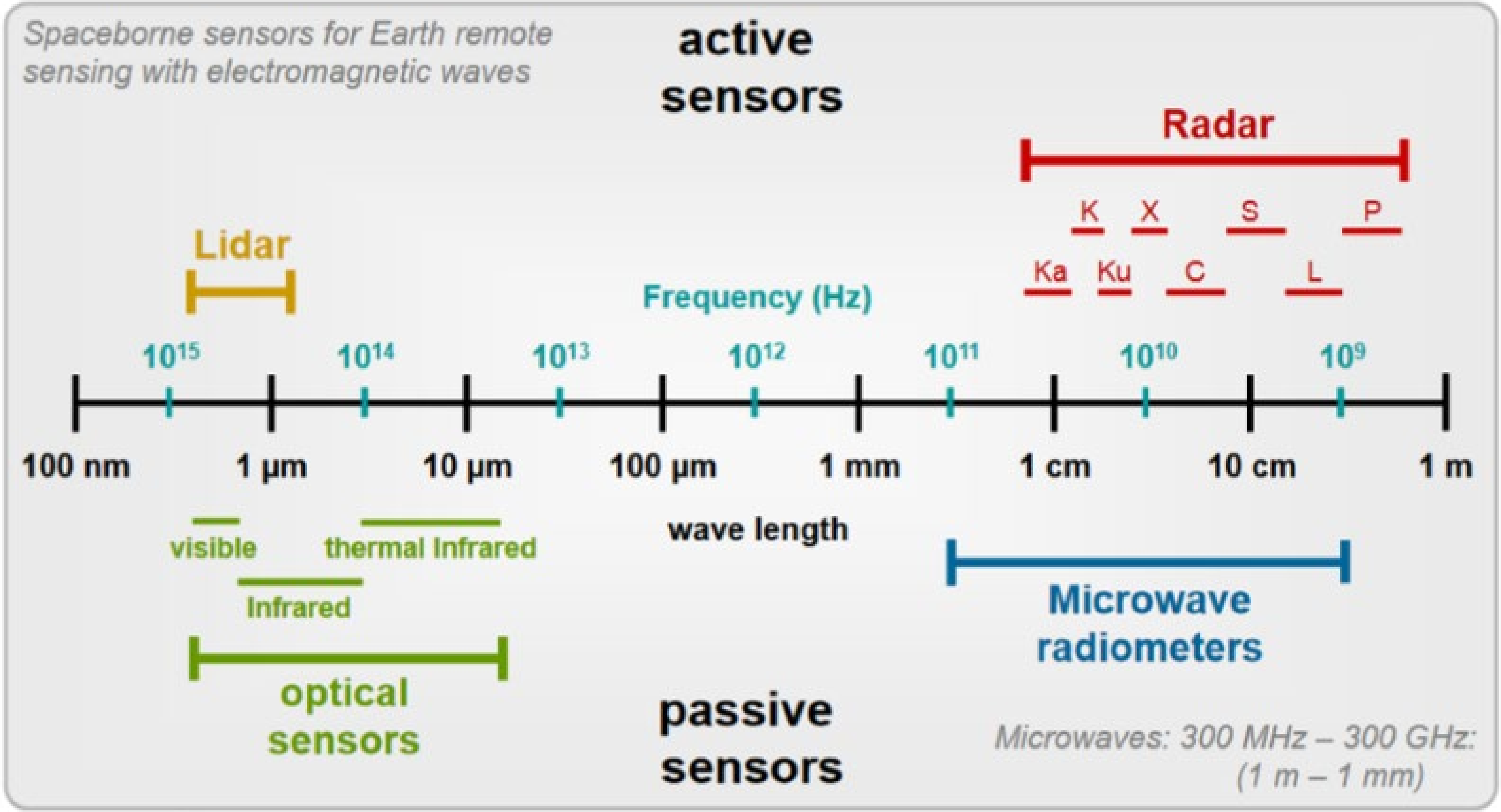
Active and Passive Sensors



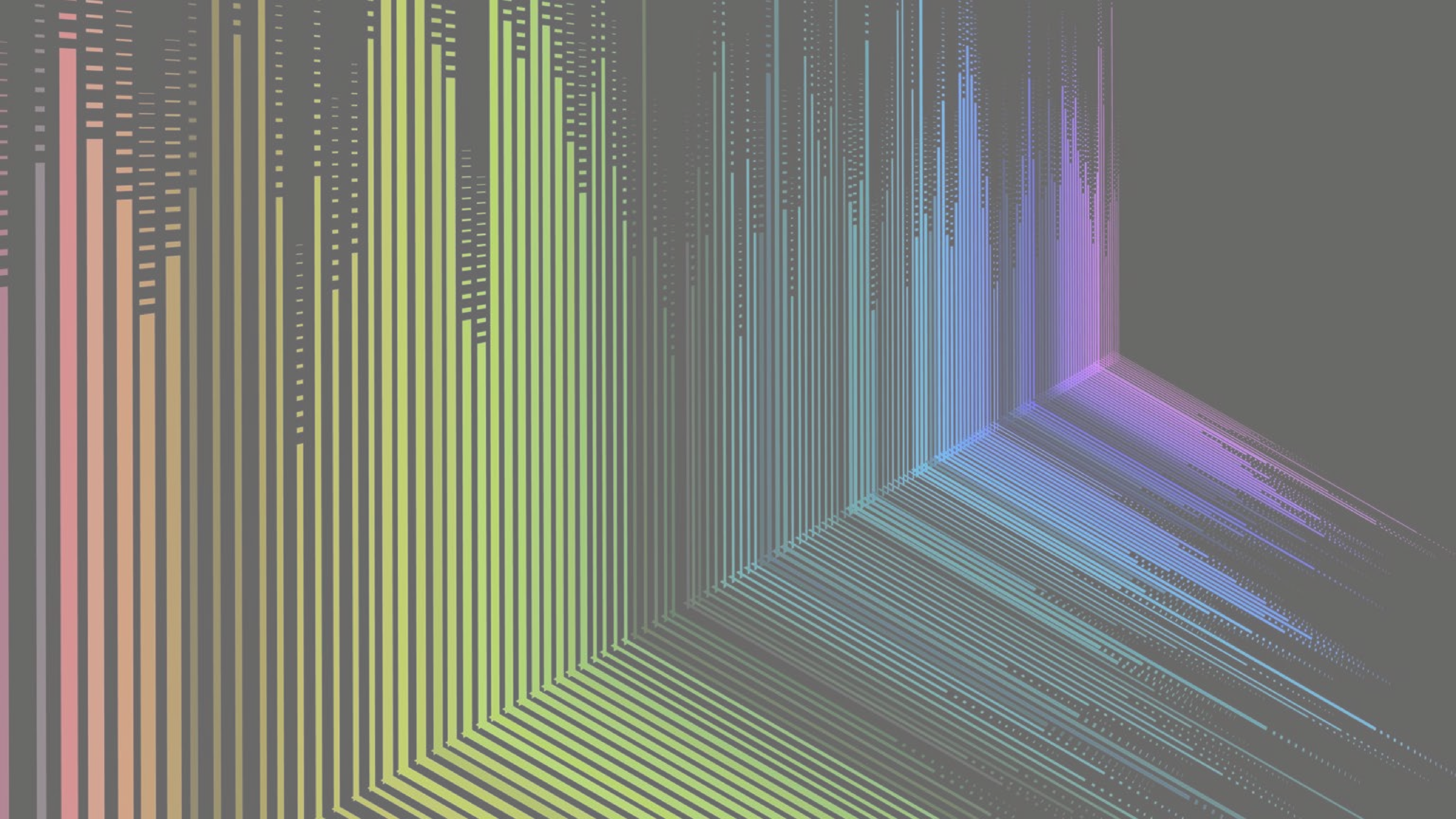
Active and Passive Sensors

- **Passive sensors** rely on natural sources of energy, most commonly the sun, to measure reflected radiation in the visible to shortwave infrared part of the spectrum or emitted longwave infrared radiation in the thermal domain (James B. Campbell & Randolph H. Wynne, 2013; Jensen, 2016).
    - Optical
    - Thermal
    - Multispectral
    - Hyperspectral
- **Active sensors**, generate their own signal, usually in the form of microwave or laser pulses, transmit it towards the Earth's surface, and measure the backscattered return (Woodhouse, 2017).
    - LiDAR
    - RADAR / SAR

Electromagnetic Spectrum



The electromagnetic spectrum typically used in remote sensing, and spectral reflectance curves show the distinct signatures of vegetation, soil, and water, which are fundamental for interpretation (Jensen, 2016).



Passive Sensors

Passive sensors = optical + thermal instruments

- Optical: reflected solar energy (visible, NIR, SWIR)
- Thermal: emitted longwave radiation (surface temperature)

Spectral signatures:

- Vegetation → red absorption, high NIR reflectance
- Soil → mineral/organic-dependent curves
- Water → strong NIR & SWIR absorption (appears dark)

Basis for optical remote sensing analysis

Multispectral & hyperspectral = passive systems

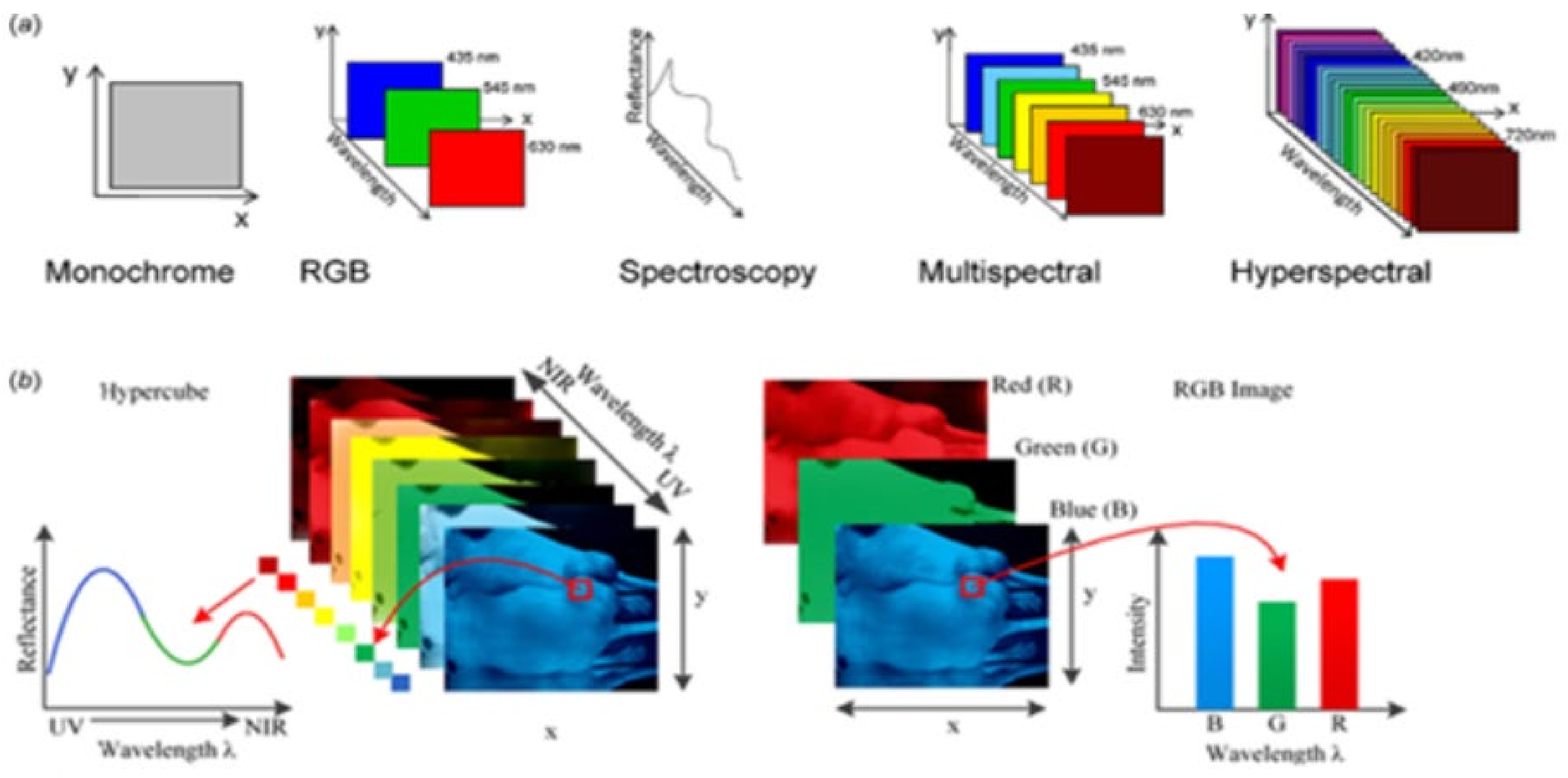
Limitation:

- **atmospheric interference** (clouds, aerosols, water vapor)

Strength:

- long record & global coverage:
  - Landsat (since 1972) → longest continuous record
  - MODIS (1999) → daily global, 36 bands

Passive Sensors



Monochrome, multispectral and hyperspectral imaging visualized (Mehta et al., 2018)

Optical

Optical remote sensing = most widely used passive modality

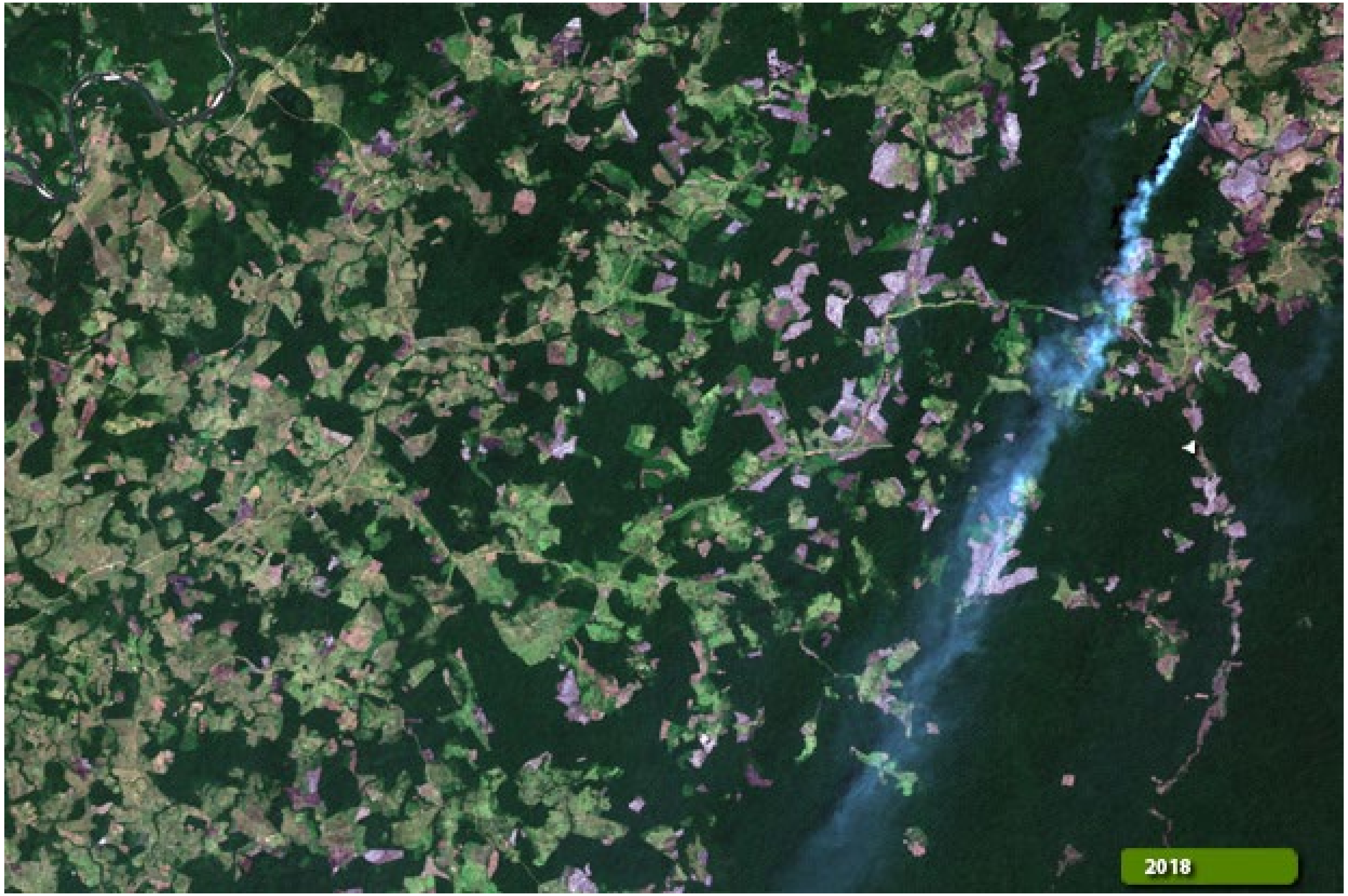
Sensor types:

- **Panchromatic** → single broad band, very high spatial resolution, low spectral detail
- **Multispectral** → 4–13 broad bands, effective for land cover, agriculture, urban, environment
- **Hyperspectral** → hundreds of narrow, contiguous bands, high spectral detail for material ID & biophysical parameters
- **Very High Resolution (VHR)** → sub-meter to few meters resolution, enables detailed urban mapping & object detection

Data processing:

- Radiometric calibration → digital numbers → radiance
- Atmospheric correction → removes scattering/absorption (O_2, O_3, H_2O)
- Geometric correction → aligns imagery to Earth's surface

Optical



Sentinel 2 - Optical Image / True Colour Composite. Source: ESA

Strengths: interpretable, long historical record, broad applications

Limitations: cloud cover, atmospheric interference

Multispectral Remote Sensing

False colour composite with RGB and NIR, Source: ESA Sentinel-2

Multispectral

Multispectral sensors:
measure reflected radiation in a limited number of broad spectral bands

Limitations:
- restricted number of bands → weaker discrimination of subtle spectral differences

Strengths:
- Balanced spatial, temporal, spectral resolution
- Efficient data volume for processing & archiving

Applications:
- Vegetation & water indices (e.g., NDVI, NDWI)
- Burned area mapping
- Land cover classification
- Agricultural monitoring & yield estimation
- Military

Multispectral Satellite Programs

Most widely used passive systems
= backbone of global monitoring for 50+ years

Landsat program (since 1972):
- Longest continuous record
- 30 m resolution (VIS, NIR, SWIR)
- Key instruments: TM, ETM+, OLI

Sentinel-2 MSI:
- 13 spectral bands (10–60 m)
- 5-day revisit cycle
- Includes **3 red-edge bands** → improved vegetation analysis

MODIS (Terra & Aqua):
- Coarser resolution
- Daily global coverage across 36 bands

Hyperspectral

- Hyperspectral sensors capture hundreds of narrow, contiguous bands (5–10 nm) enabling detection of pigments, minerals, water content, and organic compounds
- Imaging spectroscopy first developed with airborne systems (AVIRIS, HyMap) and later spaceborne sensors (Hyperion, PRISMA, EnMAP)
- Provides **continuous spectrum per pixel** for quantitative retrieval of biophysical and geochemical parameters
- Applications:
    - vegetation stress and physiology
    - mineral discrimination in geology
    - water quality monitoring in aquatic systems
- Challenges:
    - high dimensionality
    - Noise
    - atmospheric interference
    - requires radiometric, atmospheric, and geometric correction plus dimensionality reduction
- Recent missions: PRISMA (2019, 239 bands, 30 m), EnMAP (2023, 242 bands, 30 m)
- Future missions: ESA CHIME, NASA SBG → expanding global hyperspectral capacity and advancing imaging spectroscopy

Table of Hyperspectral Sensors

	Satellite based					Airplane - based				UAV-based	
Sensor	Hyperion	PROBA-CHRIS	PRISMA	ENMAP	CRISM	AVIRIS	CASI	AISA	HyMap	Headwall	Hyperspec UHD 185 - Firefly
Spectral range [nm]	357-2576	415-1050	400-2500	420-2450	362-3920	400-2500	380-1050	400-970	440-2500	400-1000	450-950
No. of Spectral bands	220	19 or 63	238	242	544	224	288	244	244	270(Nano) 324(Micro)	138
Spectral Resolution [nm]	10	34 or 17	12	6.5 and 10	6.55	10	<3.5	3.3	3.3	6 (Nano) 2.5 (Micro)	4
Operational Altitude [km]	705	830	615	652	300 (over Mars!)	1-20	1-20	1-20	1-20	<0.15	<0.15
Spatial resolution [m]	30	17-36	30	30	15-200	1-20	1-20	1-20	1-20	0.01-0.5	0.01-0.5
Year	2000 - 2017	2001 - 2024	2019 -	2022 --	2006 - 2022	1987 -	1989-	1996-	1997-	2020	2020

Overview of Hyperspectral Sensors. Specifications compiled from : (Babey & Anger, 1993; Barnsley et al., 2004; Cocks et al., 1998; Green et al., 1998; *Headwall Photonics - Hyperspectral Imaging Systems & Components*, n.d.; *Table 1 Spectral Characteristics of the CASI Data*, n.d.; Kirrilly Pfitzner, 2004; Loizzo et al., 2018; Miko, n.d.; S. Murchie et al., 2007; S. L. Murchie et al., 2009; Pearlman et al., 2003; van der Meer et al., 2012).

Vicarious Calibration and Atmospheric Correction

- Accurate hyperspectral analysis requires atmospheric correction to convert radiance to surface reflectance
- Atmospheric gases (O_2, O_3, CO_2, H_2O) produce absorption features that can be misinterpreted as surface signatures if uncorrected
- Multispectral sensors often avoid major absorption bands, but hyperspectral sensors cover full spectrum and are highly sensitive to atmospheric effects
- Correction ensures reliable identification of surface materials and prevents misinterpretation of gas absorption features
- Dedicated software: MODTRAN, FLAASH used for atmospheric correction
- When unavailable, vicarious calibration methods apply ground reference targets or invariant features for approximate corrections
- Vicarious calibration does not allow strict spectral comparison but provides sufficiently accurate reflectance for material identification and scene analysis

Spectral Indices

- Spectral indices are mathematical combinations of spectral bands designed to highlight properties of the Earth’s surface
- They simplify complex reflectance patterns by emphasizing vegetation, water, or disturbance features
- **NDVI** (Tucker, 1979): uses red absorption by chlorophyll and NIR reflectance of plant cells → values near 1 = dense vegetation, near 0/negative = soil or water
- **NDWI** (Gao, 1996): green and NIR bands to detect water bodies
- **NBR** (Key & Benson, 2006): shortwave infrared bands to map burned areas and fire severity
- **MSAVI** (Qi et al., 1994): corrects soil influence in sparsely vegetated areas, useful in arid regions
- In hyperspectral data, specialized indices detect narrow absorption features:
- **PRI** (Gamon et al., 1992) for photosynthetic efficiency
- **Red-edge indices** for chlorophyll concentration (Delegido et al., 2011)
- Indices are computationally simple and effective for global vegetation monitoring, drought detection, deforestation mapping, and yield estimation
- Limitations include atmospheric interference, calibration issues, and saturation in dense vegetation
- Despite challenges, spectral indices remain fundamental tools in remote sensing

Active Sensors

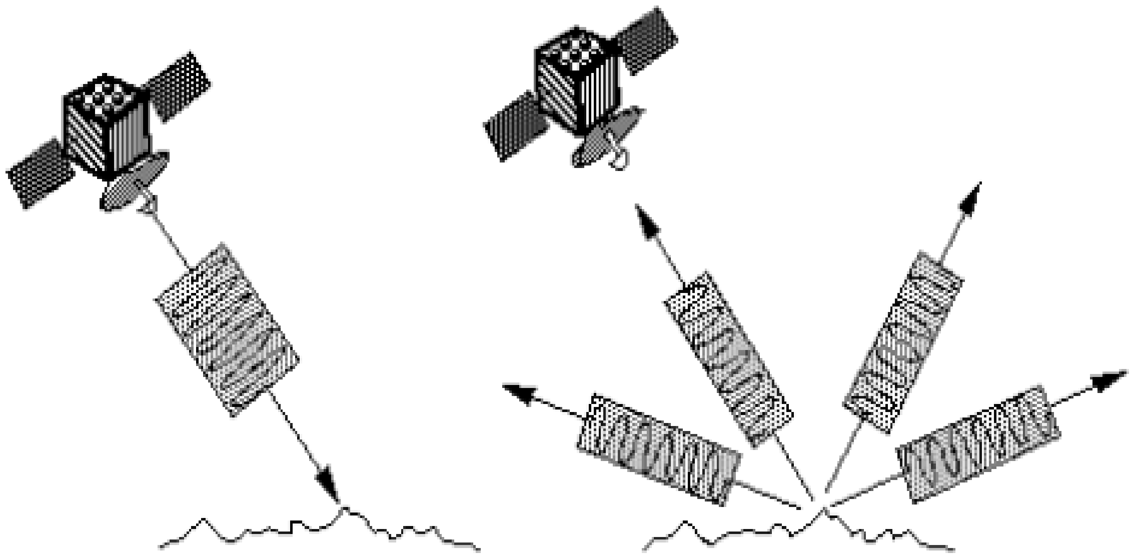
- Active remote sensing systems transmit their own energy and record the backscattered response
- Operate independently of sunlight, usable day and night, and penetrate clouds, haze, and smoke
- Radar is the most widely used active sensing technology, working in the microwave spectrum
- Lidar uses laser pulses in visible/NIR range, mainly for DSM, DEM, topographic mapping, and vegetation structure analysis
- Radar sensitivity: surface roughness, moisture content, dielectric properties
- Early radar (1930s–40s) showed object detection with radio waves; side-looking airborne radar (SLAR) in 1950s enabled systematic Earth imaging
- Lidar measures return time of laser pulses → very high vertical resolution of canopy and terrain
- Lidar limited in spatial coverage from satellites but essential in airborne campaigns
- Radar provides global satellite coverage and is a cornerstone of Earth observation

Radar of the type used for detection of aircraft. It rotates steadily, sweeping the airspace with a narrow beam. Air Force Museum, Hatzerim, Israel. Source: Wikipedia

Basic Principles of Radar

- Radar (RAdio Detection And Ranging) is an active remote sensing system transmitting microwave pulses and recording backscatter from Earth's surface
- Unlike passive optical sensors, radar generates its own illumination → independent of sunlight, unaffected by clouds, haze, or smoke → provides consistent all-weather, day-and-night observations
- Origins in early 20th century radio wave experiments; rapid development in 1930s–40s for military applications (aircraft detection, navigation) with pioneers such as Robert Watson-Watt
- Post-WWII radar adapted for scientific uses, including meteorology and geoscience
- 1950s: introduction of Side-Looking Airborne Radar (SLAR) providing continuous ground imagery; limited azimuth resolution due to antenna size constraints
- Breakthrough with **Synthetic Aperture Radar (SAR)**: uses platform motion to synthesize a long antenna, greatly improving resolution
- 1978: NASA's **Seasat** demonstrated feasibility of spaceborne SAR, proving global radar imaging from orbit
- 1990s: dedicated SAR missions (ESA ERS-1/2, Canada Radarsat-1) established systematic environmental monitoring and solidified radar's role in Earth observation

Basic Principles of Radar

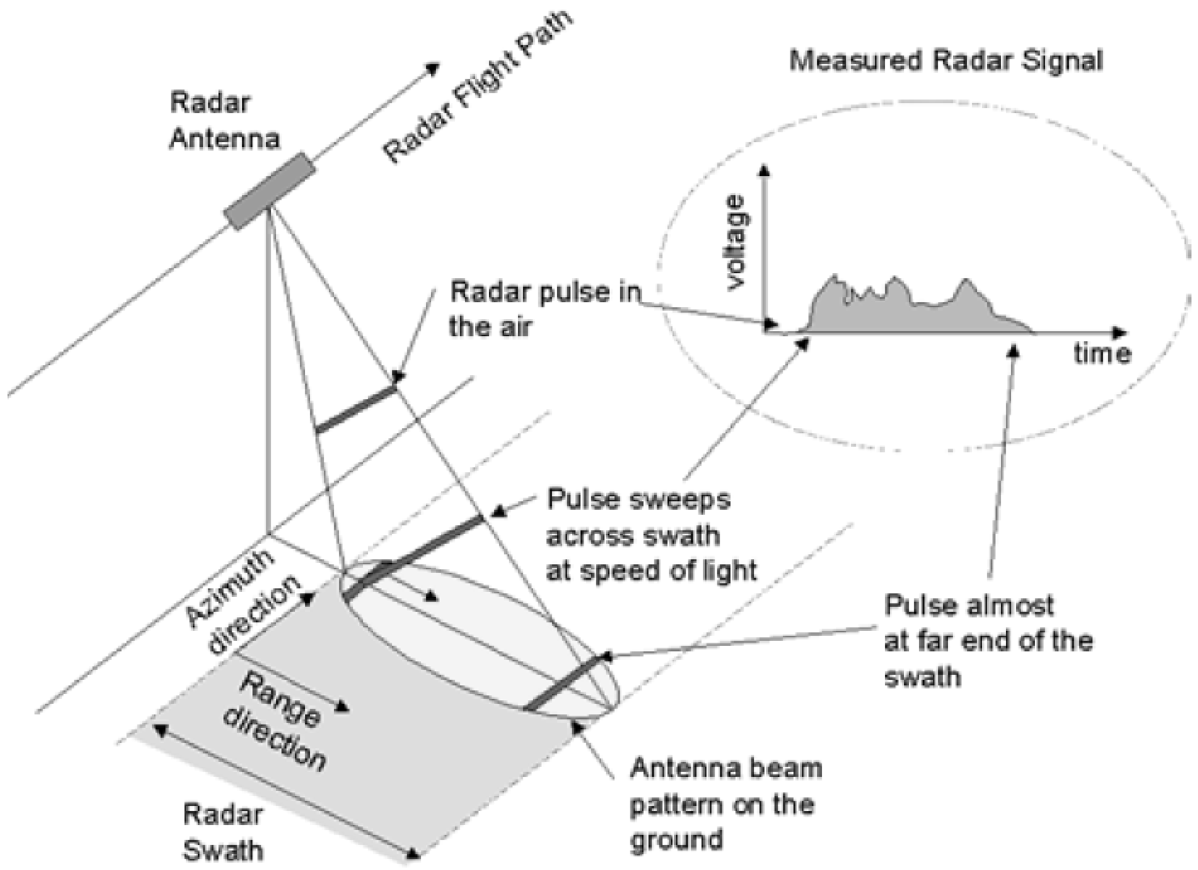


Echoes received back by the Antenna (European Space Agency, 2007)

- transmitting microwave pulses
- recording backscattered energy
- using system geometry and wavelength to capture information about the Earth’s surface

(Torres et al., 2012)

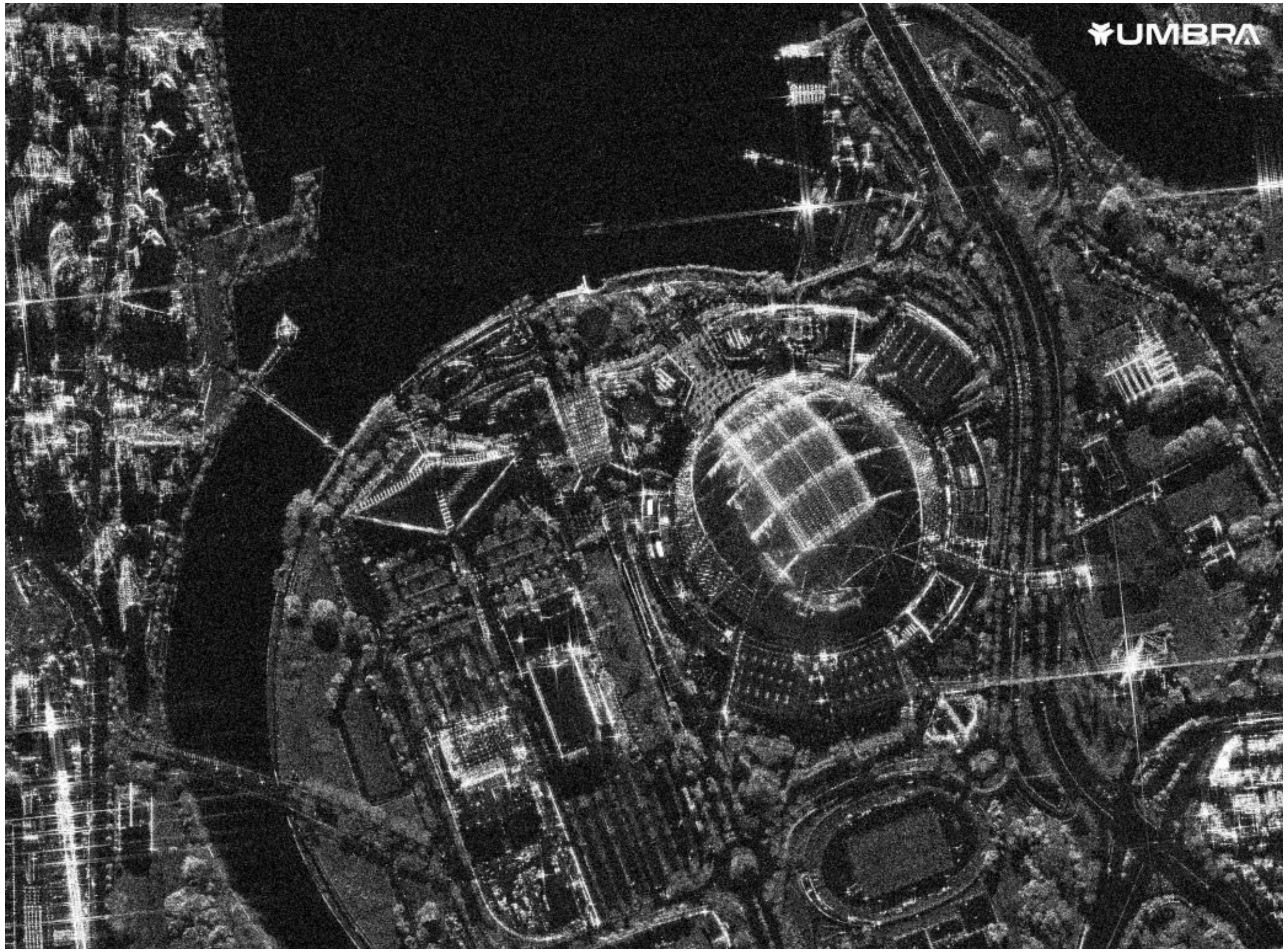
Sidelooking Radar



Imaging geometry for a side-looking radar system (Van Zyl & Kim, 2011)

- Side-looking airborne radar (SLAR) was the first major advance in radar imaging
- An aircraft-mounted antenna transmitted pulses obliquely to the ground and recorded backscatter to form images
- Resolution limited by antenna length: higher altitude → wider footprint → reduced azimuth resolution
- Constraint made SLAR unsuitable for high-resolution spaceborne applications

Synthetic Aperture Radar (SAR)

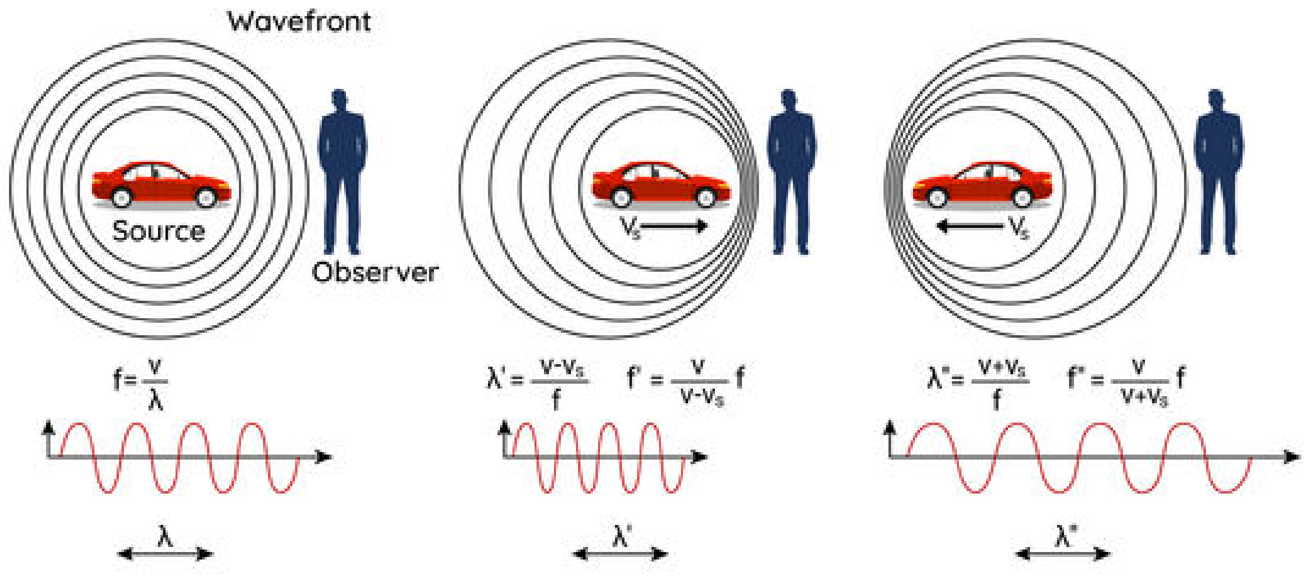


https://www.maxar.com/maxar-intelligence/products/sar-imagery

- Synthetic aperture principle invented by Carl Wiley in 1952
- Exploited Doppler frequency shifts from platform motion to synthetically extend antenna length
- Coherent combination of successive radar pulses formed a “synthetic” antenna, enabling much finer azimuth resolution than physical antennas
- Foundation for Synthetic Aperture Radar (SAR)
- First spaceborne SAR: NASA’s Seasat (1978), operated 106 days, proved feasibility for global monitoring
- Subsequent missions built global SAR capacity:
    - ESA ERS-1 (1991) and ERS-2
    - Canada’s Radarsat series
    - Japan’s ALOS PALSAR missions
    - ESA Sentinel-1 (since 2014, open-access C-band SAR)

Doppler Effect in SAR

- The Doppler effect is the frequency shift caused by relative motion between source and receiver
- Approaching targets → higher frequency, receding targets → lower frequency
- Successive echoes along the flight path are coherently combined using these Doppler shifts
- Processing across varying frequencies synthesizes a much longer antenna aperture
- Result: improved azimuth resolution and smaller effective ground pixel size



https://www.optomet.com/knowledge-technology/doppler-effect/

SAR Frequency Bands and Applications

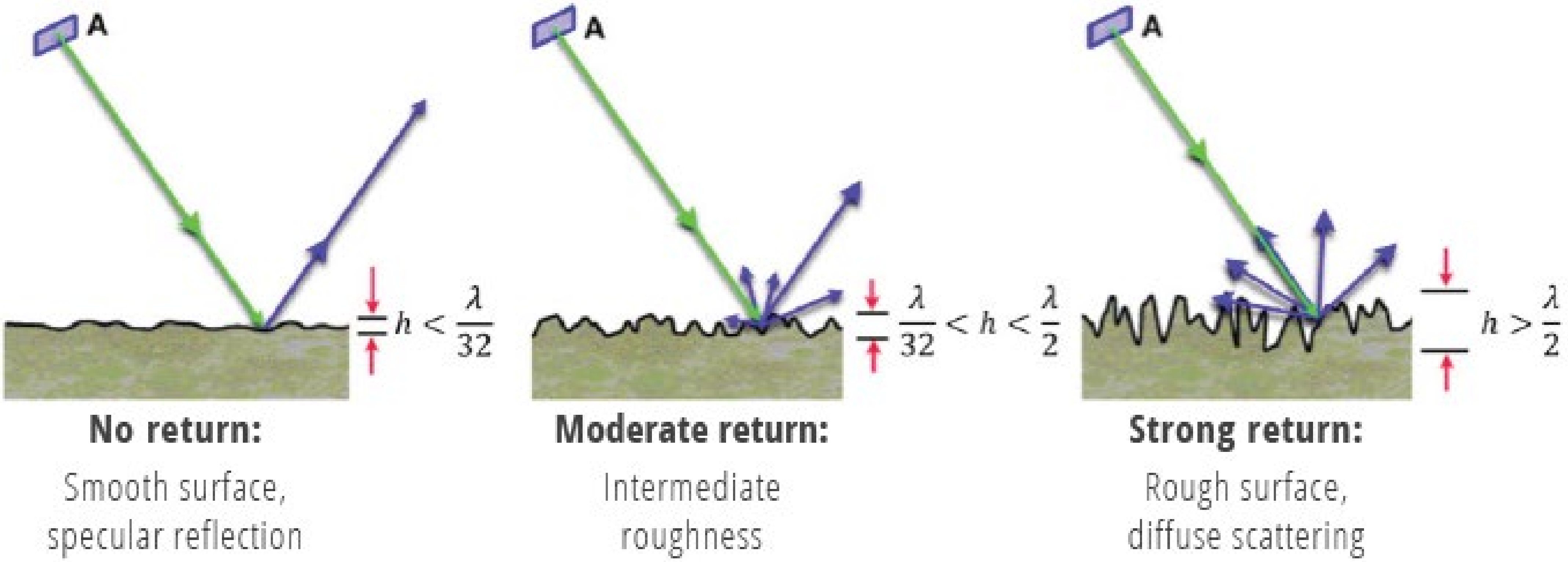
- SAR instruments operate at different microwave frequency bands, each with specific characteristics and applications
- X-band (2.4–3.8 cm): very high spatial resolution, suited for urban monitoring and infrastructure studies, limited vegetation penetration
- C-band (3.8–7.5 cm): long-standing workhorse (e.g., Sentinel-1), balances resolution, canopy penetration, and wide-swath imaging
- L-band (15–30 cm): deeper penetration into vegetation canopies, essential for biomass estimation, forest monitoring, and subsurface detection in dry soils
- P-band (30–100 cm): strongest penetration, enables measurement of forest structure and biomass, but affected by ionospheric distortions; ESA Biomass mission will provide first global P-band SAR observations

SAR Frequency Bands and Applications

Name	Wavelength	Example of sensors	Example of typical applications
P-band	~ 65 cm	NISAR,Biomass	First P-band spaceborne; vegetation mapping and assessment
L-band	~ 23 cm	ALOS PALSAR	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)
S-band	~ 10 cm	NISAR	Agriculture monitoring, higher vegetation density
C-band	~ 5 cm	ERS-1/2 SAR, RADARSAT-1/2, ENVISAT ASAR, RISAT-1, Sentinel-1	SAR Workhorse (global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence); ice, maritime ocean navigation
X-band	~ 3 cm	TerraSAR-X,COSMO-SkyMed, Capella, ICEYE	High-resolution SAR (urban monitoring; ice and snow, little penetration into vegetation cover; fast coherence decay in vegetated areas)
K-band	~ 1.2 cm	-	Primarily climate & atmosphere-related applications, e.g. H2O absorption & rainfall. Also, military domain applications, e.g., surveillance

SAR Bands (Flores et al., 2019)

Reflection



Conceptual sketch of the dependence of surface roughness on the sensor wavelength λ: (a) smooth, (b) intermediate, and (c) rough. (Flores et al., 2019)

Reflection

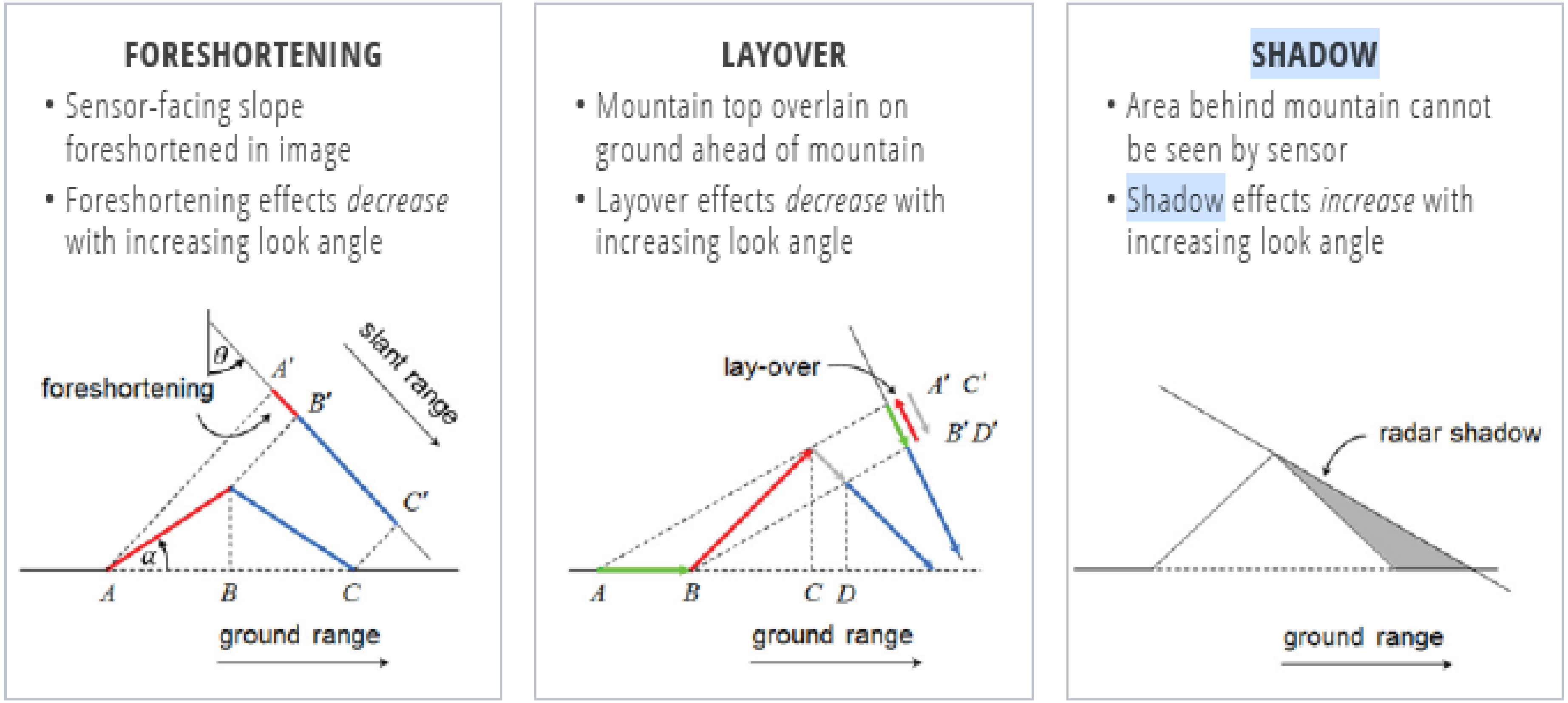
- In radar and SAR, backscatter depends on surface geometry, roughness, and dielectric properties

- Smooth surfaces (e.g., calm water) reflect energy away → appear dark
- Rough surfaces and complex targets scatter energy back → appear bright

- Urban areas produce strong returns via double-bounce reflections
- Vegetation canopies generate volume scattering

- SAR records both amplitude and phase, enabling intensity imaging plus advanced methods like interferometry and polarimetry
- These techniques provide information beyond what optical imagery can capture

Geometric Distortions

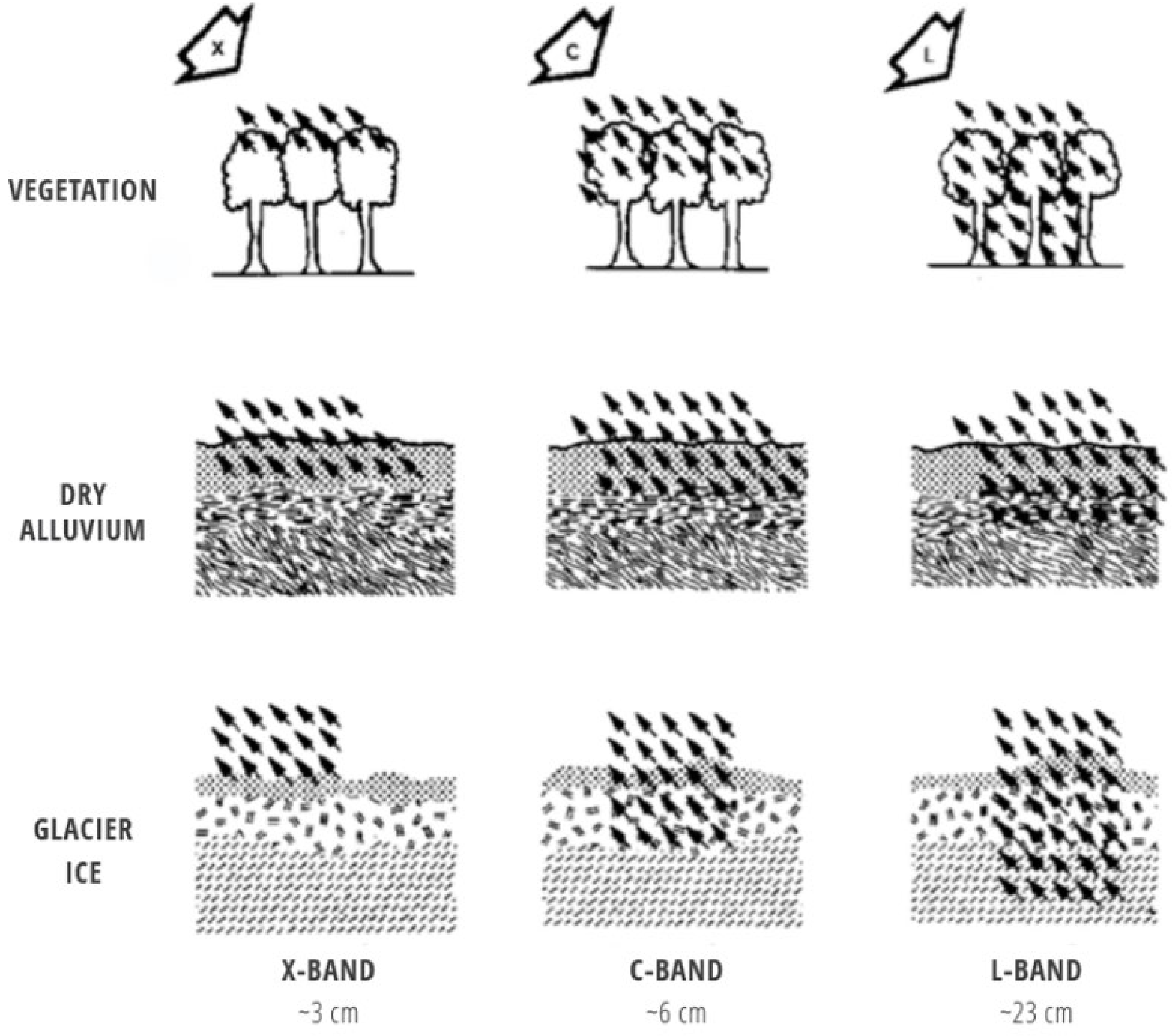


Main geometric distortions on SAR images with their dependence on acquisition geometry: (a) foreshortening, (b) layover, and (c) shadow. (Flores et al., 2019)

Geometric Distortions

- SAR images are affected by geometric distortions due to side-looking geometry
- Foreshortening: slopes facing sensor appear compressed
- Layover: tall objects imaged before their base
- Radar shadows: steep terrain blocks illumination, leaving dark areas
- Distortions can be corrected using digital elevation models (DEMs) for geometric correction

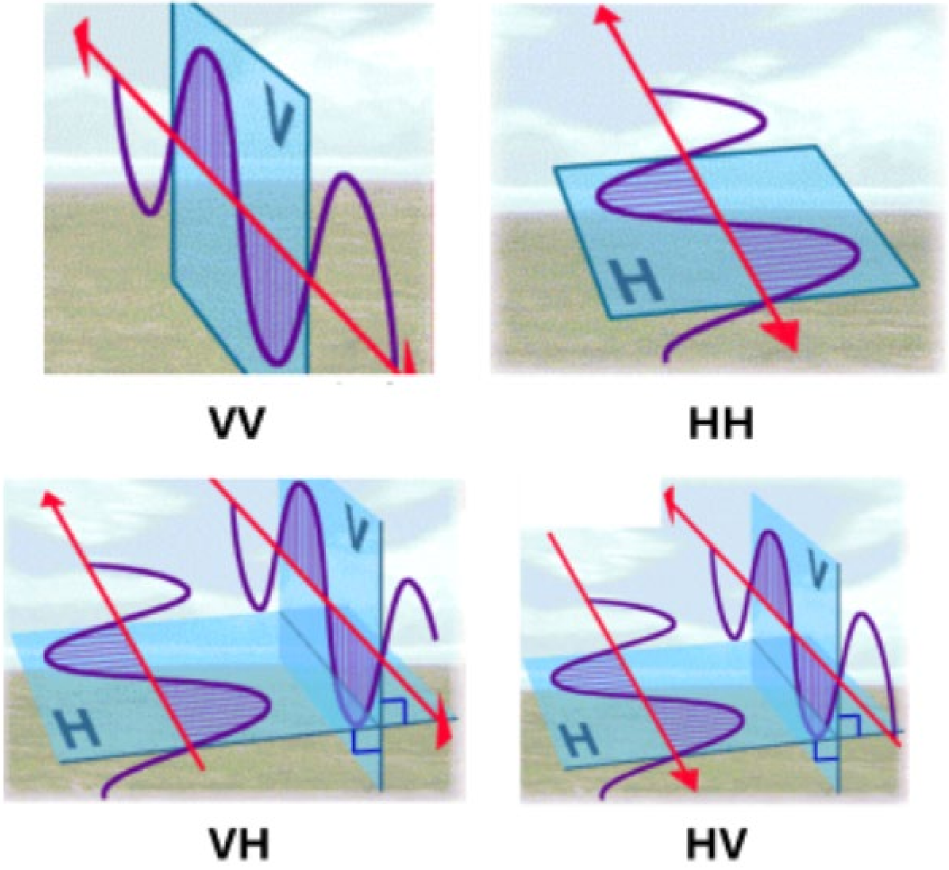
Penetration



Penetration of different wavelengths for different materials (Meyer, 2019)

- SAR penetration depends on wavelength, polarization, and target dielectric properties
- Longer wavelengths (L-band, P-band) penetrate deeper into vegetation and dry soils; shorter X-band is limited to surface interactions
- In forests, L-band and P-band interact with trunks and branches → useful for structure and biomass estimation
- Soil penetration decreases with higher moisture, as water strongly absorbs microwaves
- Dry snow and sand allow deeper penetration; wet snow, water, or saturated soils appear dark due to absorption and reflection
- Applications include soil moisture retrieval, flood mapping under vegetation, and monitoring permafrost and ice structures

Polarization

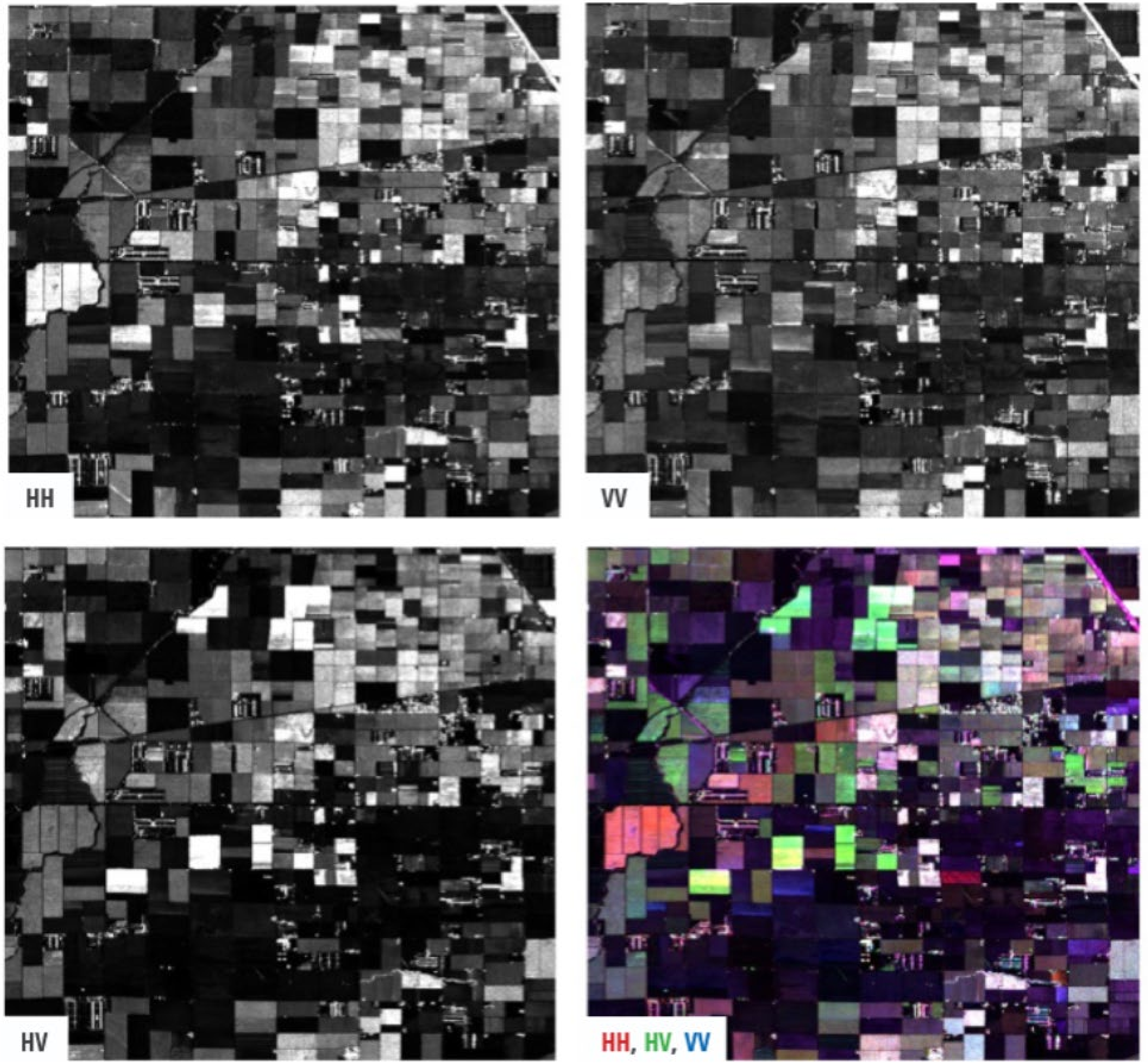


Single polarization	HH or VV
Single polarization	HH or VV
Dual polarization	HH + HV, or VV + VH, or HH + VV
Alternating polarization	HH + HV, alternating with VV + VH
Polarimetric (Quad-pol	HH, VV, HV, VH

- Polarization is a key dimension in radar measurements
- Modern SAR systems transmit and receive in horizontal (H) or vertical (V) modes
- Four polarization combinations: HH, HV, VH, VV
- Co-polarized channels (HH, VV) → surface scattering and double-bounce effects
- Cross-polarized channels (HV, VH) → sensitive to volume scattering, especially in vegetation canopies

Polarization

Illustration of how different polarizations (HH, VV, HV, and color composites) bring out different features in an agricultural scene from California's Central Valley. The different orchards and crops in this area display different polarized backscatter behavior (Flores et al., 2019, p. 219)



Speckle

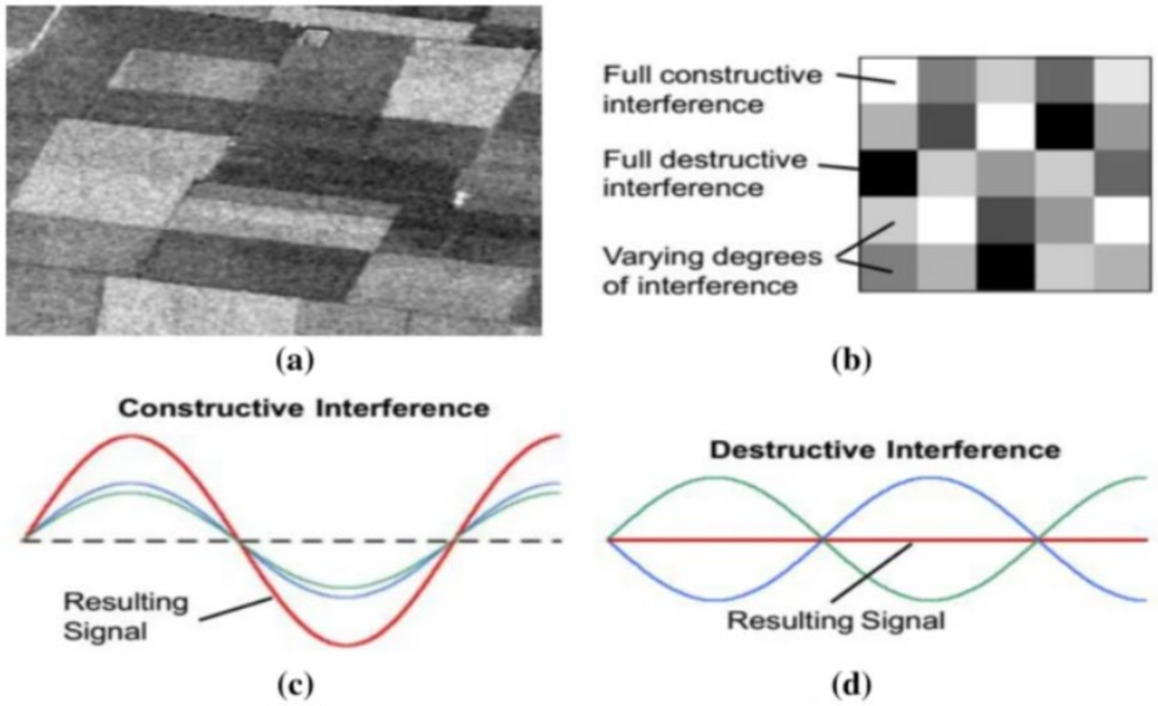
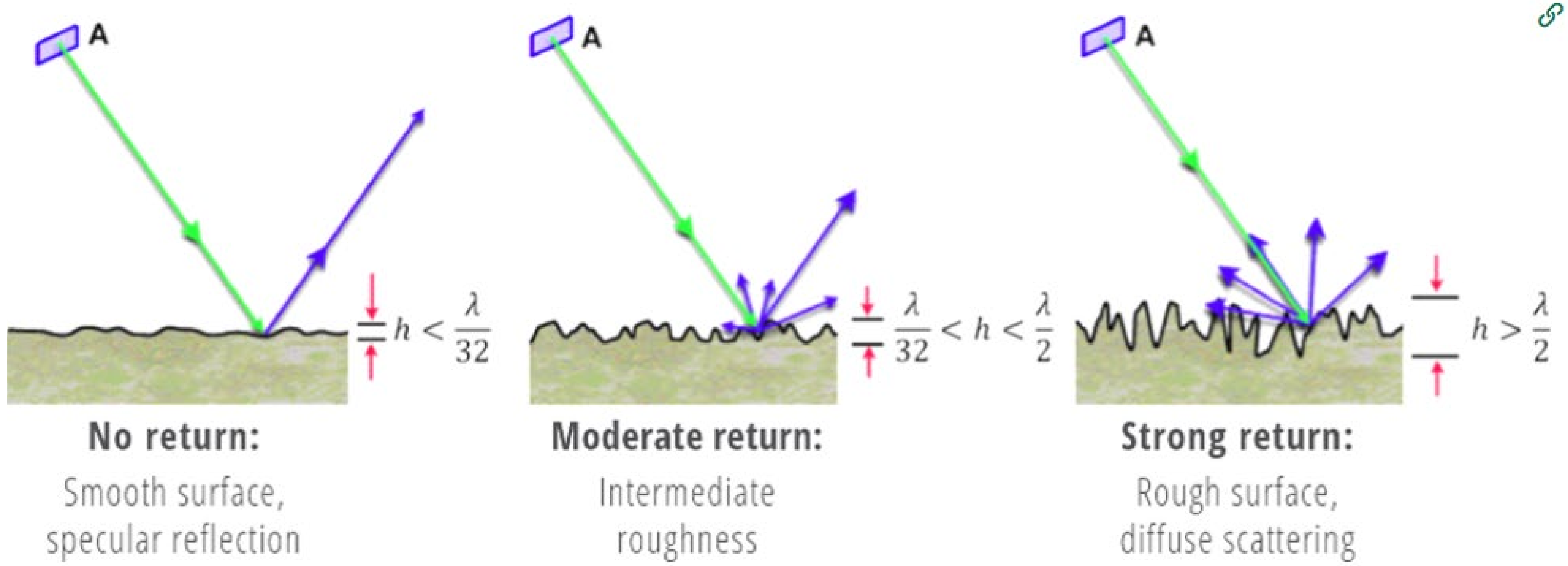


Illustration of the speckle effect from Singh et al. (2021):
(a) Agricultural fields showing a grainy texture caused by
(c) constructive and
(d) destructive interference of backscattered waves

- Speckle is a granular texture in SAR imagery caused by coherent interference of scattered waves within a resolution cell
- It is multiplicative noise, often modeled by an exponential distribution, and while it carries statistical information, it complicates interpretation and analysis
- Speckle reduction is a key preprocessing step in SAR
- Classical filtering approaches:
    - **Lee filter** (adaptive, preserves edges)
    - **Frost filter** (statistical smoothing)
- **Multilooking** (averages independent looks, reduces variance but lowers spatial resolution)
- Modern approaches:
    - **Non-local means (NLM)** → compares image patches, averages statistically similar ones, preserves fine details
    - **Iterative weighted maximum likelihood NLM** (Deledalle et al., 2009) → uses statistical similarity and iterative refinement, superior for low SNR SAR data
- Balancing speckle reduction with detail preservation is critical for accurate classification and quantitative analysis

Backscattering Basics

- Backscattering in SAR is the portion of the transmitted microwave pulse scattered back to the sensor after interacting with the surface
- Return signal depends on geometry, dielectric properties, and roughness of the target



Roughness as a factor of backscattering (Meyer, 2019)

Backscattering Basics

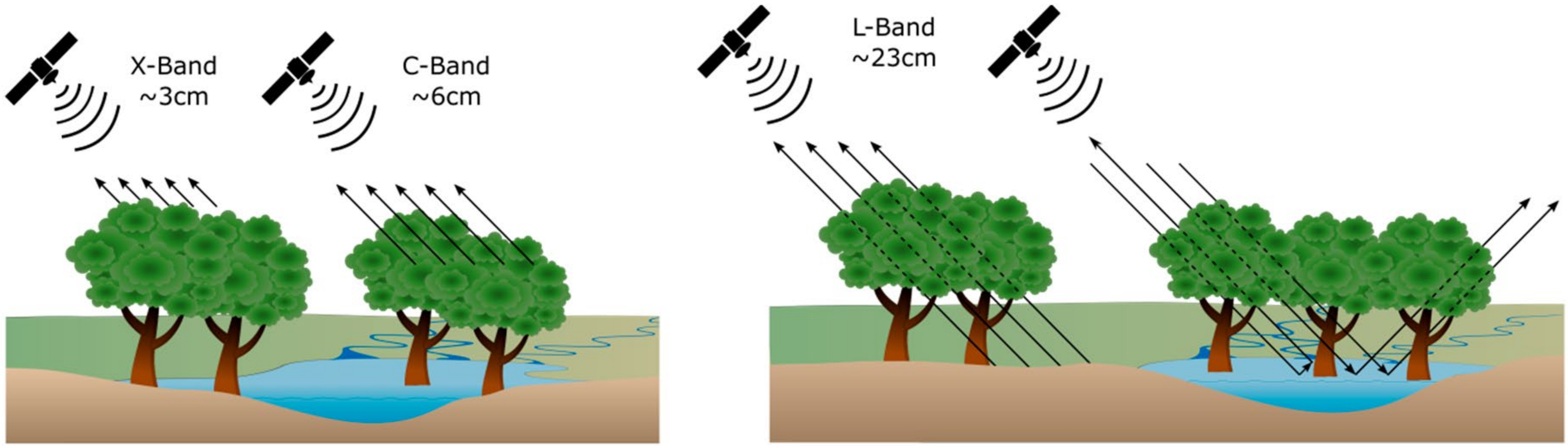
- HH backscatter → strong in double scattering from man-made structures (e.g., buildings, ships, corner reflectors)
- VV backscatter → linked to surface scattering from rough surfaces (e.g., bare soils, disturbed water)
- VH backscatter → characteristic of volume scattering within vegetation and forest canopies
- These scattering distinctions form the basis of SAR image interpretation and signature analysis

Roughness as a factor of backscattering (Meyer, 2019)

Backscattering Basics

X-band (~3 cm) → interacts mainly with the canopy top, sensitive to leaves and small branches, limited penetration.
C-band (~6 cm) → penetrates deeper than X-band, interacts with mid-canopy and larger branches, commonly used for vegetation and soil moisture studies.
L-band (~23 cm) → penetrates through canopy, interacts with trunks and ground surface, enabling biomass estimation and subsurface detection in dry soils.

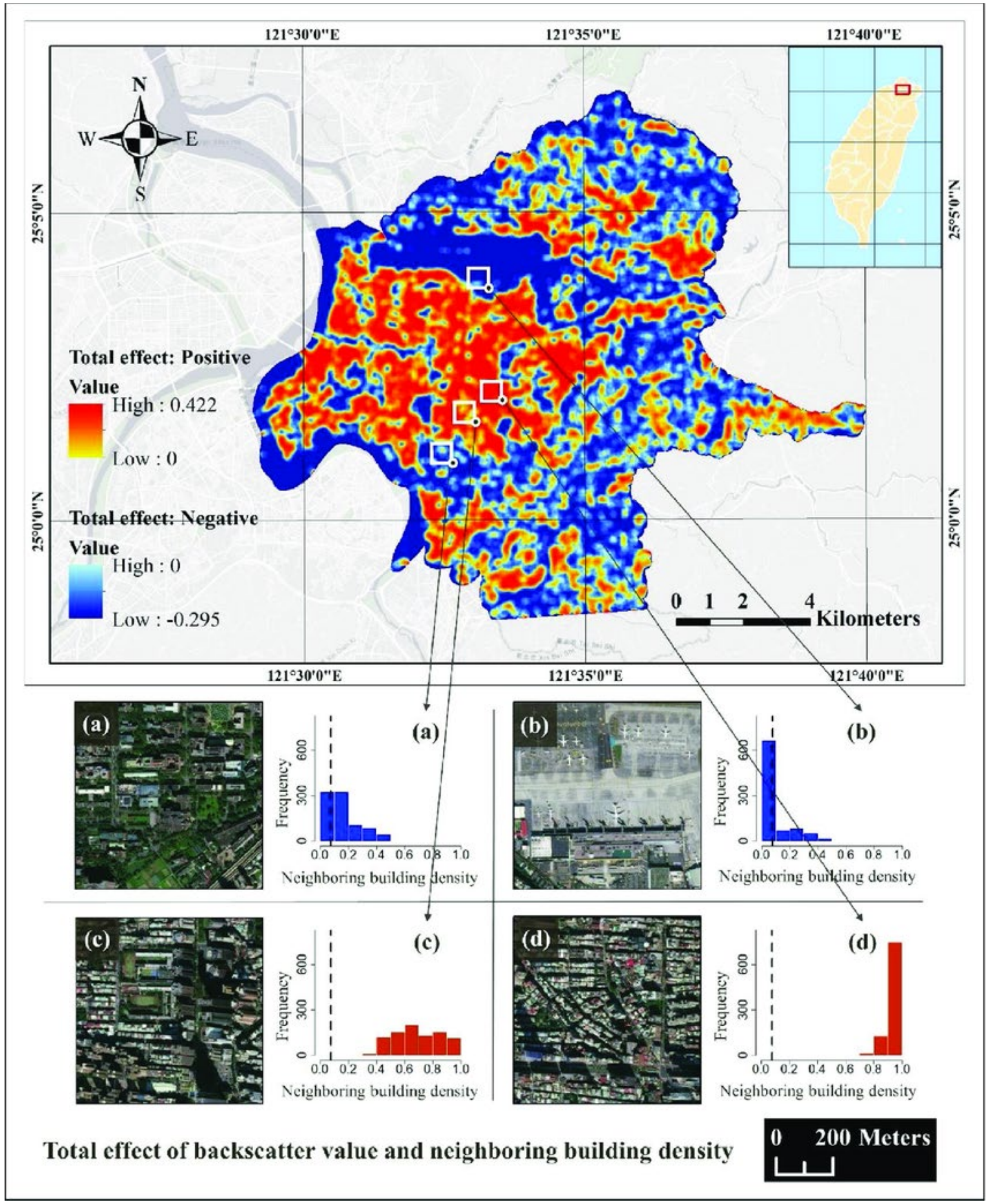
Penetration depth increases with wavelength → shorter wavelengths capture fine canopy details, while longer wavelengths reveal forest structure and ground conditions.



Radar backscattering mechanisms for different SAR wavelengths: X- and C-band (left) and L-band (right) (Ottinger & Kuenzer, 2020)

RADAR Cross Section (RCS)

- Radar cross section (RCS) expresses the strength of the backscattered signal
- Controlled by multiple factors:
  - Surface roughness relative to radar wavelength
  - Dielectric constant of the target material
  - Incidence angle of the radar beam
  - Geometric arrangement of scatterers
- Wavelength plays a key role:
  - **Longer wavelengths (L-, P-band)** → deeper penetration into vegetation and dry soils
  - **Shorter wavelengths (X-band)** → interact mainly with fine-scale features such as leaves and small branches



Backscatter: Total effect of the backscatter values in urban water detection (Liao & Wen, 2020)

Backscatter: practical Use

Main map shows spatial distribution of **total backscatter effects** in an urban area.

- **Positive values (red–yellow)** → strong backscatter, linked with high neighboring building density.
- **Negative values (blue)** → weak backscatter, often associated with low density or open areas such as water.

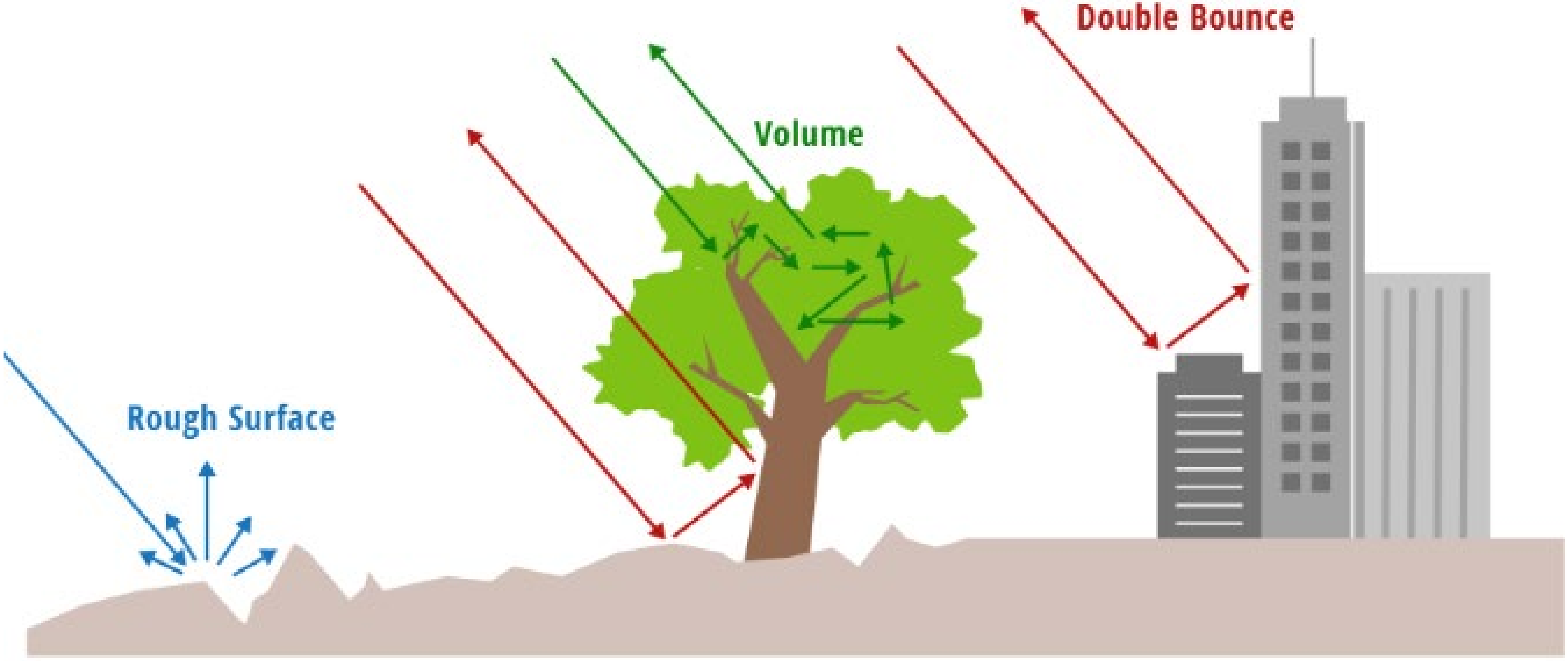
Study area is georeferenced: Taiwan, (coordinates provided).

Insets:
(a) Low-density residential → weak backscatter, histogram skewed toward low values.
(b) Industrial/parking area → weak backscatter, histogram concentrated at very low density.
(c) Medium-density urban core → higher, mixed backscatter values, histogram more balanced.
(d) High-density residential blocks → strong backscatter, histogram peaks at high density.

Interpretation:
- Backscatter intensity correlates with **neighboring building density**.
- High density = stronger radar returns due to multiple scattering (double-bounce).
- Low density or water = weaker returns (smooth surfaces, low scattering).

Practical use:
Demonstrates how SAR backscatter can be applied in **urban structure analysis** and **urban water detection**.

Scattering Types

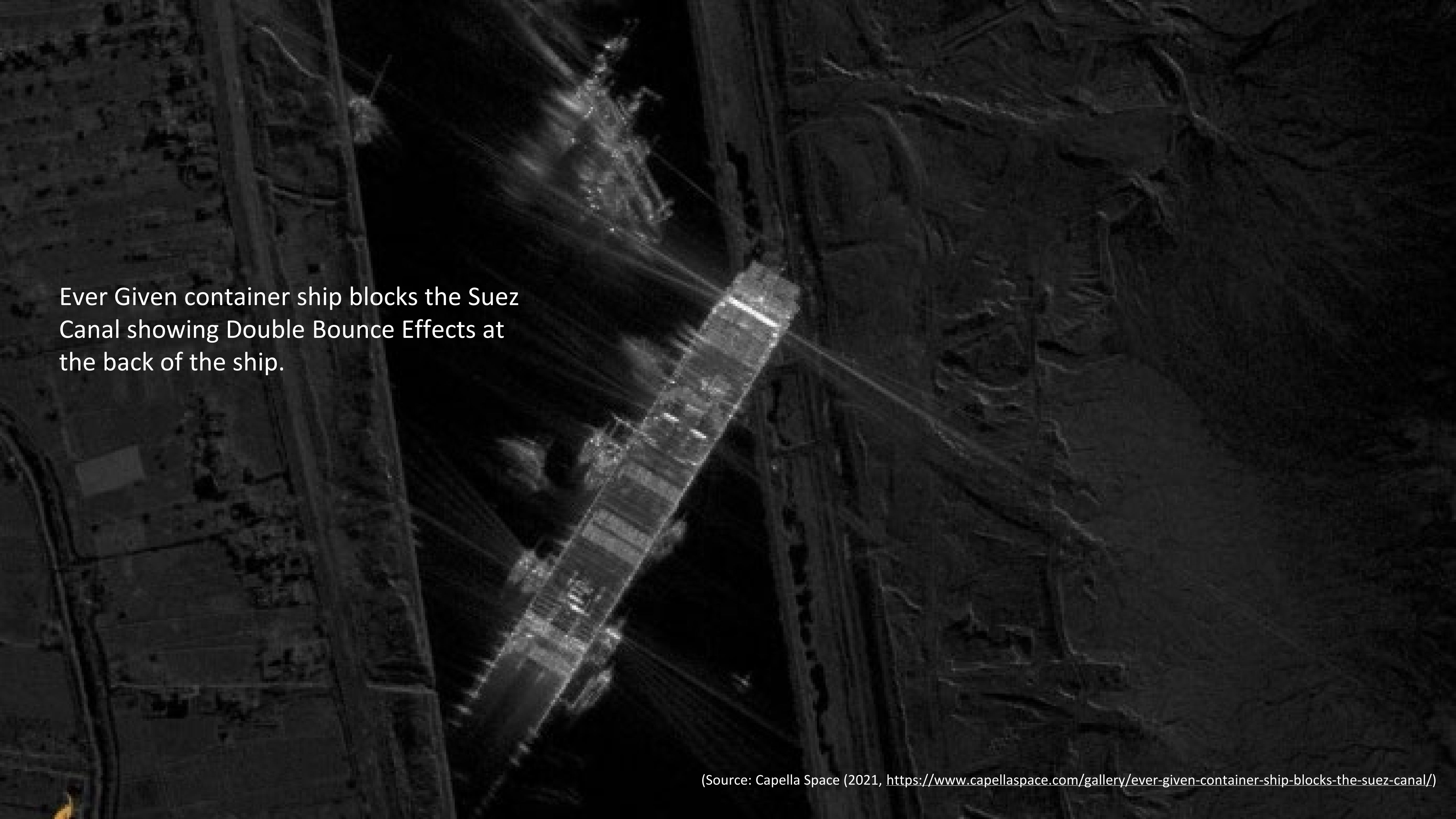


Scattering Types

- **Specular Scattering**
  - Occurs on smooth surfaces relative to radar wavelength
  - Energy reflected away from sensor → very low backscatter
  - Examples: calm water, smooth asphalt → appear dark in SAR imagery
- **Diffuse Scattering**
  - Happens as surface roughness increases relative to wavelength
  - Energy scattered in multiple directions → stronger returns
  - Examples: bare soil, agricultural fields, disturbed water
- **Volume Scattering**
  - Radar waves penetrate medium and undergo multiple reflections
  - Typical in vegetation (leaves, twigs, trunks), snow, or fine soils
  - Produces strong cross-polarized returns (HV, VH)
  - Crucial for forest and vegetation studies

Scattering Types: Double Bounce Scattering

- Double-bounce scattering occurs when a radar wave is reflected twice before returning to the sensor
- Typical geometry: vertical surface (building wall, tree trunk) + adjacent horizontal surface (ground, calm water) → efficient corner reflector
- Produces strong radar returns, especially in **urban areas** (buildings, ports, ships)
- In forests, can occur between trunks and ground, especially in flooded vegetation → useful for wetland monitoring
- Polarimetric SAR detects double-bounce via strong **co-polarized signals (HH, VV)**, enabling separation from surface and volume scattering
- Scattering distinctions:
  - Strong **HH** → predominance of double scattering, man-made structures appear bright
  - Strong **VV** → rough surface scattering (bare soils, rough water)
  - Strong **VH** → volume scattering (vegetation, forest canopies)



Ever Given container ship blocks the Suez Canal showing Double Bounce Effects at the back of the ship.

(Source: Capella Space (2021, https://www.capellaspace.com/gallery/ever-given-container-ship-blocks-the-suez-canal/)

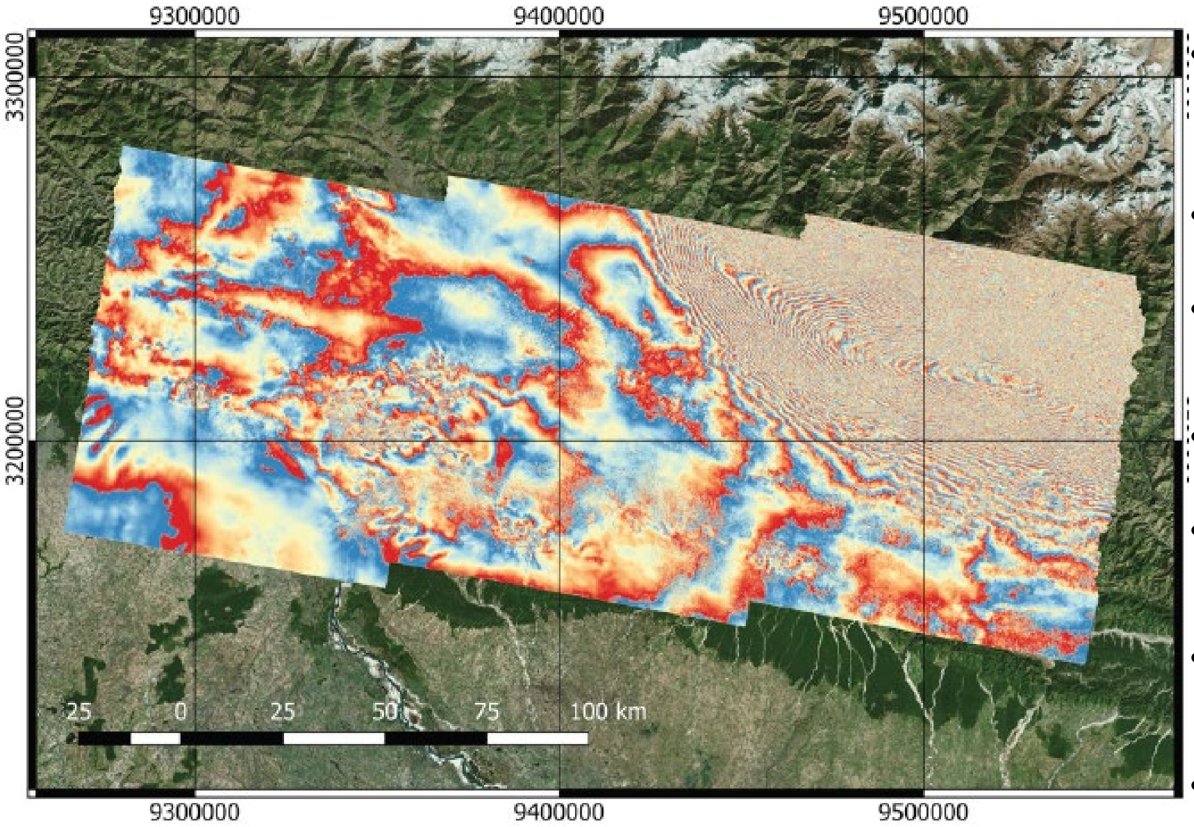
Advanced SAR Techniques

Sentinel 1: interferometric SAR (InSAR) Image. Source: ESA

SAR: beyond optical Capabilities

- InSAR, Polarimetric SAR and Coherence Analysis extend SAR beyond optical capabilities, providing insights into:
  - vegetation structure
  - soil conditions
  - urban environments

InSAR

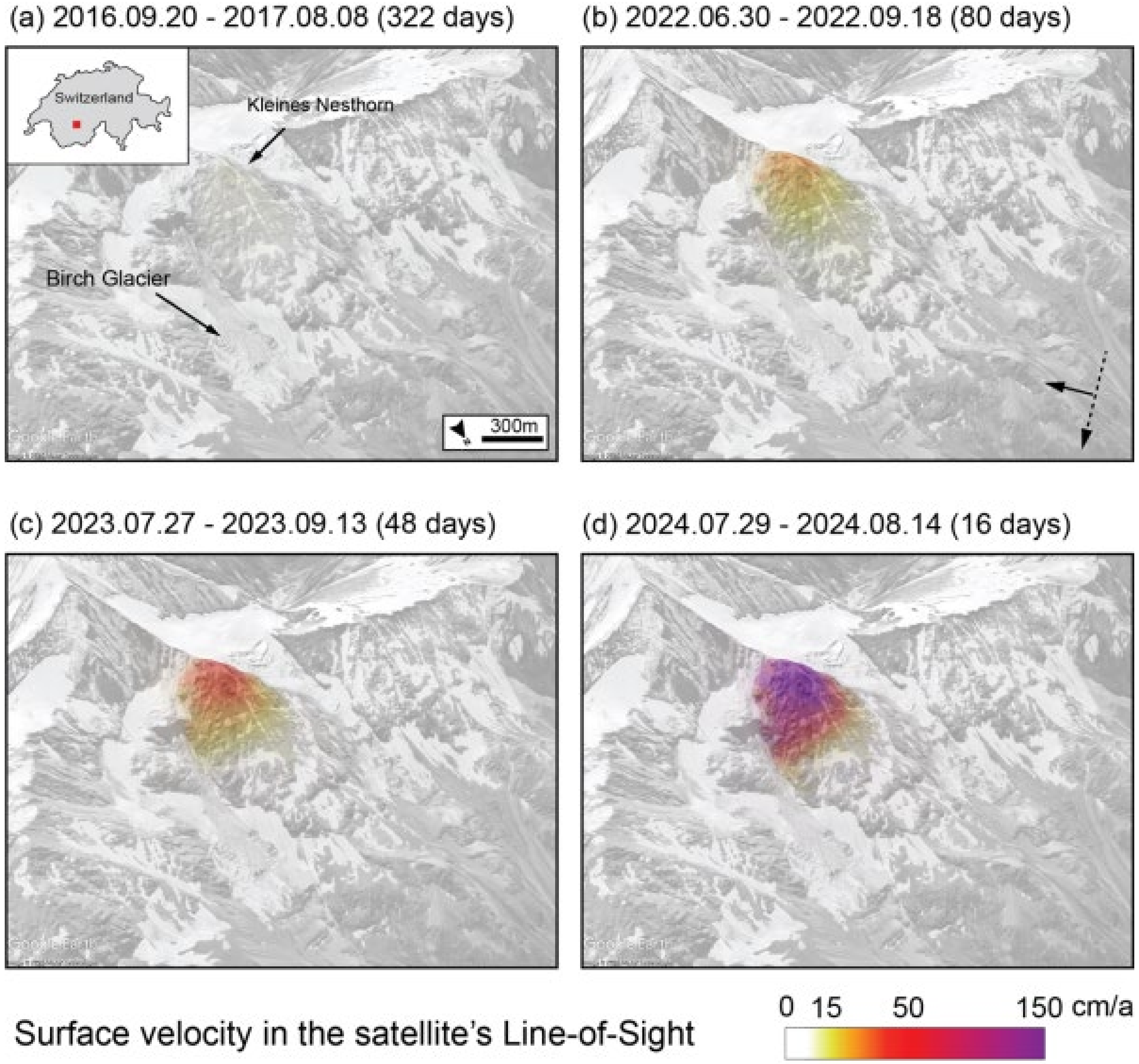


Geocoded Gorkha earthquake interferogram mapped in QGIS. The interferogram is used measure and map ground deformation with very high precision (Flores et al., 2019).

Closely spaced fringes → larger deformation gradients (the ground is moving more abruptly over short distances).
Widely spaced fringes → smaller deformation gradients (the ground is moving more smoothly).

- SAR interferometry (InSAR) measures phase differences between acquisitions to derive elevation models and ground deformation with centimeter precision
- Applications: earthquake displacement mapping, volcanic monitoring, glacier velocity measurements
- Interferometric Synthetic Aperture Radar (InSAR) uses phase differences between multiple SAR acquisitions to measure topography and ground deformation
- Provides centimeter- to millimeter-level precision in detecting surface changes
- Sentinel-1 time series enable generation of interferograms, where colored fringes represent subtle displacements over time
- InSAR builds on radar's long history, with innovations like synthetic aperture processing expanding resolution and applicability
- Widely used for monitoring earthquakes, volcanoes, landslides, subsidence, and infrastructure stability
- Time-series methods (PS-InSAR, SBAS-InSAR) achieve millimetric precision over years → critical for infrastructure monitoring and hazard assessment


InSAR Use Case: Blatten, Lötschental



https://eo4society.esa.int/2025/08/08/satellite-radars-reveal-early-signs-of-slope-instability-years-before-blatten-rock-ice-avalanche/

InSAR Use Case: Blatten, Lötschental

- Surface velocity in the satellite's Line-of-Sight (LoS) over the Birch Glacier and Kleines Nesthorn, derived from selected L-band interferograms spanning from 2016 to 2024.
- (a) ALOS 2 PLASAR2 data T096D-F2-5
- (b-d) SAOCOM-1 S4-T213. Images are acquired in descending orbit, right looking mode (see arrows in panel b for reference).
- Velocities range from <15 cm/year (yellow) to >150 cm/year (purple).
- The interferograms reveal increasing velocities in the years before the 2025 rock/ice avalanche occurred.

Polarimetric SAR

- Polarimetric SAR enables scattering decomposition:
- Freeman–Durden model → separates surface, double-bounce, volume scattering
- Yamaguchi model → adds helix scattering for more detailed classification
- These approaches extend SAR beyond optical capabilities, providing insights into vegetation structure, soil conditions, and urban environments

Coherence Analysis

- Coherence analysis quantifies correlation between acquisitions; loss of coherence signals change (building collapse, flooding, vegetation disturbance) → valuable for disaster monitoring and land cover studies