ENGO 697

Remote Sensing Systems and Advanced Analytics

Session 4: SAR, hyperspectral, passive microwave and LiDAR systems

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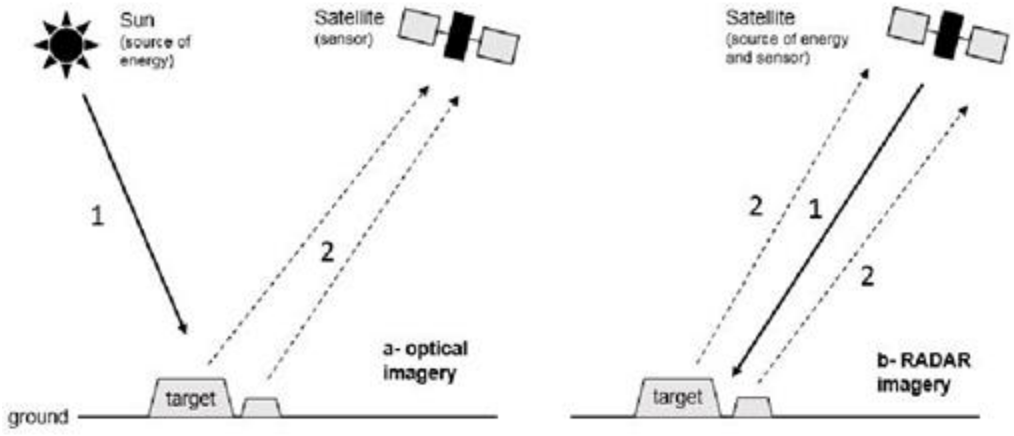
Outline

- ➔ SAR Remote Sensing
- ➔ Passive Microwave
- ➔ Hyperspectral remote sensing
- ➔ LiDAR
- ➔ Questions

Active Microwave Imaging Systems



Passive Imaging System: Detect the *reflected or emitted* electromagnetic radiation from natural sources, e.g., cameras, spectrometer, microwave radiometer, etc.

Active Imaging System: Detected *reflected* responses from objects illuminated by *artificially-generated* energy sources, e.g., real aperture radar, synthetic aperture radar (SAR).

RADAR: Radio Detection and Ranging; 1904 Europeans demonstrated use for detecting ships in fog

SLAR: Side Looking Airborne RADAR, developed during World War II, for all weather, day-and-night aircraft operations;

SAR: Synthetic Aperture RADAR, airborne systems developed in 1950's;

Active sensors work independently with the sun radiation, and can work 24 hours a day.

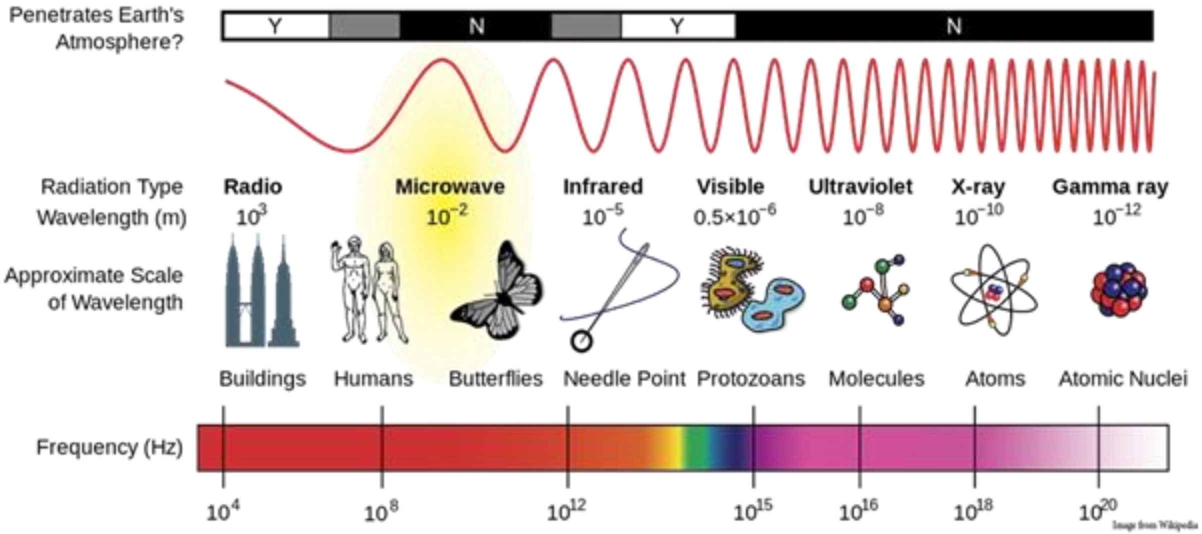
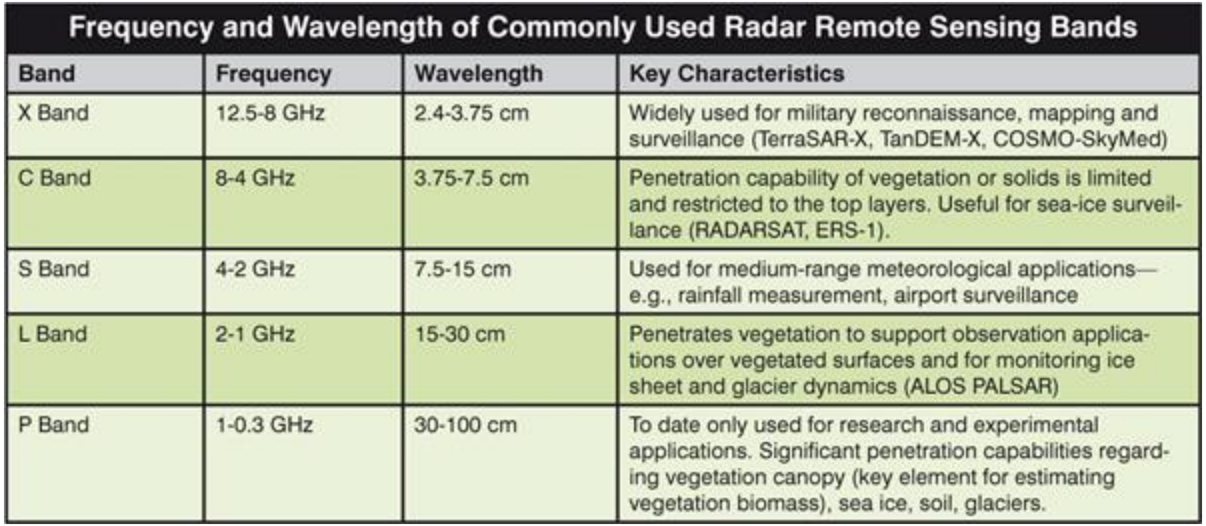


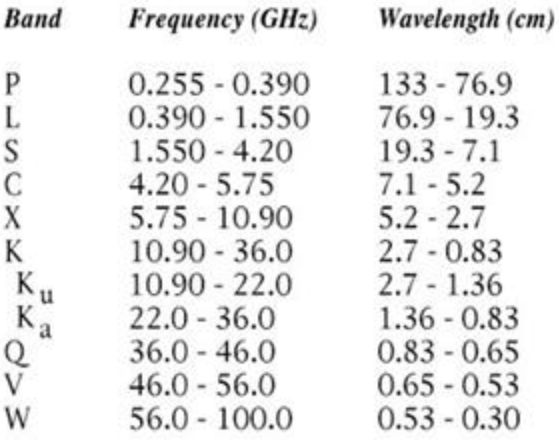
Image from Wikipedia



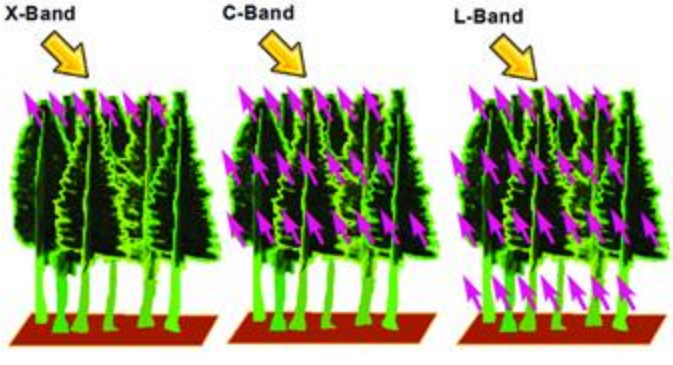
Frequency and Wavelength of Commonly Used Radar Remote Sensing Bands

Band	Frequency	Wavelength	Key Characteristics
X Band	12.5-8 GHz	2.4-3.75 cm	Widely used for military reconnaissance, mapping and surveillance (TerraSAR-X, TanDEM-X, COSMO-SkyMed)
C Band	8-4 GHz	3.75-7.5 cm	Penetration capability of vegetation or solids is limited and restricted to the top layers. Useful for sea-ice surveillance (RADARSAT, ERS-1).
S Band	4-2 GHz	7.5-15 cm	Used for medium-range meteorological applications—e.g., rainfall measurement, airport surveillance
L Band	2-1 GHz	15-30 cm	Penetrates vegetation to support observation applications over vegetated surfaces and for monitoring ice sheet and glacier dynamics (ALOS PALSAR)
P Band	1-0.3 GHz	30-100 cm	To date only used for research and experimental applications. Significant penetration capabilities regarding vegetation canopy (key element for estimating vegetation biomass), sea ice, soil, glaciers.

SAR wavelength, range? What happens if too short, or too long?

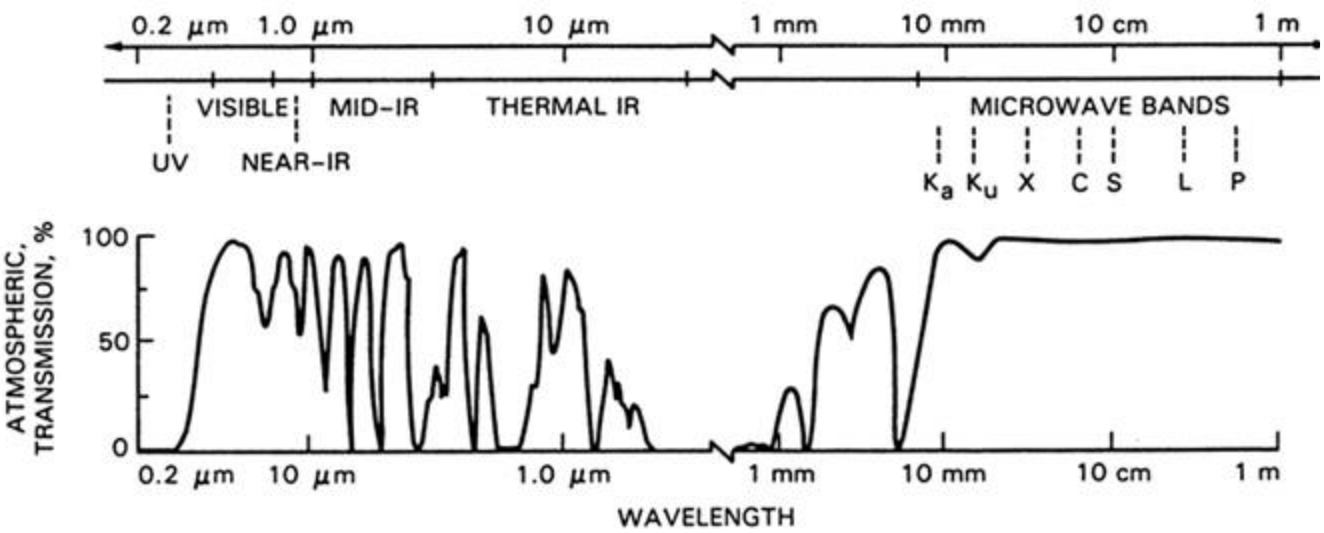


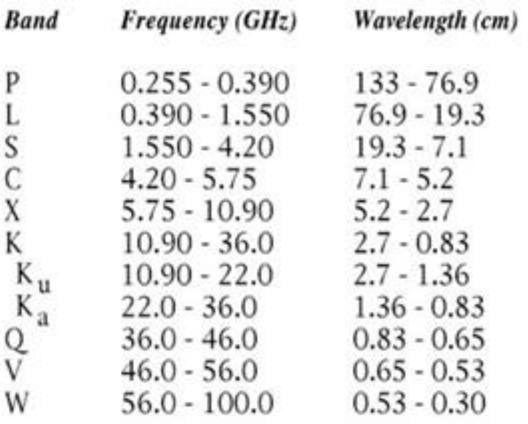
Band	*Frequency (GHz)*	*Wavelength (cm)*
P	0.255 - 0.390	133 - 76.9
L	0.390 - 1.550	76.9 - 19.3
S	1.550 - 4.20	19.3 - 7.1
C	4.20 - 5.75	7.1 - 5.2
X	5.75 - 10.90	5.2 - 2.7
K	10.90 - 36.0	2.7 - 0.83
K_u	10.90 - 22.0	2.7 - 1.36
K_a	22.0 - 36.0	1.36 - 0.83
Q	36.0 - 46.0	0.83 - 0.65
V	46.0 - 56.0	0.65 - 0.53
W	56.0 - 100.0	0.53 - 0.30



X-band: 3.75–2.5 cm; C-band: 7.5–3.75 cm; L-band: 30–15 cm

Why Q, V, W, K bands are rarely used in SAR?





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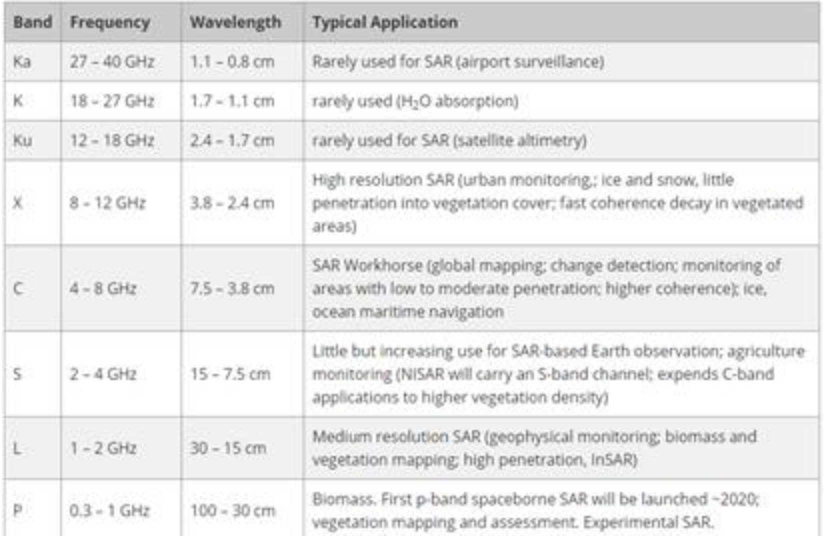
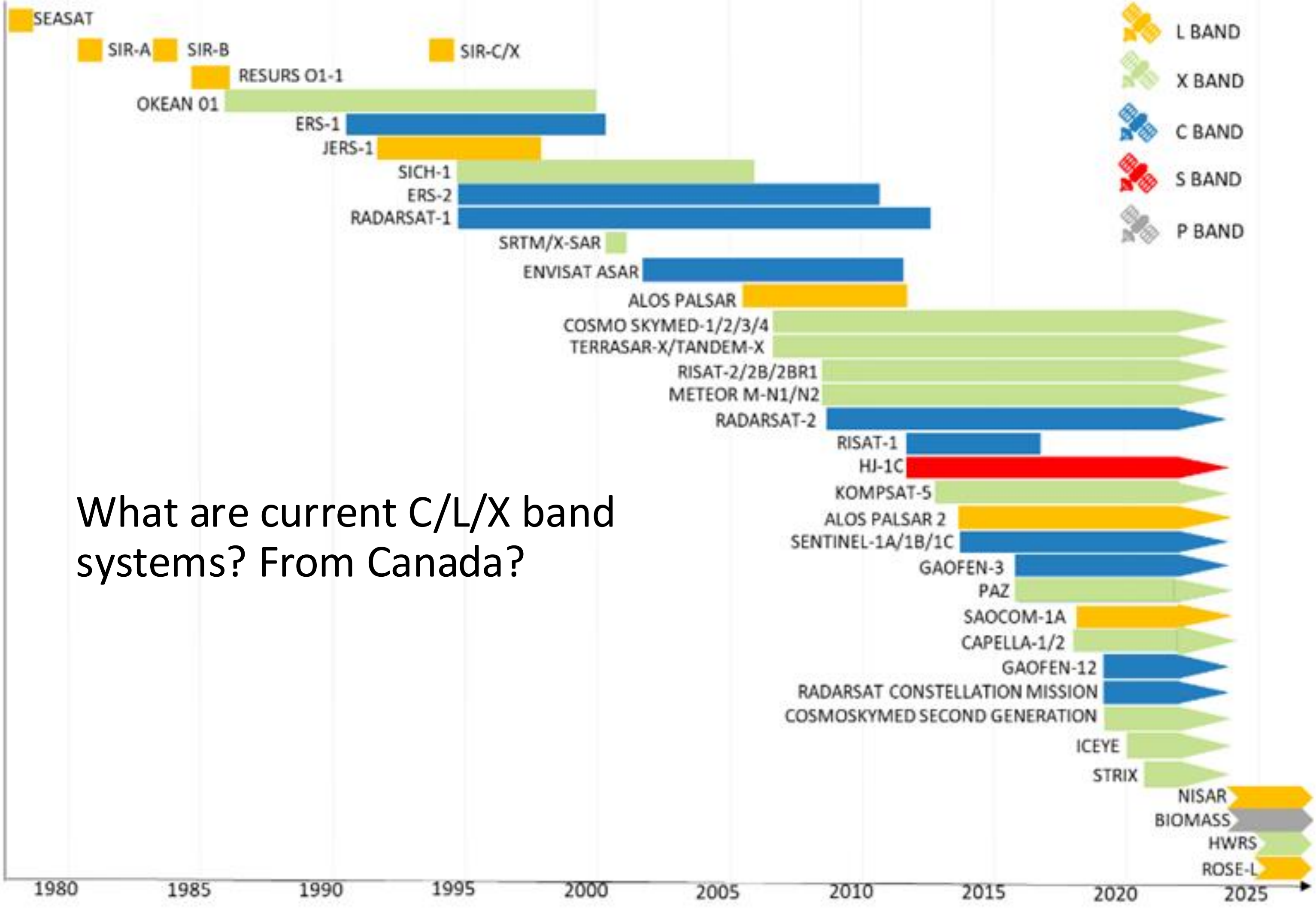
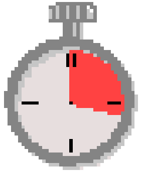


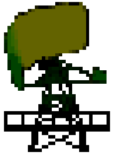
Band	Frequency	Wavelength	Typical Application
Ka	27 – 40 GHz	1.1 – 0.8 cm	Rarely used for SAR (airport surveillance)
K	18 – 27 GHz	1.7 – 1.1 cm	rarely used (H_2O absorption)
Ku	12 – 18 GHz	2.4 – 1.7 cm	rarely used for SAR (satellite altimetry)
X	8 – 12 GHz	3.8 – 2.4 cm	High resolution SAR (urban monitoring,; ice and snow, little penetration into vegetation cover; fast coherence decay in vegetated areas)
C	4 – 8 GHz	7.5 – 3.8 cm	SAR Workhorse (global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence); ice, ocean maritime navigation
S	2 – 4 GHz	15 – 7.5 cm	Little but increasing use for SAR-based Earth observation; agriculture monitoring (NISAR will carry an S-band channel; expends C-band applications to higher vegetation density)
L	1 – 2 GHz	30 – 15 cm	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)
P	0.3 – 1 GHz	100 – 30 cm	Biomass. First p-band spaceborne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR.

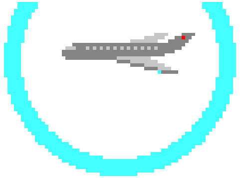


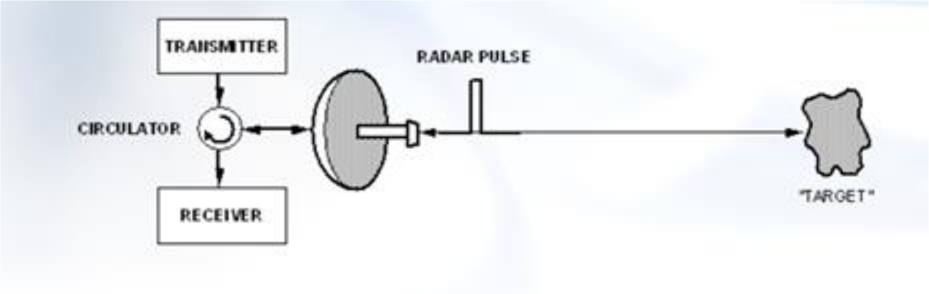
What are current C/L/X band systems? From Canada?

Radar - How to measure distance and detect?



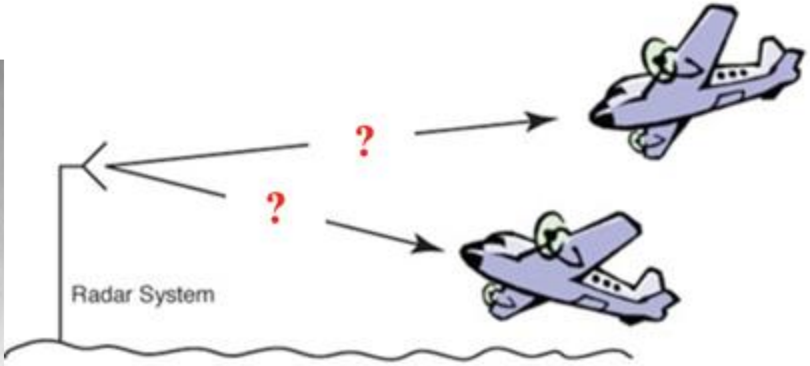


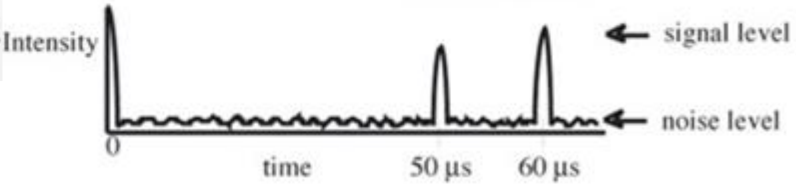


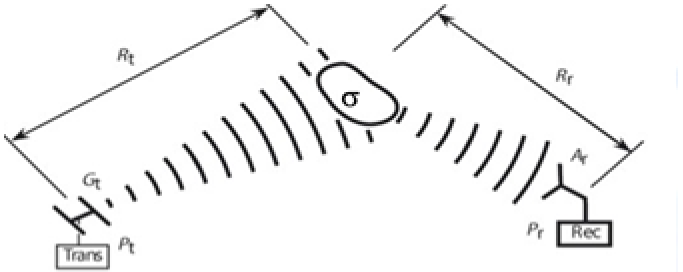


- **RA**DAR = **Ra**dio **D**etection **A**nd **R**anging
- Since radar pulses propagate at the speed of light, the difference to the "target" is proportional to the time it takes between the transmit event and reception of the radar echo

Radar - Which one closer? Why intensities different?







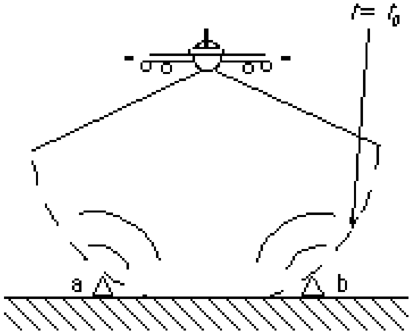
$$Pr = \frac{P_t}{4\pi R_t^2} \times G_t \times \sigma \times \frac{1}{4\pi R_r^2} \times A_r$$

- G_t is the "Antenna Gain";
- σ is the "cross section" of the target.

Radar equation describe Pr (i.e., the power returned to the receiving antenna) as a function of distances, scattering properties of the target (cross section), sending power intensity, and antenna gain (the extend to which the antenna is directionally sending out signal).

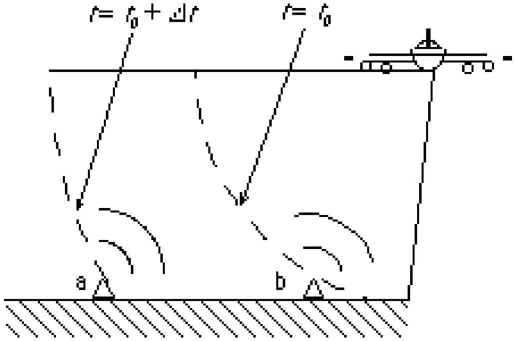
SAR: Side Looking System

Side-looking vs. nadir-looking, which one can discriminate target a from b?



(a)

The ambiguity associated with a nadir-looking radar.



(b)

Side-looking geometry resolves the ambiguity

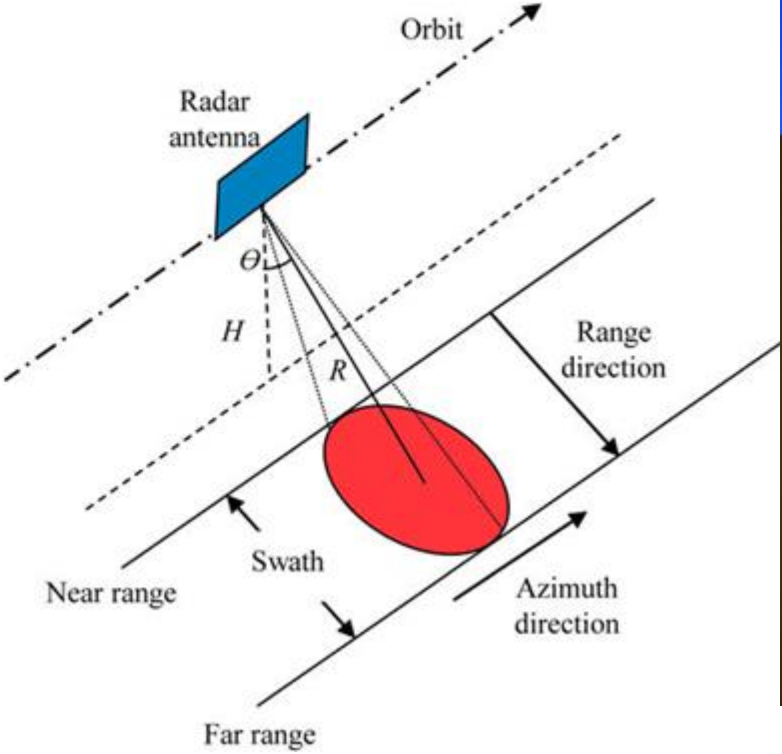
(https://www.csr.utexas.edu/rs/sensors/whatissar/rar.html)

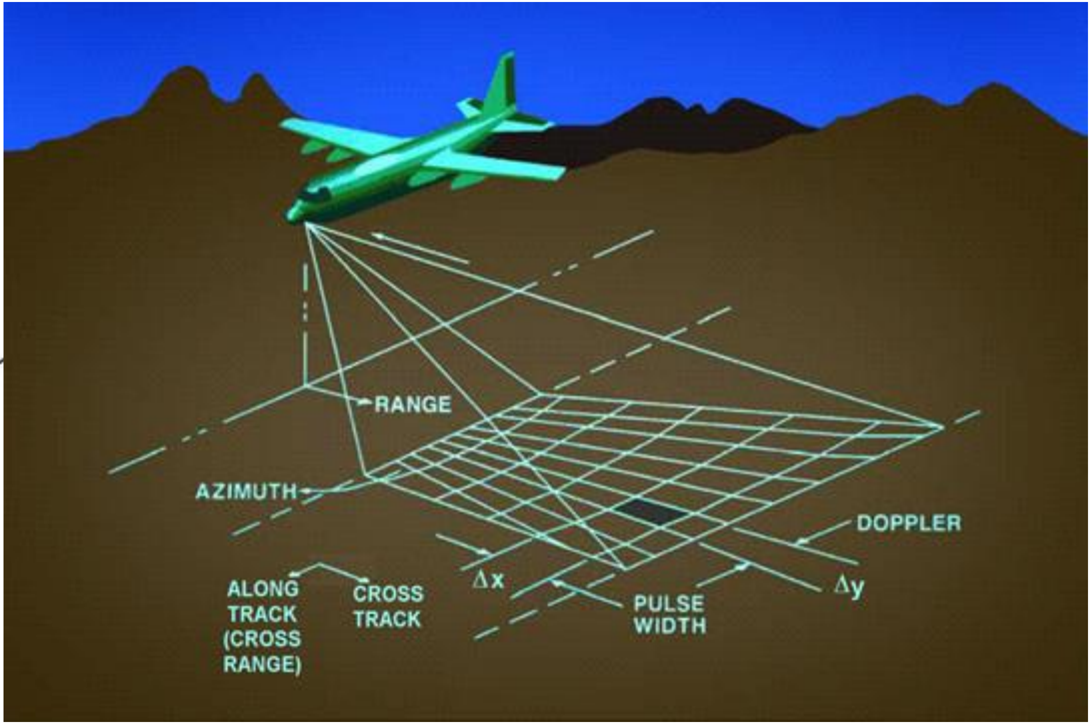
SAR and RADAR use distance (i.e., the arrival time of the received signal) to discriminate positions of the targets.

Fig. (a) -- down-looking or nadir-looking, two targets have equal distance --> signal returns to antenna simultaneously → antenna cannot discriminate the two targets.

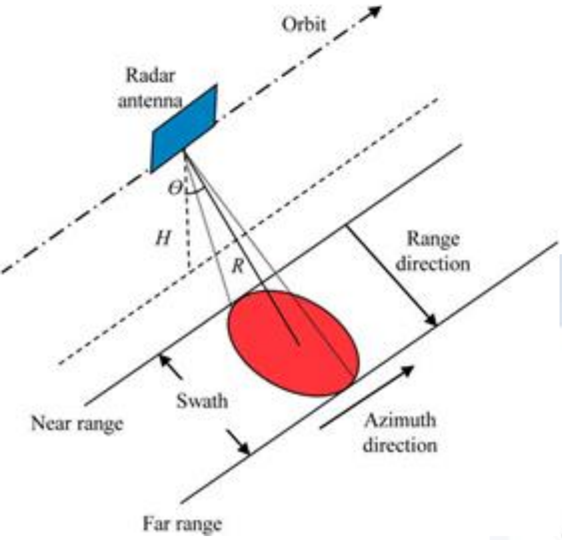
Fig. (b) -- side-looking, two targets have different distances --> signal returns to antenna at different times → antenna can discriminate the two targets.

Radar Geometry - Range? Azimuth? Swath? Resolution cell?

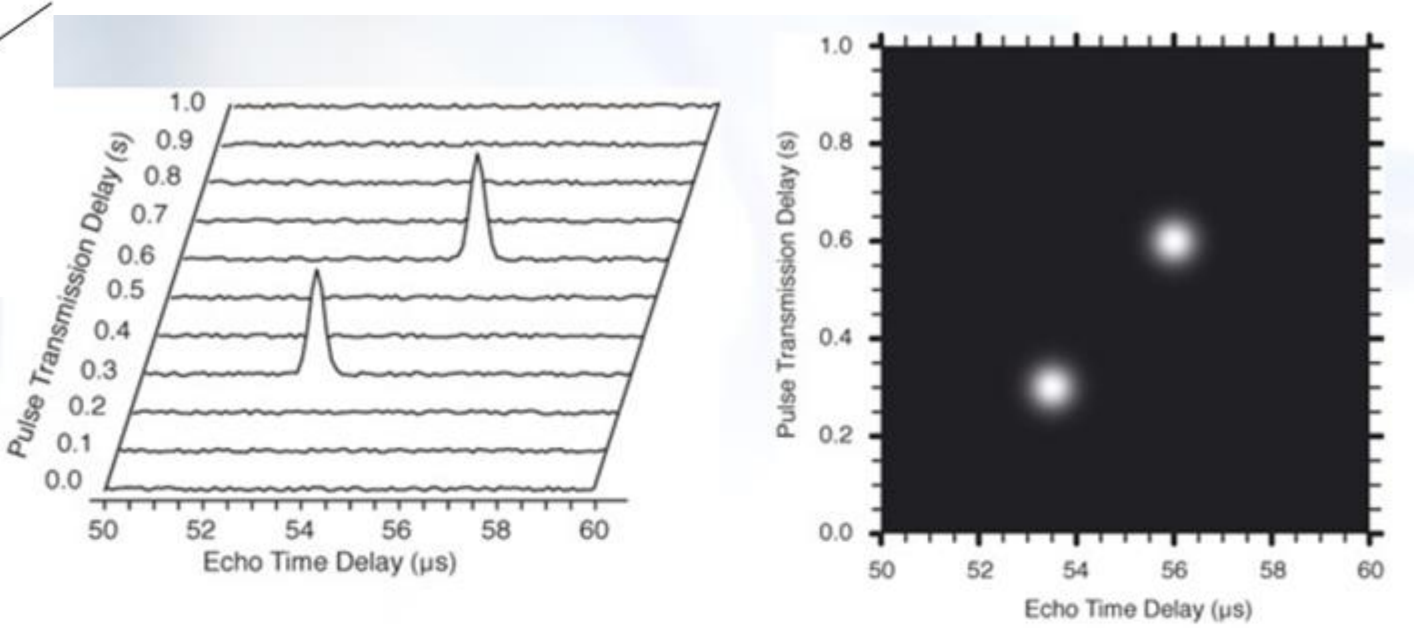




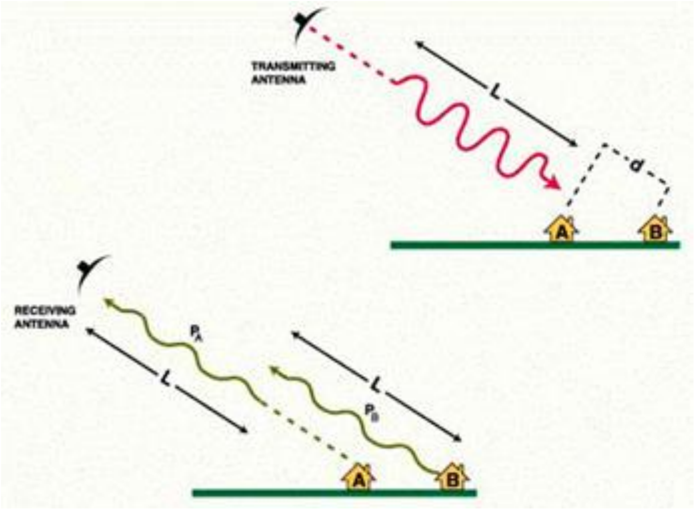
Imaging Radar - How to get an image?



Between these two white spots (two targets), which one is closer to the sensor? Which one is detected earlier?



Range Reolution - Can Radar discriminate A from B



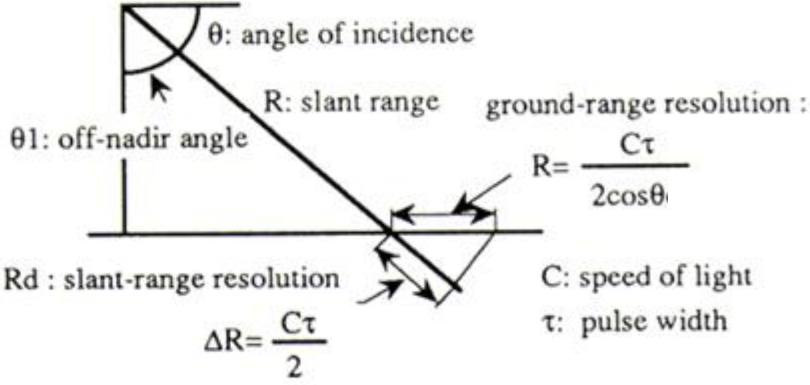
For the radar to be able to distinguish A and B, their echoes PA and PB must be received at different times.

If **L** (i.e., the pulse length) and **d** (i.e., the slant range distance between A and B) satisfy:

L < 2**d**

PA and **PB** would not overlap and the two signals would be recorded separately.

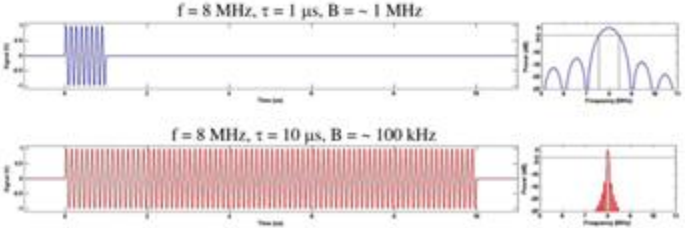
So, Radar range resolution (across track resolution) is equal to **L/2**, meaning that., shorter **L** (shorter duration, or bigger frequency B which is also called bandwidth) leads to higher discrimination capability.



$$R = \frac{C\tau}{2\cos\theta}$$

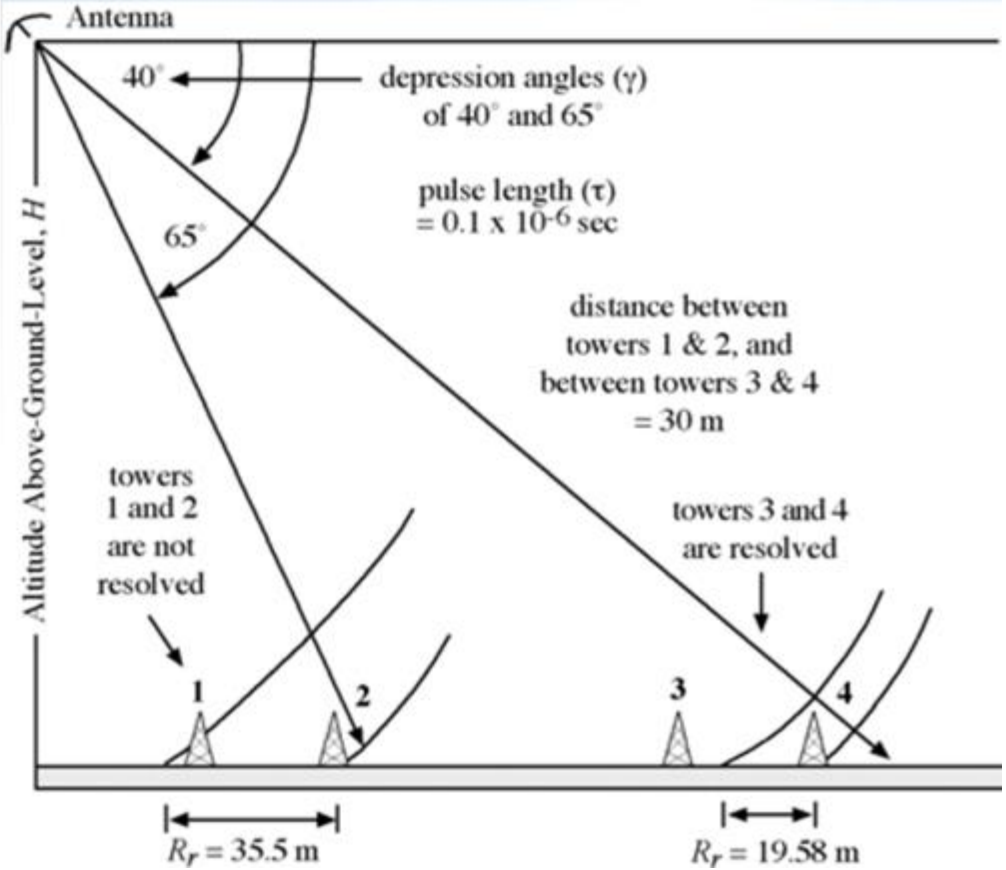
$$\Delta R = \frac{C\tau}{2}$$

Pulses with short durations have wide bandwidths whereas pulses with long durations have narrow bandwidths.



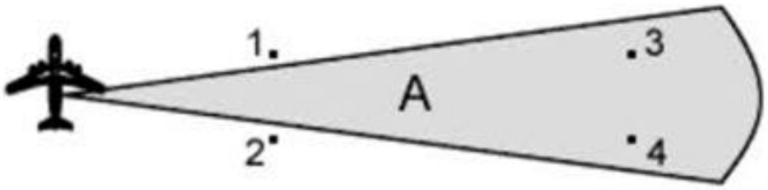
$$B \cong \frac{1}{\tau} \text{ [Hz]}$$

$$R_r = \frac{\tau c}{2\cos\gamma} = \frac{\text{pulse length} \times \text{speed of light}}{2\cos(\text{depression angle})}$$



Why far-range has higher resolution than near-range?

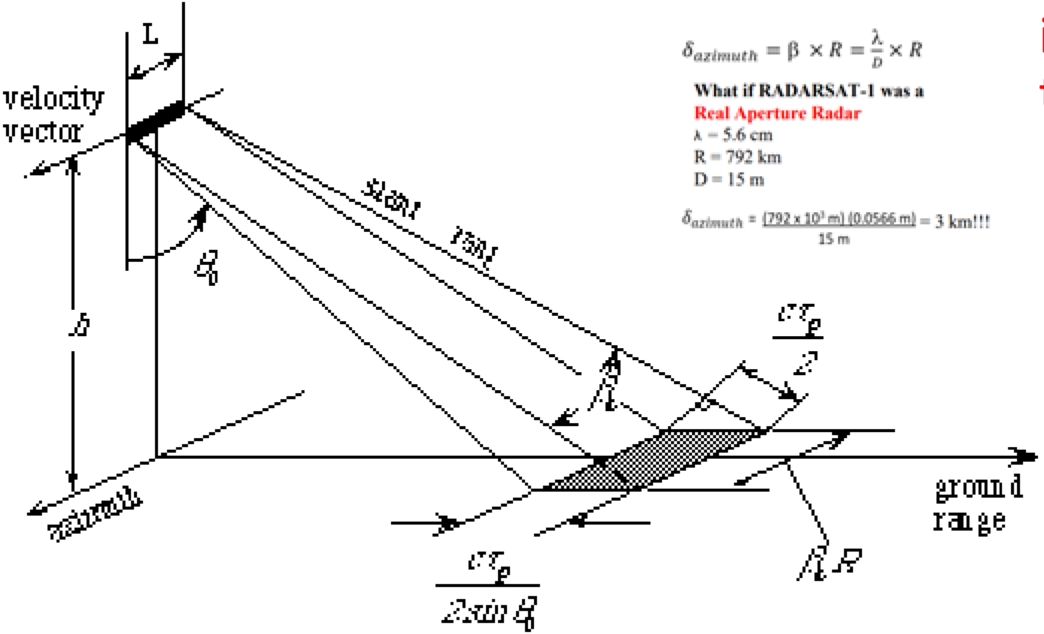
Azimuth Reolution - Can Radar discriminate target 3 from target 4?



© CCRS / CCT

Can Radar discriminate target 1 from target 2? Beam-width, Why near range has higher azimuth-resolution?

How does antenna length D influence azimuth resolution? How to get higher resolution?

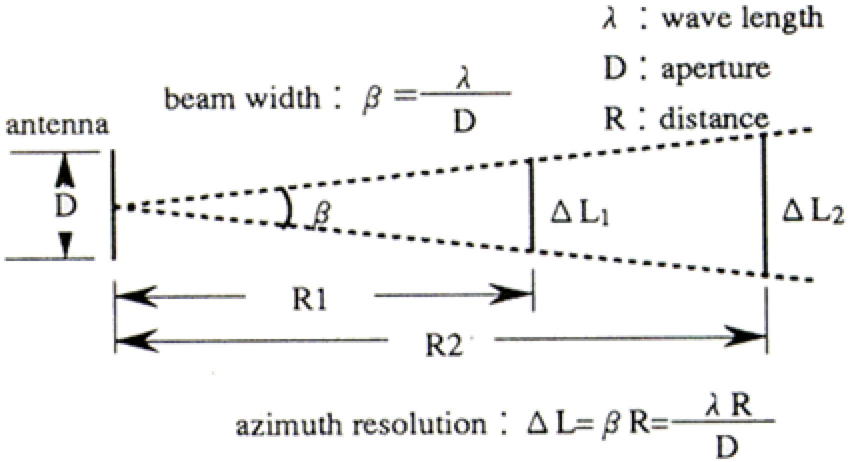


$$\delta_{azimuth} = \beta \times R = \frac{\lambda}{D} \times R$$

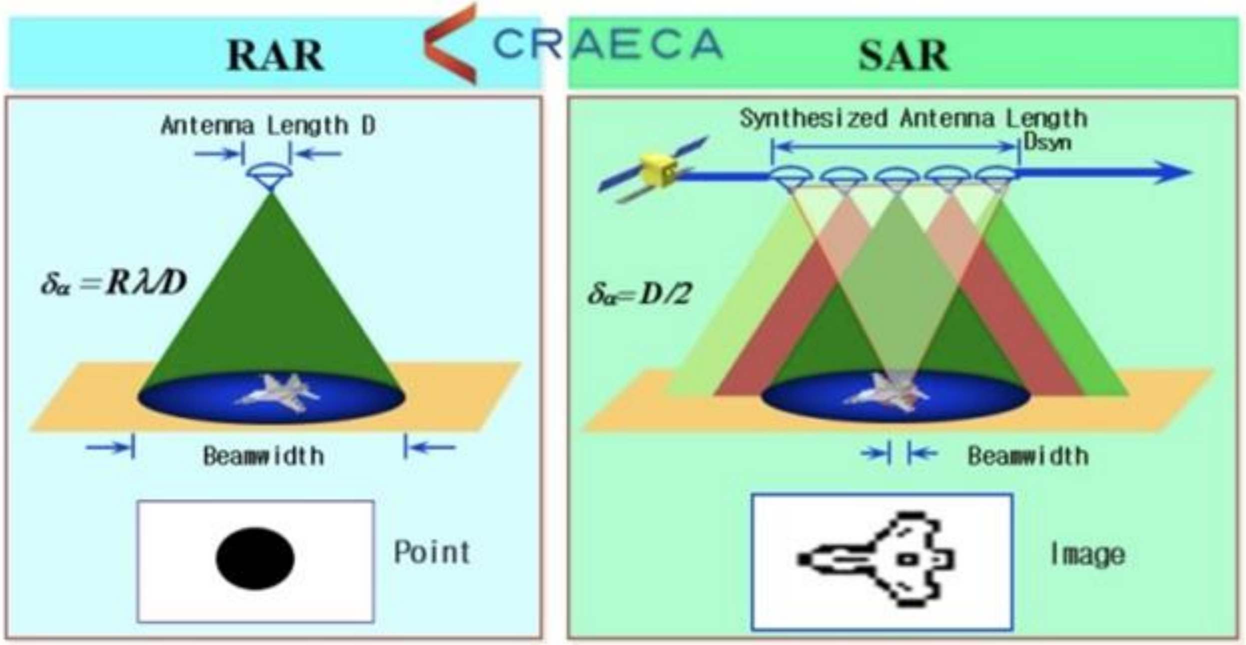
What if RADARSAT-1 was a
Real Aperture Radar

$\lambda = 5.6$ cm
R = 792 km
D = 15 m

$$\delta_{azimuth} = \frac{(792 \times 10^3\ \text{m})(0.0566\ \text{m})}{15\ \text{m}} = 3\ \text{km!!!}$$



How does SAR synthesizes an extremely long antenna to improve azimuth resolution?



Resolution

- Range $\delta_p = c/2B \sin\theta$ (Wide Bandwidth)
- Azimuth $\delta_a = R\lambda / D_{syn}$ (Beam Synthesis)

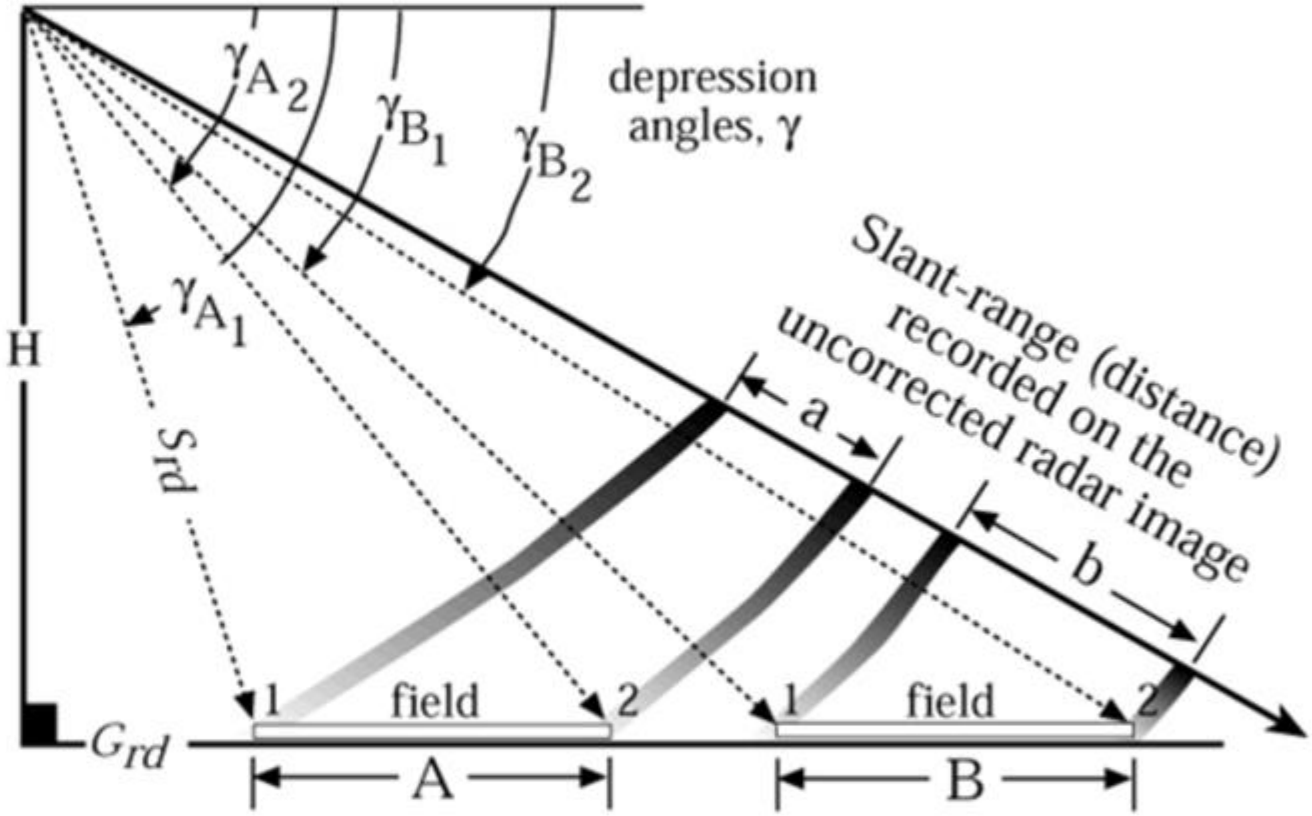
The SAR works similar of a phased array, but contrary of a large number of the parallel antenna elements of a phased array, SAR uses one antenna in time-multiplex. The different geometric positions of the antenna elements are result of the moving platform now.

The SAR-processor stores all the radar returned signals, as amplitudes and phases, for the time period *T* from position A to D. Now it is possible to reconstruct the signal which would have been obtained by an antenna of length $v \cdot T$, where v is the platform speed. As the line of sight direction changes along the radar platform trajectory, a synthetic aperture is produced by signal processing that has the effect of lengthening the antenna. Making *T* large makes the „synthetic aperture" large and hence a higher resolution can be achieved.

As a target (like a ship) first enters the radar beam, the backscattered echoes from each transmitted pulse begin to be recorded. As the platform continues to move forward, all echoes from the target for each pulse are recorded during the entire time that the target is within the beam. The point at which the target leaves the view of the radar beam some time later, determines the length of the simulated or synthesized antenna. The synthesized expanding beamwidth, combined with the increased time a target is within the beam as ground range increases, balance each other, such that the resolution remains constant across the entire swath.

The achievable azimuth resolution of a SAR is approximately equal to one-half the length of the actual (real) antenna and does not depend on platform altitude (distance).

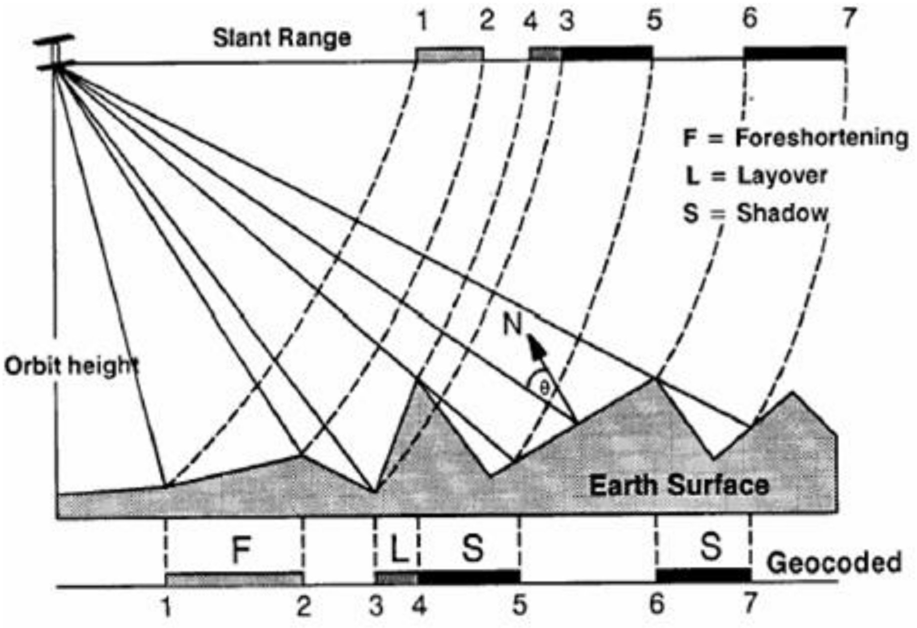
Slant-Range Display versus Ground-Range Display

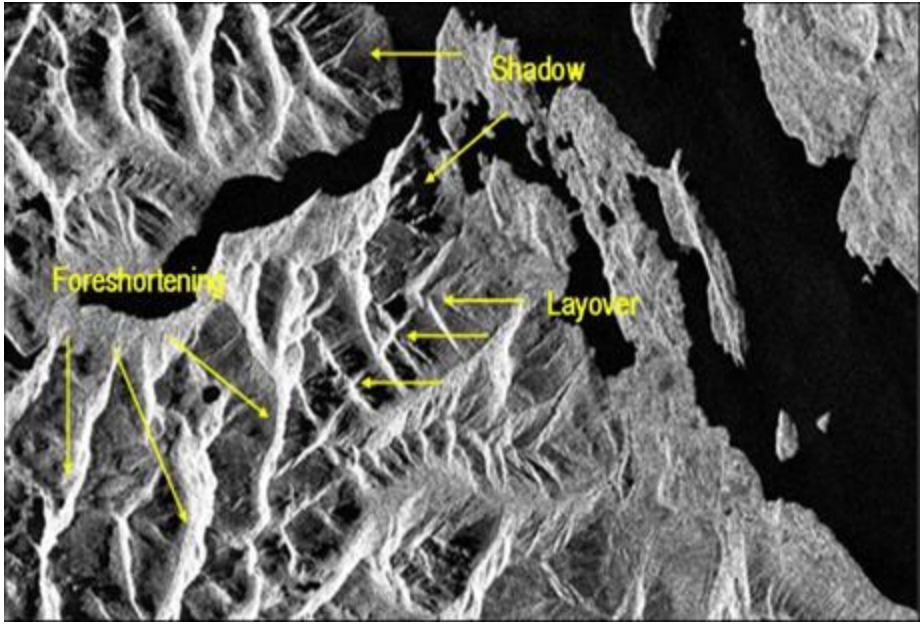


Ground-range (distance) on corrected radar image

Radar records slant-range distances, which need to be transformed to ground-range distances to correct the image.

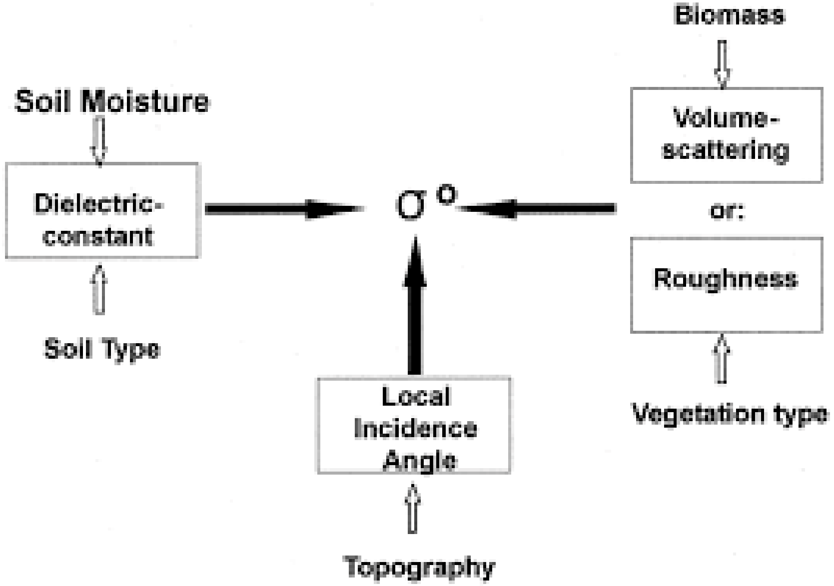
Geometric Effects: Foreshortening, Layover and Shadow





RADAR measures the distance to targets in slant-range rather than the true horizontal distance along the ground.
(1) Foreshortening: the base 1 and the top 2 are closer in slant range, and the slope appears "compressed" on SAR image;
(2) Layover: the top 4 is closer to radar than the base, and the slope appears "reversed" on SAR image; Layover looks similar to foreshortening on SAR image;
(3) Shadow: the radar beam cannot illuminate some areas due to vertical features or slopes;

Radar Equation: Backscattering



Soil Moisture

Dielectric-constant

Soil Type

σ^o

Local Incidence Angle

Topography

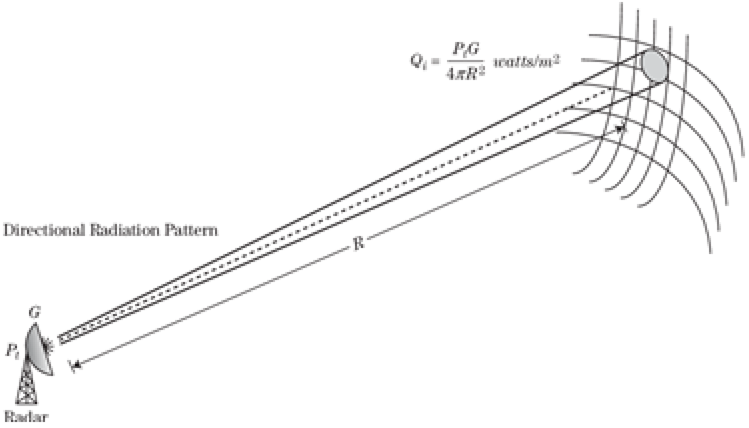
Biomass

Volume-scattering

or:

Roughness

Vegetation type



$$P_r = \frac{\sigma\, G^2\, \lambda^2}{(4\pi)^3\, R^4} \times P_t$$

P_r (Watts [1 joule/second]) is the power received by the antenna from the target at polarization *r*

P_t (Watts [1 joule/second]) is the power transmitted by the antenna toward the target at polarization *t*

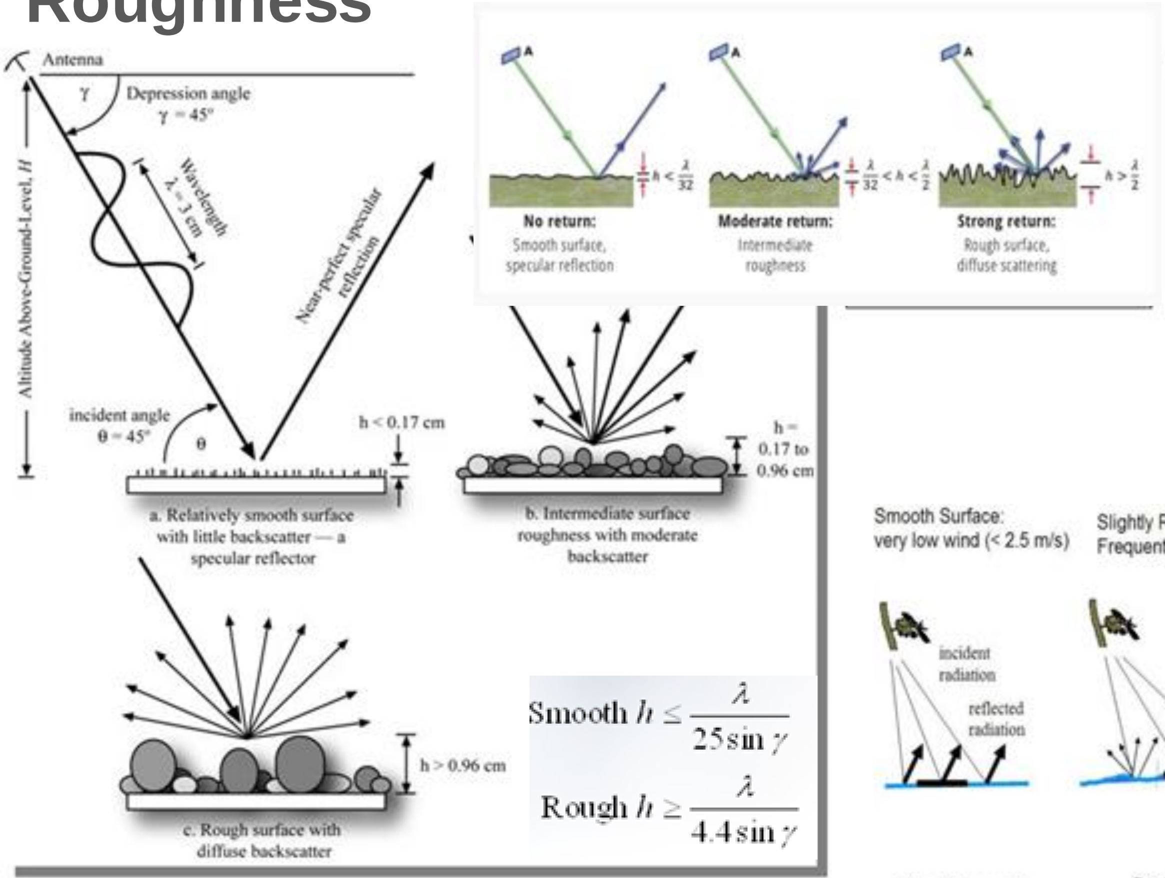
λ (meter) is the microwaves wavelength

G (unitless) is the gain of the radar antenna that describes the antenna's:

- Directivity: ratio of the power produced by the antenna to the power produced by a hypothetical isotropic antenna
- Electrical efficiency: how well the antenna converts input electrical power into transmitted microwaves in direction of the target; converts scattered microwaves arriving from the target direction into electrical power

σ (m^2) is the target radar cross section defined as a measure of the size and ability of the target to reflect received microwaves toward the direction of the radar antenna

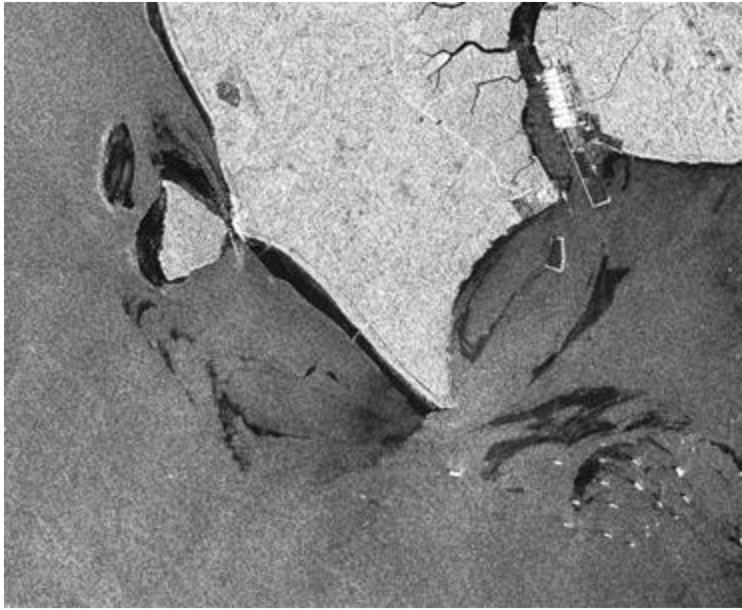
Influence of Surface Roughness

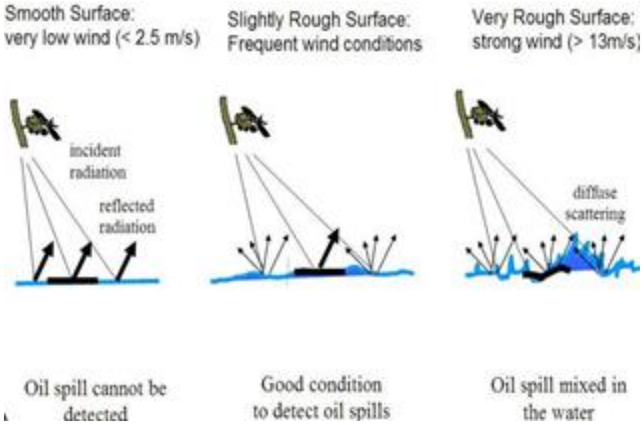


Smooth $h \le \dfrac{\lambda}{25\sin\gamma}$

Rough $h \ge \dfrac{\lambda}{4.4\sin\gamma}$

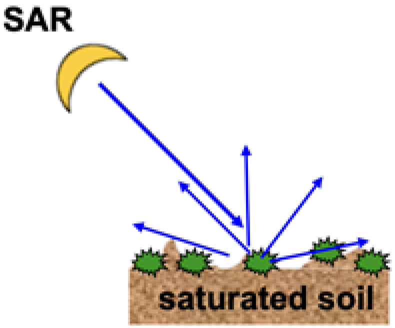
Jensen, 2008





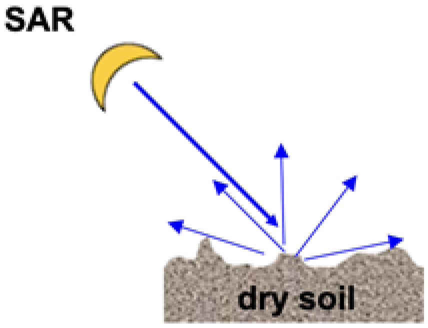
Oil spills -->
smooth surface -->
low backscattering
--> dark-spots on SAR image

How does dielectric constant influence SAR backscattering



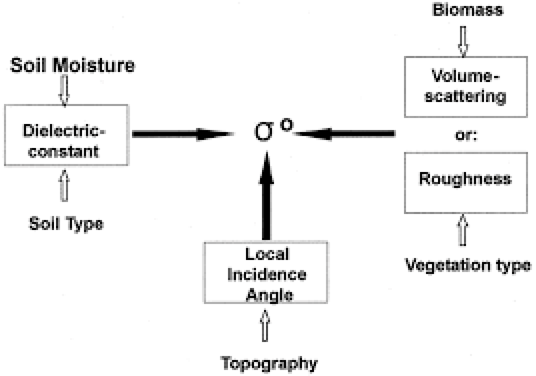
High dielectric constant,
more energy reflected

HIGH BACKSCATTER

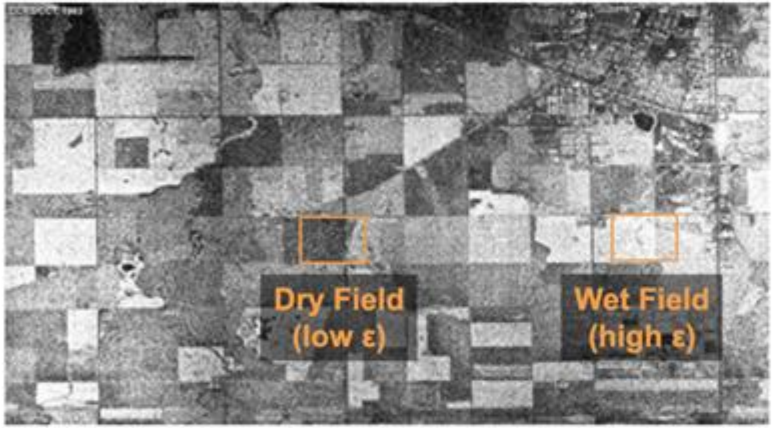


Low dielectric constant,
little energy reflected

LOW BACKSCATTER



Material	ε	Material	ε
Sea water	81	Rock	5-8
Fresh water	81	Debris	12-30
Wet earth	10	Hardpan	4-7
Dry earth	5	Soil (sandy, dry)	4-6
Sand (saturated)	10-30	Soil (sandy, wet)	15-30
Sand (dry)	4-6	Soil (loamy, dry)	4-6
Snow	2	Soil (loamy, wet)	10-20
Glacier ice	3	Permafrost	4-8
Ice	3.5		



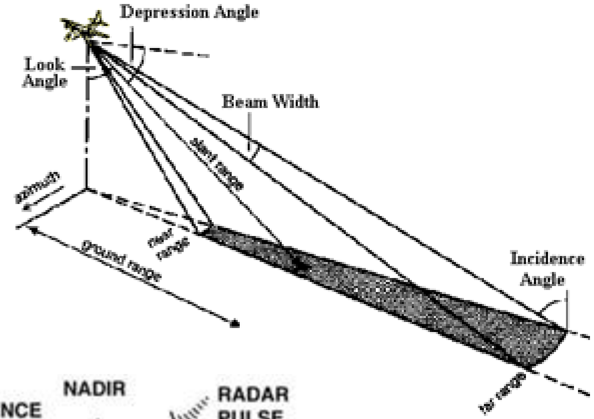
Fields near Melfort, Saskatchewan, as observed by CCRS Airborne SAR

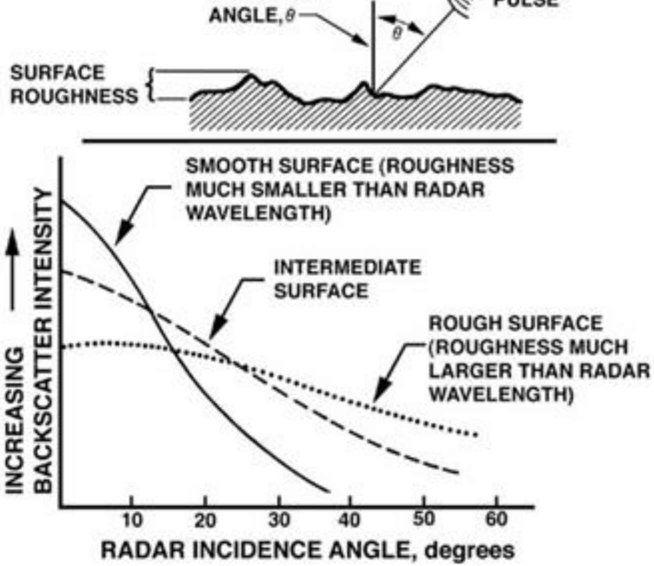
SAR -- Incidence Angle Effect

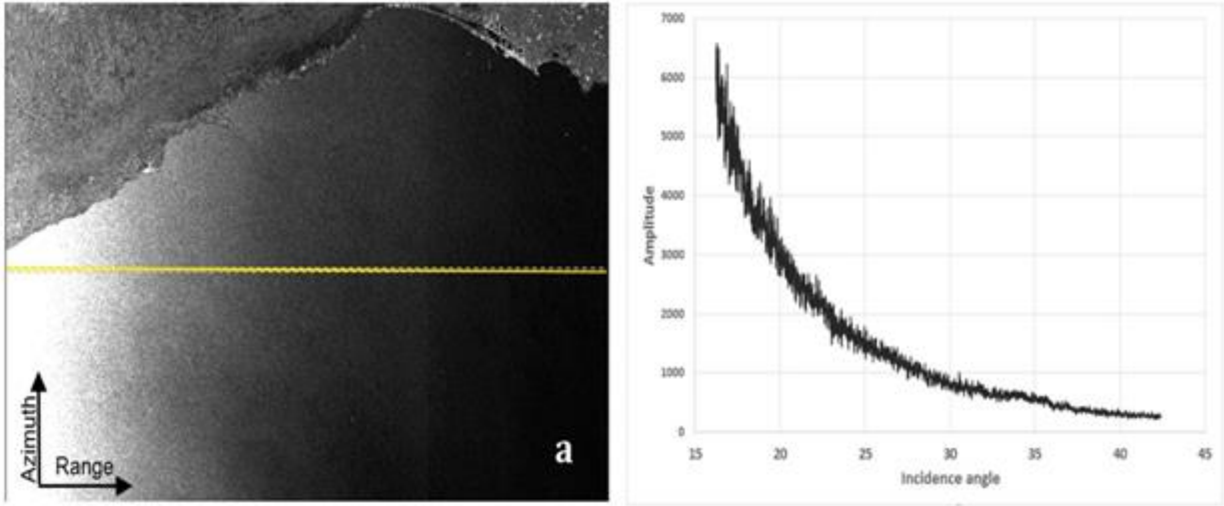
(1) Local incidence angle (LIA) increases from near range to far range;

(2) Smaller LIA leads to stronger backscattering;

(3) Rough surface is less influenced by LIA;

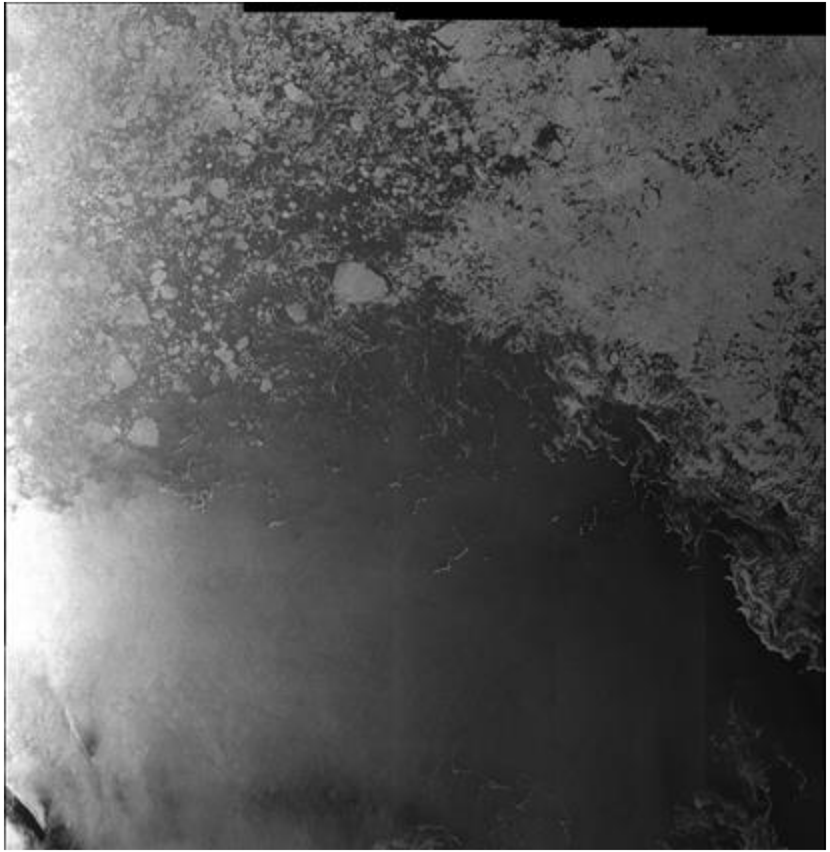




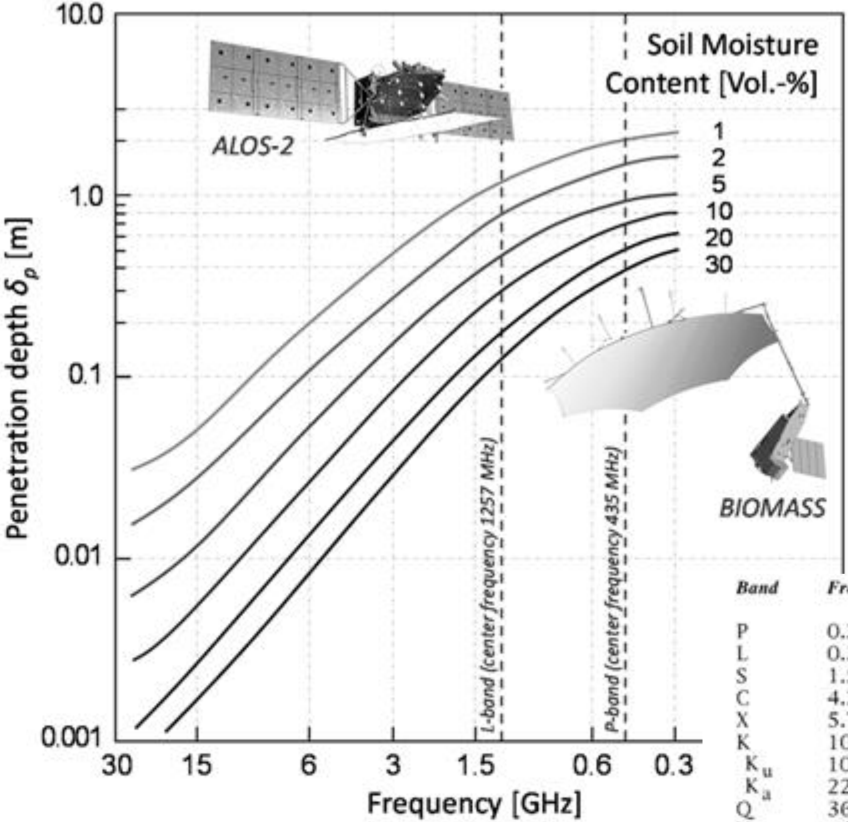


An example of ENVISAT ASAR Wide Swath Mode over sea area (Topouzelis etc. 2016).

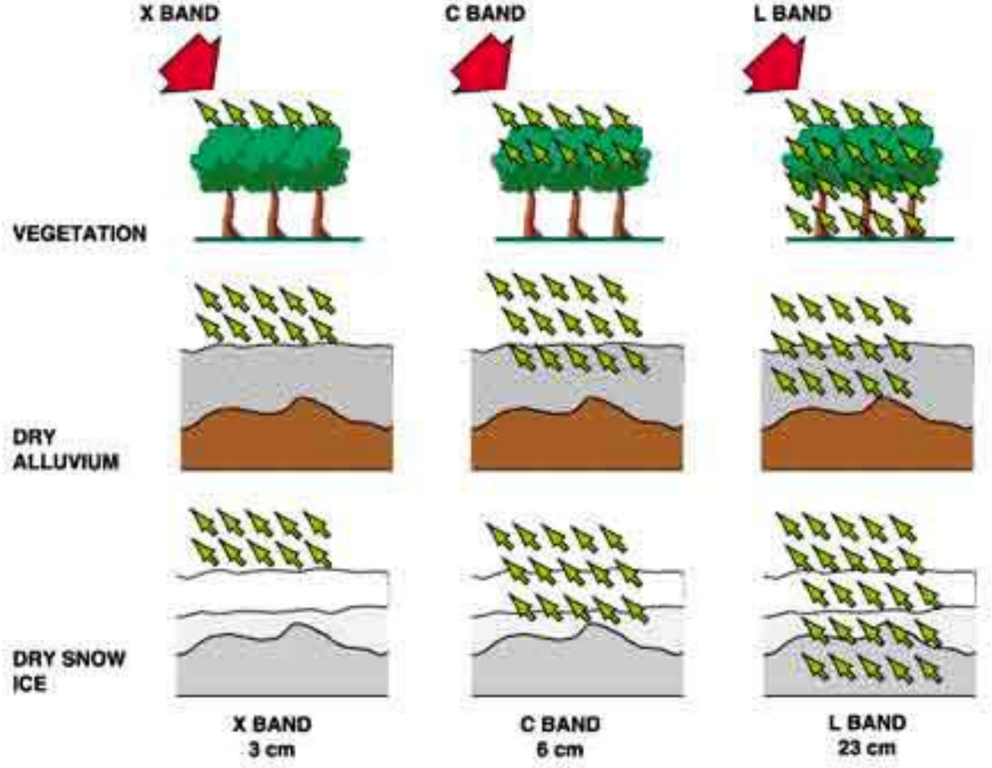
Strong “incidence angle effect” in HH

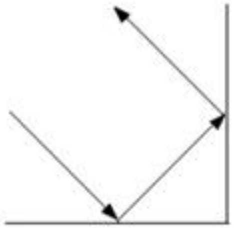


Penetration depth ← Dielectric constent + Wavelength

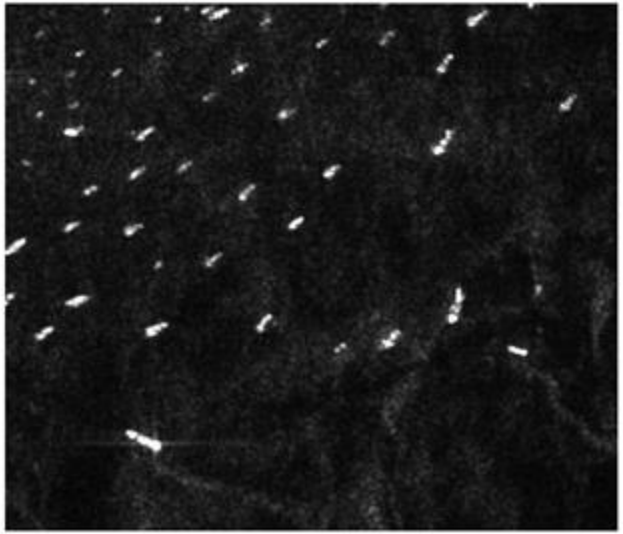


Band	*Frequ*	
P	0.25	
L	0.39	
S	1.55	
C	4.20	
X	5.75	
K	10.9	
K_u	10.9	
K_a	22.0	
Q	36.0 - 46.0	0.83 - 0.65
V	46.0 - 56.0	0.65 - 0.53
W	56.0 - 100.0	0.53 - 0.30

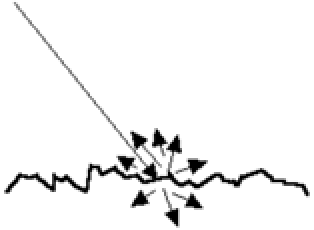




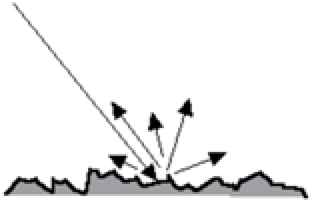
Corner Reflection: When two smooth surfaces form a right angle facing the radar beam, the beam bounces twice off the surfaces and most of the radar energy is reflected back to the radar sensor.



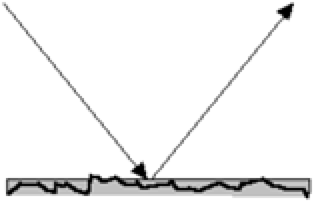
This SAR image shows an area of the sea near a busy port. Many ships can be seen as bright spots in this image due to corner reflection. The sea is calm, and hence the ships can be easily detected against the dark background.



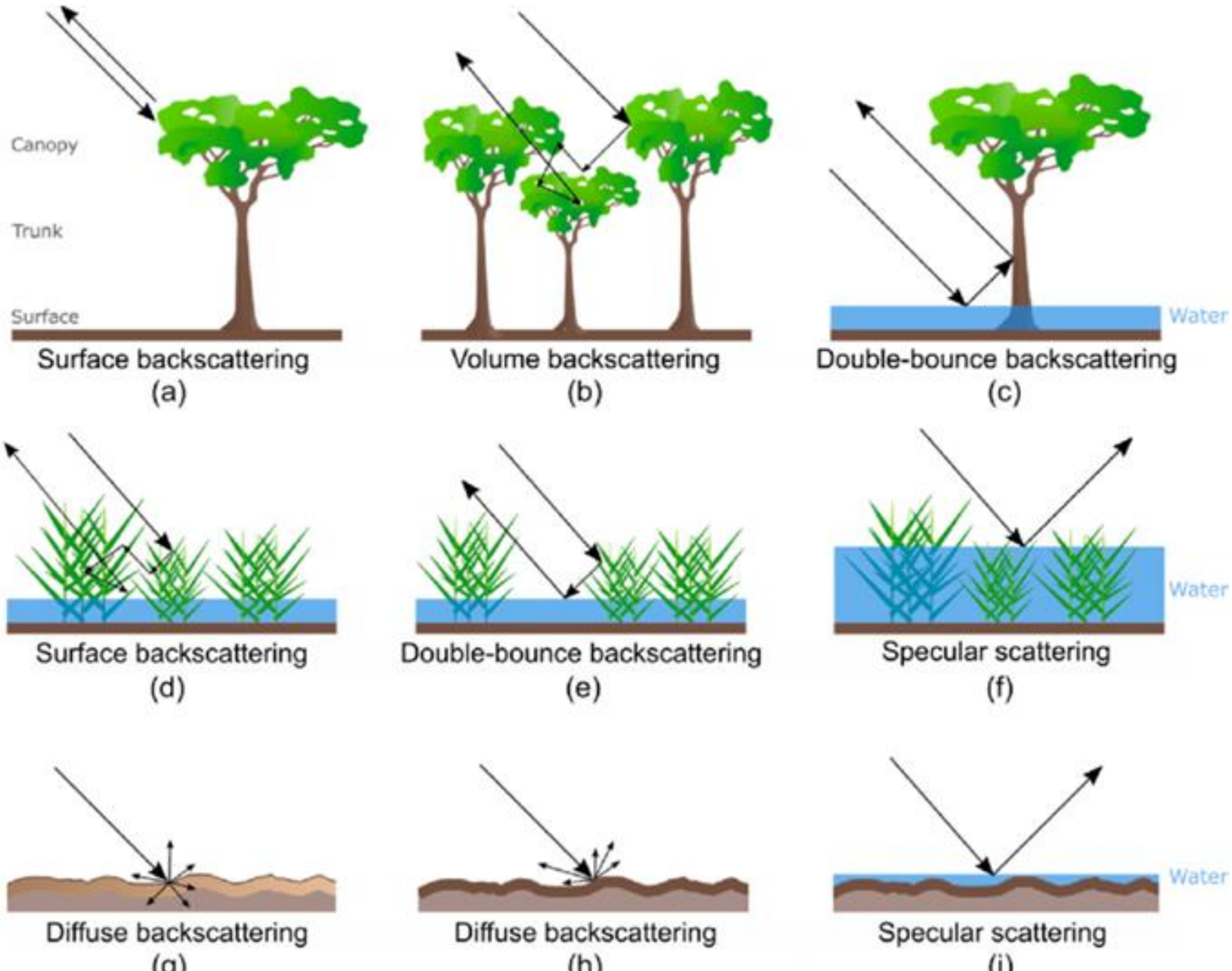
Dry Soil: Some of the incident radar energy is able to penetrate into the soil surface, resulting in less backscattered intensity.



Wet Soil: The large difference in electrical properties between water and air results in higher backscattered radar intensity.



Flooded Soil: Radar is specularly reflected off the water surface, resulting in low backscattered intensity. The flooded area appears dark in the SAR image.



Surface backscattering (a)

Volume backscattering (b)

Double-bounce backscattering (c)

Surface backscattering (d)

Double-bounce backscattering (e)

Specular scattering (f)

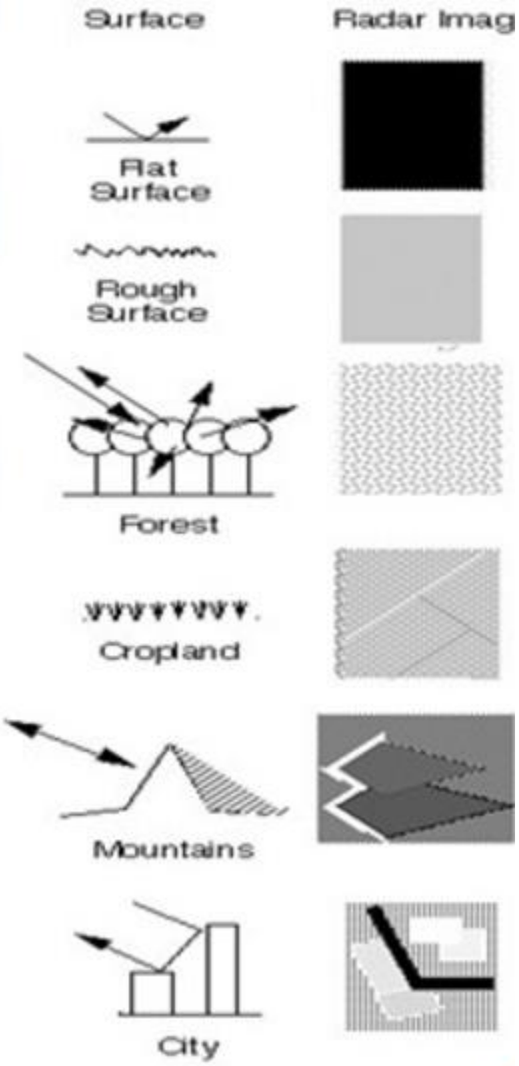
Diffuse backscattering (g)

Diffuse backscattering (h)

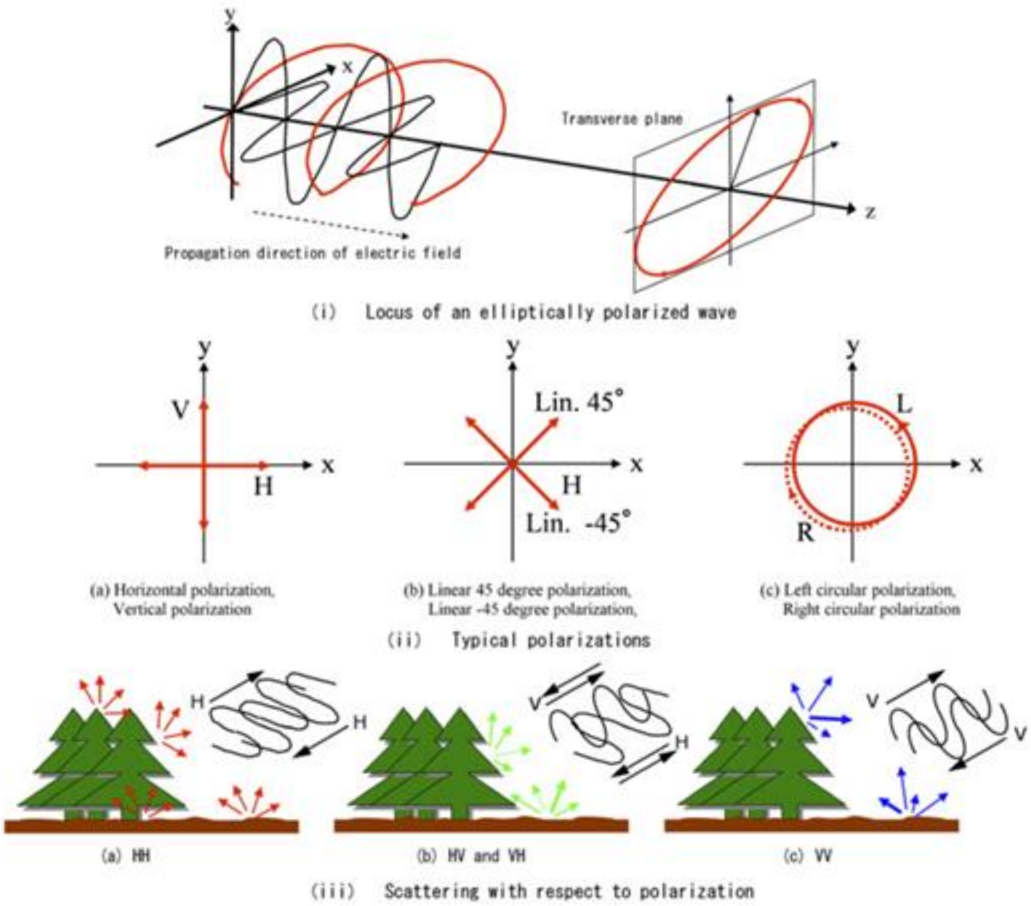
Specular scattering (i)

Radar backscattering mechanisms for forest, wetland and soil surfaces. (a,b,g,h): Nonflooded condition; signal scattering in the crown and on the ground. (c-f,i): submerged wetland/open water; strong double-bounce reflection between the tree trunks and the water surface. (g-i): Ground surface in wet (g), dry (h) and flooded conditions

San Fransisco 1950's



SAR Polarization



(i) Locus of an elliptically polarized wave

(a) Horizontal polarization, Vertical polarization

(b) Linear 45 degree polarization, Linear -45 degree polarization,

(c) Left circular polarization, Right circular polarization

(ii) Typical polarizations

(iii) Scattering with respect to polarization

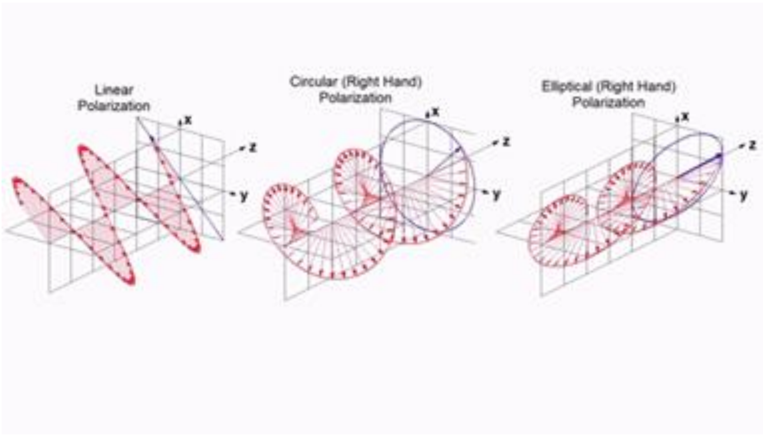
Polarization, wavelength and intensity are three key characteristics of radiation. *SAR can control the sending and receiving polarizations. Different send and receive polarization combinations lead to different channels in SAR system*.

SAR HH channel: send H, receive H polarization;

SAR HV channel: send H, receive V polarization;

SAR VH channel: send V, receive H polarization;

SAR VV channel: send V, receive V polarization;

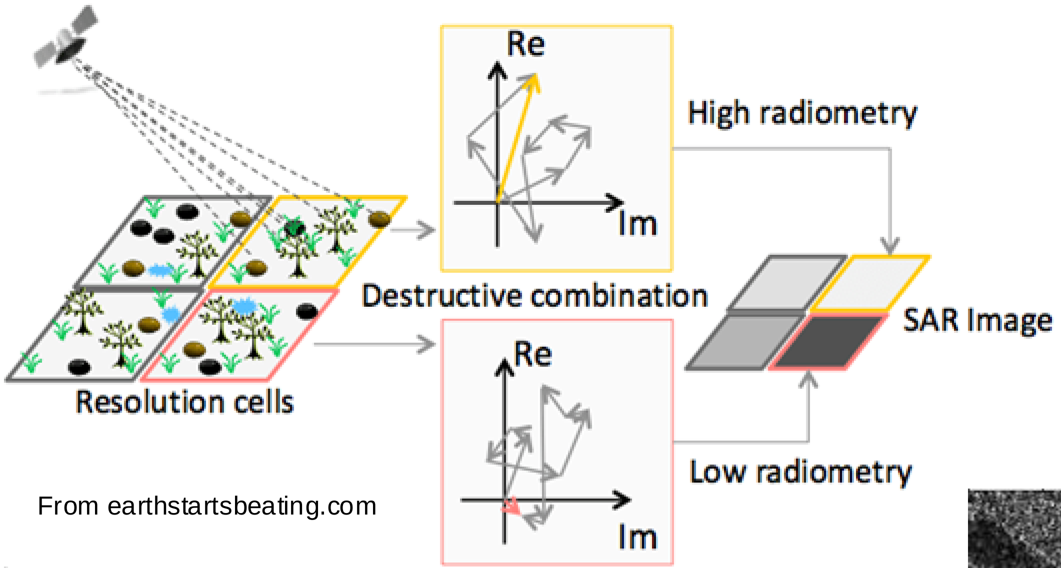


What causes SAR Speckle Noise

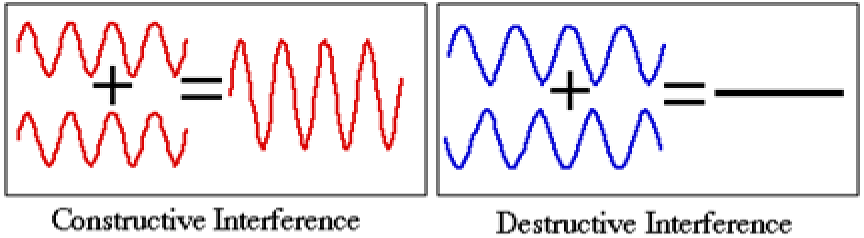
(1) The constructive or destructive interference among many scatters within a SAR resolution cell lead to either bright or dark intensity value on SAR image.

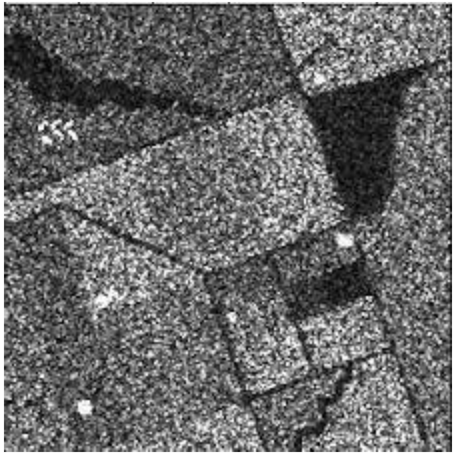
(2) Bright land cover types tend to have stronger noise effect, while dark land cover classes are less influenced by speckle noise;

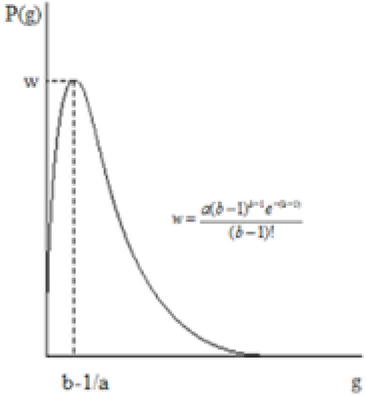
(3) Statistically, the intensity value of speckle noise can be described by a long-tail Gamma distribution, which is different from the Gaussian noise that appears on optical remote sensing images.



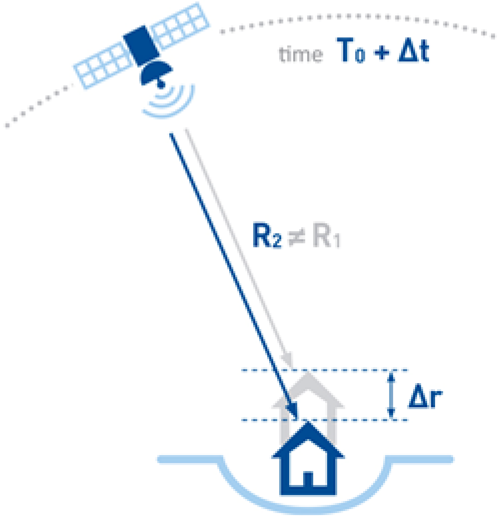
From earthstartsbeating.com

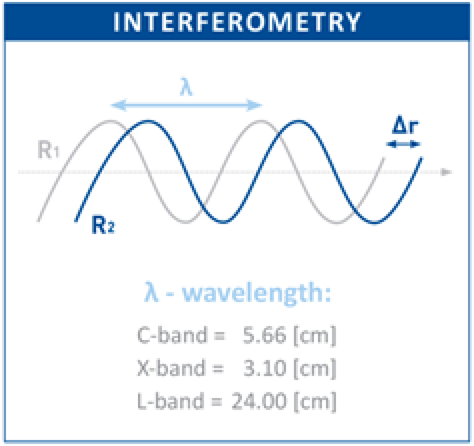




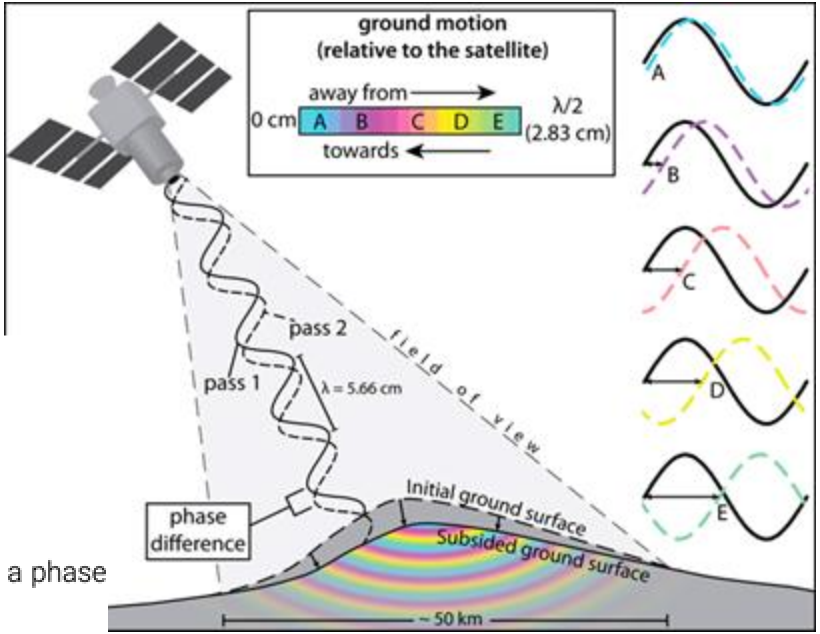


SAR Interferometry: how to use the change in signal phase to measure the change in surface hight?





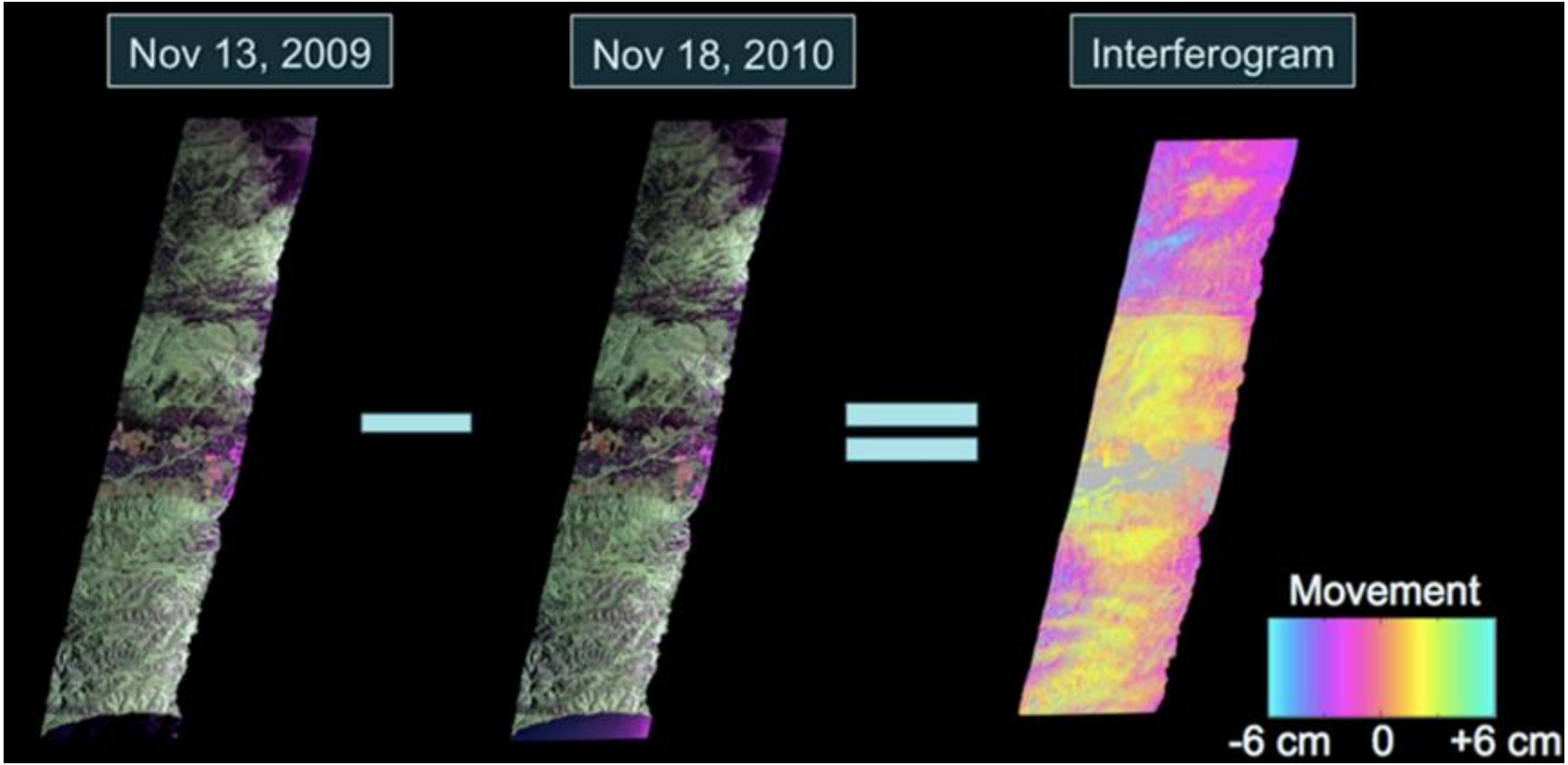
Which wavelength provides higher accuracy? X, C, or L?



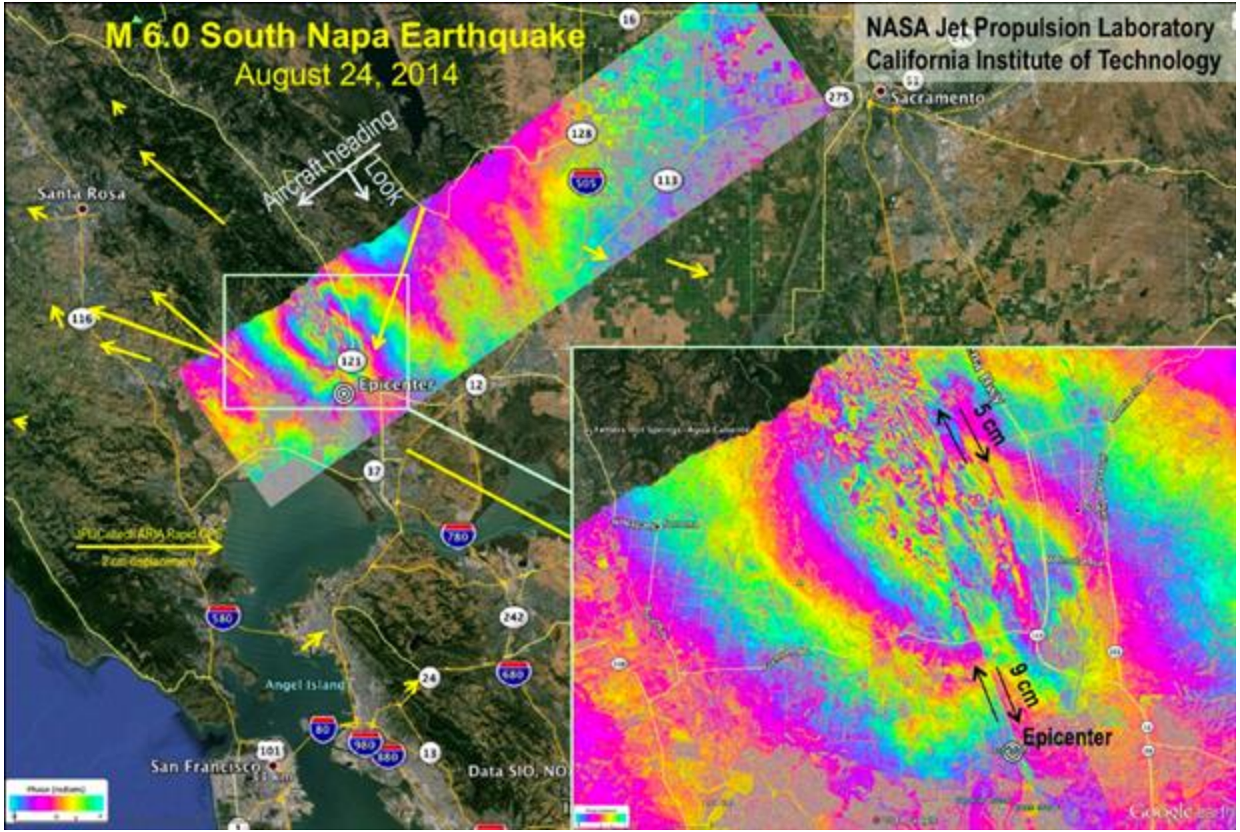
The change in signal phase (Δφ) is expressed by the equation below:

$$\Delta\varphi = \frac{4\pi}{\lambda}\Delta R + \alpha$$

Where λ is the wavelength, ΔR is the displacement in the Line Of Sight (LOS) and α is a phase shift due to different atmospheric conditions at the time of the two radar acquisitions.

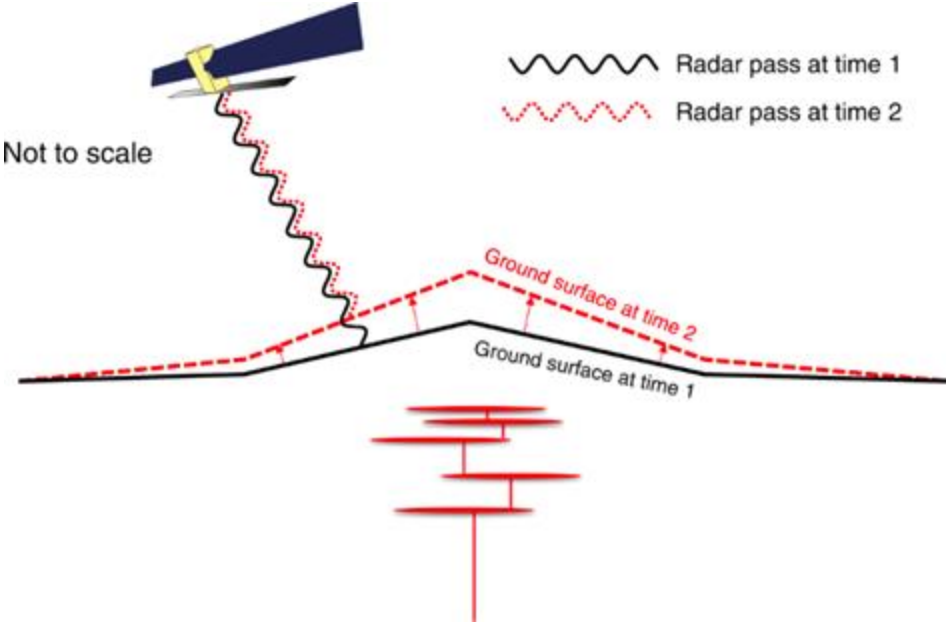


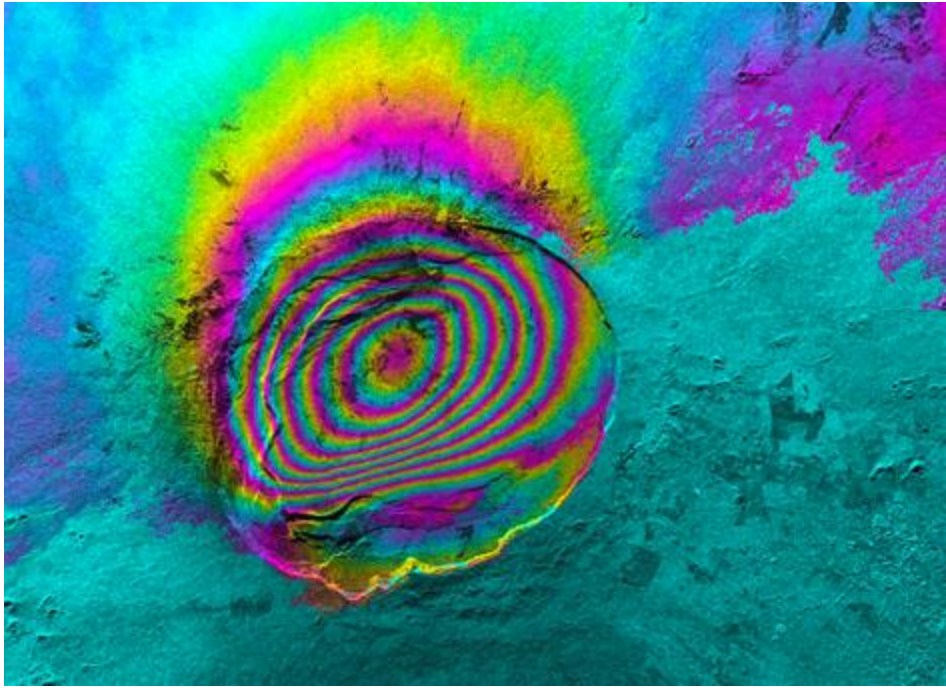
An example of an interferogram from the airborne UAVSAR instrument obtained over the San Andreas Fault in California. The fault line can be identified in the upper half where the pink and yellow colors meet. This color change in the “fringe” is caused by surface movement the occurred between the observation dates of the two polarimetric images combined to produce the interferogram. Credit: NASA/JPL-Caltech



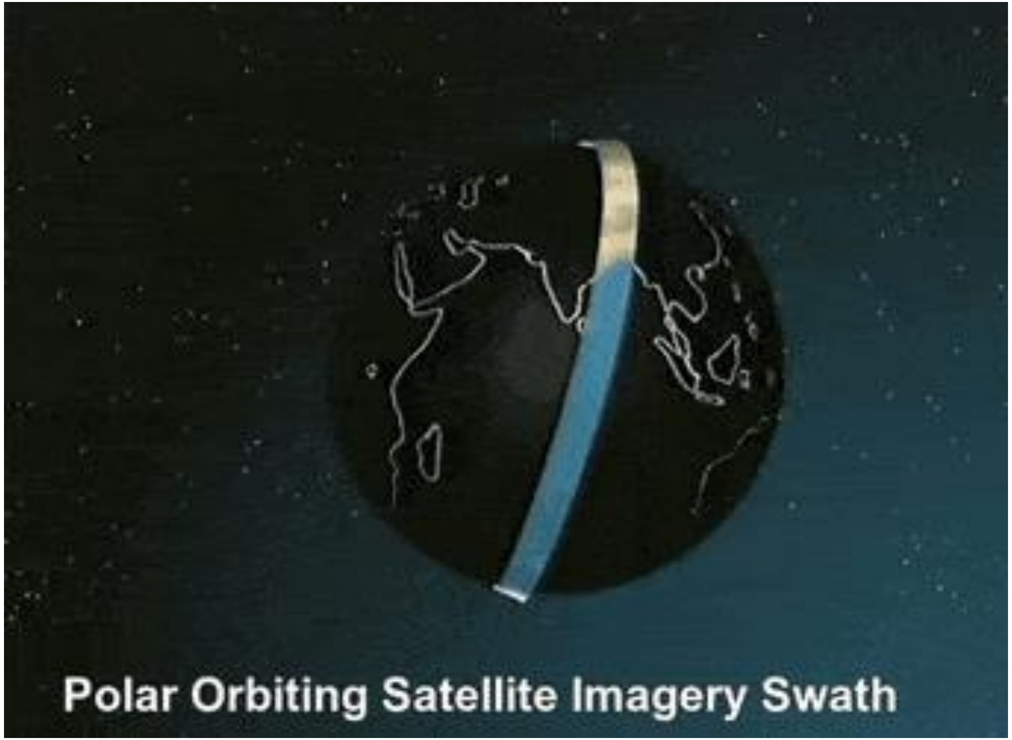
This interferogram produced from UAVSAR data shows the fault movement after the 2014 Napa earthquake in Northern California. Each color band cycle shows 12 cm of displacement toward the airborne instrument, which flew to the north of the radar swath, traveling in a southwest direction and looking to the southeast. The ground motion is seen where the fringe colors are displaced. Credit: NASA/JPL-Caltech

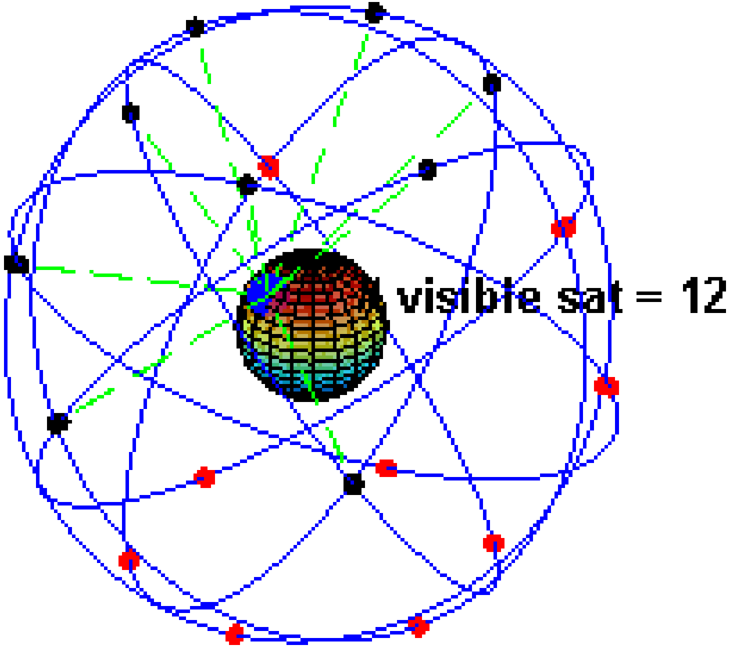
Which direction/area has stronger changes in the line-of-sight direction?



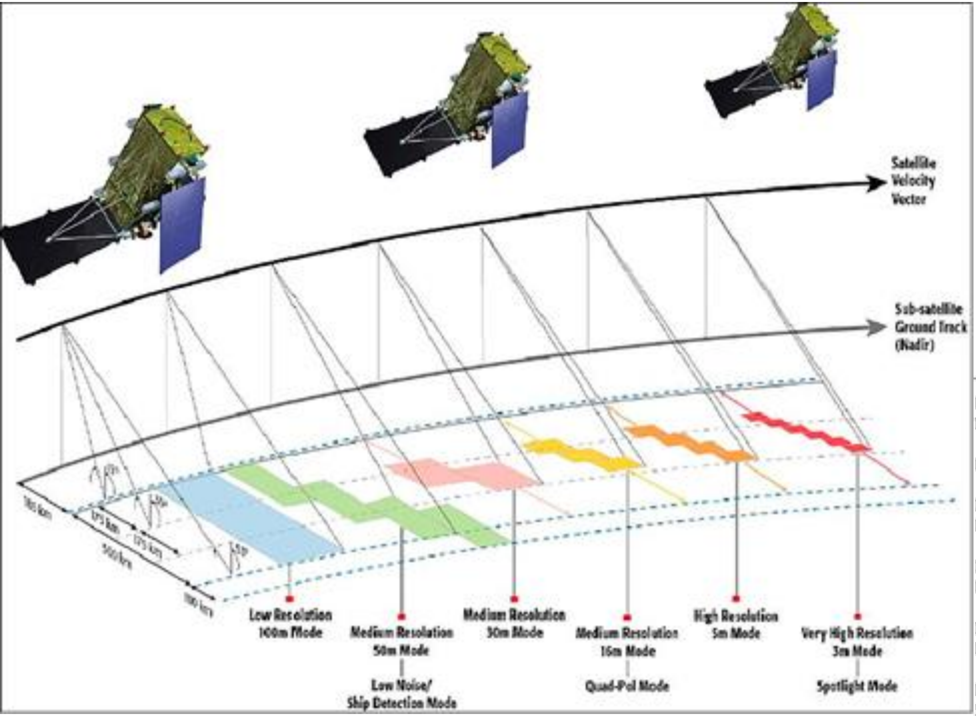


RADARSAT Constellation Mission (RCM)

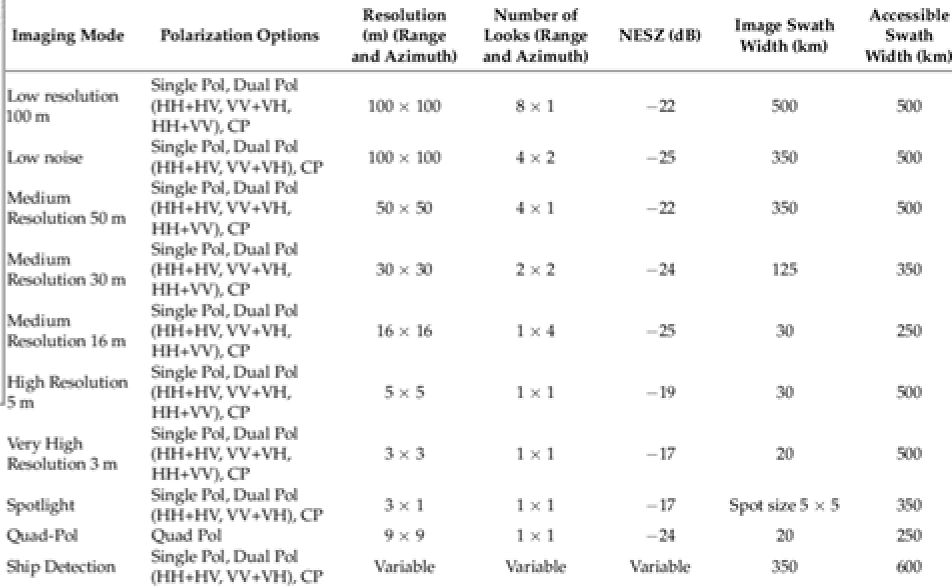




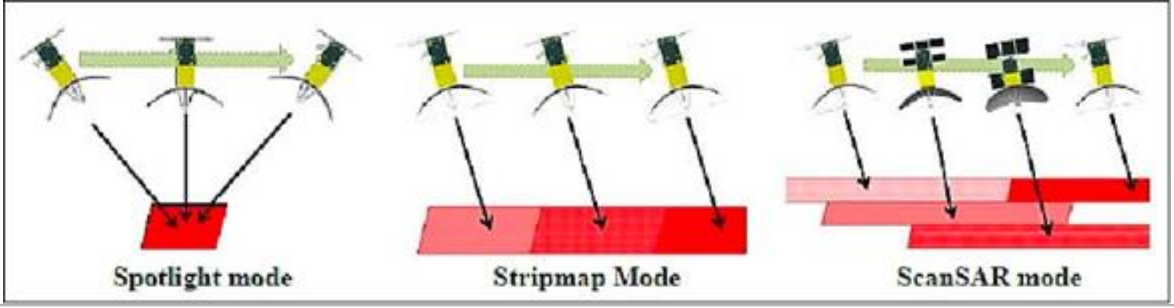
RADARSAT Constellation Mission (RCM) Imaging Modes

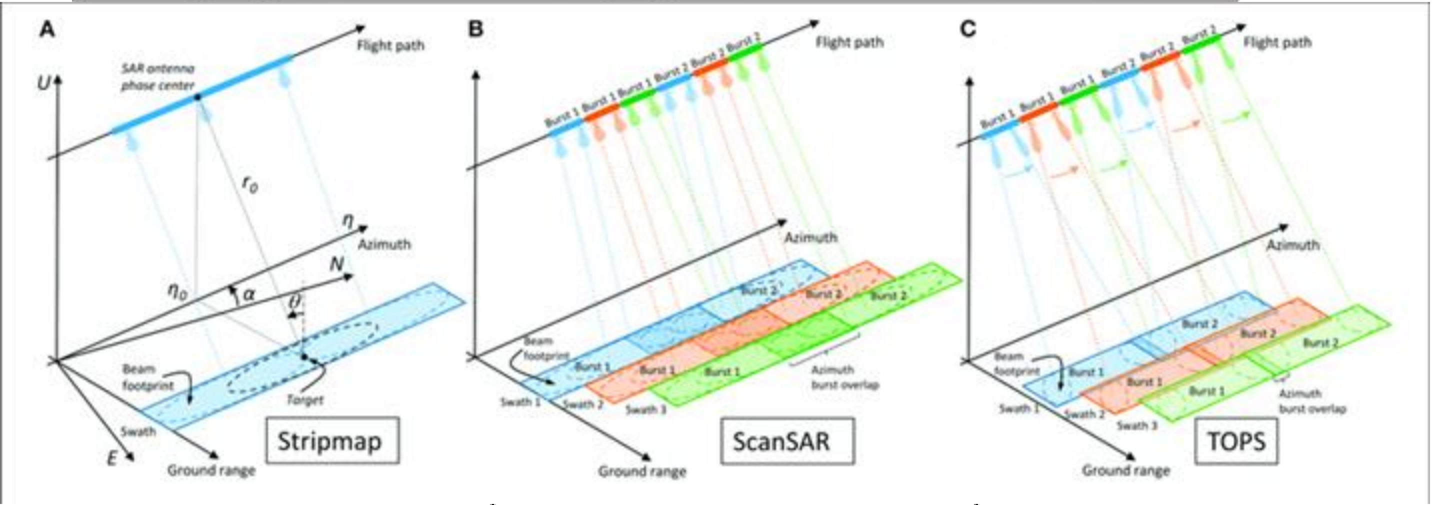


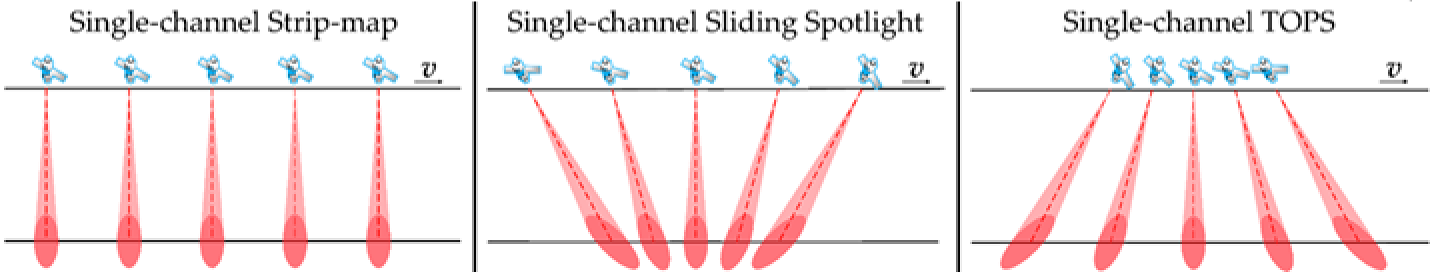
Resolution vs. Swatch width?



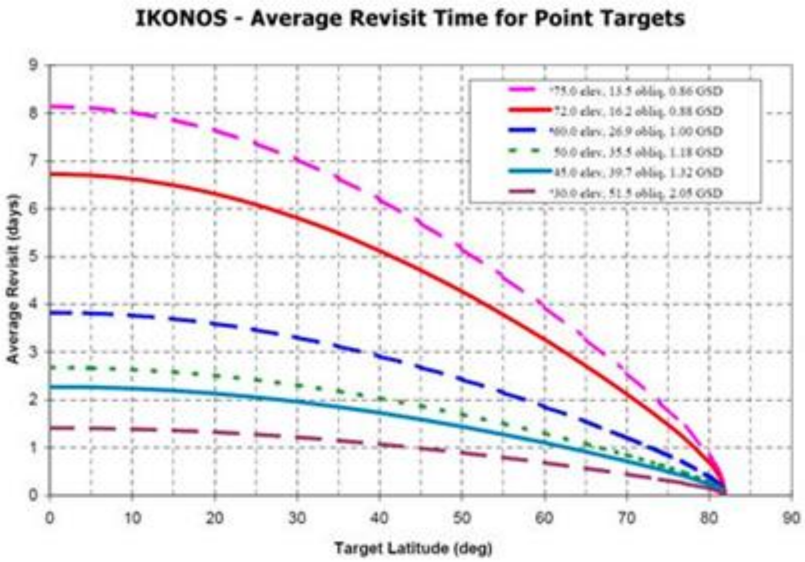
Imaging Mode	Polarization Options	Resolution (m) (Range and Azimuth)	Number of Looks (Range and Azimuth)	NESZ (dB)	Image Swath Width (km)	Accessible Swath Width (km
Low resolution 100 m	Single Pol, Dual Pol (HH+HV, VV+VH, HH+VV), CP	100 × 100	8 × 1	−22	500	500
Low noise	Single Pol, Dual Pol (HH+HV, VV+VH), CP	100 × 100	4 × 2	−25	350	500
Medium Resolution 50 m	Single Pol, Dual Pol (HH+HV, VV+VH, HH+VV), CP	50 × 50	4 × 1	−22	350	500
Medium Resolution 30 m	Single Pol, Dual Pol (HH+HV, VV+VH, HH+VV), CP	30 × 30	2 × 2	−24	125	350
Medium Resolution 16 m	Single Pol, Dual Pol (HH+HV, VV+VH, HH+VV), CP	16 × 16	1 × 4	−25	30	250
High Resolution 5 m	Single Pol, Dual Pol (HH+HV, VV+VH, HH+VV), CP	5 × 5	1 × 1	−19	30	500
Very High Resolution 3 m	Single Pol, Dual Pol (HH+HV, VV+VH, HH+VV), CP	3 × 3	1 × 1	−17	20	500
Spotlight	Single Pol, Dual Pol (HH+HV, VV+VH), CP	3 × 1	1 × 1	−17	Spot size 5 × 5	350
Quad-Pol	Quad Pol	9 × 9	1 × 1	−24	20	250
Ship Detection	Single Pol, Dual Pol (HH+HV, VV+VH), CP	Variable	Variable	Variable	350	600

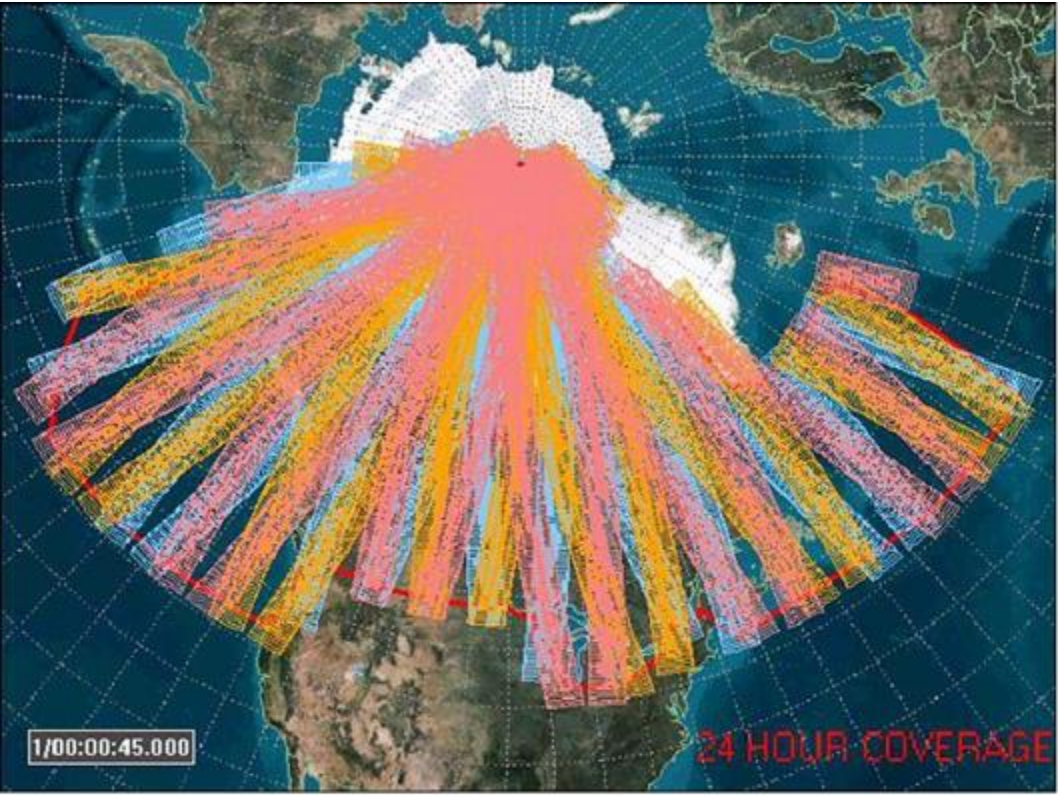

Spotlight mode
Stripmap Mode
ScanSAR mode

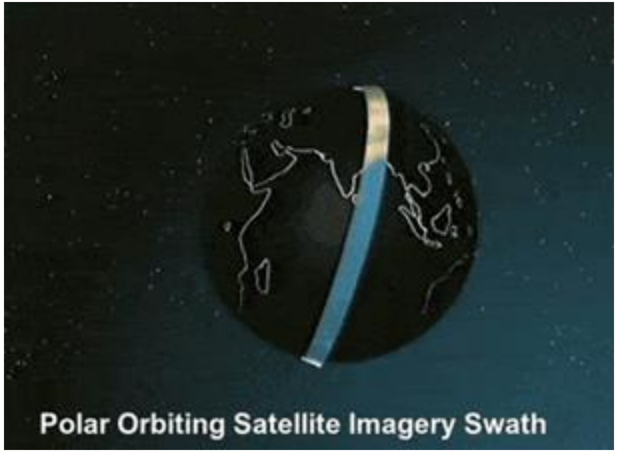

A
Flight path
SAR antenna phase center
U
r_0
η
Azimuth
N
η_0
α
θ
Beam footprint
Target
Swath
E
Ground range
Stripmap
B
Flight path
Burst 1
Burst 2
Azimuth
Beam footprint
Swath 1
Swath 2
Swath 3
Azimuth burst overlap
Ground range
ScanSAR
C
Flight path
Burst 1
Burst 2
Azimuth
Beam footprint
Swath 1
Swath 2
Swath 3
Azimuth burst overlap
Ground range
TOPS

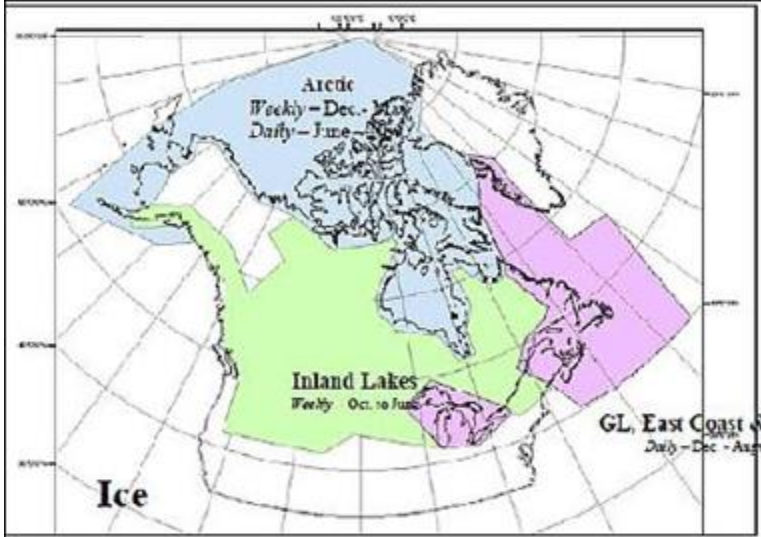

Single-channel Strip-map
v
Single-channel Sliding Spotlight
v
Single-channel TOPS
v

Temporal resolution - high latitude higher, why?








Ice


Oil Pollution


Marine Winds


Vessel Detection


asc-csa.gc.ca
RADARSAT CONSTELLATION

Advantages and Disadvantages of SAR

Advantages:

(1) all weather and day-and-night operation capability;

(2) strong penetration capability;

(3) sensitive to surface roughness and dielectric properties (water content, biomass, oil spills, ice);

(4) measure distance (by interferometric SAR);

(5) strong structure discriminative capability (by polarimetric SAR);

Disadvantages:

(1) incidence angle noise;

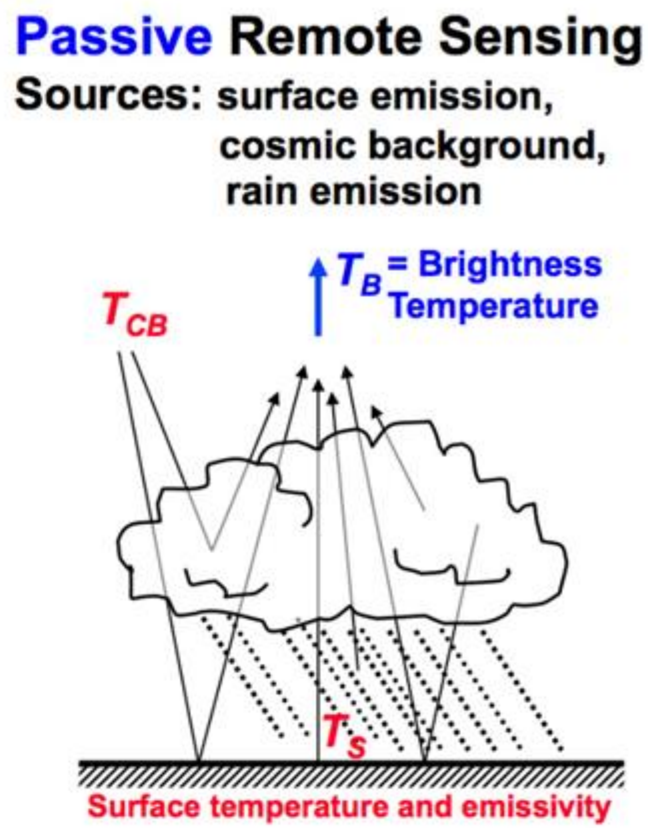
(2) speckle noise;

(3) geometric distortions;

Outline

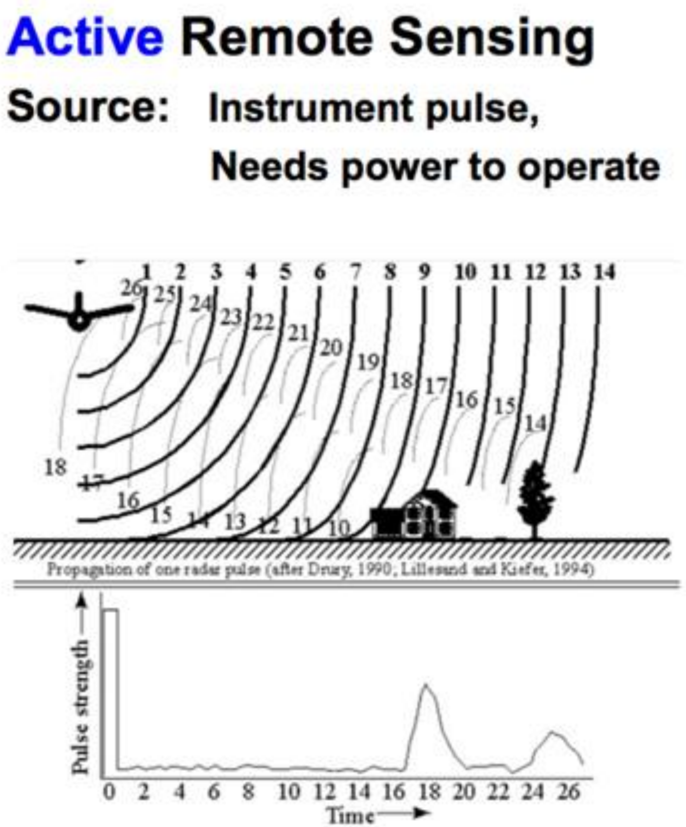
- ➔ SAR Remote Sensing
- ➔ Passive Microwave
- ➔ Hyperspectral remote sensing
- ➔ LiDAR
- ➔ Questions

Passive Microwave vs. Radar?



Passive Remote Sensing

Sources: surface emission,
cosmic background,
rain emission

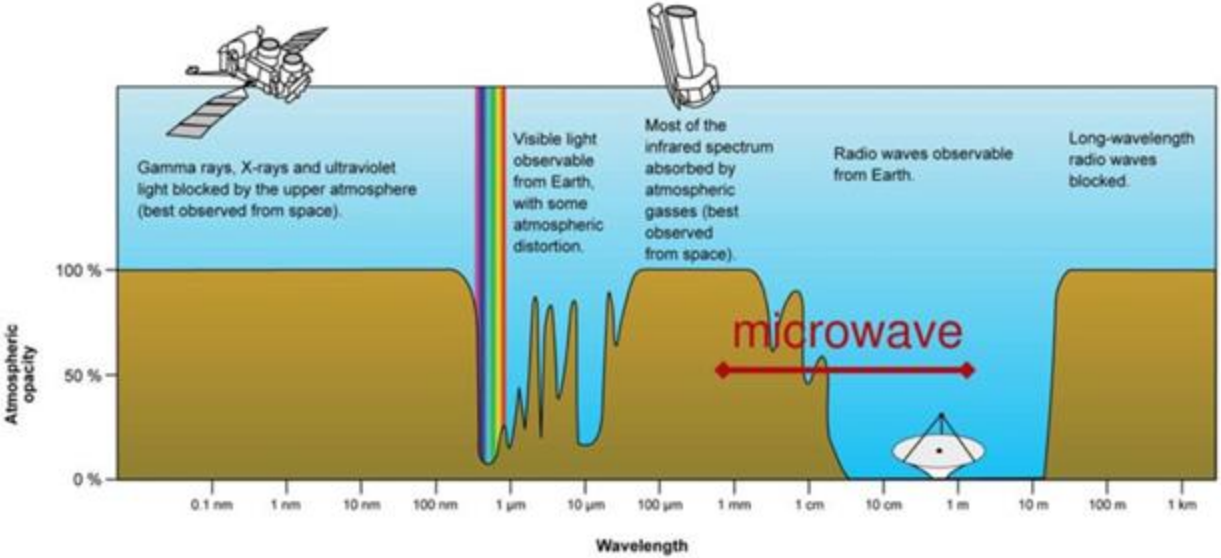


Active Remote Sensing

Source: Instrument pulse,
Needs power to operate

Propagation of one radar pulse (after Drury, 1990; Lillesand and Kiefer, 1994)

What wavelengths ranage? What if < 3 cm?



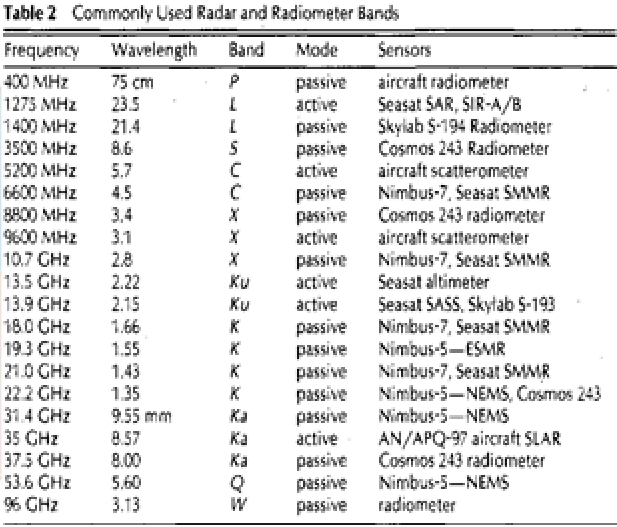


Table 2 Commonly Used Radar and Radiometer Bands

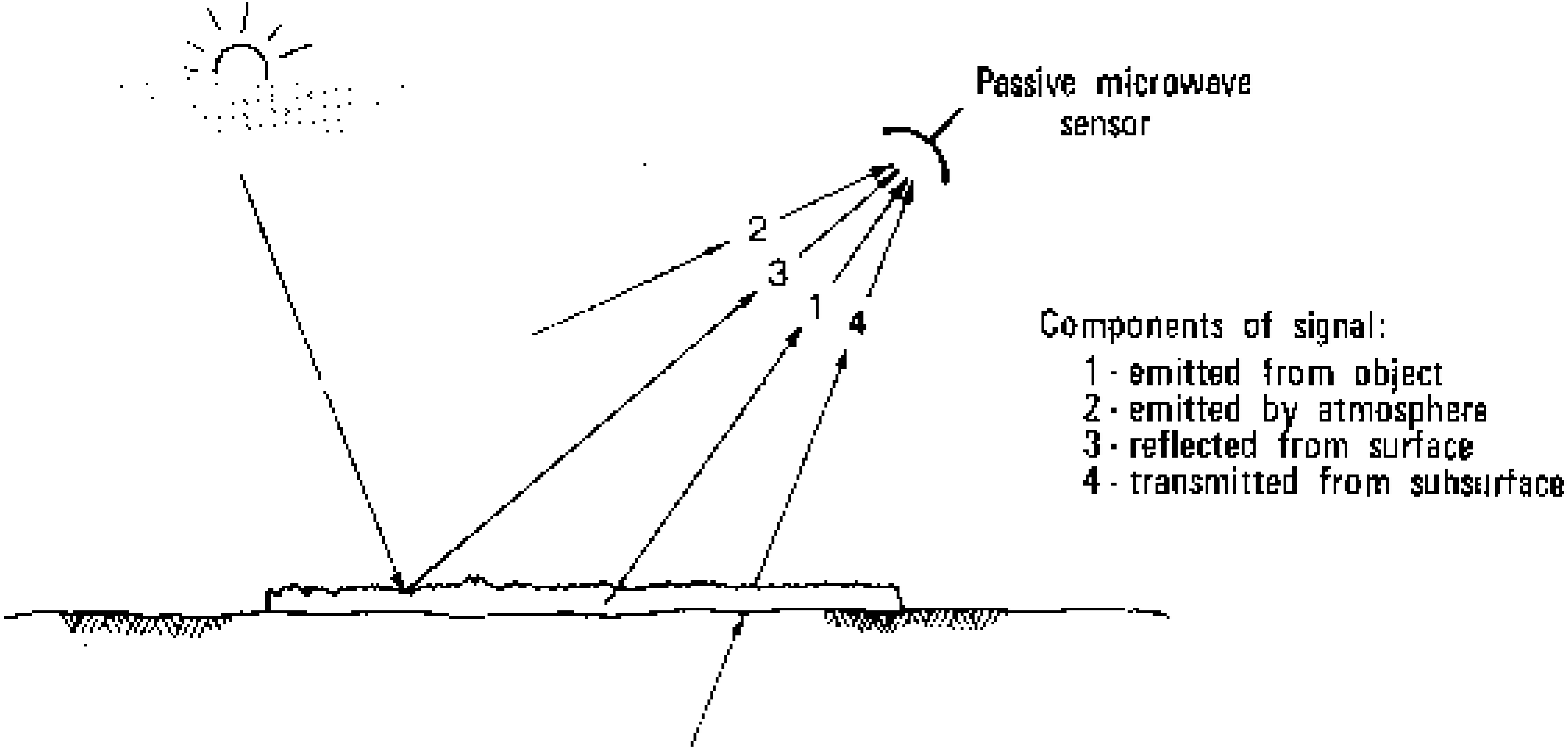
Frequency	Wavelength	Band	Mode	Sensors
400 MHz	75 cm	*P*	passive	aircraft radiometer
1275 MHz	23.5	*L*	active	Seasat SAR, SIR-A/B
1400 MHz	21.4	*L*	passive	Skylab S-194 Radiometer
3500 MHz	8.6	*S*	passive	Cosmos 243 Radiometer
5200 MHz	5.7	*C*	active	aircraft scatterometer
6600 MHz	4.5	*C*	passive	Nimbus-7, Seasat SMMR
8800 MHz	3.4	*X*	passive	Cosmos 243 radiometer
9600 MHz	3.1	*X*	active	aircraft scatterometer
10.7 GHz	2.8	*X*	passive	Nimbus-7, Seasat SMMR
13.5 GHz	2.22	*Ku*	active	Seasat altimeter
13.9 GHz	2.15	*Ku*	active	Seasat SASS, Skylab S-193
18.0 GHz	1.66	*K*	passive	Nimbus-7, Seasat SMMR
19.3 GHz	1.55	*K*	passive	Nimbus-5—ESMR
21.0 GHz	1.43	*K*	passive	Nimbus-7, Seasat SMMR
22.2 GHz	1.35	*K*	passive	Nimbus-5—NEMS, Cosmos 243
31.4 GHz	9.55 mm	*Ka*	passive	Nimbus-5—NEMS
35 GHz	8.57	*Ka*	active	AN/APQ-97 aircraft SLAR
37.5 GHz	8.00	*Ka*	passive	Cosmos 243 radiometer
53.6 GHz	5.60	*Q*	passive	Nimbus-5—NEMS
96 GHz	3.13	*W*	passive	radiometer

- Recall the "windows" of low opacity, which allow the transmission of only certain EMR (caused by the absorption spectra of the gasses in the atmosphere)

- Atmospheric attenuation of μwave radiation is primarily through absorption by H_20 & O_2 - absorption is strongest at the shortest wavelength; attenuation is low for λ > 3 cm.

- μwave radiation is not greatly influenced by cloud or fog, especially for λ > 3 cm.

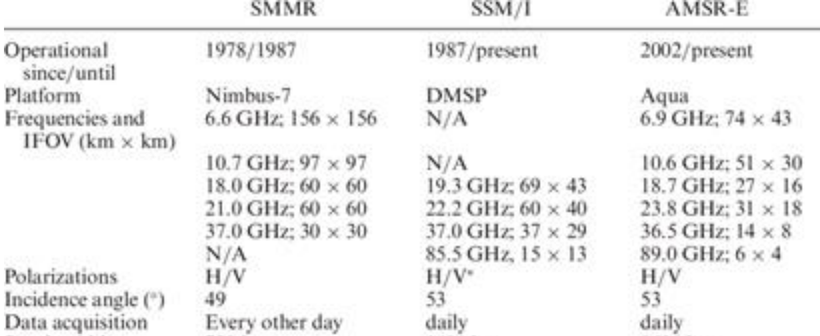
What are components of Passive Microwave Signal?



Components of signal:

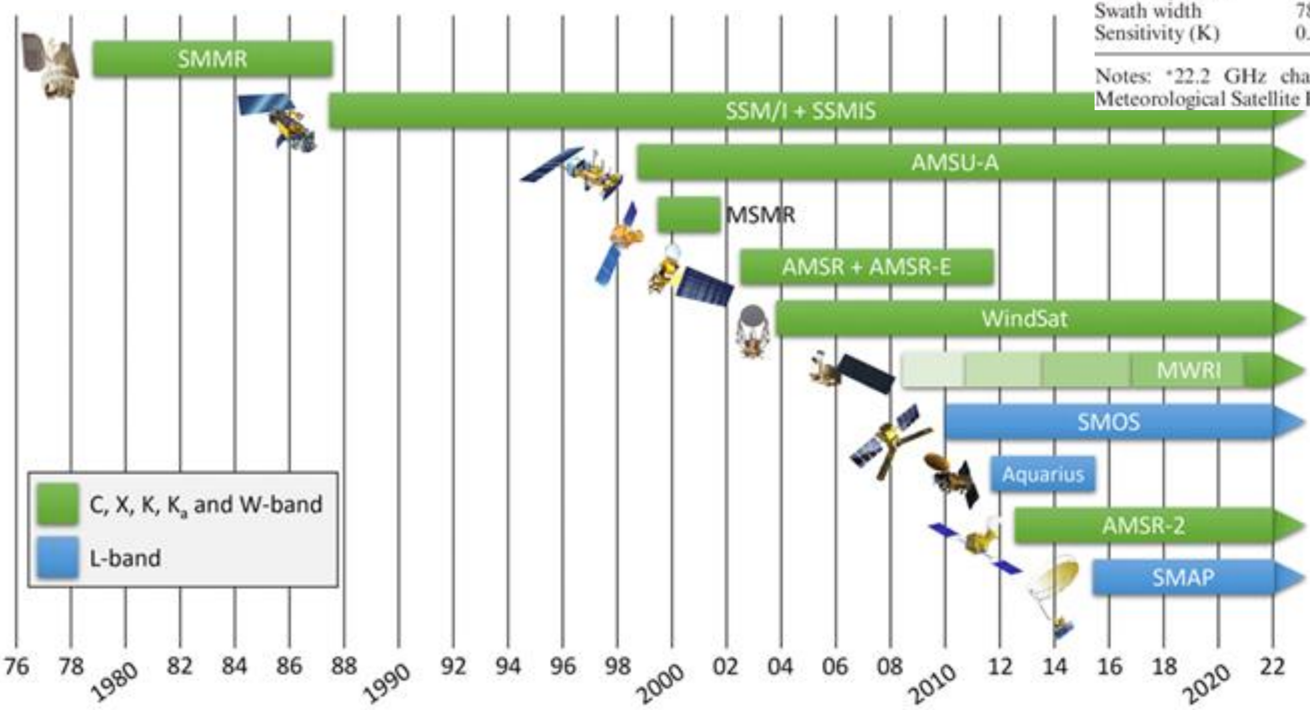
1 - emitted from object
2 - emitted by atmosphere
3 - reflected from surface
4 - transmitted from subsurface

What wavelengths?



	SMMR	SSM/I	AMSR-E
Operational since/until	1978/1987	1987/present	2002/present
Platform	Nimbus-7	DMSP	Aqua
Frequencies and IFOV (km × km)	6.6 GHz; 156 × 156	N/A	6.9 GHz; 74 × 43
	10.7 GHz; 97 × 97	N/A	10.6 GHz; 51 × 30
	18.0 GHz; 60 × 60	19.3 GHz; 69 × 43	18.7 GHz; 27 × 16
	21.0 GHz; 60 × 60	22.2 GHz; 60 × 40	23.8 GHz; 31 × 18
	37.0 GHz; 30 × 30	37.0 GHz; 37 × 29	36.5 GHz; 14 × 8
	N/A	85.5 GHz, 15 × 13	89.0 GHz; 6 × 4
Polarizations	H/V	H/V*	H/V
Incidence angle (°)	49	53	53
Data acquisition	Every other day	daily	daily
Swath width	780 km	1400 km	1600 km
Sensitivity (K)	0.9–1.5	0.8–1.1	0.3–1.1

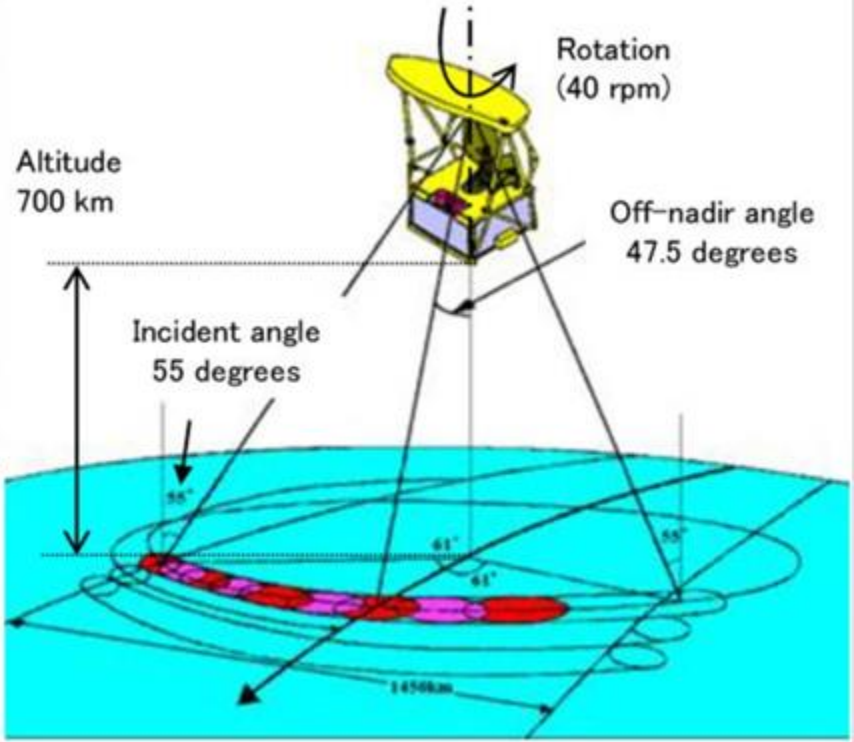
Notes: *22.2 GHz channel is only available in vertical polarization. DMSP, Defense Meteorological Satellite Program.



AMSR2 Characteristics

Scan type	Conical scan
Swath width	>1450 km
Antenna	Offset parabolic antenna with deployment mechanism 2-meter-diameter aperture
Incidence angle	55 degree
Dynamic range	2.7K-340K

Center frequency [GHz]	NEDT [K]	Beam width [degree] (Ground resolution [km])
6.925 / 7.3	< 0.34/0.43	1.8(35 x 62)
10.65	< 0.70	1.2(24 x 42)
18.7	< 0.70	0.65(14 x 22)
23.8	< 0.60	0.75(15 x 26)
36.5	< 0.70	0.35(7 x 12)
89.0 A/B	< 1.20/1.40	0.15(3 x 5)



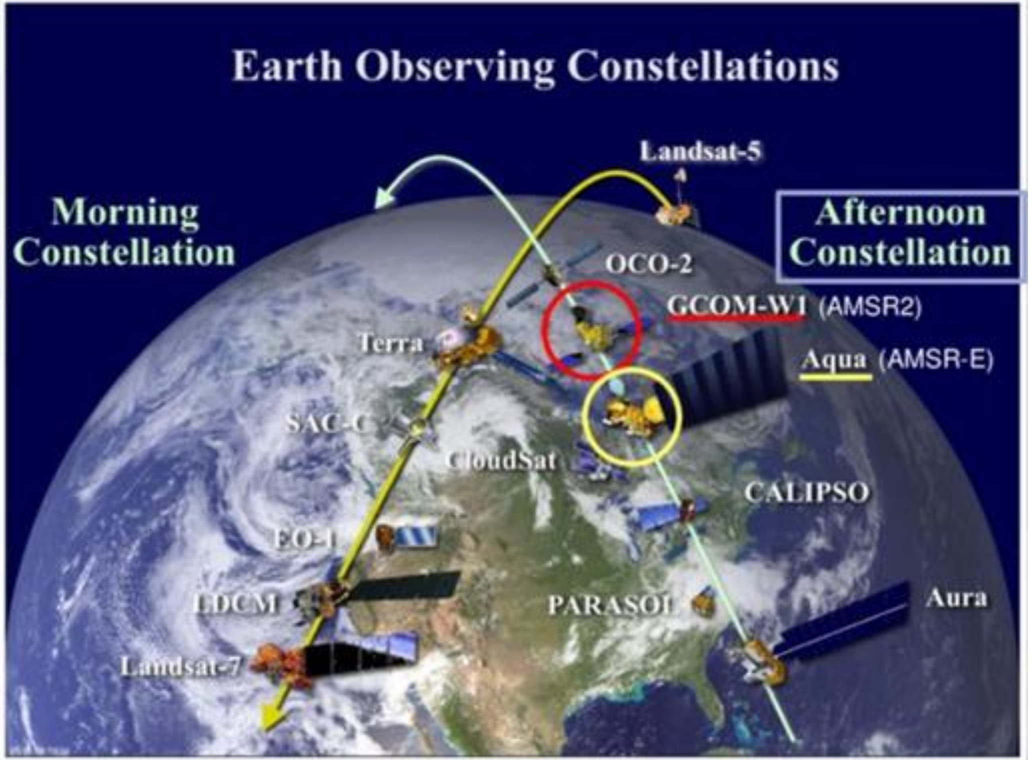
Scan Geometry

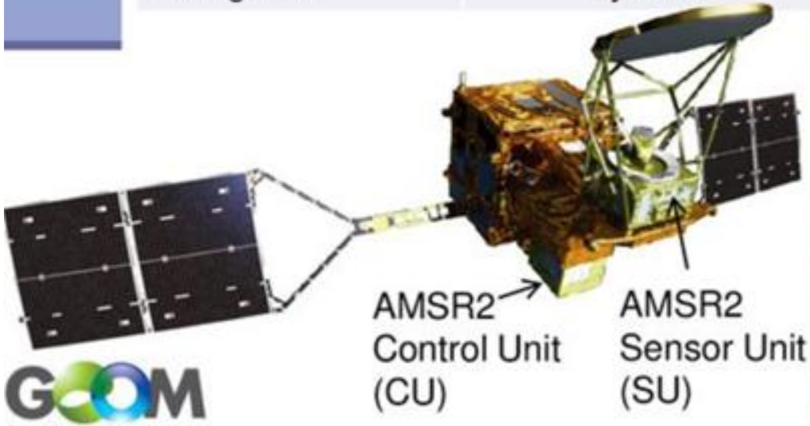
Wavelength vs. Resolution?

GCOM-W	
Orbit	Sun synchronous sub-recurrent orbit
Recurrence cycle	16 days
Altitude	700 km
Inclination	98.2 deg
Local sun time of descending node	1:30
mass	<1,991kg
power	> 3,880W
Design life	5 years

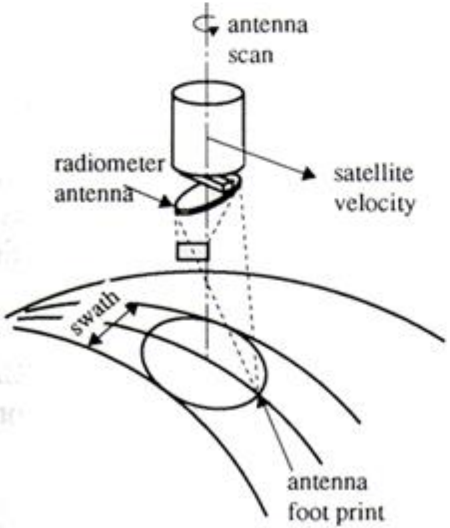
GCOM-W orbit

- Identical to that of Aqua
- Joining Afternoon constellation
- Located in front of Aqua

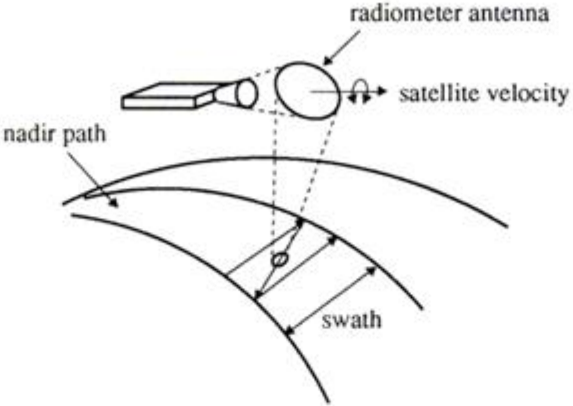




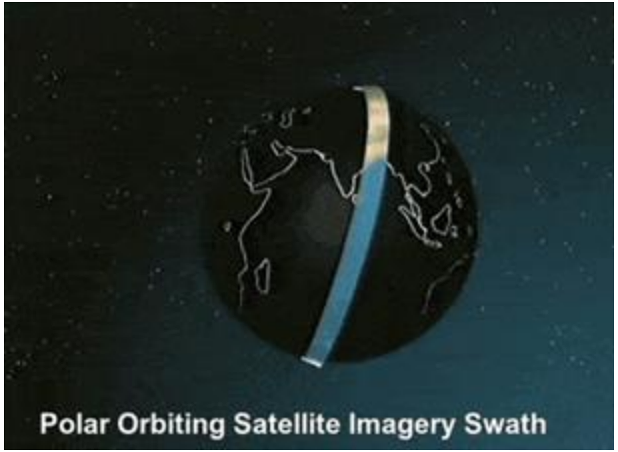
Conical scanning: how is it different from cross-track scanning



(a) conical scanning type



(b) cross-track scanning type



Why radiance in PM is linear function of brightness temperature?

Radiation is governed by Planck’s Law

$$B(\lambda,T) = c_1 / \{ \lambda^5 [e^{c_2/\lambda T} - 1] \}$$

λ = wavelengths in um, T = temperature of emitting surface (deg K), $c_1 = 1.191044 \times 10^{-5}$ (mW/m^2/ster/cm^{-4}), $c_2 = 1.438769$ (cm deg K)

In microwave region $c_2/\lambda T << 1$, so that

$$e^{c_2/\lambda T} = 1 + c_2/\lambda T$$ **+ second order** *(recall that $e^x = 1 + x/1! + x^2/2! + \ldots$)*

And classical Rayleigh Jeans radiation equation emerges

$B_\lambda(T) \approx [c_1 / c_2] [T / \lambda^4] = \varepsilon_\lambda [c_1 / c_2] [T_B / \lambda^4]$, **where $T = \varepsilon_\lambda T_B$, with ε_λ being emisivity.**

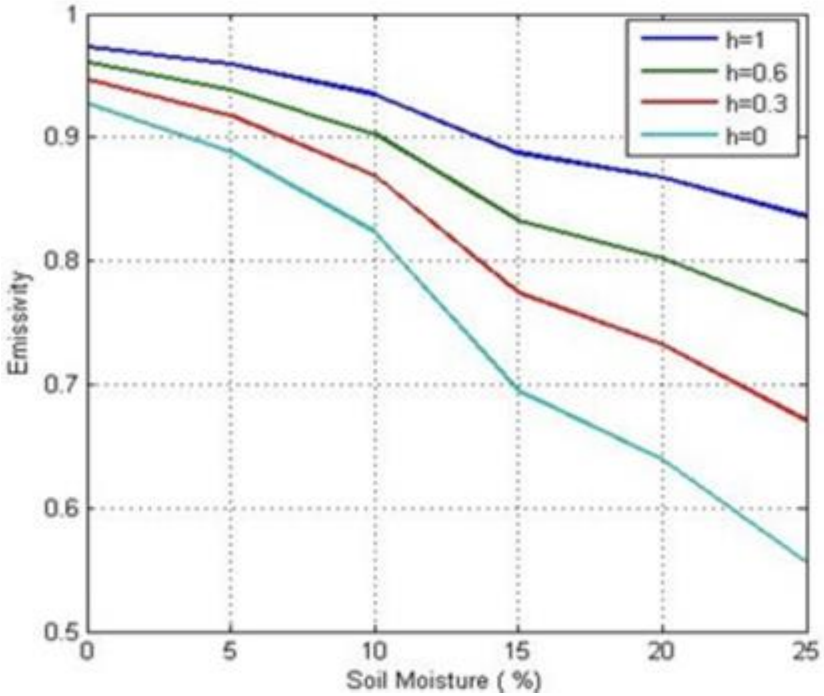
Radiance is linear function of brightness temperature.

Passive Microwave Sensing of Land Surface Emissivity Differences

- Microwave emissivity is a function of the "dielectric constant"
- Most earth materials have a dielectric constant in the range of 1 to 4 (air=1, veg=3, ice=3.2)
- Dielectric constant of liquid water is **80**
- Thus, moisture content affects brightness temperature
- Surface roughness also influences emissivity

Material	ε	Material	ε
Sea water	81	Rock	5-8
Fresh water	81	Debris	12-30
Wet earth	10	Hardpan	4-7
Dry earth	5	Soil (sandy, dry)	4-6
Sand (saturated)	10-30	Soil (sandy, wet)	15-30
Sand (dry)	4-6	Soil (loamy, dry)	4-6
Snow	2	Soil (loamy, wet)	10-20
Glacier ice	3	Permafrost	4-8
Ice	3.5		

Emisivity changes with polarization, wavelenght/frequency, dielectric constant, surface roughness and viewing angle.

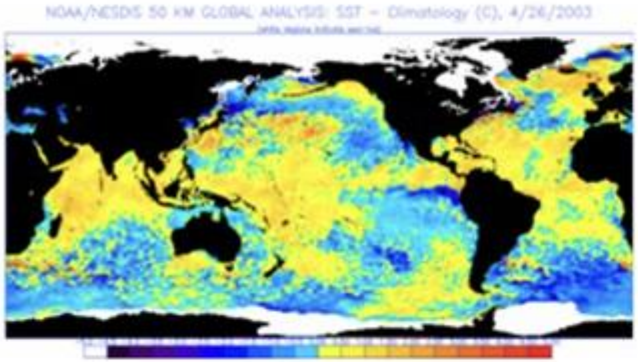


Emissivity vs. soil moisture (dielectric constent) and surface roughness (h)

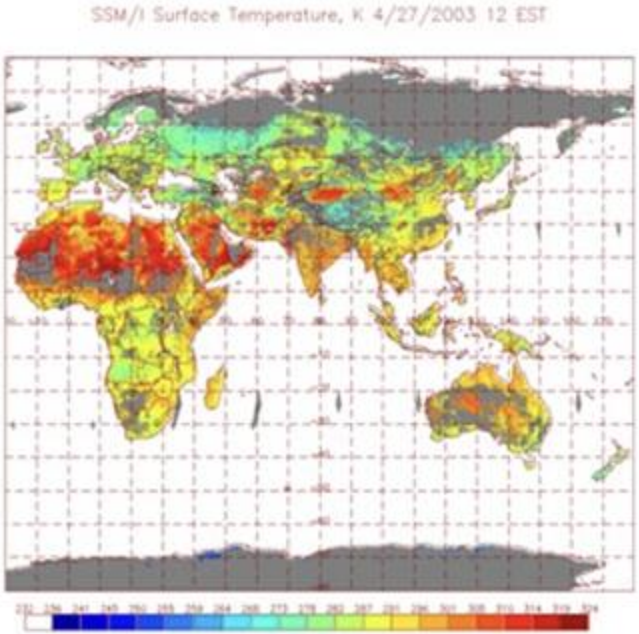
Passive Microwave Applications

- Soil moisture
- Snow water equivalent
- Sea/lake ice extent, concentration and type
- Sea surface temperature
- Atmospheric water vapor
- Surface wind speed
- Cloud liquid water
- Rainfall rate

- Sea surface temperature



- Land surface temperature



$$B_\lambda(T) \approx \varepsilon_\lambda \, [c_1 / c_2] \, [T_B / \lambda^4]$$

Emisivity changes with polarization, wavelenght/frequency, dielectric constant, surface roughness and viewing angle.

Passive Microwave Remote Sensing from Space

Advantages

- Penetration through non-precipitating clouds
- Radiance is linearly related to temperature (i.e. the retrieval is nearly linear)
- Highly stable instrument calibration
- Global coverage and wide swath

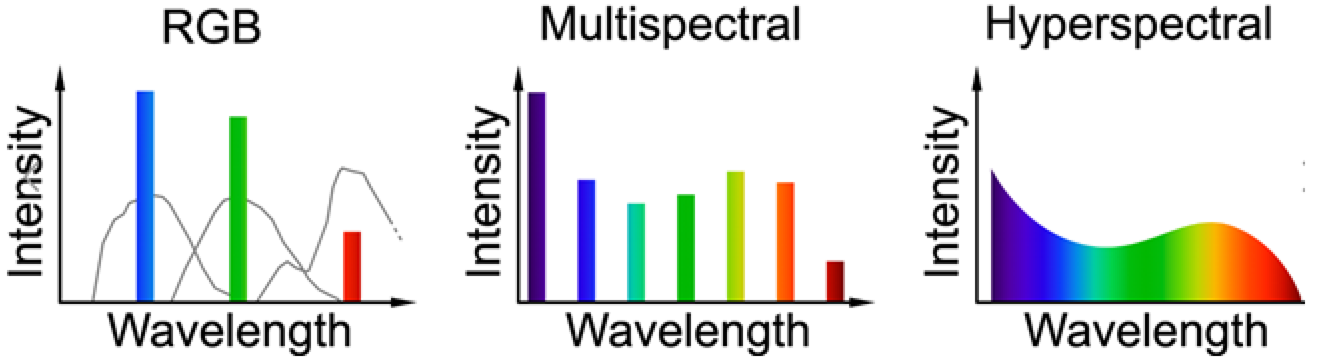
Disadvantages

- Larger field of views (10-50 km) compared to VIS/IR sensors
- Variable emissivity over land
- Polar orbiting satellites provide discontinuous temporal coverage at low latitudes (need to create weekly composites)

Outline

- ➔ SAR Remote Sensing
- ➔ Passive Microwave
- ➔ Hyperspectral remote sensing
- ➔ LiDAR
- ➔ Questions

Hyperspectral Remote Sensing



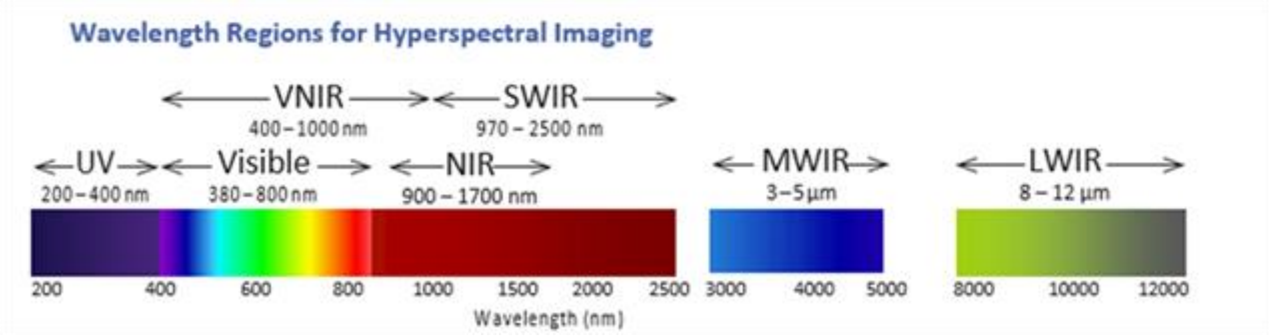


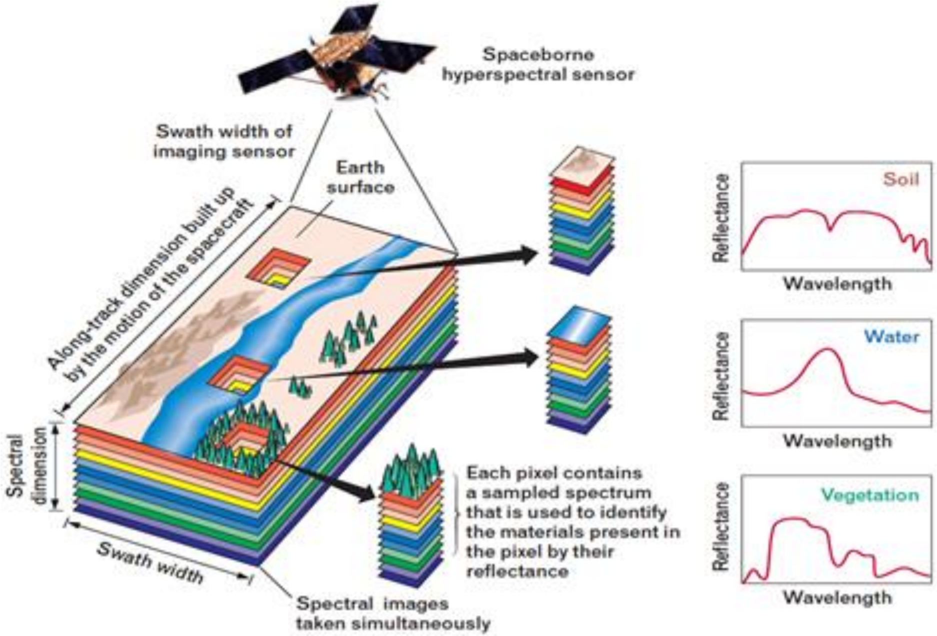
Image from wiki.tum.de and middletonspectral.com

RGB sensors have only three visible channels (i.e., R, G, B).

Multispectral sensors have more than 3 channels at VNIR and SWIR portions of the spectrum (400nm-2500nm).

Hyperspectral sensors typically have hundreds of continuous channels at VNIR and SWIR portions of the spectrum (400nm-2500nm).

Hyperspectral Environmental Remote Sensing



What do we want from hyperspectral image (HSI)?

-- ***informative features*** extraction for visualization

-- ***subtle class labels***, e.g., different crop types mapping, diseased and healthy crops discrimination;

-- ***biochemical parameters***, e.g., chlorophyll content and water content in leaves;

-- ***biophysical parameters***, e.g., leaf area index (LAI)

-- ***geochemical parameters***, e.g., soil heavy metal concentration, soil moisture;

Difficulties:

-- the large ***data volume*** of hyperspectral image (HSI);

-- the innate ***high-dimensionality*** of HSI;

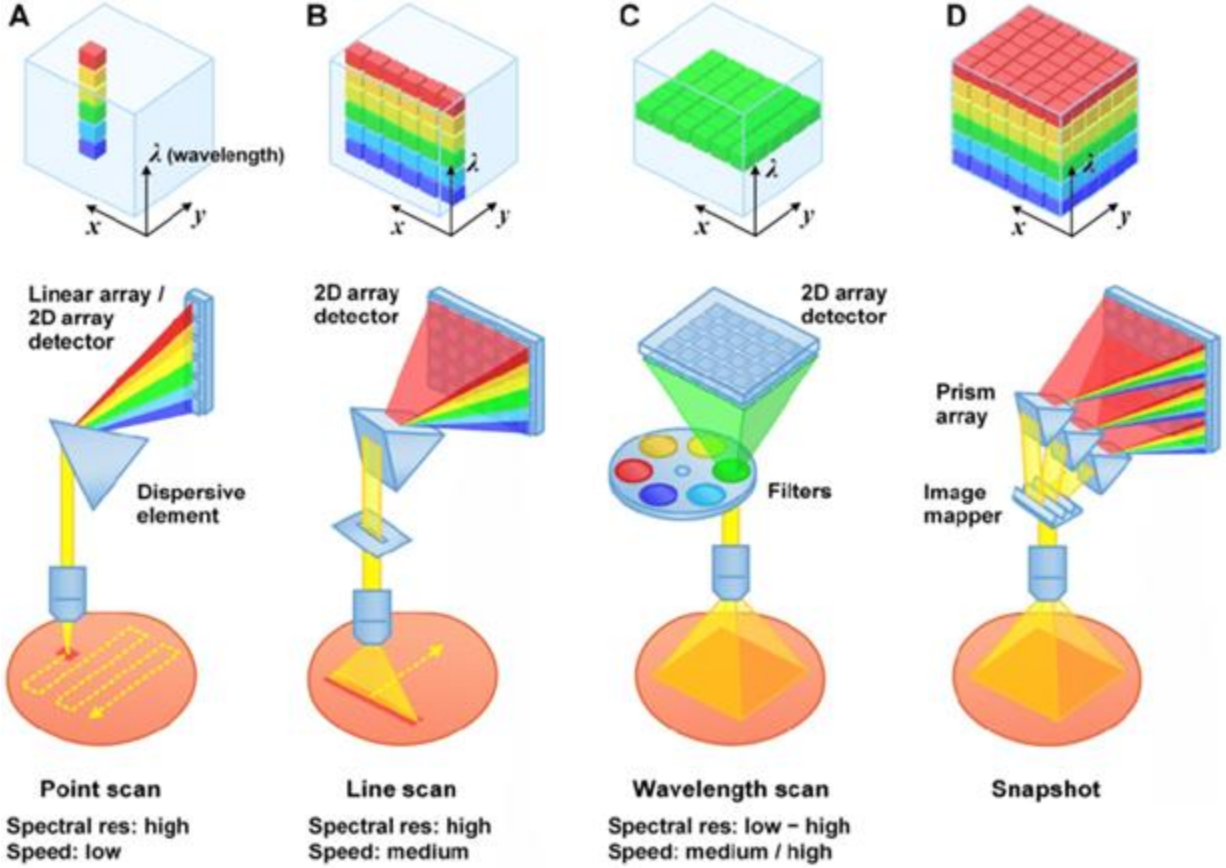
-- the ***spatial-spectral heterogeneity*** in HSI;

-- the ***limited training samples***;

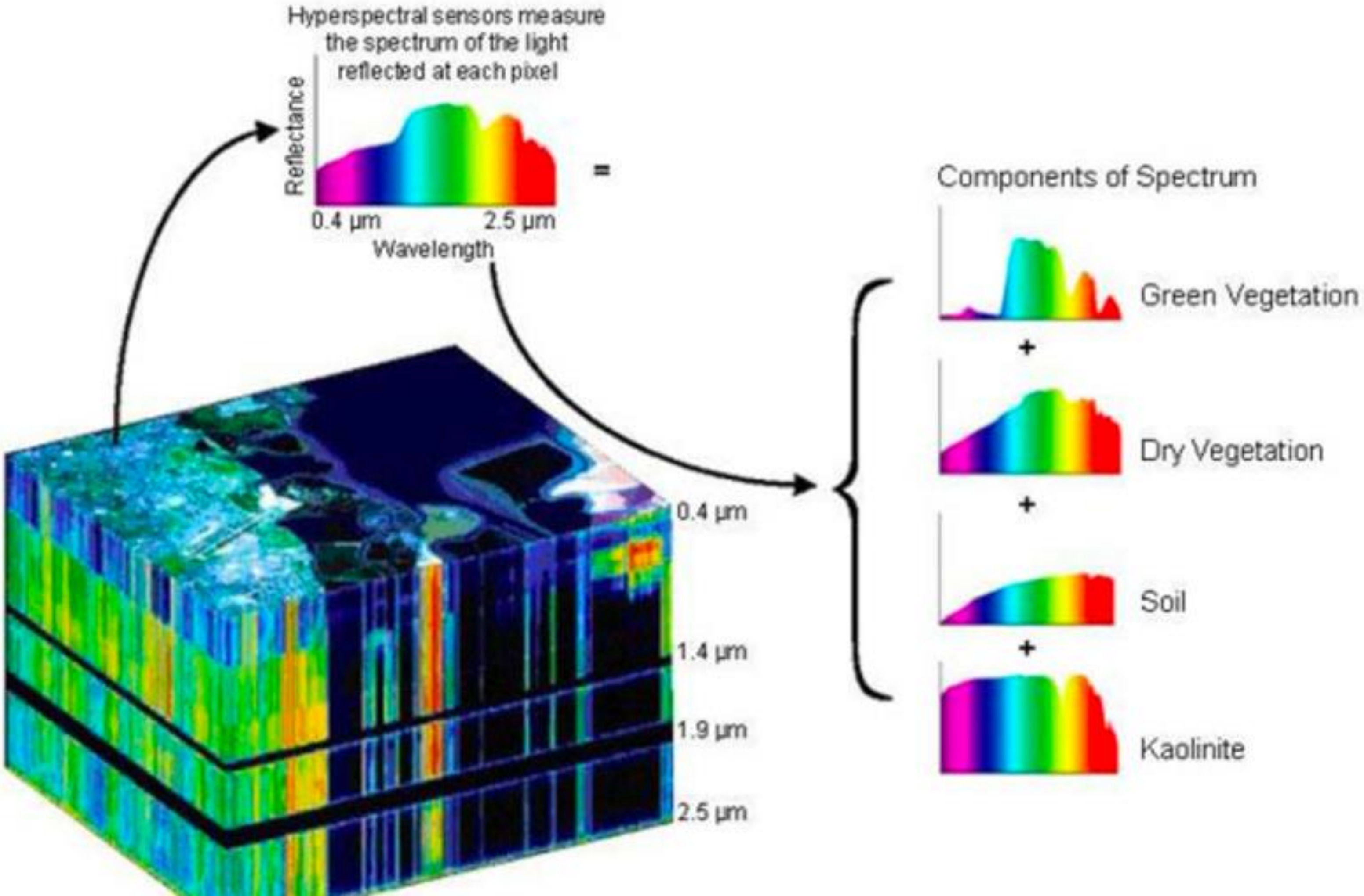
-- the ***noise effect*** in HSI, and many other factors;

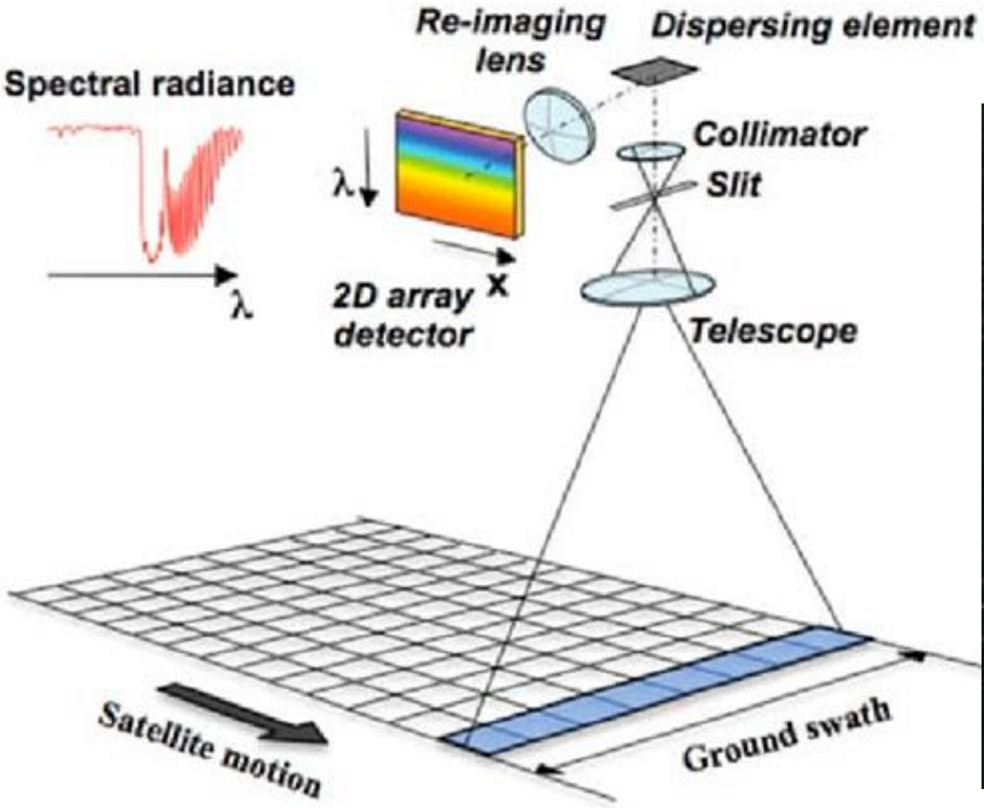
Image Source http://www.markelowitz.com

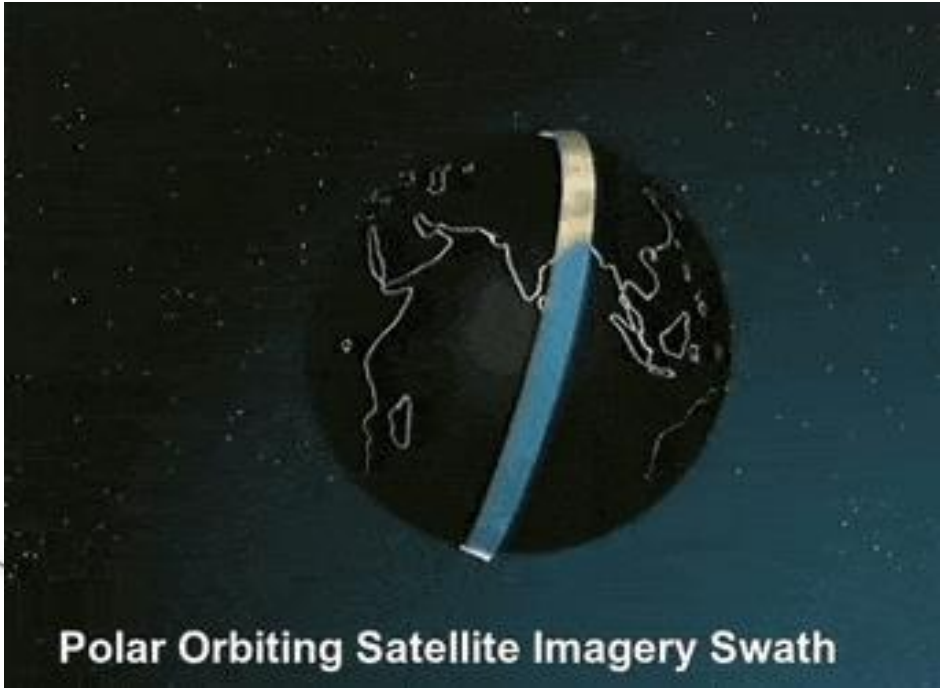
Hyperspectral Imaging Approaches



(A) Point scan. (B) Line scan (i.e. ”pushbroom”). (C) Wavelength scan. (D) Snapshot.


Hyperspectral sensors measure the spectrum of the light reflected at each pixel
Reflectance
0.4 µm
2.5 µm
Wavelength
=
Components of Spectrum
Green Vegetation
+
Dry Vegetation
+
Soil
+
Kaolinite
0.4 µm
1.4 µm
1.9 µm
2.5 µm





Pushbroom imaging approach

2. Crop classification Using Deep Learning and Spatial Modeling AVIRIS

Hyperspectral Image with 224 Channels -- North-western Indiana, two-thirds **agriculture**, and one-third **forest** or other natural perennial **vegetation**

True color RGB image

Ground truth map

2. Crop classification Using Deep Learning and Spatial Modeling AVIRIS

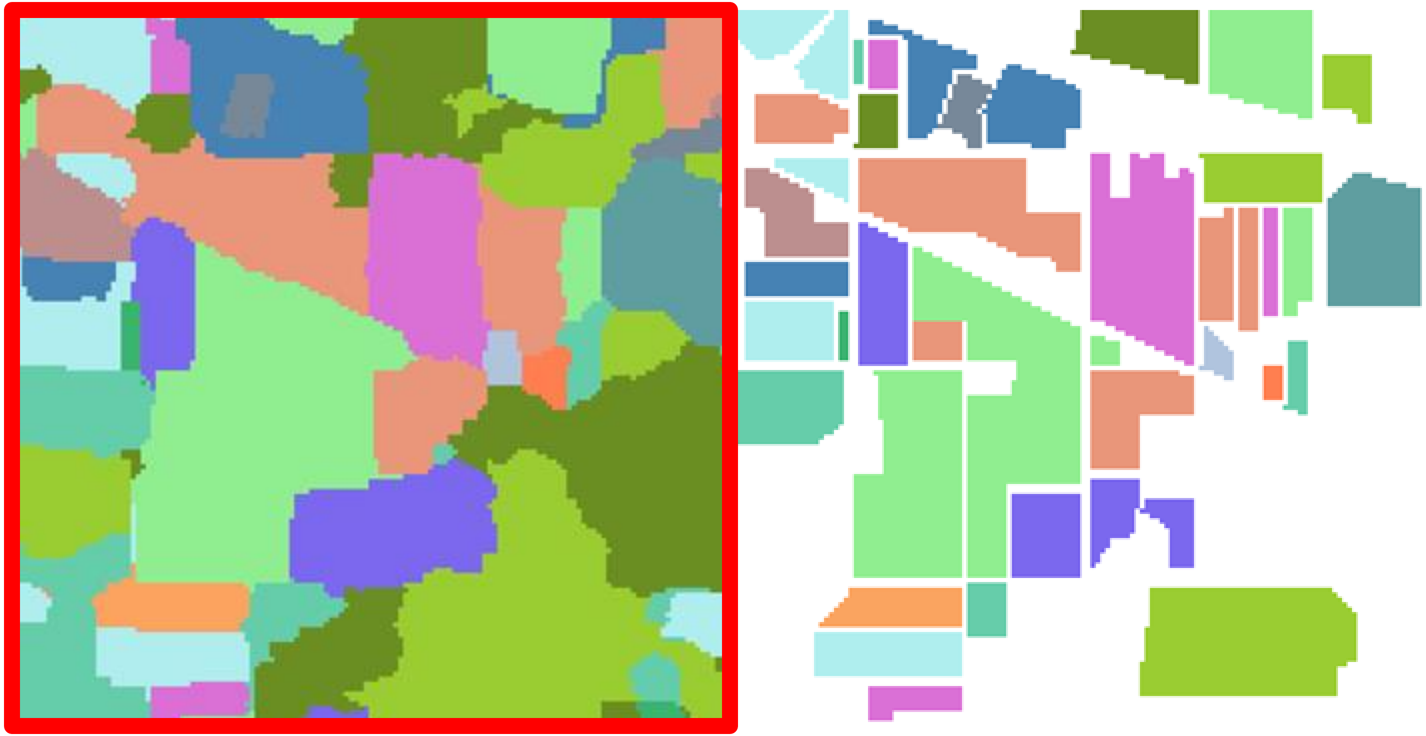
Hyperspectral Image with 224 Channels -- North-western Indiana, two-thirds **agriculture**, and one-third **forest** or other natural perennial **vegetation**

True color RGB image

Can you effectively ***discriminate*** the 16 classes on this image, and why?

1. Crop classification Using Deep Learning and Spatial Modeling AVIRIS

Hyperspectral Image with 224 Channels -- North-western Indiana, two-thirds **agriculture**, and one-third **forest** or other natural perennial **vegetation**



Visual classification very difficult:

Too many channels!

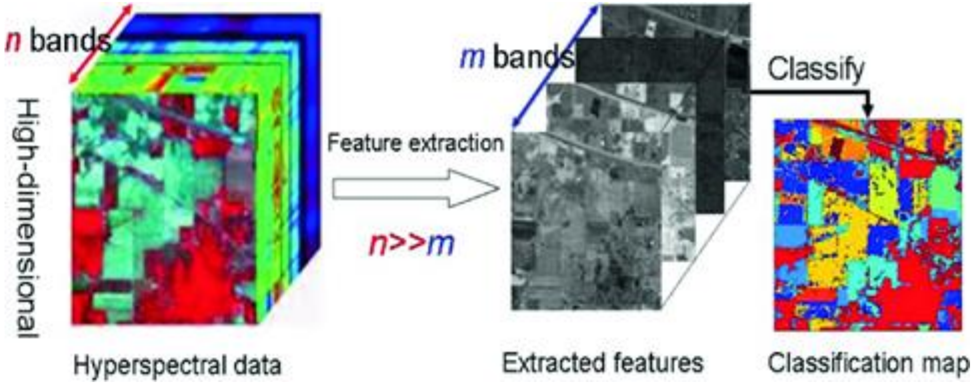
Weak class signatures hiding in high-dimensional space;

Just visualizing 3 bands cannot tell the differences;

Spatial Modeling and Deep neural network classifier achieved ***97.45%*** overall accuracy using ***5% of the training samples*** in each class;

2. Feature Extraction - Why Important?

Transforming **high-dimensional** spectral space into **low-dimensional** space, where the **most informative latent patterns** in hyperspectral images can be **revealed**.



-- ***Visualization, exploration, pattern discovery***

-- ***Dimension reduction to avoid "the curse of dimensionality"***

-- ***Data compression, reduce spectral redundancy***

-- ***Reduce the need on large training samples***

Approaches:

-- Selecting several informative bands from many bands; **drawbacks: ignore many other bands; which bands? bias in knowledge;**

-- Simple nonlinear transformation of several bands, e.g., NDVI, NDSI; **drawbacks: ignore many other bands; which bands? bias in knowledge;**

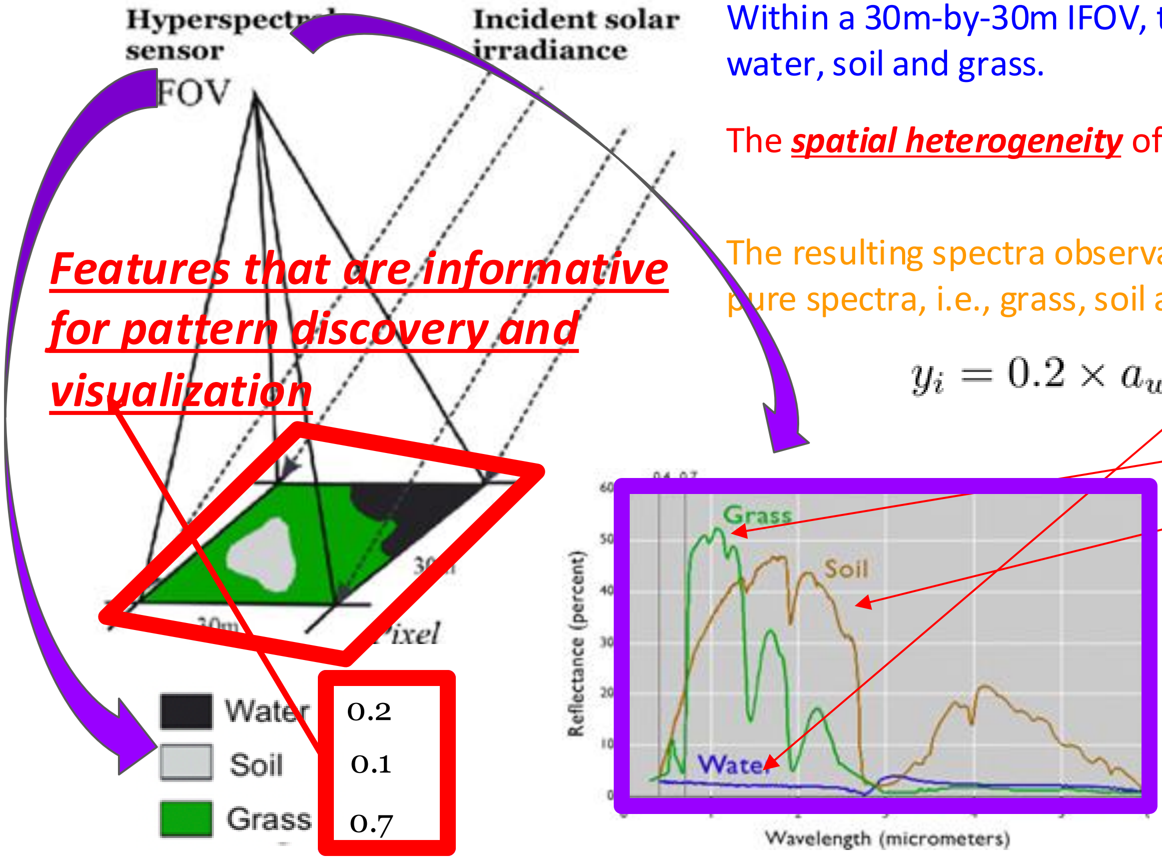
-- Linear transformation of all bands, e.g., PCA, ICA; **drawbacks: how to transform? Statistical approaches, not informative; linear;**

Solutions:

-- Use **physical model** (spectral mixture models) to guide feature extraction process, disentangle high-dimensional spectra into limited endmembers and their fractional abundance;

-- Unsupervised deep learning approaches, e.g., auto-encoder;

Spectral Unmixing for Feature Extraction



<u>Features that are informative for pattern discovery and visualization</u>

Within a 30m-by-30m IFOV, there are ***<u>multiple land cover classes</u>***, i.e., water, soil and grass.

The ***<u>spatial heterogeneity</u>*** of land cover classes leads to ***<u>mixed pixels in HSI</u>***.

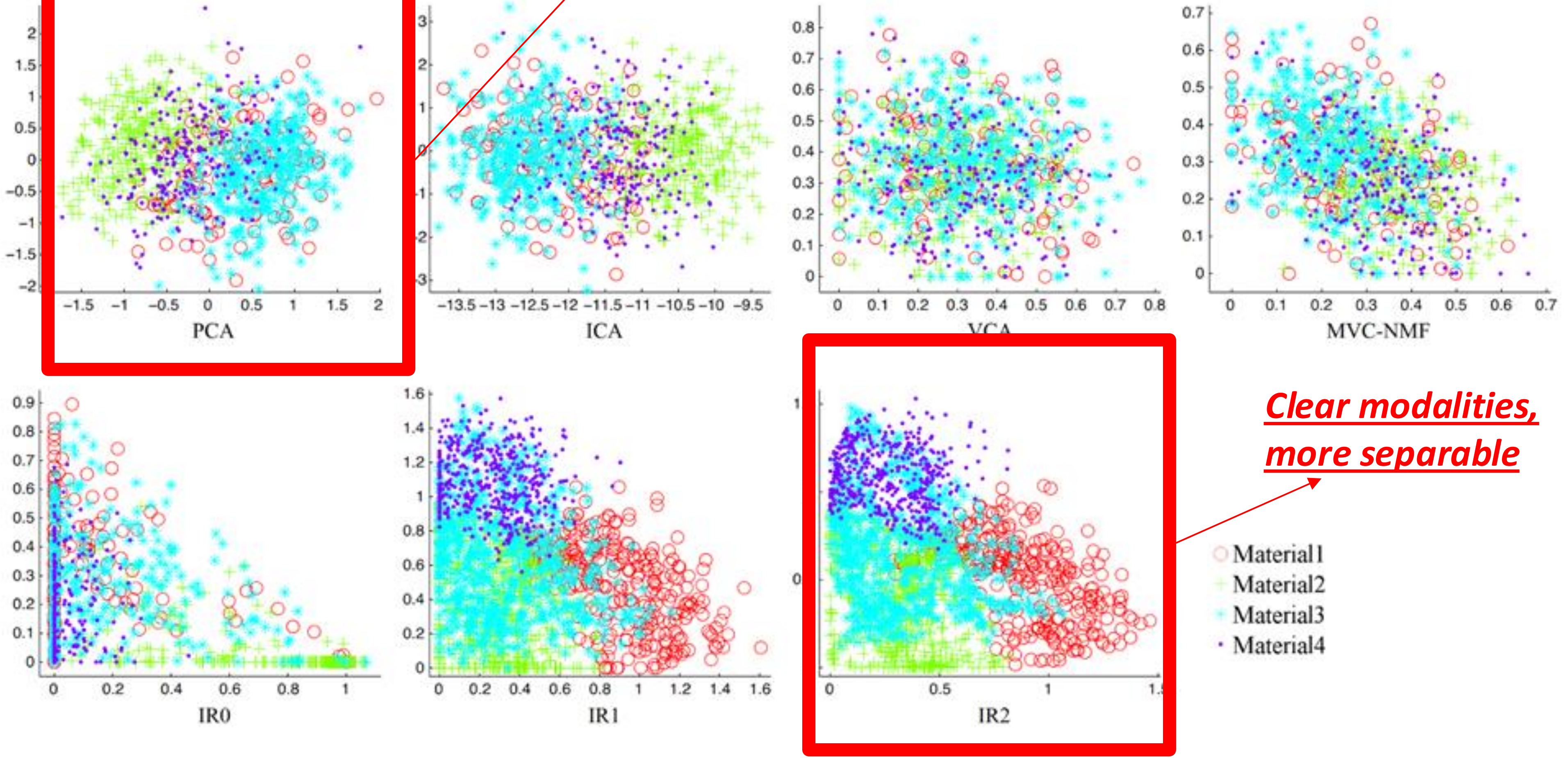
The resulting spectra observation of this mixed pixel is a mixture of three pure spectra, i.e., grass, soil and water.

$$y_i = 0.2 \times a_{water} + 0.7 \times a_{grass} + 0.1 \times a_{soil}$$

Spectral unmixing aims to ***<u>quantify the within-pixel spatial heterogeneity</u>*** by decomposing the mixed pixel into pure spectra (i.e., ***<u>endmembers</u>***) and their fractional proportions (i.e., ***<u>abundances</u>***).

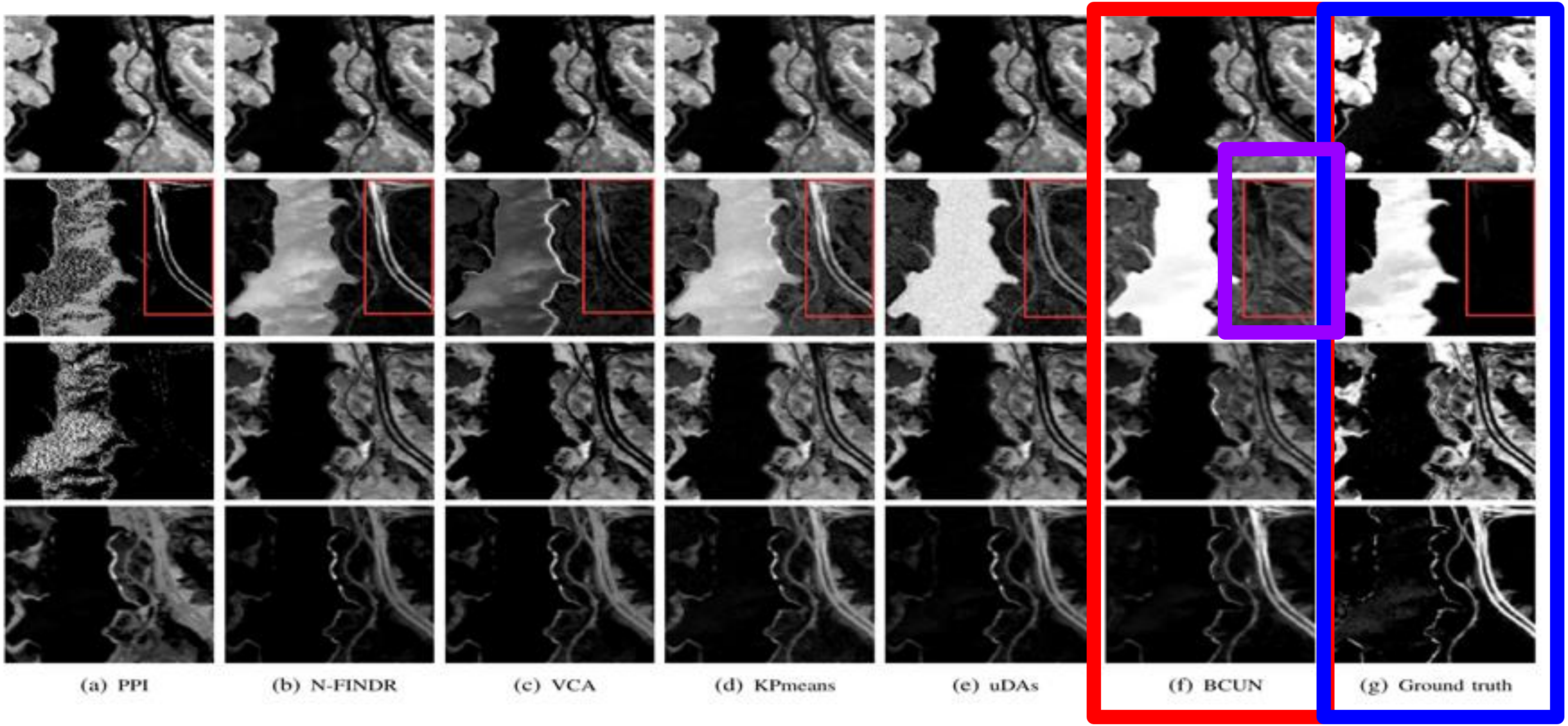
Spectral unmixing is essential for ***<u>Discovering patterns using a limited number of abundances maps</u>***

Classes are not separable



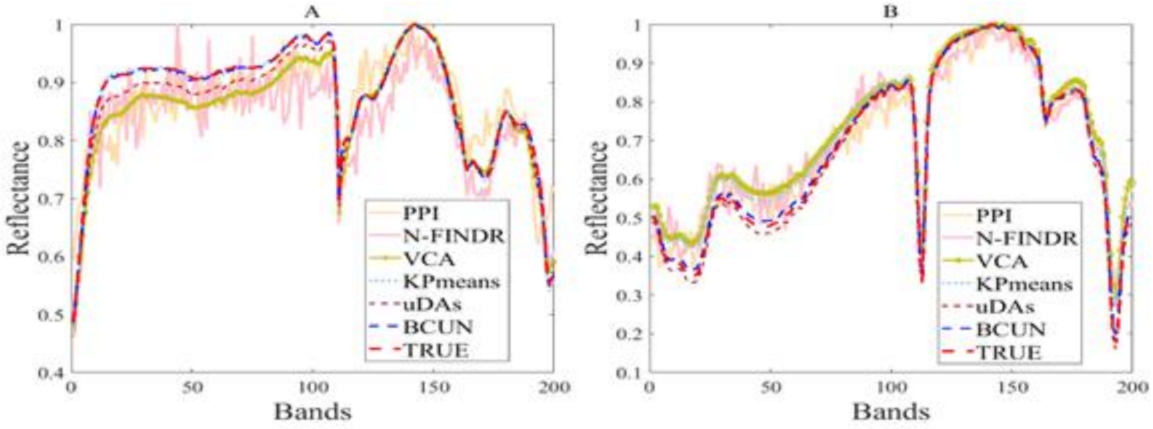
Clear modalities, more separable

Abundance Estimation Results

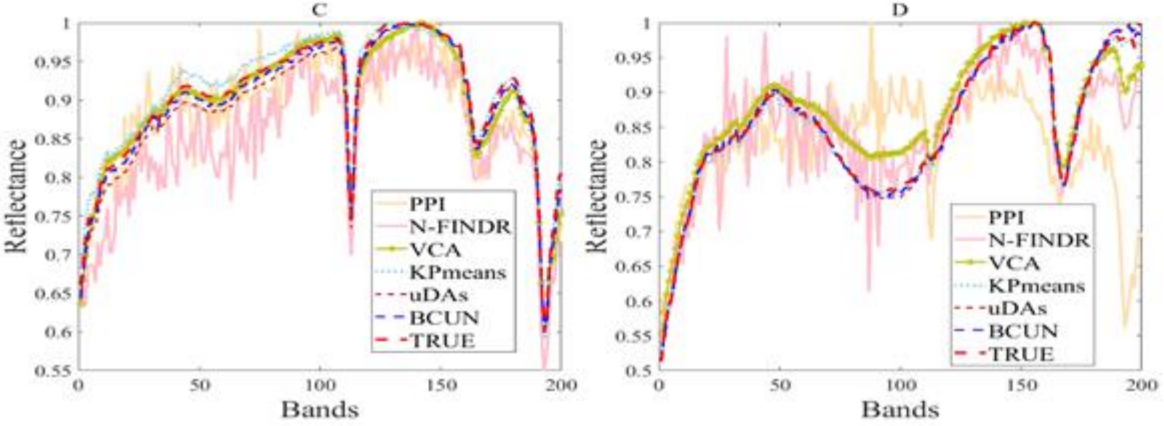

(a) PPI (b) N-FINDR (c) VCA (d) KPmeans (e) uDAs (f) BCUN (g) Ground truth

The abundance maps achieved by different methods on four endmembers (tree, water, soil, road) respectively ***from top to bottom.***

Endmembers Estimation Results



(a) Endmember 1 (b) Endmember 2



(c) Endmember 3 (d) Endmember 4

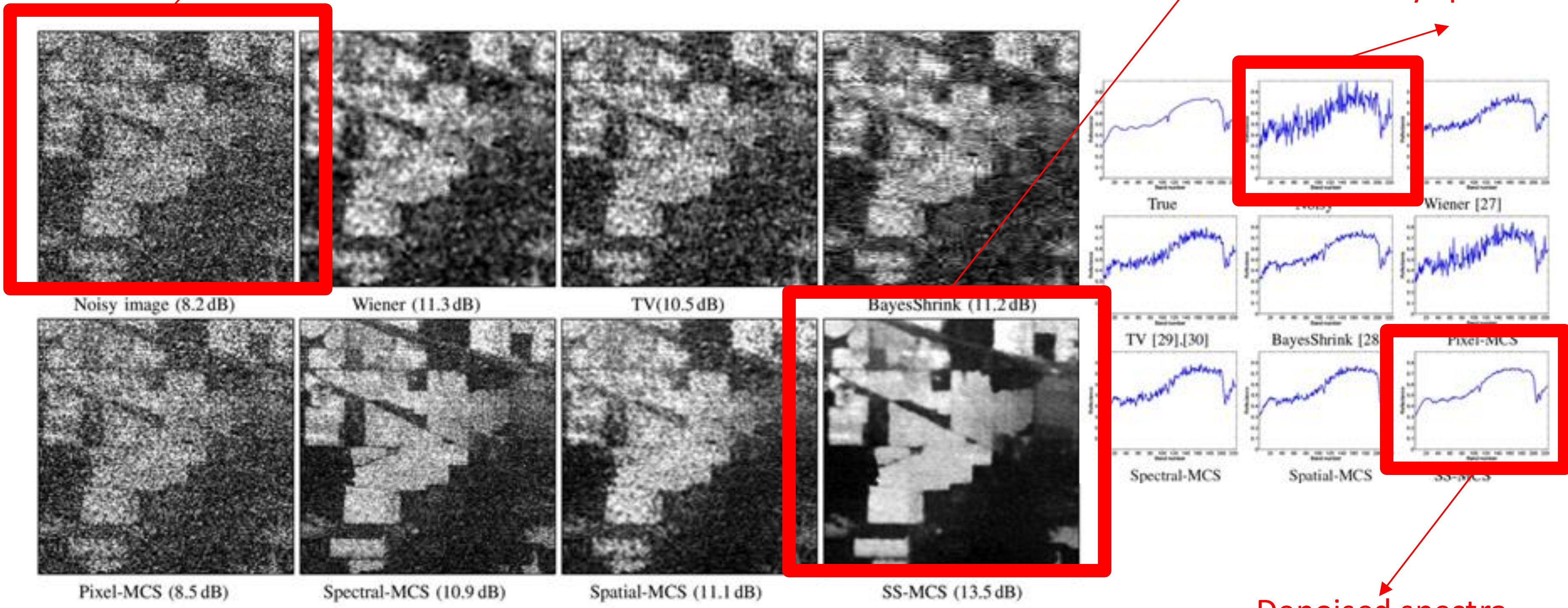
The ***proposed method*** provides endmember spectral curves that are ***closest to the ground truth***.

Denoising of Hyperspectral Crop Scene

Raw noisy hyperspectral band image

denoised hyperspectral band image

Noisy spectra



Noisy image (8.2 dB)
Wiener (11.3 dB)
TV(10.5 dB)
BayesShrink (11.2 dB)
Pixel-MCS (8.5 dB)
Spectral-MCS (10.9 dB)
Spatial-MCS (11.1 dB)
SS-MCS (13.5 dB)

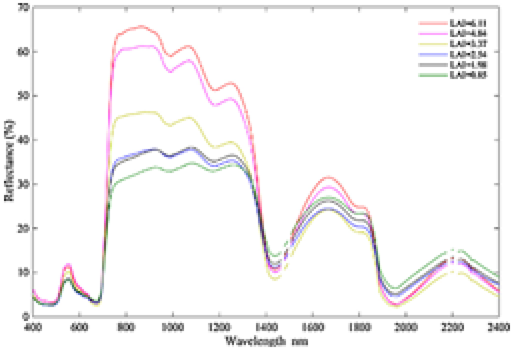
True
Noisy
Wiener [27]
TV [29],[30]
BayesShrink [28]
Pixel-MCS
Spectral-MCS
Spatial-MCS
SS-MCS

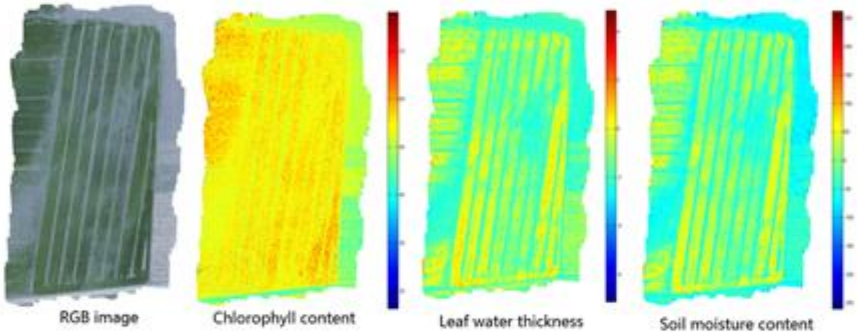
Denoised spectra

Fig. 20. Denoising results achieved by different methods, on band 219 of Indian Pines image. The SNR values are shown in parenthesis. The proposed SS-MCS method increases the SNR of noisy image dramatically by 5.3 dB. Moreover, it recovers the scene signal from intense noise pollution. Using information in adjacent channels, spectral-MCS also highlights the signals, but also preserves large amount of noise.

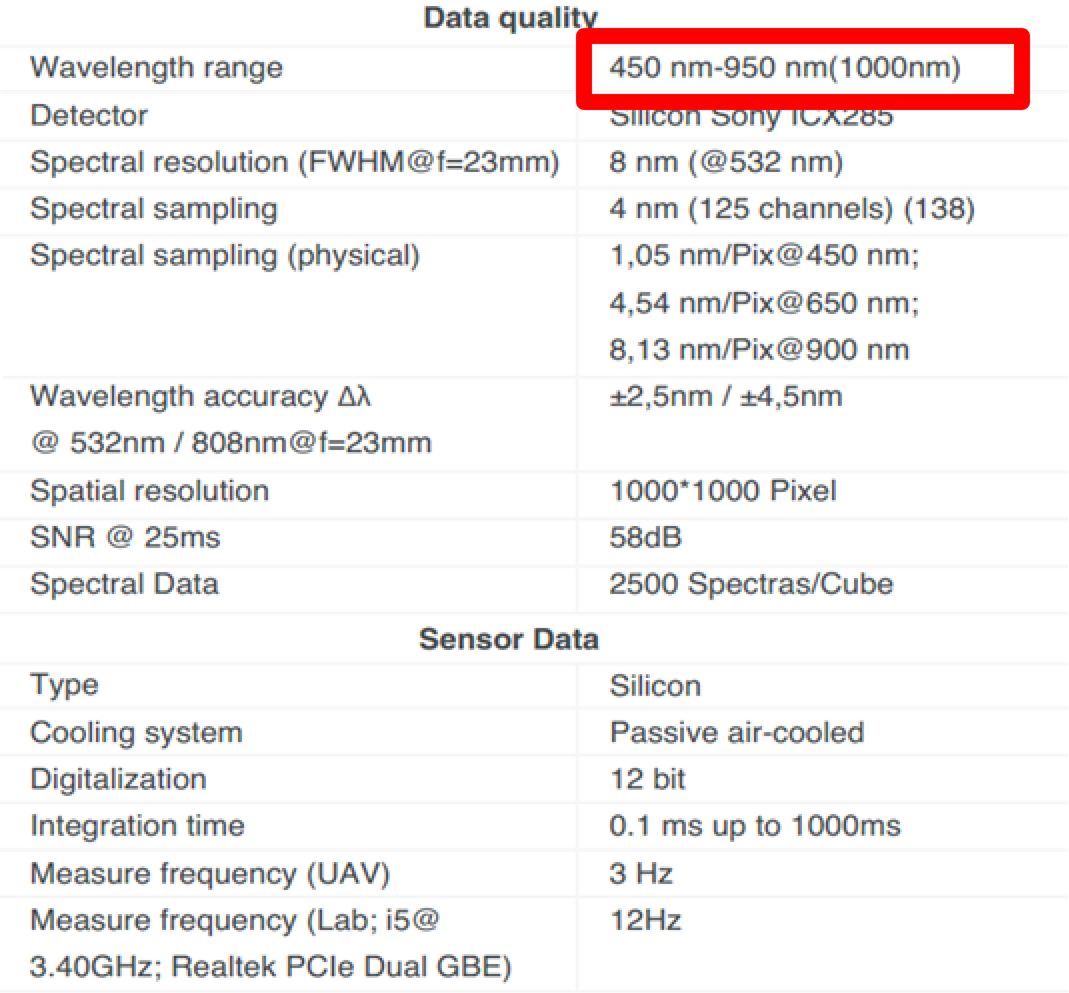
Hyperspectral Canopy Monitoring

- **Platforms**: satellite, UAV, manned airplane
- **Biophysical** & **biochemical Parameters**: e.g., LAI, Chlorophyll content
- **Models**: physical models & empirical models
- **Many Applications**: e.g., precision agriculture



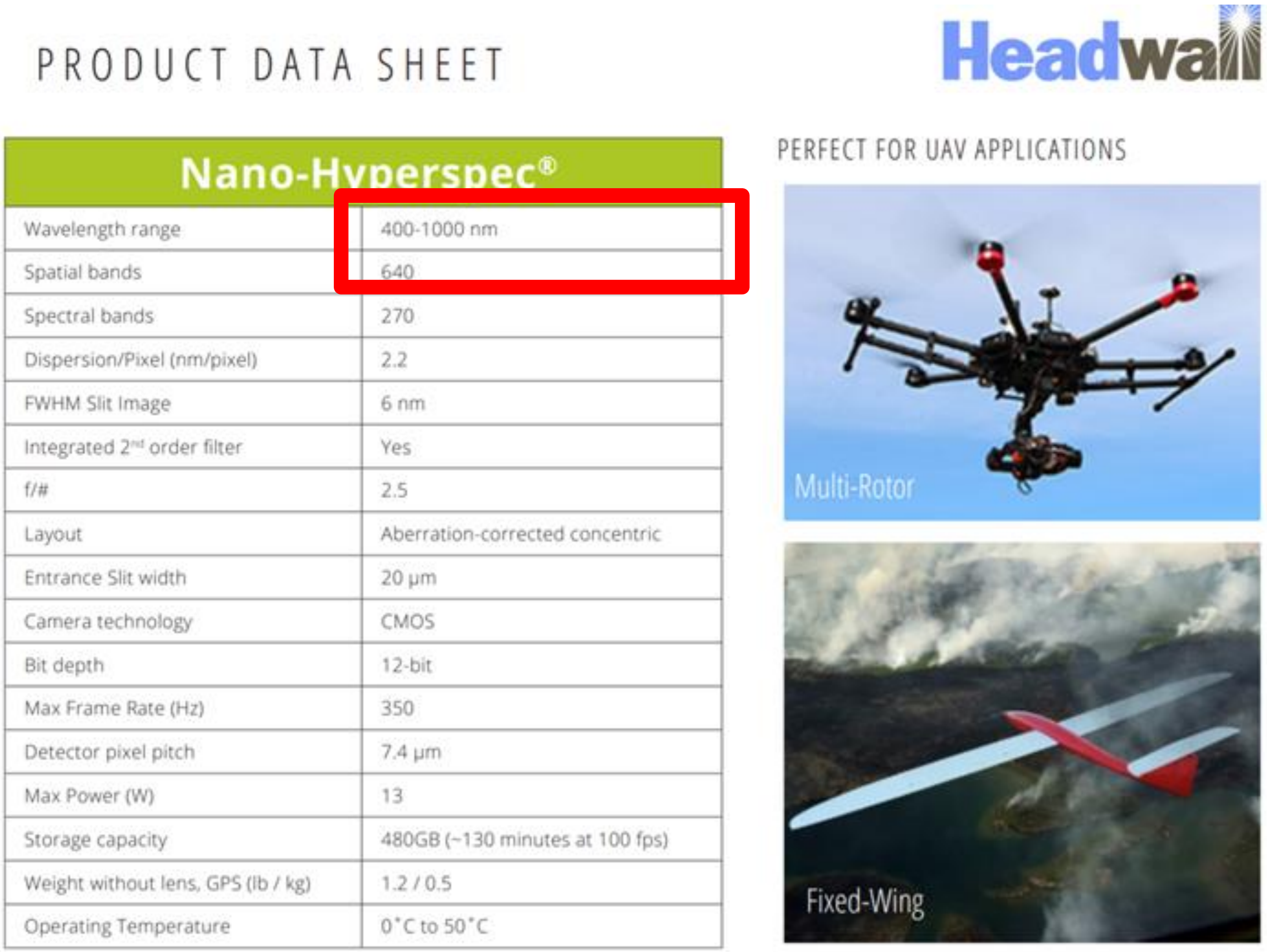


Cubert Frame Camera



Data quality	
Wavelength range	450 nm-950 nm(1000nm)
Detector	Silicon Sony ICX285
Spectral resolution (FWHM@f=23mm)	8 nm (@532 nm)
Spectral sampling	4 nm (125 channels) (138)
Spectral sampling (physical)	1,05 nm/Pix@450 nm; 4,54 nm/Pix@650 nm; 8,13 nm/Pix@900 nm
Wavelength accuracy Δλ @ 532nm / 808nm@f=23mm	±2,5nm / ±4,5nm
Spatial resolution	1000*1000 Pixel
SNR @ 25ms	58dB
Spectral Data	2500 Spectras/Cube
Sensor Data	
Type	Silicon
Cooling system	Passive air-cooled
Digitalization	12 bit
Integration time	0.1 ms up to 1000ms
Measure frequency (UAV)	3 Hz
Measure frequency (Lab; i5@ 3.40GHz; Realtek PCIe Dual GBE)	12Hz

Headwall Pushbroom Camera



PRODUCT DATA SHEET

Headwall

Nano-Hyperspec®	
Wavelength range	400-1000 nm
Spatial bands	640
Spectral bands	270
Dispersion/Pixel (nm/pixel)	2.2
FWHM Slit Image	6 nm
Integrated 2nd order filter	Yes
f/#	2.5
Layout	Aberration-corrected concentric
Entrance Slit width	20 µm
Camera technology	CMOS
Bit depth	12-bit
Max Frame Rate (Hz)	350
Detector pixel pitch	7.4 µm
Max Power (W)	13
Storage capacity	480GB (~130 minutes at 100 fps)
Weight without lens, GPS (lb / kg)	1.2 / 0.5
Operating Temperature	0°C to 50°C

PERFECT FOR UAV APPLICATIONS

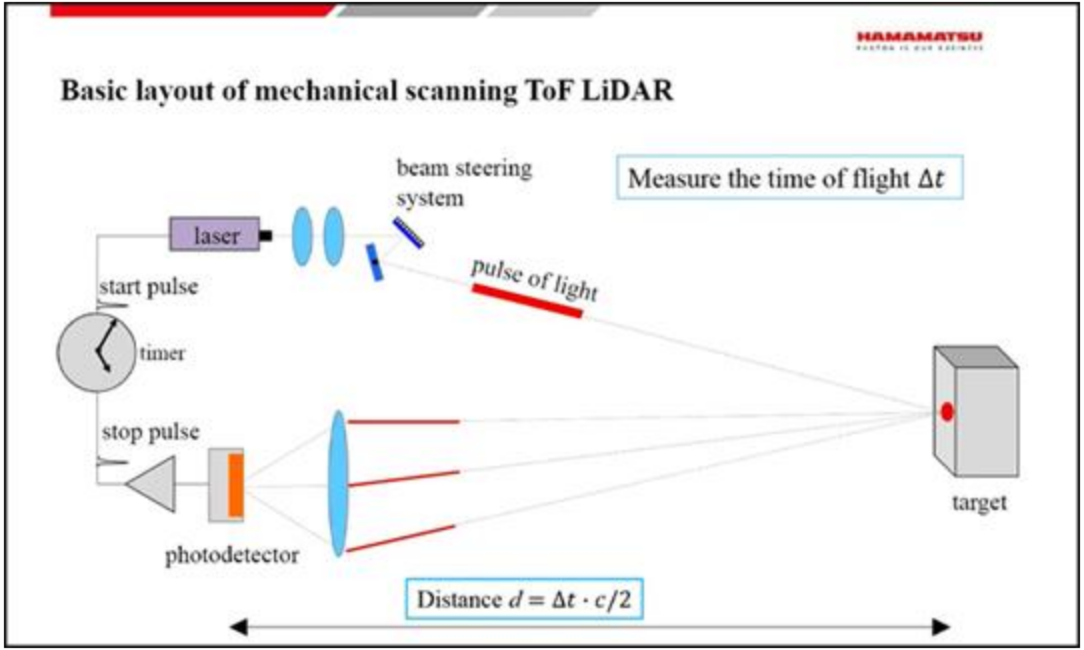
Multi-Rotor

Fixed-Wing

Outline

- ➔ SAR Remote Sensing
- ➔ Passive Microwave
- ➔ Hyperspectral remote sensing
- ➔ LiDAR
- ➔ Questions

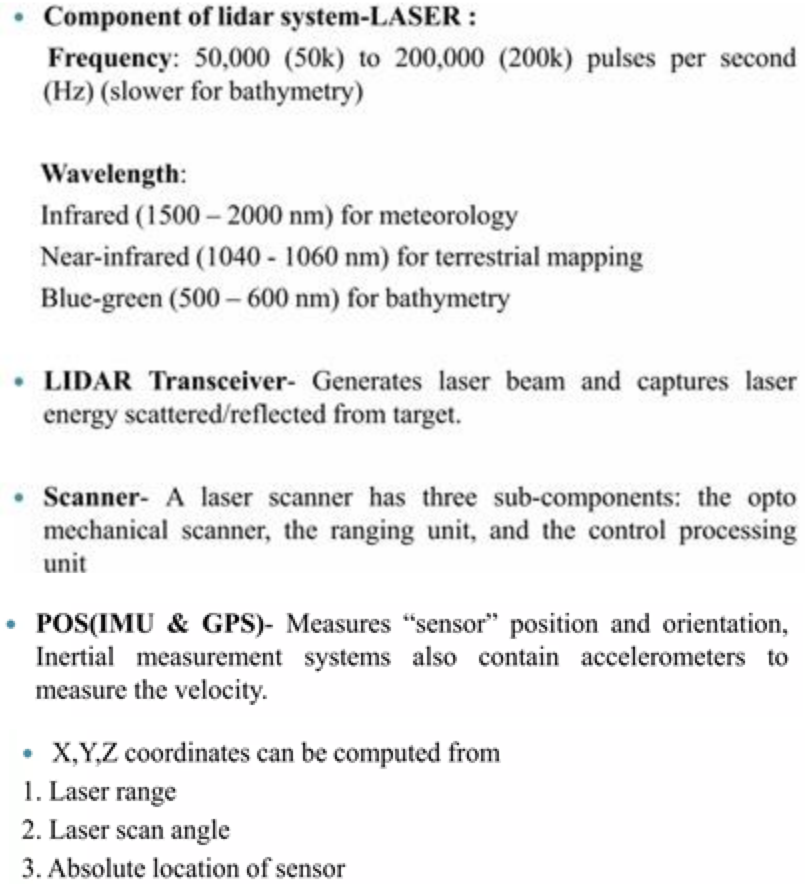
LiDAR (Light Detection And Ranging) - how to measure distance? Comparing with RADAR?



Basic layout of mechanical scanning ToF LiDAR

Measure the time of flight Δt

Distance $d = \Delta t \cdot c/2$



- **Component of lidar system-LASER :**

  Frequency: 50,000 (50k) to 200,000 (200k) pulses per second (Hz) (slower for bathymetry)

  Wavelength:

  Infrared (1500 – 2000 nm) for meteorology

  Near-infrared (1040 - 1060 nm) for terrestrial mapping

  Blue-green (500 – 600 nm) for bathymetry

- **LIDAR Transceiver-** Generates laser beam and captures laser energy scattered/reflected from target.

- **Scanner-** A laser scanner has three sub-components: the opto mechanical scanner, the ranging unit, and the control processing unit

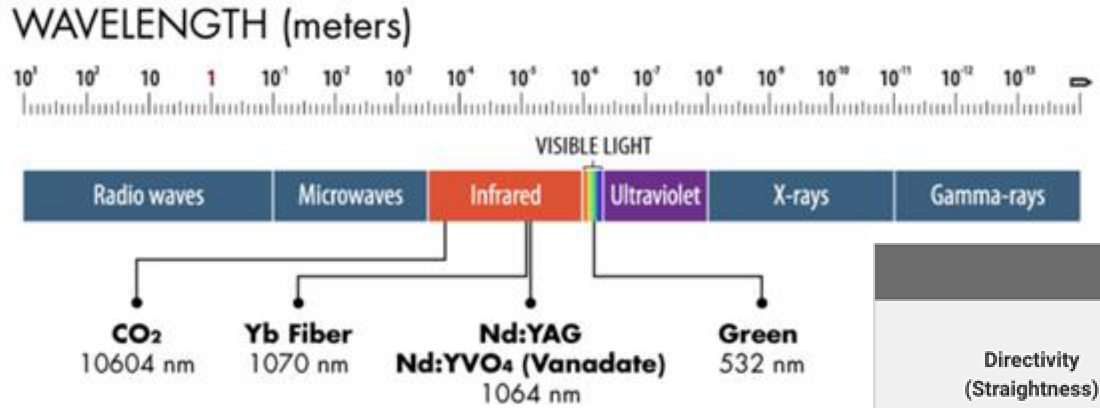
- **POS(IMU & GPS)-** Measures "sensor" position and orientation, Inertial measurement systems also contain accelerometers to measure the velocity.

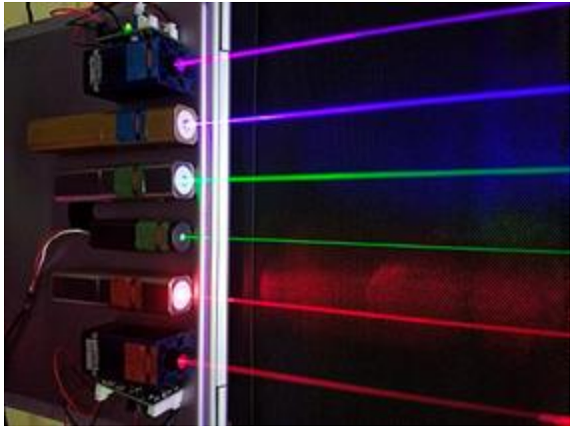
- X,Y,Z coordinates can be computed from

1. Laser range
2. Laser scan angle
3. Absolute location of sensor

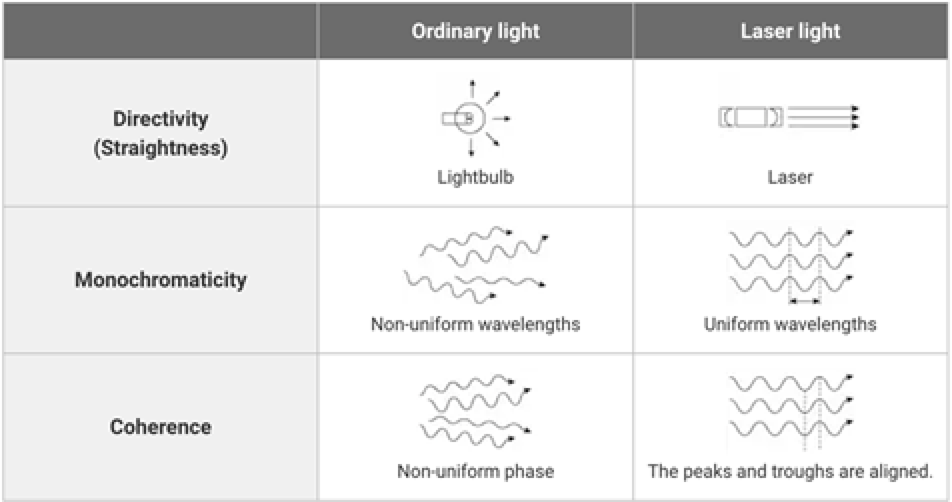
Laser (Light amplification by stimulated emission of radiation) -

is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation.





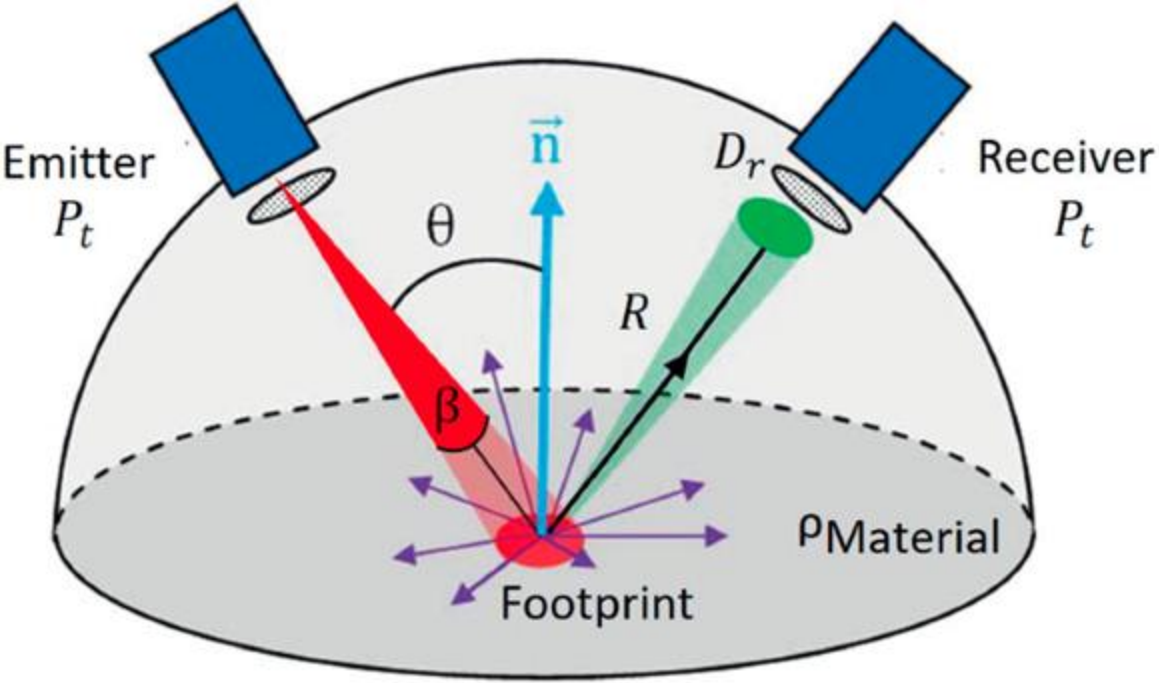
Red (660 & 635 nm), green (532 & 520 nm), and blue-violet (445 & 405 nm) lasers



	Ordinary light	Laser light
Directivity (Straightness)	Lightbulb	Laser
Monochromaticity	Non-uniform wavelengths	Uniform wavelengths
Coherence	Non-uniform phase	The peaks and troughs are aligned.

Spectral range?
Differences with ordinary light?

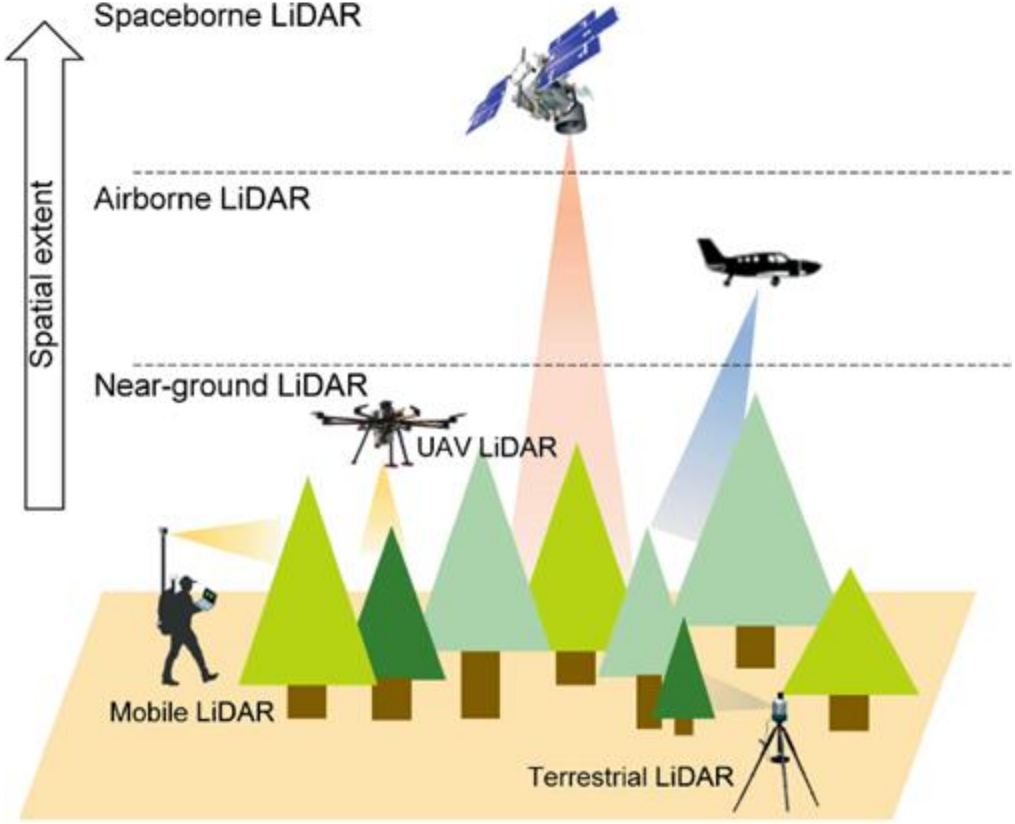
LiDAR Equation - What determines intensity? Comparing with RADAR?



$$P_r = P_t \cdot \rho \cdot \cos(\theta) \cdot \frac{\pi D^2}{4\text{R}} \cdot \eta_{atm} \cdot \eta_{sys}$$

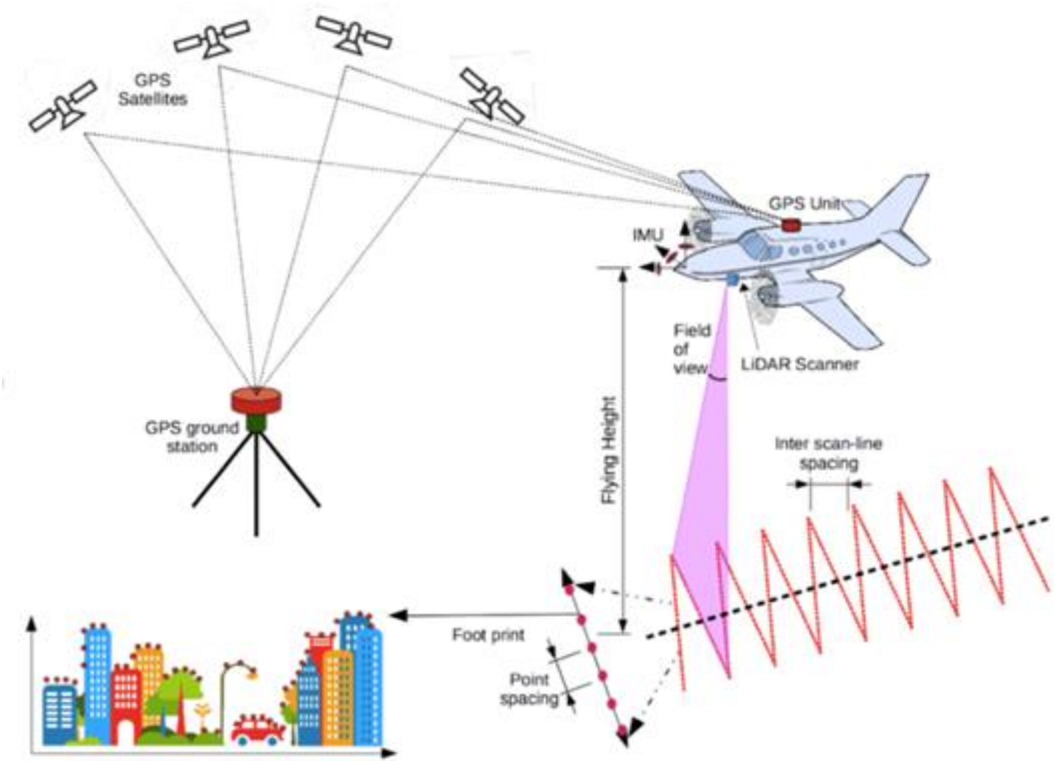
P_r	Received energy
P_t	Transmitted energy
ρ	Reflectance of target surface
θ	Incidence angle
Ω_s	Scattering steradian solid angle
R	Travel distance of sub-beam
D	Aperture diameter
η_{atm}	Efficient of optical system
η_{sys}	Atmospheric attenuation

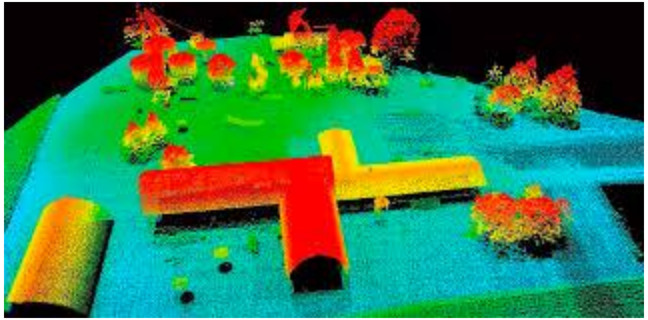
LiDAR - What Platforms?

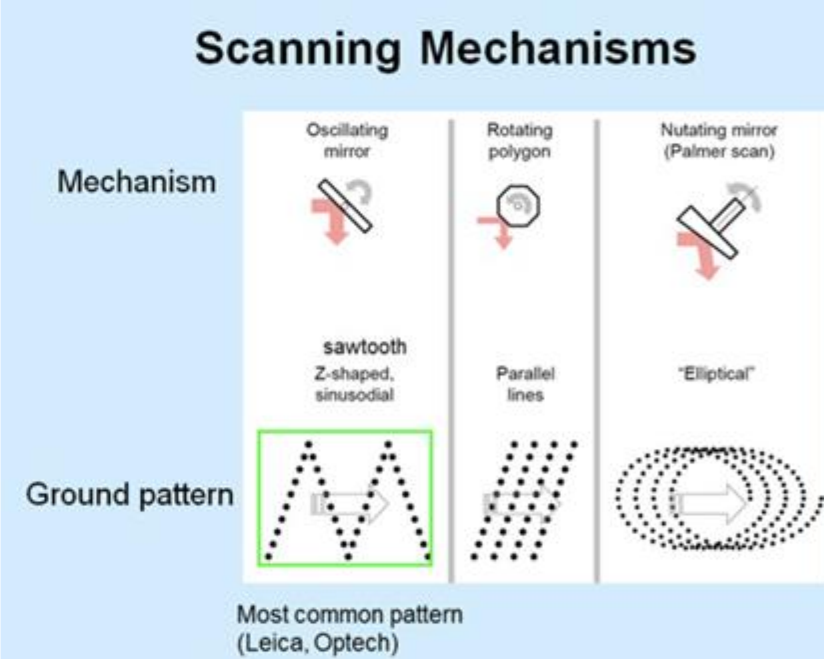


- AERIAL/AVIATION(Airborne)
  - For highly detailed, local elevation data
  - Small area where high density is needed
- SATELLITE(space borne)
  - covers large areas with less detail
- TERRESTRIAL(ground spaced)

Airborne LiDAR Geometry - how to calculate X, Y, Z?





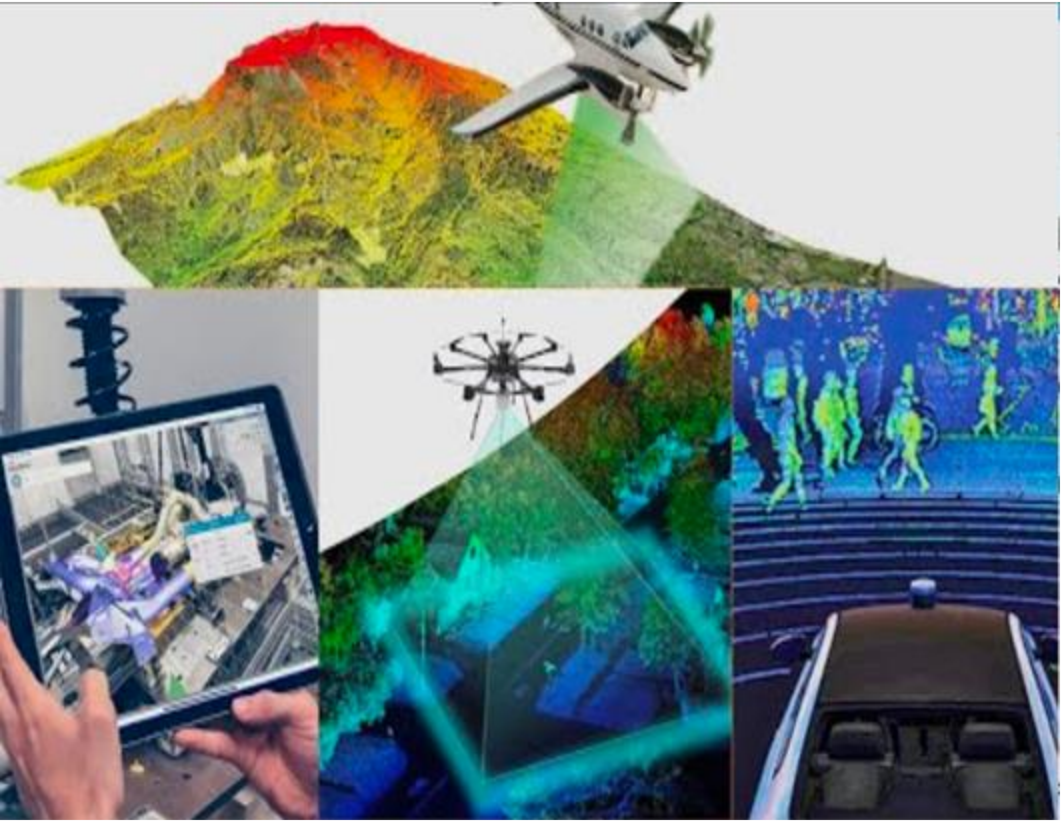


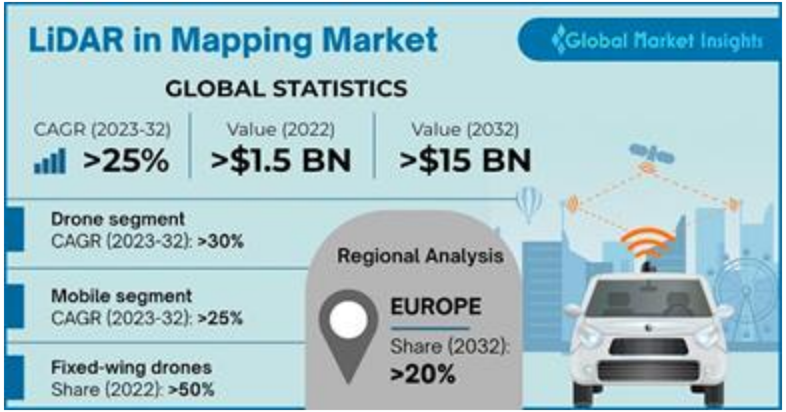
Scanning Mechanisms

	Oscillating mirror	Rotating polygon	Nutating mirror (Palmer scan)
Mechanism			
	sawtooth Z-shaped, sinusodial	Parallel lines	"Elliptical"
Ground pattern			

Most common pattern (Leica, Optech)

LiDAR - What Applications?





LiDAR in Mapping Market

Global Market Insights

GLOBAL STATISTICS

CAGR (2023-32)	Value (2022)	Value (2032)
>25%	>$1.5 BN	>$15 BN

Drone segment
CAGR (2023-32): >30%

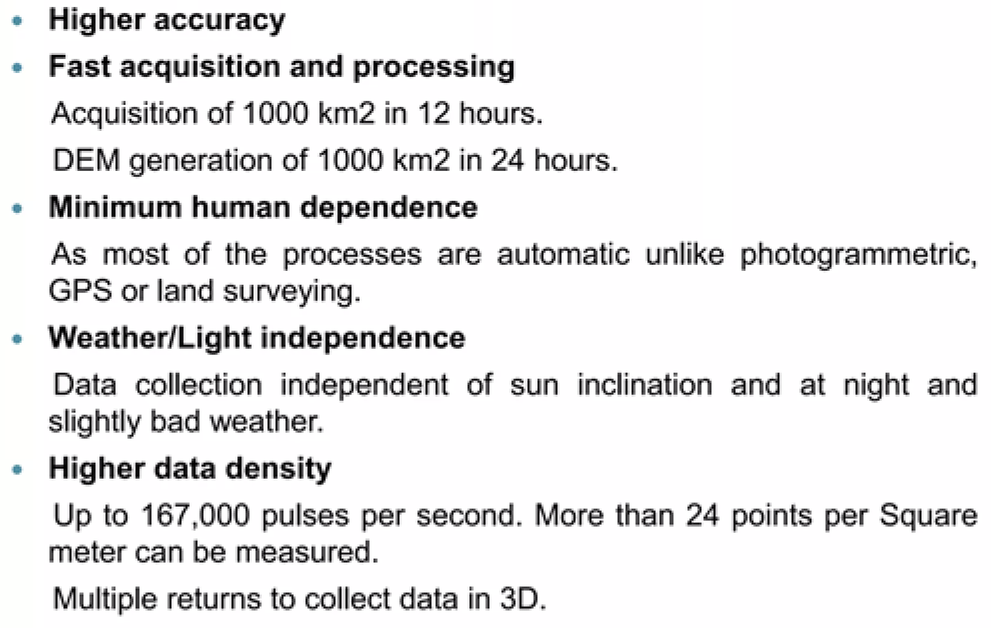
Mobile segment
CAGR (2023-32): >25%

Fixed-wing drones
Share (2022): >50%

Regional Analysis
EUROPE
Share (2032):
>20%

- **Agriculture** : Create a Topographical map of the fields and reveals the slopes and sun exposure of the farm land.
- **Autonomous vehicles**: Autonomous vehicles use LIDAR for obstacle detection and avoidance to navigate safely through environments.
- **Geology and soil science**: ICE Sat (Ice, Cloud, and land Elevation Satellite).
- **Law enforcement**: LIDAR speed guns
- Surveying, Transport , wind farm optimization and many more.
- Atmospheric Remote Sensing and Meteorology.

LiDAR Advantages:



- **Higher accuracy**
- **Fast acquisition and processing**

  Acquisition of 1000 km2 in 12 hours.

  DEM generation of 1000 km2 in 24 hours.
- **Minimum human dependence**

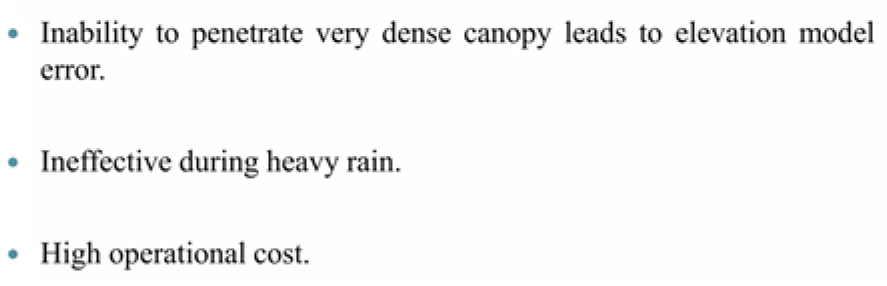
  As most of the processes are automatic unlike photogrammetric, GPS or land surveying.
- **Weather/Light independence**

  Data collection independent of sun inclination and at night and slightly bad weather.
- **Higher data density**

  Up to 167,000 pulses per second. More than 24 points per Square meter can be measured.

  Multiple returns to collect data in 3D.

Disadvantages:



- Inability to penetrate very dense canopy leads to elevation model error.
- Ineffective during heavy rain.
- High operational cost.

Sensors	Pros	Cons
Camera	• High-speed imaging • Passive sensor • Best for recognition • No need for high power • Inexpensive • Infrared or thermal availability • Interference-free • High sensing resolution • AI and deep learning research are very advanced	• Light and visibility dependent • Easily affected by shadow or reflections • Get dirty frequently • Direct 3D is not possible without any stereo
LiDAR	• Direct 3D information • Performed in both day and night • Very high accuracy measurements • High resolution • At present, AI research is very advanced	• Very expensive • No appearance information • Ineffective under rain and fog • Have rotating parts • Most of LiDAR is not a deep learning base yet
RADAR	• Captures direct distance and velocity • Inexpensive • Performed both day and night • Immunity to adverse weather • Detect potentially long-range • Reliable and proven technology • Solid state	• Provides very noisy output • Object boundary detection is not good • Limited classification capability • Poor resolution • Unable to detect small objects • AI research just started

Questions?