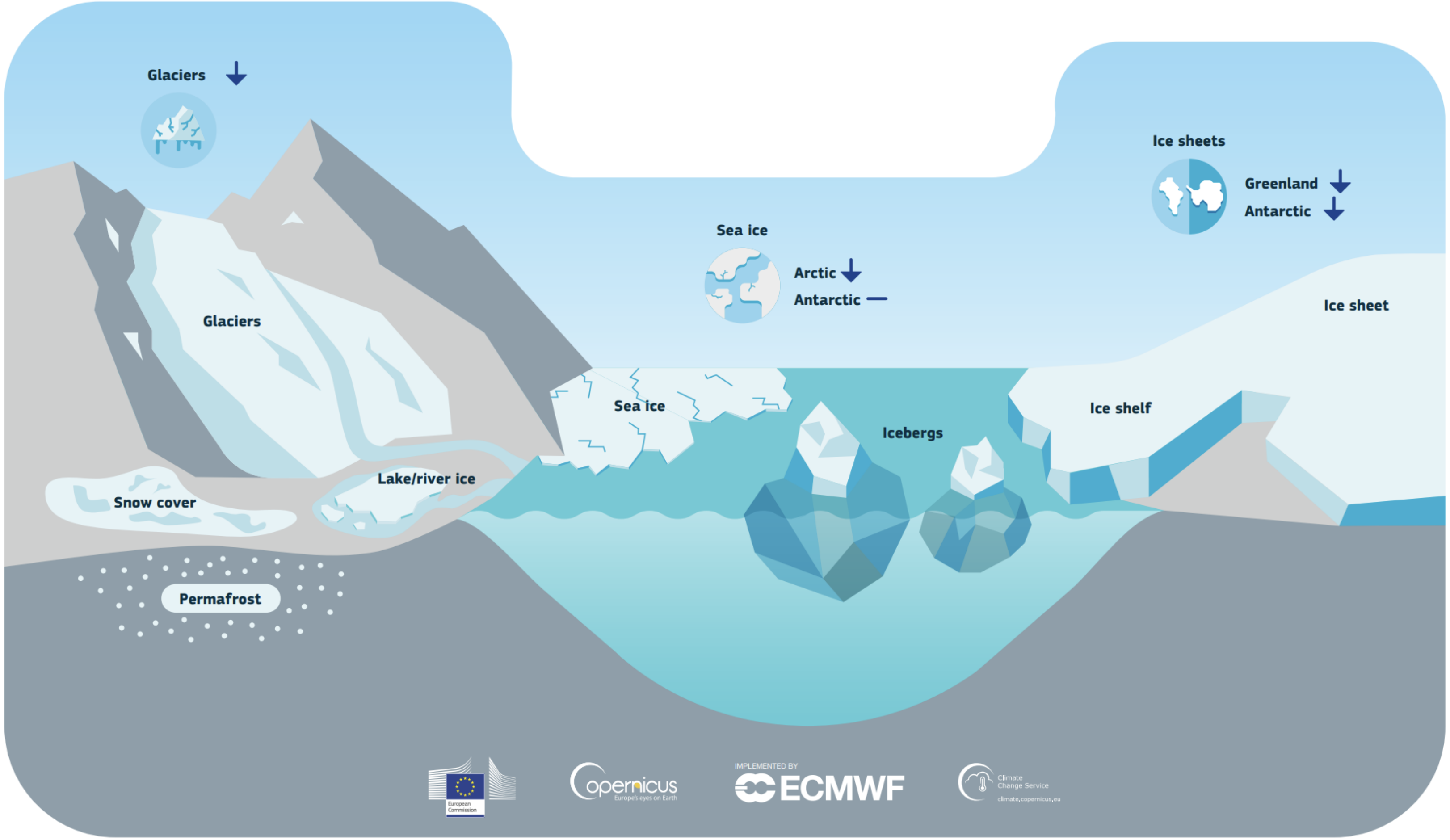
Introduction of Remote Sensing and Drone for Snow and Glacier Monitoring

Contents

- A brief introduction into cryospheric studies
- Glaciers, glacial system and mass balance
- Remote sensing of snow/glaciers
- Parametric indicators related to glacier analysis
- Glacier Mass Balance, glacier velocity
- Image classification for glacier mapping

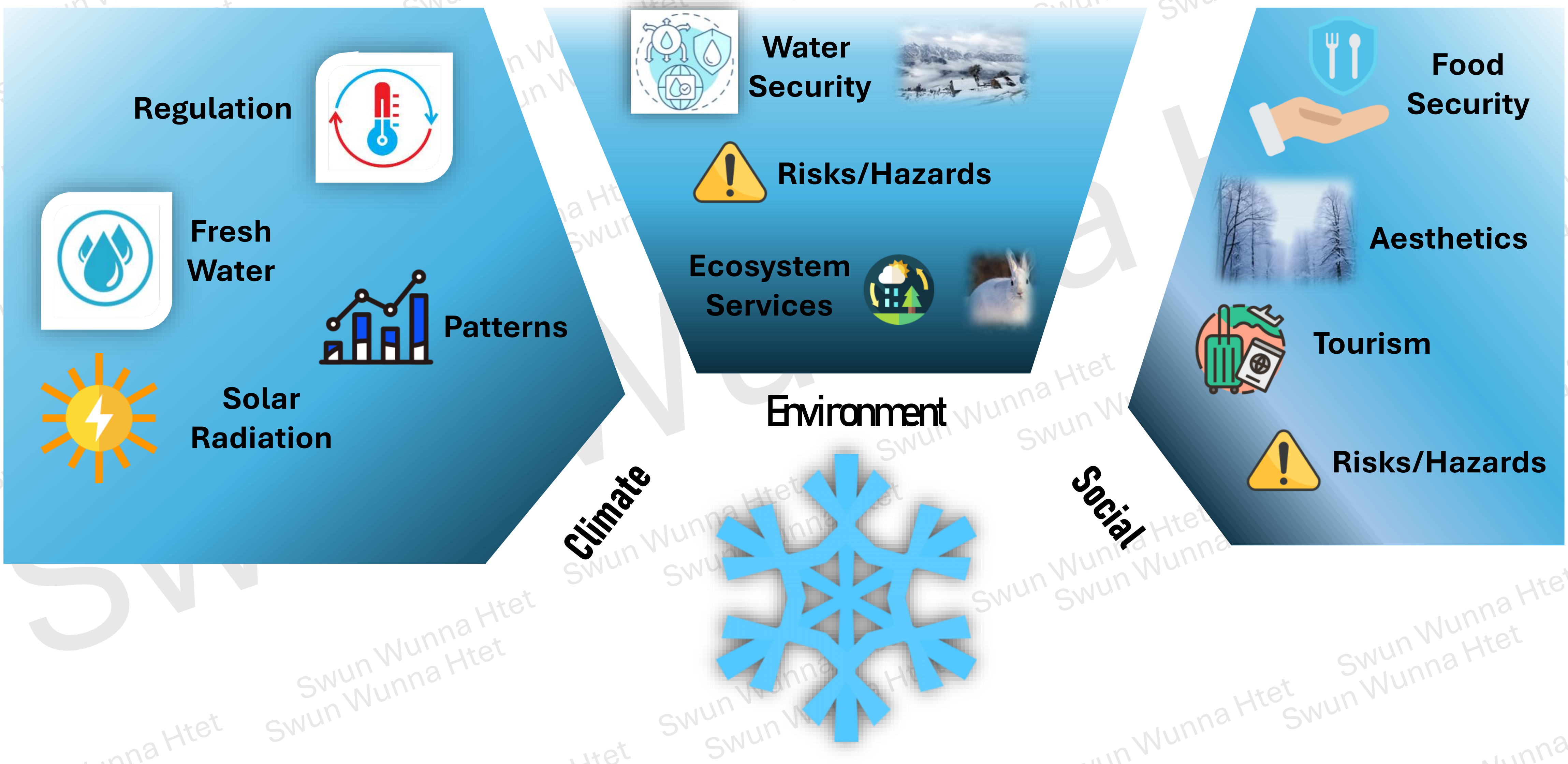
Cryosphere Studies

- Cryosphere: frozen water component of the Earth System.
- Composed the ice, snow, glaciers, permafrost areas, glacial lakes, frozen rivers and lakes.
- Important role in regulating the climate of the Earth.



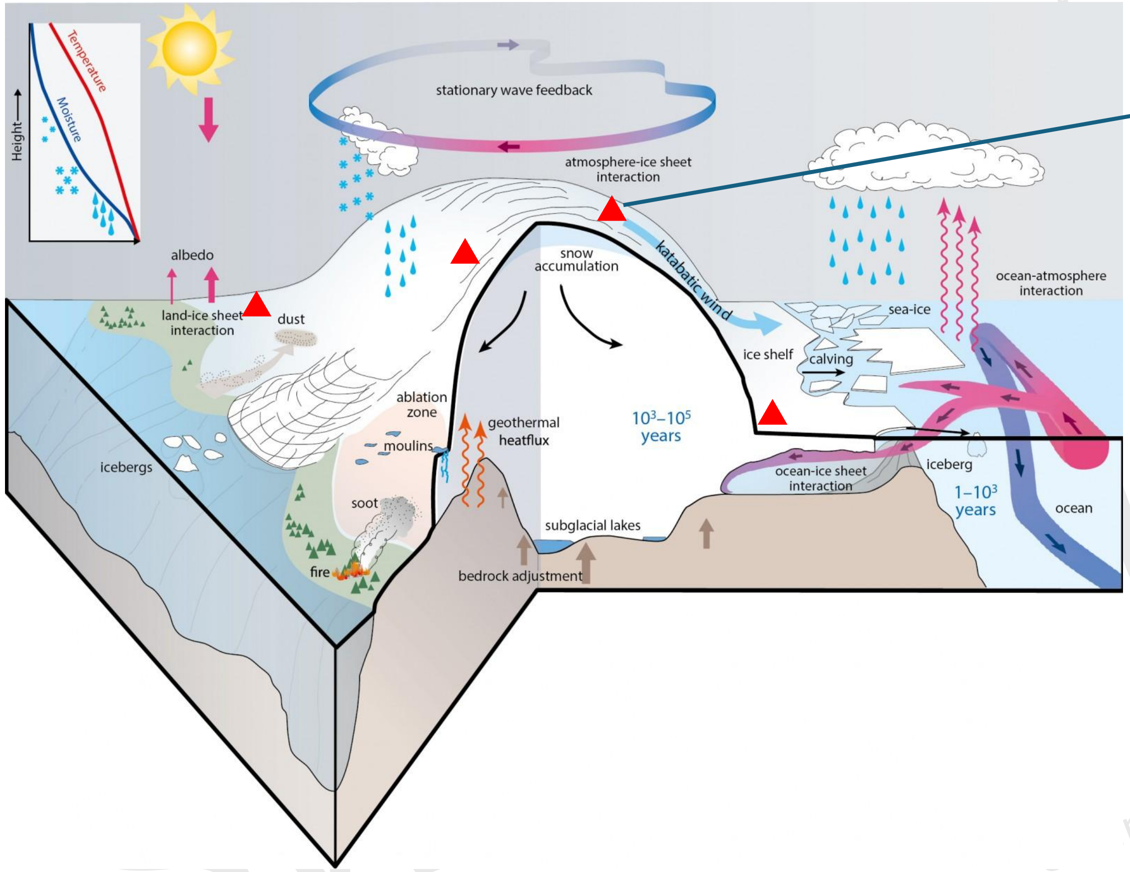
Source:
https://oceanservice.noaa.gov/facts/cryosphere.html#:~:text=The%20term%20%E2%80%9Ccryosphere%E2%80%9D%20comes%20from,areas%20of%20snow%20and%20permafrost., https://climate.copernicus.eu/climate-indicators/cryosphere#:~:text=The%20cryosphere%20exerts%20an%20important,absorbed%20by%20land%20and%20oceans.

Why we monitor snow and glaciers?



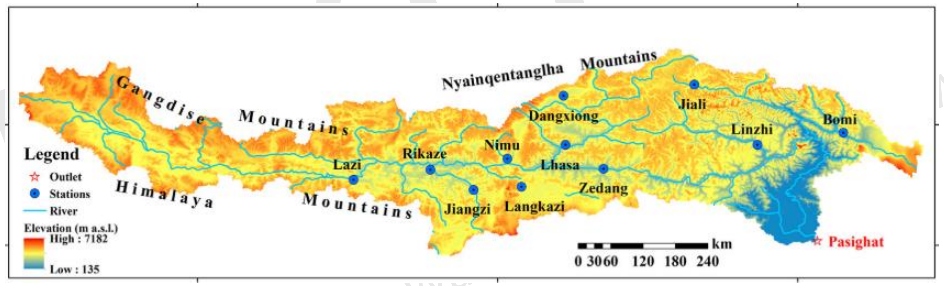
How we monitor snow characteristics?

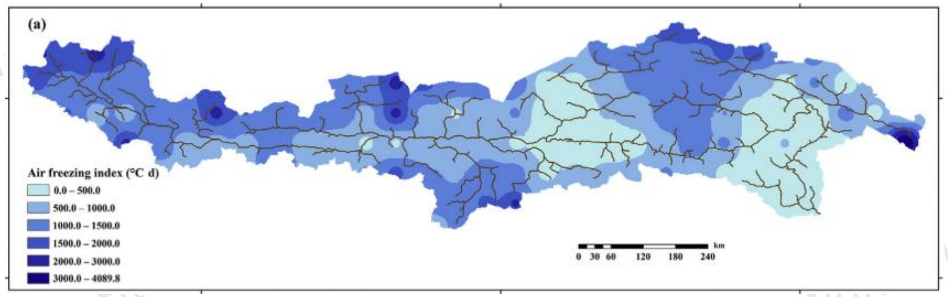
Traditional monitoring/ Geodetic monitoring



Station monitoring

On-site measurement



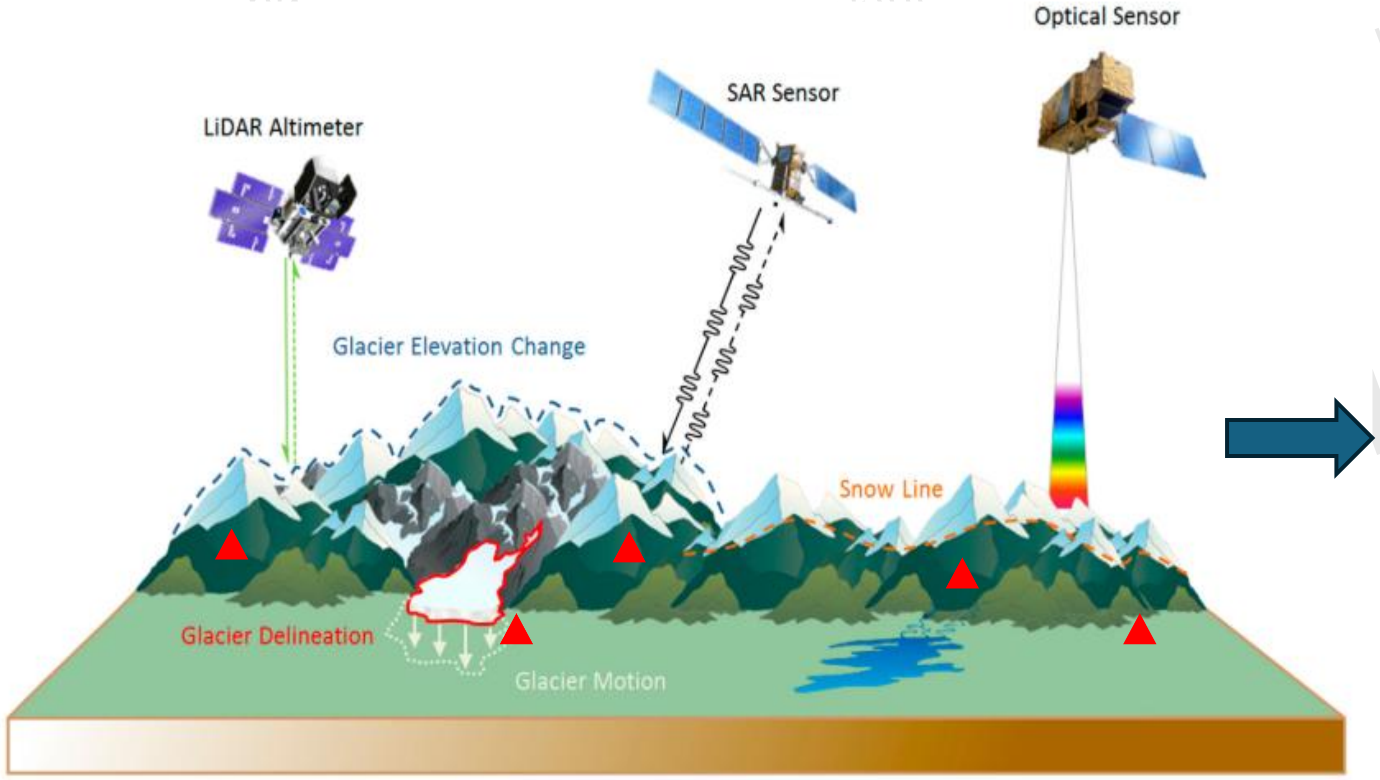


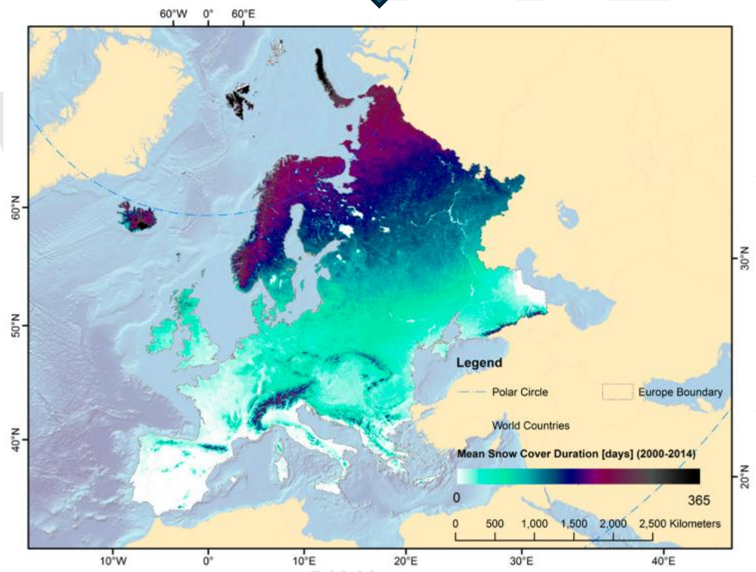
Spatial Interpolation for spatial distribution maps

Source: *https://blogs.egu.eu/divisions/cr/2015/12/11/image-of-the-week-ice-sheets-in-the-climate/*

LIU, L., LUO, D. L., WANG, L., HUANG, Y. D., & CHEN, F. F. (2021). Dynamics of freezing/thawing indices and frozen ground from 1900 to 2017 in the upper Brahmaputra River Basin, Tibetan Plateau. Advances in Climate Change Research, 12(1), 6–17. https://doi.org/10.1016/j.accre.2020.10.003

Integration with Remote Sensing





With satellite integration to quantification of snow in spatio-temporal manner, we can address the snow condition of the inaccessible locations with reliable consistency.

Source: Hu, Z., Kuenzer, C., Dietz, A. J., & Dech, S. (2017). The potential of earth observation for the analysis of cold region land surface dynamics in Europe-A review. *Remote Sensing*, *9*(10). https://doi.org/10.3390/rs9101067

Traditional Survey vs Remote Sensing vs UAV Survey

Why one more advantageous over another?

Criteria	Traditional Survey	Remote Sensing	UAV Application
Time	*	*****	****
Resources Demand	*	****	***
Data Access	**	*****	*
Spatial Representation	***	****	*****

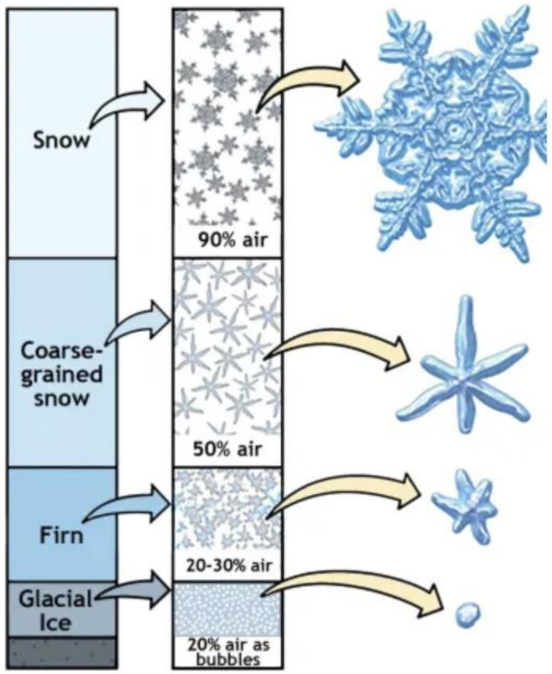
* = least favorable, ***** = most favorable, NA = Not Applicable

Source: Kongoli, C., Key, J., & Smith, T. M. (2019). Mapping of snow depth by blending satellite and in-situ data using two-dimensional optimal interpolation-application to AMSR2. Remote Sensing, 11(24). https://doi.org/10.3390/rs11243049

What is a glacier?

Definition

- Glacier : accumulation of ice and snow that slowly flows over land.
- Mostly common in higher elevations due to more snow accumulation than snowmelt.
- All long-term snow accumulation, once reaching surplus, eventually flows downhill. (Example of Ice skating on ice)



Source: https://laulima.hawaii.edu/access/content/group/dbd544e4-dcdd-4631-b8ad-3304985e1be2/book/chapter12/glaciers.htm, https://nsidc.org/learn/parts-cryosphere/glaciers#:~:text=Glaciers%20begin%20to%20form%20when,and%20shape%20of%20sugar%20grains.

Glacier Types

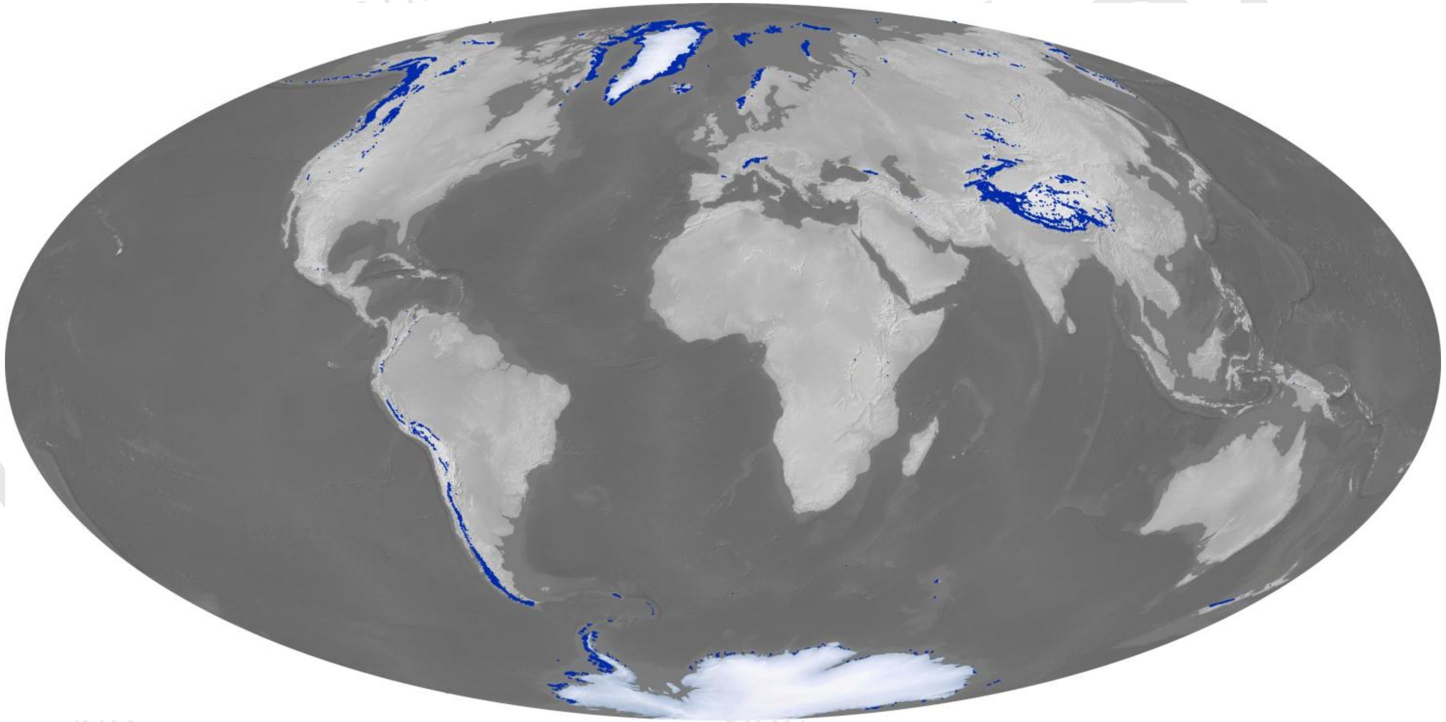
Exercise

Can you identify which glacier type these are? What kind of glaciers do your country have?

Source: https://laulima.hawaii.edu/access/content/group/dbd544e4-dcdd-4631-b8ad-3304985e1be2/book/chapter12/glaciers.htm, https://nsidc.org/learn/parts-cryosphere/glaciers#:~:text=Glaciers%20begin%20to%20form%20when,and%20shape%20of%20sugar%20grains.

Where are glaciers?

Most glaciers are found in regions of high snowfall in winter and low temperatures in summer. These conditions ensure that the snow that accumulates in the winter is not lost during the summer. Examples of such regions are Alaska, Patagonia, and the Himalayas. The Arctic islands of Canada get much less snowfall, but it is cold enough through the year that glaciers can form. In short, glaciers form at high latitudes or high elevations. Closer to the equator, higher elevations are required for needed snowfall and lower temperatures.

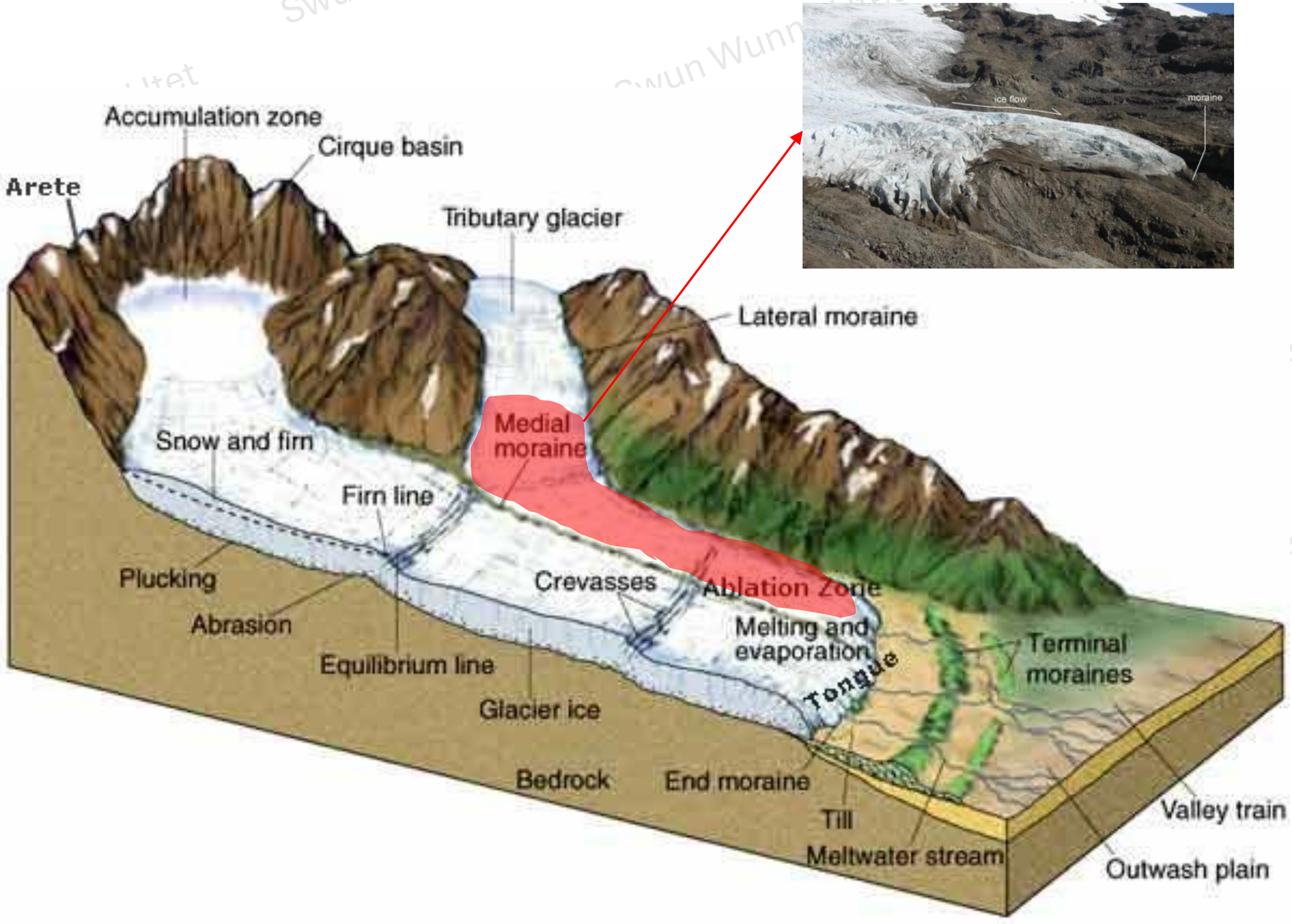


Source: https://nsidc.org/learn/parts-cryosphere/glaciers#:~:text=Glaciers%20begin%20to%20form%20when,and%20shape%20of%20sugar%20grains.

General Geomorphological Features of Glaciers

From year-round accumulation of snow building up upon the Alpine mountains, in the long-term such accumulation causes pressure at the base of the snow to form ice-layer, forming glaciers.

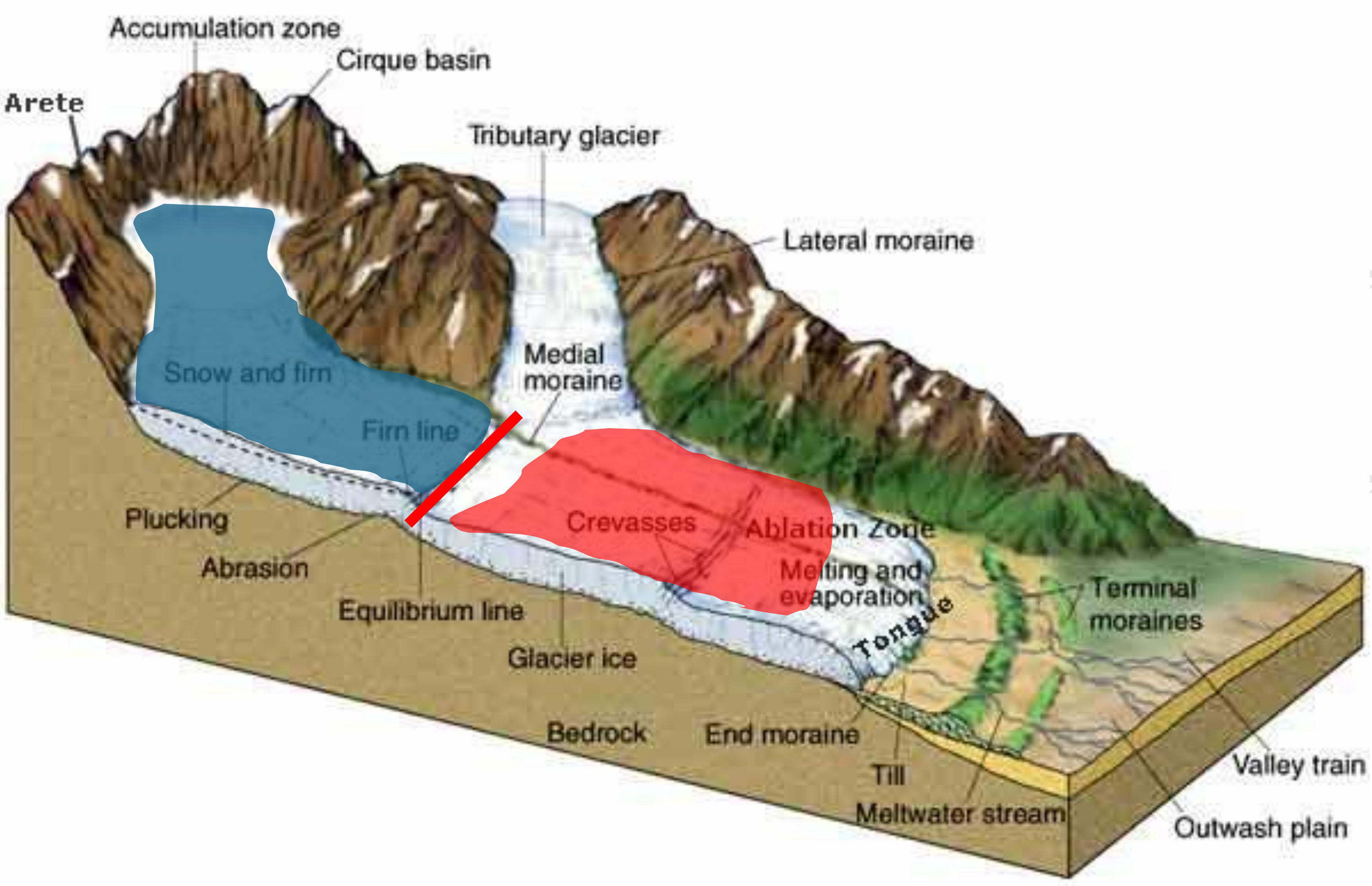
Moraine: ridge or pile of unsorted debris (composed of rocks, sand and soil deposited by



Source: https://laulima.hawaii.edu/access/content/group/dbd544e4-dcdd-4631-b8ad-3304985e1be2/book/chapter12/glaciers.htm

General Geomorphological Features of Glaciers

Accumulation zone: area of glacier covered by seasonal snow
Ablation zone: lower part of the glacier where more snowmelt is lost more than snow accumulation.
Equilibrium line: unique line representing zero mass balance. (used in glacier studies to estimate the glacier mass balance).
Glacier Boundary: line between glacier and non-glaciers. Can be detected by False Color Composite.



Source: https://laulima.hawaii.edu/access/content/group/dbd544e4-dcdd-4631-b8ad-3304985e1be2/book/chapter12/glaciers.htm

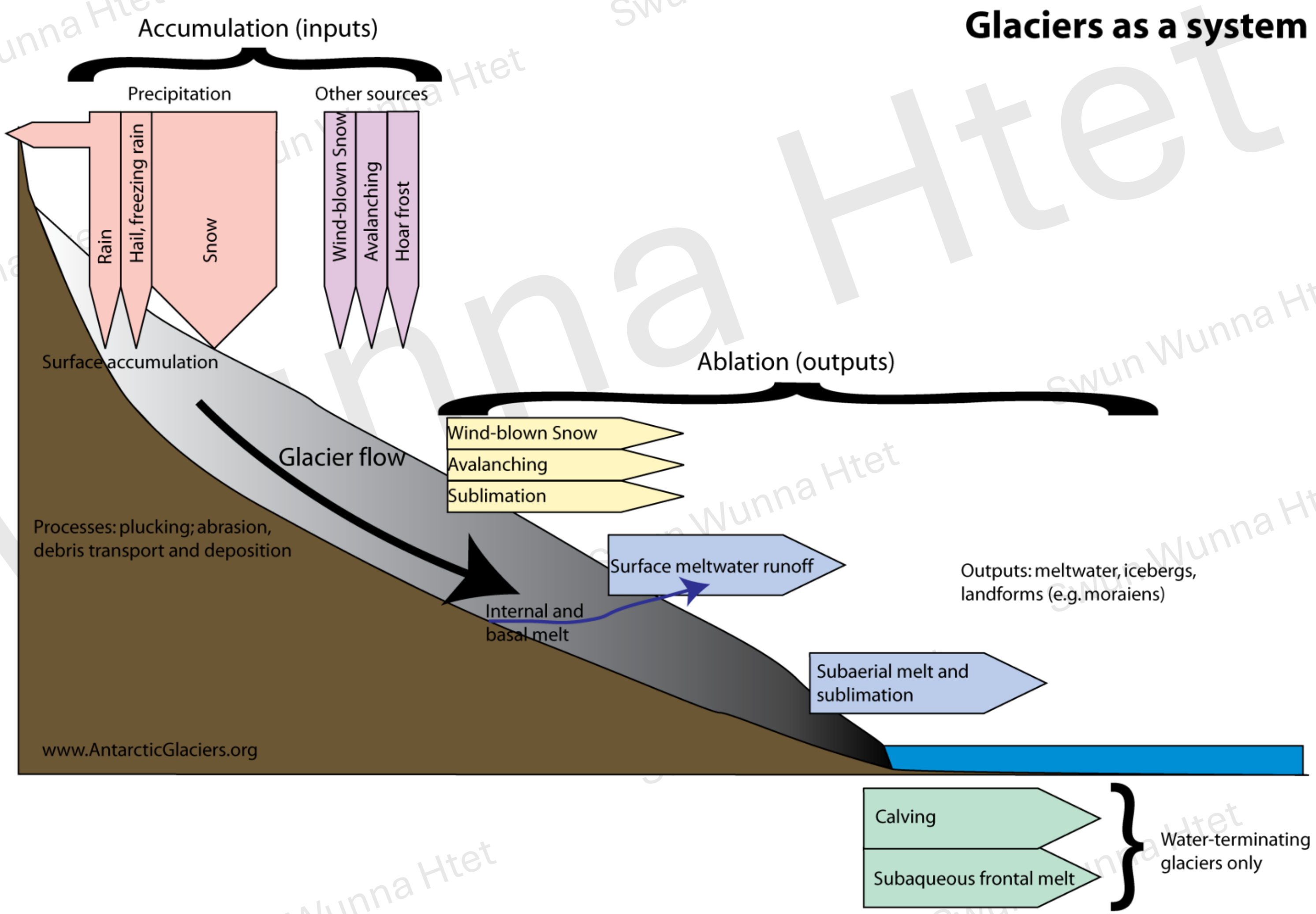
General Geomorphological Features of Glaciers

Glacier System

Input comes from precipitation (rain, hail, snow). Occurred at **accumulation zone**.

Output comes from ablation zone (snowmelt, snow sublimation, glacial flow).

The balance of accumulation and ablation is termed as glacial mass balance.

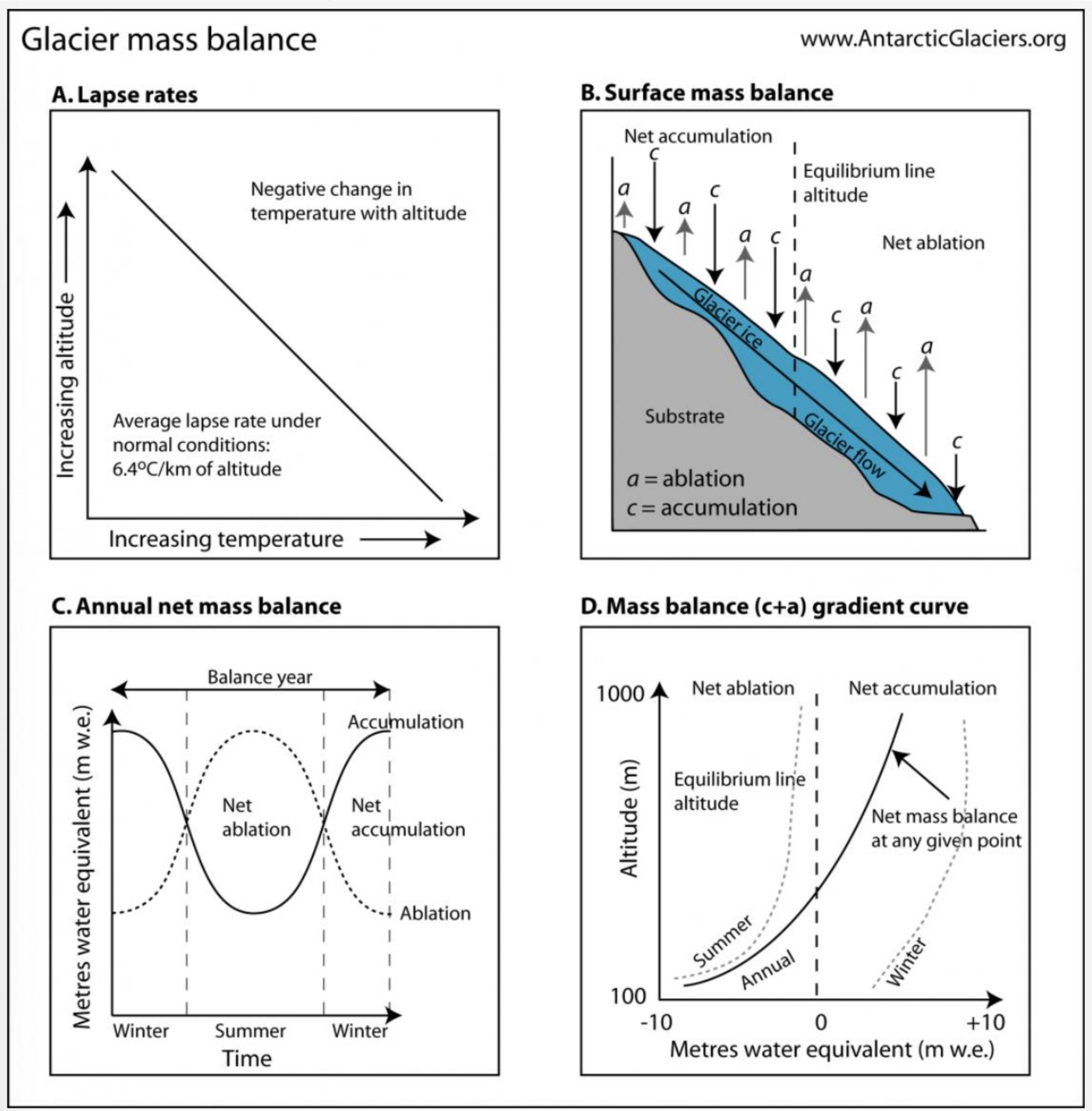


Source: *https://laulima.hawaii.edu/access/content/group/dbd544e4-dcdd-4631-b8ad-3304985e1be2/book/chapter12/glaciers.htm*

Glacial Mass Balance

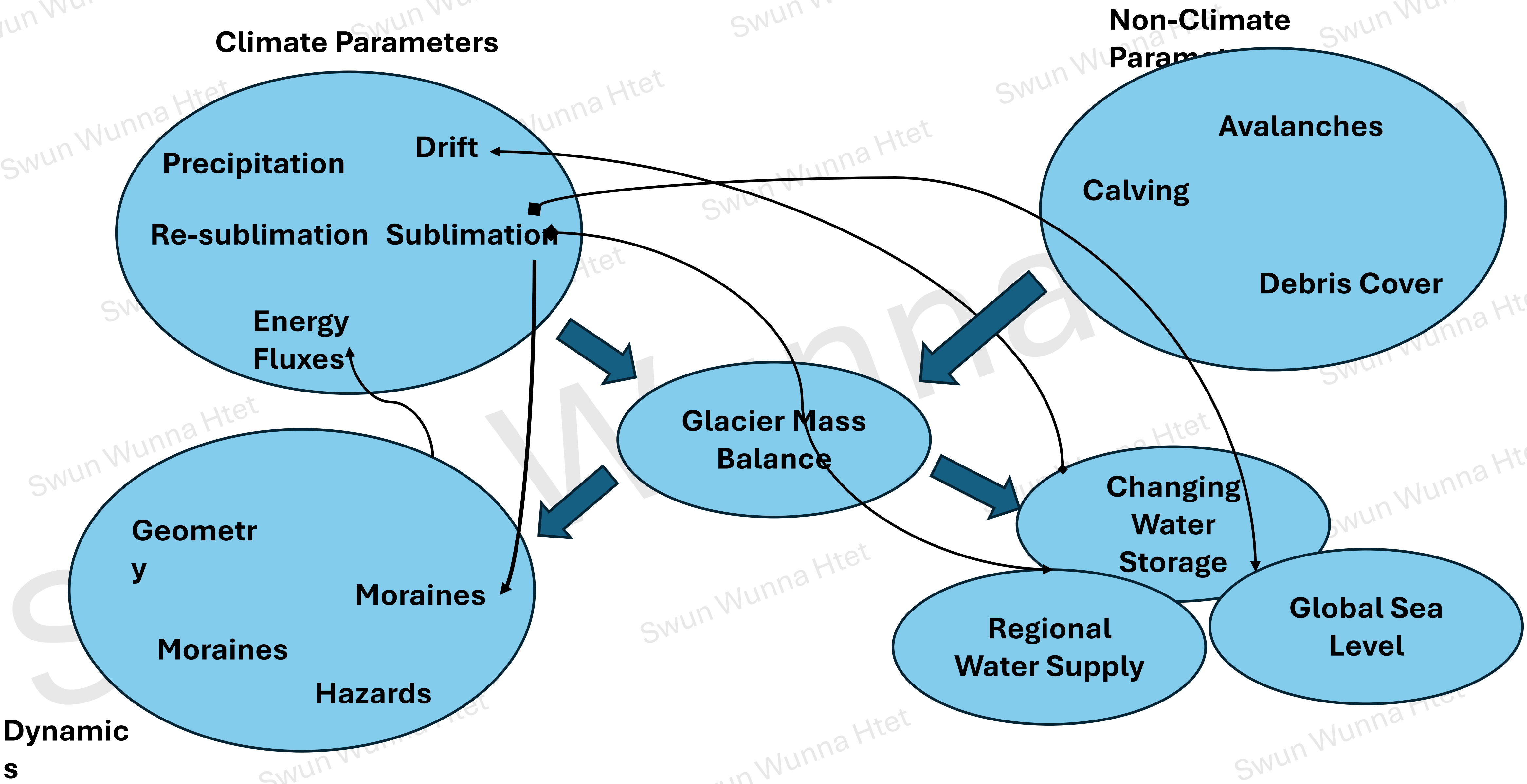
A brief Introduction

- **Glacier mass balance** is the quantitative expression of a glacier's volumetric change throughout time.
- Note that **the air temperature varies with altitude. This controls the melting and accumulation (and the amount).**
- **Glacier mass balance is seasonal-dependent.**



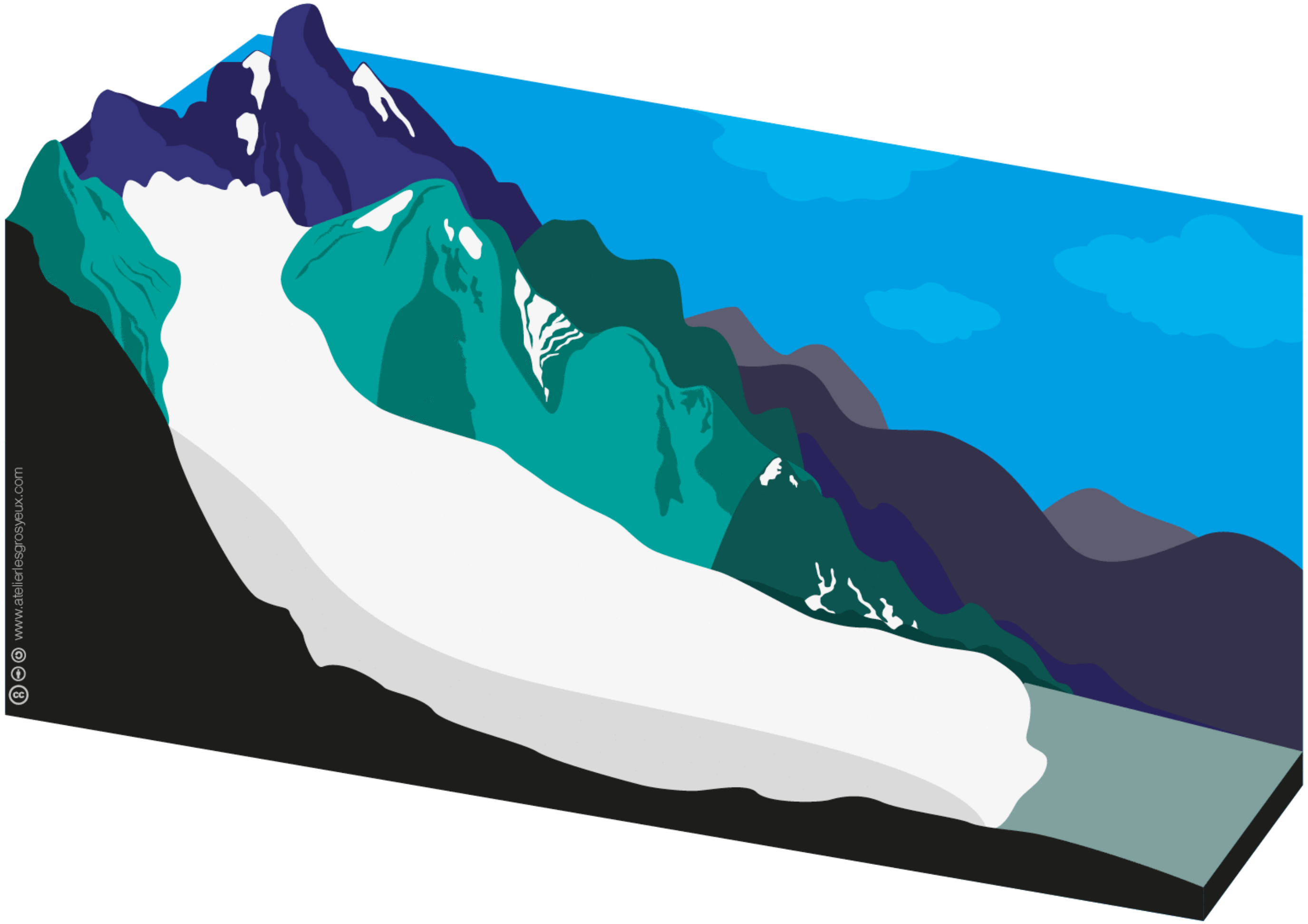
Source: https://laulima.hawaii.edu/access/content/group/dbd544e4-dcdd-4631-b8ad-3304985e1be2/book/chapter12/glaciers.htm

Role of Glacier Mass Balance



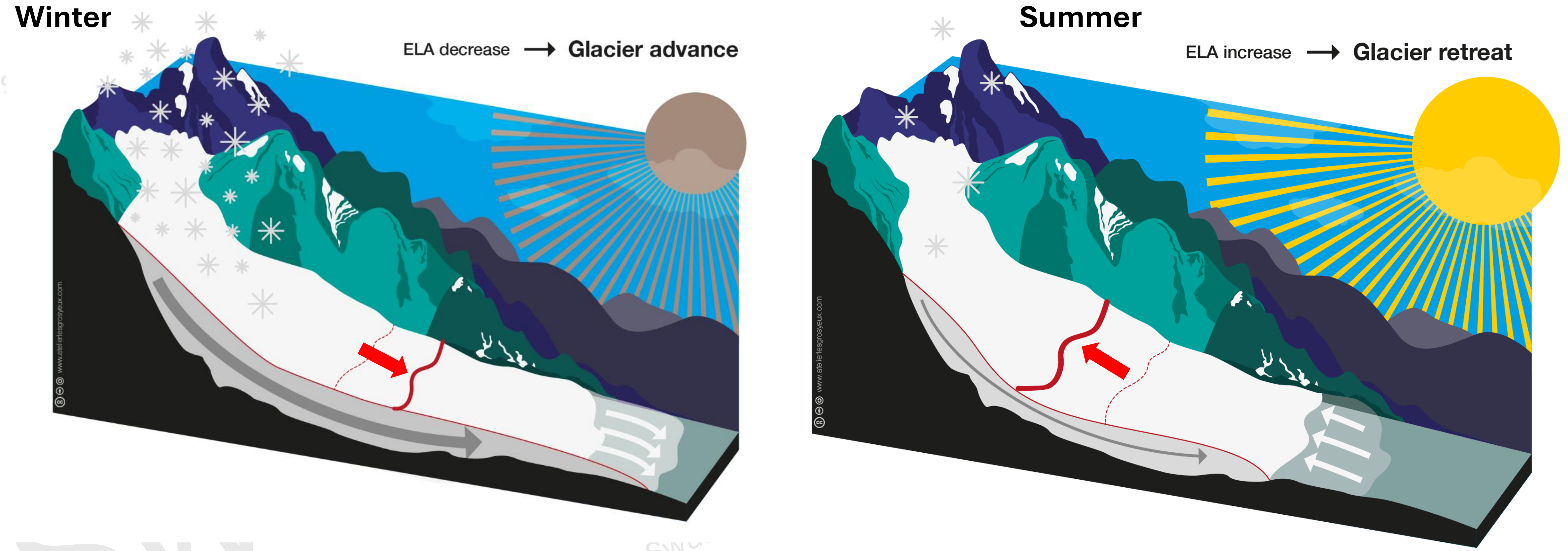
Source: Kaser, G., Fountain, A. G., & Jansson, P. (2003). A Manual for monitoring the mass balance of mountain glaciers with particular attention to low latitude characteristics; Technical documents in hydrology. IHPVI Technical Documents in Hydrology, 2003(59), 1–137. https://wgms.ch/downloads/Kaser_etal_UNESCO_2003.pdf

The way how glacier balance works



Source: https://edu.oggm.org/es/latest/glacier_debriscovered.html

Seasonal behaviour of Glaciers



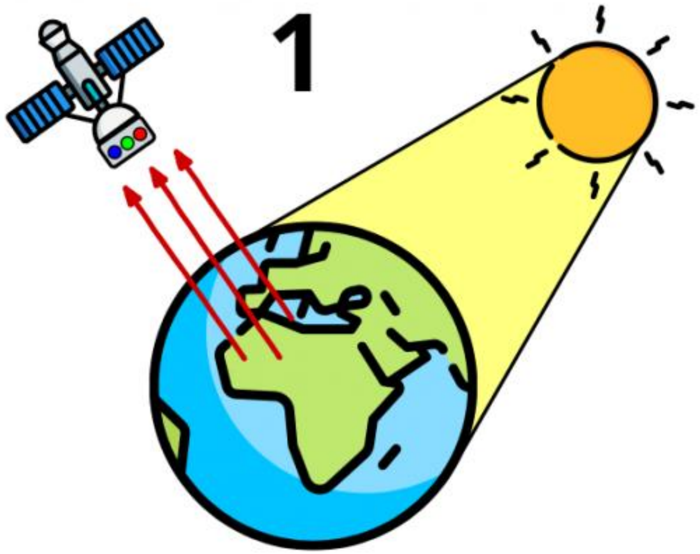
ELA = Equilibrium Line Altitude

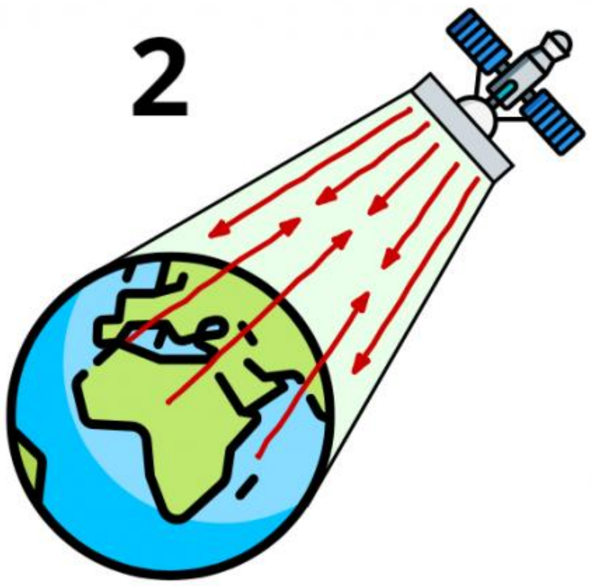
Source: https://edu.oggm.org/es/latest/glacier_basics.html

Accumulation area of Glärnischgletscher, a small mountain glacier in NE Switzerland. Aerial photo J. Alean, 1982.

Source: https://www.swisseduc.ch/glaciers/glossary/accumulation-area-en.html

Two Types of Remote Sensing

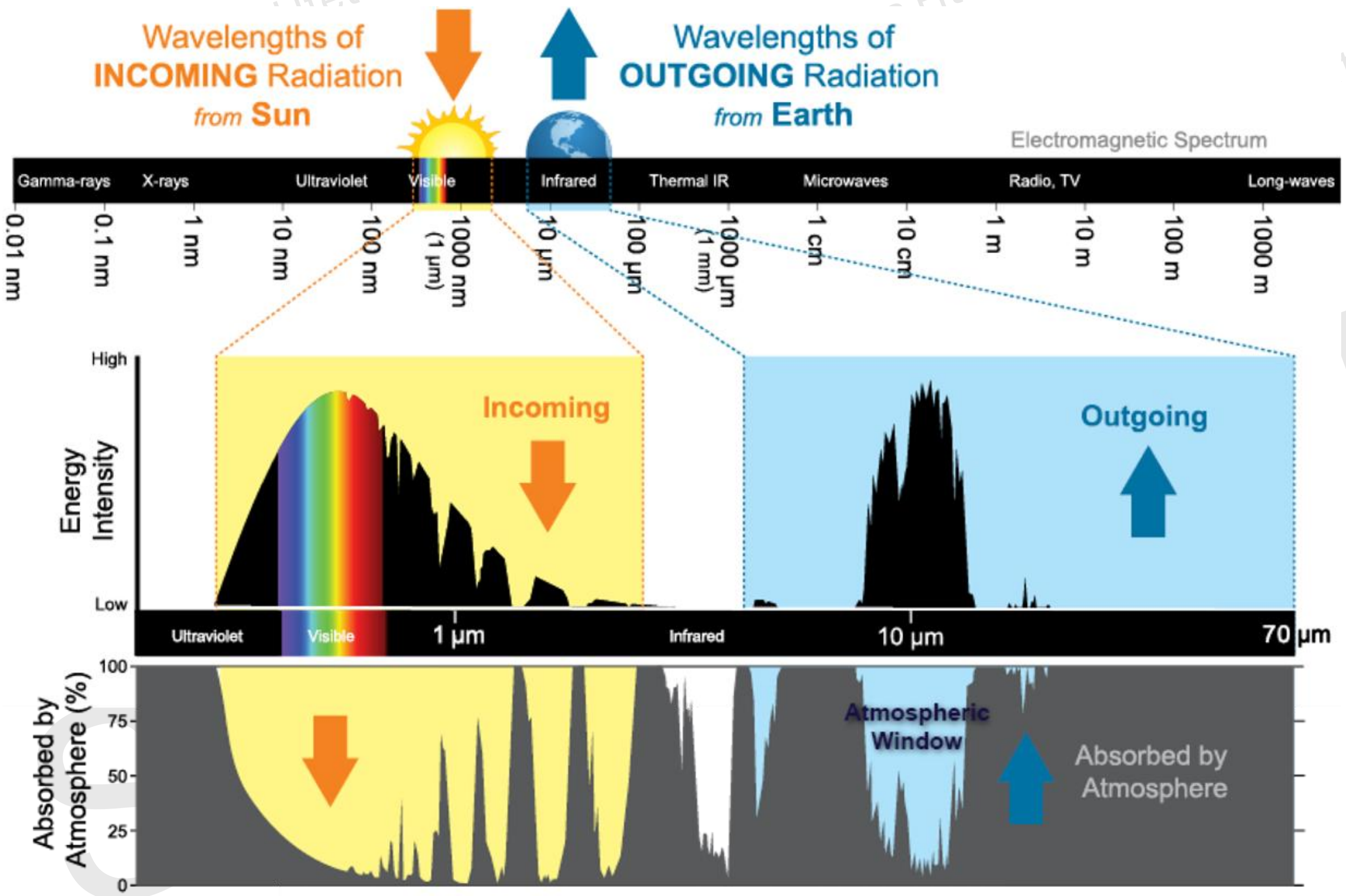




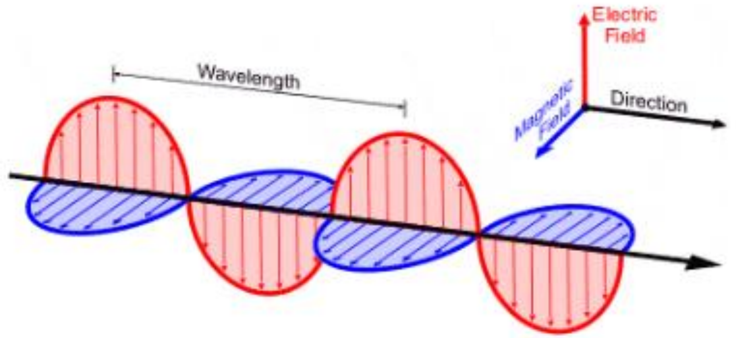
- Active (Microwave or Radar)
  - Source: satellite sensor
  - Receive backscatter from the target to the sensor.
- Passive (Multispectral/Hyperspectral/ Optical)
  - Source: sun
  - Receive reflectance from the target to the sensor
- More will be discussed further.

Electromagnetic Spectrum

Interaction with the atmosphere



Visible Spectrum wavelength range = 380 to 700 nm

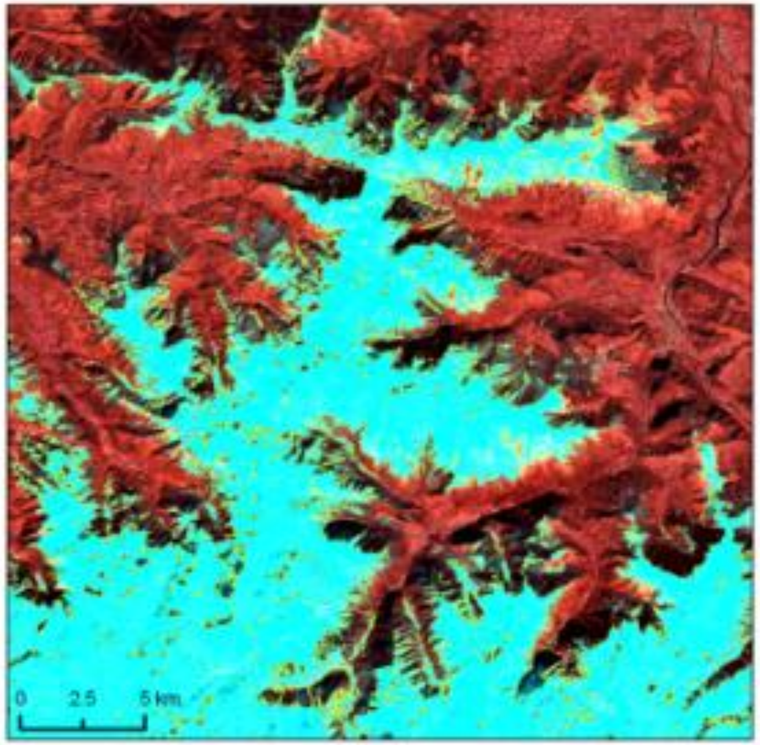


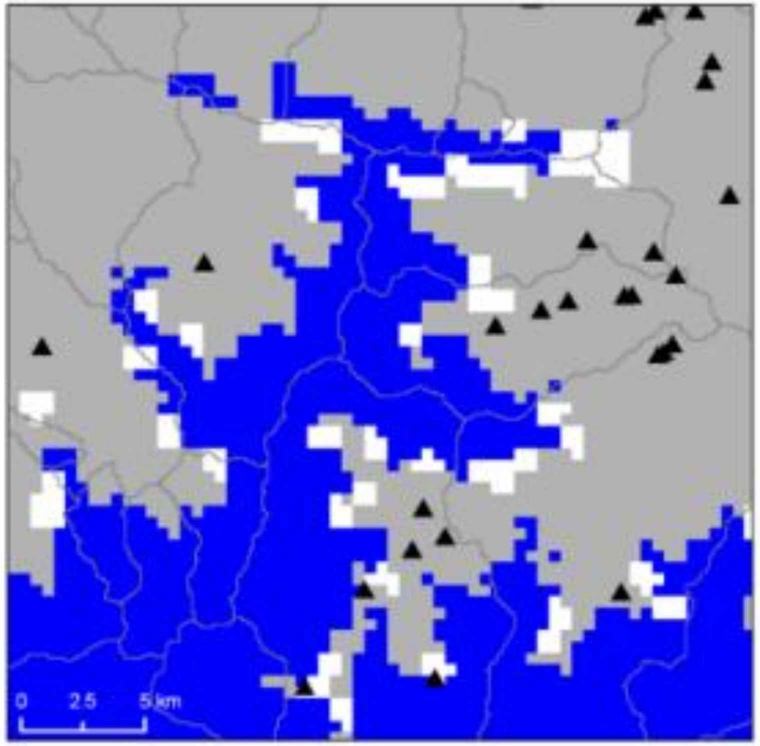
Electromagnetic Component

Only a small portion of the electromagnetic waves are reflected to the space, depending on the wavelength portion 'atmospheric window'. Thus, satellite sensors are designed according to the atmospheric window for reflectance detection.

Spatial Resolution of Satellite Images

What is our required detail level to investigate?





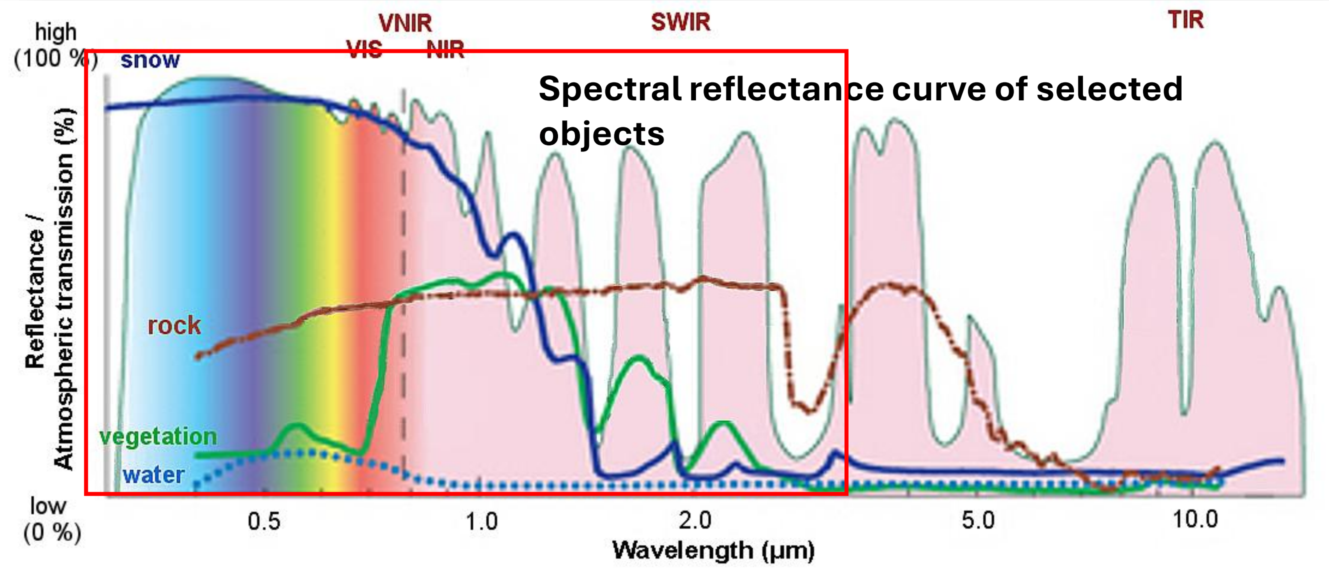
- Notice the demarcation of the snow cover boundary being detailed.
- This is the case where UAV is quite favoured because of the UAV images can be obtained at very high spatial resolution (at cm scale).

Two different views of the same snow cover (Vicdessos valley, Ariege Pyrenees)
MODIS (500 m) on the right, Landsat 8 (30 m) on the left
Teal color means snow in the left image.

Source: Dumont, M., & Gascoin, S. (2016). Optical Remote Sensing of Snow Cover. In *Land Surface Remote Sensing in Continental Hydrology* (pp. 115–137). Elsevier. https://doi.org/10.1016/B978-1-78548-104-8.50004-8

Optical Properties of Snow

Multi-spectral (VNIR, SWIR) range

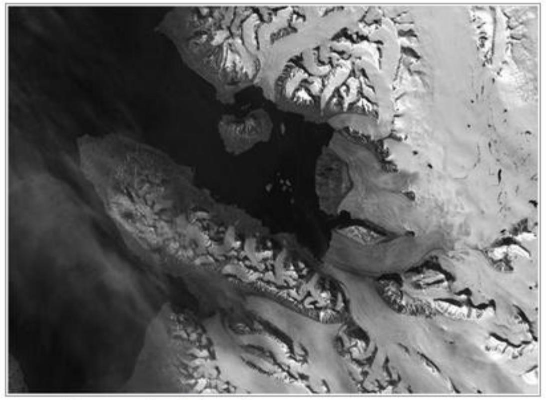


- Unique property: snow reflects almost all the energy back to sensor (white).
- Reflected portion: VNIR and NIR
- Obtainable snow properties:
  - Snow albedo
  - Snow cover area (SCA)
  - Snow grain size (limited)
  - Snow water equivalent (SWE) (limited)

Glaciers on Svalbard (Example)

True color composite (RGB)

Red



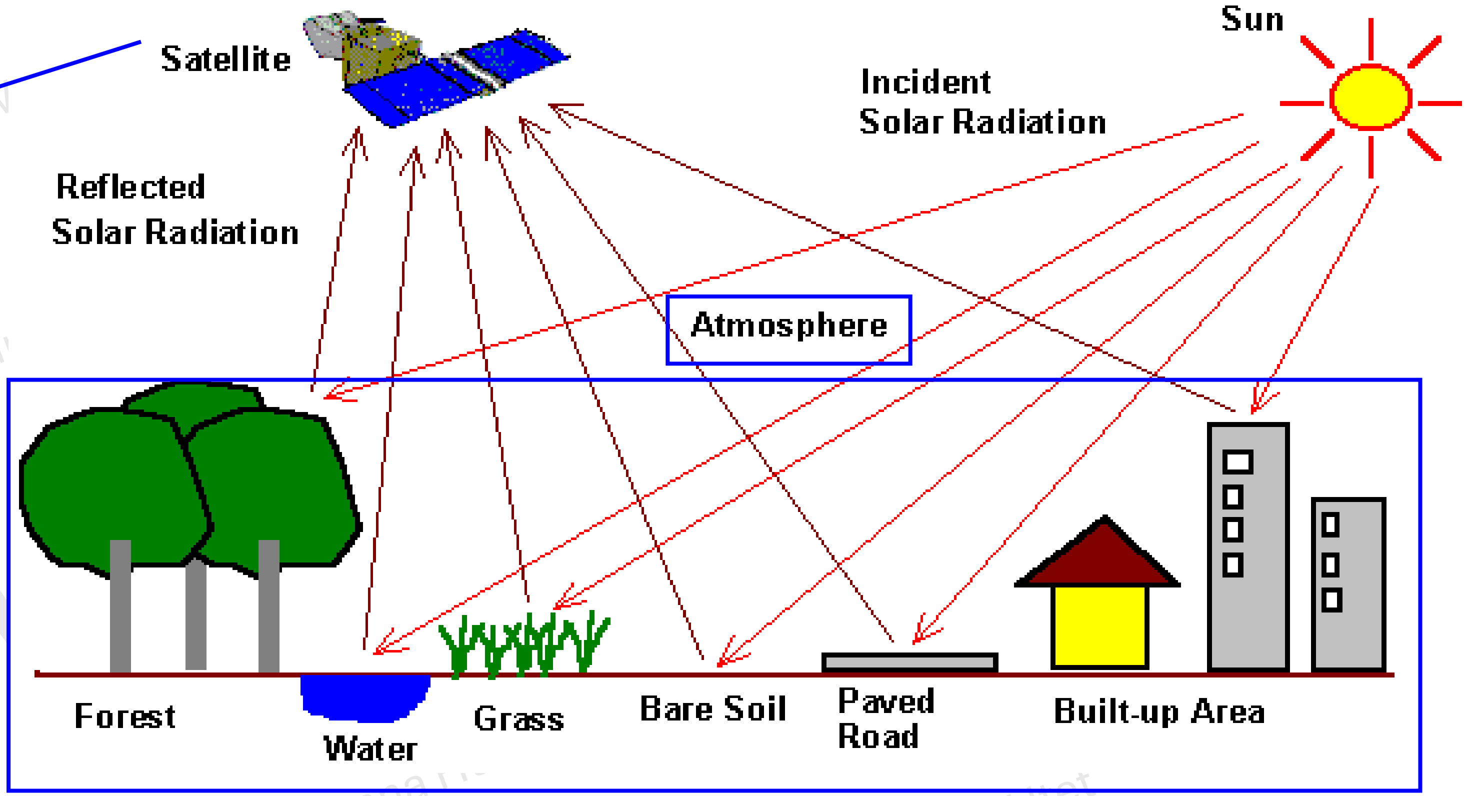
Near Infrared (NIR)

Shortwave Infrared (SWIR)

Source: https://www.esa.int/SPECIALS/Eduspace_Global_EN/SEM0O7TWLUG_0.html

Optical Properties of Snow

Multi-spectral (VNIR, SWIR) range



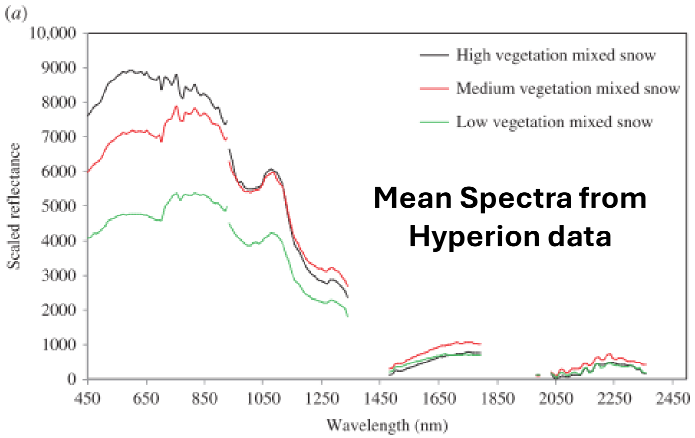
The energy reflected from the ground back to the sensor is influenced by the atmosphere and the earth objects.

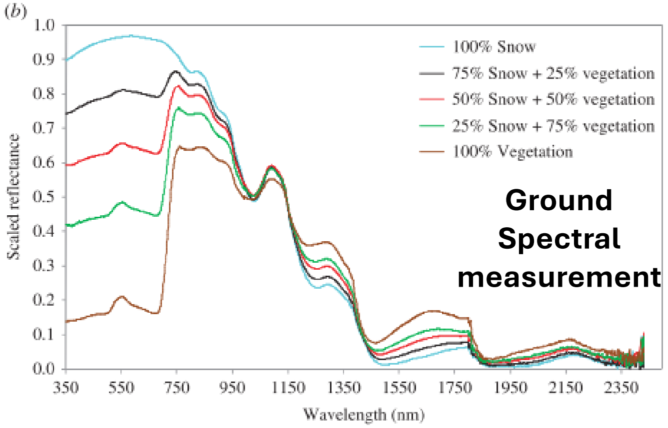
Source: Dong, C. (2018). Remote sensing, hydrological modeling and in situ observations in snow cover research: A review. *Journal of Hydrology*, *561*(February), 573–583. https://doi.org/10.1016/j.jhydrol.2018.04.027

Negi, H. S., Jassar, H. S., Saravana, G., Thakur, N. K., Snehmani, & Ganju, A. (2013). Snow-cover characteristics using Hyperion data for the Himalayan region. *International Journal of Remote Sensing*, *34*(6), 2140–2161. https://doi.org/10.1080/01431161.2012.742213

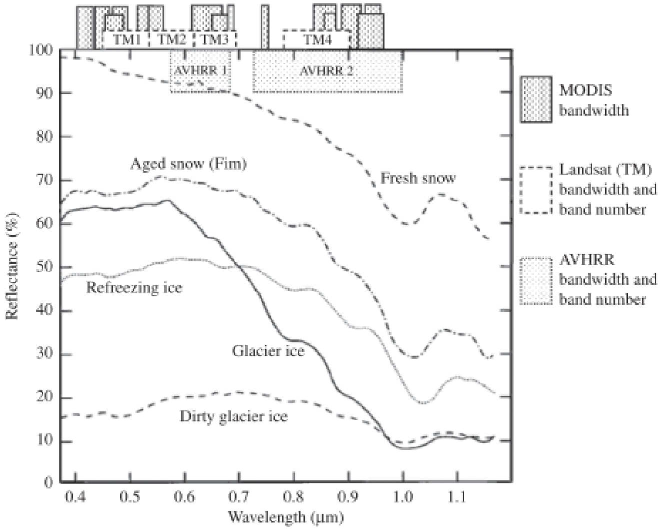
Ground object interference to snow reflectance

Multi-spectral (VNIR, SWIR) range

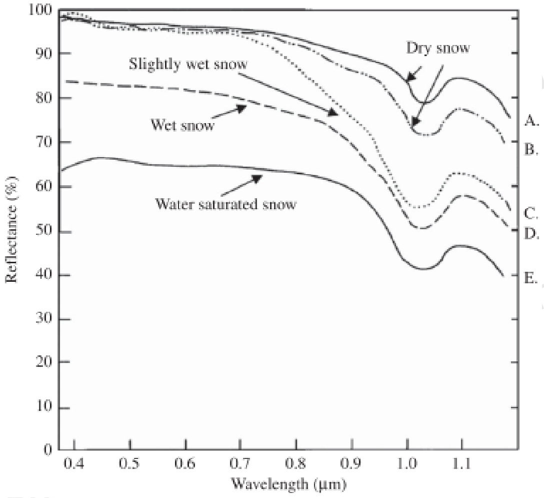




Reflectance of difference surface types related to snow cover. Band widths of Landsat(TM), MODIS (M), AVHRR integrated

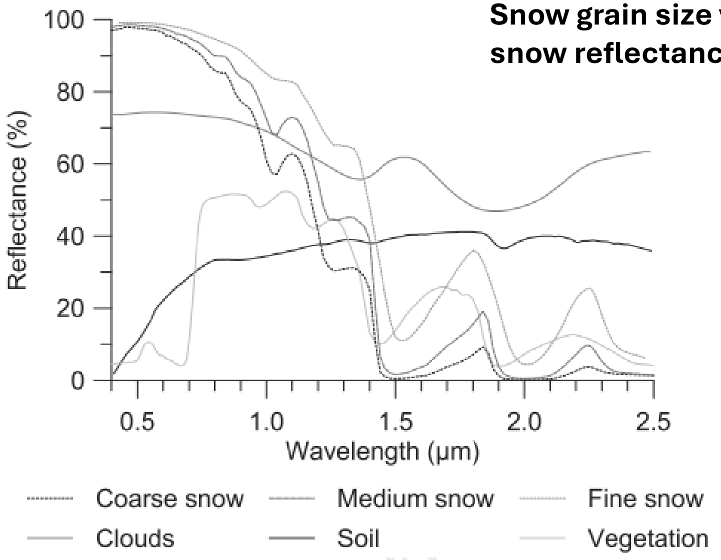


- Surrounding contribution of vegetation's canopy density, type of snow, ice, water content, and other land cover types can influence on the actual snow reflectance.



Reflectance of different snow age and wetness stages

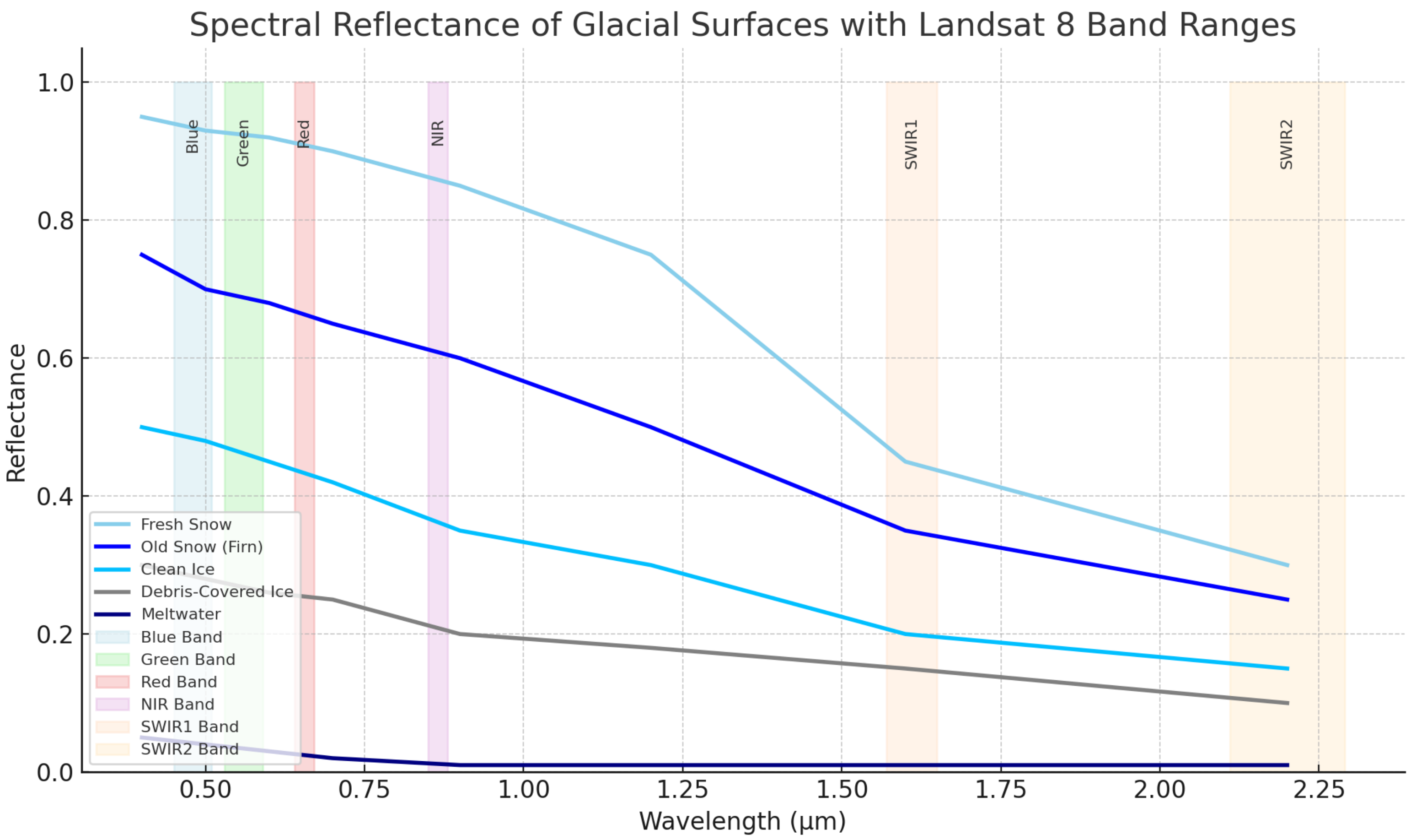
Snow grain size vs snow reflectance



Source: Negi, H. S., Jassar, H. S., Saravana, G., Thakur, N. K., Snehmani, & Ganju, A. (2013). Snow-cover characteristics using Hyperion data for the Himalayan region. *International Journal of Remote Sensing*, *34*(6), 2140–2161. https://doi.org/10.1080/01431161.2012.742213
Dietz, A. J., Kuenzer, C., Gessner, U., & Dech, S. (2012). Remote sensing of snow - a review of available methods. *International Journal of Remote Sensing*, *33*(13), 4094–4134. https://doi.org/10.1080/01431161.2011.640964

Different Glacier Features respond different spectral reflectance curves

A quick glance (at global scale)



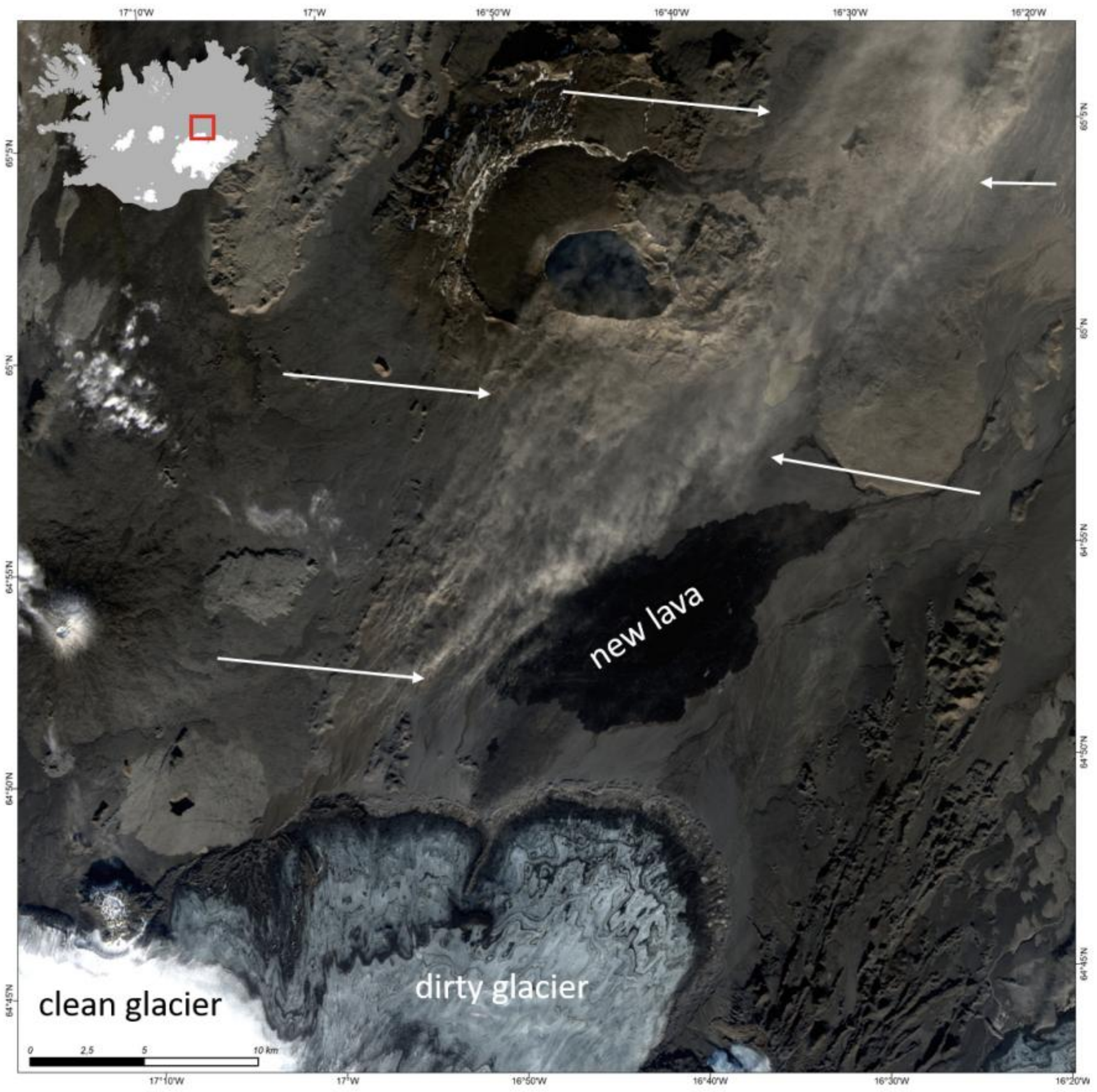
Source: Dozier, J. (1989). "Spectral signature of alpine snow cover from the Landsat Thematic Mapper.“, DOI:https://doi.org/10.1016/0034-4257(89)90101-6

Painter, T. H. et al. (2003). "Radiative forcing of anthropogenic aerosols on snow.“, DOI: 10.1029/2002JD002514

Warren, S. G. (1982). "Optical properties of snow.“, *Reviews of Geophysics and Space Physics*

MODIS and ASTER Spectral Libraries (USGS/NASA),

Example: Dirty Glacier vs Clean Glacier

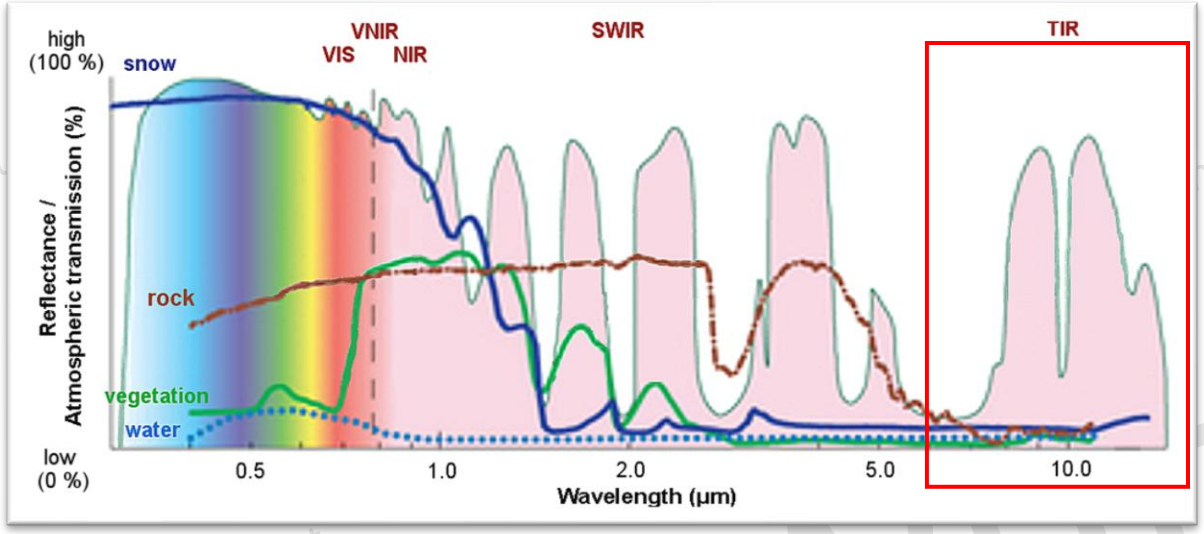


LANDSAT image of the Vatnajökull glacier (lower left corner, clean (dirty) glacier) polluted with dust (lower middle, dirty glacier) while a dust storm (brown dust plume indicated with white arrows) originating from the 5 glacial flood plain Dyngjusandur over the new lava (dark surface in the center of the image) from the Holuhraun eruption 2014-2015. Source and date: NASA & USGS, 20th October 2016

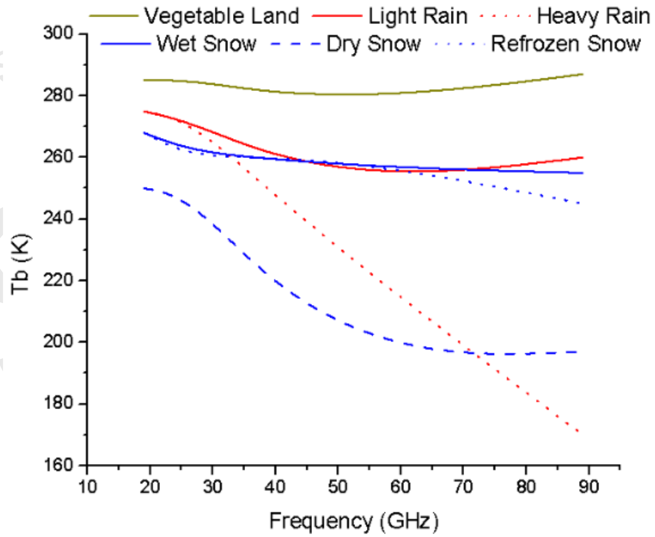
Source: Boy, M., Thomson, E. S., Acosta Navarro, J.-C., Arnalds, O., Batchvarova, E., Bäck, J., Berninger, F., Bilde, M., Brasseur, Z., Dagsson-Waldhauserova, P., Castarède, D., Dalirian, M., de Leeuw, G., Dragosics, M., Duplissy, E.-M., Duplissy, J., Ekman, A. M. L., Fang, K., Gallet, J.-C., … Kulmala, M. (2019). Interactions between the atmosphere, cryosphere, and ecosystems at northern high latitudes. Atmospheric Chemistry and Physics, 19(3), 2015–2061. https://doi.org/10.5194/acp-19-2015-2019

Thermal Approach to Snow

TIR range



- Thermal infrared gives information of brightness temperature which reflects on the physical properties of the snowpack (liquid water content, snow density, grain size, etc).
- Current limitation is the modelling necessity to establish the relationship between the thermal infrared radiation and the snowpack parameters.
- Cloud cover also affects to TIR range.



Brightness temperatures VS different frequencies

Source: Murioz, J. (2013). Synergistic Use of Remote Sensing for Snow Cover and Snow Water Equivalent Estimation. *British Journal of Environment and Climate Change*, *3*(4). https://doi.org/10.9734/bjecc/2013/7699

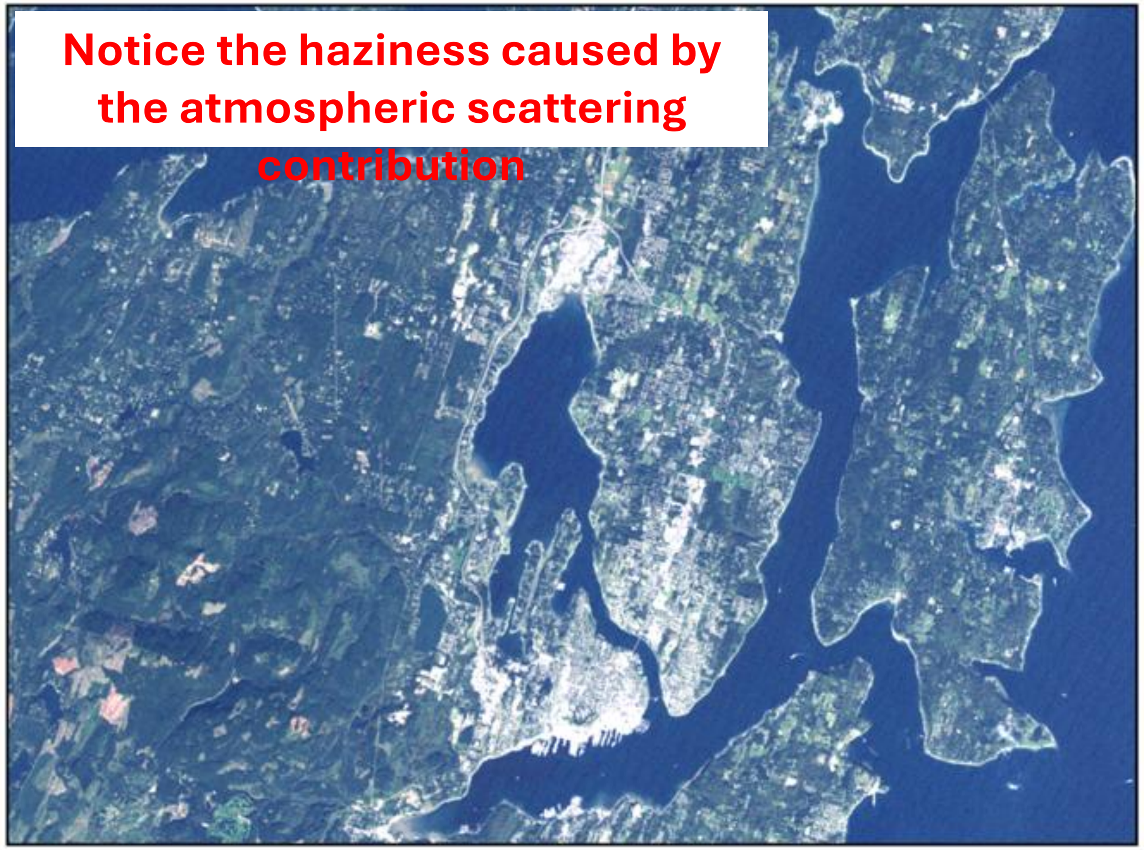
Example Optical Sensors and Satellites

Data Availability

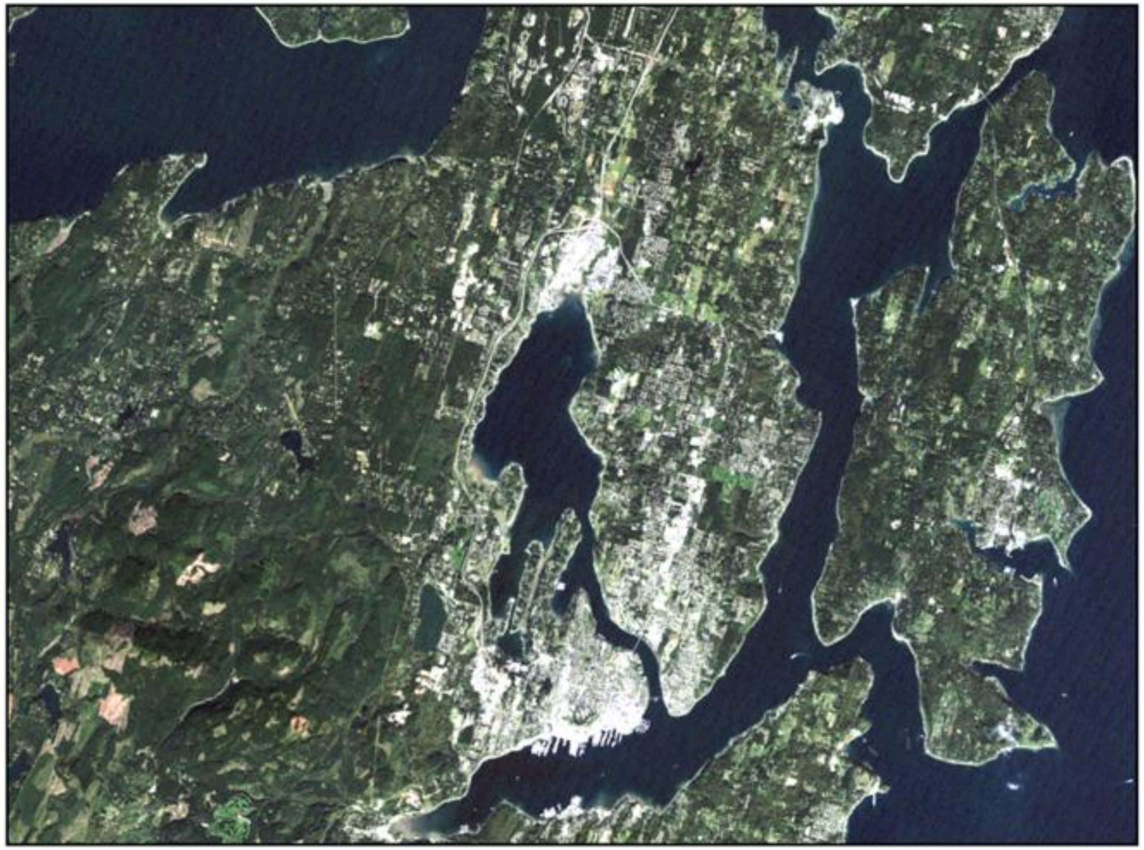
Sensors	Satellite	Bands	Spatial Resolution	Revisit Period
MSI	Sentinel-2	VIS, SWIR	10, 20, 60 m	10 /5 days (with combined constellation)
OLCI, SLSTR	Sentinel-3	VIS, SWIR, TIR	300, 500, 1000 m	27 days
AVHRR	NOAA	VIS, SWIR, TIR	1000 m	Daily
MODIS	TERRA, AQUA	VIS, SWIR, TIR	1000 m	Daily, 2, 8, 16 days
ASTER	TERRA	VIS, SWIR, TIR, Stereo	15, 30, 90 m	16 days
ETM+	Landsat 5, 7	VIS, SWIR, TIR	15, 30, 60 m	8 days
OLI, TIRS	Landsat 8, 9	VIS, SWIR, TIR	15, 30, 100 m	8 days
HRV	SPOT 5	VIS, SWIR	2.5, 5, 10 m	1 – 3 days
Dig-Camera	IKONOS	VIS<, NIR (4 Chan.)	1, 4 m	1-3 days
Dig-Camera	QuickBird	VIS, NIR (4 Chan.)	0.7, 2.5 m	3 days
Dig-Camera	Pleiades	VIS, NIR	0.5, 2 m	Daily

Correction of Atmospheric Artefacts

For Optical Sensors



Top of Atmosphere Reflectance

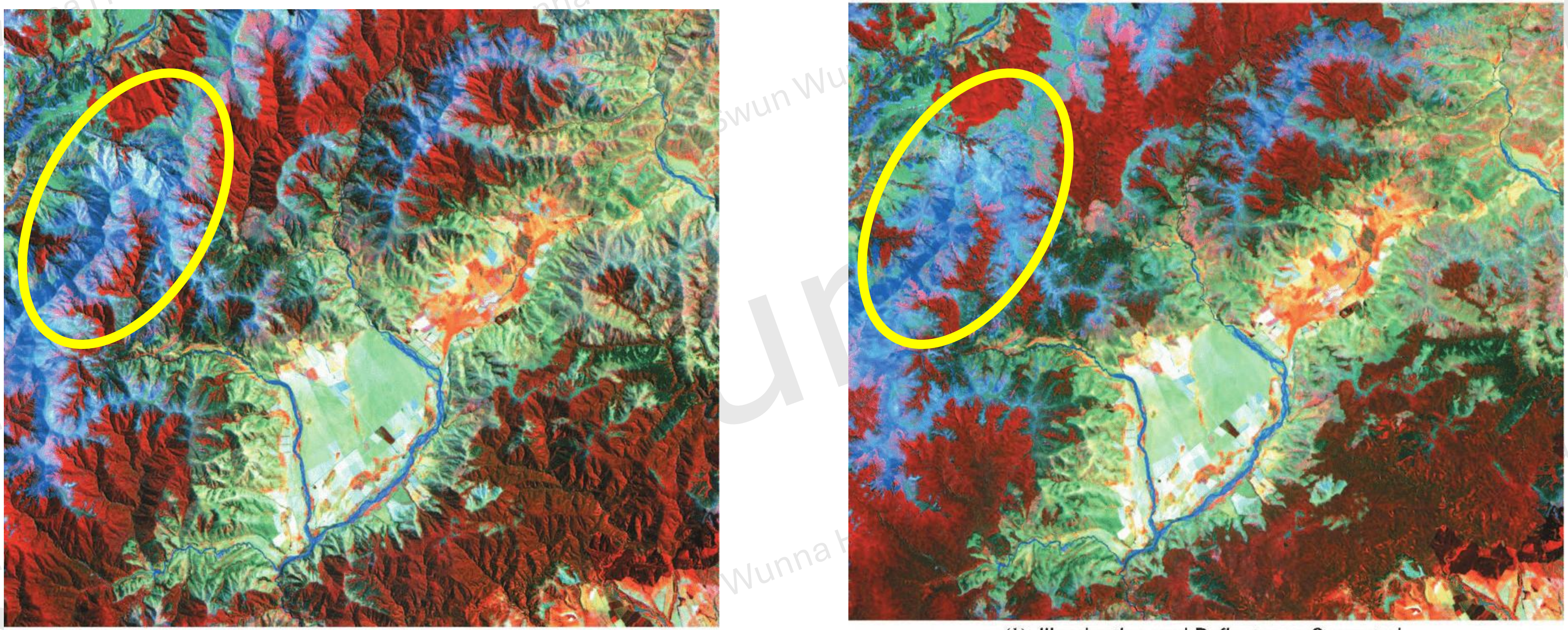


Surface Reflectance

Left: Landsat 5 Collection 2 Top of Atmosphere reflectance image (bands 4,3,2) and Right: Landsat 5 Collection 2 atmospherically corrected surface reflectance image for an area over Bremerton, Washington, path 47 row 27 acquired on October 6, 2010.

Correction of Terrain Artefacts

For Optical Sensors



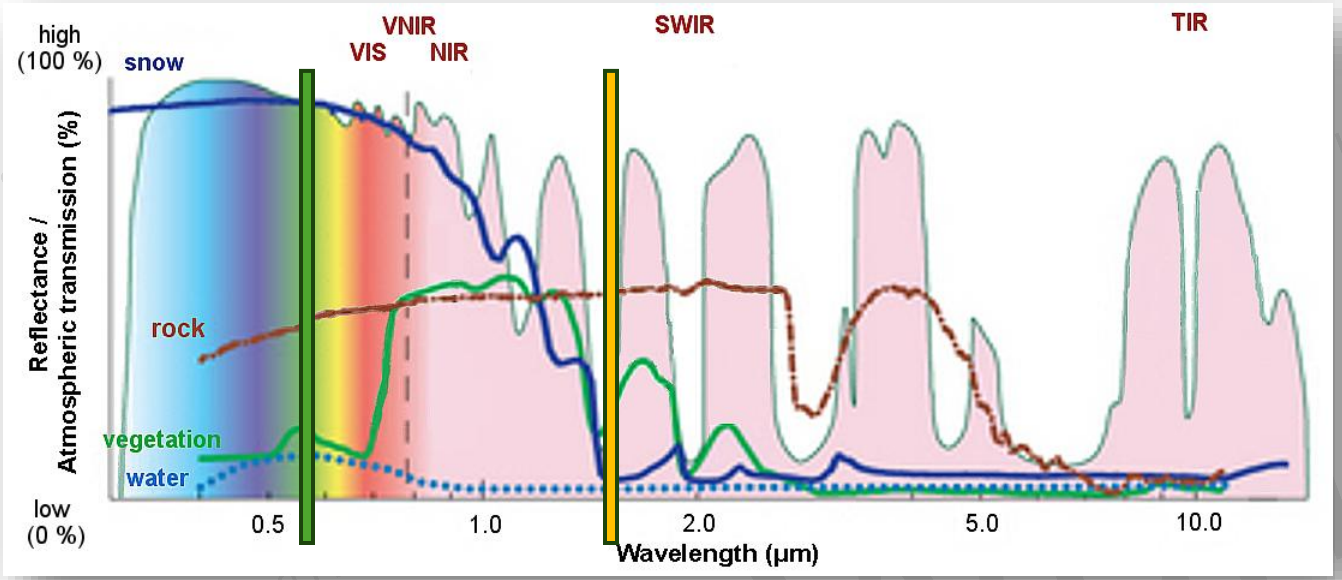
(a) Original

(b) Illumination and Reflectance Corrected

Left: SPOT4 Original and Right: Terrain Corrected SPOT 4 image

Normalized Difference Snow Index (NDSI)

Threshold-based snow classification



$$NDSI = \frac{Green - SWIR}{Green + SWIR}$$

Green = Green band

SWIR = Shortwave infrared band

- The concept behind is that snow typically has high visible reflectance and very low reflectance in shortwave infrared region (which makes it more potent in detecting snow from most cloud types).
- Value ranges from -1 to 1.
- NDSI <= 0 : snow-free land surface
- NDSI > 0 : some snow present; probability of snow increases as value close to 1 (Riggs et. Al., 2016)

Source: *https://nsidc.org/data/user-resources/help-center/what-ndsi-snow-cover-and-how-does-it-compare-fsc#:~:text=The%20Normalized%20Difference%20Snow%20Index,Fractional%20Snow%20Cover%20(FSC)*.

Normalized Difference Snow Index (NDSI)

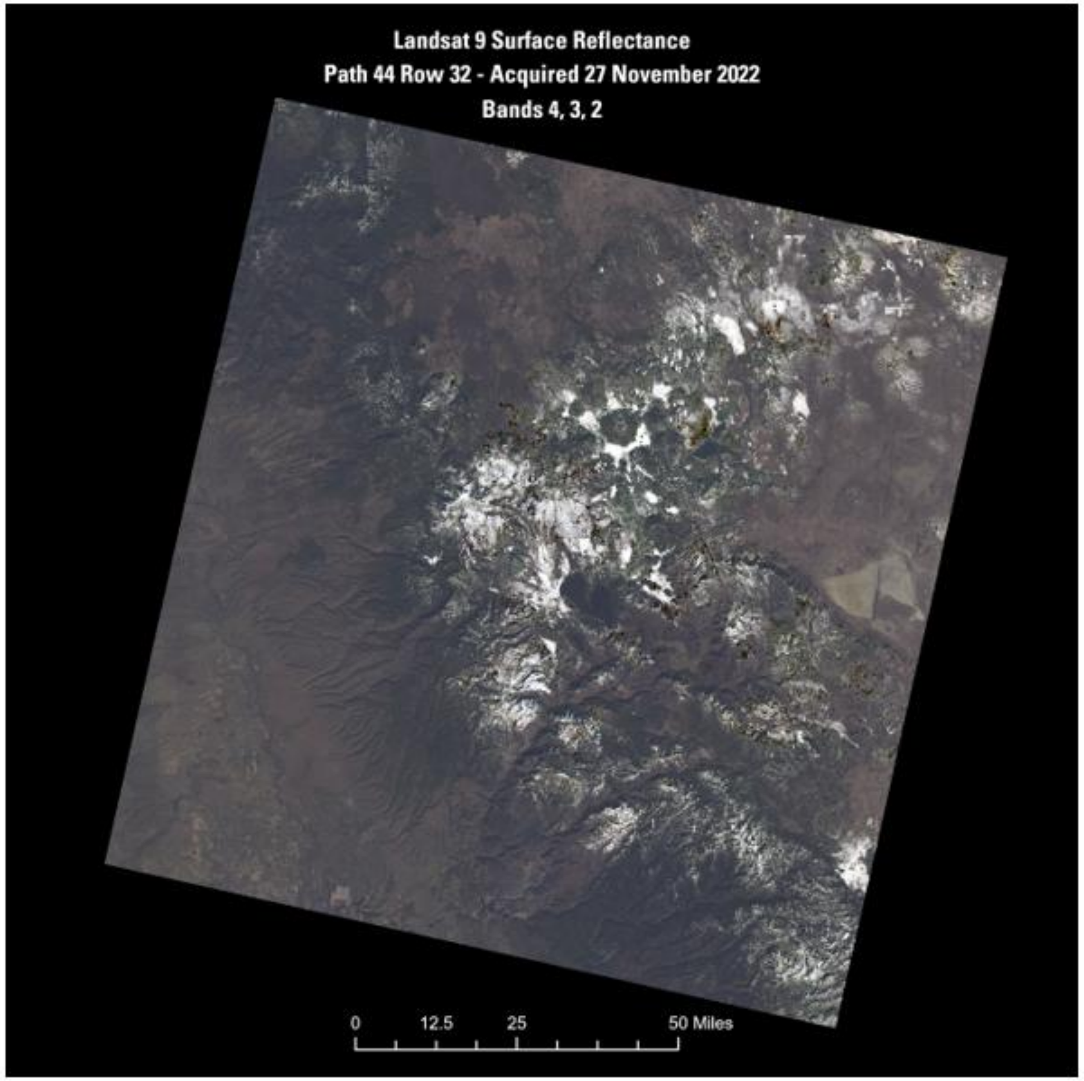
List of Applications

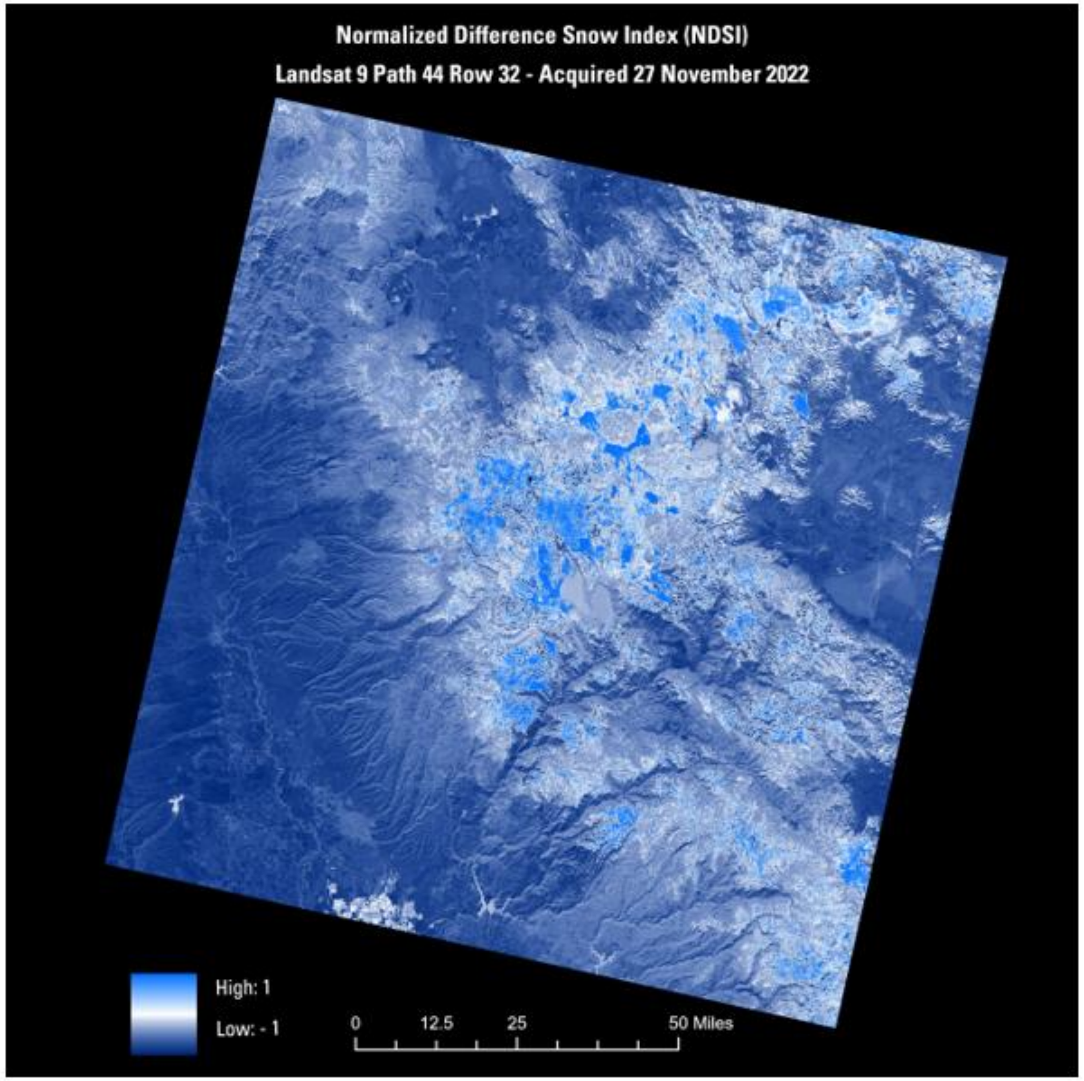
- Snow Cover Detection
- Snowline Mapping
- Discrimination between snow and cloud.
- Glacial ice detection in complex terrain

Source: https://bikeshbade.com.np/tutorials/Detail/?title=Normalized%20Difference%20Snow%20Index%20(NDSI)&code=24

Normalized Difference Snow Index (NDSI)

Example for Landsat 9 Surface Reflectance





Source: https://www.usgs.gov/landsat-missions/normalized-difference-snow-index

Normalized Difference Snow Index (NDSI)

Usage

Advantages

- In binary classification of snow, the setting critical threshold for snow/no snow varies across the world.
- NDSI is primarily used for snow classification, not quantification of snow properties.
- Quick implementation

Disadvantages

- The geometry of snow reflectance is influenced by slope and aspect.
- The purity of snow influences the snow reflectance.
- The underlying land type can influence snow reflectance (particular SWIR range)

Practical – 1: Snow Covered Area (SCA) Calculation Using NDSI Thresholding Method

Snow-covered Area (SCA)

- Definition: the amount of land covered by snow at a given time.
- Predict snowfall or rainfall.
- Useful indicator for climate change as the time of snowfall is influence by regional climate conditions. In hydrology, the dissipation or extension of SCA helps to understand imminent moment of snowmelt discharge.
- With time series interpretation, the snowfall characteristics and related phenomenon can be studied well.

$$\mathrm{SCA} = \frac{\sum Snow\ pixels}{Total\ Number\ of\ Observations} * 100$$

Source: https://www.epa.gov/climate-indicators/climate-change-indicators-snow-cover#:~:text=%22Snow%20cover%22%20refers%20to%20the,snow%20on%20the%20ground%20melts.

Practical – 2: Trend Analysis of Snow Cover Using MODIS Dataset

Background

Mann-Kendall Test

- Non-parametric trend testing method to see whether there exists a significant changes or not over time.
- Advantages: data doesn't need normal distribution, no effects by outliers or unexpected breaks in time series.
- Disadvantages: not appropriate for cyclical trends occurrences (if the trend pattern is cyclical in nature). Doesn't tell the magnitude of the trend.
- Value: -1 (decreases trend) , +1 (increases trend)

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(y_j - y_i)$$

Background

Theil-Sen's Trend Magnitude (TSA) Approach

- Non-parametric method of checking the significance of the magnitude of change.
- Advantages:` more robust slope estimation method then least-squared method because of outliers not influenced to slope calculation.
- Disadvantages: Sensitive to empty values.

$$Sen's\ Slope = median(\frac{x_2 - x_1}{t_2 - t_1})$$

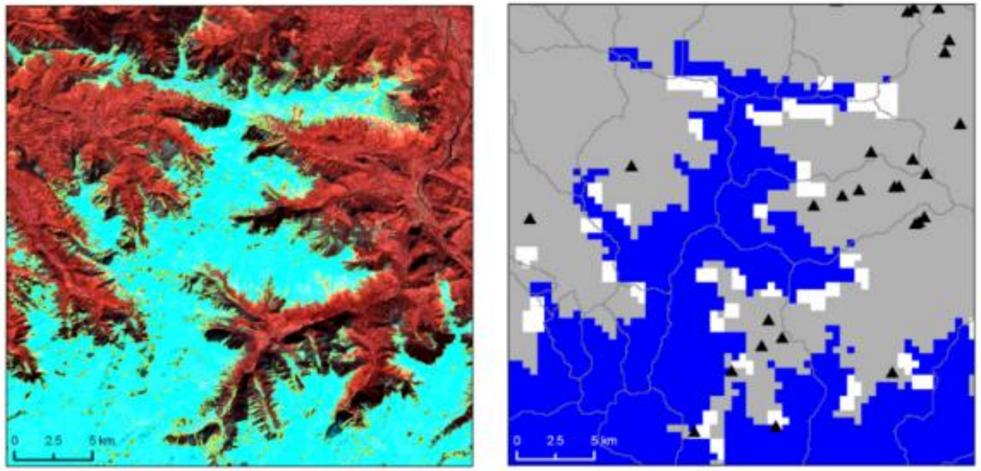
We will see more about the actual calculation in excel sheet.

Glacier Dynamics (part 1)

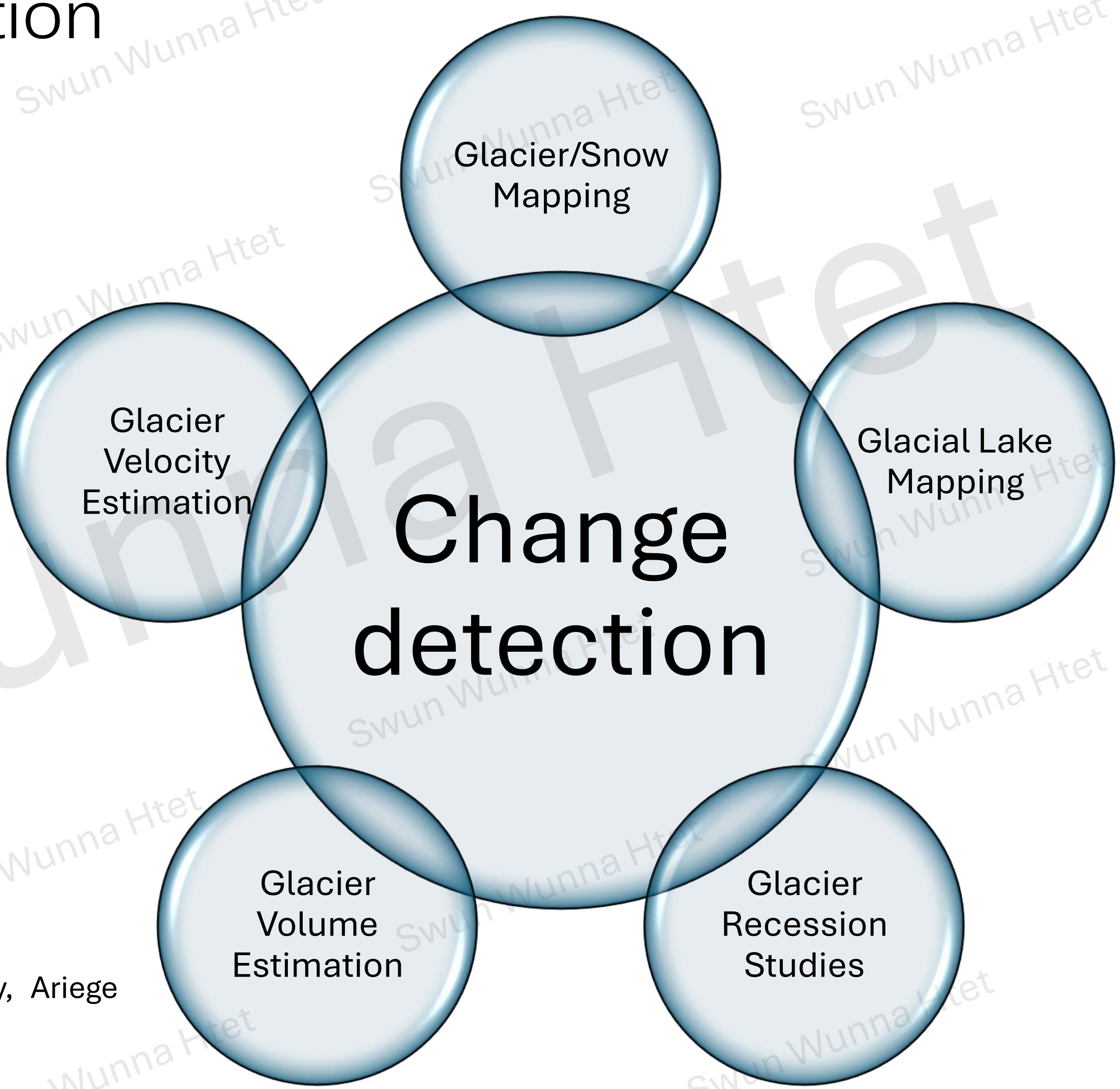
Object-based Change Detection

In Glacier Studies

- **Numerous applications to urban, forest, military, landslides, etc.,**
- **Usually, small localities of changes are the characteristics of glacier changes by mapping.**
- **Thus, either high-resolution satellite imagery or UAV images are the main ideals for glacier detection and monitoring.**



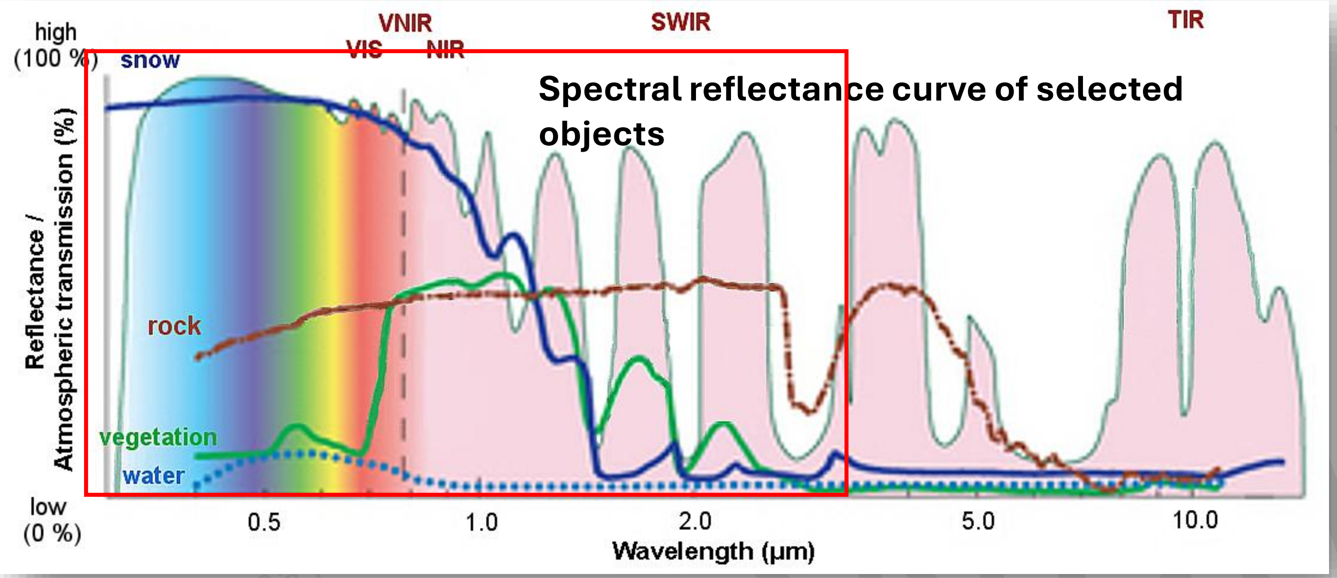
Two different views of the same snow cover (Vicdessos valley, Ariege Pyrenees)
MODIS (500 m) on the right, Landsat 8 (30 m) on the left
Teal color means snow in the left image.



Source: Dumont, M., & Gascoin, S. (2016). Optical Remote Sensing of Snow Cover. In *Land Surface Remote Sensing in Continental Hydrology* (pp. 115–137). Elsevier. https://doi.org/10.1016/B978-1-78548-104-8.50004-8

Optical Properties of Snow

Multi-spectral (VNIR, SWIR) range

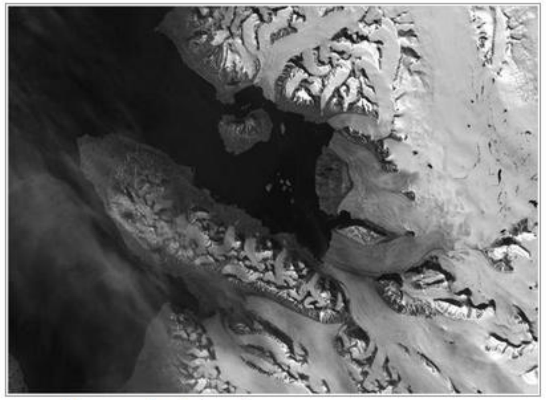


- Unique property: snow reflects almost all the energy back to sensor (white).
- Reflected portion: VNIR and NIR
- Obtainable snow properties:
  - Snow albedo
  - Snow cover area (SCA)
  - Snow grain size (limited)
  - Snow water equivalent (SWE) (limited)

Glaciers on Svalbard (Example)

True color composite (RGB)

Red



Near Infrared (NIR)

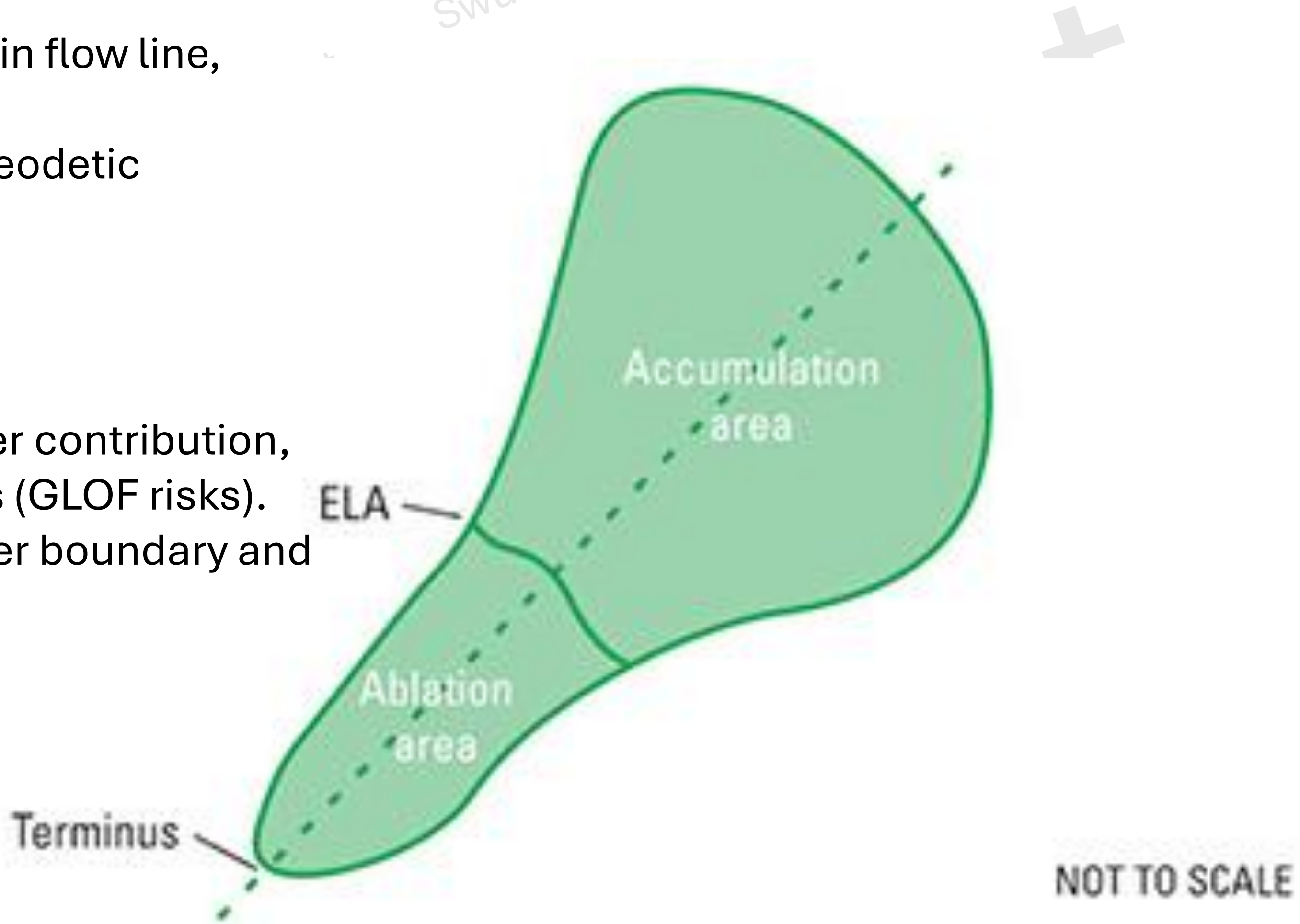
Shortwave Infrared (SWIR)

Source: https://www.esa.int/SPECIALS/Eduspace_Global_EN/SEM0O7TWLUG_0.html

Glacier Analytical Indicators

Glacier Length and Glacier Area

- Glacier length is typically measure along the main flow line, from the head to the terminus.
- Glacier Area can be delineated by using NDSI/ geodetic measurements/image classification.
- Advantage
  - Easy to implement.
- Disadvantage
  - length does not help in estimating meltwater contribution, runoff timing, or glacial lake outburst floods (GLOF risks).
  - Cloud cover affects the delineation of glacier boundary and other parameters.

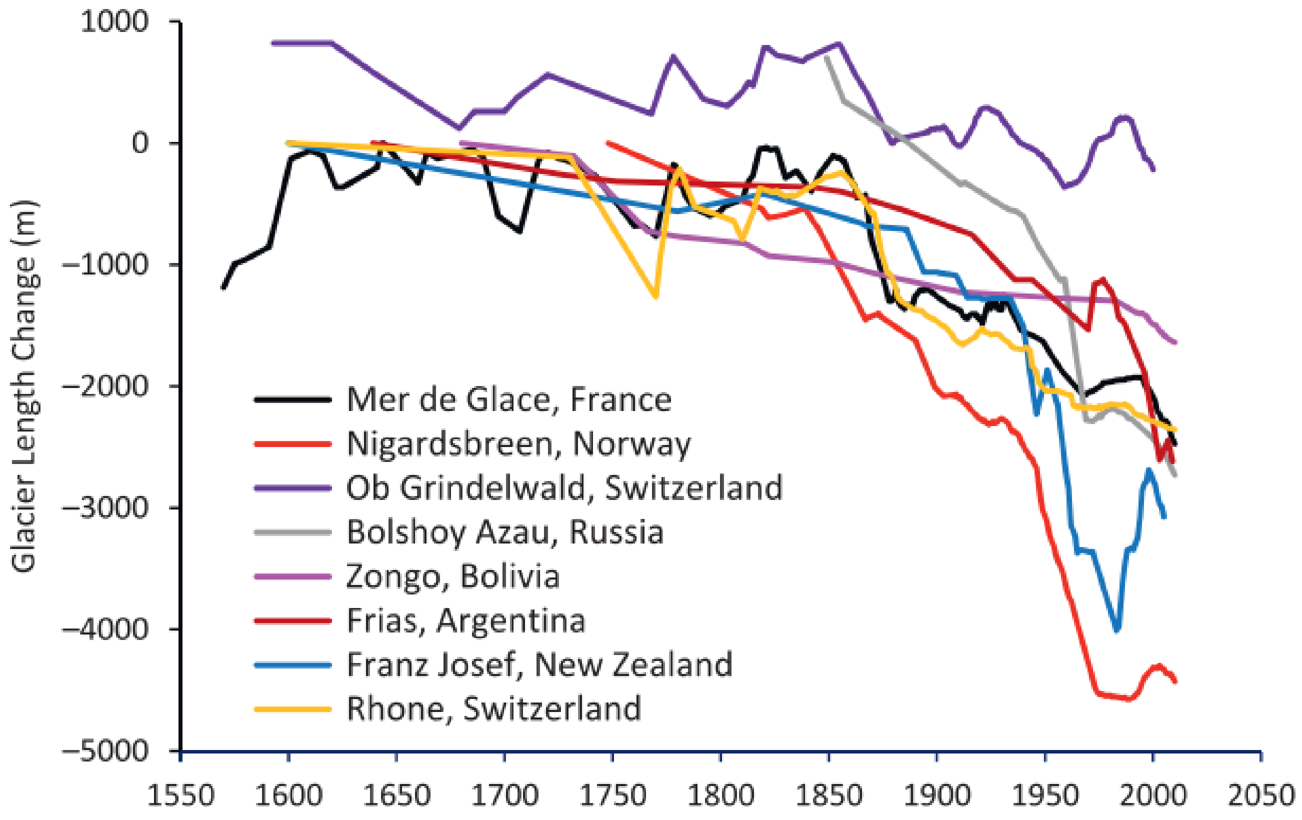


Hypothetical Graph of Glacier Length and Glacier

Source: *Shahgedanova, M. (2021). Climate change and melting glaciers. In The Impacts of Climate Change (pp. 53–84). Elsevier.* https://doi.org/10.1016/B978-0-12-822373-4.00007-0

Glacier Analytical Indicators

Glacier Length and Glacier Area (Example)

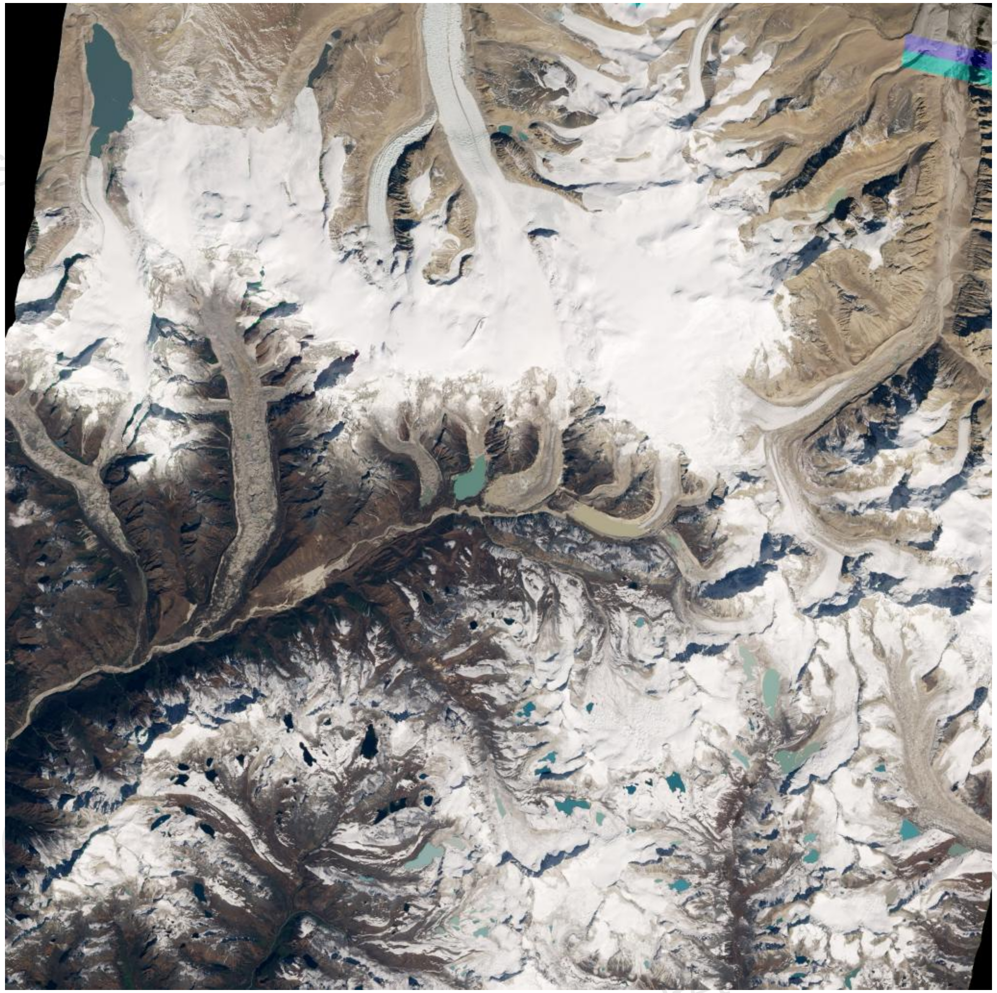


Example of long-term records of glacier length change (m) from different parts of the world.

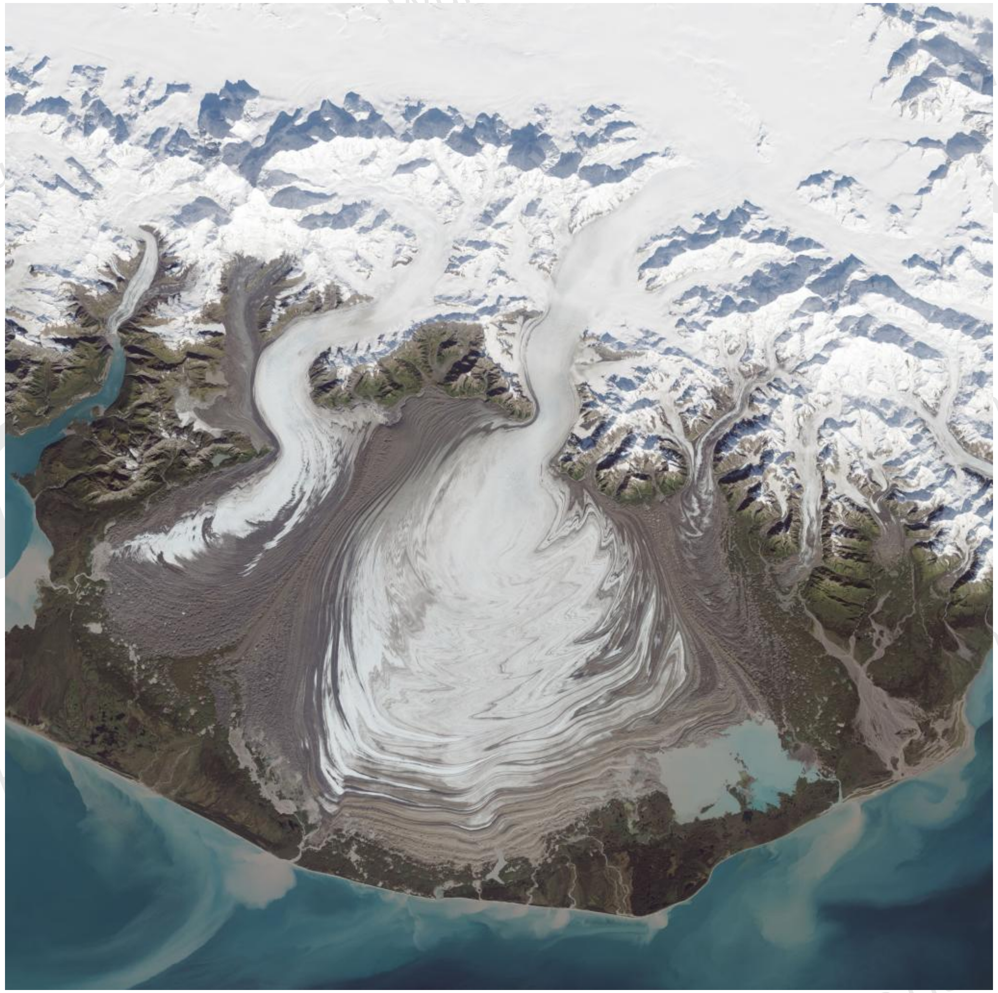
Source: *Shahgedanova, M. (2021). Climate change and melting glaciers. In The Impacts of Climate Change (pp. 53–84). Elsevier.* https://doi.org/10.1016/B978-0-12-822373-4.00007-0

Glacier Analytical Indicators

Glacier Length and Glacier Area



Thorthormi Glacier, Bhutan (October 28, 2009) AVNIR-2



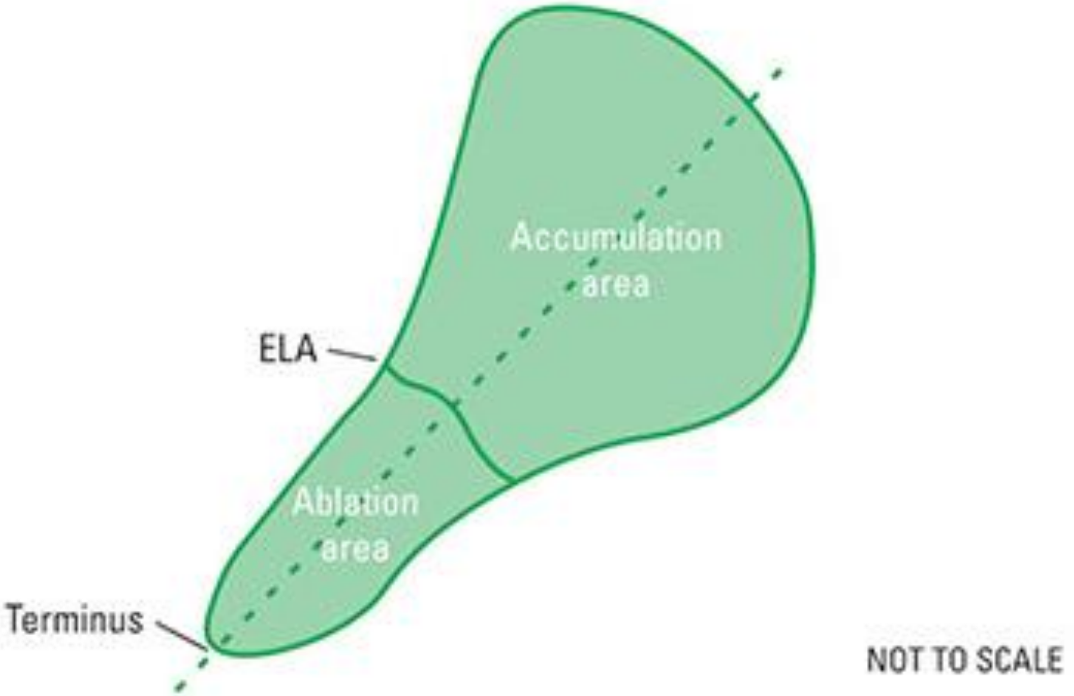
Malaspina Glacier, Alaska (September 24th, 2014) Landsat-8 OLI sensors

Source: *https://earthobservatory.nasa.gov/images/86767/malaspina-glacier-Alaska*, *https://earthobservatory.nasa.gov/images/40962/thorthormi-glacier-lake-bhutan*

Glacier Analytical Indicators

ELA determination

- Assumption that at the end of the cycle, snowline is identical with the ELA.
- If compared with other years, it gives you information of the glacier's health and mass balance.
- Rising ELA = Negative mass balance (glacier shrinking).

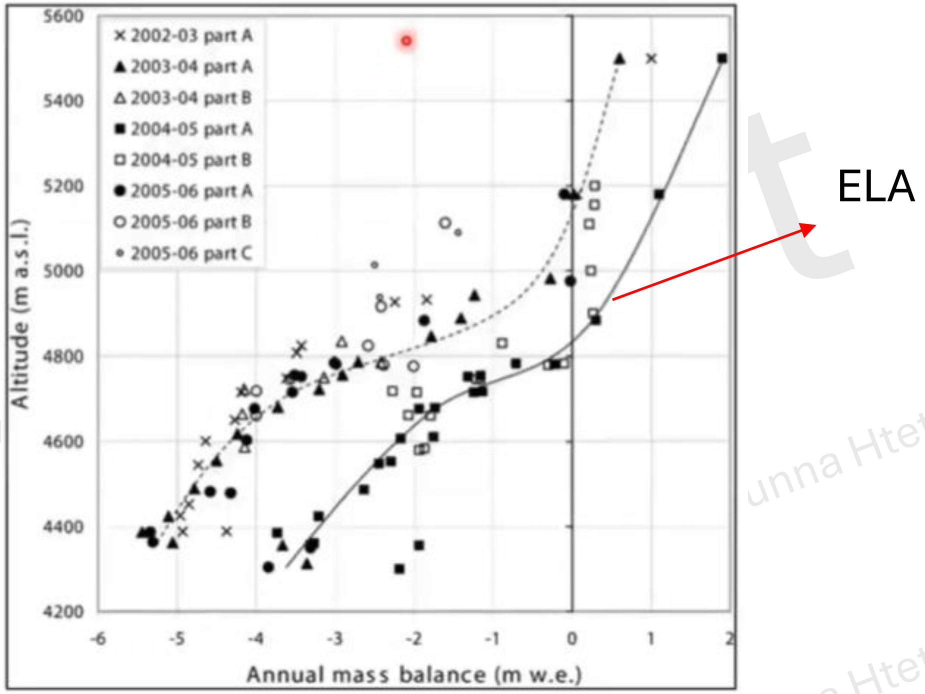


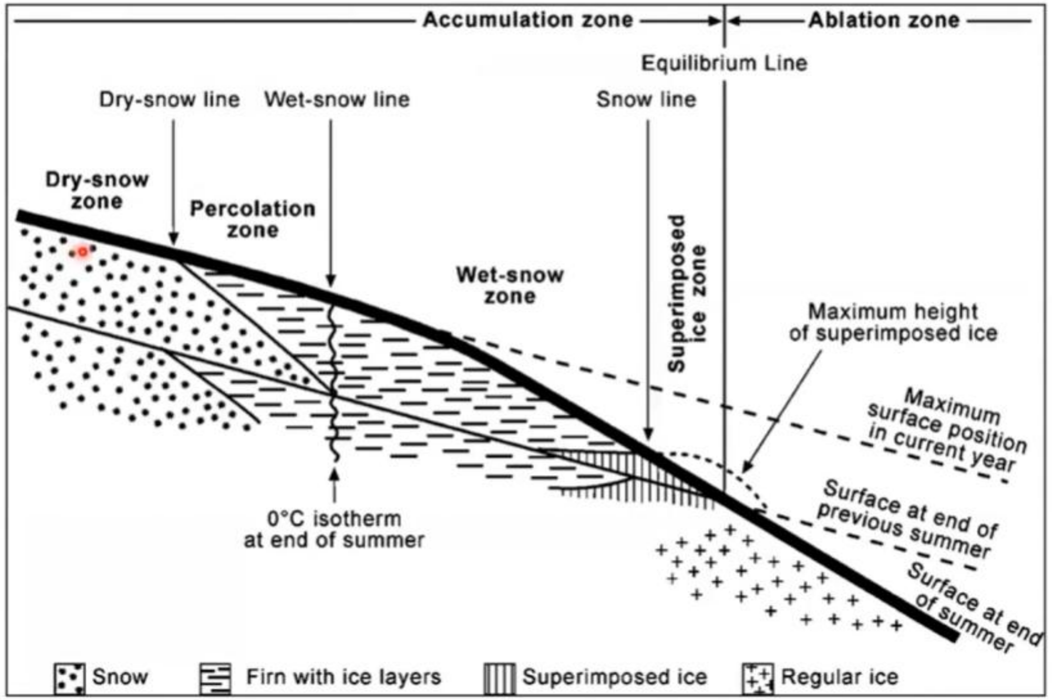
Source: *Shahgedanova, M. (2021). Climate change and melting glaciers. In The Impacts of Climate Change (pp. 53–84). Elsevier. https://doi.org/10.1016/B978-0-12-822373-4.00007-0*

Equilbrium Line Altitude (ELA)

How to define

- Dry-snow zone: no snow melting
- Percolation zone: some melting of snow, pass through the snowpack and freezes again (increasing temperature) by isothermic action. The entire melted water is consumed by snowpack.
- Since there are no superimposed ice, the snowline itself becomes equilibrium line at the end of summer. (especially in Himalayas).
- Note: The relationship between altitude and mass balance cannot be derived by satellite images.





Source: https://www.youtube.com/watch?v=kQYlwl-

How to measure glacier mass balance?

Equilibrium Line Altitude (ELA) method

Disadvantage: In the high glacial altitude, ice is more representative in ELA line delineation. Thus, underestimation/overestimation of snowline could introduce bias.

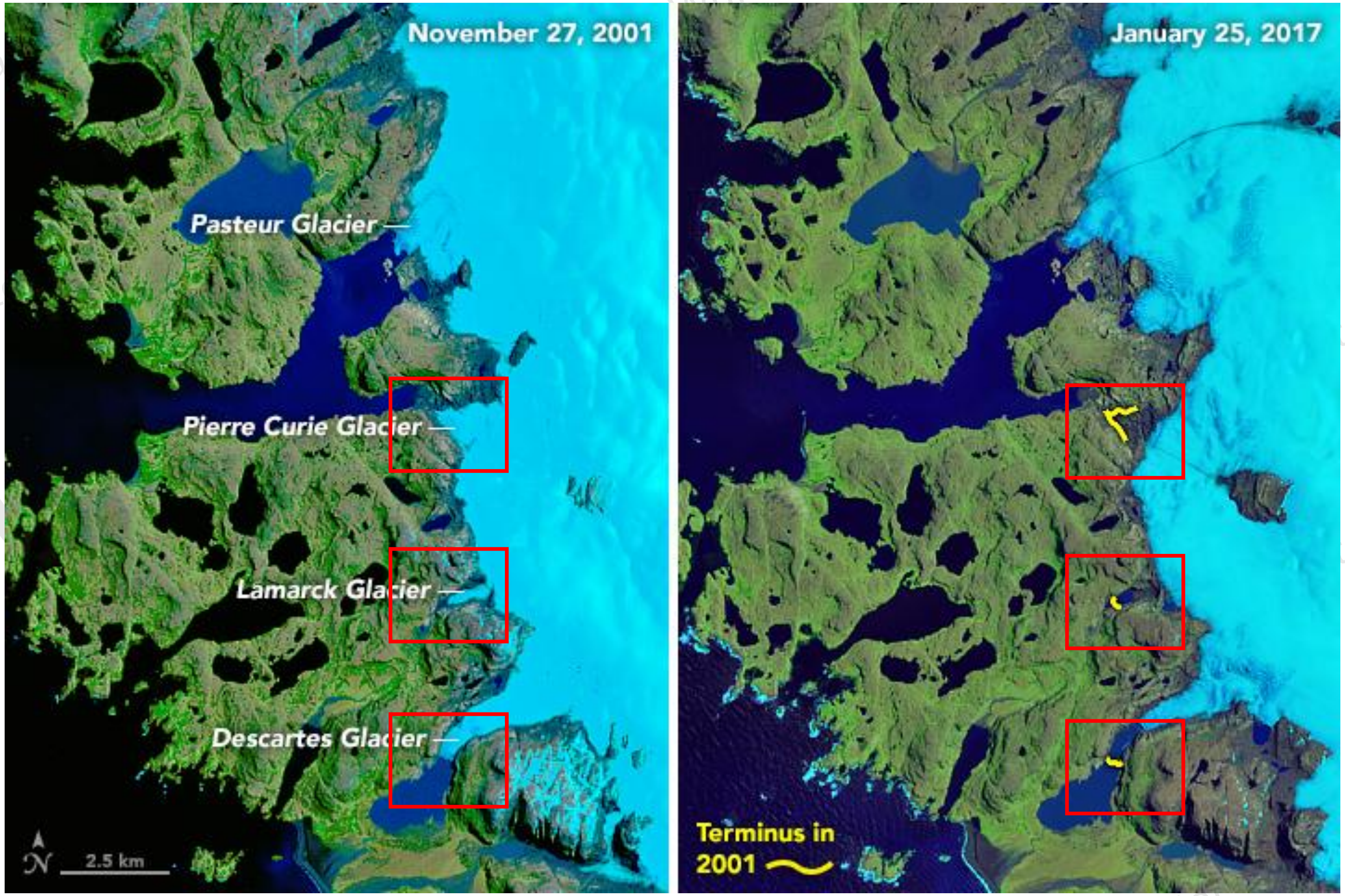
Source: https://www.youtube.com/watch?v=kQYlwl-

Glacier Analytical Indicators

Glacier Change Rate

- Also known as rate of advance or retreat of glaciers (Change in distance per time).
- As glaciers move slowly, the commonly expressed physical quantity is meters per year (m/yr).
- This would be very useful if yearly measurement data are available.

$$\boldsymbol{Rate = \frac{\Delta Distance}{\Delta Time}}$$



Source: https://geog1000labmanual.pressbooks.tru.ca/chapter/lab-alpine-glacier-analysis-3/

Glacier Analytical Indicators

Glacier Change Rate with Sen's Slope Estimator

- Non-parametric method of checking the significance of the magnitude of change.
- Advantages
  - more robust slope estimation method then least-squared method because of outliers not influenced to slope calculation.
- Disadvantages
  - Sensitive to empty values.

$$Sen's\ Slope = median(\frac{x_2 - x_1}{t_2 - t_1})$$

Year	Moved Distance (meters)	ΔChange (m/year)
2010	3250	-
2011	3270	20
2012	3210	-60
2013	3230	20
2014	3180	-50
2015	3160	-20

Source: https://geog1000labmanual.pressbooks.tru.ca/chapter/lab-alpine-glacier-analysis-3/

Band Combinations for Snow Detection

Example for Landsat 8

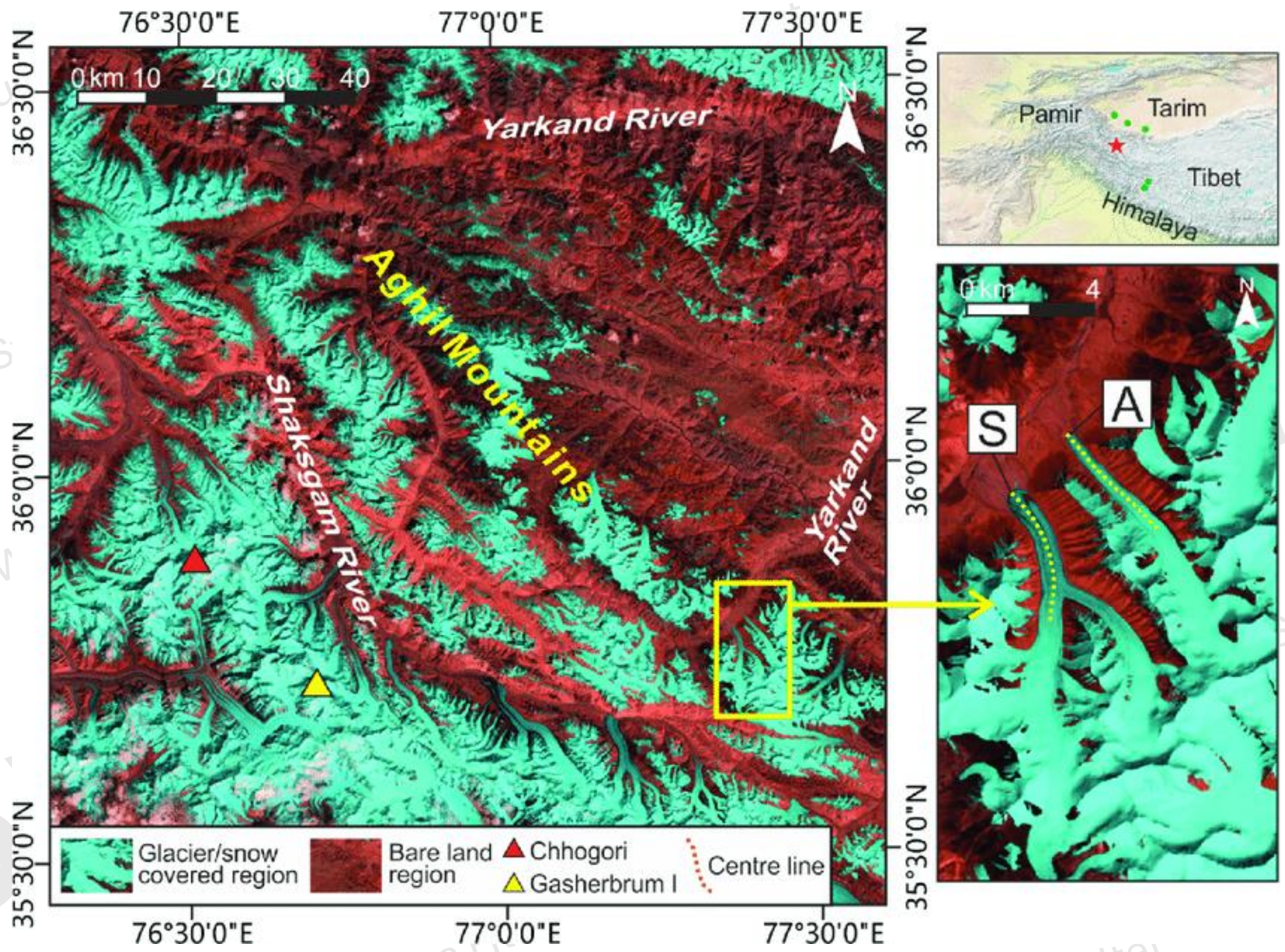
Natural Color	4 3 2
False Color (urban)	7 6 4
Color Infrared (vegetation)	5 4 3
Agriculture	6 5 2
Atmospheric Penetration	7 6 5
Healthy Vegetation	5 6 2
Land/Water	5 6 4
Natural With Atmospheric Removal	7 5 3
Shortwave Infrared	7 5 4
Vegetation Analysis	6 5 4

Band	Wavelength	Useful for mapping
Band 1 - coastal aerosol	0.43-0.45	Coastal and aerosol studies
Band 2 - blue	0.45-0.51	Bathymetric mapping, distinguishing soil from vegetation and deciduous from coniferous vegetation
Band 3 - green	0.53-0.59	Emphasizes peak vegetation, which is useful for assessing plant vigor
Band 4 - red	0.64-0.67	Discriminates vegetation slopes
Band 5 - Near Infrared (NIR)	0.85-0.88	Emphasizes biomass content and shorelines
Band 6 - Short-wave Infrared (SWIR) 1	1.57-1.65	Discriminates moisture content of soil and vegetation; penetrates thin clouds
Band 7 - Short-wave Infrared (SWIR) 2	2.11-2.29	Improved moisture content of soil and vegetation; penetrates thin clouds
Band 8 - Panchromatic	0.50-0.68	15 meter resolution, sharper image definition
Band 9 - Cirrus	1.36-1.38	Improved detection of cirrus cloud contamination
Band 10 - TIRS 1	10.60-11.19	100 meter resolution, thermal mapping and estimated soil moisture
Band 11 - TIRS 2	11.50-12.51	100 meter resolution, improved thermal mapping and estimated soil moisture

Source: https://www.usgs.gov/faqs/what-are-best-landsat-spectral-bands-use-my-research?utm_source=chatgpt.com , https://www.esri.com/arcgis-blog/products/product/imagery/band-combinations-for-landsat-8?utm_source=chatgpt.com

Band Combinations for Snow Detection

Example for Landsat 8



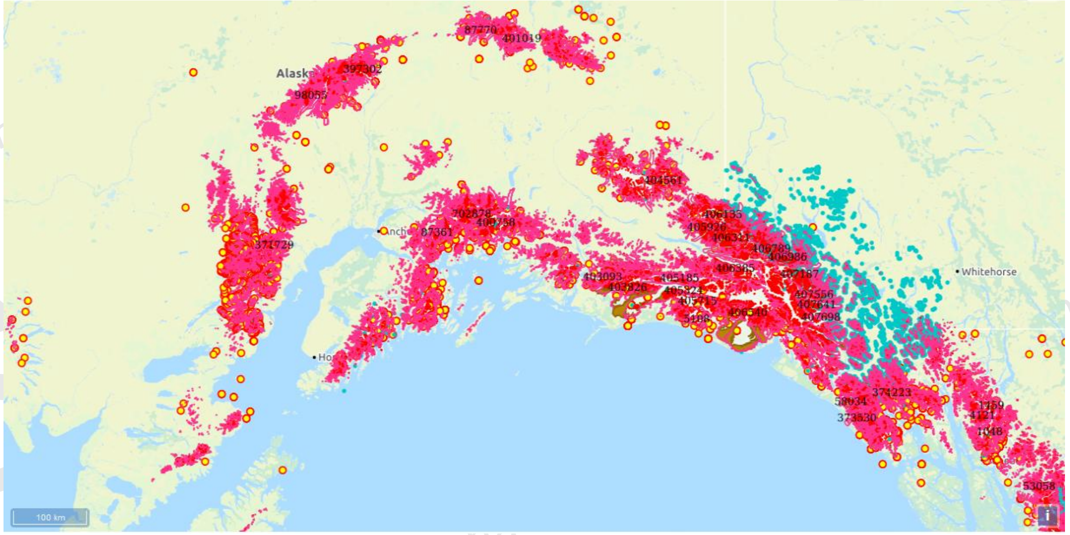
Landsat 8 OLI image (band combination of 6, 5, and 4) of the study area on 8 September 2016. The red star in the topographic map locates the studied glaciers and the green spots represent the locations of meteorological stations.

Source: Lv, M., Guo, H., Yan, J., Wu, K., Liu, G., Lu, X., Ruan, Z., & Yan, S. (2020). Distinguishing Glaciers between Surging and Advancing by Remote Sensing: A Case Study in the Eastern Karakoram. *Remote Sensing*, *12*(14), 2297. https://doi.org/10.3390/rs12142297

Global Datasets for Glaciers

GLIMS: Global Land Ice Measurements from Space

- Developed by NSIDC (National Snow and Ice Data Center)
- Data inventory for the world’s glaciers/ a comprehensive, global database of land ice through repeat surveys.
- Source: https://nsidc.org/data/glims/data
- Parameters: Glacier area, geometry, surface velocity, snowline elevation.



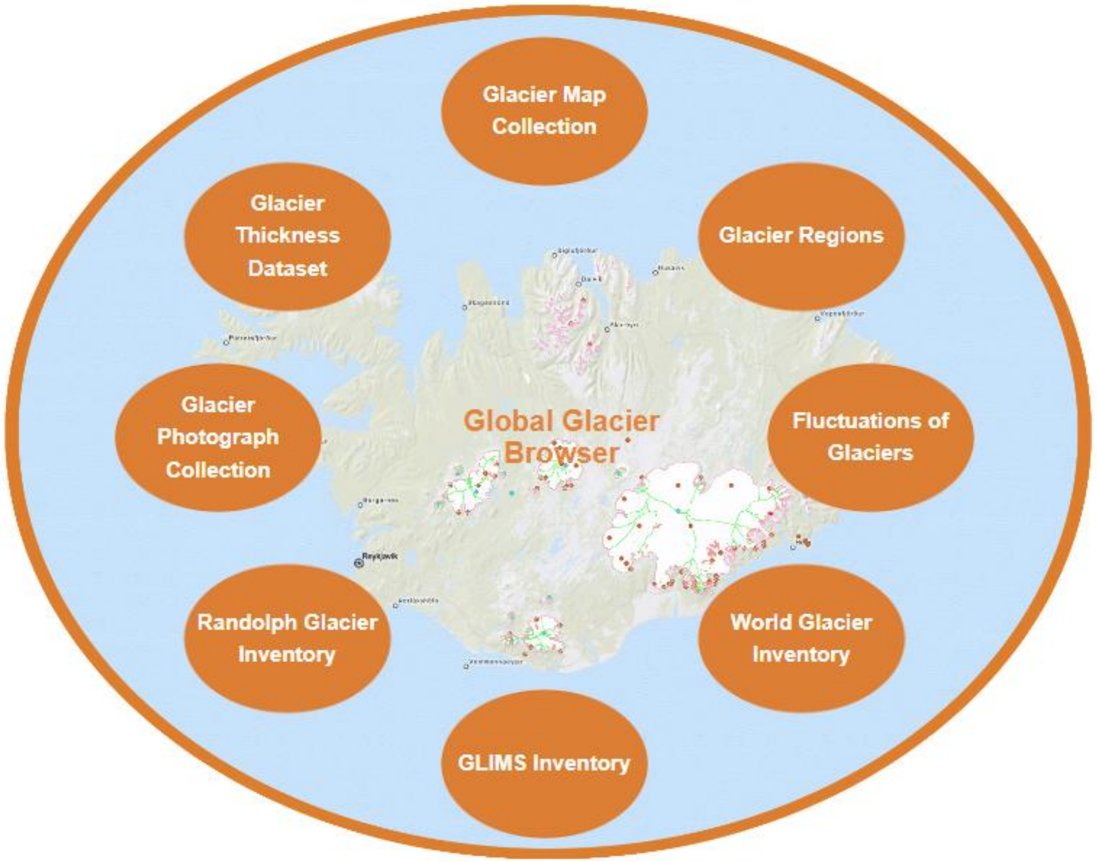
A sample image of Alaskan glaciers from the GLIMS glaci viewer application. — Credit: NSIDC

Source: *https://nsidc.org/data/glims/data*

Global Datasets for Glaciers

GTN-G (Global Terrestrial Network for Glaciers)

- Framework for the internationally coordinated monitoring of glaciers and ice caps in support of the United Nations Framework Convention on Climate Change (UNFCCC)
- Source: https://www.gtn-g.ch/
- Parameters: In-situ records of glacier mass balance, length change, area and volume, glacier outline, glacier thickness.



Source: *https://nsidc.org/data/glims/data*

Practical – 3: Natural Year of Glacier Estimation

Glacier Dynamics (part 2)

How to measure glacier mass balance?

Stratigraphic method and Fixed Date Method

- Historically known as natural mass balance year.
- estimated at an interval of a year when glacier mass is at minimum.
  - Note: natural mass balance year is the periods between two successive minimum glacier mass points (typically from end of one ablation season to end of next late summer)
  - Idea is identifying the snowpack last year and estimate how much accumulation the snowpack received
  - Advantage
    - *Accurate glacier dynamics, consistency in mass.*
  - *Disadvantage*
    - *Doesn't follow calendar year because snowfall at every year doesn't start at the same date which is influenced by other parameters.*
- Fixed date method: mainly on mass change between fixed dates.
  - Advantage
    - common approach in RS application.
  - Disadvantage
    - *satellite acquisition constrained by orbit schedule, cloud cover and sensor availability.*

How to measure glacier mass balance?

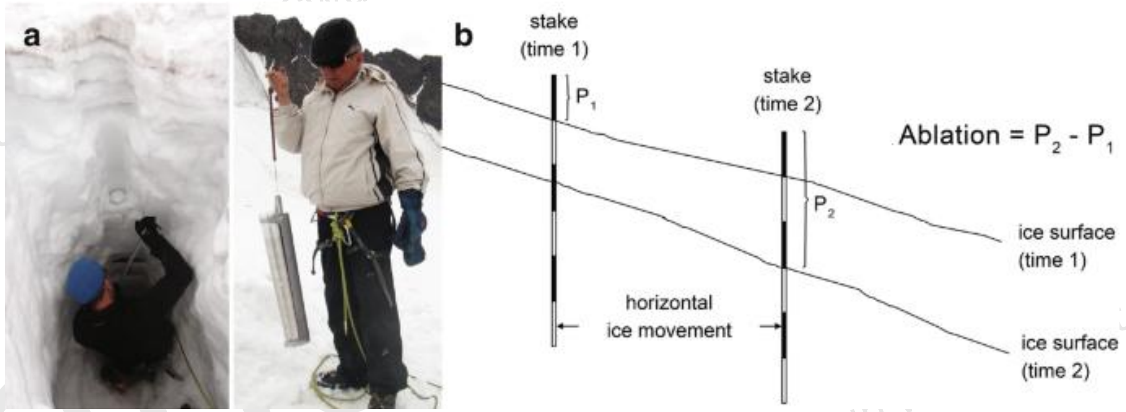
Fixed Date Method

- Mainly on mass change between fixed dates.
- In some areas, peak period of accumulation and ablation may be the same. (Continuous snowfall throughout the year, continuous ablation throughout another year).
- Advantage:
  - common approach in RS application, does not require stratigraphy of snow.
- Disadvantage:
  - *satellite acquisition constrained by orbit schedule, cloud cover and sensor availability.*
  - *Measurement of mass balance from this method gives net value, not gross value. (**Net** = How much mass balance at the later date, **gross** = considers both accumulation and ablation).*

How to measure glacier mass balance?

Glaciological Method

- Certain conventional measurements are done in the field.
- Numerous vertical stake measurement along the glacier zone (defined by elevation zonations), predominantly in ablation area.
- In accumulation area, you create a pit of snow at different places, measure how much the thickness of snow, snow density, to get total mass of ice.
- **Disadvantage**:
    - Since the glaciers are moving (either naturally or by avalanches), the stakes you've marked at the glaciers can be fallen.
    - Requires human efforts.
    - Spatial variability of the snowpack is not properly detected.

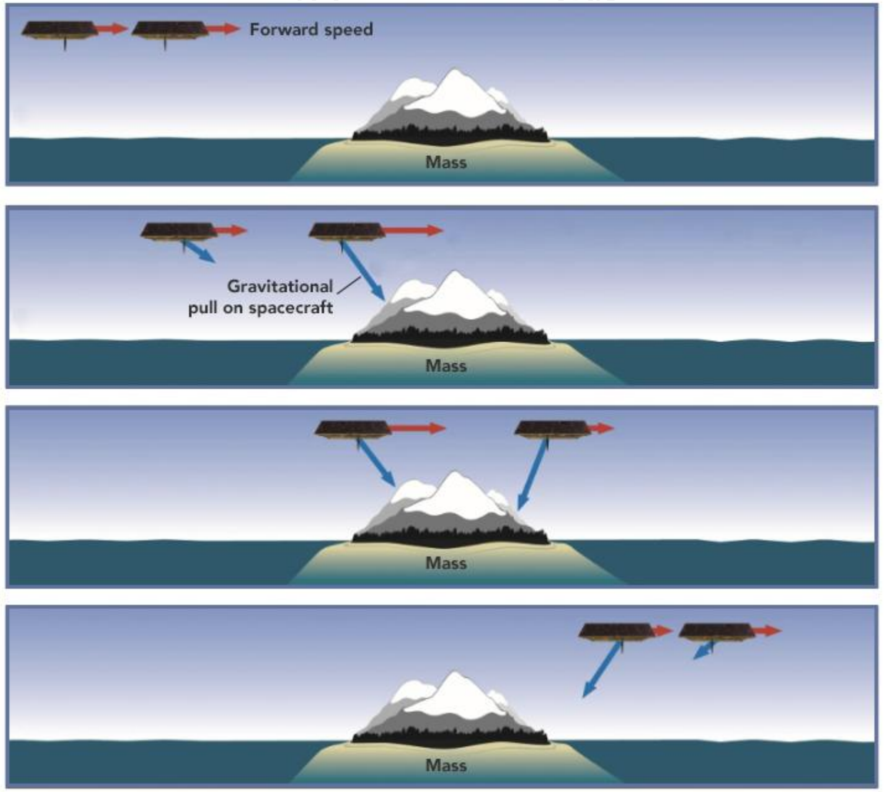


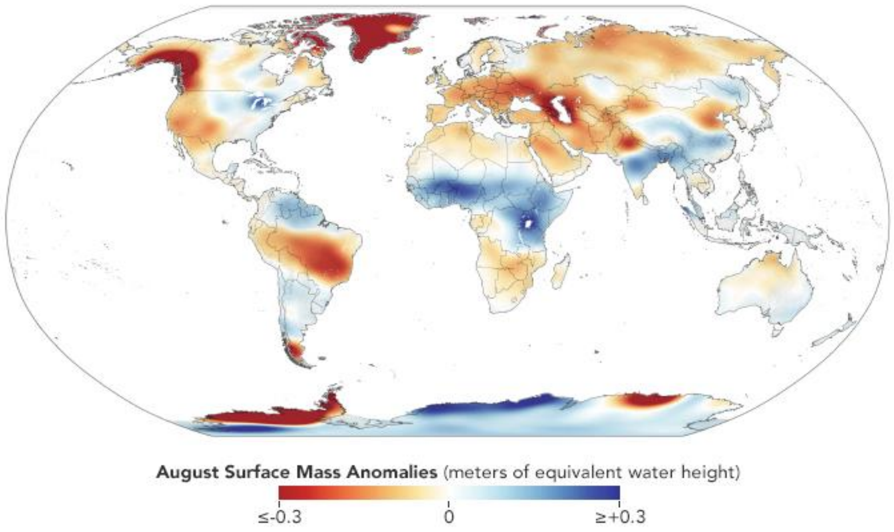
Source: https://www.youtube.com/watch?v=kQYlwl-2gH8

How to measure glacier mass balance?

Gravimetric Method

- Recent methodology which applies the change in the Earth's gravitation field related to the redistribution of mass in the Earth's system.
- Measure its gravitational field and its changes to draw conclusion about mass change.
- Mass change caused by changes in groundwater storage, decay of ice sheets/glaciers.
- Drawback : Very coarse spatial resolution makes them applicable to large ice sheets. Not suitable for mountain glaciers.

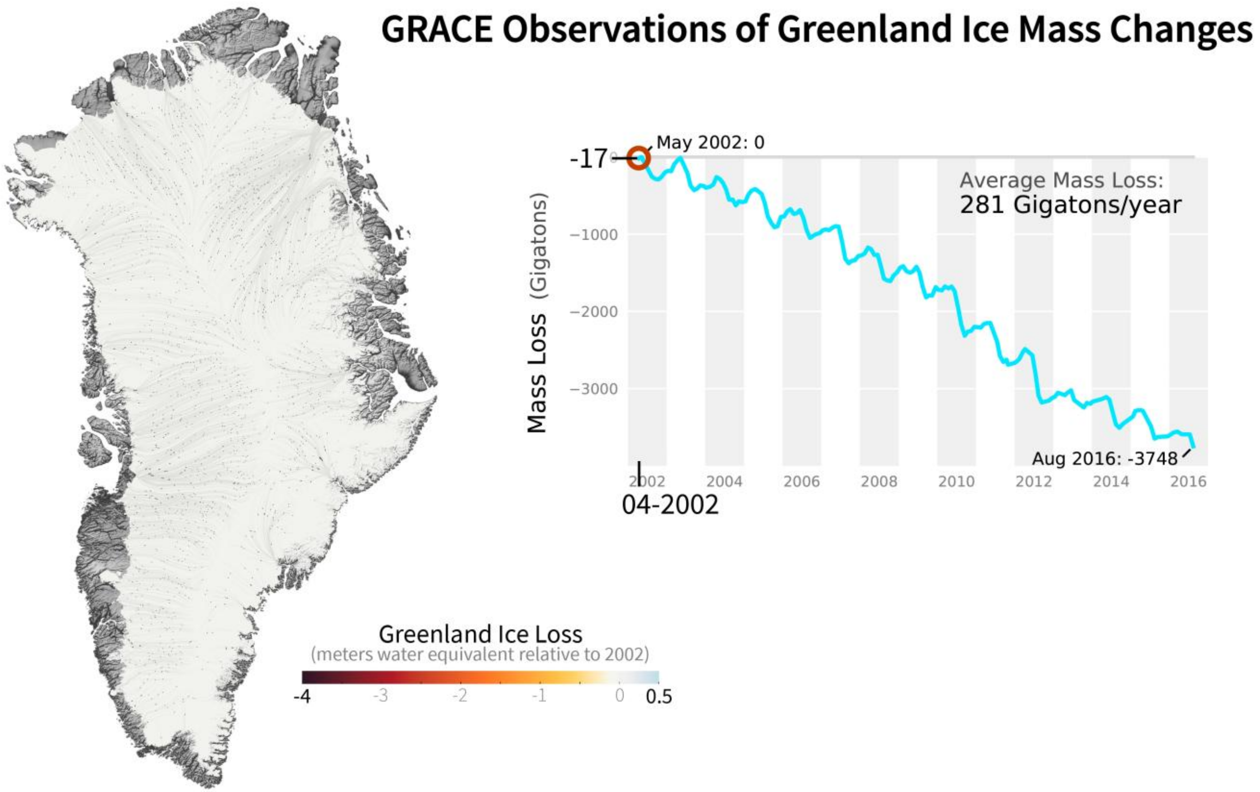




Source: https://earthobservatory.nasa.gov/images/147437/taking-a-measure-of-sea-level-rise-gravimetry,
Hagg, W. (2022). Glaciology and Glacial Geomorphology. In *Glaciology and Glacial Geomorphology*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-

How to measure glacier mass balance?

Gravimetric Method



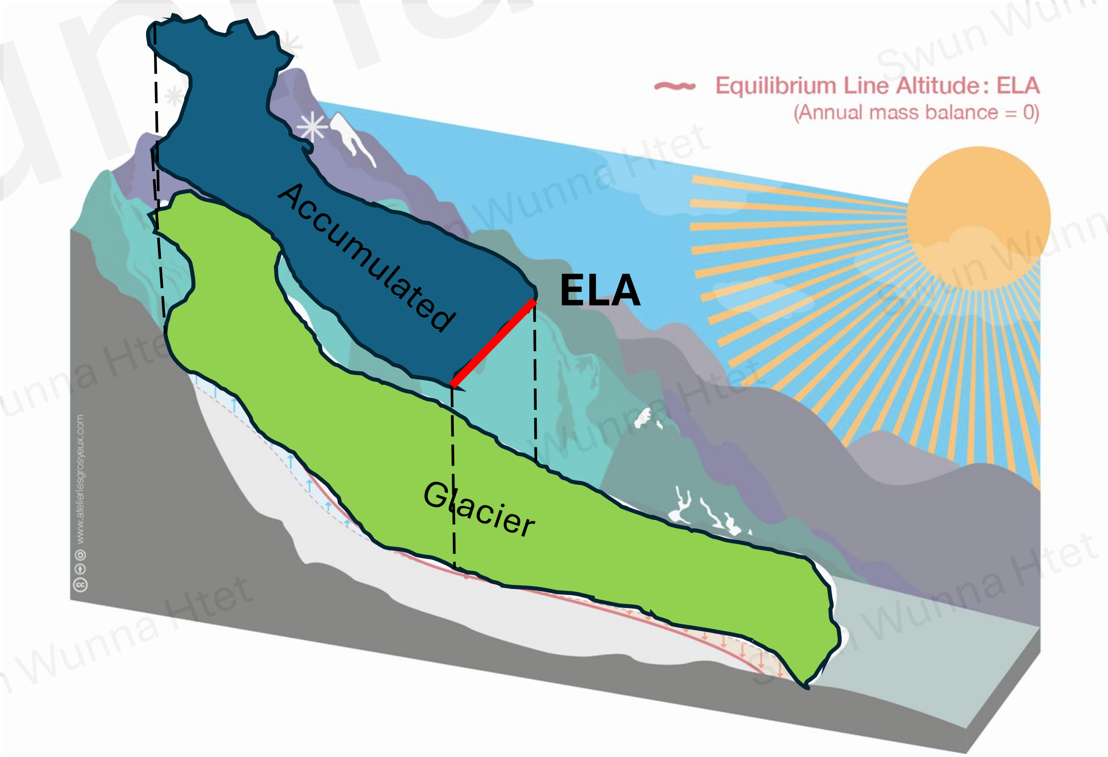
Source: *https://earthobservatory.nasa.gov/images/147437/taking-a-measure-of-sea-level-rise-gravimetry*

Glacier Analytical Indicators

Accumulation-Area Ratio (AAR)

- Ratio of area of accumulation area to the total surface area of the glacier.
- AAR is applied to glacier at the end of the balance year (end of ablation season, just before the first fresh snowfalls of the next accumulation season. If not measured correctly, you have mistakenly count seasonal snow as accumulation (overestimation).
- 0.6 – 0.7 (Alpine glaciers in mid latitudes, higher in the tropics).
- Value between 0 and 1: 0 indicating it is in balance with climate (neither shrinking nor growing)
- AAR correlates well with climatic mass balance and ELA (inverse correlation; lower ELA means higher AAR.
- Disadvantage: Cloud cover affects the delineation of glacier boundary and other parameters.

$$AAR = \frac{Area_{Accu}}{Area_{Glacier}}$$



Source: https://edu.oggm.org/es/latest/glacier_basics.html

Glacier Analytical Indicators

Glacier Volume & Mass Balance Estimation Using Elevation Difference

- Surface elevation difference from two different times t1 and t2.
- The glacier boundary must be set up first before applying pixel area.
- Typical application with UAV.

$$\Delta V = \sum(\Delta h \times A)$$

ΔV = volume change
A = Area of each pixel

$$\Delta M = \Delta V \times \rho$$

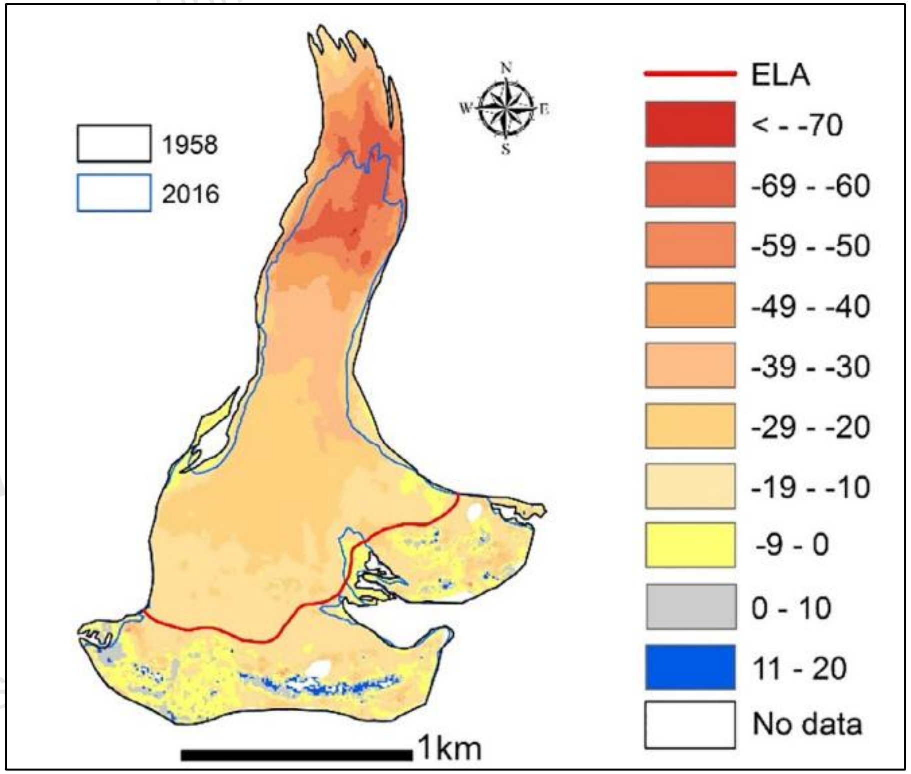
ΔM = Mass Change (kg)
ρ = representative ice/snow zone density (kg/m^3)

$$B = \frac{\Delta M}{A_{glacier} \times \rho_{water}}$$

B = Specific mass balance (Unit: m w.e/yr)

$$B_A = B \times Glacier\ Area$$

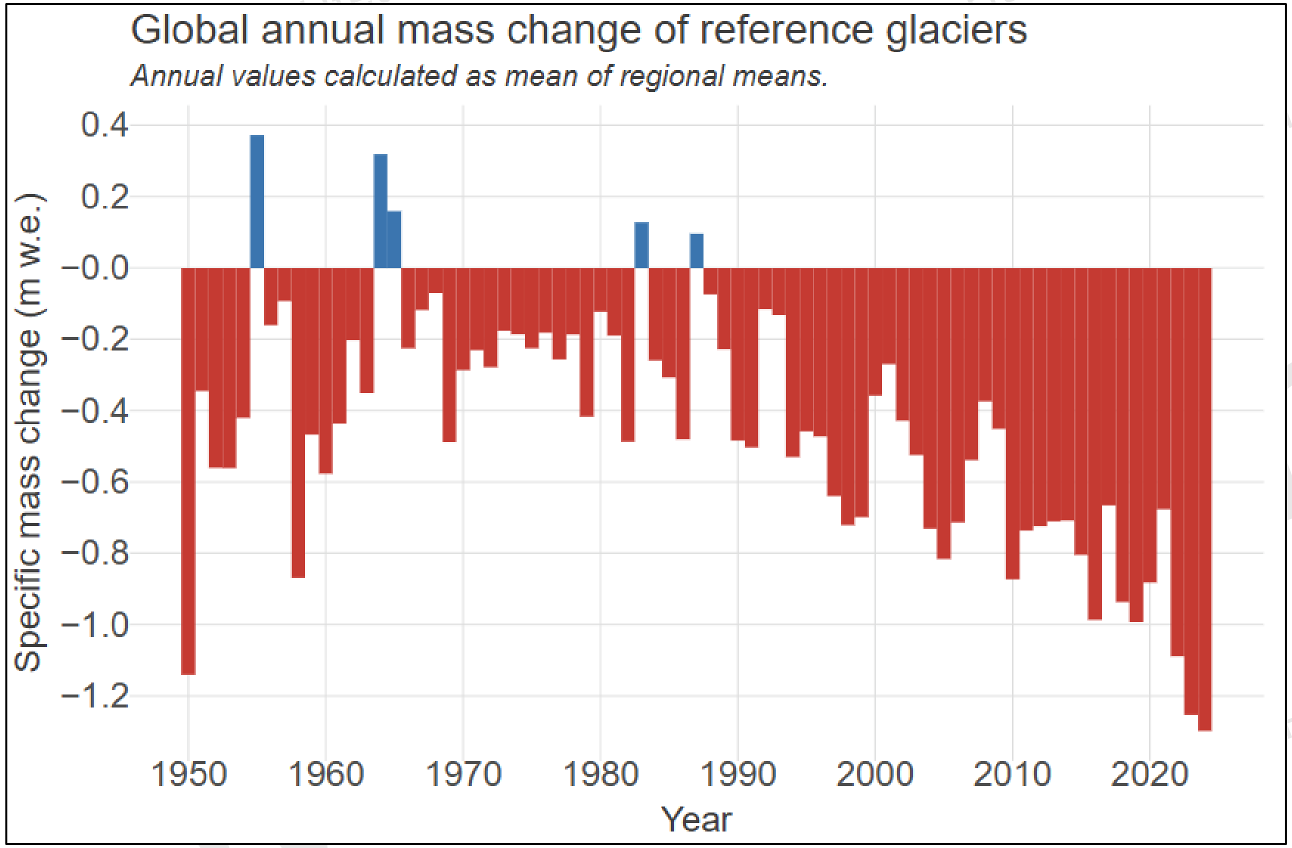
B_A = Annual mass balance (Unit: m w.e/yr)

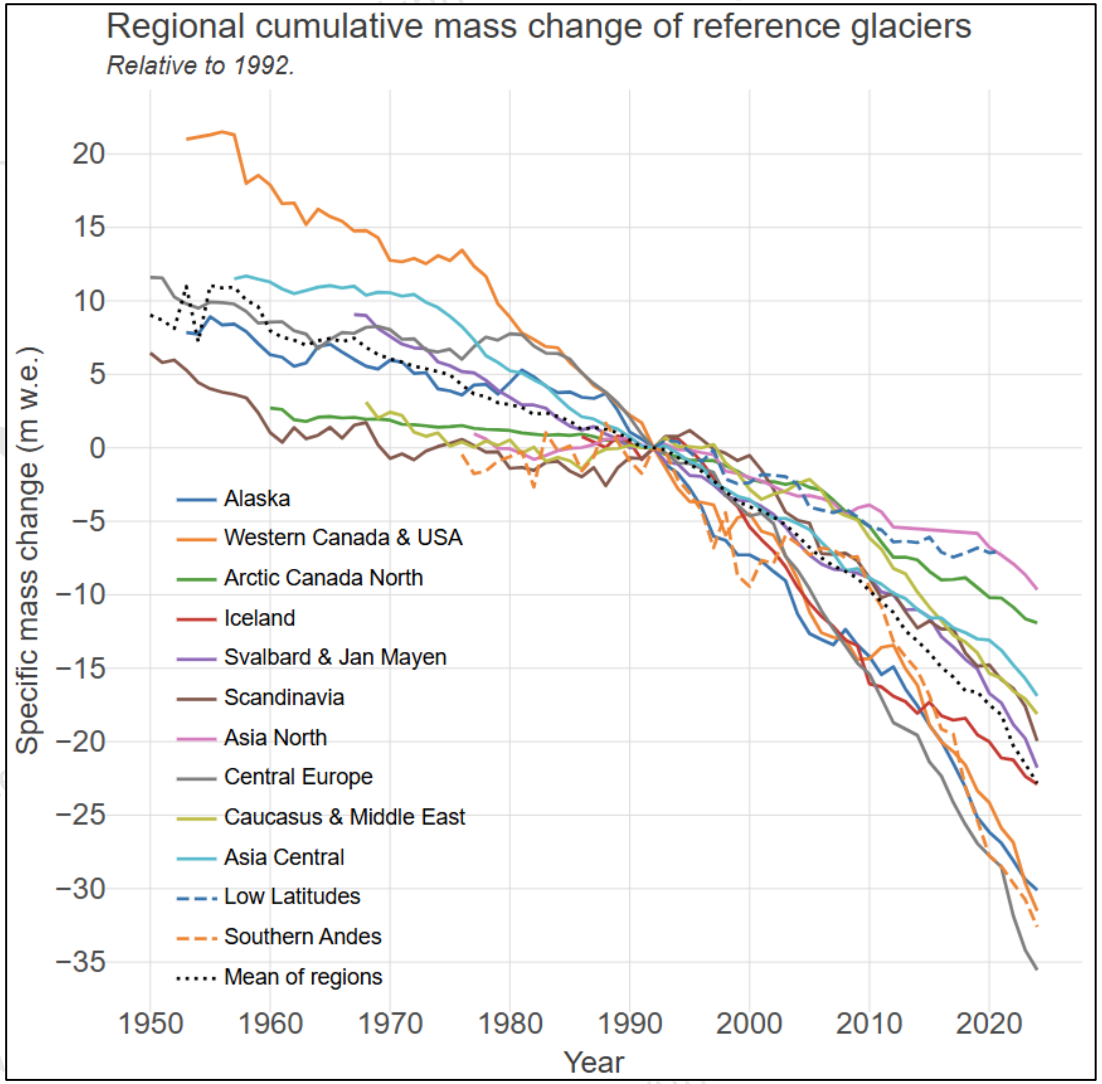


Changes in surface elevation of Tuyukus glacier between 1958 and 2016.

Source: *Shahgedanova, M. (2021). Climate change and melting glaciers. In The Impacts of Climate Change (pp. 53–84). Elsevier. https://doi.org/10.1016/B978-0-12-822373-4.00007-0*

Status of Global Glaciers





Source: https://wgms.ch/global-glacier-

Practical – 4: Glacier Velocity Estimation Using Sentinel-1 data and ESA-SNAP Software

Glacier Analytical Indicators

Glacier Velocity

- Velocity measurements of glacial flows can be determined from repeat optical or radar image.
- Estimation sub-seasonally and more accurately is possible with Sentinel 1, 2 imagery.
- Measurement methods
  - In-situ GPS/Stake measurement
  - Optical imagery (Sentinel 2, Landsat)
  - Synthetic Aperture Radar (SAR) (Sentinel 1)
  - Feature tracking or interferometry(InSAR)
  - Time-lapse UAV measurements
- Application: assessment in glacier monitoring, climate change, seasonality variability investigation, local hydrological impact from glacier melt.

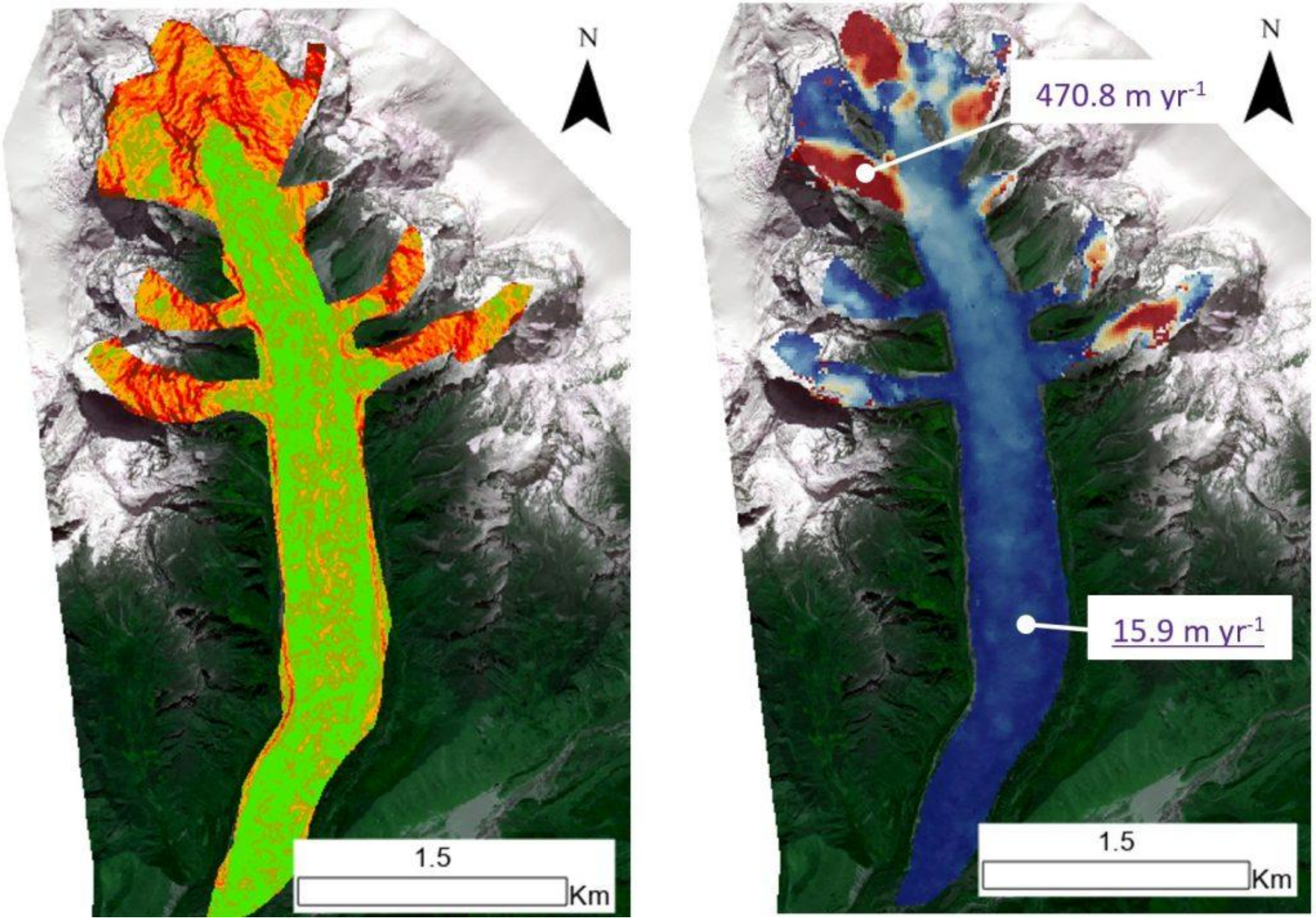
Timelapse Sentinel-2 imagery of Osbornebreen, Svalbard, in the period 17 July to 25 August 2020, Svalbard, showing rapid glacier flow.

Source: https://www.nve.no/hydrology/glaciers/copernicus-glacier-service/glacier-velocity/

Glacier Analytical Indicators

Glacier Velocity

- Accelerated: more mass to the glacier terminus, faster melt and accelerating recession.
- Slow: down waste in situ.
- On mountain glaciers, ice velocity is usually measured in meters per year (m yr^{-1})
- Rate : <10 m yr^{-1} - > 500 m yr^{-1}.



A comparison of glacier surface gradient (left), and ice velocity (right) for Tshojo Glacier in Bhutan. For surface gradient and ice velocity, darker red corresponds to steeper slopes and higher ice speeds, whereas light green corresponds to shallower slopes and blue to slower ice speeds.

Source: https://www.nve.no/hydrology/glaciers/copernicus-glacier-service/glacier-velocity/, https://www.antarcticglaciers.org/glaciers-and-climate/observing-and-monitoring-glaciers-and-ice-sheets/measuring-glacier-velocity/

Glacier Analytical Indicators

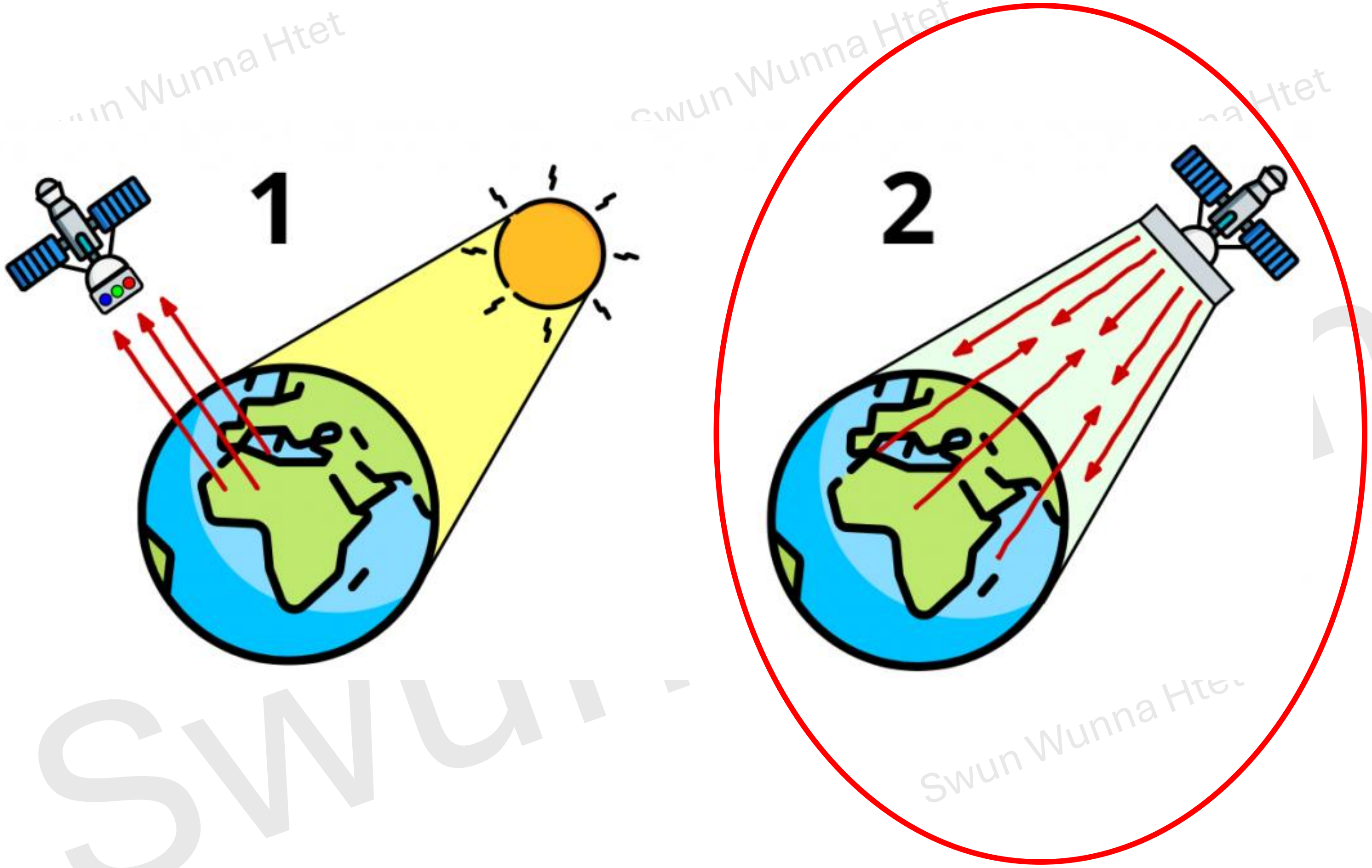
Glacier Velocity (How to measure?)

1. Feature Tracking (Point-based Analysis)
    - Identify distinct visual features (e.g., rocks, textures, corners) and track their position.
    - Advantage: straightforward method, fast; especially with UAV.
    - Disadvantage: hard to detect in homogeneous area (smooth snow).

2. Offset Tracking (Image-based Analysis)
    - Measures the shift (offset) of local pixel neighbourhood (patches) between two images by using normalized cross-correlation.
    - Advantage: Works on radar, optical and UAV images.
    - Disadvantage: sensitive to noise and image quality, computationally expensive.

Source: https://www.nve.no/hydrology/glaciers/copernicus-glacier-service/glacier-velocity/, https://www.antarcticglaciers.org/glaciers-and-climate/observing-and-monitoring-glaciers-and-ice-sheets/measuring-glacier-velocity/

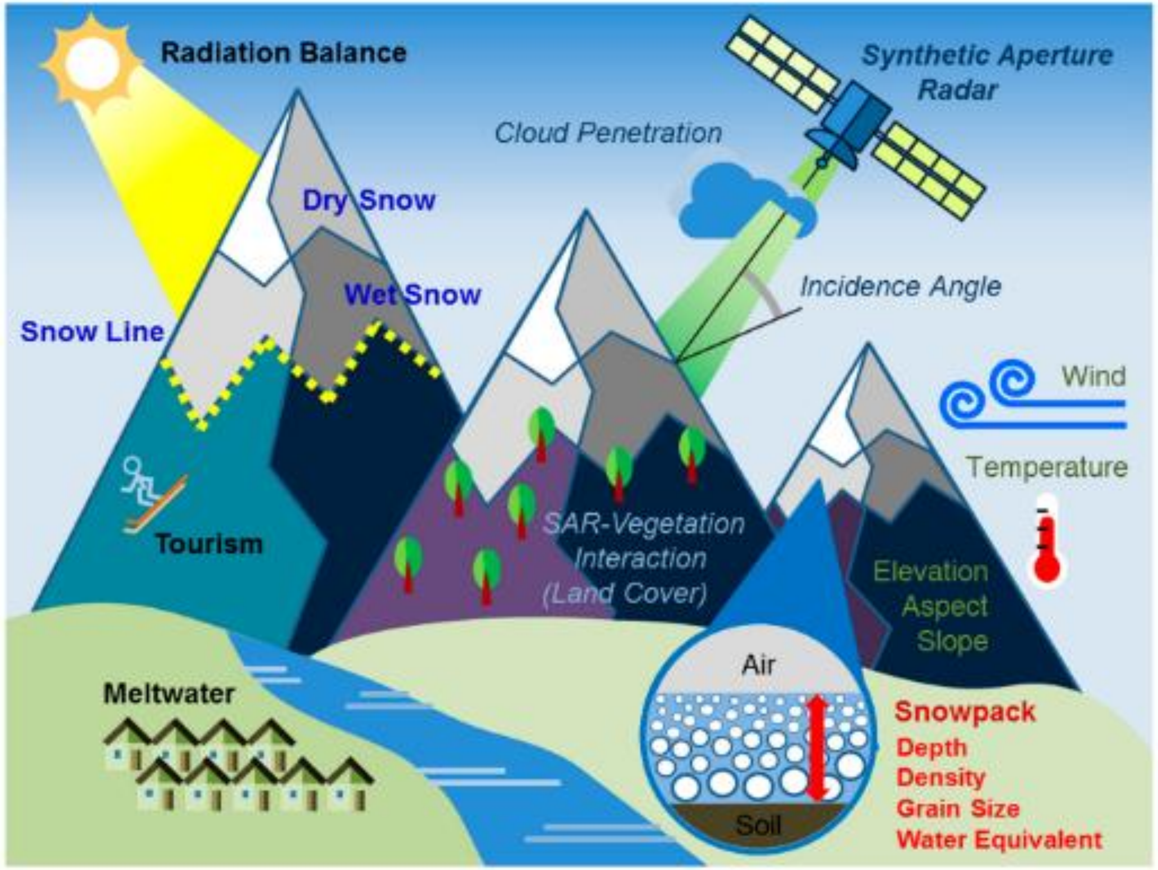
Two Types of Remote Sensing



- Active (Microwave or Radar)
  - Source: satellite sensor
  - Receive backscatter from the target to the sensor.
- Passive (Multispectral/Hyperspectral/ Optical)
  - Source: sun
  - Receive reflectance from the target to the sensor

Radar Remote Sensing Approach

Synthetic Aperture Radar (SAR)



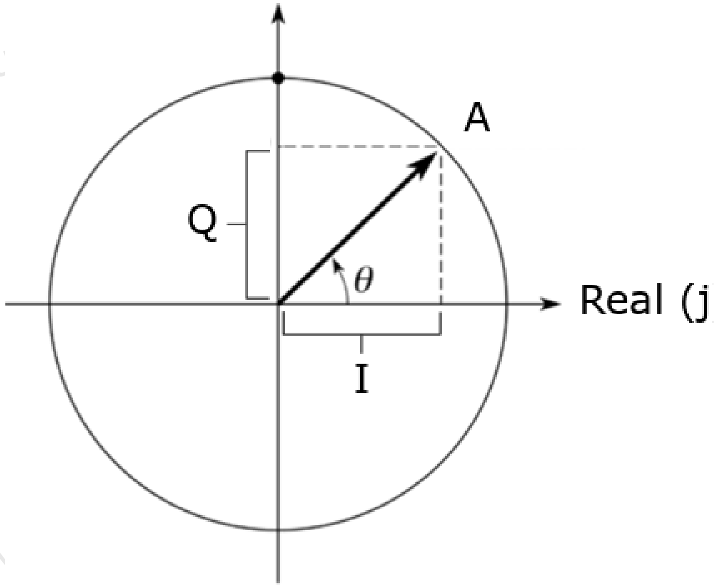
Different snow types and snow line (deep blue)
SAR-related characteristics (italic)
Factors influence snow (green)
Snowpack parameters (red)

- An alternative development for obtaining more unique information about the earth's objects with better image resolution using advanced signal-processing.
- **Advantages**: weather, platform and day/night independence, interferometry.
- **Disadvantages**: requires background knowledge of physics, geometry, hard to preprocess data manually.
- **RADAR** : Radio Detection and Ranging (using radio waves to detect the presence of objects and determine the distance and angular position).
- Pulses of microwave energy are transmitted towards area of interest, and received echoes are recorded and registered into images

Source: Murioz, J. (2013). Synergistic Use of Remote Sensing for Snow Cover and Snow Water Equivalent Estimation. *British Journal of Environment and Climate Change*, *3*(4). https://doi.org/10.9734/bjecc/2013/7699

RADAR Basics

Starts from Complex Numbers



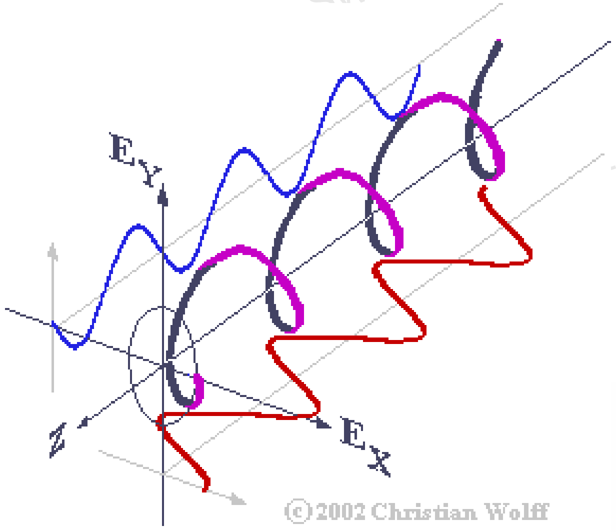
I = In-Phase = A cos(θ)

Q = Quadrature = A sin(θ)

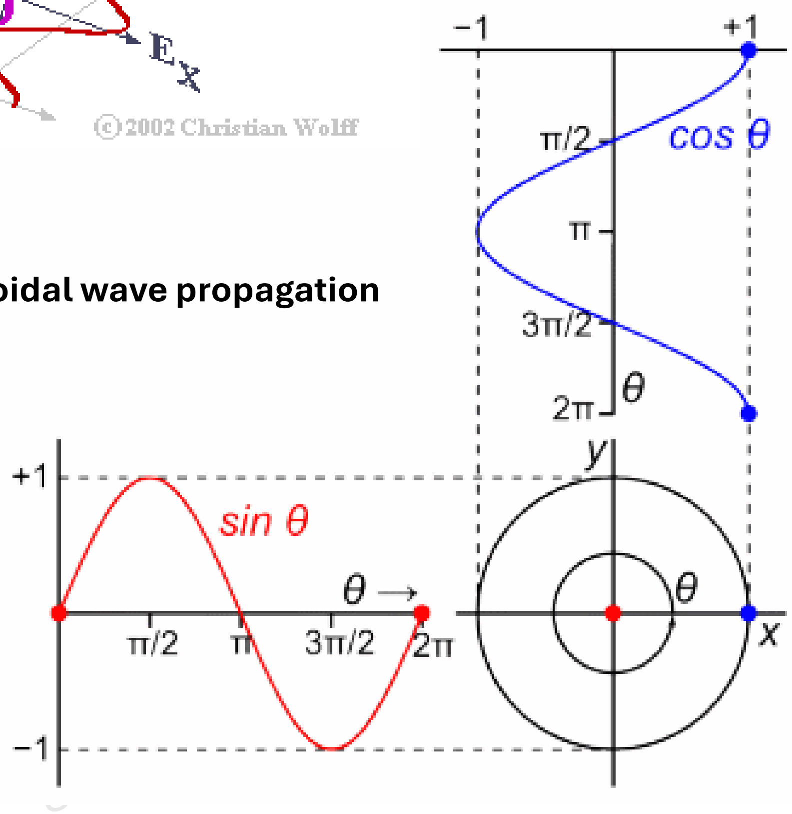
Amplitude A = sqtr(I² + Q²)

tan(θ) = Q/I or

Phase θ = tan-¹(I/Q)



Sinusoidal wave propagation



$x = A \times \cos\theta$

$y = A \times \sin\theta$

$$\omega = \frac{2\pi}{T} = 2\pi f \ (rad\ s^{-1})$$

ω = angular frequency (speed)

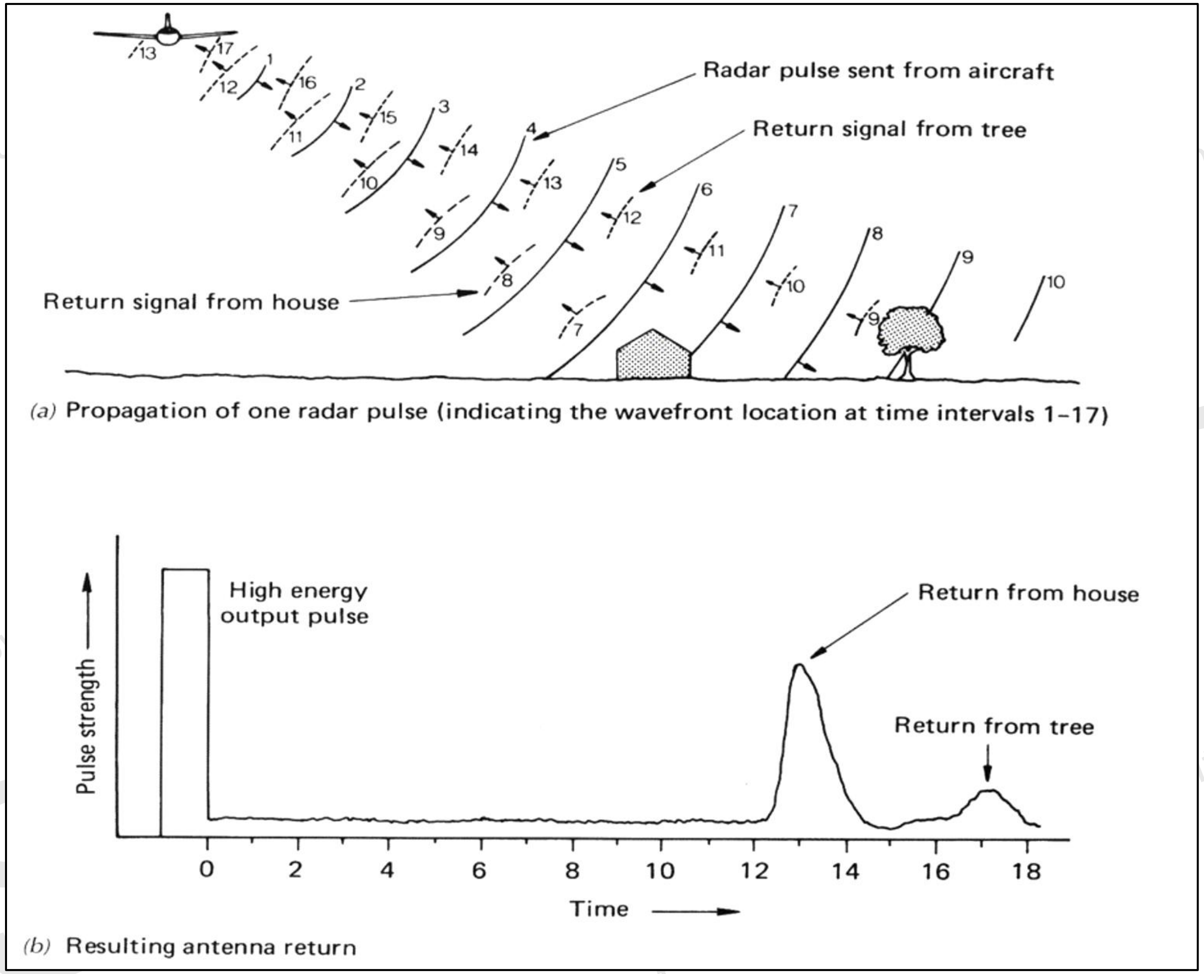
T = period (seconds)

F = ordinary frequency

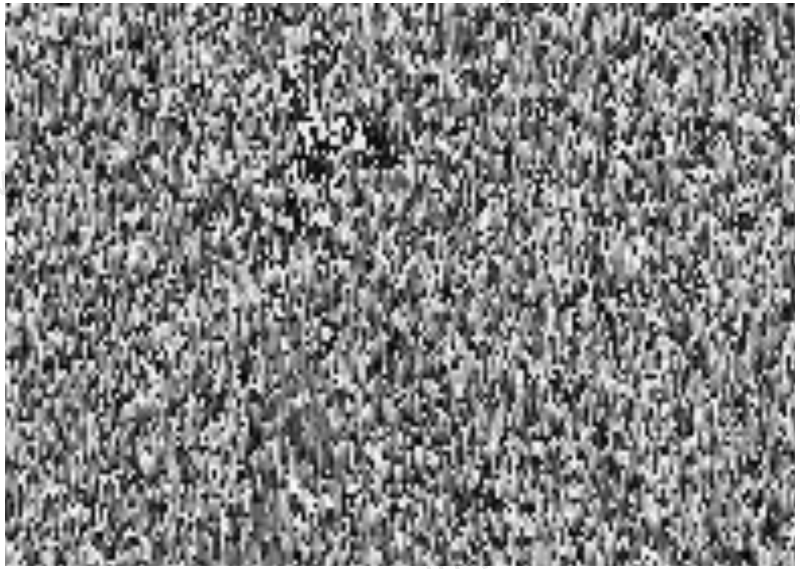
Where at anytime, $\omega T = \theta$

Radar Signal to Imaging

Amplitude and Phase (SAR Signal Characteristics)



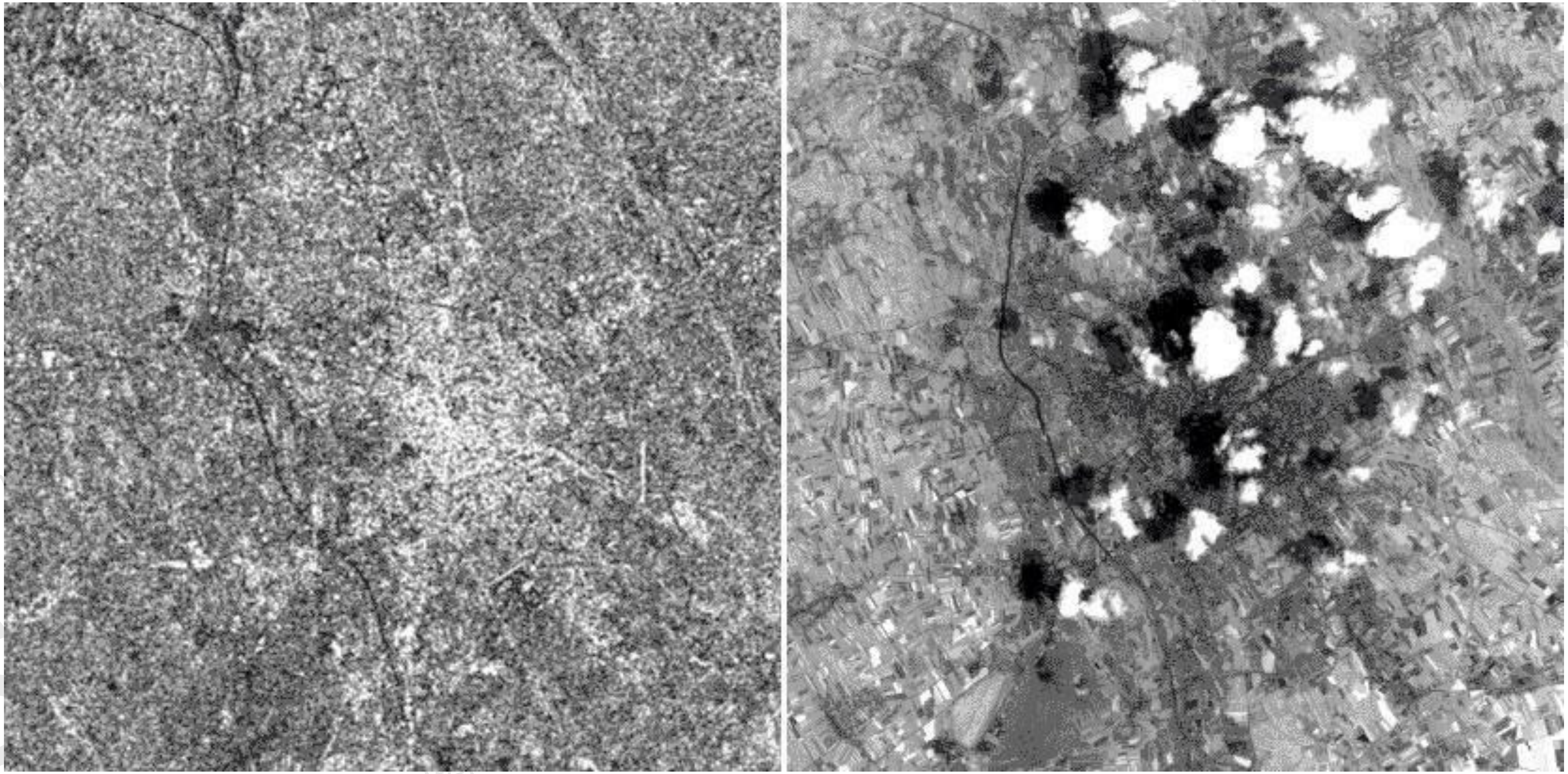
Amplitude (A)



Phase (Φ)

Amplitude (A): Strength of the radar response (Height of EM wave)
Intensity ($I = A^2$) = proportion of microwave backscattered from target to sensor
Phase (Φ) : Fraction of one complete sine wave (determined by the distance between the satellite antenna and the ground targets.

Example SAR image vs Multispectral Image



Images over the city of Udine, Italy by ERA-1 (left) & Landsat-5 (right)
Image acquisition: 4 July 1993, 9:59 a.m. (GMT) (Left) & 9:14 a.m (GMT)

Source: Salvatore G.P. Virdis (Aug 2019), AT 76.9073 Principles and Applications of InSAR, Satellite radar images,

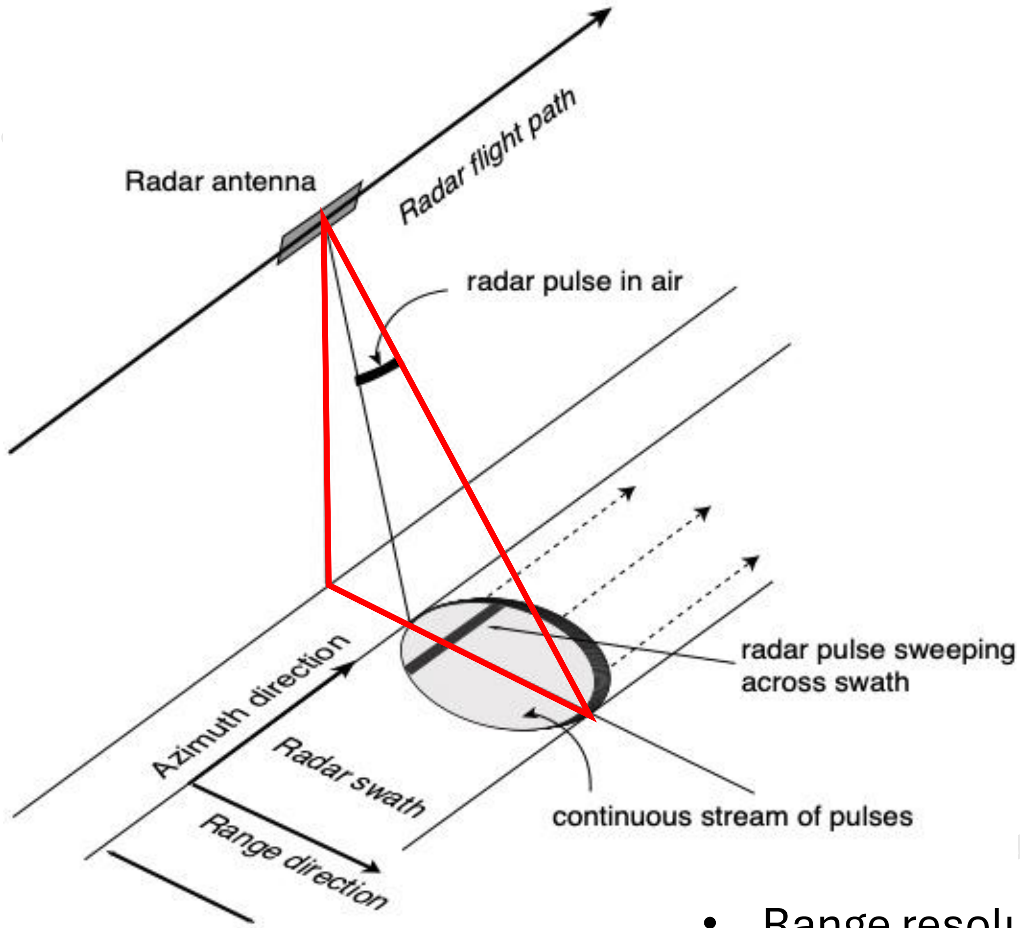
Radar Wavelengths

Band	Frequency (GHz)	Wavelength (cm)	Type Application
Ka	27 – 40 GHz	1.1 – 0.8	Rarely used for SAR (airport surveillance)
K	18 – 27 GHz	1.7 – 1.1	rarely used (H2O absorption)
Ku	12 – 18 GHz	2.4 – 1.7	rarely used for SAR (satellite altimetry)
X	8 – 12 GHz	3.8 – 2.4	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	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	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	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)
P	0.3 – 1 GHz	100 - 30	Biomass. First p-band spaceborne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR.

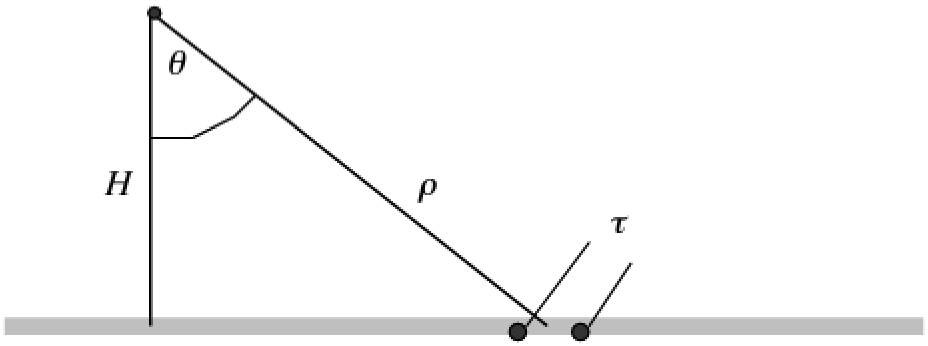
Source: https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar

SAR Geometric Properties

Range Resolution



Range Resolution (end view)



θ	-	look angle
H	-	spacecraft height
B	-	bandwidth of radar
τ	-	pulse length $1/B$
C	-	speed of light

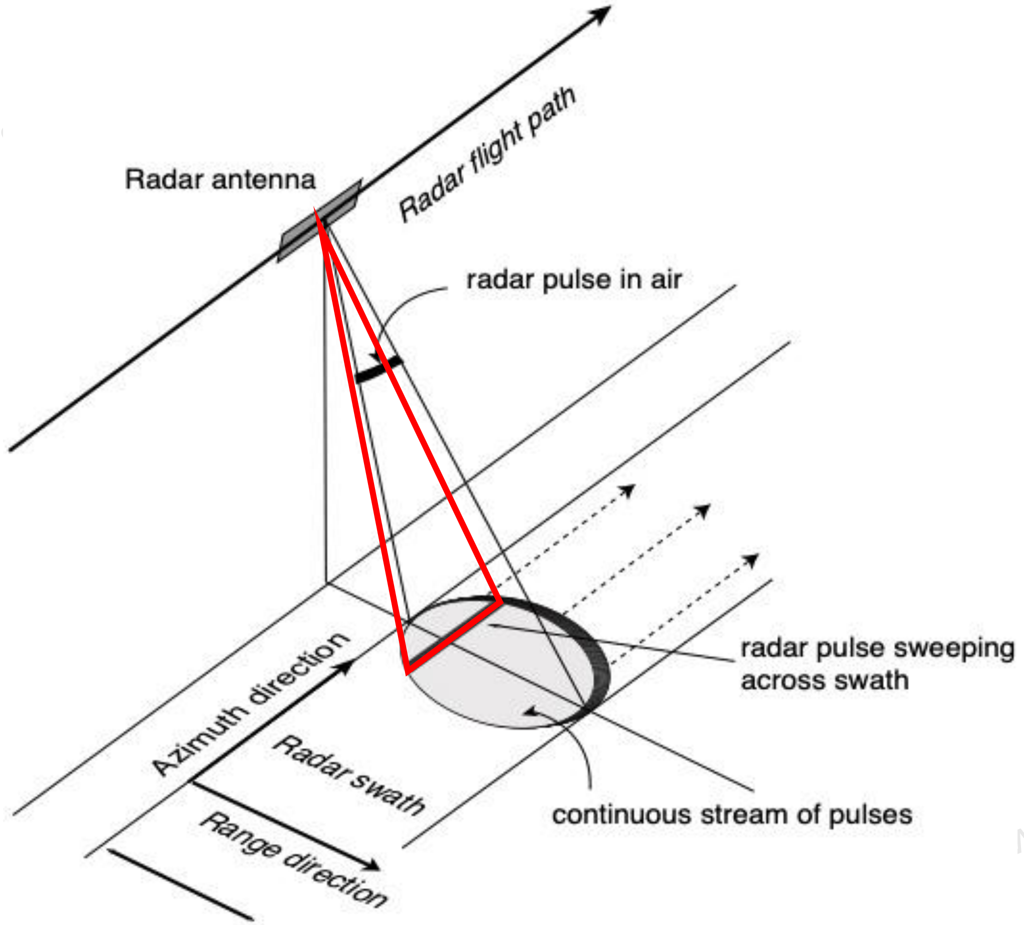
$$\Delta r = \frac{C\tau}{2}$$ - slant range resolution

$$R_r = \frac{C\tau}{2}\frac{1}{\sin\theta}$$ - ground range resolution

- Range resolution is infinite for vertical look angle, better as look angle increases.
- Height of platform is independent to range resolution.
- Increasing band width improves range resolution.

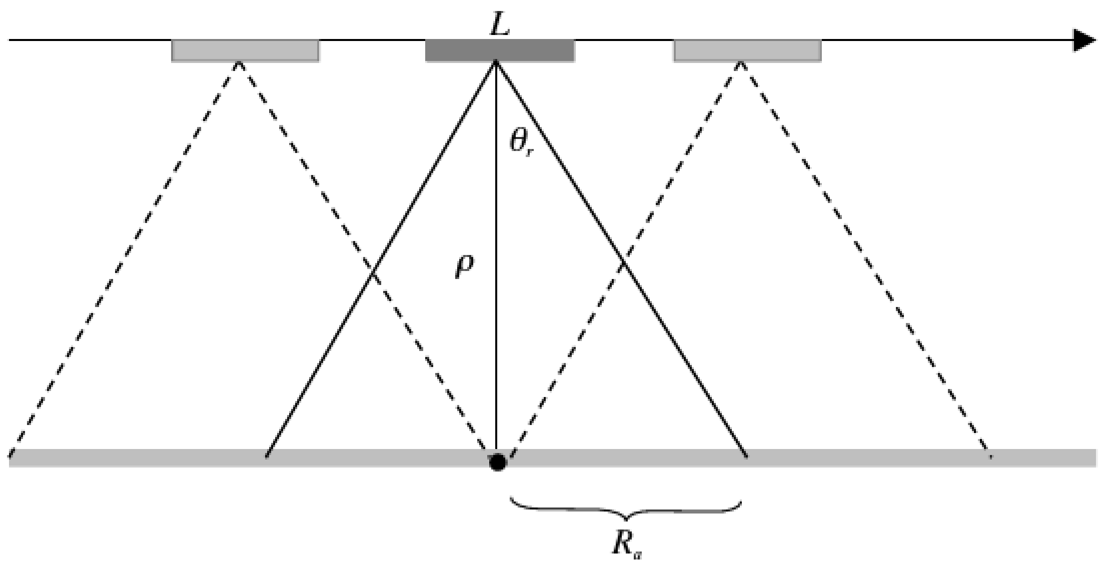
SAR Geometric Properties

Azimuth Resolution



Azimuth resolution is independent of height of spacecraft & and improves as height antenna is longer. In practice, we don't go constructing antenna like 20 km. (Frequency Modulation)

Azimuth Resolution (top view)



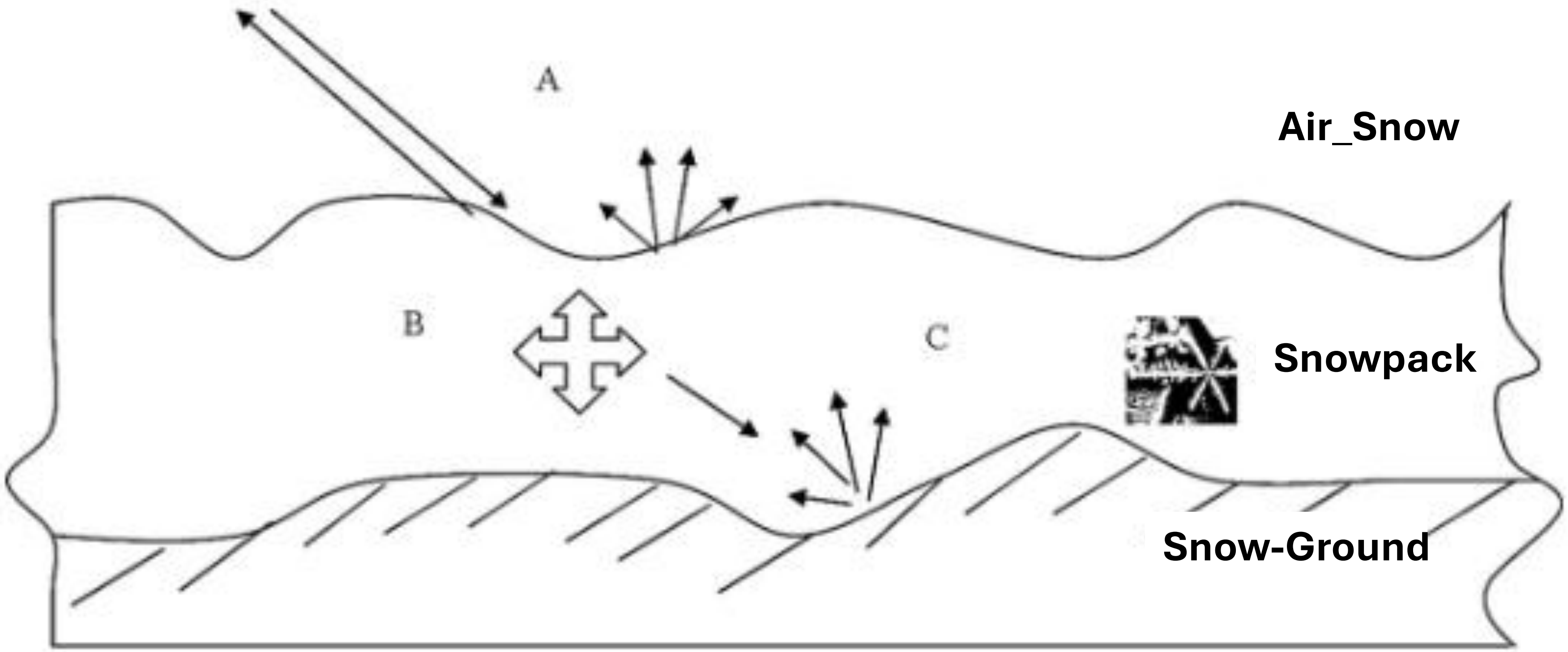
L	-	length of radar antenna
ρ	-	nominal slant range $H/\cos\theta$
λ	–	wavelength of radar

$\sin\theta_r = \lambda / L$ - diffration resolution

$R_a = \rho \sin\theta_r = \dfrac{\rho\lambda}{L} = \dfrac{\lambda H}{L\cos\theta}$ - half - length of ground illumination

$\boxed{R_a' = \dfrac{\lambda\rho}{2R_a} = \dfrac{L}{2} \quad \text{- theoretical resolution of strip - mode SAR}}$

What influences on radar Backscatter characteristics?

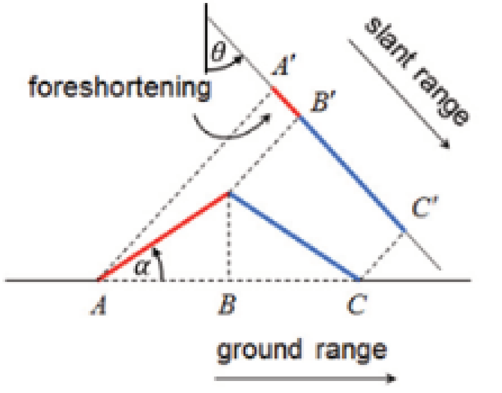


SAR Geometric Properties

Geometric distortions on SAR images

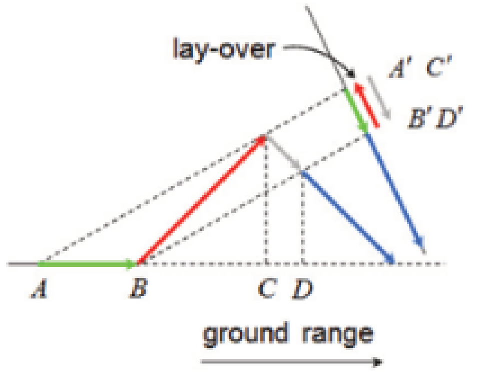
FORESHORTENING

- Sensor-facing slope foreshortened in image
- Foreshortening effects *decrease* with increasing look angle



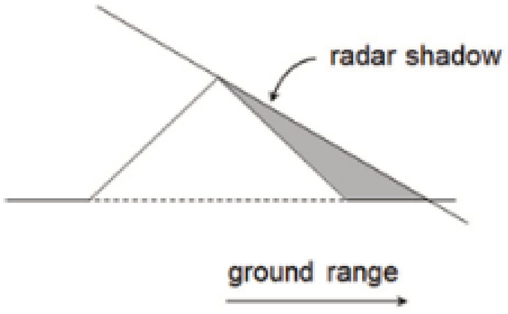
LAYOVER

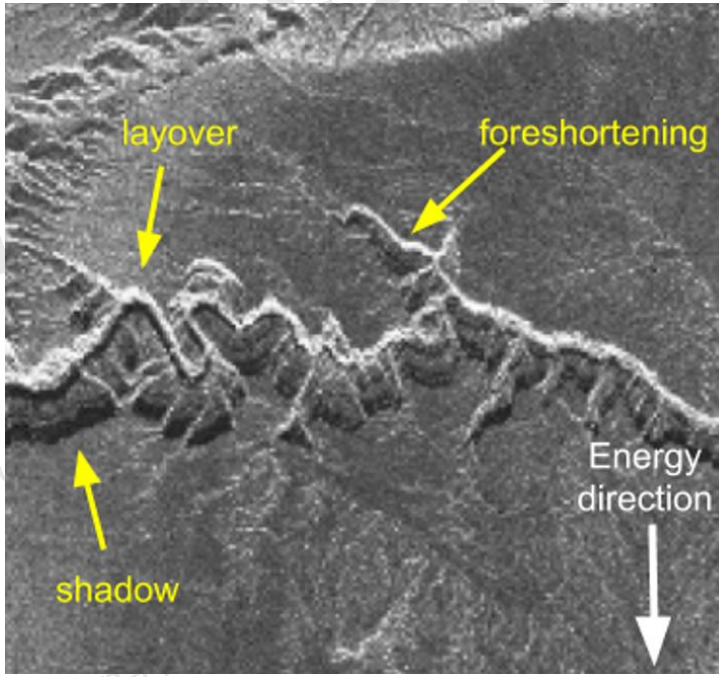
- Mountain top overlain on ground ahead of mountain
- Layover effects *decrease* with increasing look angle



SHADOW

- Area behind mountain cannot be seen by sensor
- Shadow effects *increase* with increasing look angle

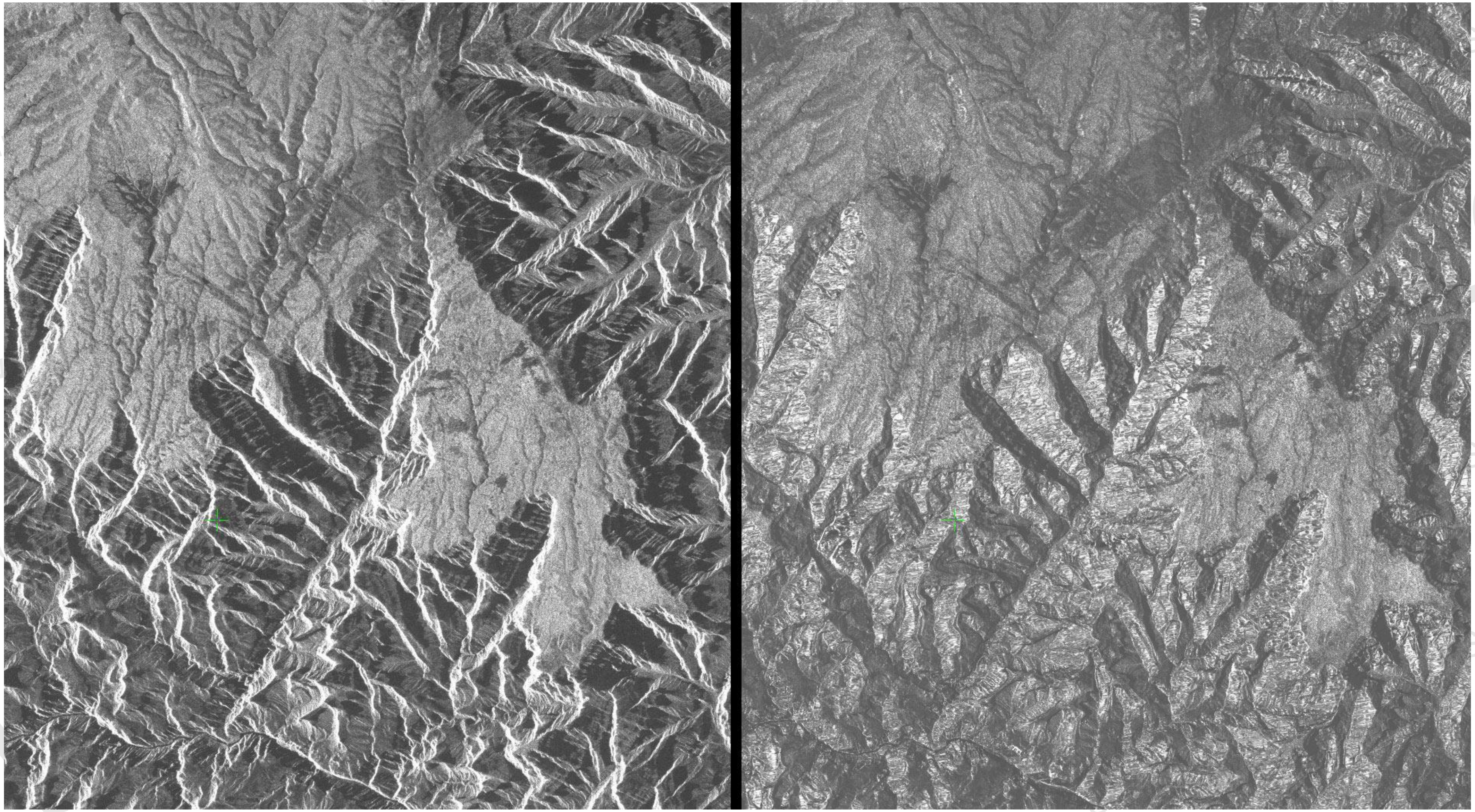




Examples of Geometric Effects in SAR Imagery (Image Credit: ERS, ESA 2011. Retrieved from ASF DAAC 20 January 2020.

Source: Flores,Anderson., Herndon, K. E., Thapa, R. B., & Cherrington, E. (2019). *THE SAR Comprehensive Methodologies for Forest*. 307. https://doi.org/10.25966/nr2c-s697
https://www.capellaspace.com/sar-101-an-introduction-to-synthetic-aperture-radar/

Terrain Correction SAR images



These two images of part of the Grand Canyon are processed from the samePALSAR data. The image on the left is uncorrected. The image on the right is terrain-corrected. In the uncorrected image, the sides ofthe canyon appear to be stretched on one side andcompressed onthe other side. ASFDAAC 2014; Includes Material ©JAXA/METI 2008. https://www.asf.alaska.edu/sar-data/palsar/terrain-corrected-rtc/

Source: G.P Salvadore Virdis (2019): AT 76.9037 Principles and Applications of InSAR; Satellite radar images.

SAR Geometric Properties

Look angle and Incidence Angle

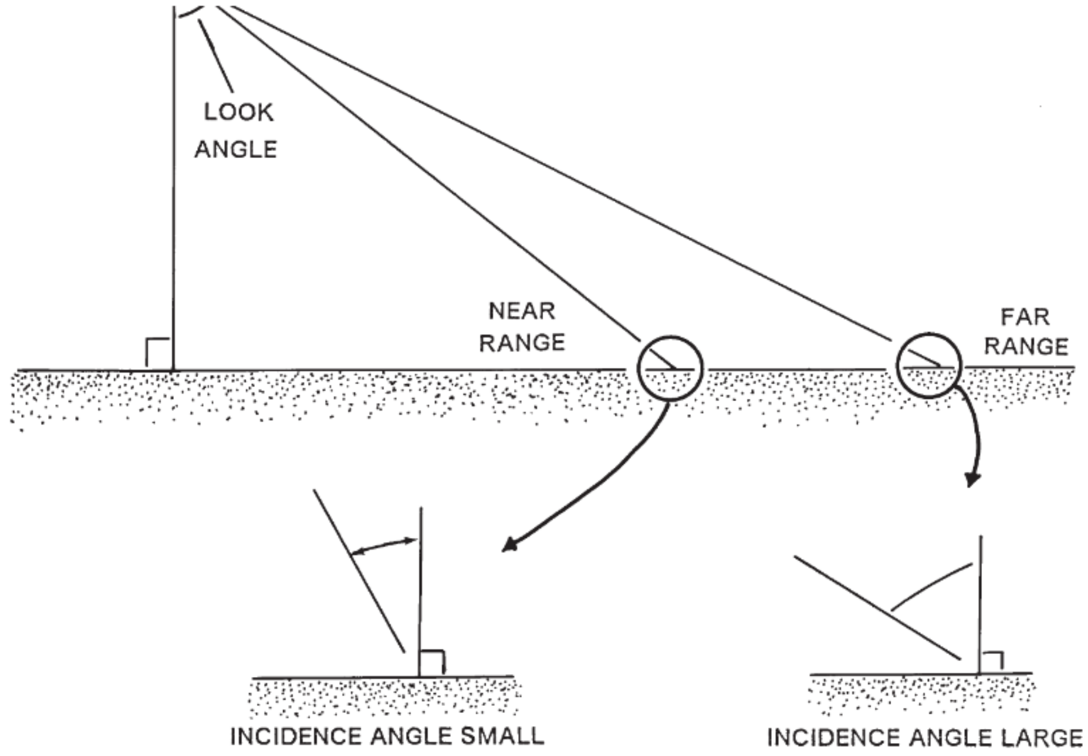
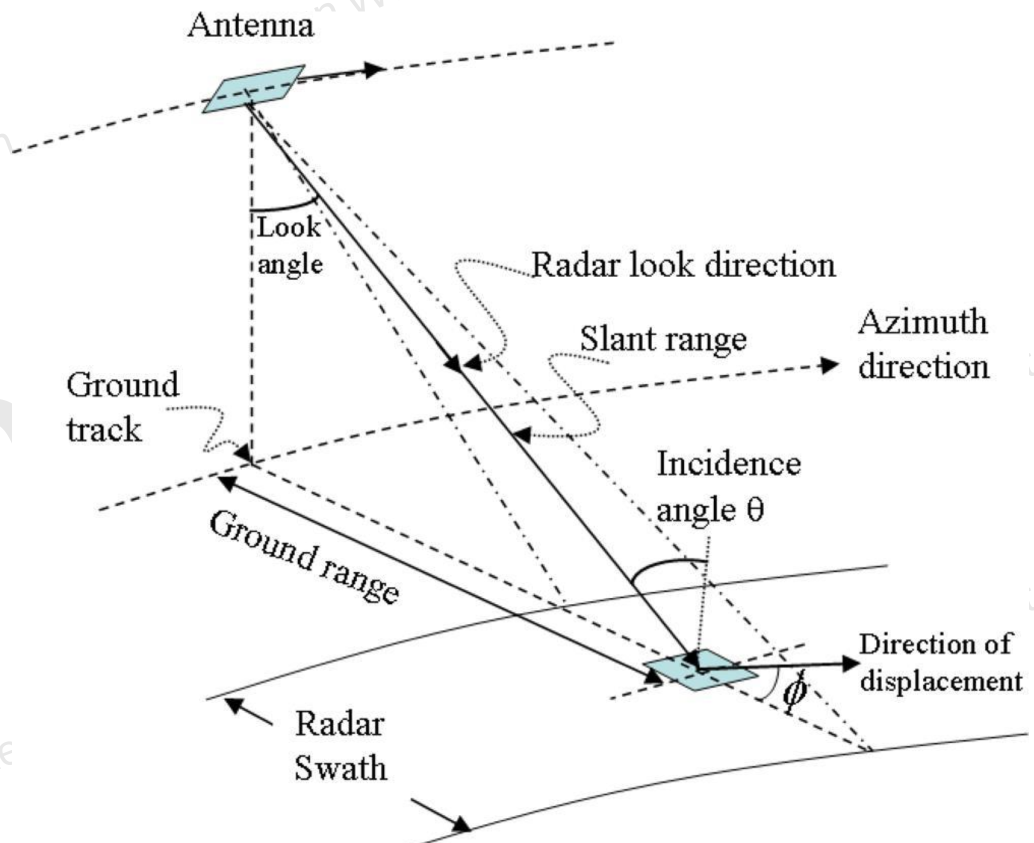


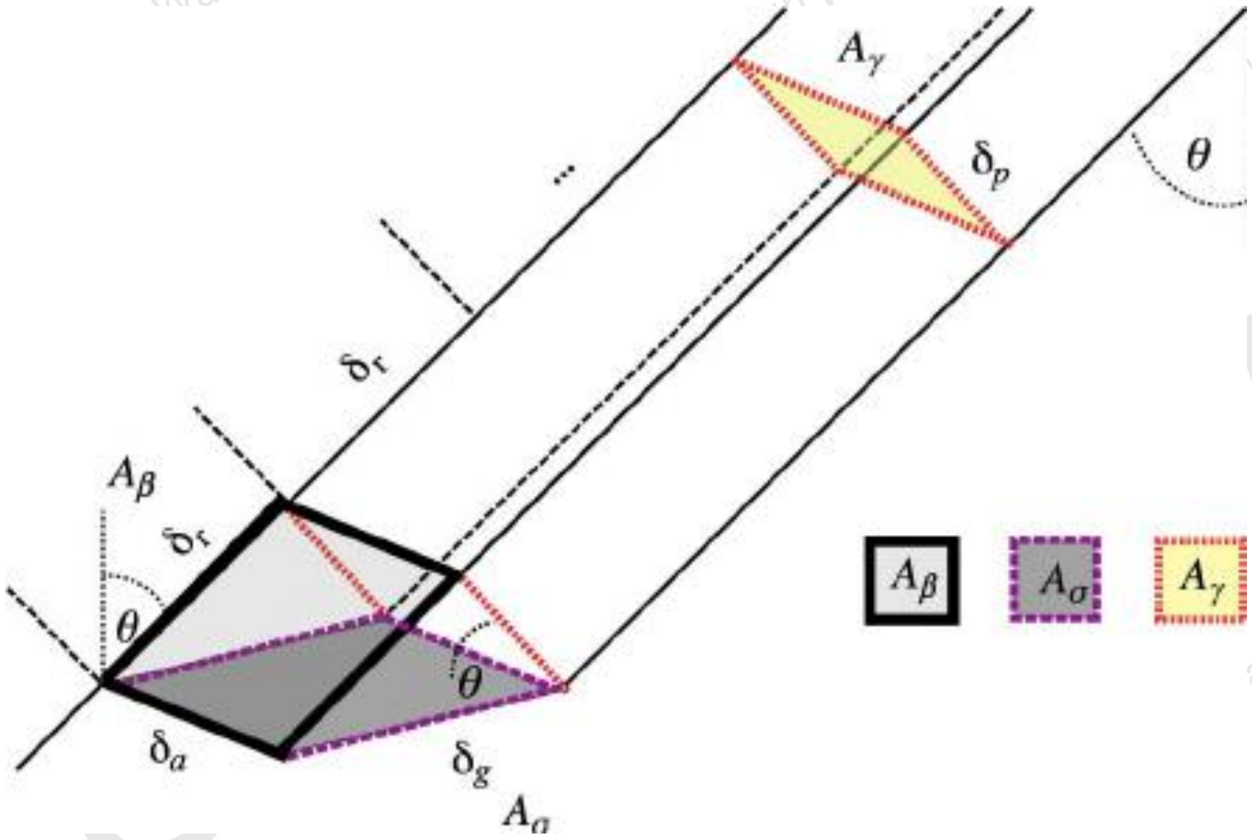
FIGURE 7.11. Look angle and incidence angle.



Source: G.P Salvadore Virdis (2019): AT 76.9037 Principles and Applications of InSAR; Satellite radar images.

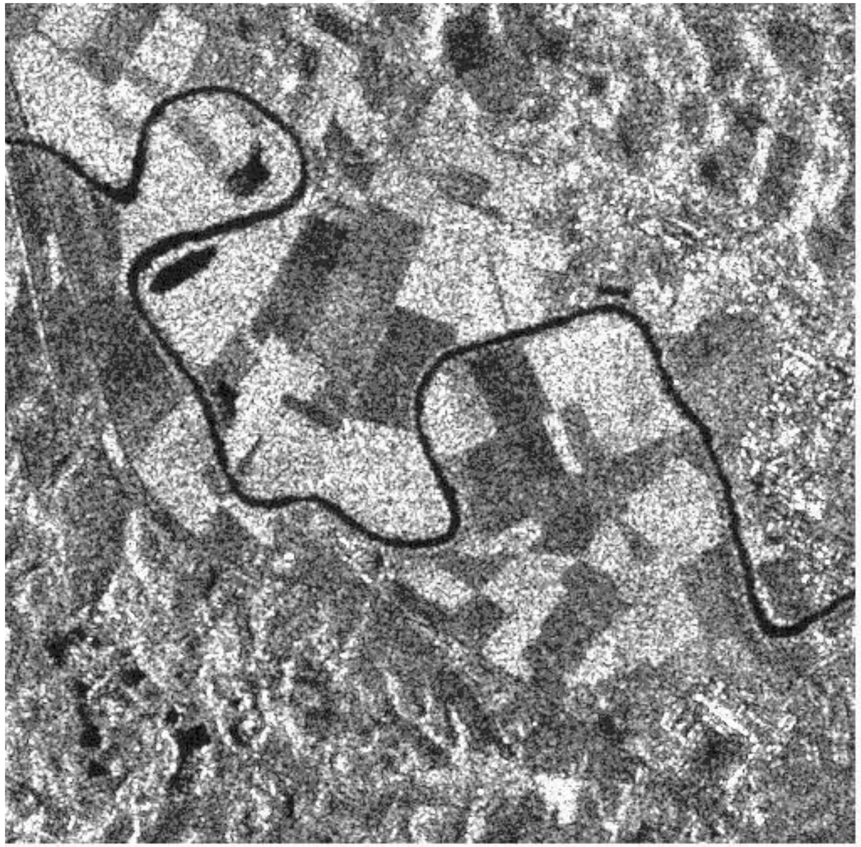
Types of Radar Backscatter Geometry

Normalized Backscatter

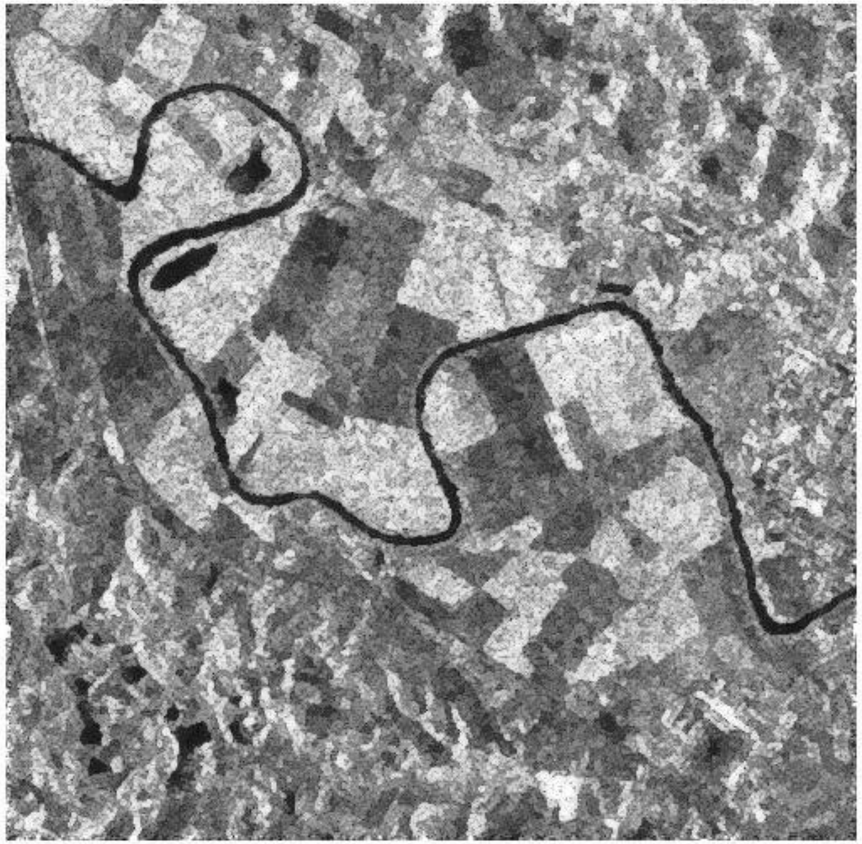


- Gamma ($\gamma_\circ$) : normalized to an area perpendicular to the line of sight.
- Beta ($\beta_\circ$): normalized to an area defined in slant range plane
- Sigma ($\sigma_\circ$):normalized to an area perpendicular to the line of sight.

Speckle Effect



Original



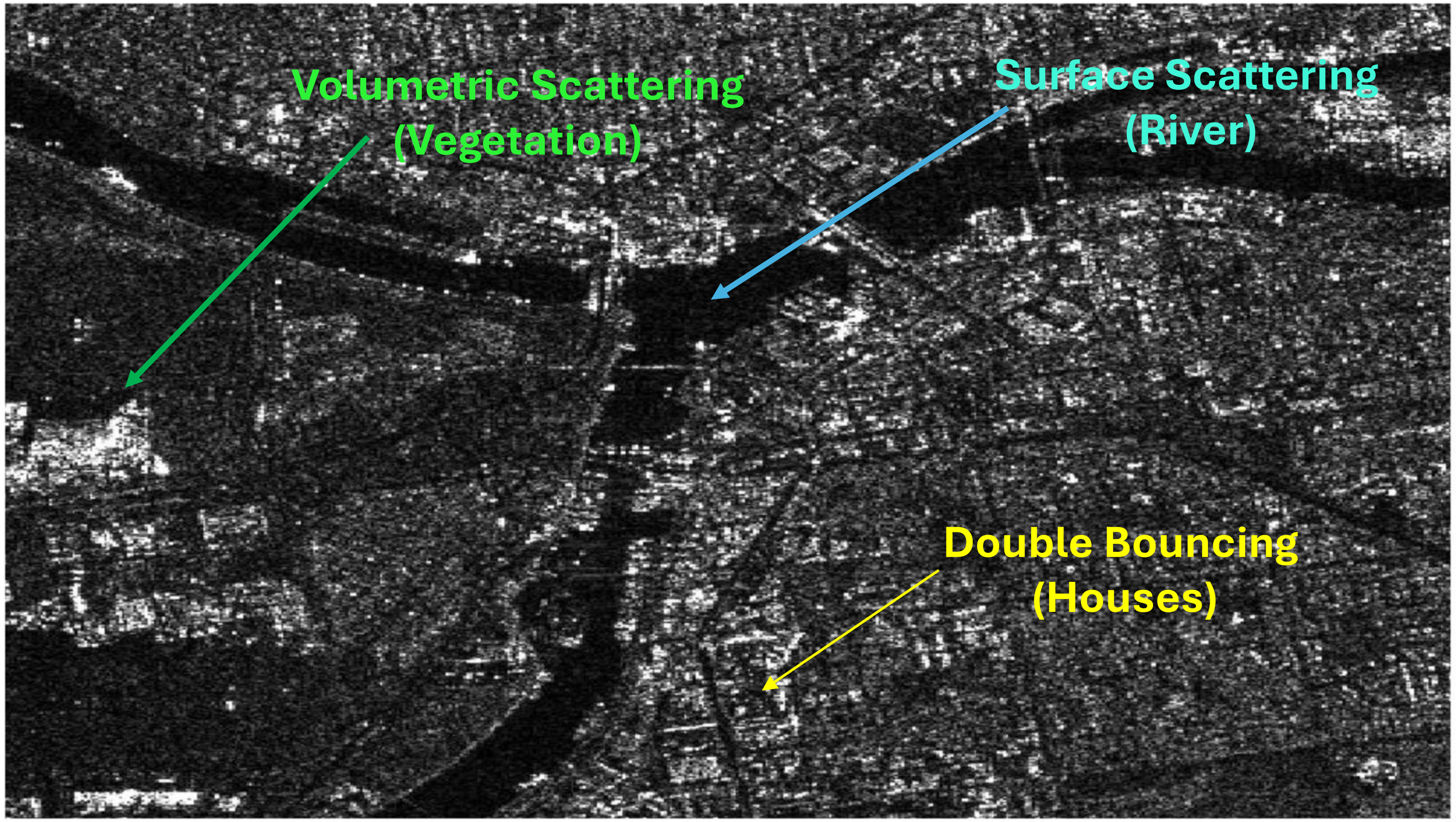
Removing Speckle Effects

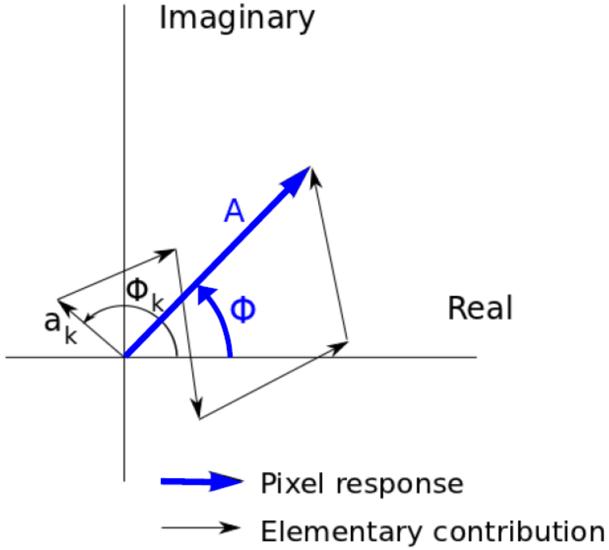
Speckle occurs due to occurrence of individual scatters in each pixels combining positive and negative interferences (salt-and-pepper) effect.

This causes otherwise uneven backscatter return, because generally SAR is a coherent imaging method.

Source: G.P Salvadore Virdis (2019): AT 76.9037 Principles and Applications of InSAR; Satellite radar images.

Scattering Mechanism of SAR Data

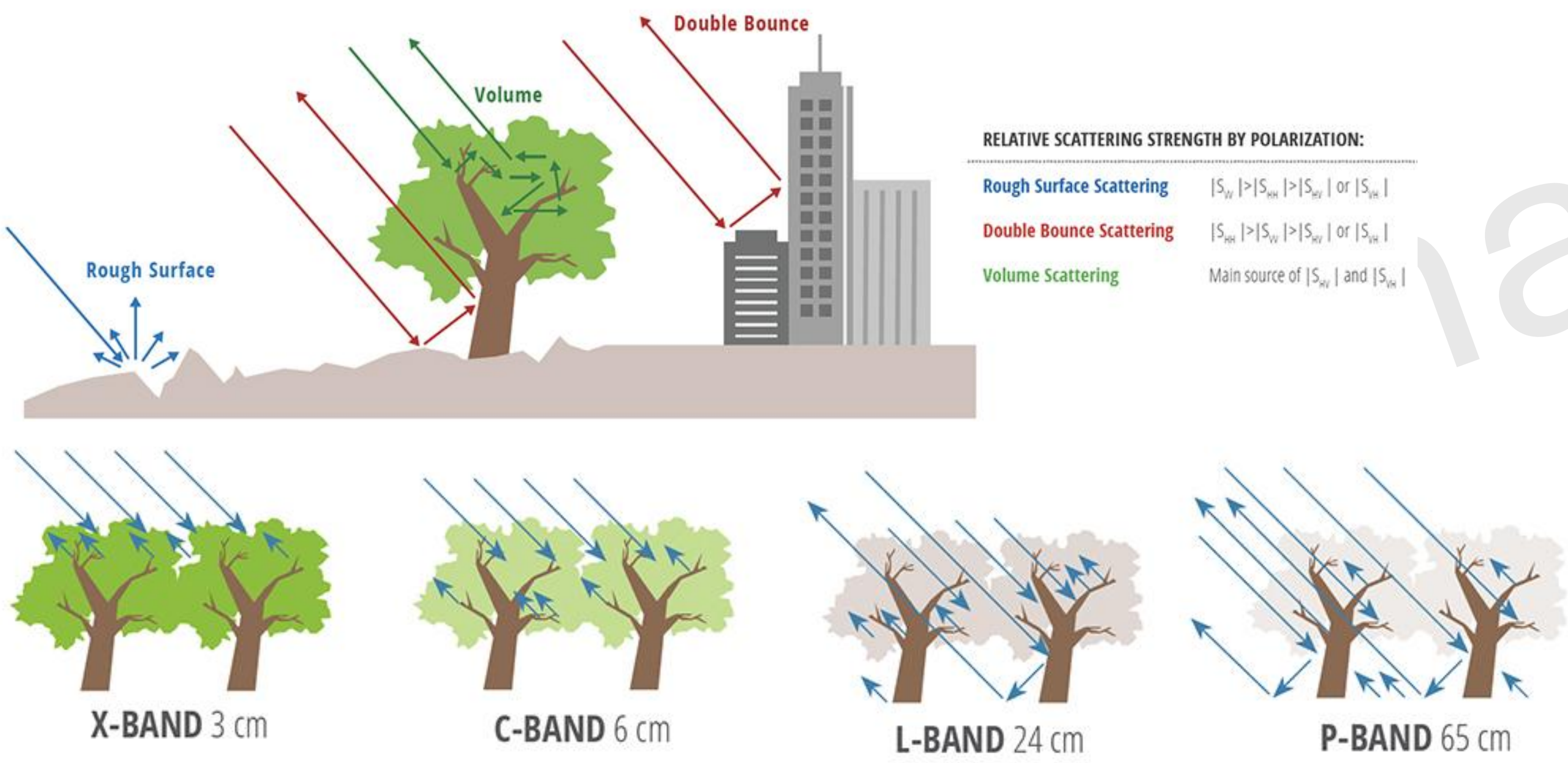




single look image detected by the Sentinel-1 mission.

Source: Lattari F, Gonzalez Leon B, Asaro F, Rucci A, Prati C, Matteucci M. Deep Learning for SAR Image Despeckling. Remote Sensing. 2019; 11(13):1532.
https://doi.org/10.3390/rs11131532

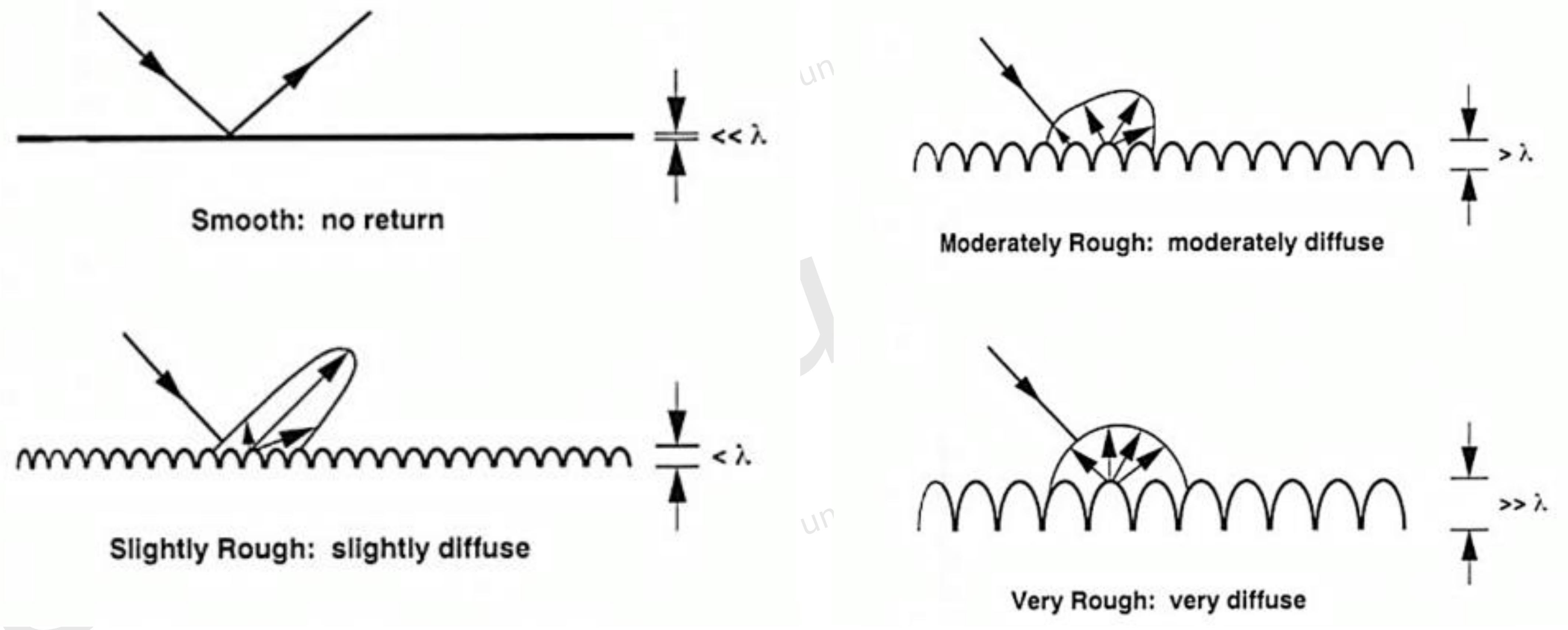
Radar Scattering and Radar Wavelength



- Depending on the wavelength of radar wave, the backscatter signal mechanism back to sensor will have different influences.
- But then, the type of the Earth's object also plays some role in backscatter.
- Penetration is controlled by wavelength type and object type.

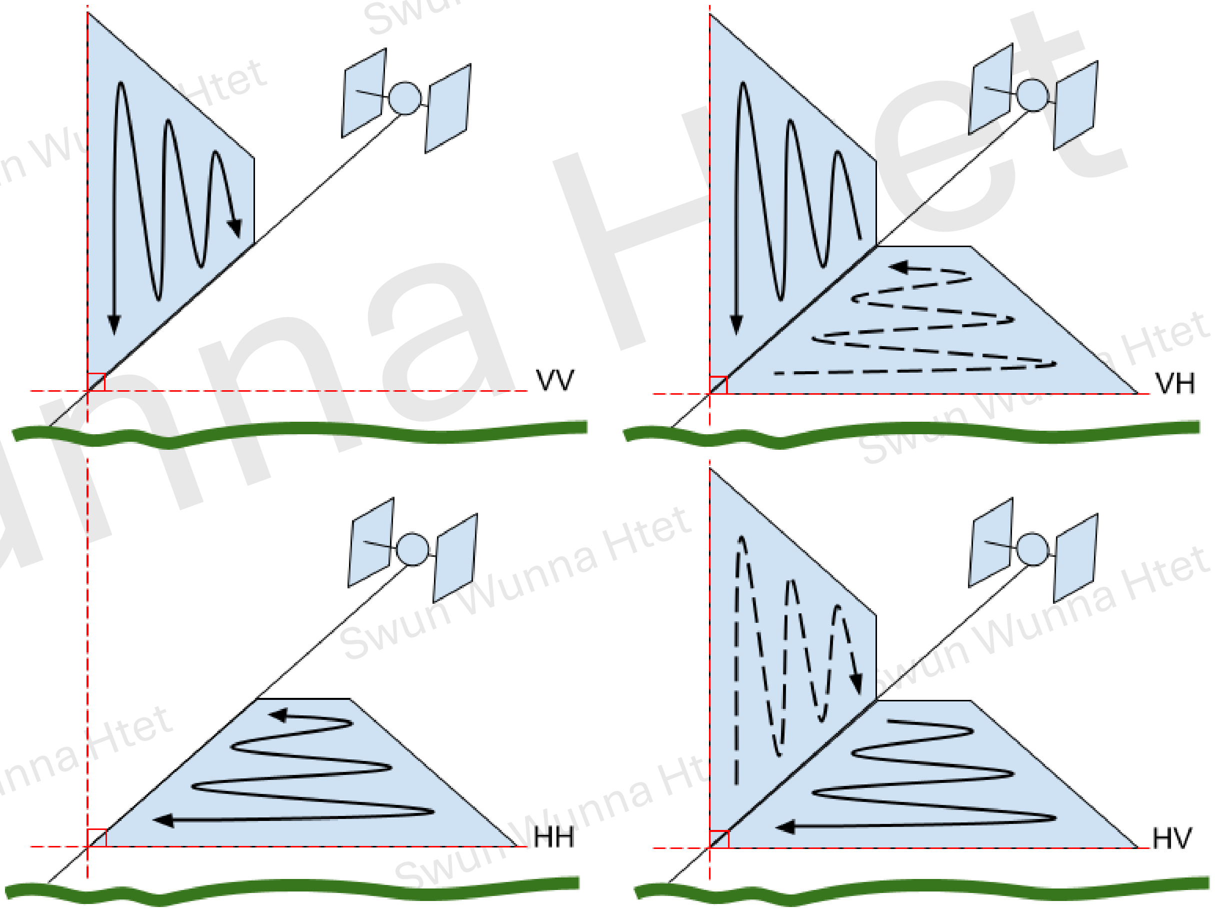
Source: https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar

Surface Roughness can influence backscatter values too



Radar Polarization

- Polarization = orientation of the plane in which the transmitted electromagnetic wave oscillates.
- Four types:
  - VV
  - VH
  - HV
  - HH
    - *Note: V = Vertical, H = Horizontal.*
    - *1st element of pair = Transmit; 2nd element of pair = Receive*



Source: *https://hyp3-docs.asf.alaska.edu/guides/introduction_to_sar/*

Interferometric SAR (InSAR)

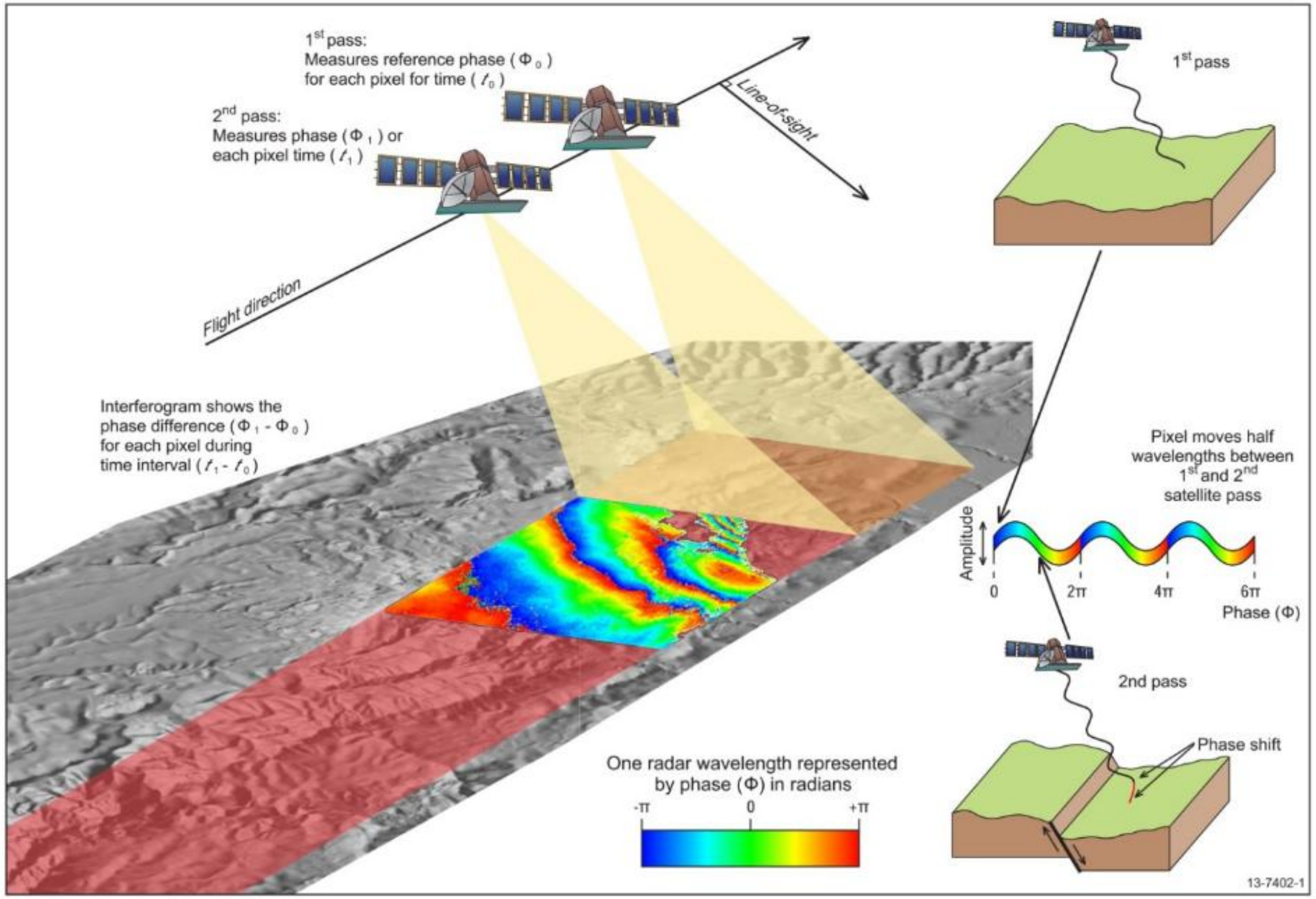


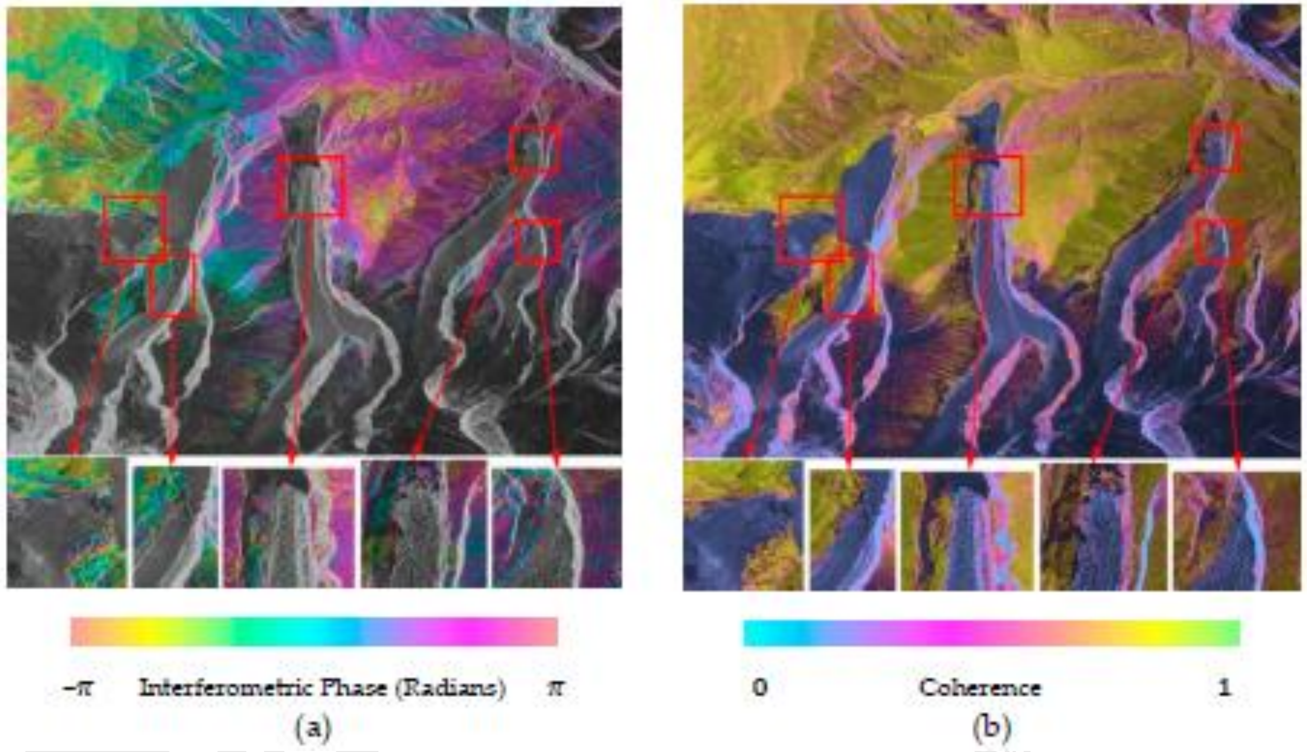
Figure 1.1: Cartoon depiction of the InSAR methodology. Two SAR images of the same area are acquired at different times. If the surface moves between the two acquisitions a phase shift occurs and an interferogram maps this phase difference.

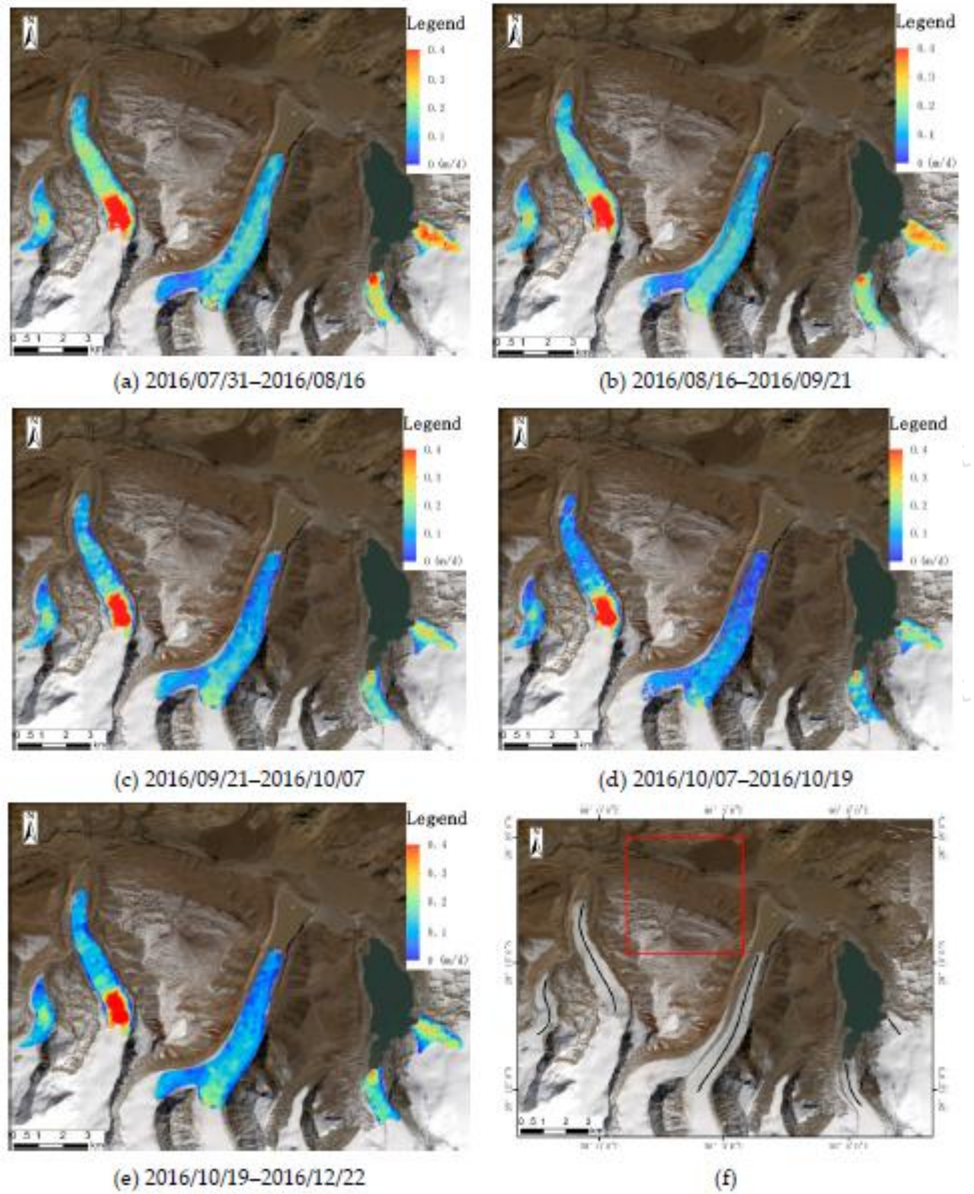
- Advantages: detect vertical displacement
- Disadvantages: vertical movement could also be from ground deformation

Source: Garthwaite, M. C., Nancarrow, S., Hislop, A., Thankappan, M., Dawson, J. H., & Lawrie, S. (2015). The Design of Radar Corner Reflectors for the Australian Geophysical Observing System: a single design suitable for InSAR deformation monitoring and SAR calibration at multiple microwave frequency bands. In Australian Gov Report (Issue April). https://doi.org/10.11636/Record.2015.003

Example: Glacial Surface Velocity

From InSAR





Source: Fan, J., Wang, Q., Liu, G., Zhang, L., Guo, Z., Tong, L., Peng, J., Yuan, W., Zhou, W., Yan, J., Perski, Z., & Sousa, J. (2019). Monitoring and Analyzing Mountain Glacier Surface Movement Using SAR Data and a Terrestrial Laser Scanner: A Case Study of the Himalayas North Slope Glacier Area. *Remote Sensing*, *11*(6), 625.

Application of Radar Images in Cryosphere Studies

- Snowmelt mapping
- Snow Water Equivalent (SWE)
- Glacier Dynamics/ mass balance changes

Available SAR satellites

Table 8
SAR satellite systems.

Name	Launch	Country	Tandem option	Band	Polarization	Resolution range (m)	Swath width (km)	Orbit repeat cycle (day)
ERS-1	1991	EU	ERS-2	C	VV	30–26	102–84	35
ERS-2	1995	EU	ERS-1 and EnviSat	C	VV	30–26	102–84	35
EnviSat	2002	EU	ERS-2	C	VV, HH, VV + HH, HH + HV, VV + VH	28 × 28 950 × 980	5–400	35
RADARSAT-1	1995	Canada	RADARSAT-2	C	HH	8–100	45–500	24
RADARSAT-2	2007	Canada	RADARSAT-1	C	HH, VV, HV, VH (single, dual or quad)	3 × 1 100 × 100	18–500	24
ALOS	2006	Japan	No	L	HH, VV, HH + HV, VV + VH, HH + HV + VV + VH	7–100	30–450	46
ALOS-2	2014	Japan	No	L	HH, VV, HV, HH + HV, VV + VH, HH + HV + VV + VH	3 × 1 100 × 100	25–350	14
TerraSAR-X	2007	Germany	TanDEM-X	X	HH, VV, HV, VH (single or dual)	1 × 1 16 × 16	5 × 10–1500 × 100	11
TanDEM-X	2010	Germany	TerraSAR-X	X	HH, VV, HV, VH (single or dual)	1 × 1 16 × 16	5 × 10–1500 × 100	11
KOMPSAT-5	2013	South Korea	No	X	HH, HV, VH, VV	1–20	5–100	28
Sentinel-1	2014	EU	Twin sat in 2016	C	HH, VV, HH + HV, VV + VH	5 × 5 25 × 40	20–400	12

HH: Horizontal transmit and Horizontal receive, VV: Vertical transmit and Vertical receive, HV: Horizontal transmit and Vertical receive, VH: Vertical transmit and Horizontal receive.

Notice that the SAR systems revisit time might not be enough for snow monitoring procedure.

But it has its snow applications

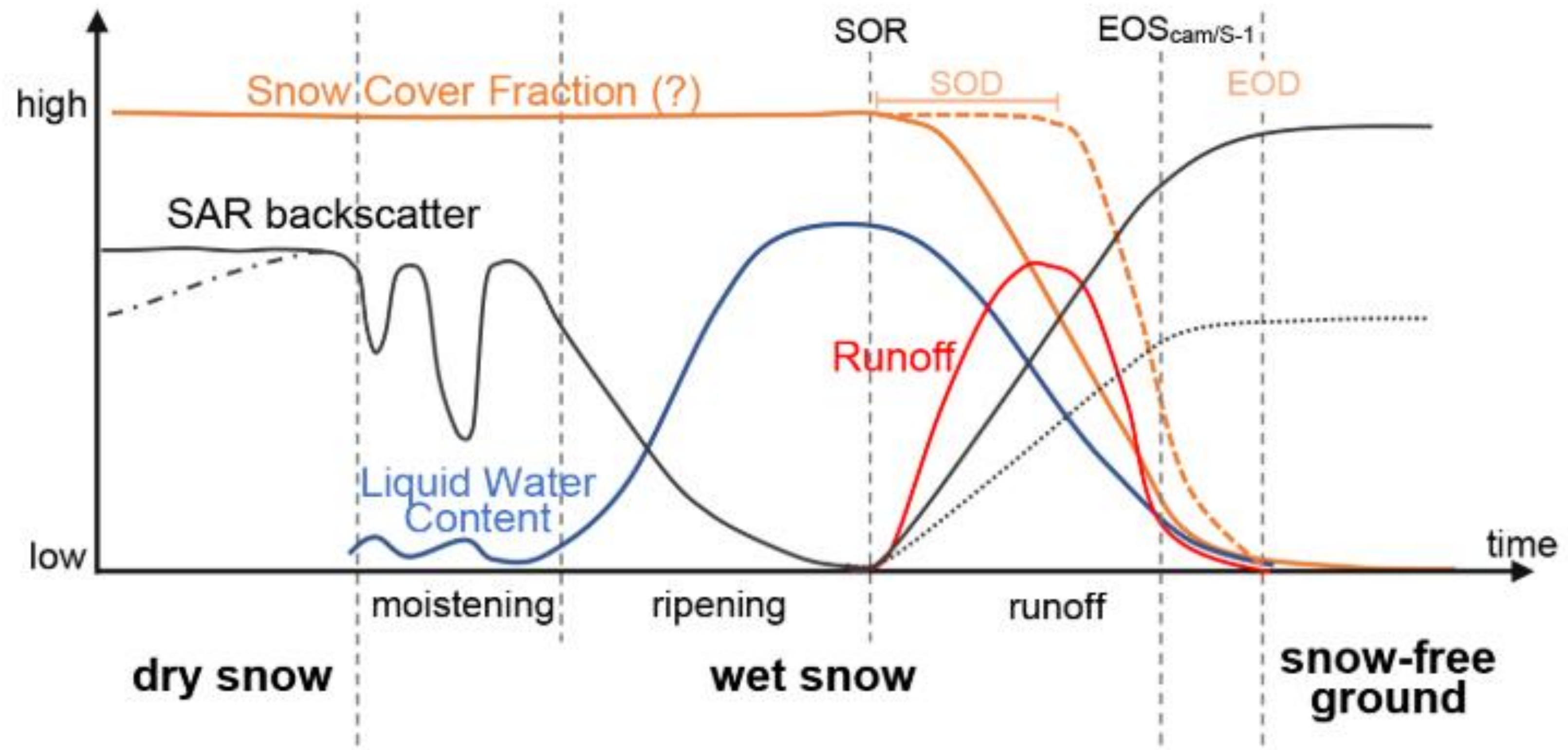
Multispectral vs Microwave

Which is more advantageous?

Type of Remote Sensing	**Advantages**	**Disadvantages**
Multispectral	• A variety of temporal revisit (from daily to 16 days) • Snow visible within spectral range • Physics behind is quite well-studied.	• Coarser spatial resolution (Not for commercial satellites) • Atmosphere correction required. • Cloud, shadow cover. • Limited for snow grain size researches. • Confusion between snow, ice and cloud
Microwave	• Cloud penetration/ no effect by weather condition • Day or night • Finer spatial resolution • Substantial ground penetration • Polarization (V and H component) • Interferometry possible.	• Image geometry • **Low** temporal resolution • Speckle effect • Sensitive to moisture, water content in the ground. • Required detailed understanding of radar system.

Backscatter vs liquid water content (Snow Hydrology Application)

Buchelt, S., Skov, K., Rasmussen, K. K., & Ullmann, T. (2022).



Schematic illustration of seasonal evolution of synthetic aperture radar (SAR) backscatter intensity above snow with corresponding snow phases and properties

Source: Buchelt, S., Skov, K., Rasmussen, K. K., & Ullmann, T. (2022). Sentinel-1 time series for mapping snow cover depletion and timing of snowmelt in Arctic periglacial environments: case study from Zackenberg and Kobbefjord, Greenland. *The Cryosphere*, *16*(2), 625–646. https://doi.org/10.5194/tc-16-625-2022

Available SAR-specific toolboxes

Applications and softwares (Free)

- **MapReady**: Developed by the Alaska Satellite Facility. More information and download: https://asf.alaska.edu/how-to/data-tools/asf-mapready/ .
- Sentinel Application Platform
- **(SNAP):** Developed by ESA. More information and download: http://step.esa.int/main/download/
- **PolSARpro**—Developed by ESA. More infor- mation and download: https://earth.esa.int/web/polsarpro/home.

Practical – 5: Snow Wetness Detection Using Sentinel-1 SAR Data Product

Overall methodology

Nagler's Method

- Select two SAR images
  - One sensed during snow covered period (WS)
  - Reference which is snow free or dry-snow period (suggested to acquire scene under dry snow conditions recorded during wintertime). (RF)
- Create a ratio map
  - $\frac{\sigma_{WS}^0}{\sigma_{RF}^0} < -3dB,\ wet\ snow$, otherwise, it's termed as dry snow.

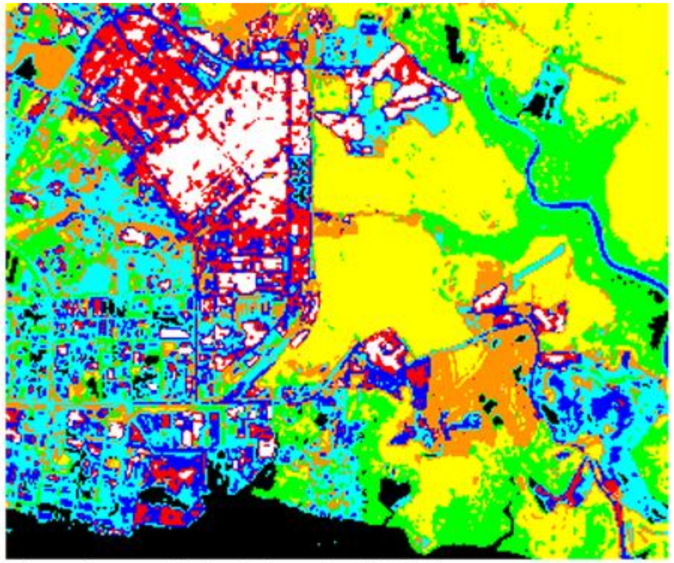
Practical –6: Supervised image classification for glaciers using GEE and Machine Learning Technique

Image Classification (to LULC Map)

- The routines for remote sensing will never be fulfilled without land cover/ land use (LULC) classification which can be managed through the process of image classification.

From this SPOT multispectral imagery

into this thematic map



Source: Al-doski, J., Mansor, S. B., Zulhaidi, H., & Shafri, M. (2013). *Image Classification in Remote Sensing*. 3(10), 141–148. https://www.iiste.org/Journals/index.php/JEES/article/download/7807/7873

Land Cover and Land Use

- Land = service provider as basis for biological and human activities (Agriculture, forestry, economic resource)
- Land cover = physical cover such as grassland, forest, bare land, water bodies)
- Land use = the defined area with its related socio-economic purpose (pasture, mining, agricultural fields, PA)



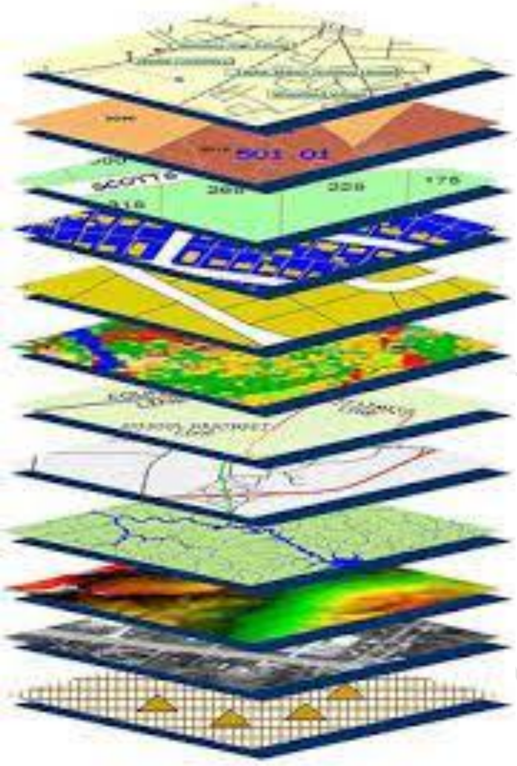

Salwa Thasveen, M., & Suresh, S. (2021). Land - Use and Land - Cover Classification Methods: A Review. *2021 Fourth International Conference on Microelectronics, Signals & Systems (ICMSS)*, 1–6. https://doi.org/10.1109/ICMSS53060.2021.9673623

Agilandeeswari, L., Prabukumar, M., Radhesyam, V., Phaneendra, K. L. N. B., & Farhan, A. (2022). Crop Classification for Agricultural Applications in Hyperspectral Remote Sensing Images. *Applied Sciences*, *12*(3), 1670. https://doi.org/10.3390/app12031670

Al-doski, J., Mansor, S. B., Zulhaidi, H., & Shafri, M. (2013). *Image Classification in Remote Sensing*. *3*(10), 141–148. https://www.iiste.org/Journals/index.php/JEES/article/download/7807/7873

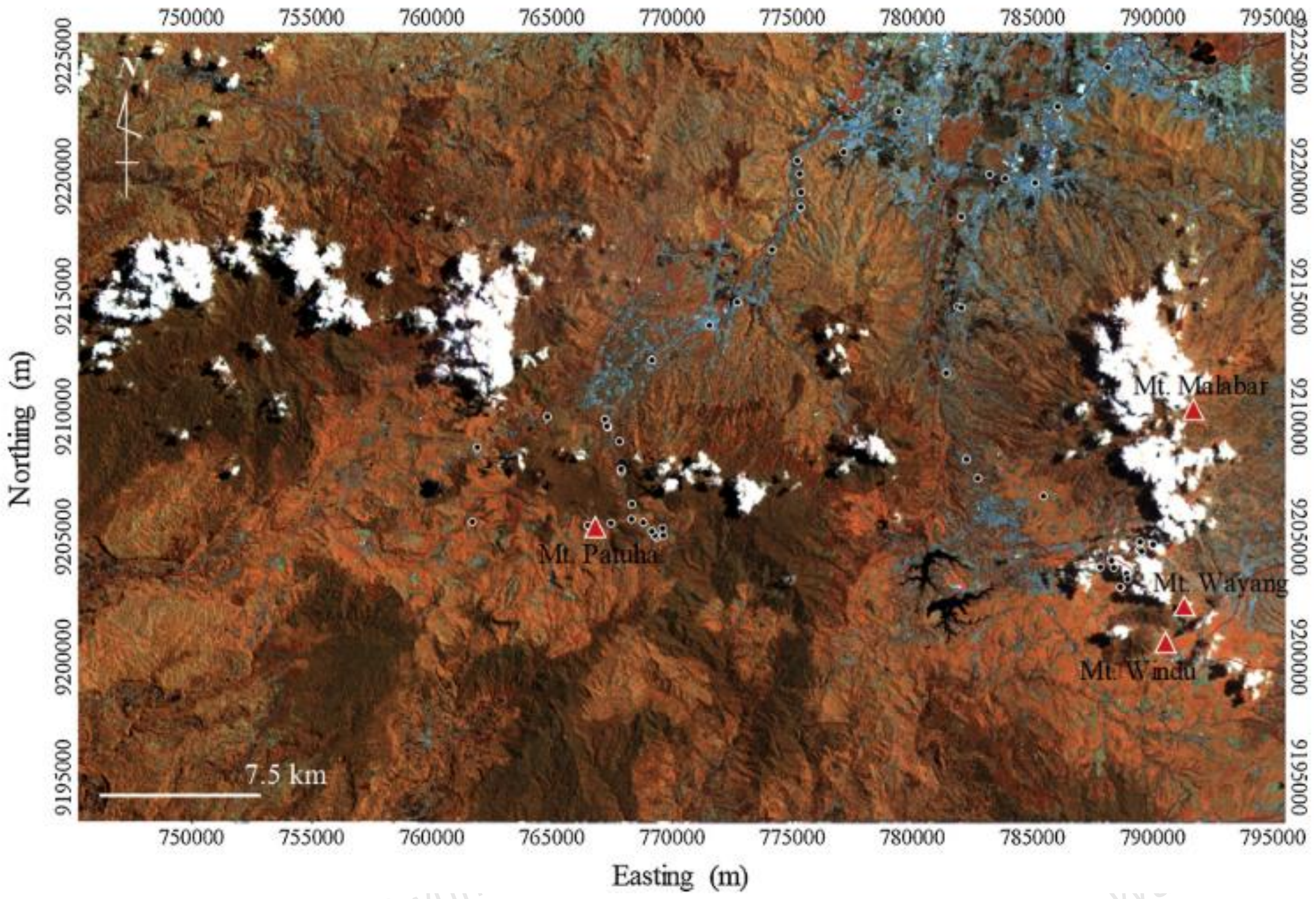
Applications of LULC Data

- Socioeconomic Development
- Policy Development
- Environmental Sustainability
- Disaster Management
- Planning & Management
- Agriculture



https://www.satpalda.com/blogs/significance-of-land-use-land-cover-lulc-maps#:~:text=LULC%20maps%20has%20there%20wide,help%20of%20other%20geospatial%20datasets.

Cloud Contamination in Satellite Imagery



- Except for SAR imagery, cloud contamination cannot be ignored in multispectral and hyperspectral imagery.
- Cloud masking (removal of cloud pixels) is one of the processing steps to process.

Type of LULC Classification

Supervised Classification

- Training data input defined by users.
- Training classifier to classify the input image.
- Computation time versus number of features.
- Prior user knowledge of the input training data property.

Unsupervised Classification

- No training data input.
- Clustering pixels related to each other from input image and assign classes as outputs.
- Generally, the accuracy is less than supervised method.

Classification Algorithms

Supervised Classification

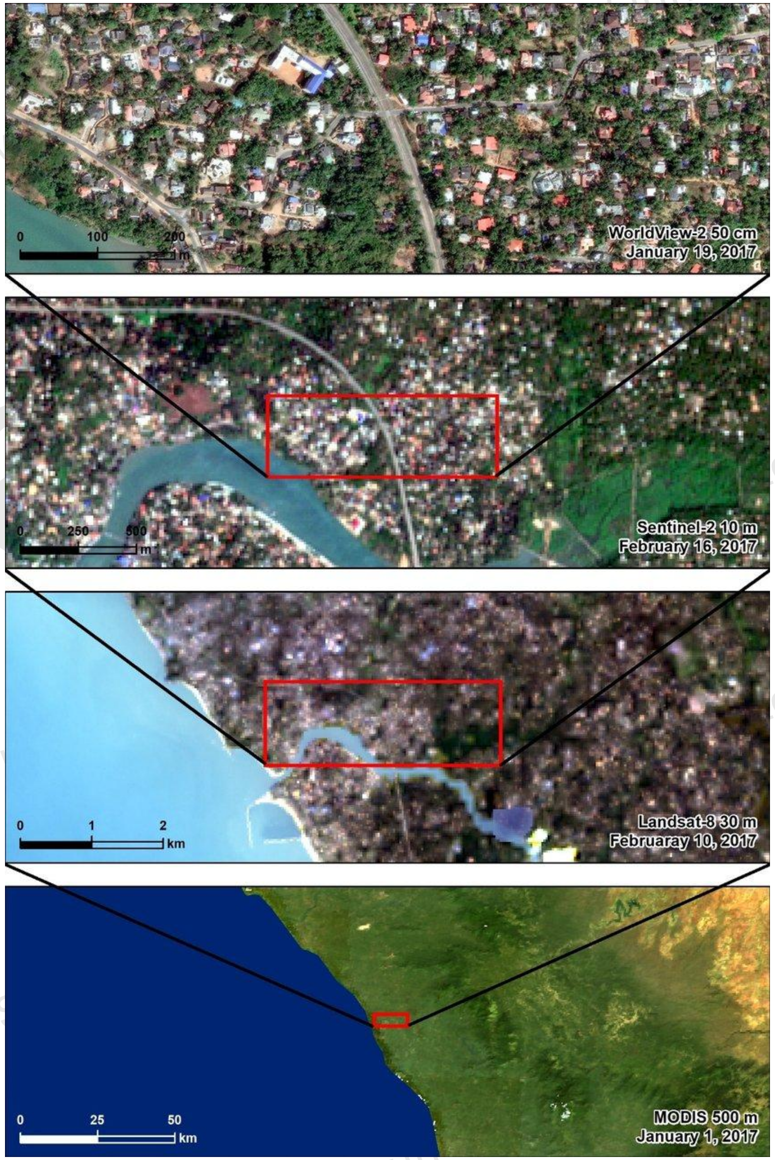
- Random Forest (GEE)
- Maximum Likelihood
- Support Vector Machine (SVM)
- Parallelepiped Method
- Minimum Distance

Unsupervised Classification

- K-Mean Algorithm (GEE)
- ISODATA Clustering

Training Data Preparation for Supervised Classification

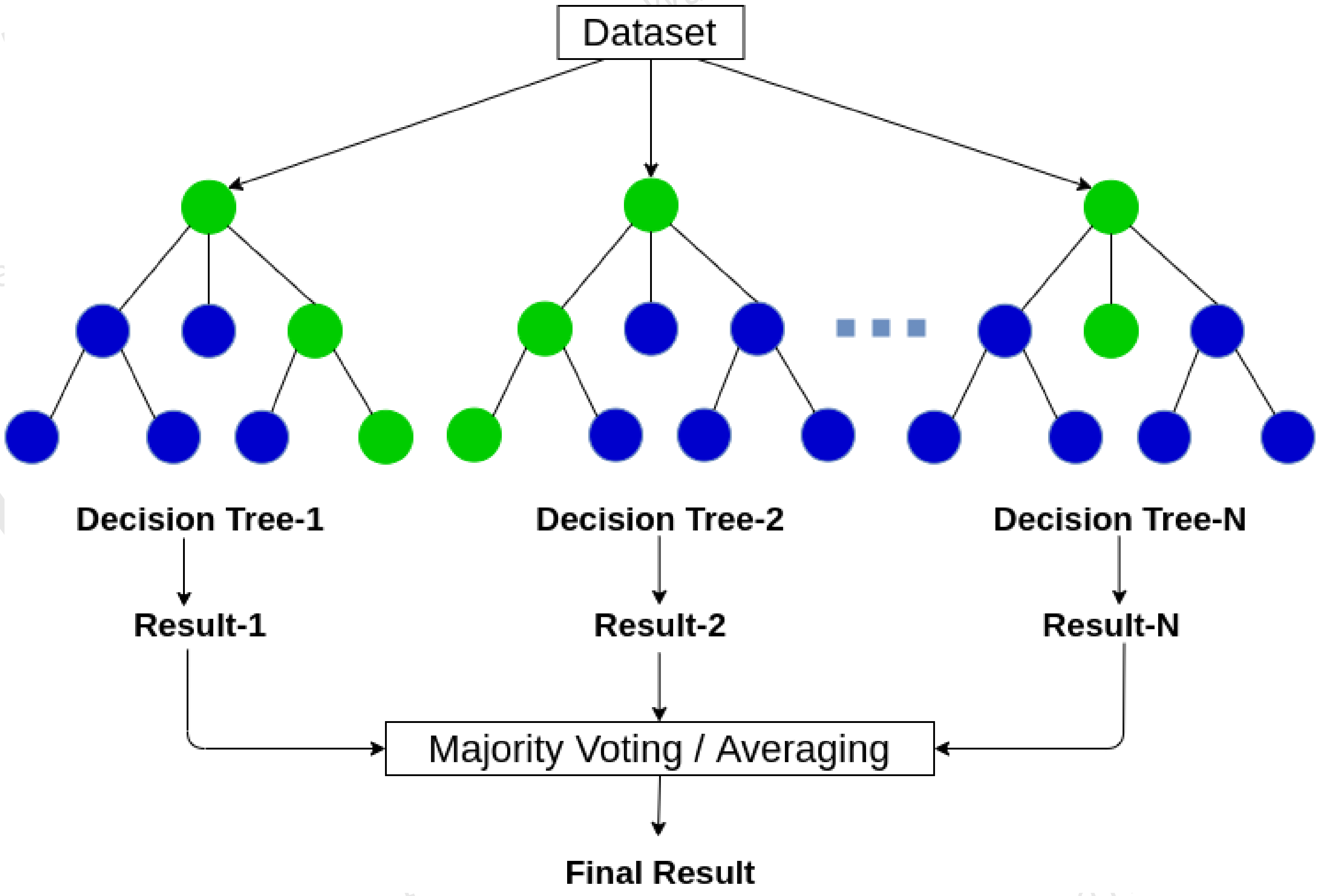
- High-resolution satellite imagery provides reliable info to training data properties.
- Training data should cover all important land cover classes and avoid wrong collocation of pixels to classes of interest.
- The statistical nature of training sample (number of samples, sample distribution type, validation strategy).



Dean, A. . (2020). *Earth Observation and the Global Environment Facility. Technical Guide. Prepared for the Scientific and Technical Advisory Panel to the Global Environment Facility.* Washington, DC. March.

Random Forest

- A general term for ensemble methods using decision tree framework to create multiple randomly drawn decision trees, averaging the results and output to strong prediction/classification.
- Advantages = reduces overfitting, not biased, capable of handling missing data, both parametric and non-parametric

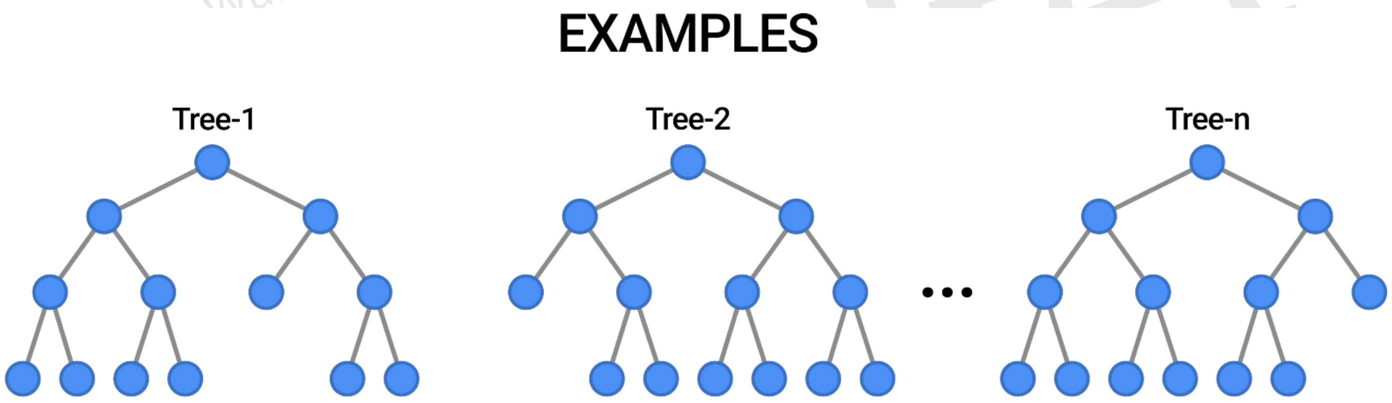


Gislason, P. O., Benediktsson, J. A., & Sveinsson, J. R. (2006). Random Forests for land cover classification. *Pattern Recognition Letters*, *27*(4), 294–300. https://doi.org/10.1016/j.patrec.2005.08.011

https://ai-pool.com/a/s/random-forests-understanding

Random Forest (Continued)

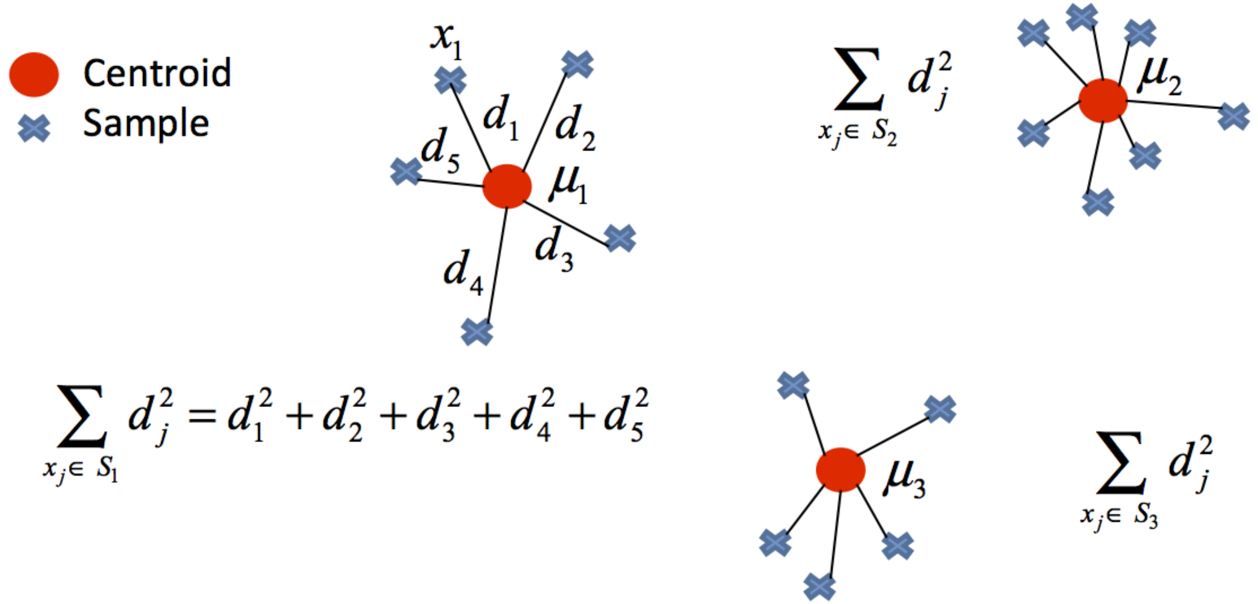
- Computation estimation
  $Time = cT\sqrt{M}Nlog(N)$
  c= constant
  T = Number of trees
  M = Number of variables
  N = Number of samples



Gislason, P. O., Benediktsson, J. A., & Sveinsson, J. R. (2006). Random Forests for land cover classification. *Pattern Recognition Letters*, *27*(4), 294–300. https://doi.org/10.1016/j.patrec.2005.08.011

https://blog.tensorflow.org/2021/05/introducing-tensorflow-decision-forests.html

K-mean Algorithm



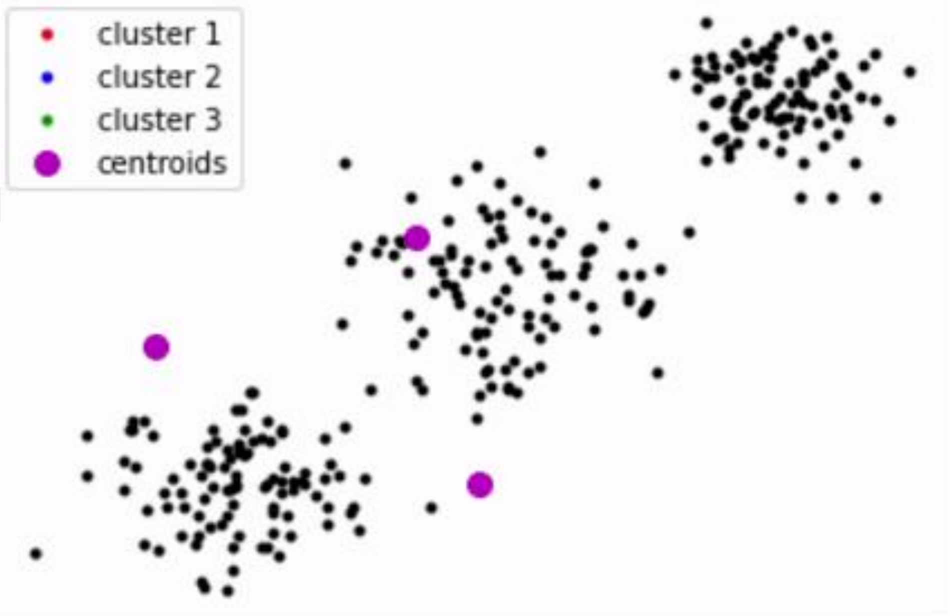
$$\min_{S} E(\mu_i) = \sum_{x_j \in S_1} d_j^2 + \sum_{x_j \in S_2} d_j^2 + \sum_{x_j \in S_3} d_j^2$$

- The algorithm will group sample points into "k" groups based on their spectral characteristics.
- Grouping is proceeded by finding the minimum sum of distances between each sample point and the cluster centroid.

https://www.uniovideo.es/compnum/labs/new/kmeans.html#:~:text=K%2Dmeans%20is%20an%20unsupervised,the%20group%20or%20cluster%20centroid.

K-mean Algorithm (Continued)

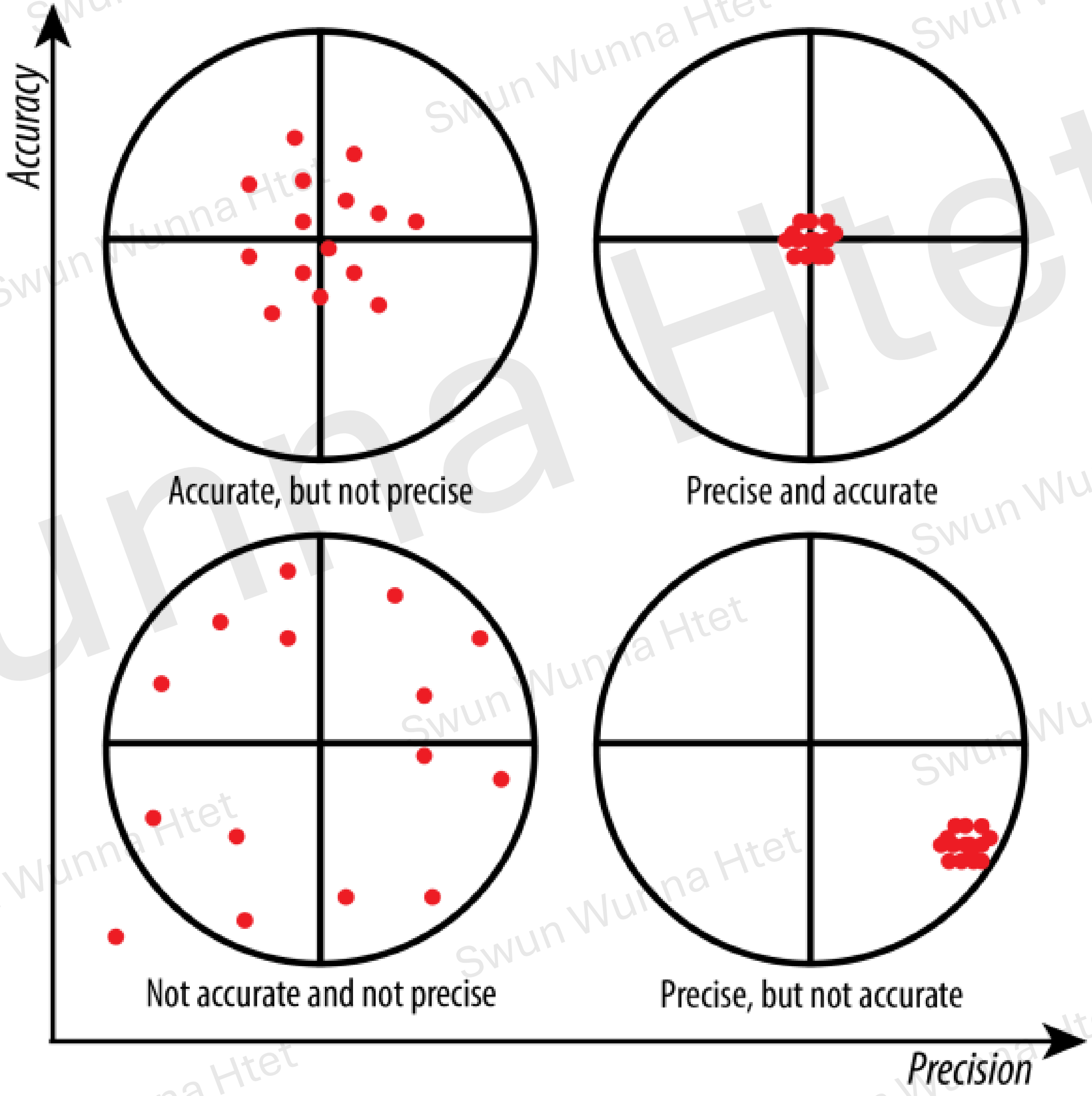
1. Determine the number of groups “k” to classify.
2. Assignment of sample points to the centroids
3. Update the centroids.



https://www.unioviedo.es/compnum/labs/new/kmeans.html#:~:text=K%2Dmeans%20is%20an%20unsupervised,the%20group%20or%20cluster%20centroid.

Accuracy Assessment of LULC Classification

Don't forget to validate your results for the consistency and reliability.



https://wp.stolaf.edu/it/gis-precision-accuracy/

Accuracy Assessment (Continued)

Sampling Design

- It is the essential routine of any LULC classification, as collecting the reference data for a specific area is expensive.
- Critical points for selecting sampling design:
  1. Land cover classification scheme for the sampling data must be the same as the one used in the classification.
  2. There must be equal probability for all area to be sampled.
  3. The sampling size to achieve a proper statistical accuracy for each LC class must be sufficient.

Accuracy Assessment (Continued)

Error Matrix Parameters

- *Error matrix is a comparison table between the reference data and the classified output. Used as the quantitative method of characterizing the image classification accuracy.*

1. $Overall\ accuracy\ (OA) = \frac{Total\ number\ of\ correctly\ classified\ pixels}{Total\ number\ of\ pixels}$
2. User's accuracy (UA) = probability that a pixel was predicted to be in a certain class is that class
3. Producer's accuracy (PA) = probability that a pixel in a class was classified correctly.
4. Commission error (EC) = proportion of a pixel that was predicted to be in a class but do not belong to that class
5. Omission error (EO) = proportion of the observed pixel on the ground that are not classified on the map

Congalton, R. G. (2001). Accuracy assessment and validation of remotely sensed and other spatial information. *International Journal of Wildland Fire*, *10*(3–4), 321–328. https://doi.org/10.1071/wf01031

Error Matrix (Confusion Matrix)

		REFERENCE DATA					
CLASSIFICATION DATA		A	B	C	…	N	Total
	A						
	B						
	C						
	…						
	N						
	Total						

Column totals = total number of reference pixels in each class

Raw totals = total number of classified pixels in each class

Diagonal totals = total number of pixels correctly classified according to the reference data

Cindy Schmidt & Amber McCullum: *Assessing the Accuracy of Land Cover Classifications (ARSET Training)* (Feb 13, 2018)

Error Matrix Parameters (Example)

CLASSIFICATION DATA	REFERENCE DATA			
Classes	A	B	C	Row Total
A	24	10	4	38
B	5	30	2	37
C	1	1	23	25
Column Total	30	41	29	100

$$OA = \frac{Diagonal\ total}{Total\ pixels} = \frac{24 + 30 + 23}{100} = 77\%$$

$$PA_A = \frac{Diagonal\ value\ (A)}{Total\ pixels\ in\ row\ (A)} = \frac{24}{38} = 63\%$$

$$PA_B = \frac{Diagonal\ value\ (B)}{Total\ pixels\ in\ row\ (B)} = \frac{30}{37} = 81\%$$

$$PA_C = \frac{Diagonal\ value\ (C)}{Total\ pixels\ in\ row\ (C)} = \frac{23}{25} = 92\%$$

$$UA_A = \frac{Diagonal\ value\ (A)}{Total\ pixels\ in\ column\ (A)} = \frac{24}{30} = 80\%$$

$$UA_B = \frac{Diagonal\ value\ (B)}{Total\ pixels\ in\ column\ (B)} = \frac{30}{37} = 81\%$$

$$PA_C = \frac{Diagonal\ value\ (C)}{Total\ pixels\ in\ row\ (C)} = \frac{23}{25} = 92\%$$

Cindy Schmidt & Amber McCullum: *Assessing the Accuracy of Land Cover Classifications (ARSET Training)* (Feb 13, 2018)

Kappa Statistics

Kappa Coefficient	Classification can be regarded as
Below 0.4	Poor
0.41 - 0.60	Moderate
0.61 - 0.75	Good
0.76 - 0.80	Excellent
0.81 and above	Almost Perfect

- The kappa coefficient is another accuracy indicator can be estimated easily from the confusion matrix or error matrix that is widely used in classification accuracy assessment.
- Value ranges from 0 to 1, from inaccurate classification into perfect classification.

$$k = \frac{Observed\ - Expected}{1\ - Observed}$$

Where: k = Kappa coefficient (0 – 1)

Observed = probability of correct classification (Observed Accuracy)

Expected = probability of change agreement

Is kappa statistics good enough to determine the outcome's classification?

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journal homepage: www.elsevier.com/locate/rse

ELSEVIER

Explaining the unsuitability of the kappa coefficient in the assessment and comparison of the accuracy of thematic maps obtained by image classification

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ARTICLE INFO

Edited by Marie Weiss

Keywords:
Accuracy
Kappa coefficient
Chance
Prevalence
Bias

ABSTRACT

The kappa coefficient is not an index of accuracy, indeed it is not an index of overall agreement but one of agreement beyond chance. Chance agreement is, however, irrelevant in an accuracy assessment and is anyway inappropriately modelled in the calculation of a kappa coefficient for typical remote sensing applications. The magnitude of a kappa coefficient is also difficult to interpret. Values that span the full range of widely used interpretation scales, indicating a level of agreement that equates to that estimated to arise from chance alone all the way through to almost perfect agreement, can be obtained from classifications that satisfy demanding accuracy targets (e.g. for a classification with overall accuracy of 95% the range of possible values of the kappa coefficient is −0.026 to 0.900). Comparisons of kappa coefficients are particularly challenging if the classes vary in their abundance (i.e. prevalence) as the magnitude of a kappa coefficient reflects not only agreement in labelling but also properties of the populations under study. It is shown that all of the arguments put forward for the use of the kappa coefficient in accuracy assessment are flawed and/or irrelevant as they apply equally to other, sometimes easier to calculate, measures of accuracy. Calls for the kappa coefficient to be abandoned from accuracy assessments should finally be heeded and researchers are encouraged to provide a set of simple measures and associated outputs such as estimates of per-class accuracy and the confusion matrix when assessing and comparing classification accuracy.

Foody, G. M. (2020). Explaining the unsuitability of the kappa coefficient in the assessment and comparison of the accuracy of thematic maps obtained by image classification. *Remote Sensing of Environment*, *239*(August 2019), 111630. https://doi.org/10.1016/j.rse.2019.111630

Key Points during LULC Classification

Land Cover Class

LC class definition

Label classes' overlap (mixed pixels) in terms of spectral and spatial perspective.

Radiance artefacts

Radiance-at-sensor contributing from several sources (atmosphere, contribution from neighboring pixels, scattering processes)

Input Satellite Imagery

Wavelength characteristics (Optical, Hyperspectral or SAR)

Multi-temporal/ Time Series/ Single Date

Computation time out (Dimensionality reduction)

Spatial Resolution (Fine/medium/coarse)

Training and Reference Sampling

Distribution of samples

Sample quantity

Spatial distribution of sample location

Selection of sample points

Thank you for your kind attention