esa space solutions

Copernicus Academy

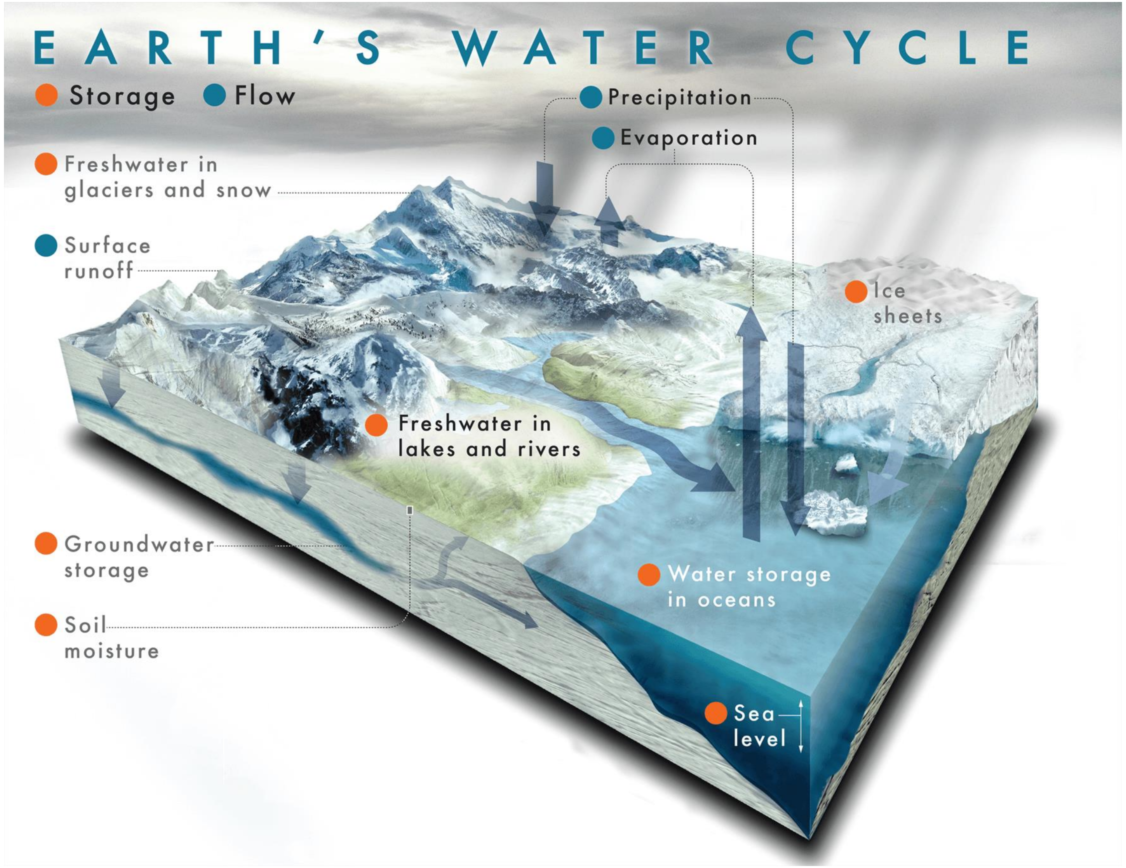
ÚSTAV GEOGRAFIE
Prírodovedecká fakulta UPJŠ v Košiciach

9. SAR and optical remote sensing for mapping ice

Why do we need information about ice

Information on snow and ice is essential for several reasons:

- Climate Monitoring
- Water Resource Management
- Natural Hazard Assessment
- Ecosystem Monitoring
- Sea Level Rise



Source:https://climatekids.nasa.gov/water-cycle//

Cryosphere

- The portion of Earth's surface where water is found in its (mostly) solid form, including snow, ice, glaciers, ice caps, ice sheets, frozen ground (permafrost), and sea ice
- It encompasses regions of both land and sea that experience freezing temperatures, and it plays a crucial role in Earth's climate system.
- The cryosphere interacts with other components of the Earth system, such as the atmosphere, oceans, and biosphere, through processes like melting, freezing, and ice-albedo feedback
- Changes in the cryosphere can have significant impacts on global climate patterns, sea level rise, freshwater availability, and ecosystems.

Source:https://discoveringthearctic.org.uk/introducing-the-arctic/snow-water-ice-permafrost/cryosphere/

Examples of ice patterns in different environments

https://blogs.egu.eu/divisions/cr/2022/04/21/more-pancakes-in-the-future/, https://www.mergili.at/worldimages/picture.php?/8968,, https://www.antarcticglaciers.org/glacial-geology/glacial-landsystems/glaciated-valley-landsystems/debris-covered-glacier-landsystems/

Typical densities of ice (and snow)

Typical densities of snow and ice (kg/m^3)	
New snow (immediately after falling in calm)	50-70
Damp new snow	100-200
Settled snow	200-300
Depth hoar	100-300
Wind packed snow	350-400
Firn	400-830
Very wet snow and firn	700-800
Glacier ice	830-917

Source: Paterson, W.S.B. 1994. *The Physics of Glaciers.*

Basic Classes and Mechanisms of Ice Formation

Class	Description	Thickness
New Ice	Ice which began to grow a few hours or days ago	0 – 10 cm
Young Ice	Transition between new and first-year ice	10 - 30 cm
First-Year Ice	Ice of no more than one winter's growth	30 – 200 cm
Old Ice	Ice that has survived at least one summer's melt; most topographic features are smoother than on first-year ice	> 200 cm

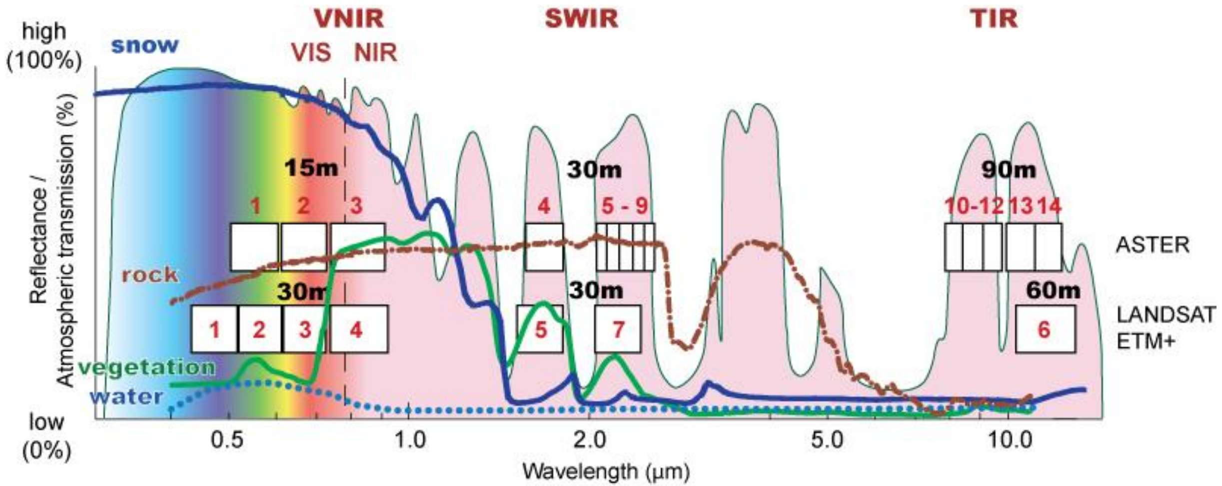
High

Low

Source: https://appliedsciences.nasa.gov/sites/default/files/2023-10/SAR_2023_Part1_Final.pdf

Remote Sensing of Ice

Selected satellites used i.a. for cryospheric applications			
C-Band	Sentinel-1	Optical	Sentinel-2 MSI
	Envisat ASAR		SPOT-5 – 7 HRV/NAOMI
	ERS-1/-2		Terra ASTER
	Radarsat-1/-2		Sentinel-3 SLSTR/OLCI
X-Band	Cosmo-Skymed		Aqua/Terra MODIS
			NPP VIIRS

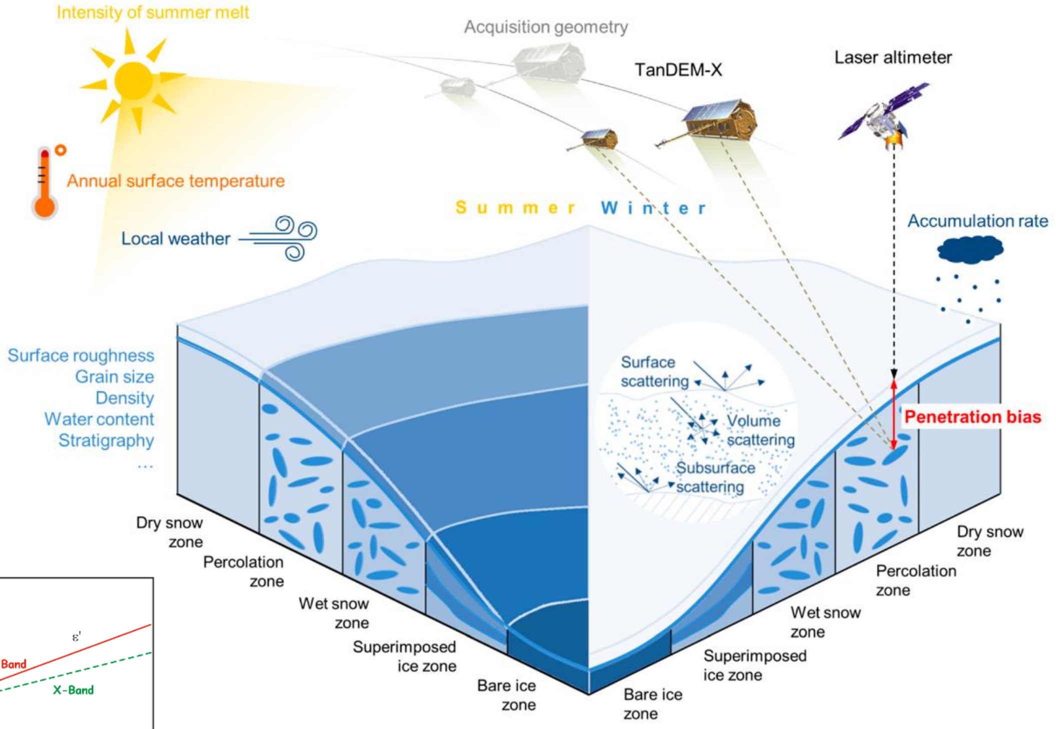


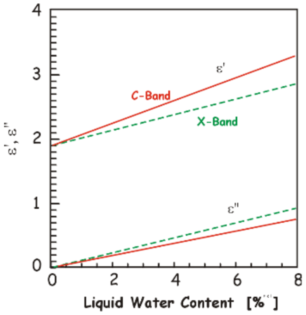
Radar for ice

Sensor	*Satellite*	*[GHz].*	*Resolution/Swath*	*Repeat*
AMI	ERS-1,-2(1991-2011)	5.3 VV	25 m - 100 km	35d/1 d
SIR-C/X-SAR	Shuttle (1994)	1.2,5.3,9.6	25 m - 40 km	2 Campaigns
SIR-C/X-SAR	SRTM (Feb.2000)	5.3 & 9.6	50/100 m - 100/200 DEM	
Present				
SAR	Radarsat1(1995-)	5.3	10,30,100 m - 100-500 km	24 d
ASAR	Envisat (2002-12)	5.3	30,100,1000 - 100-400 km	35 d
PALSAR	ADEOS (2007-11)	1.2	15/100 m - 40-350 km	46 d
TerraSAR	TerraSAR-X(2007-)	9.6	1, 3,10 m - 10,30,100 km	11 d
TerraSAR2	TanDEM-X (2010-)	9.6	in Tandem with TerraSAR-X (InSAR)	
SAR	COSMO-SkyMed	9.6	1, 3,10 m - 10-100 km	16 d, 1d, 8d
SAR	Radarsat2 (2007-)	5.3	3, 10, 30 m, 20 km 24 d	
SAR	Sentinel-1 (2013-)	5.3	10 m, 30 m 250, 400 km	12 d x 2 Sat.
Future				
SAR Constellation	Radarsat (2019 -)	5.3	3 m …100m 30 …500 km	16 d x 3 Sat.

Radar back-scatter signal

- **Physical factors:** dielectric constant of the surface materials (depends on the moisture content)
- **Geometric factors:** surface roughness, slopes, shape and orientation of the objects relative to the radar beam direction
- **The types of landcover**
- **Sensor characteristics:** Microwave frequency, polarisation and incident angle

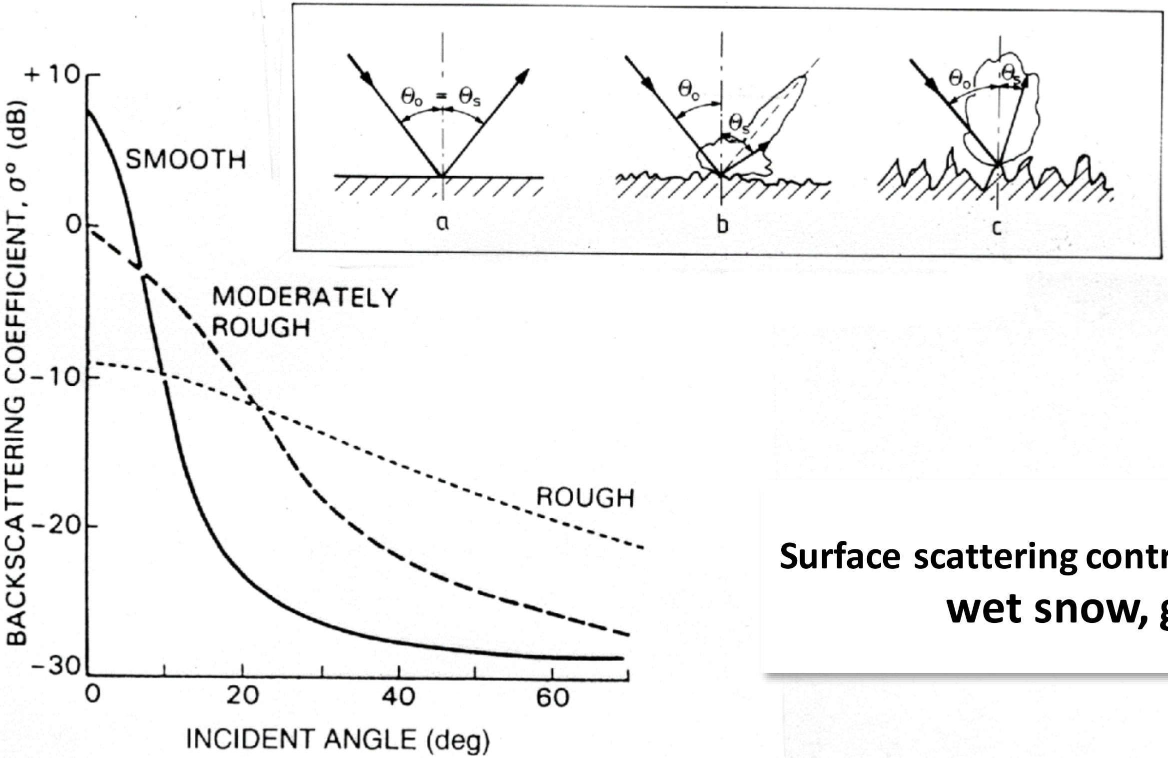




Microwave Permittivity

Source: https://www.mdpi.com/2072-4292/11/24/2903

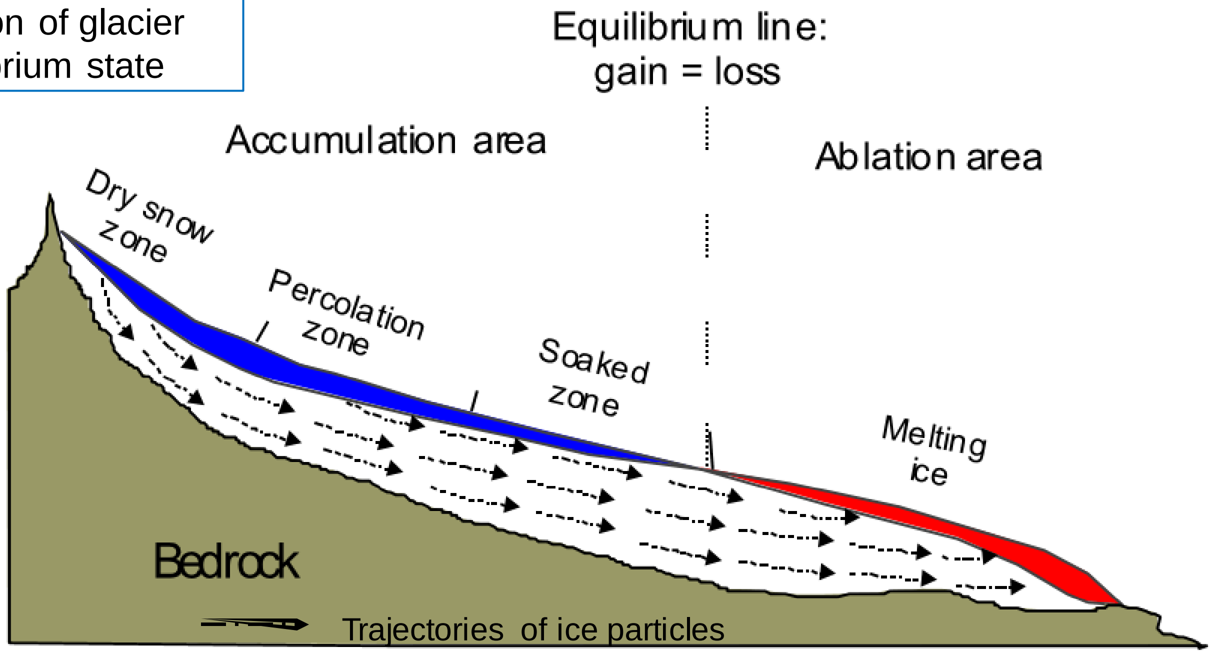
Backscattering from a Rough Surface



Surface scattering contribution dominates for
wet snow, glacier ice, soil, …

Glacier Motion by InSAR and Offset Tracking

Ice motion of glacier in equilibrium state

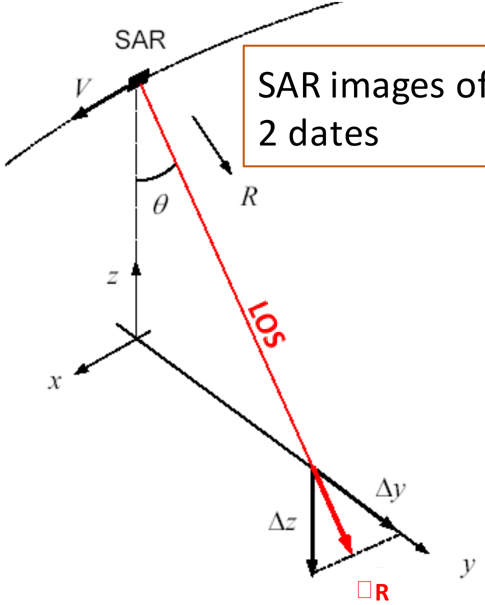


Objectives for mapping Ice Motion:

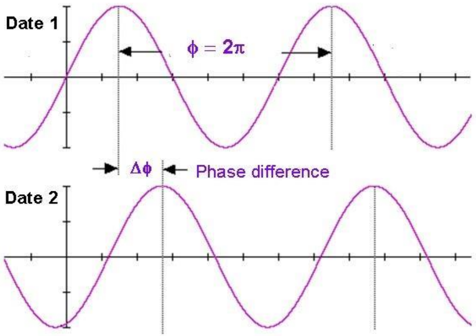
- Retrieving ice export by calving (Input/Output method for mass balance)

Interferometric measurement of displacement

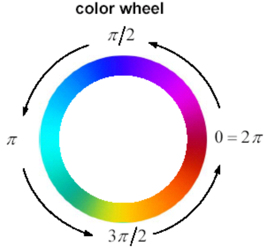
Measurement of Displacement



SAR images of 2 dates



1 Fringe

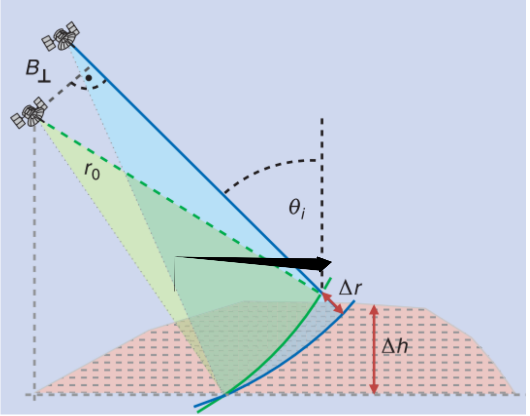


TanDEM-X

InSAR repeat track measures displacement

Requires temporal stability of radar signal phase (coherence)

InSAR for Topography



Glacier Velocity Map

Basic principle: Matching of image templates by cross correlation (along track and in range) in co-registered SAR images.

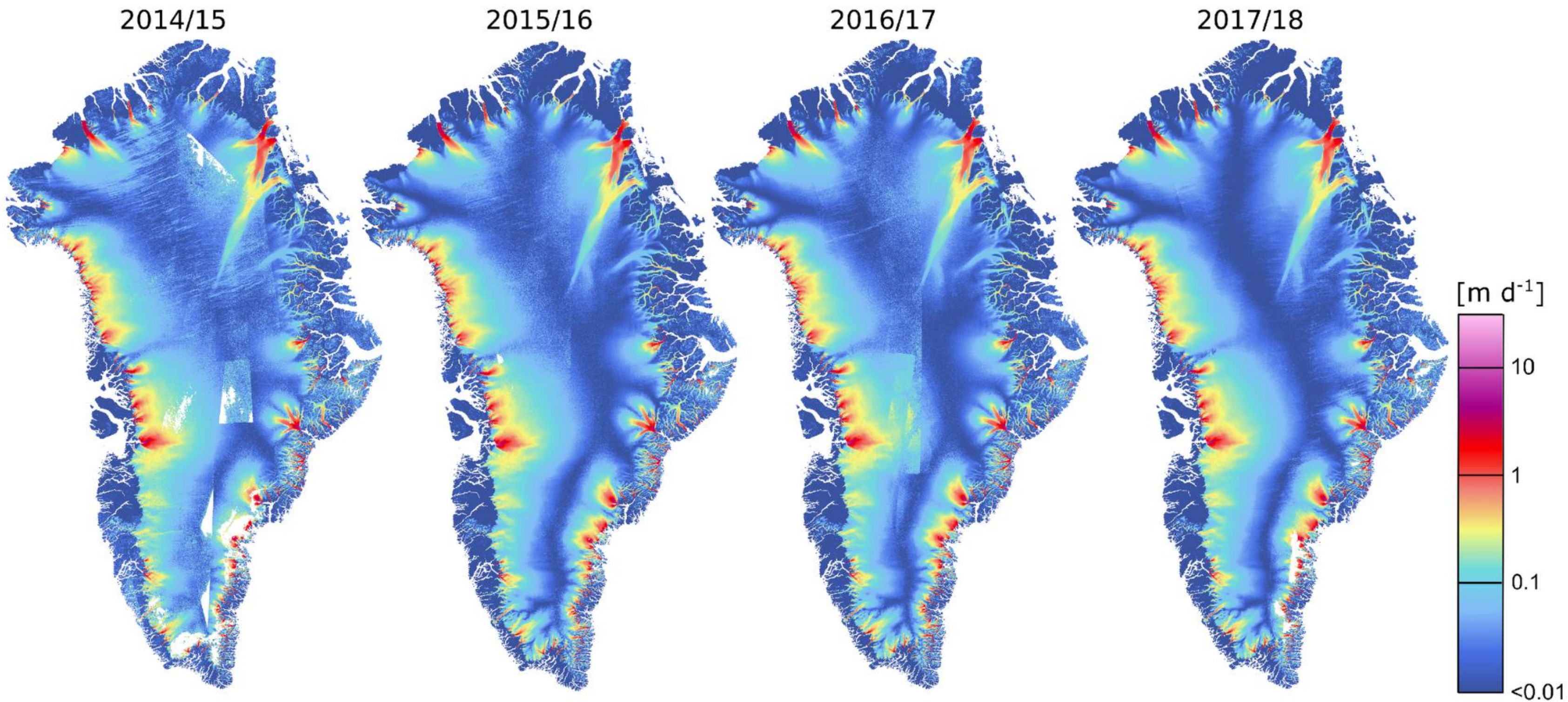
Possibilities for features to be tracked:

1. **Amplitude correlation**: Uses persistent features in backscattering amplitude images (e.g. crevasses, drainage features). Advantage: Coherence not required. Disadvantage: Lack of features in accumulation areas of glaciers (snow areas) prohibits application.
2. **Speckle tracking:** Uses coherent amplitude data (complex or magnitude). *Advantage*: Works also where no obvious amplitude features exist. No need coherence can be bridged.
3. **Coherence tracking**: Uses templates in coherence images and looks for maximum value. Method and possibilities similar to method (2).

Typical achievable accuracy in displacement: 0.2 pixels in x and y.

Errors depend on co-registration, type of features, quality of matching.

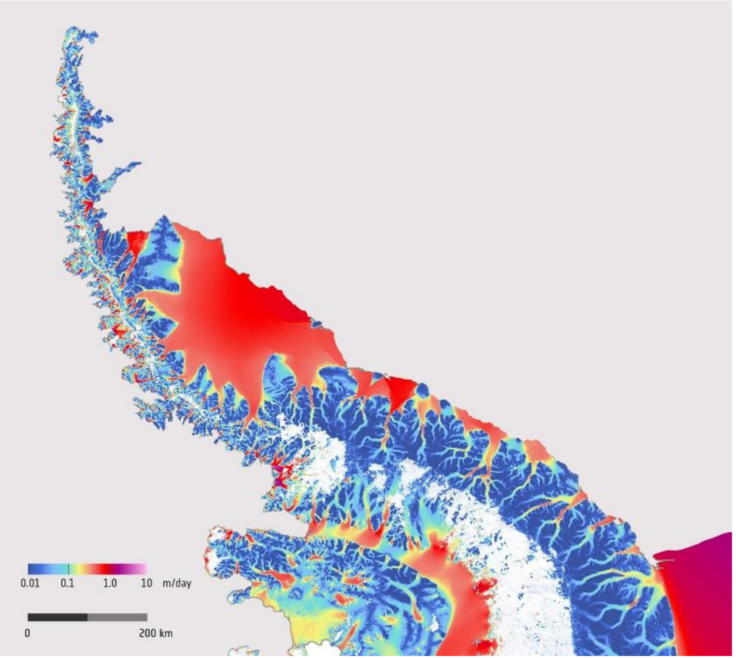
Glacier Velocity Map



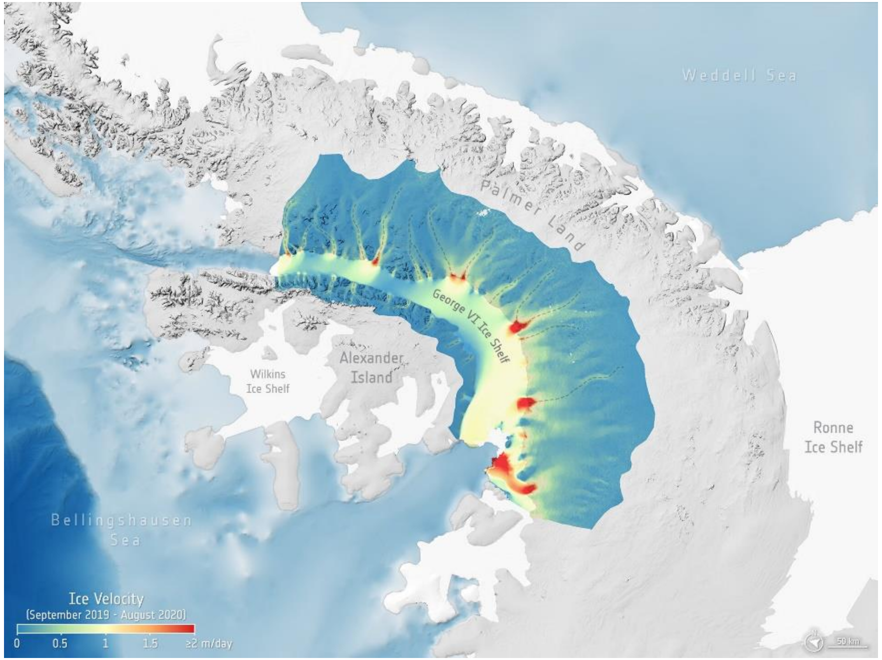
Annual ice velocity maps of Greenland from Copernicus Sentinel-1 2014-17 and winter campaign 2017/18.

Source: https://www.esa.int/ESA_Multimedia/Images/2019/07/Ice_velocity_maps_of_Greenland

Ice Flow Map



Antarctic Peninsula ice flow

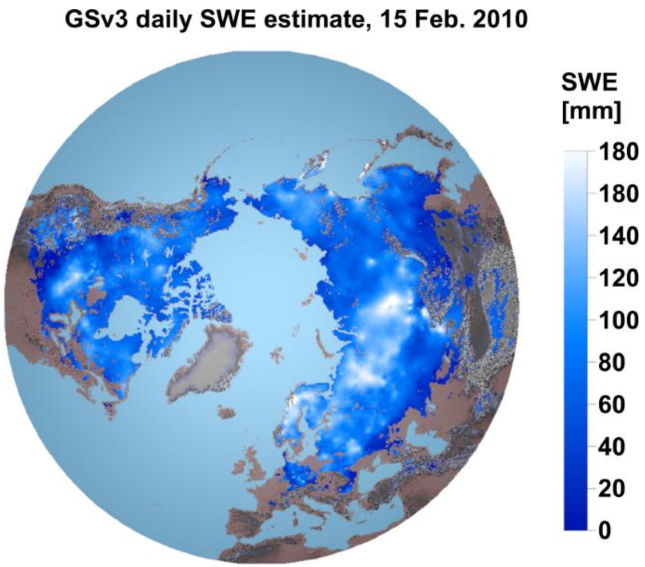


Ice-flow velocity of the George VI Ice Shelf

Source: https://www.esa.int/ESA_Multimedia/Images/2016/05/Antarctic_Peninsula_ice_flow,
https://www.esa.int/ESA_Multimedia/Images/2022/10/Ice-flow_velocity_of_the_George_VI_Ice_Shelf

Applications in Cryosphere: Radar Sensors

- Snow Water Equivalent (SWE)
- Glacier topography and volume change
- Dynamics and mass balances of ice sheets
- Glacier motion
- 3D ice surface deformation
- River ice
- Sea ice



Source: https://www.nature.com/articles/s41597-021-00939-2

Optical for ice

Incoming electromagnetic energy $_I(\lambda)$) is affected by:

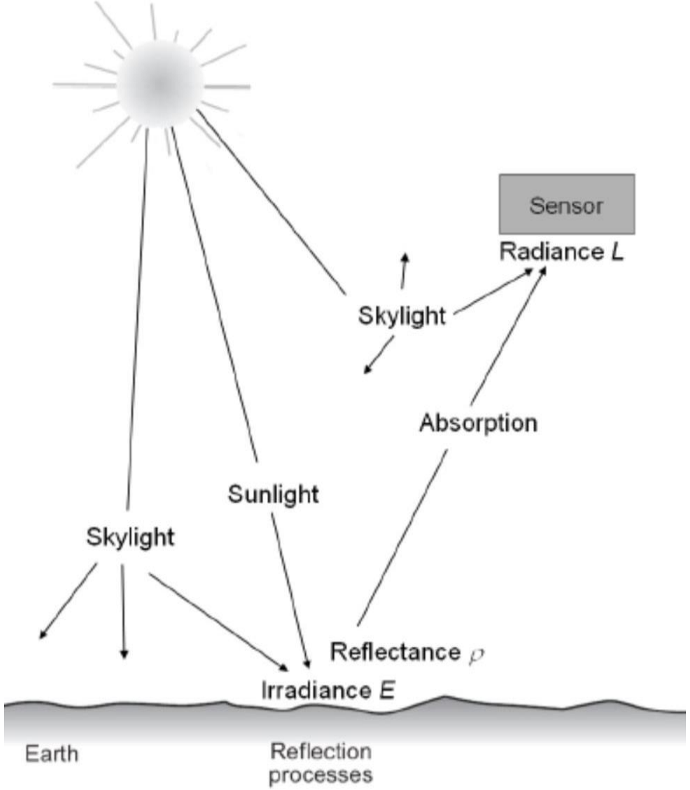
- Absorption ($E_A(\lambda)$)
- Scattering ($E_S(\lambda)$)
- Transmission ($E_T(\lambda)$)

Principle of energy conservation:

(energy can only be transferred, but neither be created nor destroyed)

$$E_I(\lambda) = E_A(\lambda) + E_S(\lambda) + E_T(\lambda)$$

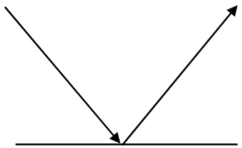
Optical sensors measure the amount of light receiving the satellite (= at-satellite radiance L), which is often converted to



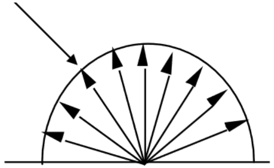
Optical for ice

Reflectance depends on

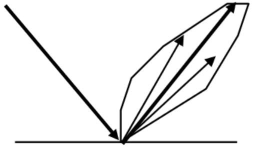
- Wavelength energy
- Atmospheric attenuation
- Geometry of the Surface
- Surface Materials



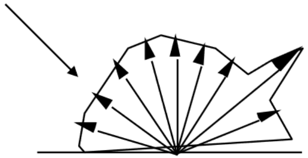
Specular reflector (mirror)



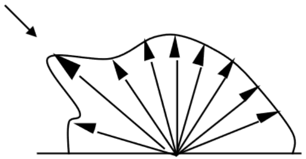
diffuse reflector (lambertian)



Nearly Specular reflector (water)



nearly diffuse reflector



Hot spot reflection

Selected Optical Sensors for Glacier Monitoring

Sensor	*Satellite*	*Bands*	*Resolution*
MSI	Sentinel-2	VIS, SWIR	10, 20, 60 m
OLCI, SLSTR	Sentinel-3	VIS, SWIR, TIR	300, 500, 1000 m
AVHRR	NOAA	VIS, SWIR, TIR	1 km
MODIS	TERRA, ACQUA	0.4 – 12 µm (36 Ch.)	250, 1000 m
ASTER	TERRA	VIS, SWIR, TIR, Stereo	15, 30, 90 m
ETM+	LANDSAT 5,7	VIS, SWIR, TIR	15, 30, 60 m
OLI - LDCM	LANDSAT 8	VIS, SWIR, TIR	15, 30, 100 m
HRV	SPOT5	VIS, SWIR	2.5, 5, 10 m
Dig-Camera	Ikonos	VIS, NIR (4 Kan.)	1, 4 m
Dig-Camera	QuickBird	VIS, NIR (4 Kan.)	0.7, 2.5 m
Dig-Camera	PLEIADES	VIS, NIR	0.5, 2.0 m

IR Bands: *NIR 0.7 – 1.2 µm; SWIR 0.7 - 2.3 µm; TIR 8 – 12 µm*

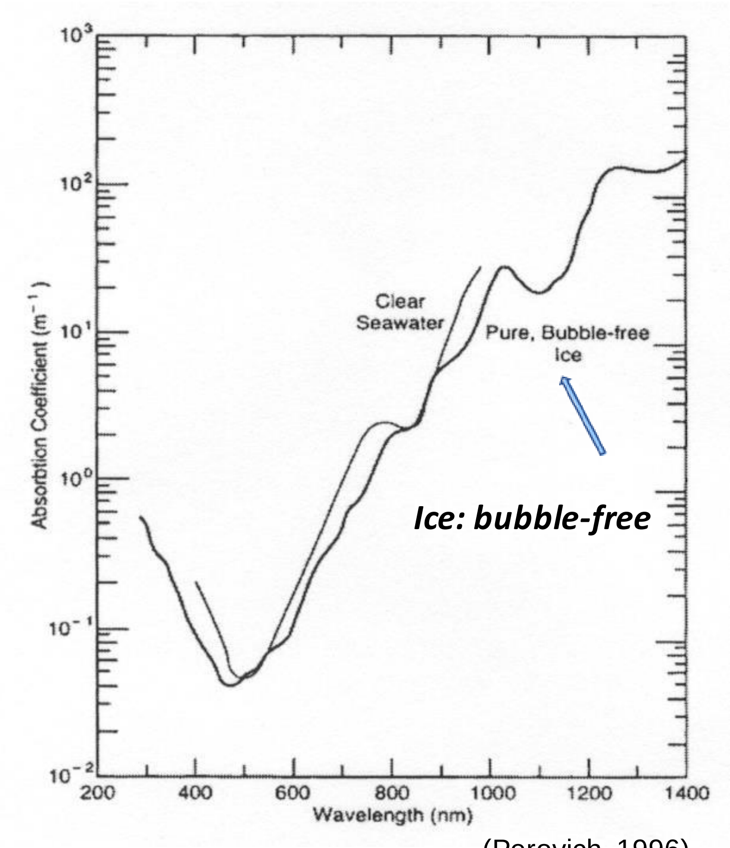
Extinction Coefficient of pure ice and sea water

Penetration depth (for intensity)

$d_p = 1/K_e$

$K_e [m^{-1}]$ extinction coefficient

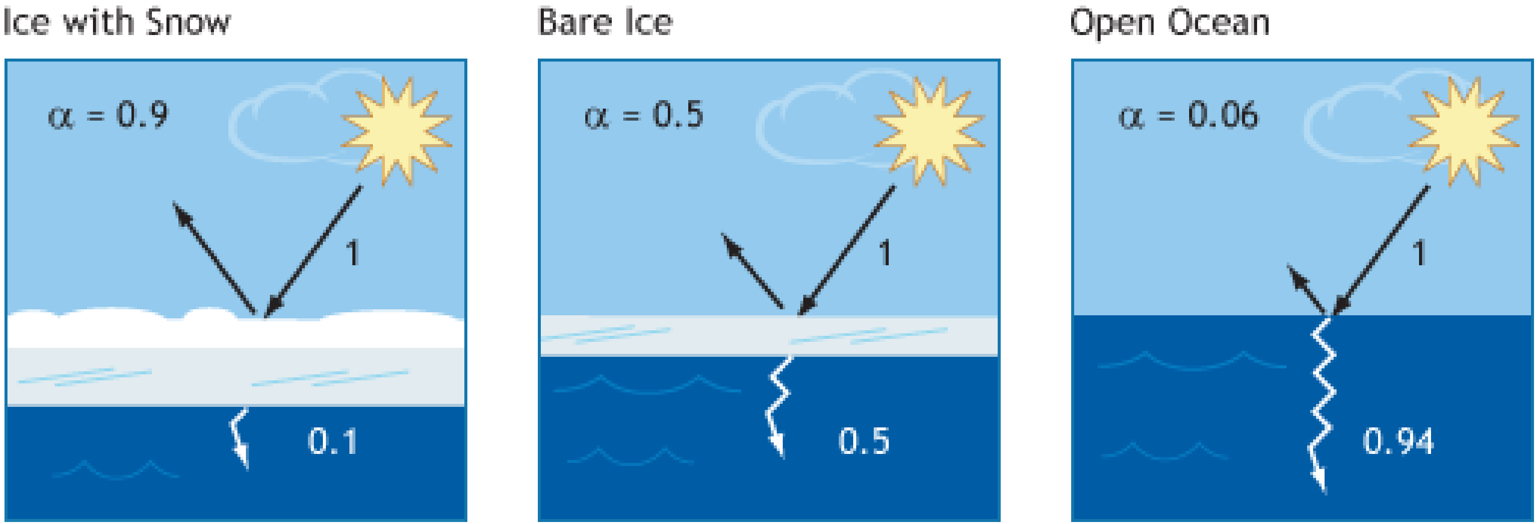
Visible light penetration in snow is a few centimetres; scattering losses dominate!



(Perovich, 1996)

Ice albedo

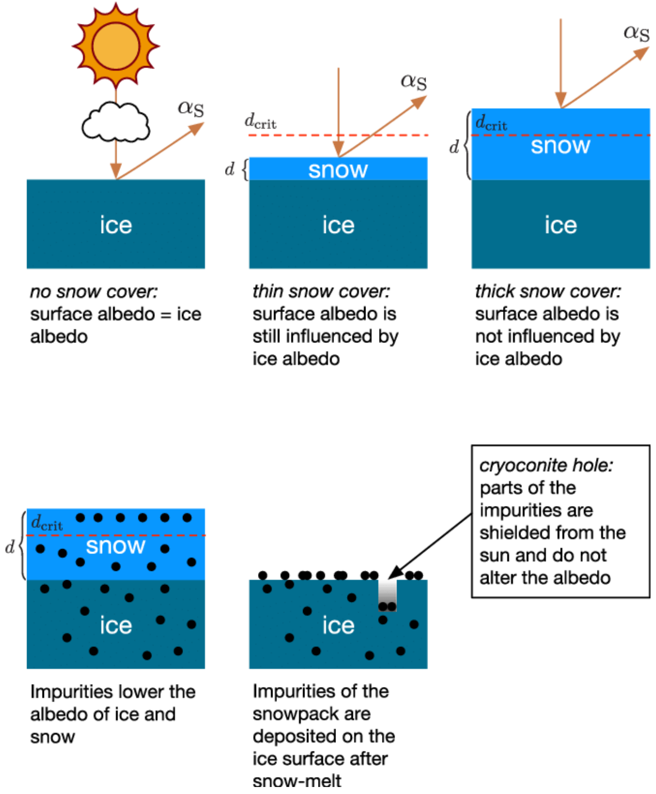
Albedo, in the context of sea ice, refers to how much solar radiation is reflected back into space. When there's no sea ice, the ocean absorbs heat. If there's sea ice, it has a higher albedo, meaning it reflects more solar radiation, resulting in less heat being absorbed by the ocean. When there's both sea ice and snow, the albedo is even higher.



https://www.us-satellite.net/sprintt/phase2/ipy07_int_albedo/ipy07_int_albedo.html

Main Factors for Spectral Reflectance of Ice (and snow)

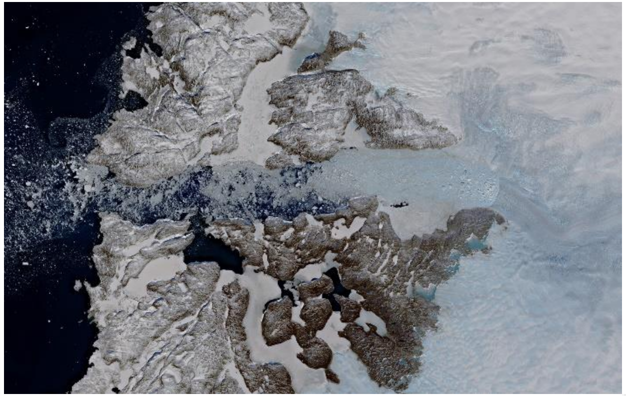
- Impurities (Soot, Dust, ...) - main factor at visible wavelengths
- Grain size; important at λ > ~ 1 μm
- Liquid water content (relevant in shortwave IR; primarily an indirect effect through grain size)
- Illumination and observation geometry (bi-directional reflectance)
- Surface roughness



https://www.cambridge.org/core/journals/journal-of-glaciology/article/albedo-reduction-of-ice-caused-by-dust-and-black-carbon-accumulation-a-model-applied-to-the-ktransect-west-greenland/3FE93E004C1793A5DC4D78FD4CD1ECB4

Applications in Cryosphere: Optical Sensors

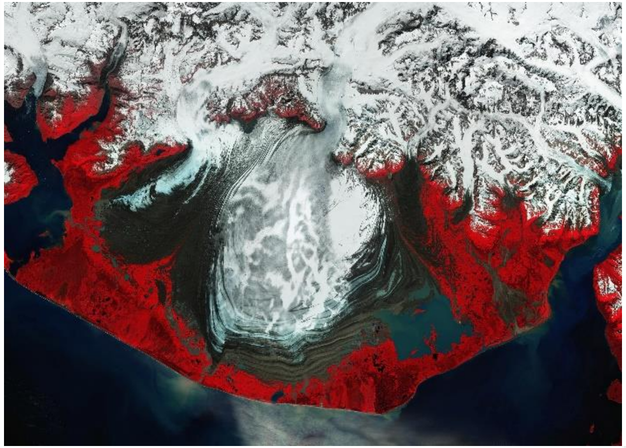
- Snow and ice areas mapping
- Lake ice monitoring
- Glacier mapping
- Albedo
- Glacier facies (snow, firn, ice, debris, supraglacial lakes, etc.)
- Snow and ice properties
- Ice motion (offset tracking)
- Ice sheet boundaries
- Surface topography



Jakobshavn Glacier

Jakobshavn Glacier in west Greenland viewed by the Copernicus Sentinel-2 mission on 29 April 2019.

CREDIT: containsmodified Copernicus Sentinel data (2019), processed by ESA



The moraines of Malaspina

The remarkable moraine patterns of Malaspina Glacier – the largest piedmont glacier in the world – are featured in this false-colour image acquired by Copernicus Sentinel-2.

CREDIT: contains modified Copernicus Sentinel data (2022), processed by ESA

Thank you for the attention