esa space solutions

Copernicus Academy

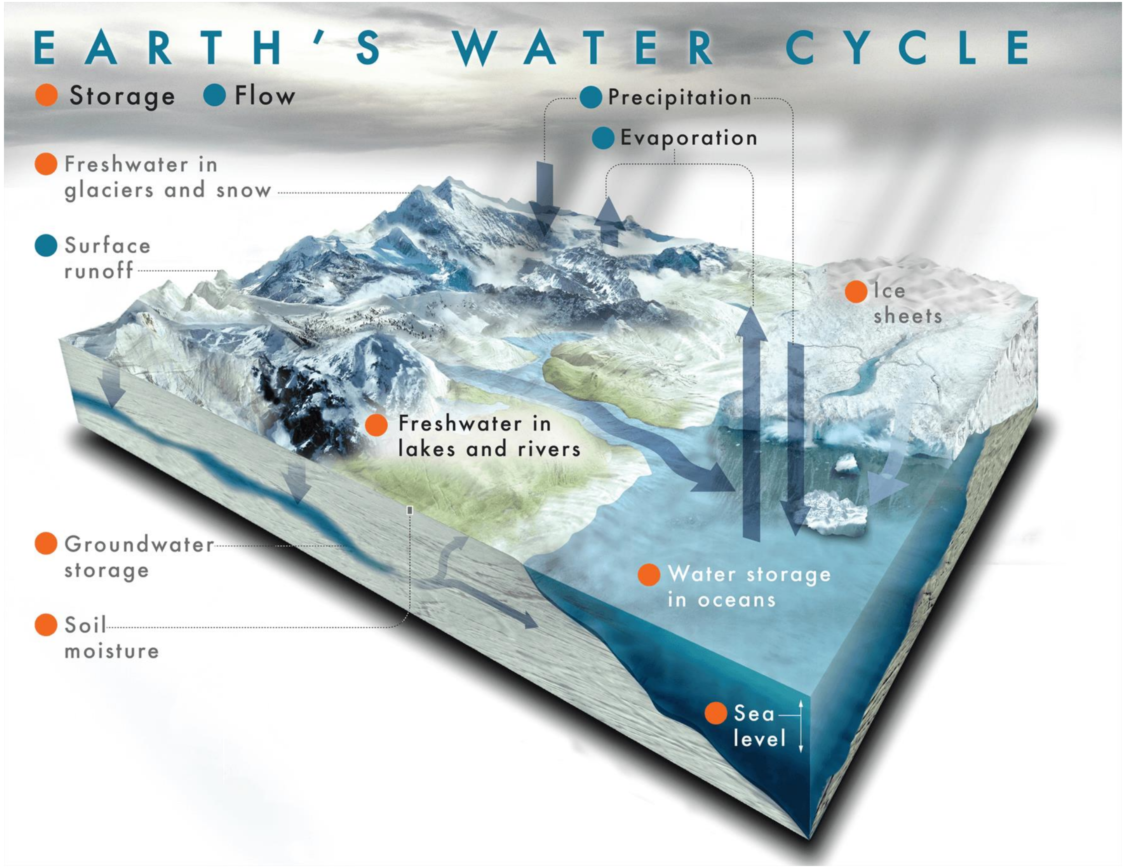
ÚSTAV GEOGRAFIE
Prírodovedecká fakulta UPJŠ v Košiciach

11. Snow and ice cover mapping using ESA Sentinel-1 and Sentinel-2 data

Why do we need information about snow and ice

Information on snow and ice is essential for several reasons:

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



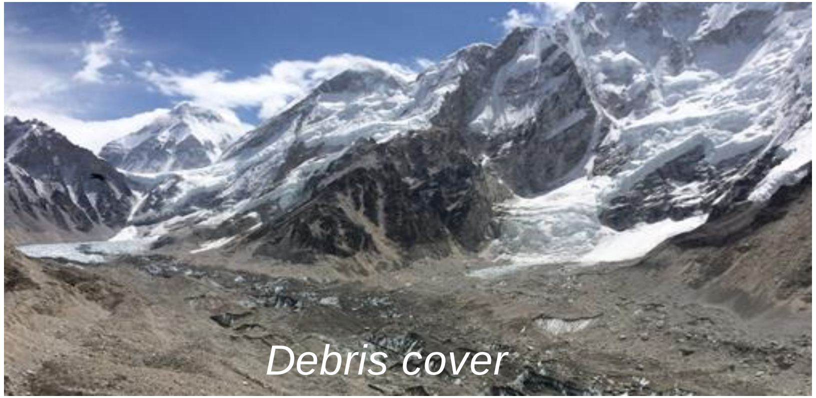
Source:https://climatekids.nasa.gov/water-cycle//

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 snow patterns in different environments


Debris cover

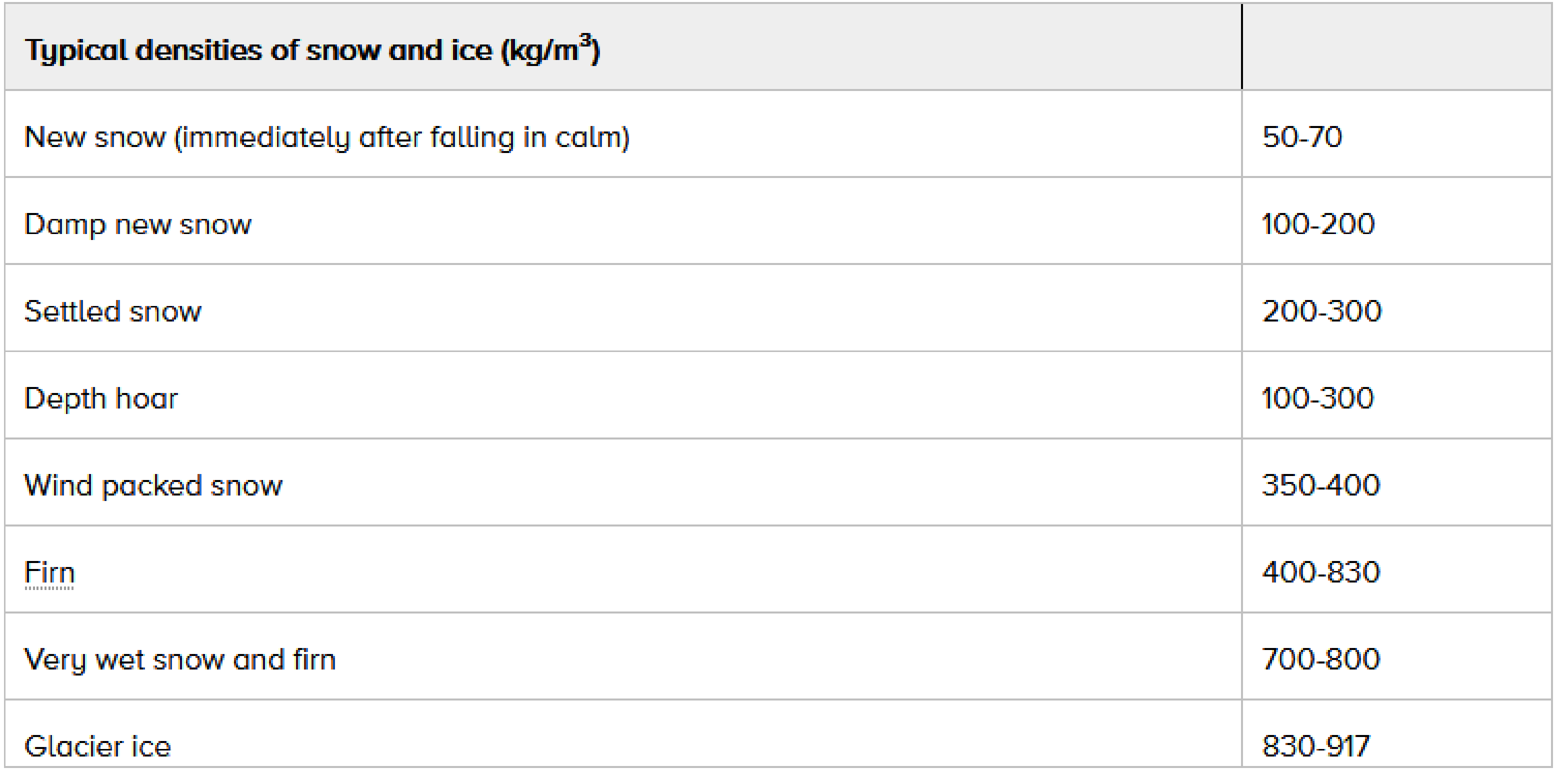

Totally snow covered plains


Glacier calving


Mountain glaciers

https://www.gadventures.com/trips/antarctica-classic-in-depth/XVAESX/, 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 snow and ice

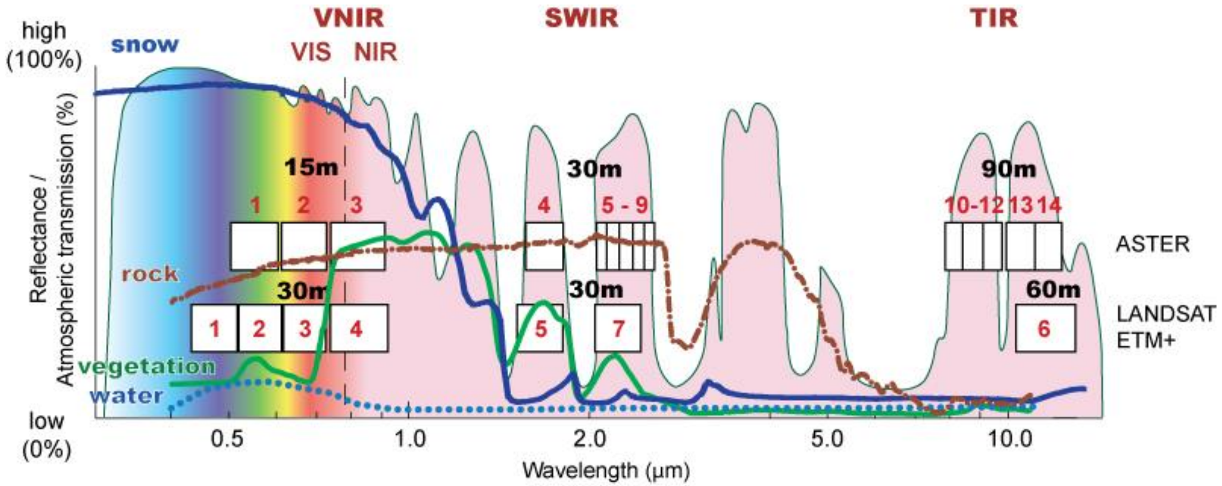


Typical densities of snow and ice (kg/m^3)	
New snow (immediately after falling in calm)	50-70
Damp new snow	100-200
Settled snow	200-300
Depth hoar	100-300
Wind packed snow	350-400
Firn	400-830
Very wet snow and firn	700-800
Glacier ice	830-917

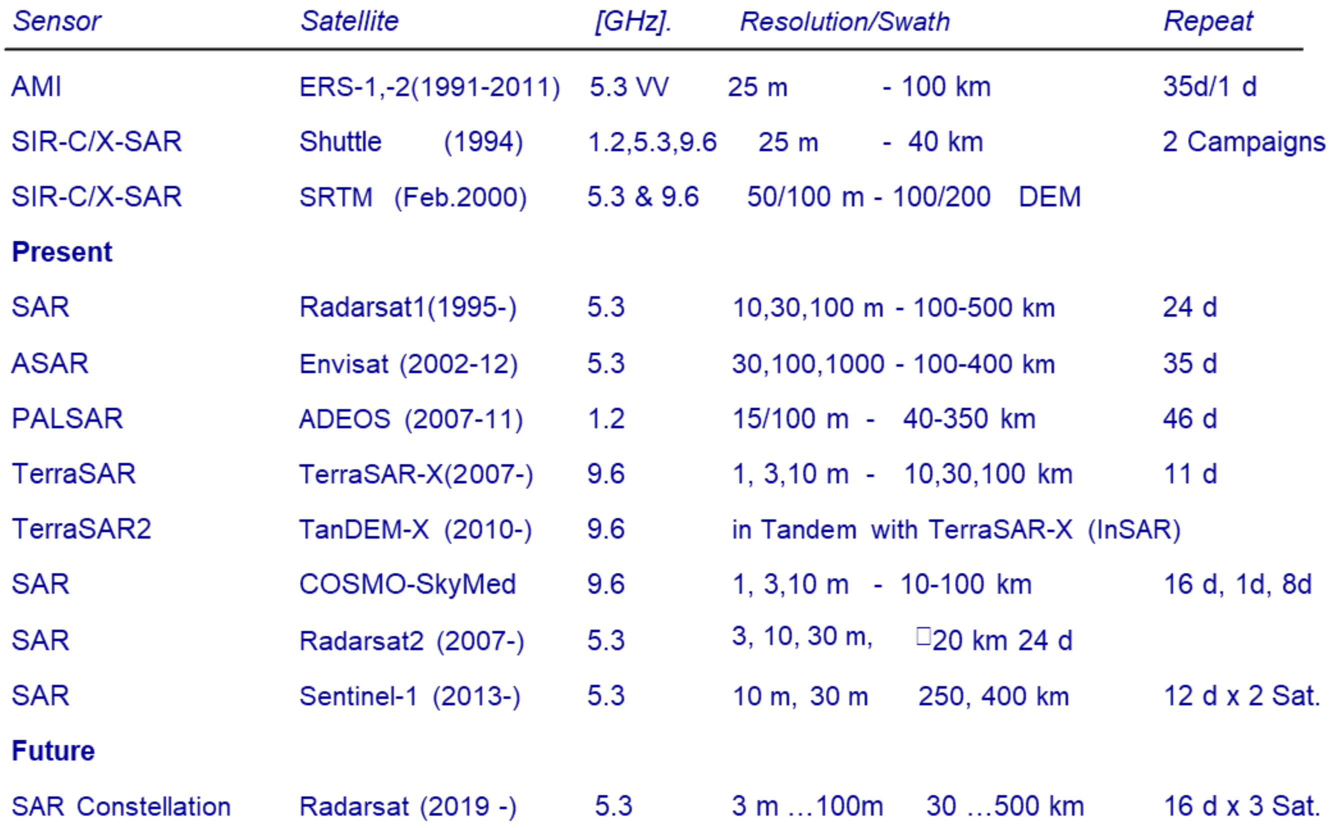
Source: Paterson, W.S.B. 1994. *The Physics of Glaciers.*

Remote Sensing of Snow and 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



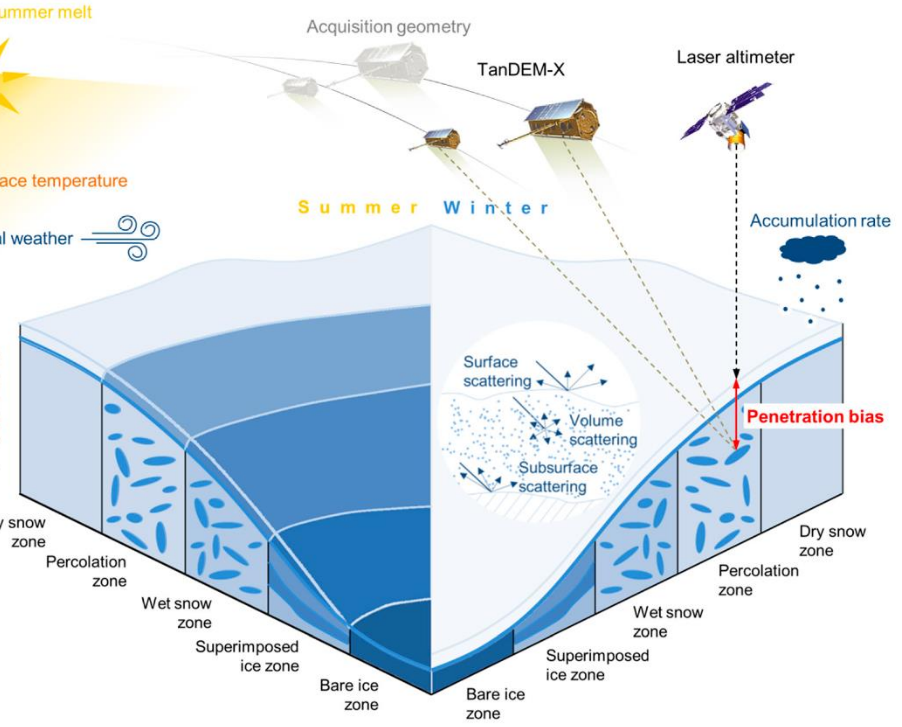
Radar for snow and ice



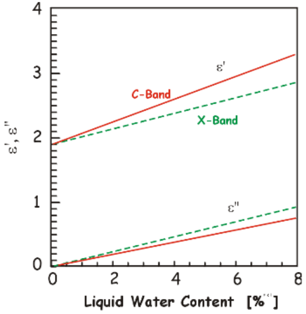
Sensor	*Satellite*	*[GHz].*	*Resolution/Swath*	*Repeat*
AMI	ERS-1,-2(1991-2011)	5.3 VV	25 m - 100 km	35d/1 d
SIR-C/X-SAR	Shuttle (1994)	1.2,5.3,9.6	25 m - 40 km	2 Campaigns
SIR-C/X-SAR	SRTM (Feb.2000)	5.3 & 9.6	50/100 m - 100/200 DEM	
Present				
SAR	Radarsat1(1995-)	5.3	10,30,100 m - 100-500 km	24 d
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



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



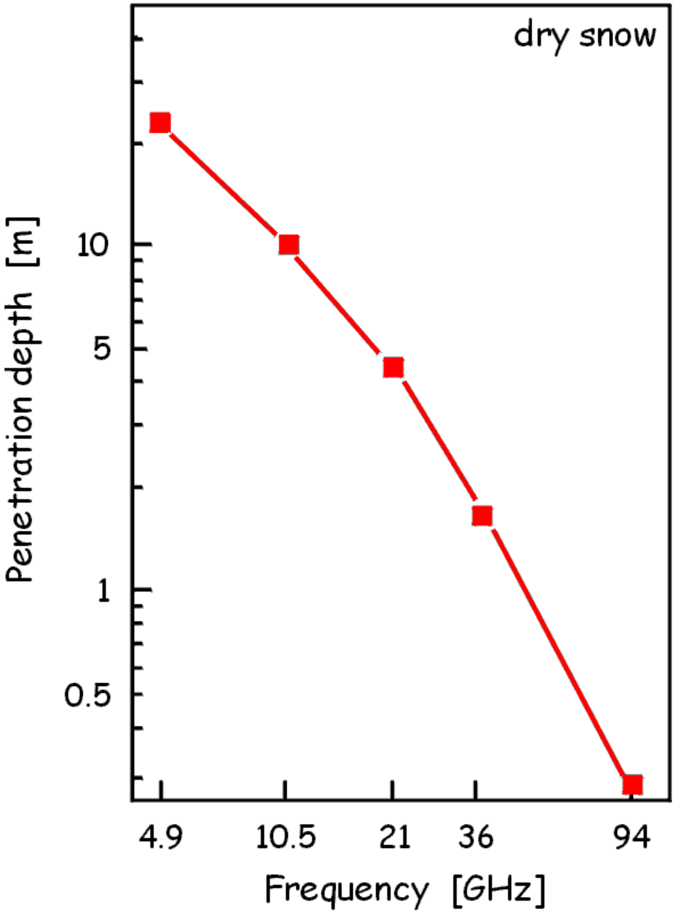
Microwave Permittivity

Microwave Penetration Depth in Dry Snow

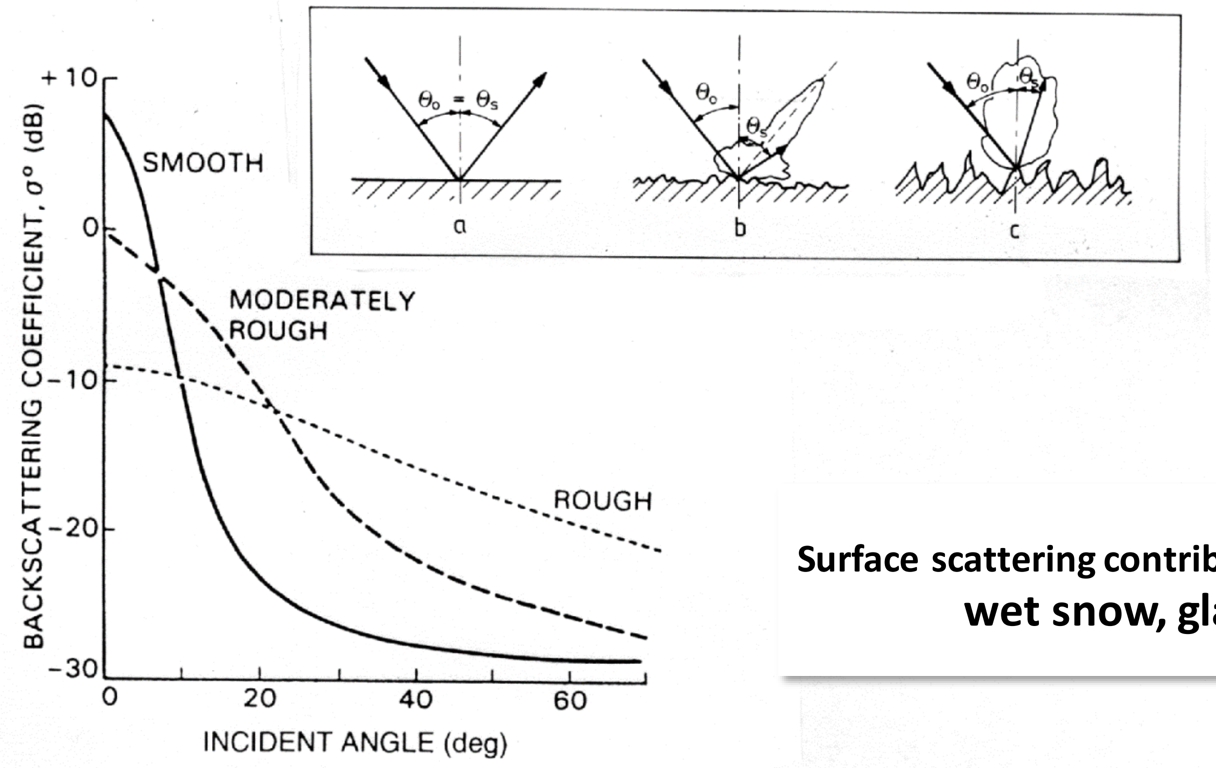
Measured by microwave radiometry:

- ■ Alpine snowpack (Mätzler, 1987)
- ⬢ Antarctic snow (Rott, 1993)
- ◆ Retrieved by inversion of satellite MW radiometry (SMMR) data, Antarctic

Dry snow: ***Attenuation dominated by scattering losses***



Backscattering from a Rough Surface



Surface scattering contribution dominates for

wet snow, glacier ice, soil, …

Factors for Backscattering of Snow (Ku to L-Band)

WET SNOW *Dominant Scattering Mechanism:* Surface Scattering

• Liquid water content	*dominant factor*
• Surface roughness	*important*
• Grain size	*small effect*

DRY SEASONAL SNOW: Scattering in the Volume and/or at Lower Interface

• σ° of medium below snow	*dominating for seasonal snow at f<10 GHz*
• Grain size	*important for f> 10 GHz*
• *Snow Mass (snow water equivalent, SWE)* →	*Little sensitivity of at X- to L-band; Ku-band sensitive to SWE, but ambiguity with grain size*

REFROZEN SNOW (*e.g. firn area on glaciers*) Volume Scattering

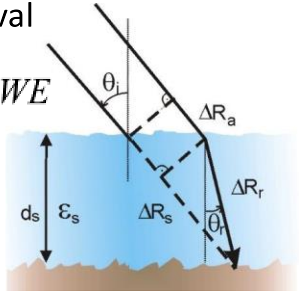
- Volume inhomogeneities (grains, grain clusters, ice lenses, ice pipes, ..)
- Internal interfaces between snow layers of different density

EO Concepts for SWE Monitoring

Approach	Strengths	Weaknesses
Passive MW 18.7 & 37 GHz 10.6 & 32 GHz	sensitive to SWE & melt; global daily coverage; independent of clouds/illumination; very long record	Coarse resolution, not suitable for mountains and forests, saturation at higher SWE
Radar (Scat or SAR): Dual: Ku & Ka Single: Ku, Ka	sensitive to SWE & melt; high resolution; independent of clouds/illumination	algorithm maturity, coverage, SWE saturation, forests
InSAR L- , C-Band	direct SWE sensitivity; high resolution avoids volume scattering issues	forests, complexity; requires advanced acquisition plan
LIDAR	direct observation of snow depth; very high resolution, minor forests and topographic issues	SWE retrieval requires snow density; No Sensor

InSAR SWE Retrieval

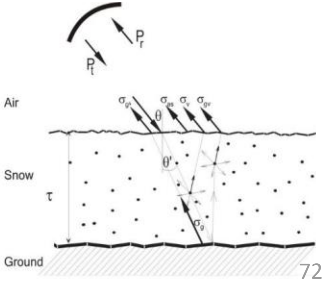
$$\Delta\phi_{snow} = \frac{1.6k}{\cos\theta_i}\Delta SWE$$



Radar (Scat or SAR)

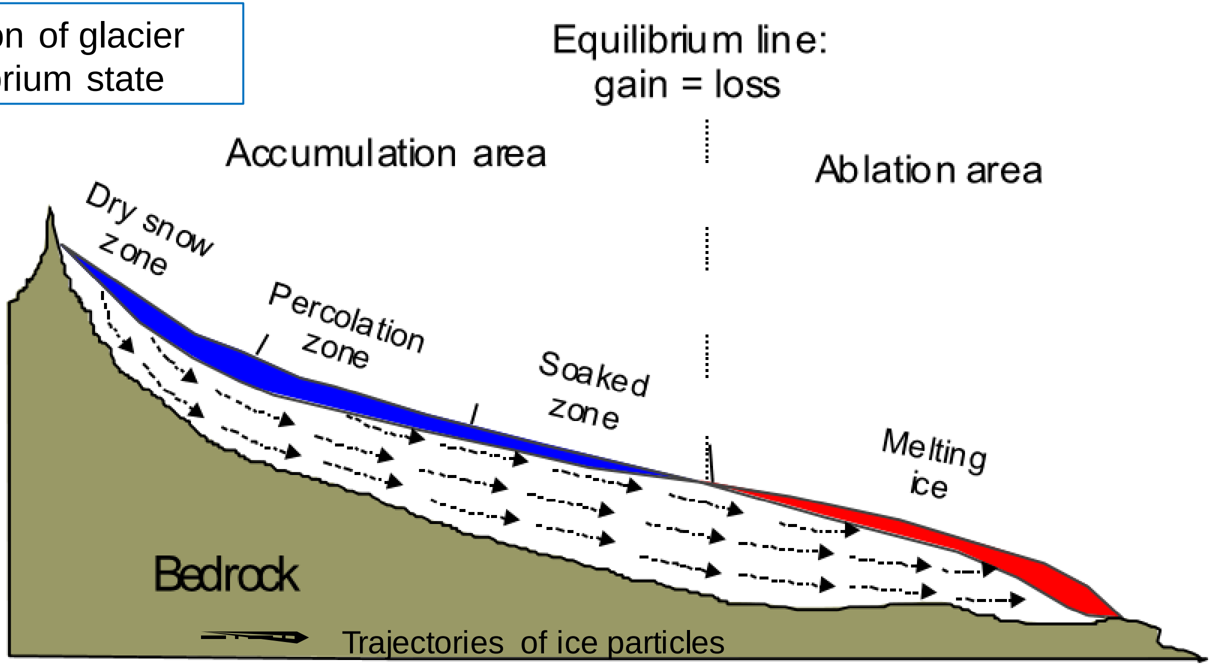
Sensitivity of backscatter to SWE depends on scattering albedo:

Dual F: Ku + Ka
Single F: Ku, Ka



Glacier Motion by InSAR and Offset Tracking

Ice motion of glacier
in equilibrium state

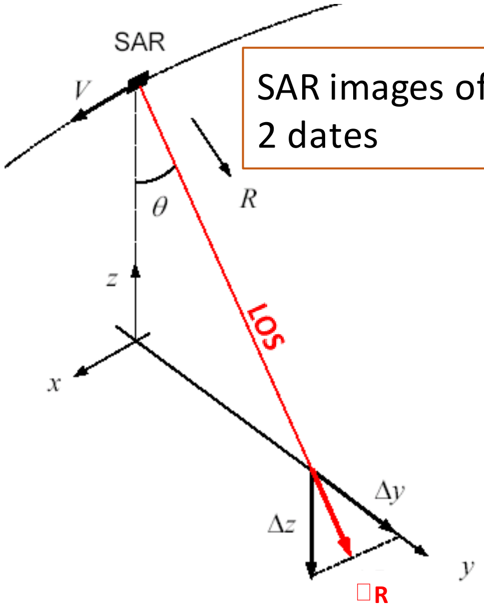


Objectives for mapping Ice Motion:

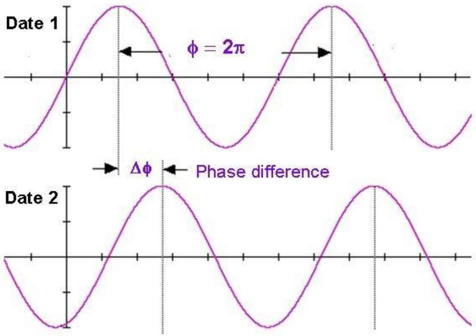
- Retrieving ice export by calving (Input/Output method for mass balance)

Interferometric measurement of displacement

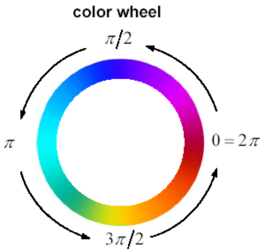
Measurement of Displacement



SAR images of
2 dates

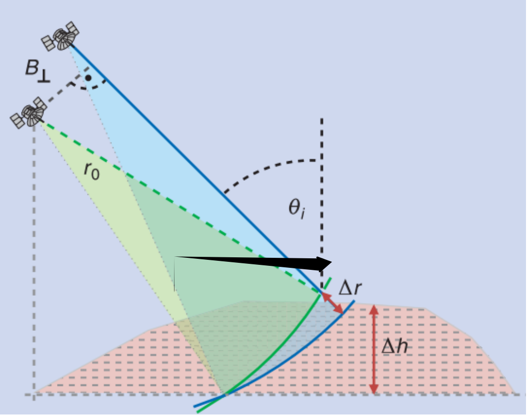


1 Fringe



TanDEM-X

InSAR for Topography



InSAR repeat track measures displacement

Requires temporal stability of radar signal phase (coherence)

Glacier Velocity Map

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

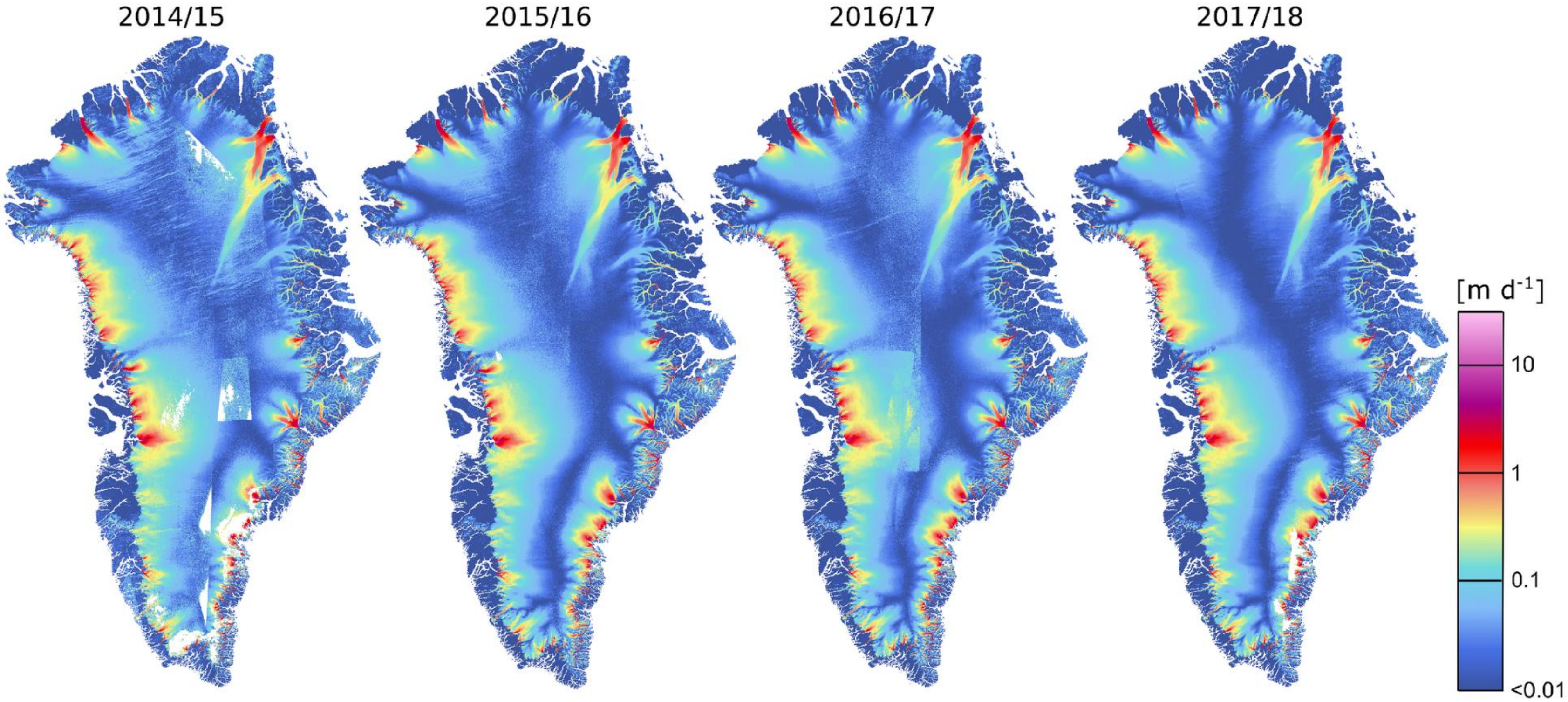
Possibilities for features to be tracked:

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.

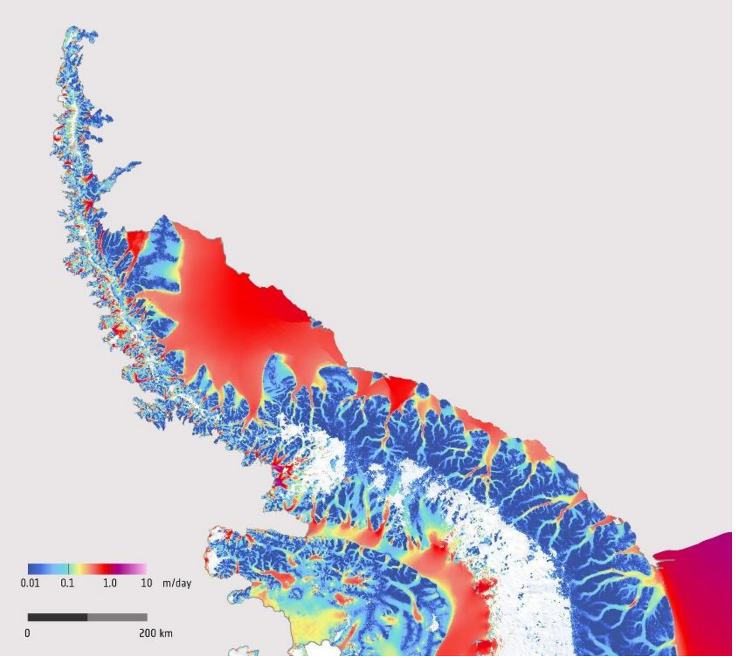
Glacier Velocity Map



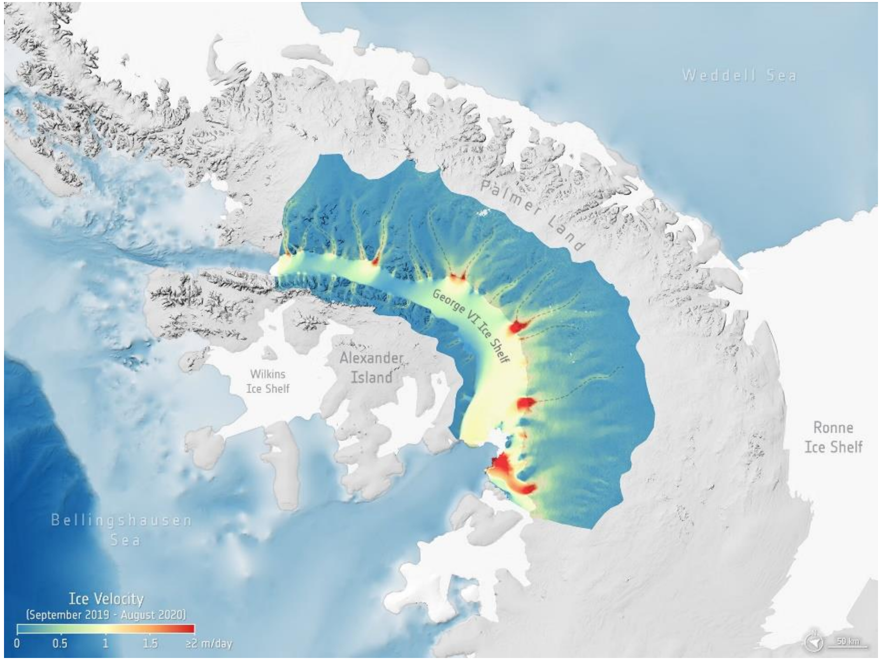
Annual ice velocity maps of Greenland from Copernicus Sentinel-1 2014-17 and winter campaign 2017/18.

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

Ice Flow Map



Antarctic Peninsula ice flow

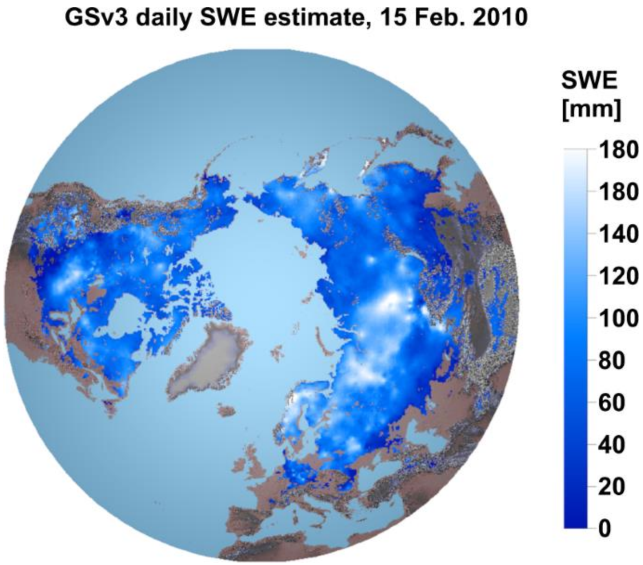


Ice-flow velocity of the George VI Ice Shelf

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 snow and ice

Incoming electromagnetic energy ${}_{I}(\lambda)$) is affected by:

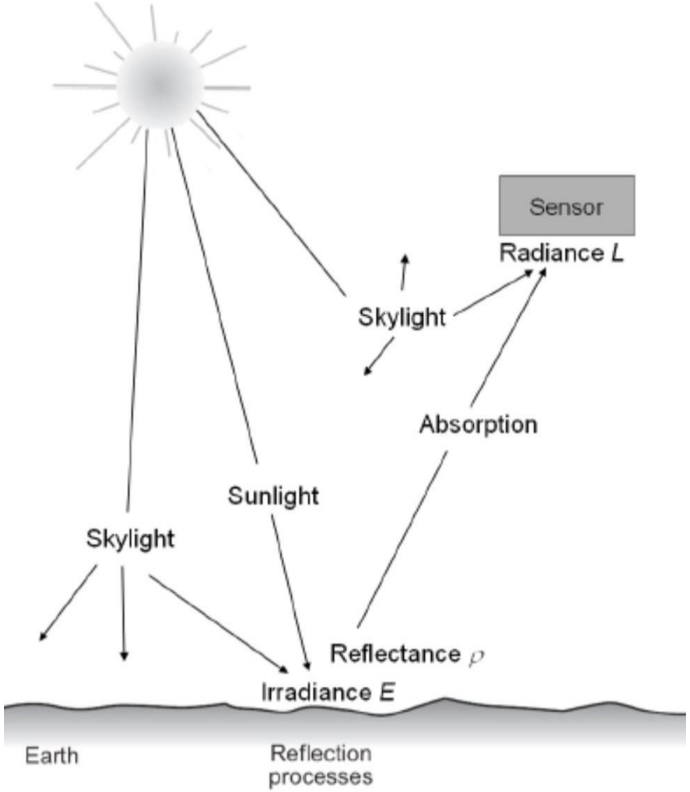
- Absorption ($E_A(\lambda)$)
- Scattering ($E_S(\lambda)$)
- Transmission ($E_T(\lambda)$)

Principle of energy conservation:

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

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

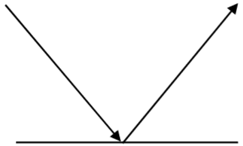
Optical sensors measure the amount of light receiving the satellite (= at-satellite radiance L), which is often converted to



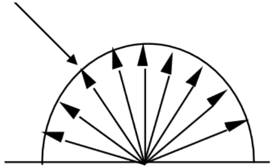
Optical for snow and ice

Reflectance depends on

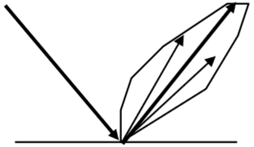
- Wavelength energy
- Atmospheric attenuation
- Geometry of the Surface
- Surface Materials



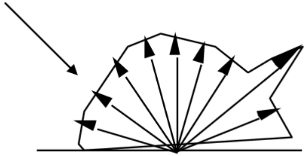
Specular reflector (mirror)



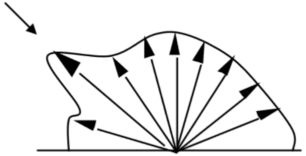
diffuse reflector (lambertian)



Nearly Specular reflector (water)

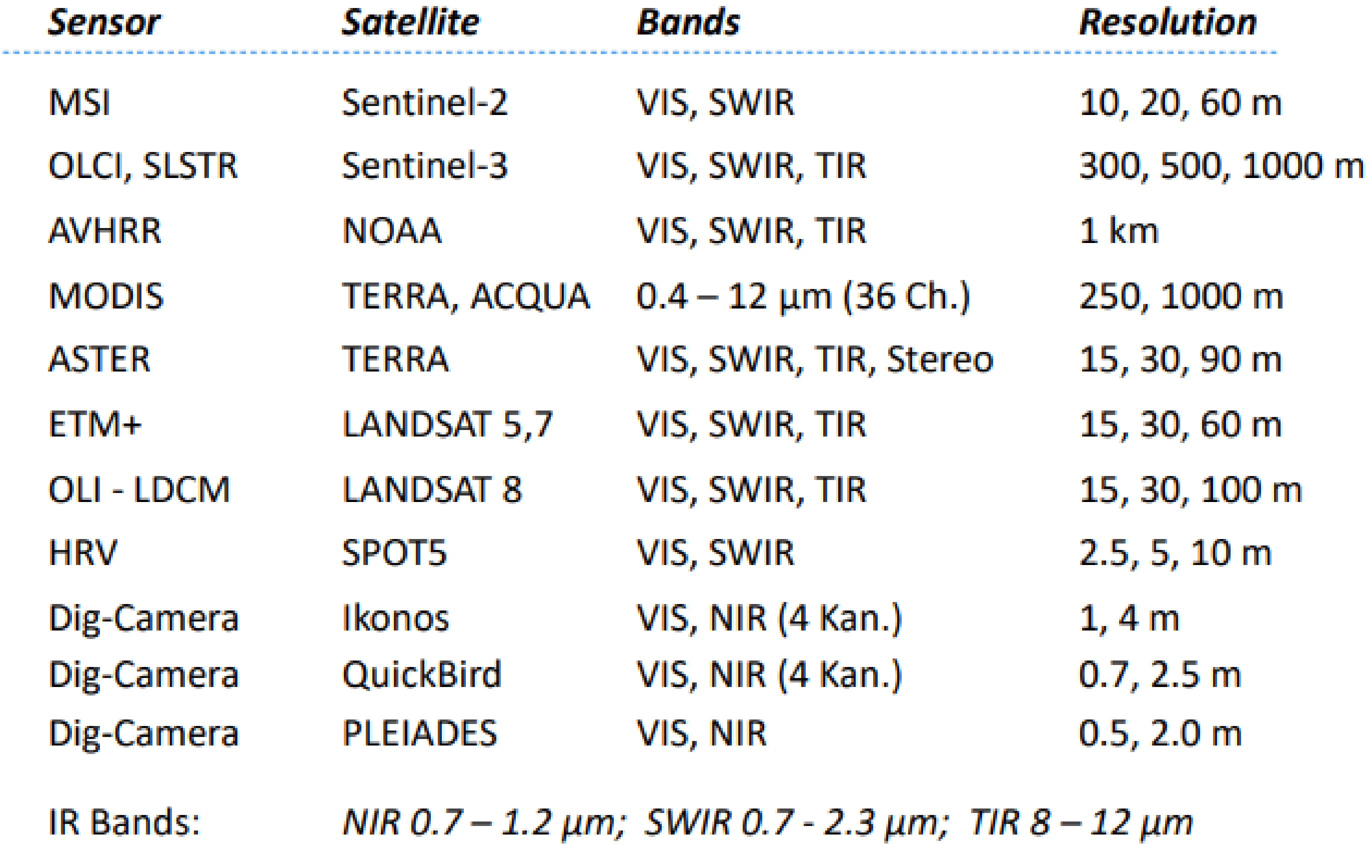


nearly diffuse reflector



Hot spot reflection

Selected Optical Sensors for Snow and 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*

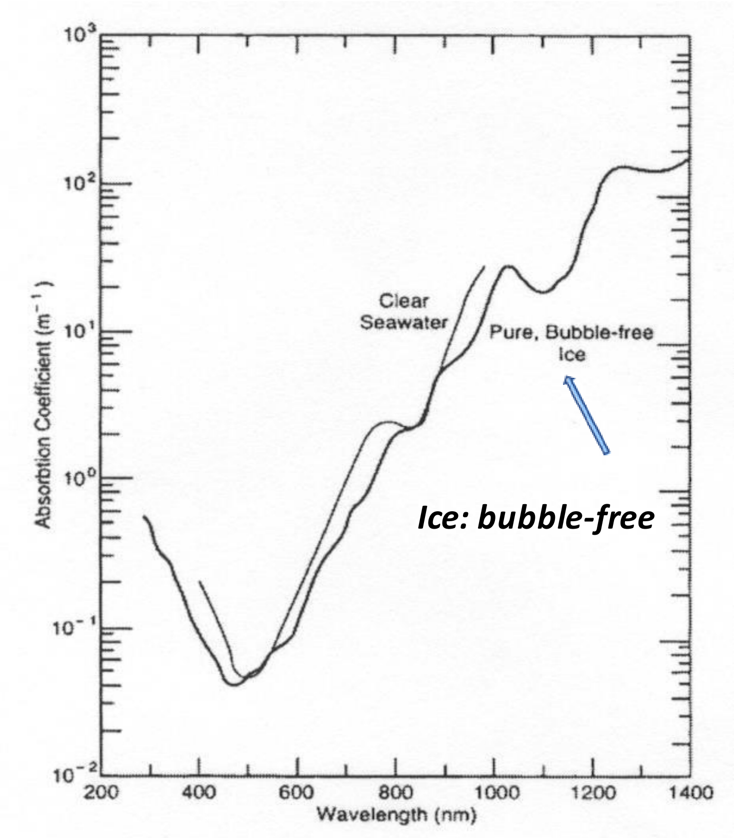
Extinction Coefficient of pure ice and sea water

Penetration depth (for intensity)

$$d_p = 1/K_e$$

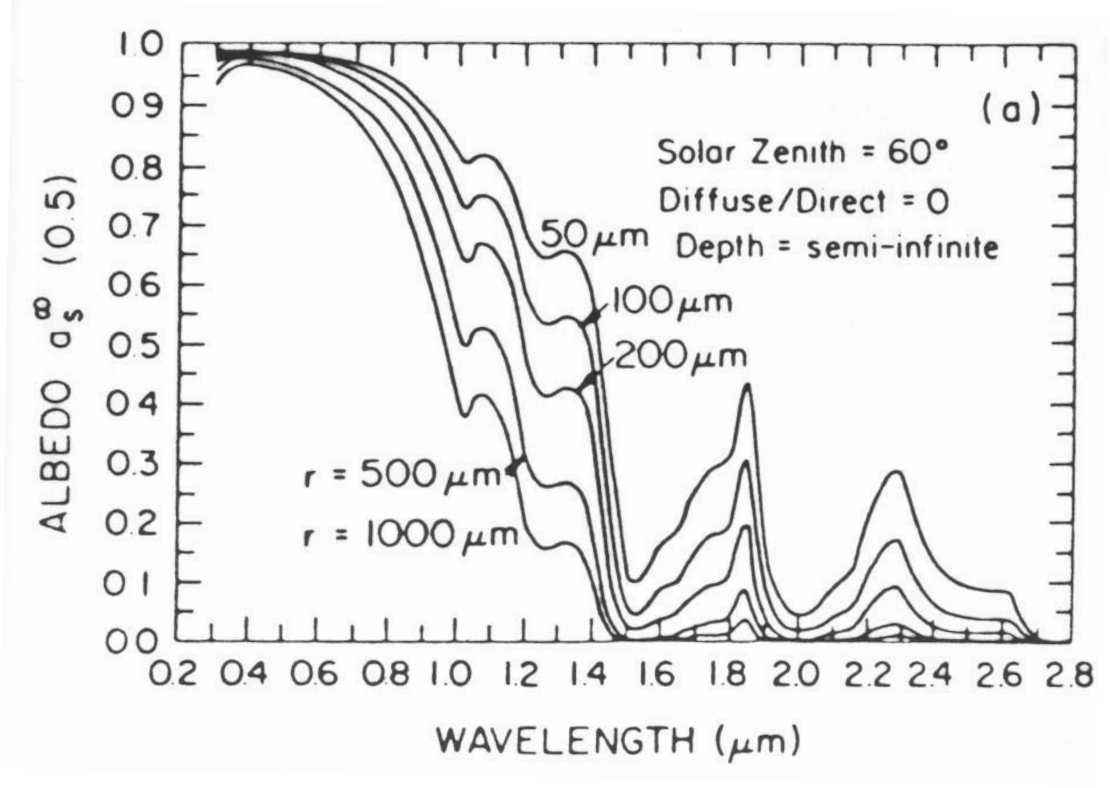
$K_e[m^{-1}]$ extinction coefficient

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



(Perovich, 1996)

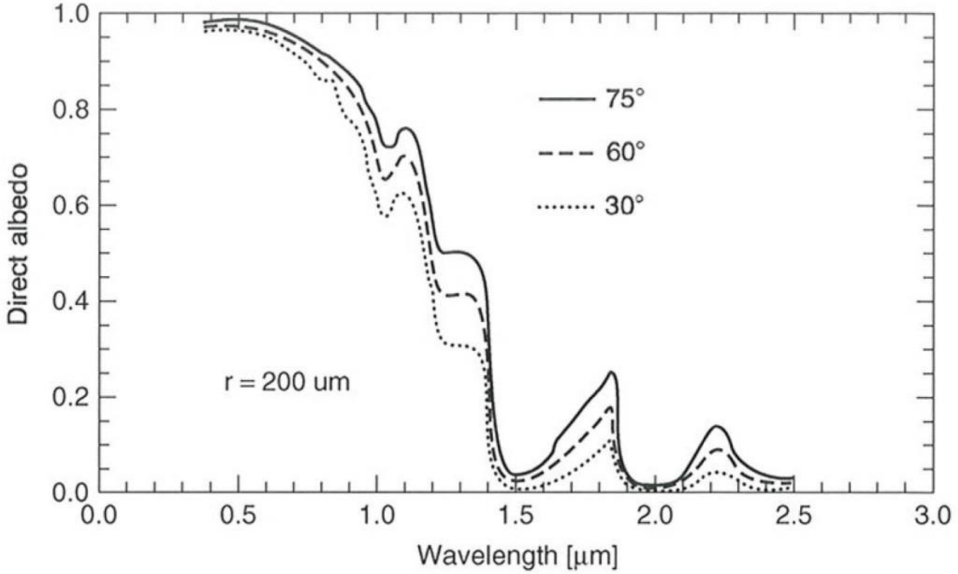
Spectral Reflectivity of Snow: Grain Size



Strong effect of grain size in near IR

Model Calculation by Wiscomb and Warren (1980)

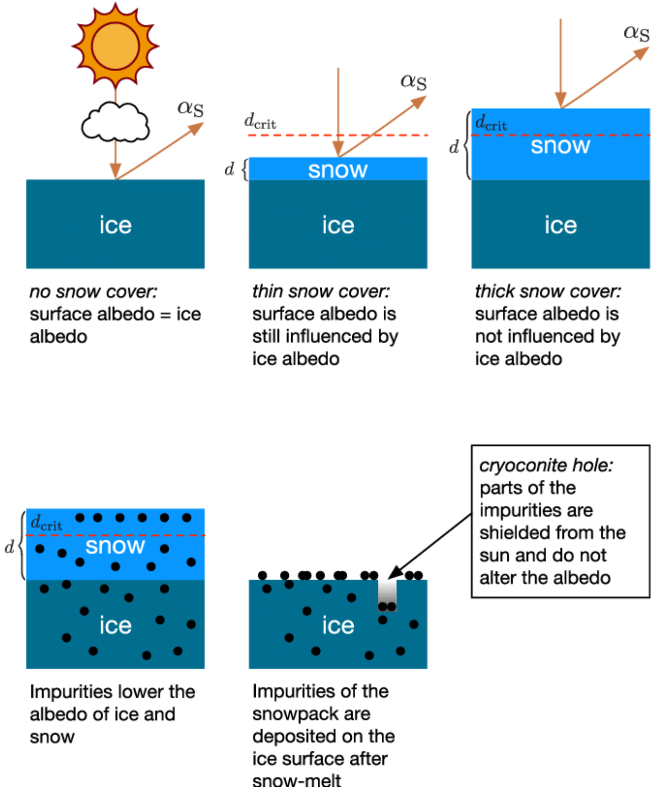
Angular Dependence of Snow Reflectivity



Snow albedo dependence on solar zenith angle

Main Factors for Spectral Reflectance of 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



no snow cover: surface albedo = ice albedo

thin snow cover: surface albedo is still influenced by ice albedo

thick snow cover: surface albedo is not influenced by ice albedo

Impurities lower the albedo of ice and snow

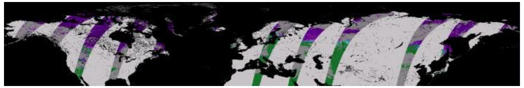
Impurities of the snowpack are deposited on the ice surface after snow-melt

cryoconite hole: parts of the impurities are shielded from the sun and do not alter the albedo

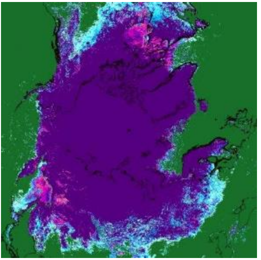
https://www.cambridge.org/core/journals/journal-of-glaciology/article/albedo-reduction-of-ice-caused-by-dust-and-black-carbon-accumulation-a-model-applied-to-the-ktransect-west-greenland/3FE93E004C1793A5DC4D78FD4CD1ECB4

Selected Snow Products from Optical Satellite data

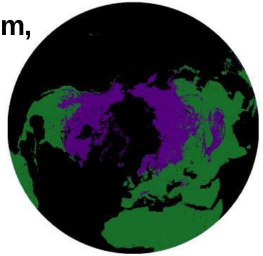
GlobSnow, 1 km, Fractional SE



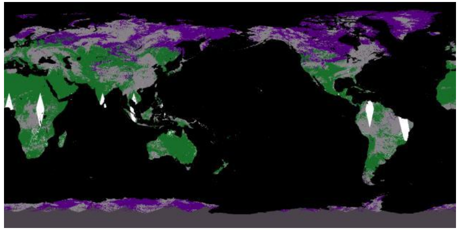
Pathfinder, 5 km, Fractional SE



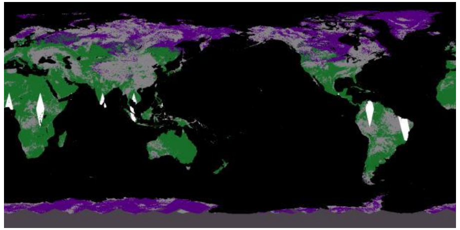
CryoClim, 5 km, Fractional SE



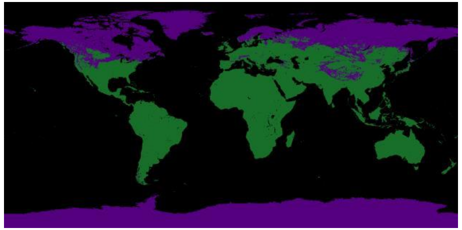
JAXA MDS10C, 5 km, Binary SE



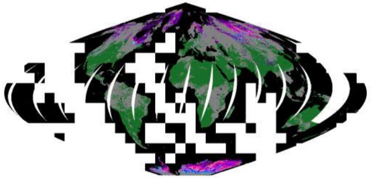
JAXA GHRM5C, 5 km, Binary SE



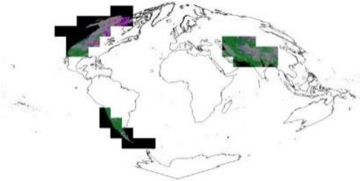
AutoSnow, 4 km, Binary SE



MOD10_C5, 0.5 km, Fractional SE

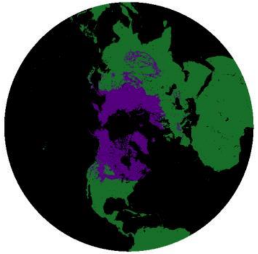


MODSCAG, 0.5 km, Fractional SE

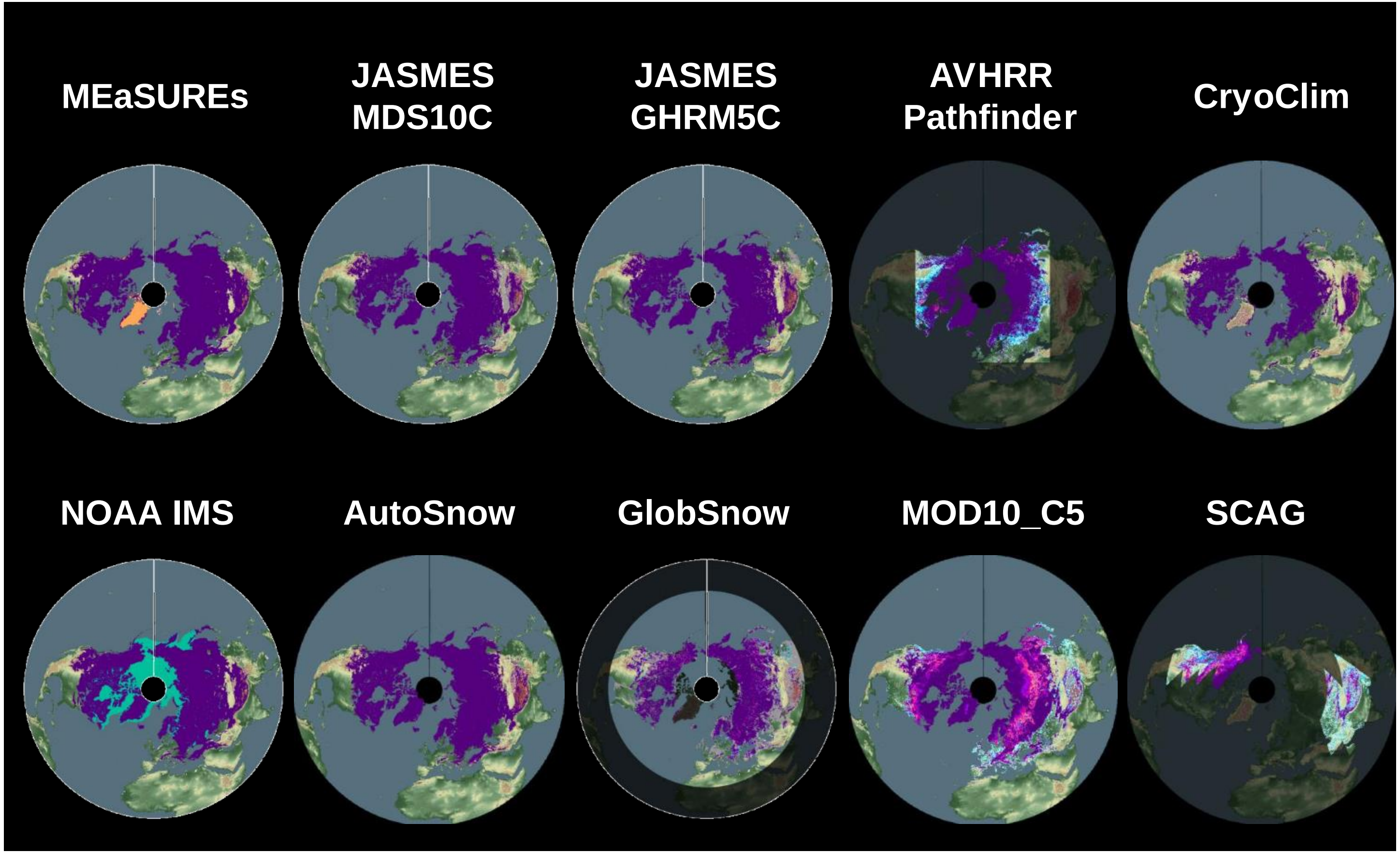


MEaSUREs, 25 km, Binary SE

IMS, 4 km, Binary SE

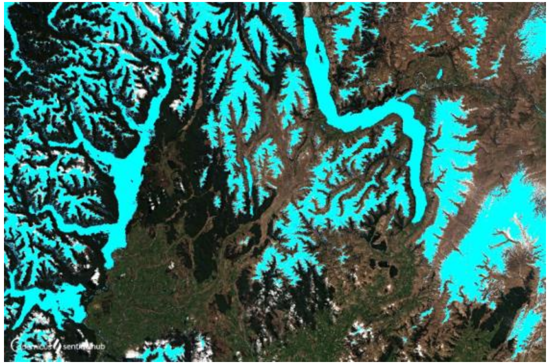


Hemispheric snow products reprojected in EASE-GRID 2.0

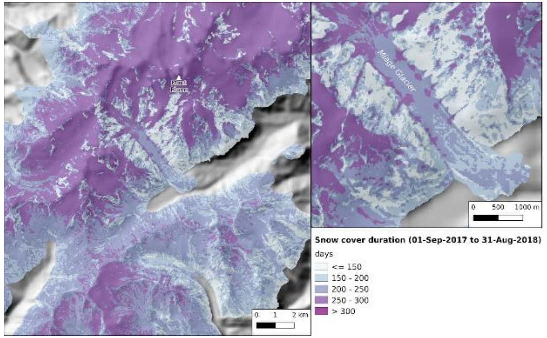


Applications in Cryosphere: Optical Sensors

- 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



Visualized NDSI over New Zealand, acquired on 2019-09-19.



Snow Cover Duration for Mont-Blanc area during an hydrological year (1 September 2016 to 31 August 2017) produced by synthesis of Theia snow-covered surface products.

Source: https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/ndsi/, https://www.theia-land.fr/en/product/snow/

Thank you for the attention