





# 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



### 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/introducin g-the-arctic/snow-water-ice-permafrost/cryosphere/

#### **Examples of snow patterns in different environments**









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-valleylandsystems/debris-covered-glacier-landsystems/

### Typical densities of snow and ice

Typical densities of snow and ice (kg/m³)	
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 (InSA	R)
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 m100m 30500 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 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**



#### 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

- $\sigma^{\circ}$  of medium below snow *dominating for seasonal snow at f<10 GHz*
- Grain size important for f> 10 GHz
- Snow Mass (snow water → Little sensitivity of at X- to L-band; equivalent, SWE) 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 <sup>(Scat or SAR):</sup> 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



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**



Objectives for mapping Ice Motion:

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

#### Interferometric measurement of displacement



Requires temporal stability of radar signal phase (coherence)

## 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  $(\lambda)$  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



#### Reflectance depends on

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



Specular reflector (mirror)



Nearly Specular reflector (water)



diffuse reflector (lambertian)



nearly diffuse reflector



Hot spot reflection

#### **Selected Optical Sensors for Snow and Glacier Monitoring**

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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  $0.7 - 1.2 \mu m$ ; SWIR  $0.7 - 2.3 \mu m$ ; TIR  $8 - 12 \mu m$ 

#### **Extinction Coefficient of pure ice and sea water**



(Perovich, 1996)

#### **Spectral Reflectivity of Snow: Grain Size**



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  $\lambda > \sim 1 \ \mu m$
- Liquid water content (relevant in shortwave IR; primarily an indirect effect through grain size)
- Illumination and observation geometry (bidirectional reflectance)
- Surface roughness



Impurities of the

ice surface after snow-melt

snowpack are deposited on the

Impurities lower the

albedo of ice and

snow

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



JAXA GHRM5C, 5 km, Binary SE

CryoClim, 5 km, Fractional SE

AutoSnow, 4 km, BinarySE



MEaSUREs, 25 km, Binary SE



IMS, 4 km, Binary SE



JAXA MDS10C, 5 km, Binary SE



MOD10\_C5, 0.5 km, Fractional SE



MODSCAG, 0.5 km, Fractional 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

For more information, see the tutorial:

<u>11. Generating high resolution binary and fractional snow</u> <u>maps from Sentinel-2 data using SNAP software</u>





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

Snow Cover Duration Mont-Blanc area for during an hydrological September (1 vear to 31 August 2016 2017) produced bv over duration (01-Sep-2017 to 31-Aug-2018) SVNTHESIS Theia Of snow-covered surface products.

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









#### Thank you for the attention

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