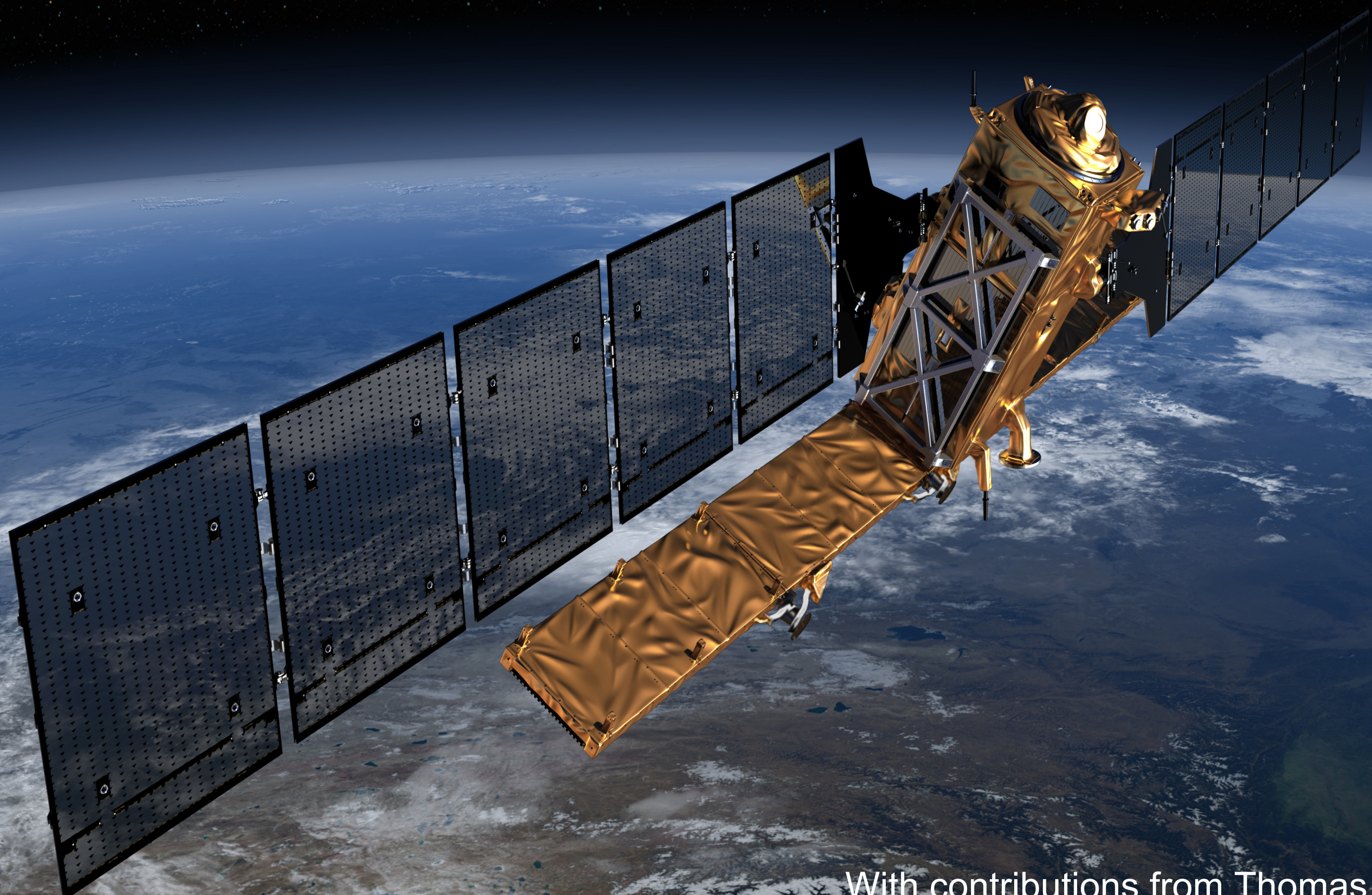
University of Zurich[UZH]

ESA Cryosphere Training Course – Sept. 16, 2016

Leeds, England

Snow on land from EO



David Small

With contributions from Thomas Nagler (ENVEO), and
David Jäger, Christoph Rohner, Adrian Schubert (UZH-RSL)

Outline

Snow on land from EO

- Motivation
- **Visible & Infrared**
- Microwave radiometry (active): **SAR**
  - Backscatter Normalisation Conventions
  - Radiometric Terrain Corrections
  - Backscatter Compositing
  - Sentinel-1 Examples

- Conclusions

Remote Sensing of Snow: Motivation

Knowledge of snow parameterisation important for

- Mitigating large economic impacts of snowfall events
- Snow wetness: run-off modelling: measurements and future prognoses
- Snow wetness: Sudden melt events inducing flooding
- Snow wetness: Hydrology
- Snow distribution and season length – interactions with land cover
- Avalanche modelling
- Climate interactions

J. Dietz, C. Kuenzer, and S. Dech, "**Global SnowPack: a new set of snow cover parameters for studying status and dynamics of the planetary snow cover extent**," Remote Sens. Lett., 6(11), pp. 844–853, Sep. 2015.

D. R. DeWalle and A. Rango, **Principles of Snow Hydrology**. Cambridge, UK: Cambridge University Press, 2008.

Multi-sensor approaches

Multiple sensors each have own strengths and weaknesses:

- VIS/IR
- Microwave (active & passive)
- Airborne Laser Scanning (ALS)

A. J. Dietz, C. Kuenzer, U. Gessner, and S. Dech, "**Remote sensing of snow – a review of available methods**," Int. J. Remote Sens., vol. 33, no. 13, pp. 4094–4134, Jul. 2012.

Strengths and weaknesses of respective measurements, e.g.:

- available at night?
- distorted in presence of steep topography?

Difficult in past to integrate e.g. VIS/IR and SAR over large regions due to lack of co-temporal products with similar resolutions / relatively homogenous properties

Future: integrate required 'harmonised' measurements, harnessing all strengths?

Visible / Infra-red

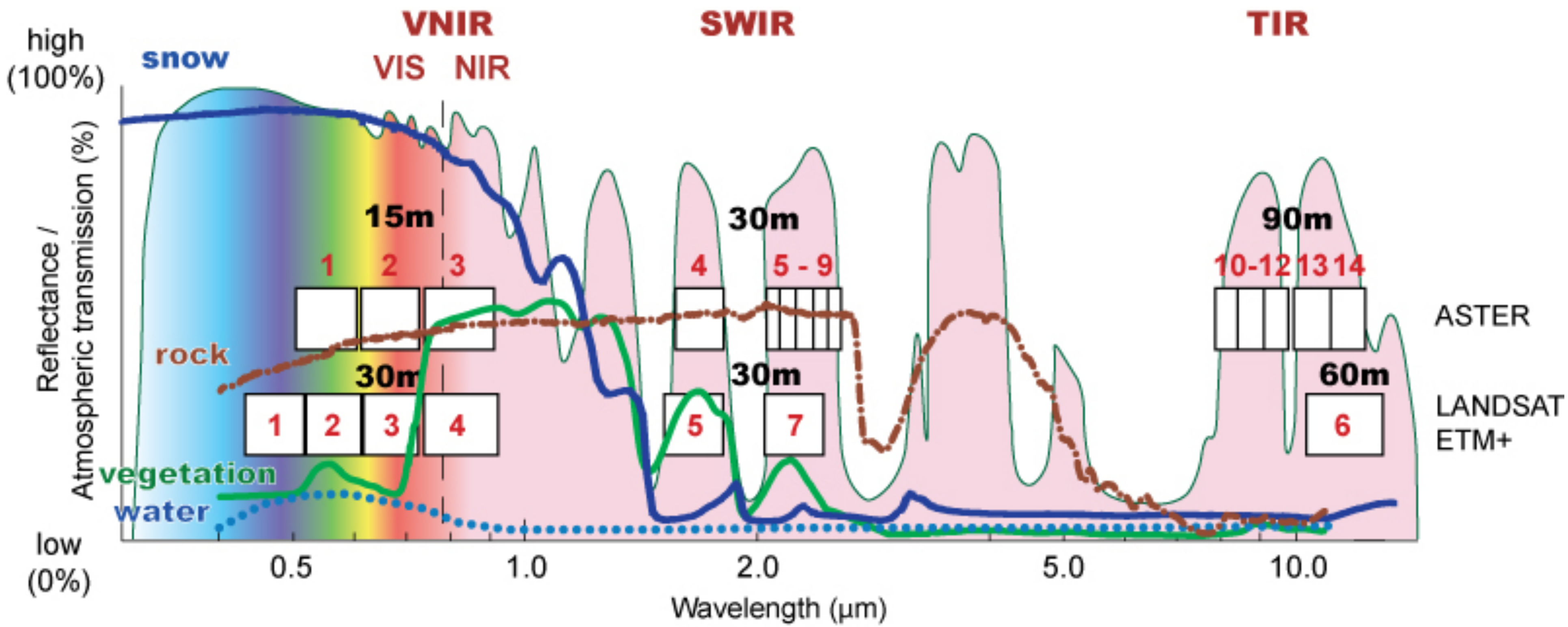
Composite Products

- Assemble wide-area coverage using set window
- Well-established for optical remote sensi
- https://lpdaac.usgs.gov/dataset_discove

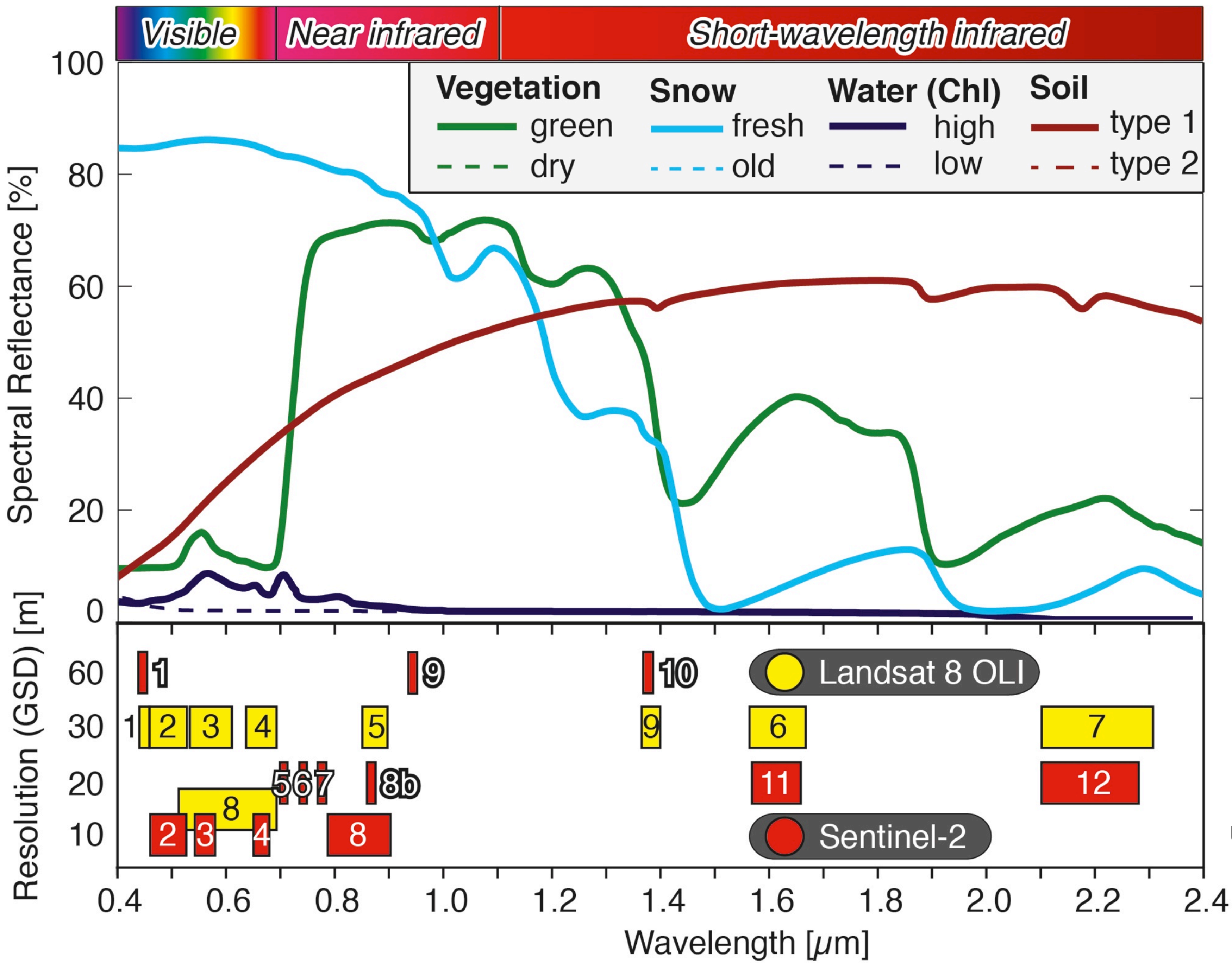
Name	Dataset	Product	Pixel Size	Tempora Granulari
MCD15A2	Combined MODIS	Leaf Area Index and Fractional Photosynthetically Active Radiation	1000	Composites
MCD15A3	Combined MODIS	Leaf Area Index and Fractional Photosynthetically Active Radiation	1000	Composites
MCD43A1	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	500	Composites
MCD43A2	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	500	Composites
MCD43A3	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	500	Composites
MCD43A4	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	500	Composites
MCD43B1	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	1000	Composites
MCD43B2	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	1000	Composites
MCD43B3	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	1000	Composites
MCD43B4	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	1000	Composites
MCD43C1	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	5600	Composites
MCD43C2	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	5600	Composites
MCD43C3	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	5600	Composites
MCD43C4	Combined MODIS	Bidirectional Reflectance Distribution Function and Albedo	5600	Composites
MOD09A1	Terra MODIS	Reflectance	500	Composites
MOD09Q1	Terra MODIS	Reflectance	250	Composites
MOD11A2	Terra MODIS	Temperature and Emissivity	1000	Composites
MOD11C2	Terra MODIS	Temperature and Emissivity	5600	Composites
MOD13A1	Terra MODIS	Vegetation Indices	500	Composites
MOD13A2	Terra MODIS	Vegetation Indices	1000	Composites
MOD13C1	Terra MODIS	Vegetation Indices	5600	Composites
MOD13Q1	Terra MODIS	Vegetation Indices	250	Composites
MOD14A2	Terra MODIS	Thermal Anomalies and Fire	1000	Composites
MOD15A2	Terra MODIS	Leaf Area Index and Fractional Photosynthetically Active Radiation	1000	Composites
MOD17A2	Terra MODIS	Gross Primary Productivity	1000	Composites
MOD44A	Terra MODIS	Vegetation Continuous Cover/Fields	250	Composites
MYD09A1	Aqua MODIS	Reflectance	500	Composites
MYD09Q1	Aqua MODIS	Reflectance	250	Composites
MYD11A2	Aqua MODIS	Temperature and Emissivity	1000	Composites
MYD11C2	Aqua MODIS	Temperature and Emissivity	5600	Composites
MYD13A1	Aqua MODIS	Vegetation Indices	500	Composites
MYD13A2	Aqua MODIS	Vegetation Indices	1000	Composites
MYD13C1	Aqua MODIS	Vegetation Indices	5600	Composites
MYD13Q1	Aqua MODIS	Vegetation Indices	250	Composites
MYD14A2	Aqua MODIS	Thermal Anomalies and Fire	1000	Composites
MYD15A2	Aqua MODIS	Leaf Area Index and Fractional Photosynthetically Active Radiation	1000	Composites
MYD17A2	Aqua MODIS	Gross Primary Productivity	1000	Composites

- Composite usage a recognised remedy to cloud-coverage issue
  - Clouds are a ***spatio-temporal*** phenomenon that introduce difficulties to interpreting single optical image sets
- For SAR data, topography introduces difficulties to interpretation of single image acquisition due to:
  - gradients in terrain (***spatial***)
  - variations in imaging geometry depending on track (***temporal***)
- Composite products could help resolve issues in interpreting SAR backscatter
- Yet no widely-established standard SAR-based composite products to date

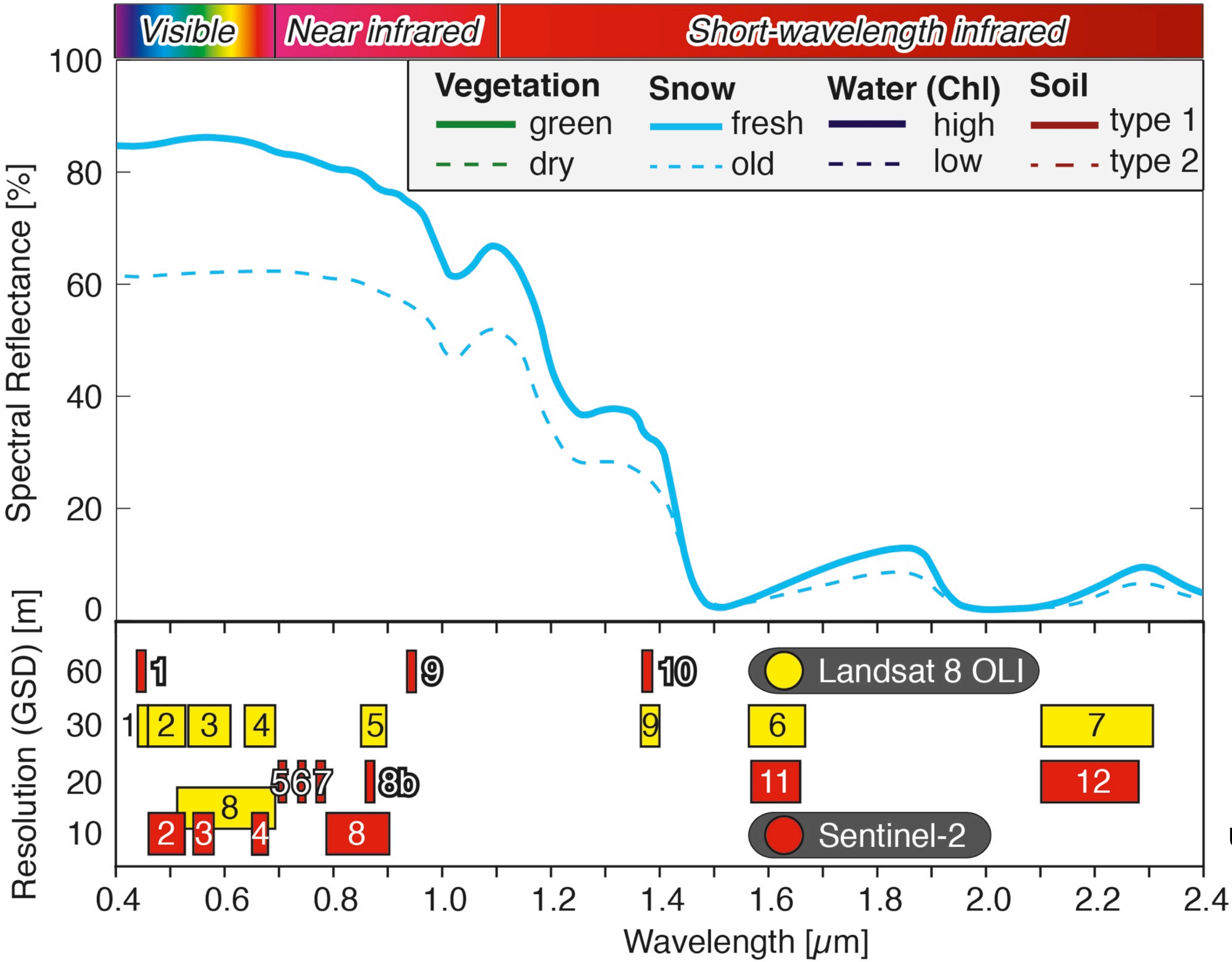
Remote Sensing of Snow: VIS/IR



ESA eduspace



Courtesy
H. Wulf,
UZH-RSL



Courtesy
H. Wulf,
UZH-RSL

Active Microwave: Synthetic Aperture Radar

Snow and Dielectric Constant: Attenuation in wet snow

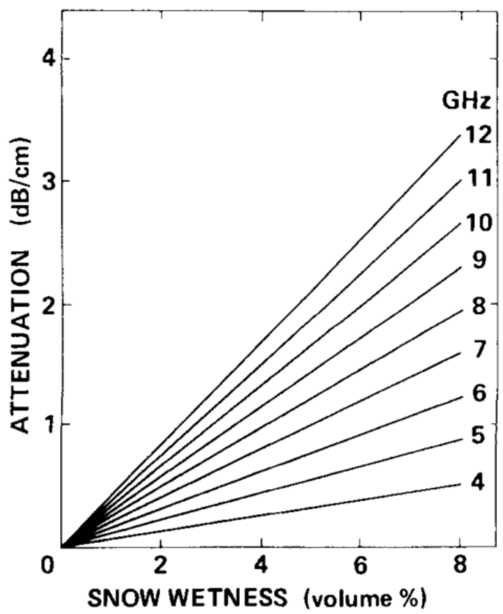
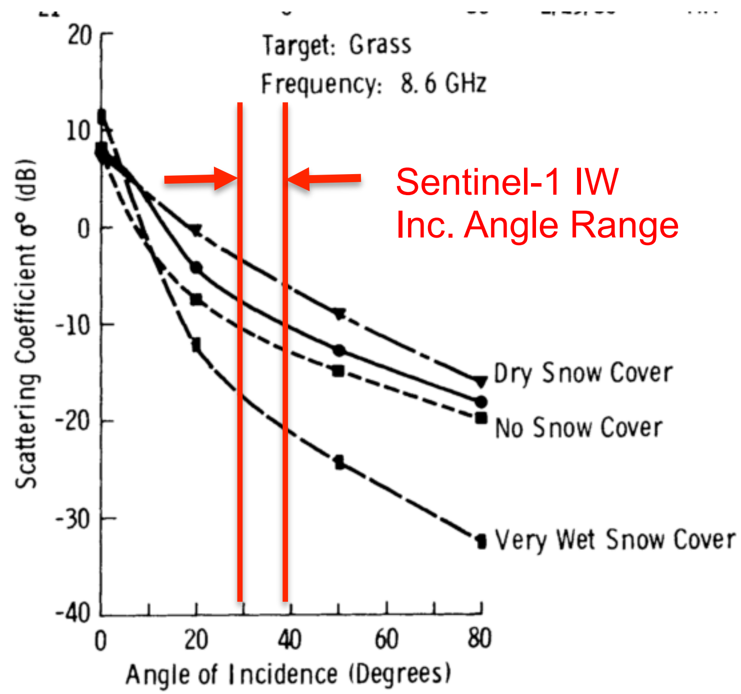


FIG. 5. Variation of attenuation with snow wetness at selected frequencies.



F. T. Ulaby, W. H. Stiles, and M. Abdelrazik, "**Snowcover Influence on Backscattering from Terrain**," IEEE Trans. Geosci. Remote Sens., vol. GE-22, no. 2, pp. 126–133, Mar. 1984.

W. I. Linlor, "**Permittivity and attenuation of wet snow between 4 and 12 GHz**," J. Appl. Phys., vol. 51, no. 5, pp. 2811–2816, May 1980.

Active Microwave: Synthetic Aperture Radar

SAR: Backscatter Normalisation Conventions

Seasonal prioritization of SAR observation windows

Normalised Radar Cross Section (NRCS)

Backscatter coefficients [dB] are *ratio of scattered to incident power* over a given **area**:

RCS

$$\sigma = k \cdot \frac{P_s}{P_i}$$

NRCS

$$\beta^0 = \frac{\sigma}{A_\beta} \qquad \sigma_E^0 = \frac{\sigma}{A_\sigma} \qquad \gamma_E^0 = \frac{\sigma}{A_\gamma}$$

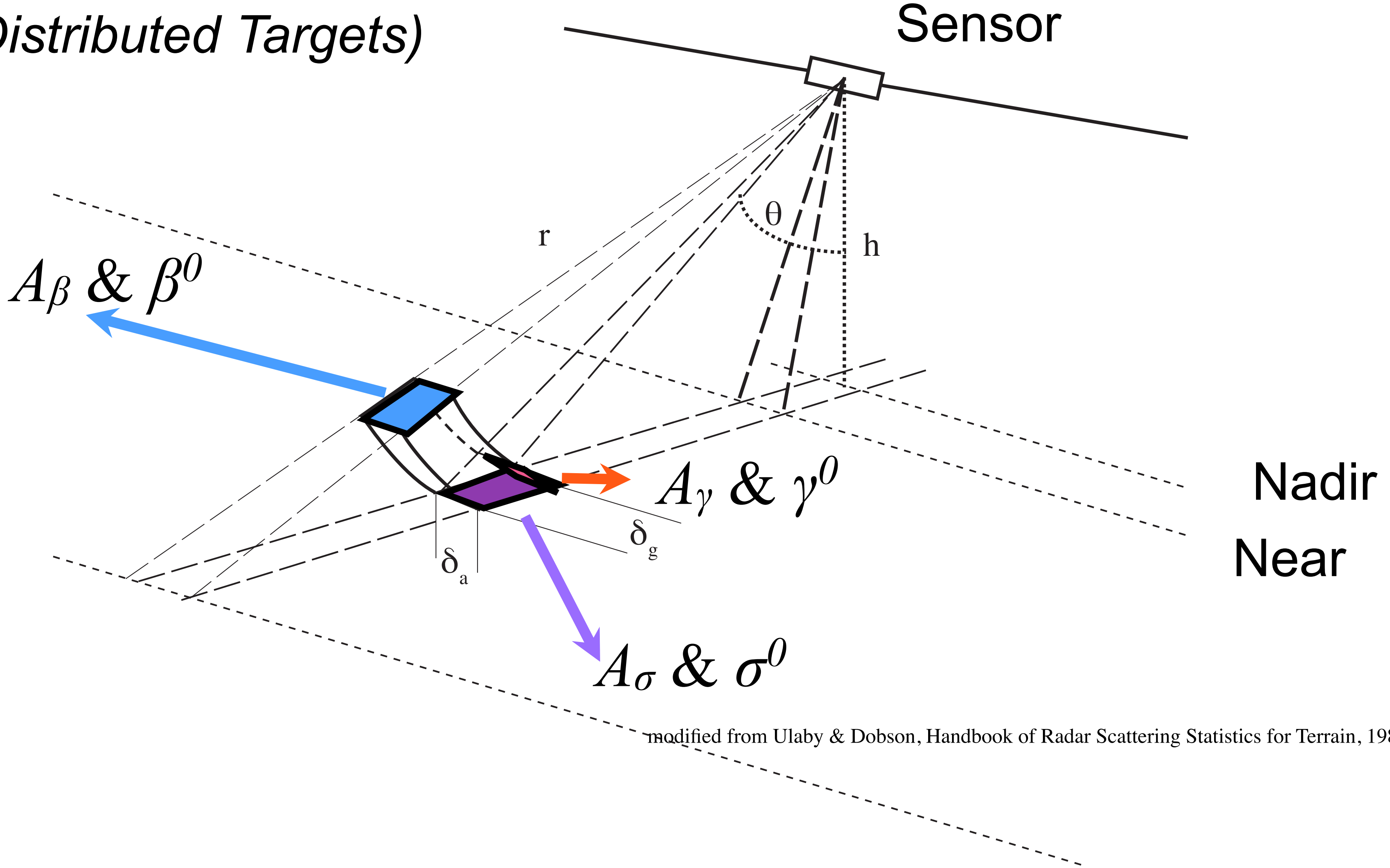
Known: transmitted & received power P_t & P_r

Derive: incident & scattered power P_i & P_s from P_t & P_r

$$\beta^0 = k \cdot \frac{f_2(P_r)}{f_1(P_t)} \cdot \frac{1}{A_\beta} \qquad \sigma_E^0 = k \cdot \frac{f_2(P_r)}{f_1(P_t)} \cdot \frac{1}{A_\sigma} \qquad \gamma_E^0 = k \cdot \frac{f_2(P_r)}{f_1(P_t)} \cdot \frac{1}{A_\gamma}$$

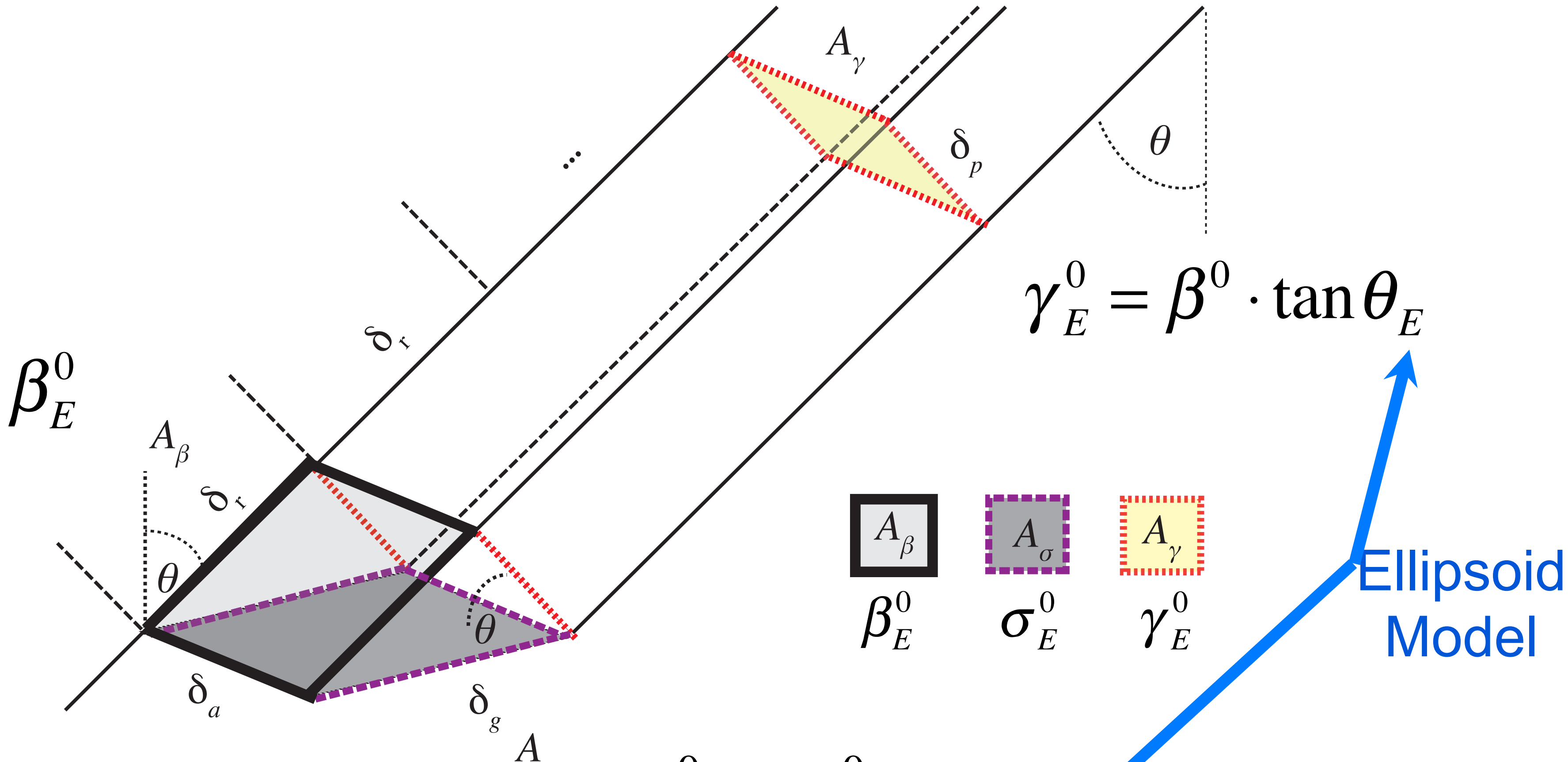
Standard Areas for Normalisation

(Distributed Targets)



modified from Ulaby & Dobson, Handbook of Radar Scattering Statistics for Terrain, 1989

Ground Illuminated Area



$$\gamma_E^0 = \beta^0 \cdot \tan\theta_E$$

$$\sigma_E^0 = \beta^0 \cdot \sin\theta_E$$

Backscatter coefficients are *relative* to *isotropic* scattering

An idealised **isotropic** scatterer will scatter *equally in all directions*

Real Imaged Objects

- can tend to scatter more **forward** than back to the sensor, focussing energy away from the measurement
  - are darker, generating **negative** *dB* values
- can focus energy **back** towards the sensor (e.g. through corner reflections), generating **positive** *dB* backscatter

Wet snow detection with dB thresholding

$$(\gamma^0_{wet} - \gamma^0_{ref}) \ \ [\mathrm{dB}]$$

When difference between candidate image backscatter and dry reference image is lower than -3dB, classify as wet snow

Developed for ERS-1 geometries, VV-pol.

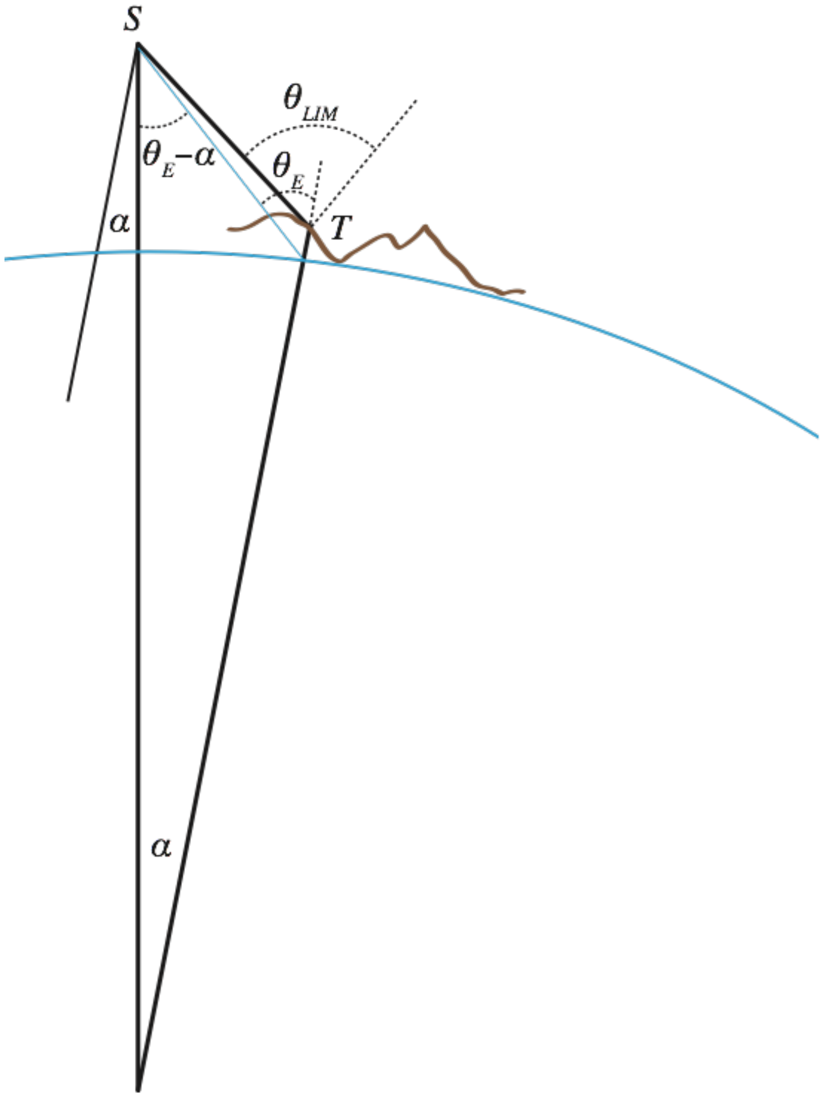
Relies on **exact repeat tracks** (e.g. 35-day ERS repeat) to avoid corruption e.g. by terrain-induced effects

N. Longépé, S. Allain, L. Ferro-Famil, E. Pottier, and Y. Durand, "**Snowpack Characterization in Mountainous Regions Using C-Band SAR Data and a Meteorological Model**," IEEE Trans. Geosci. Remote Sens., vol. 47, no. 2, pp. 406–418, Feb. 2009.

T. Nagler and H. Rott, "**Retrieval of wet snow by means of multitemporal SAR data**," IEEE Trans. Geosci. Remote Sens., vol. 38, no. 2, pp. 754–765, Mar. 2000.

N. Baghdadi, Y. Gauthier, and M. Bernier, "**Capability of Multitemporal ERS-1 SAR Data for Wet-Snow Mapping**," Remote Sens. Environ., vol. 60, no. 2, pp. 174–186, May 1997.

Spaceborne Radar Geometry



Incident Angles:

1. Nominal, from **Ellipsoid**:

$$\theta_E$$

2. Local Incident Angle, from **height model**:

$$\theta_{LIM}$$

Normalising σ for *terrain*

$$\beta^0, \sigma_E^0, \gamma_E^0$$

are each usable and widely used to normalise the backscatter σ, but one main problem remains:

Each of β^0, σ^0, γ^0 vary with the local terrain situation (forest on a hill *foreslope* is brighter than forest on *flat* ground, which is brighter than forest on a hill *backslope*)

Local Incident-angle Mask (LIM)

The most common slope-normalisation methodology found in the literature is fails to account for **non-homomorphic** (one to many correspondence) nature of relationship between Earth coordinates (map geometry) & slant range geometry (native sensor acquisition process)

Normalisation for local variation of ground scattering area expressed in map geometry:

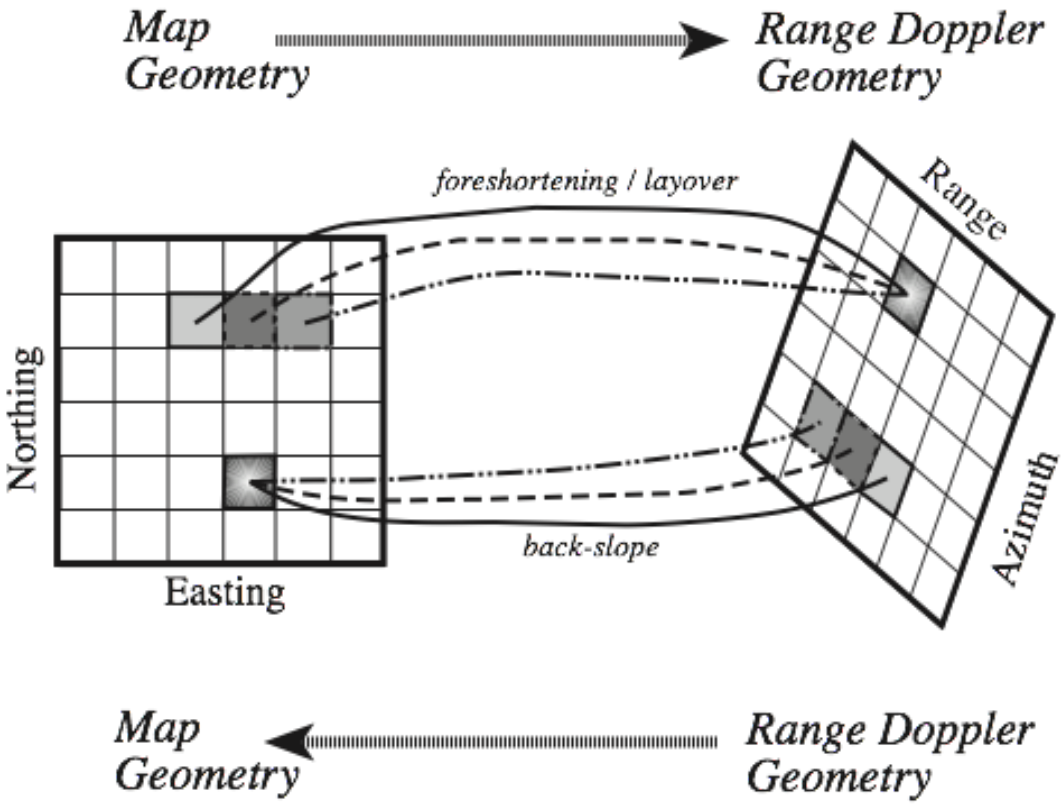
$$\sigma_T^0 \triangleq \sigma_{NORLIM}^0 = \sigma_E^0 \cdot \frac{\sin\theta_{LIM}}{\sin\theta_E}$$

Kellndorfer et al., TGRS, Sept. 1998.

Lack of Homomorphism

Dept. of Geography / Remote Sensing Laboratories

No one-to-one correspondence between slant range and map geometries on **fore-** and **back**-slopes



Radar Equation & Reference Area

Relating *received* to *transmitted* power:

$$\overline{P}_r = \frac{\lambda^2}{(4\pi)^3} \cdot \int_{\text{area illuminated}} \frac{P_t G^2}{R^4} \cdot \sigma^0 dA$$

Ulaby, Moore, Fung, 1982.

Standard equation of: $\sigma_E^0 = \beta^0 \cdot \sin\theta_E$

uses an *ellipsoid Earth model* approximation as a standard normalisation area - using ellipsoidal incidence angle θ_E as a **proxy for area**

- For radiometric terrain correction, we need to actually *perform the integration* on a DEM

Time to Leave Kansas!

The concept of a ***single*** *Local Incident Angle* determining the terrain's local normalisation area is **flawed**:

- old concept adapted from ellipsoidal incident angle for ocean, sea-ice, & *flatlands*
- fails to account for:
  - shadow
  - foreshortening
  - layover

Improve sensor model:

➡ use local contributing ***area***, not angle!

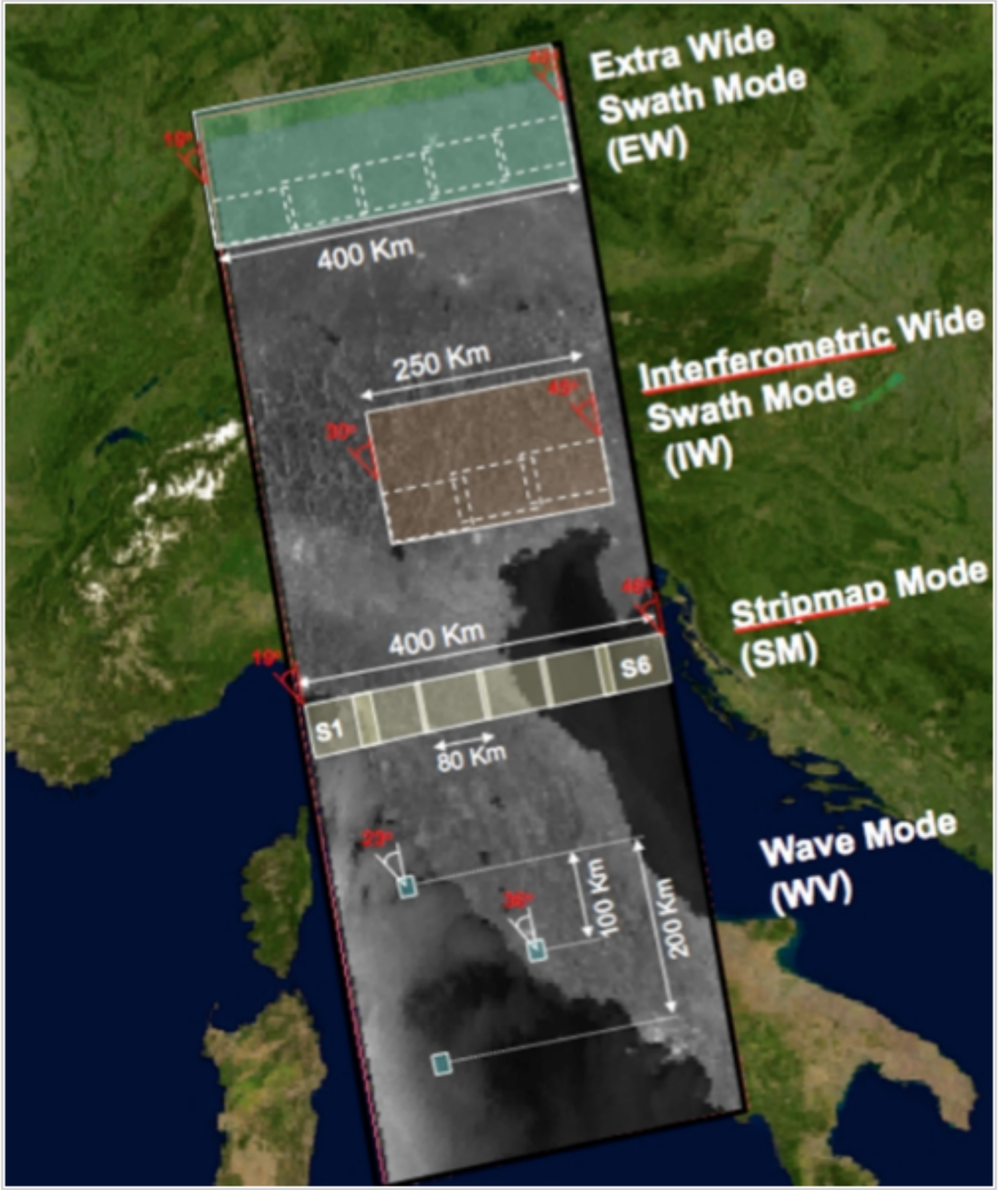
➡ and measure that area using the ***gamma*** convention

Radiometric Normalisation Conventions

Convention	1	2	3	4	5
	β^0	σ_E^0	γ_E^0	σ_T^0	γ_T^0
Earth Model	*None*	*Ellipsoid*		*Terrain*	
Reference Area	A_β	$\underline{A}_\sigma$	$\underline{A}_\gamma$	$\hat{A}_\sigma$	A_γ
Area Derivation	$\delta_r \cdot \delta_a$	$\underline{\delta}_g \cdot \delta_a$	$\underline{\delta}_p \cdot \delta_a$	$\delta_g \cdot \delta_a$	$\int_{DHM} \delta_p \cdot \delta_a$
Normalisation	$\beta^0 = \frac{\sigma}{A_\beta}$	$\beta^0 \cdot \frac{A_\beta}{\underline{A}_\sigma} = \beta^0 \cdot \sin\theta_E$	$\beta^0 \cdot \frac{A_\beta}{\underline{A}_\gamma} = \beta^0 \cdot \tan\theta_E$	$\sigma_E^0 \cdot \frac{\hat{A}_\sigma}{A_\beta} = \sigma_E^0 \cdot \frac{\sin\theta_{LIM}}{\sin\theta_E}$	$\frac{\beta^0 \cdot A_\beta}{A_\gamma}$
Product	*GTC*			*NORLIM*	*RTC*

Sentinel-1 Acquisition Modes

Dept. of Geography / Remote Sensing Laboratories



IW is main acquisition mode over land (>80%)

https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/revisit-and-coverage

Terrain-flattened Gamma Nought

Dept. of Geography / Remote Sensing Laboratories

Interlaken, Switzerland
Sentinel-1A IW GRDH VH-pol.
May 26, 2015

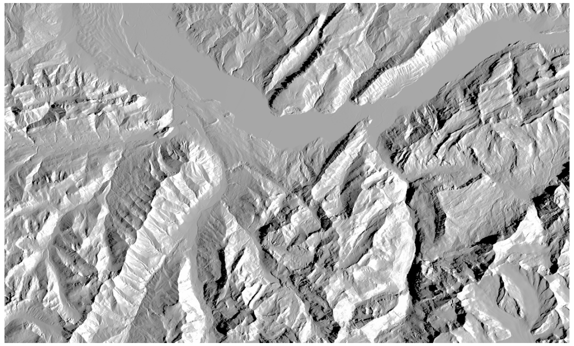
Terrain-flattening: Small D. *Flattening Gamma: Radiometric Terrain Correction for SAR Imagery*, IEEE Trans. on Geoscience & Remote Sensing, 49(8), Aug. 2011, pp. 3081-3093.

Normalise β^0: divide by simulated image

β^0 GTC

-26dB -1dB

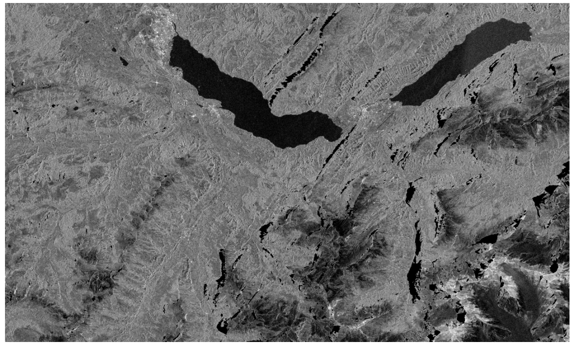
/



A_γ / A_β

=

γ_T^0



RTC

$$\gamma_T^0 = \beta^0 \cdot \frac{A_\beta}{A_\gamma}$$

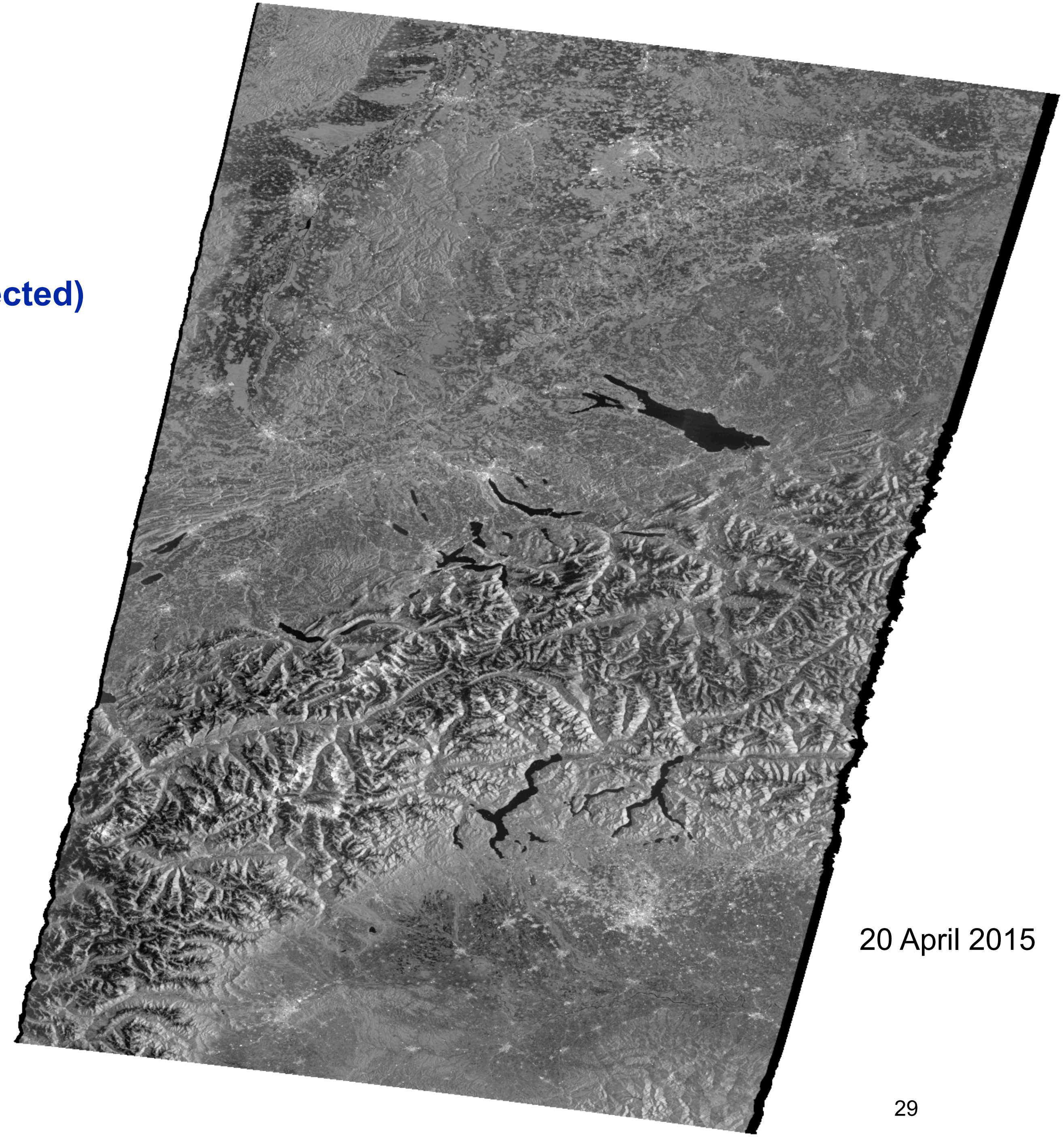
University of Zurich[UZH]

Dept. of Geography / R

Sentinel-1A: GTC
(Geometrically Terrain Corrected)

$$\gamma_E^0$$

-26dB -1dB



20 April 2015

Generated automatically from 3 IW GRDH products using SRTM3

Copernicus Sentinel data (2015)

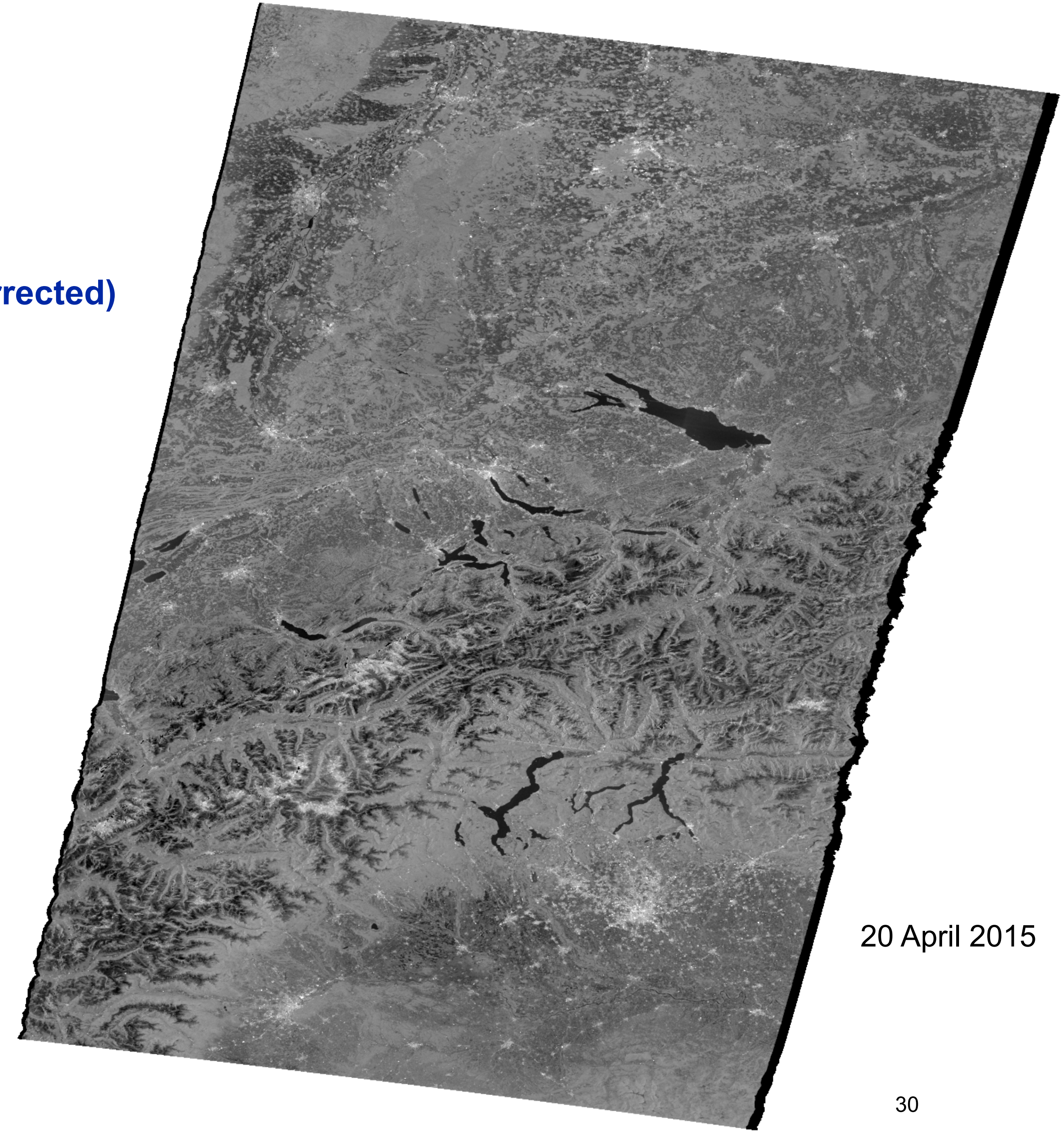
University of Zurich[UZH]

Dept. of Geography / R

Sentinel-1A: RTC
(Radiometrically Terrain Corrected)

$$\gamma_T^0$$

-26dB -1dB



20 April 2015

Generated automatically from 3 IW GRDH products using SRTM3

Contains modified Copernicus Sentinel data (2015)

University of Zurich[UZH]

Sentinel-1A: GTC
(Geometrically Terrain Corrected)

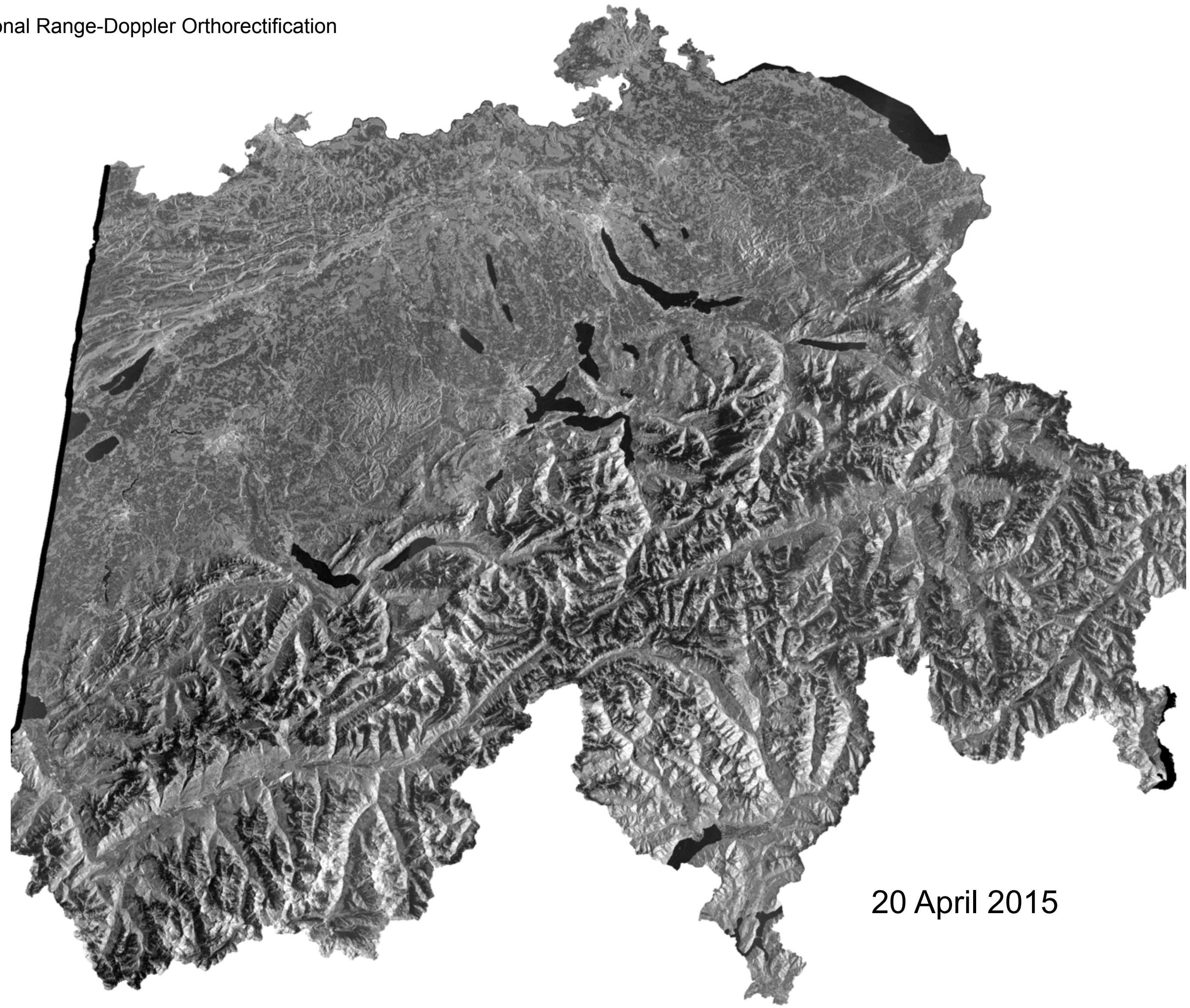
Dept. of Geography / Remote Sensing Laboratories

Conventional Range-Doppler Orthorectification

Switzerland

γ_E^0 VH-pol.

-26dB -1dB



Generated from 3 IW GRDH products using SwissALTI3D DEM (10m)

Copernicus Sentinel data (2015)

University of Zurich[UZH]

Sentinel-1A: RTC
(Radiometrically Terrain Corrected)

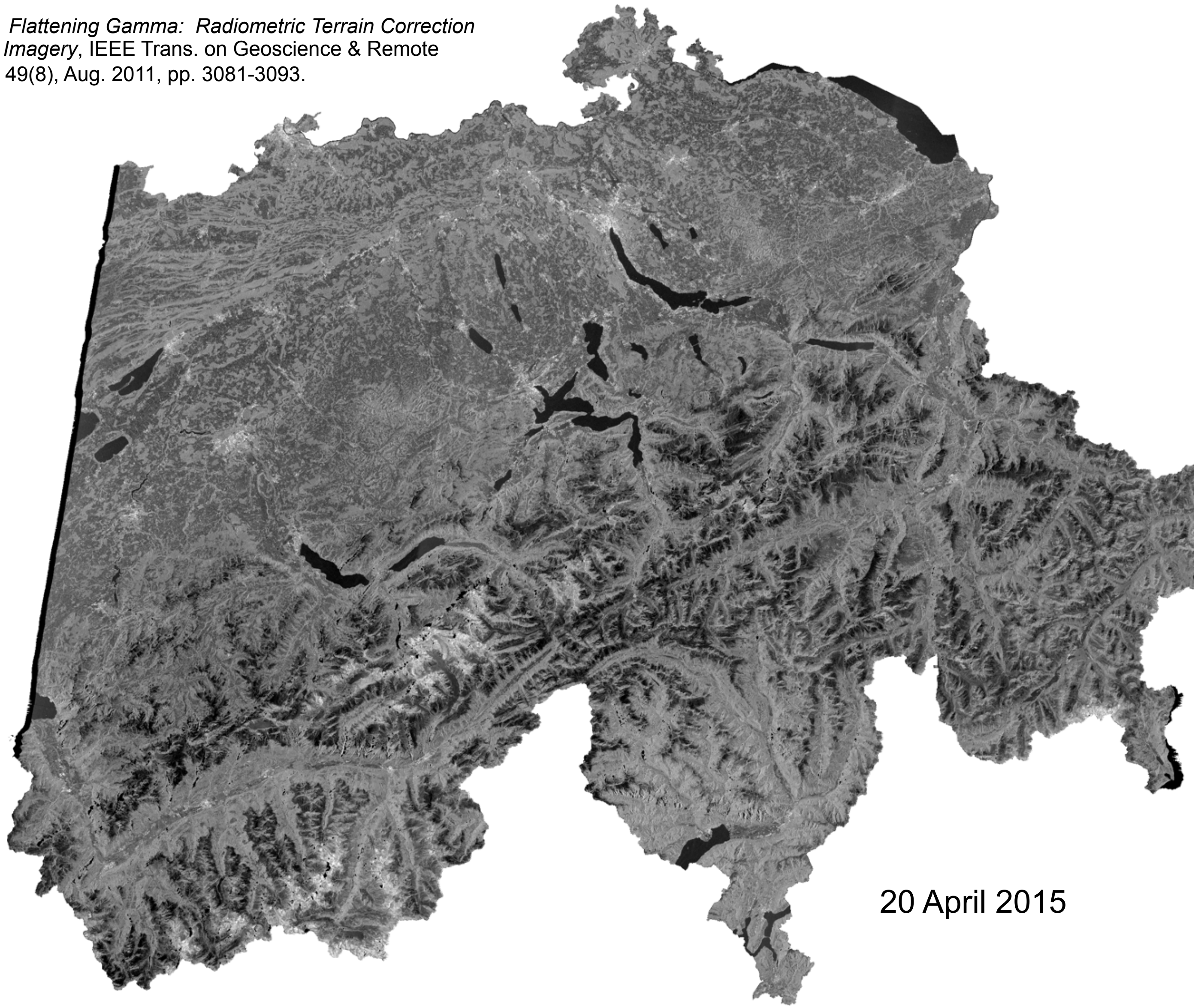
Dept. of Geography / Remote Sensing Laboratories

Switzerland

Small D. *Flattening Gamma: Radiometric Terrain Correction for SAR Imagery*, IEEE Trans. on Geoscience & Remote Sensing, 49(8), Aug. 2011, pp. 3081-3093.

γ_T^0 VH-pol.

-26dB -1dB



Generated from
3 IW GRDH products using
SwissALTI3D DEM (10m)

Contains modified Copernicus Sentinel data (2015)

20 April 2015

Backscatter Composites

University of Zurich[UZH]

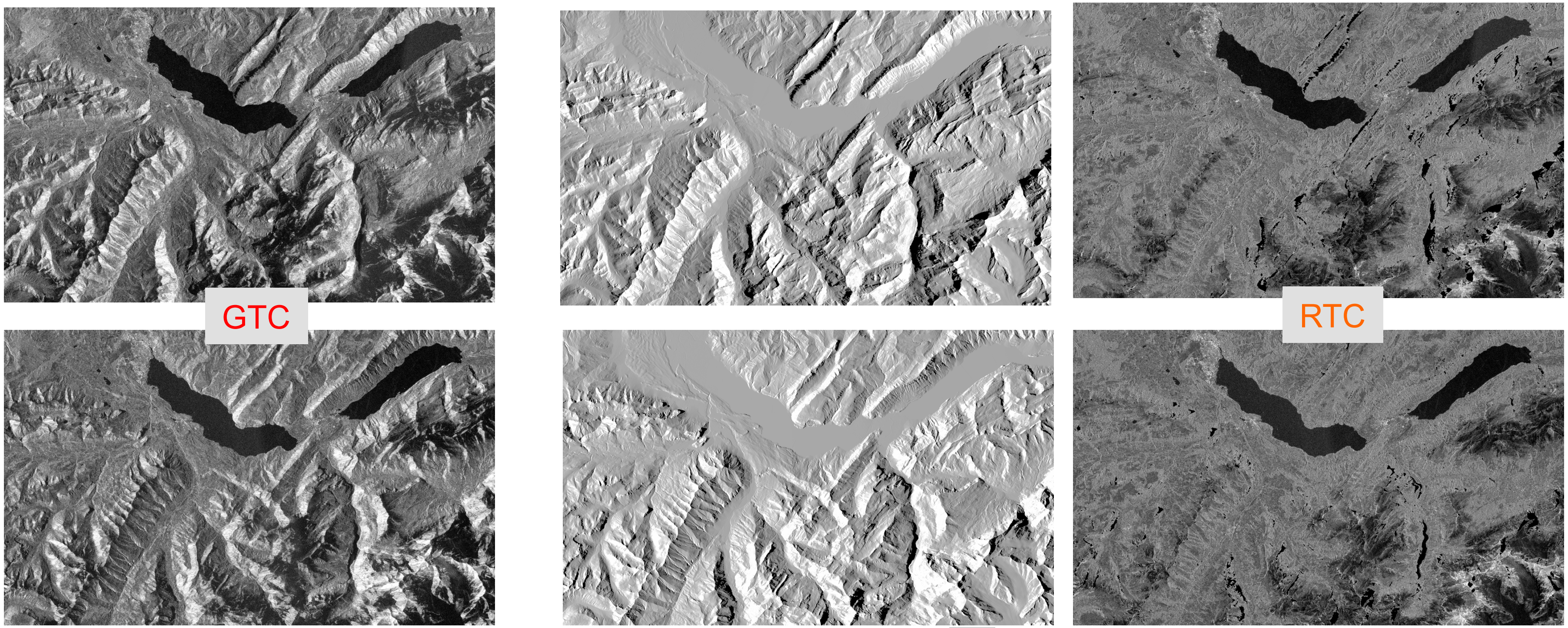
Dept. of Geography / Remote Sensing Laboratories

-26dB -1dB

γ_E^0 γ_T^0

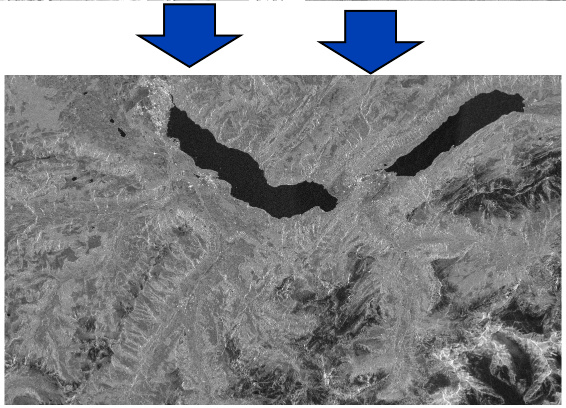
2015.05.26 (Desc.)

2015.05.27 (Asc.)



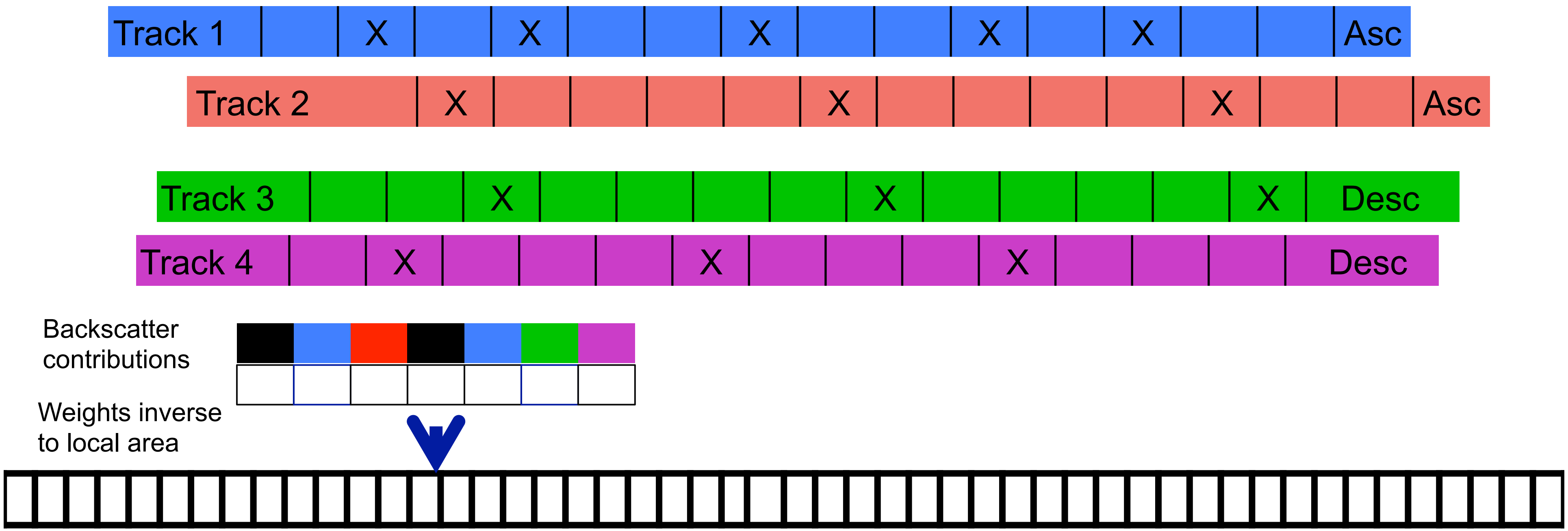
• Combine asc. & desc. observations to generate **composite** with improved local resolution
• Less shadow than single RTC, lower noise

Interlaken, Switzerland



Composite

Revisit Interval: Breaking the tyranny of exact repeat passes



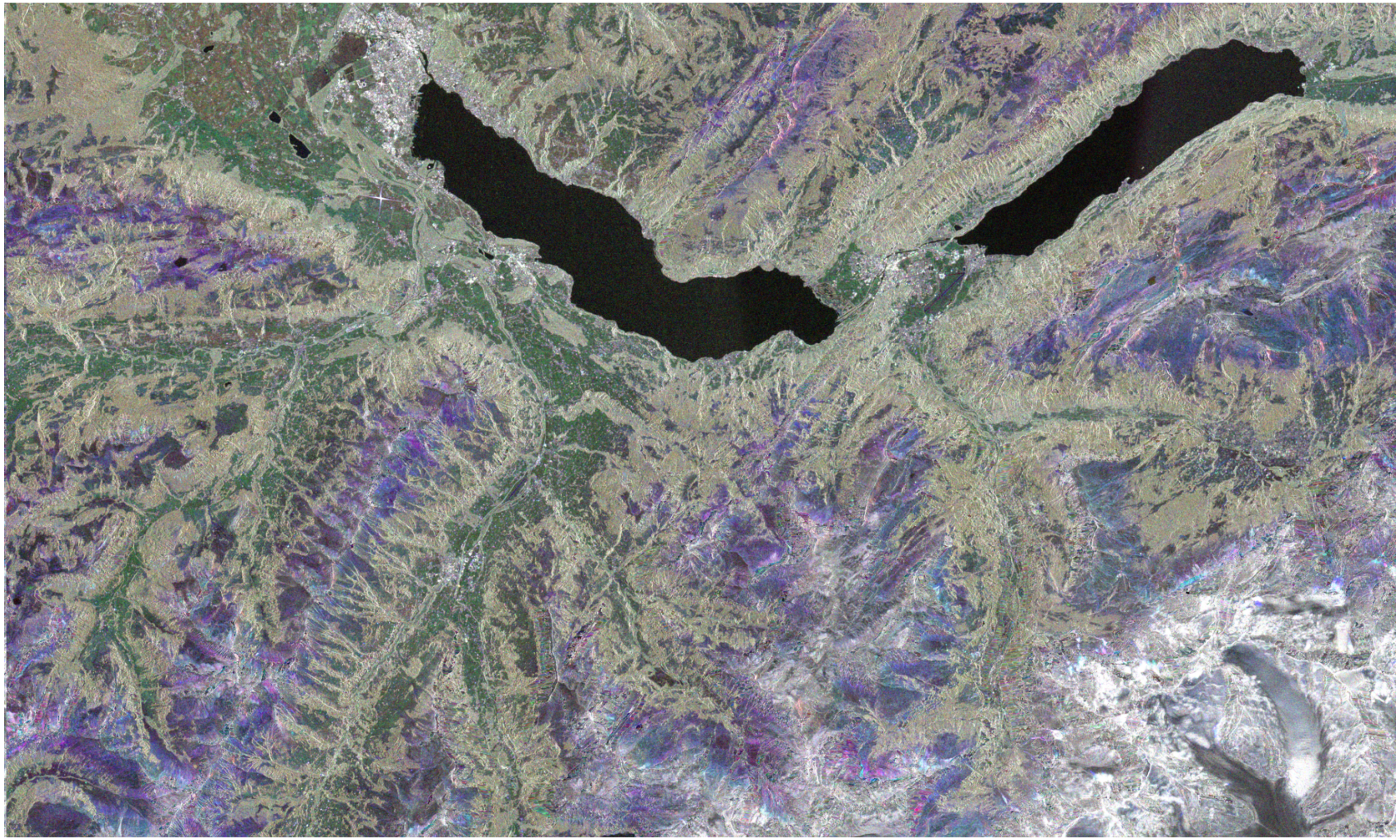
For *Regular Intervals* with temporal resolution better than repeat-pass interval

- Use moving time-window integrating information from all tracks
- The more (diverse!) data (and tracks) the better – esp. combine ascending and descending observations

Composites in RGB Time Series

-26dB -6dB

R=2015.01.02+03 / G=2015.01.14+15 / B=2015.02.07+08 ; (each Asc. + Desc.)



Interlaken, Switzerland

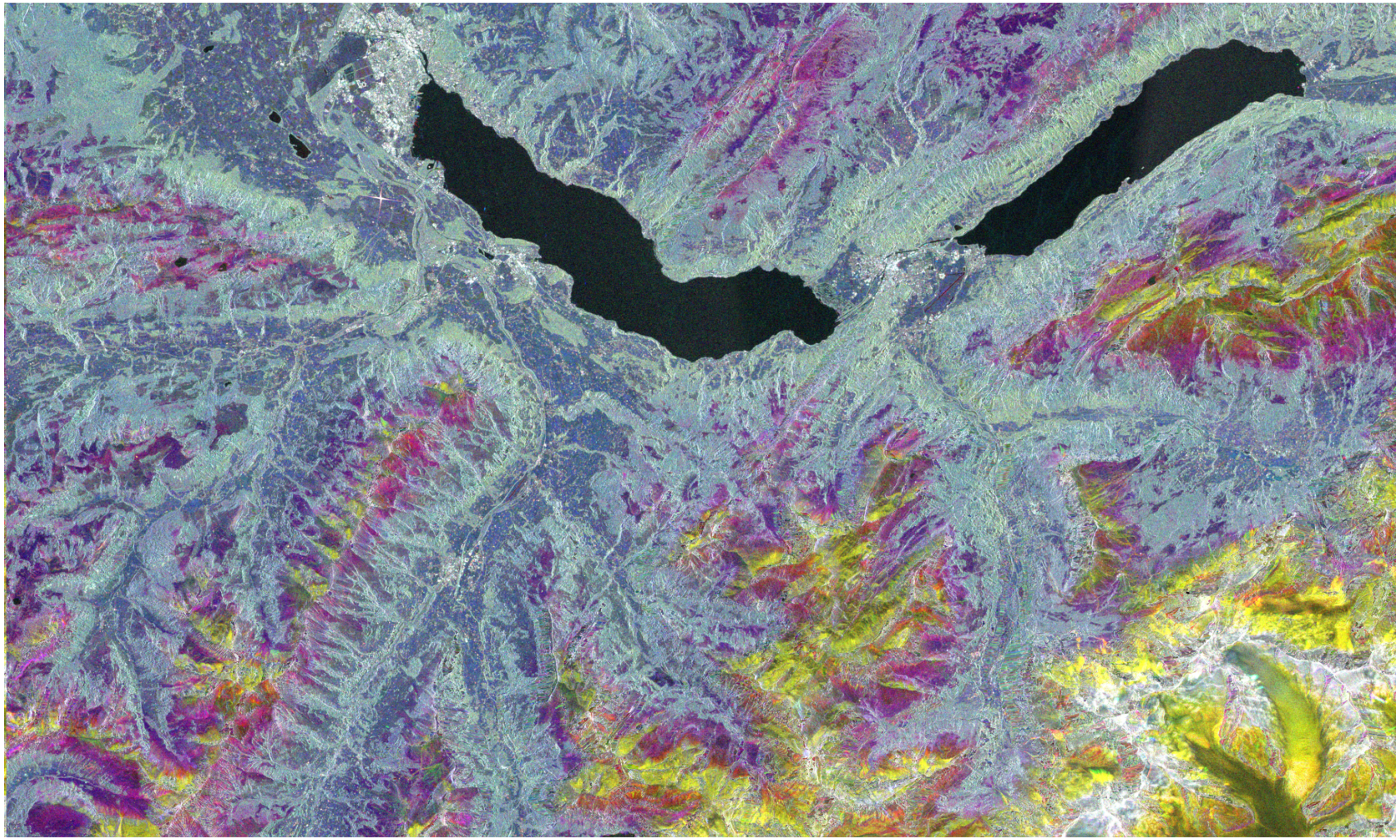
Freezing: Higher backscatter in Feb. than Jan.: Blue

University of Zurich[UZH]
Dept. of Geography / Remote Sensing Laboratories

Composites in RGB Time Series

-26dB -6dB

R=2015.02.07+08 / G=2015.04.08+09 / B=2015.05.26+27 ; (each Asc. + Desc.)

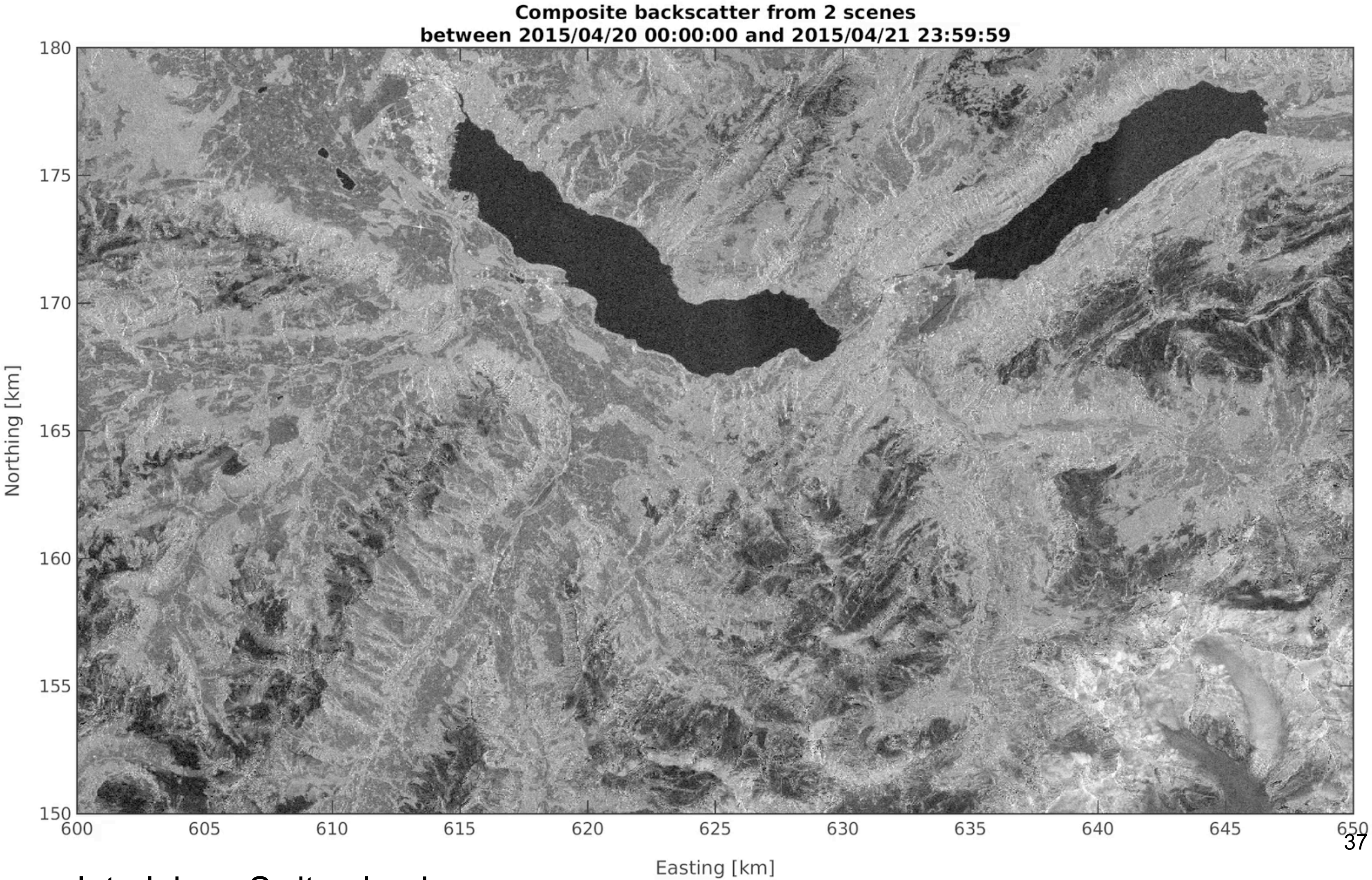


Interlaken, Switzerland *Melting*: Lower backscatter in May than Feb/Apr.: Yellow

Composites in Time Series Movie

-26dB -1dB

Jan – May 2015



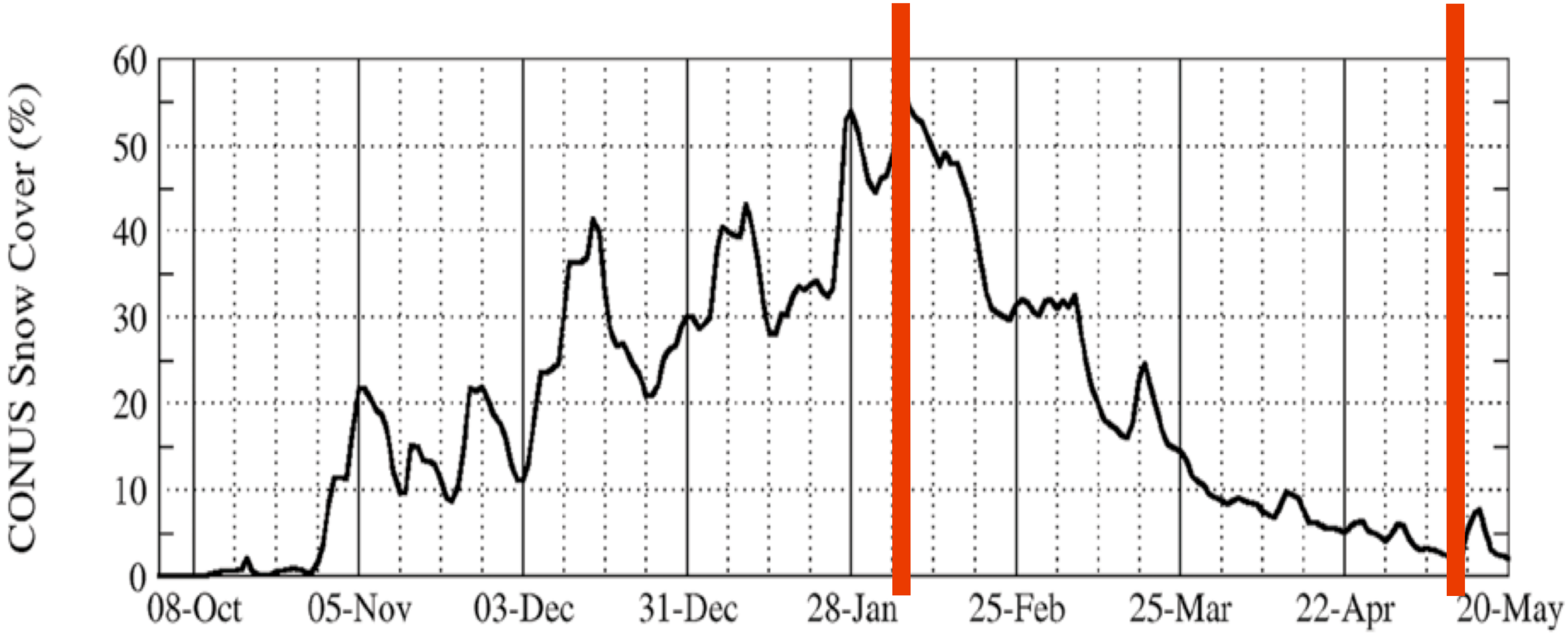
Interlaken, Switzerland

Contains modified Copernicus Sentinel data (2015)

Evolution of Snow Cover in the US

[IGOS Cryosphere Theme Report, 2007]

Fig. 3.1. Percentage of snow-covered area within the conterminous U.S. during the 2003-2004 season with corresponding unique snow depths and SWE.



Swiss Seasonal Hydrology: 1971-2012 Daily SWE plotted by elevation

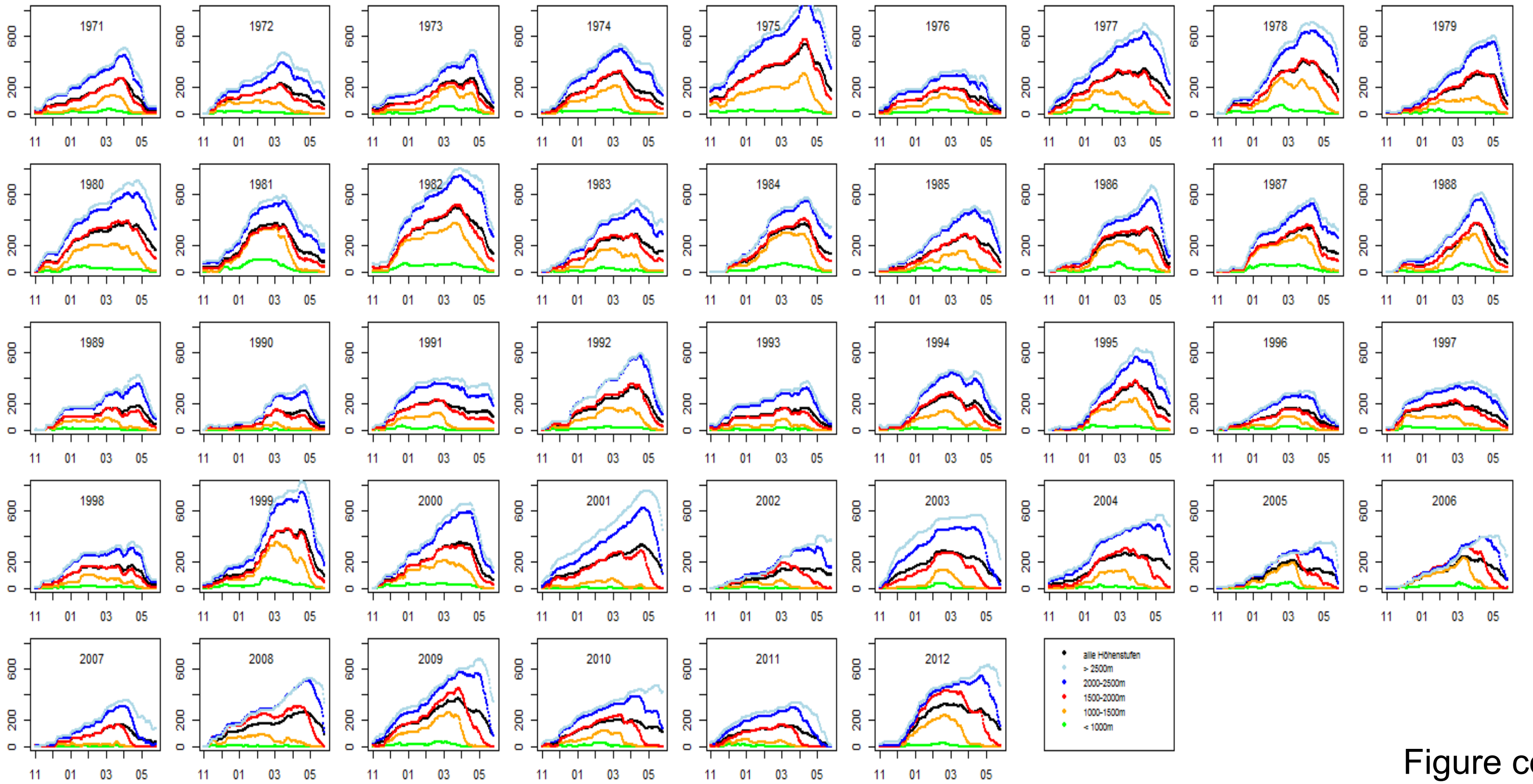


Figure courtesy
Tobias Jonas, SLF

Melting generally captured at significant elevations between Feb. 15 and May 15

Key General Recommendations of ***WMO White Paper*** on SAR Acquisition Planning for Terrestrial Snow Monitoring

R1	**Use wide-swath modes** to enable wide area monitoring with high temporal resolution (i.e. RSAT2 SCN or SCW, Sentinel-1 IW or EW, TSX "SC Wide" & CSK "Huge Region" ScanSAR modes).
R2	Build combined **ascending/descending** coverage by default into acquisition plans covering mountainous regions. Favour asc./desc. acquisition sets acquired within a **tight time window** (1-3 days) to allow a narrow time-attribution to composites generated from these sets.
R3	Concentrate snowmelt acquisitions on the **seasonal window** when the majority of snow melting occurs (March through May at temperate northern latitudes). The *highest temporal resolution possible* is requested during this critical melting period. Although some further acquisitions are also requested *outside* of this seasonal window, lower temporal resolution at these less critical times is acceptable.
R4	Standardise dual-pol. mode acquisitions on **VV/VH** combination: a cross-platform consistent polarisation simplifies combination of datasets from multiple providers (e.g. S1/RSAT2/RCM or TSX/CSK).
R5	**Harmonise acquisition plans** of satellites with compatible calibrated backscatter values (e.g. S1/RSAT2/RCM or TSX/CSK). Utilise the available diversity of orbits to achieve the desired diversity of tracks – e.g. to achieve the fullest possible ascending/descending coverage.
R6	Assure **full coverage over land also in coastal regions** when other modes are by default programmed over ocean (e.g. favour Sentinel-1 IW or EW over WV).
R7	Maintain a **regular observation plan also during the winter** to assure frequent observations of other important snow parameters, and other phenomena related to the winter period such as avalanches and rain on snow events.

http://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-4_Doc_08-01-01_Snow-SAR-DSmall-rev1.pdf

Science Requirements for wide area snowmelt monitoring

Spatial* resolution**: ***100m ✔

Variable	**Extent**	**Spatial resolution**	**Temporal resolution**	**Sensor**	**Auxiliary Data**
Snowmelt area	Regional	100m	1 to 5 days	Sentinel-1	Land cover, DEM
Snowmelt liquid water content	Regional	100m	1 to 5 days	Sentinel-1 dual polarisation	Land cover, DEM

[Malenovský, Z. et al. *Sentinels for science: Potential of Sentinel-1, -2, and -3 missions for scientific observations of ocean, cryosphere, and land*. Remote Sens. Environ. 120, 91–101 (2012)]

Temporal* resolution (target)**: ***1 day ✘

- "Observation of the ***daily*** *geographic extent of snow cover* is essential because it enables inference of several first order effects of snow on many Earth systems." [IGOS Cryosphere Theme Report, 2007]
- WMO PSTG report "Coordinated SAR Acquisition Planning for Terrestrial Snow Monitoring", PSTG-SARCWG-SNOW-001, Aug. 2014.

Data Collections

Region	DEM	Spatial sampling	Temporal resolution [days]	Sensors
Interlaken region, Switzerland	swissALTI3D (2m)	10 m	(selected) 2	S1A IW DV
European Alps	SRTM3 (3s)	3s (~90m)	16	S1A IW DV, RS2 SCW/SCN VV/VH
Coastal British Columbia, Canada	SRTM3 (3s)	3s (~90m)	24	S1A IW SV
Ellesmere Island, Canada	CDEM[1]	400m	**4**	S1A EW DH RS2 SCWA HH/HV

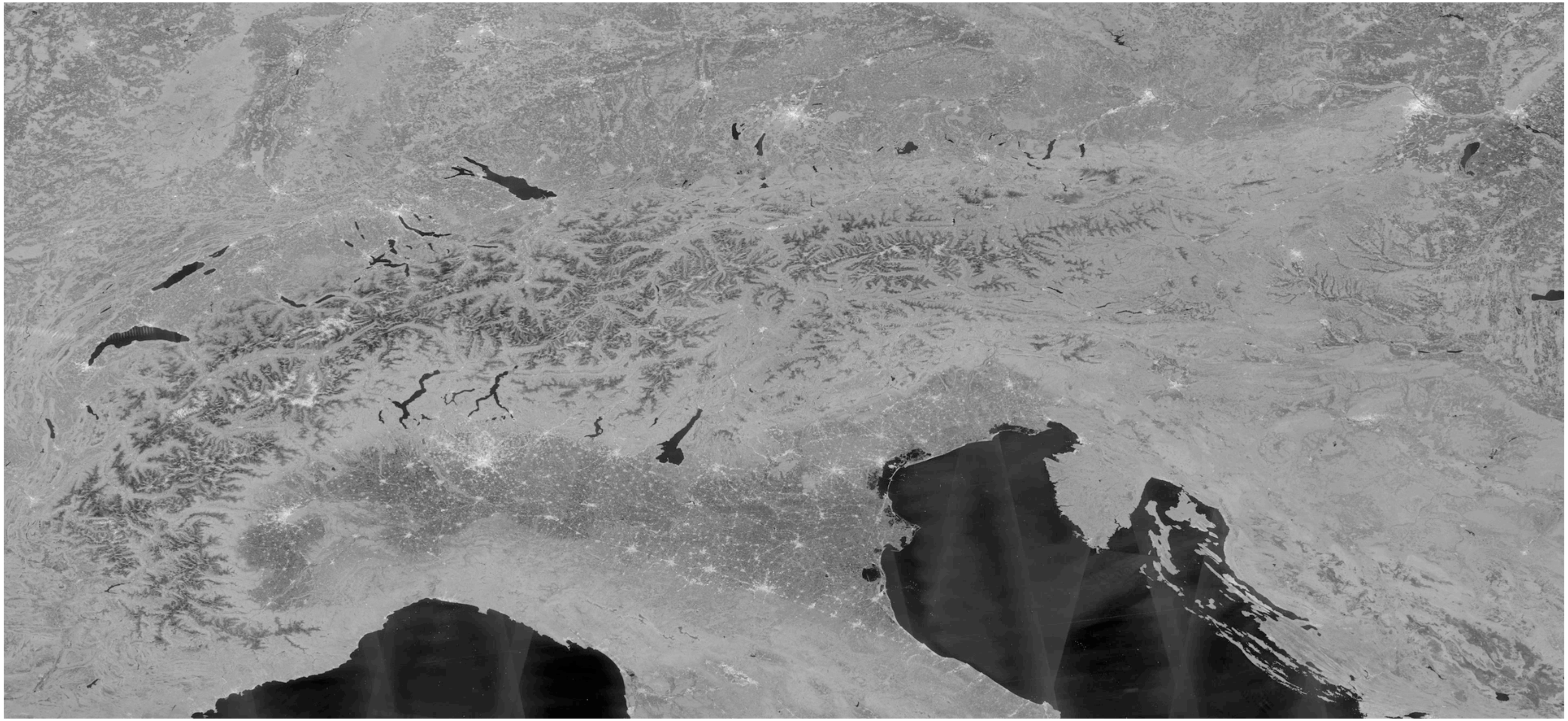
[1]M. Santoro & T. Strozzi (2012): **Circumpolar digital elevation models > 55° N**
Canadian Digital Elevation Model Product Specifications, Edition 1.1, 2013-04-01, GeoGratis

University of Zurich[UZH]

S1A Alps Backscatter Mosaic

Dept. of Geography / Remote Sensing Laboratories

S1A IW VH & VV-pol. Oct. 2014 – Aug. 2016: 12d & 16d windows
Jan.-Aug. 2016 VH 16d shown here

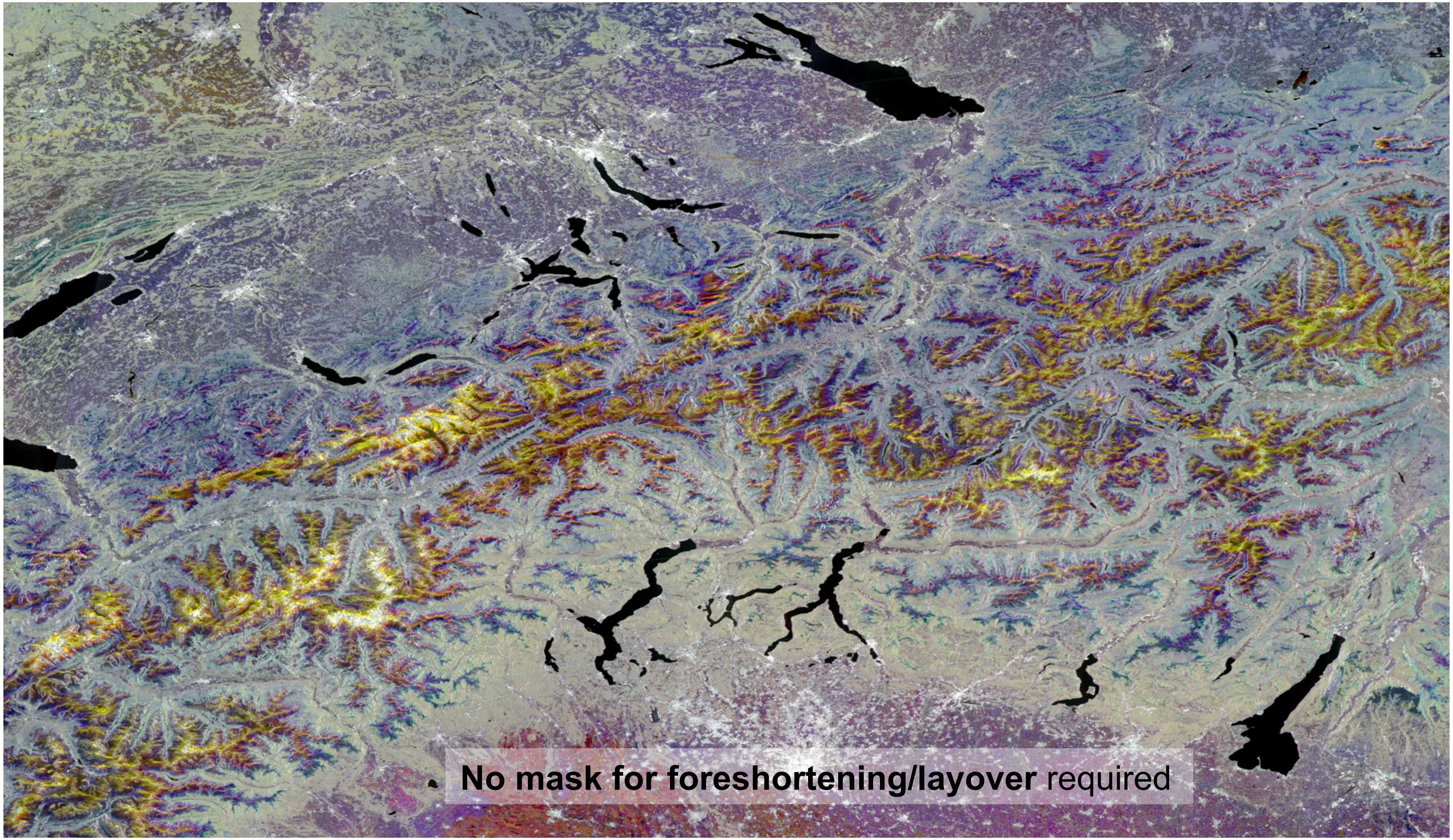


SRTM3 used for geometric and radiometric corrections

University of Zurich[UZH]

Dept. of Geography / Remote Sensing Laboratories

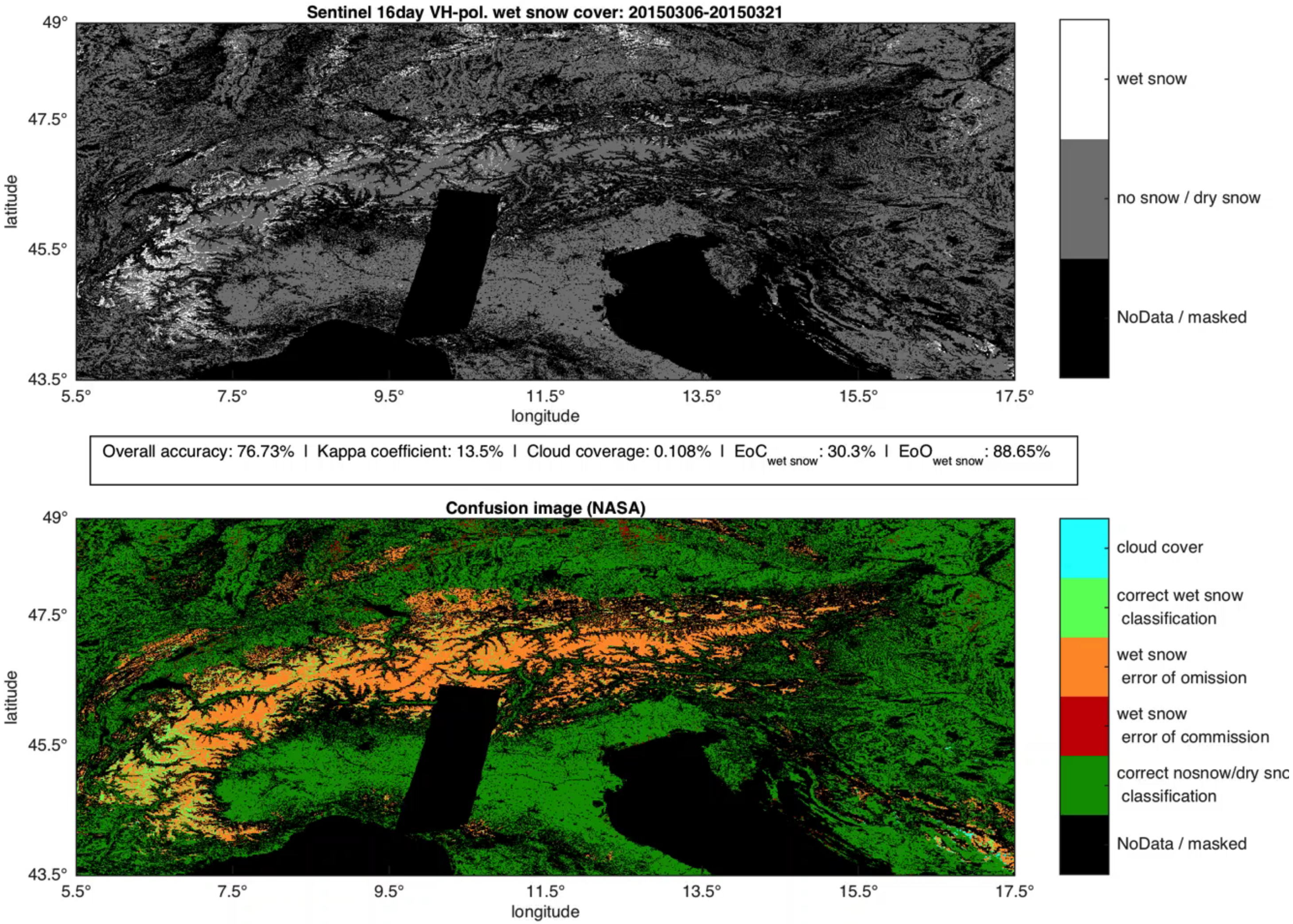
Sentinel-1 IW 16d Composites 2015 VH: March 14-29, April 7-22, May 25-June 9; -23dB (black) to -6dB (white)



S1A Alps Wet Snow Maps

S1A IW 2015
VH & VV-pol.

S1-based wet snow classifications compared with NASA MODIS snow products

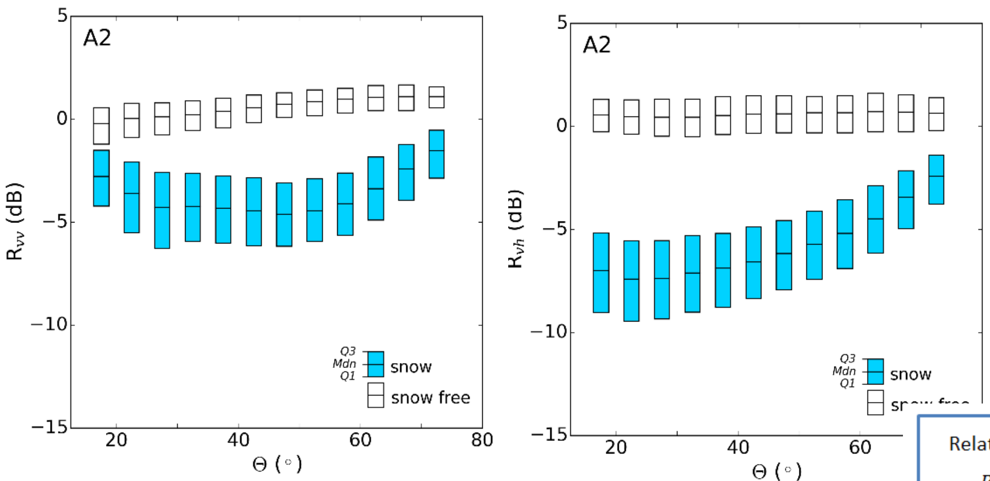


University of Zurich[UZH]

Sentinel-1 Dual Pol Snow Mapping Method (ENVEO)

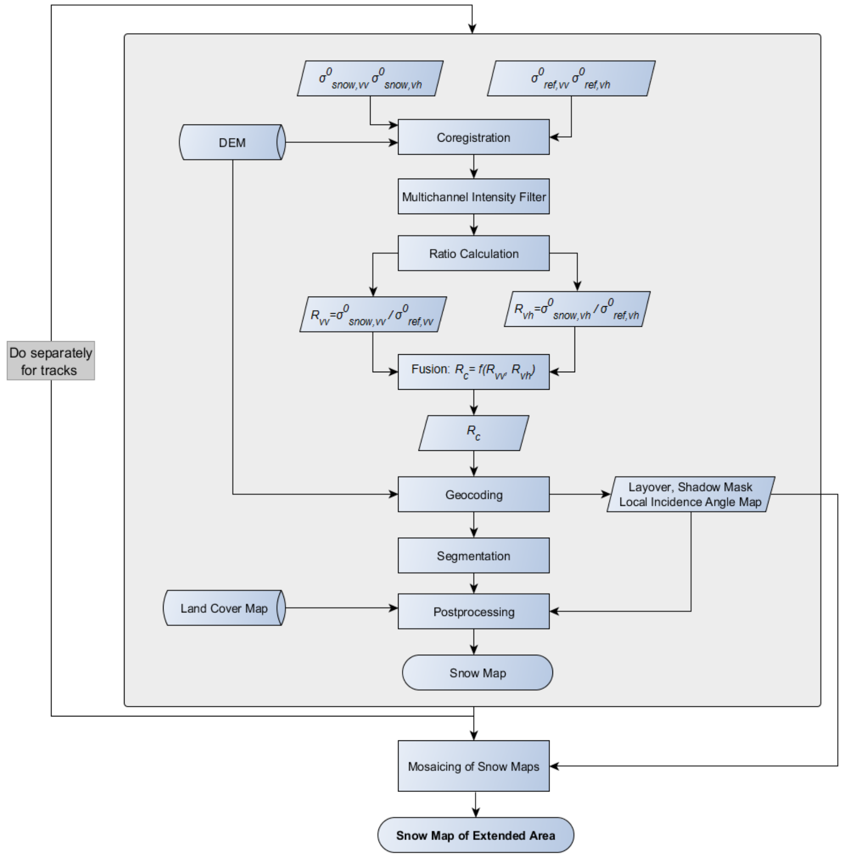
Dept. of Geography / Remote Sensing Laboratories

Backscatter ratio (median, Mdn, 1st and 3rd quartile) for Sentinel-1 *VV*- and *VH*- polarized channels in dependence on local incident angle. Test area Ötztal.



Nagler et al. 2016; Rem. Sens., 2016, 8(4), 348, doi:10.3390/rs8040348

Figure courtesy Thomas Nagler



Relation for merging R_{vv} and R_{vh} ratios in order to create a combined single channel, R_c:

$$R_c = W\,R_{vh} + (1 - W)\,R_{vv}.$$

With:

$$IF\ (\theta < \theta_1) \rightarrow \{W = 1.0\}$$

$$IF\ (\theta_1 \le \theta \le \theta_2) \rightarrow \left\{W = k\left[1 + {(\theta_2 - \theta)}/{(\theta_2 - \theta_1)}\right]\right\},$$

$$IF\ (\theta > \theta_2) \rightarrow \{W = k\}$$

We use $k = 0.5$, $\theta_1 = 20°$, $\theta_2 = 45°$, θ is the local incidence angle.

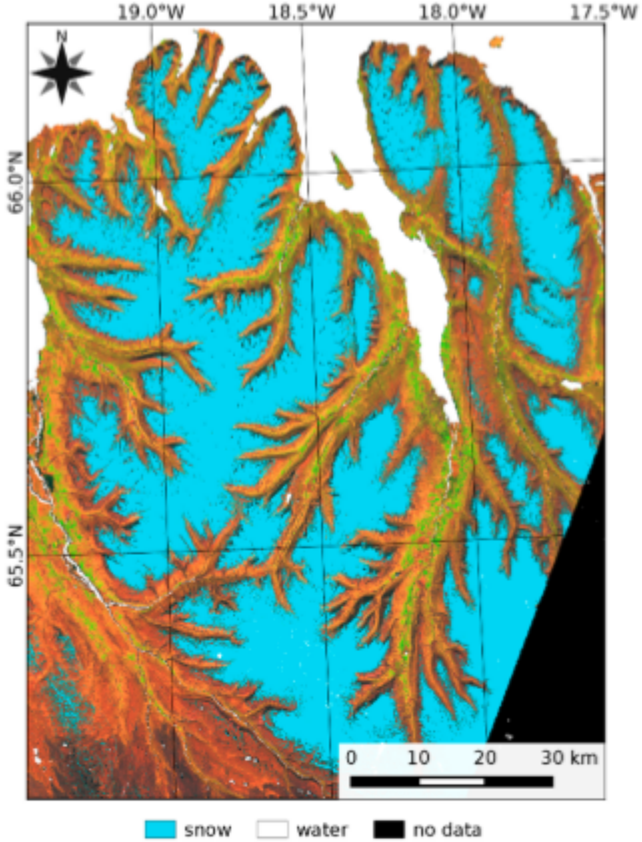
Wet snow segmentation rule: $R_c < THR$, with THR = -2 dB .

University of Zurich[UZH]

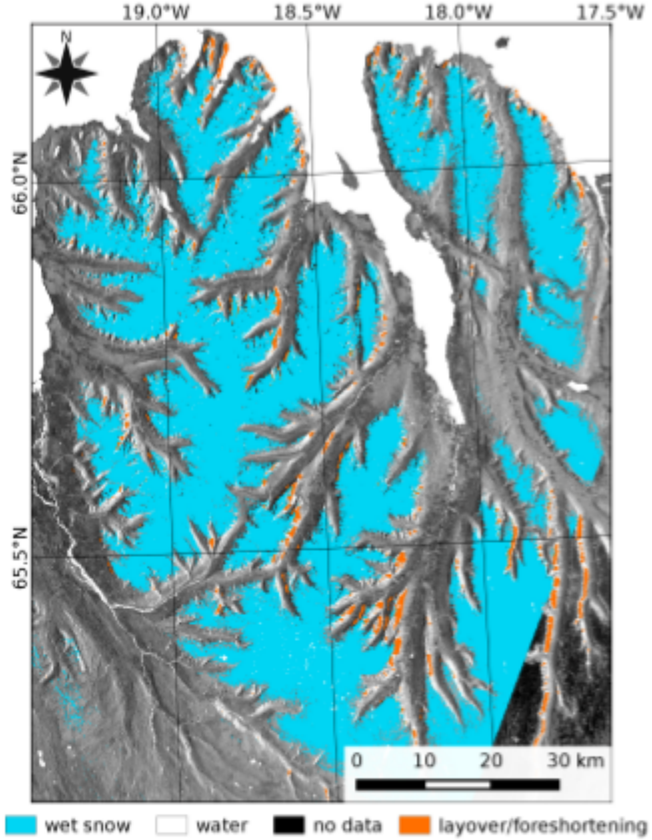
Example of S1 Snow Melt and Landsat TM Snow Extent – Tröllaskagi Peninsula, Iceland

Dept. of Geography / Remote Sensing Laboratories

Landsat-8, 27 June 2015;



Sentinel-1, 26 June 2015;



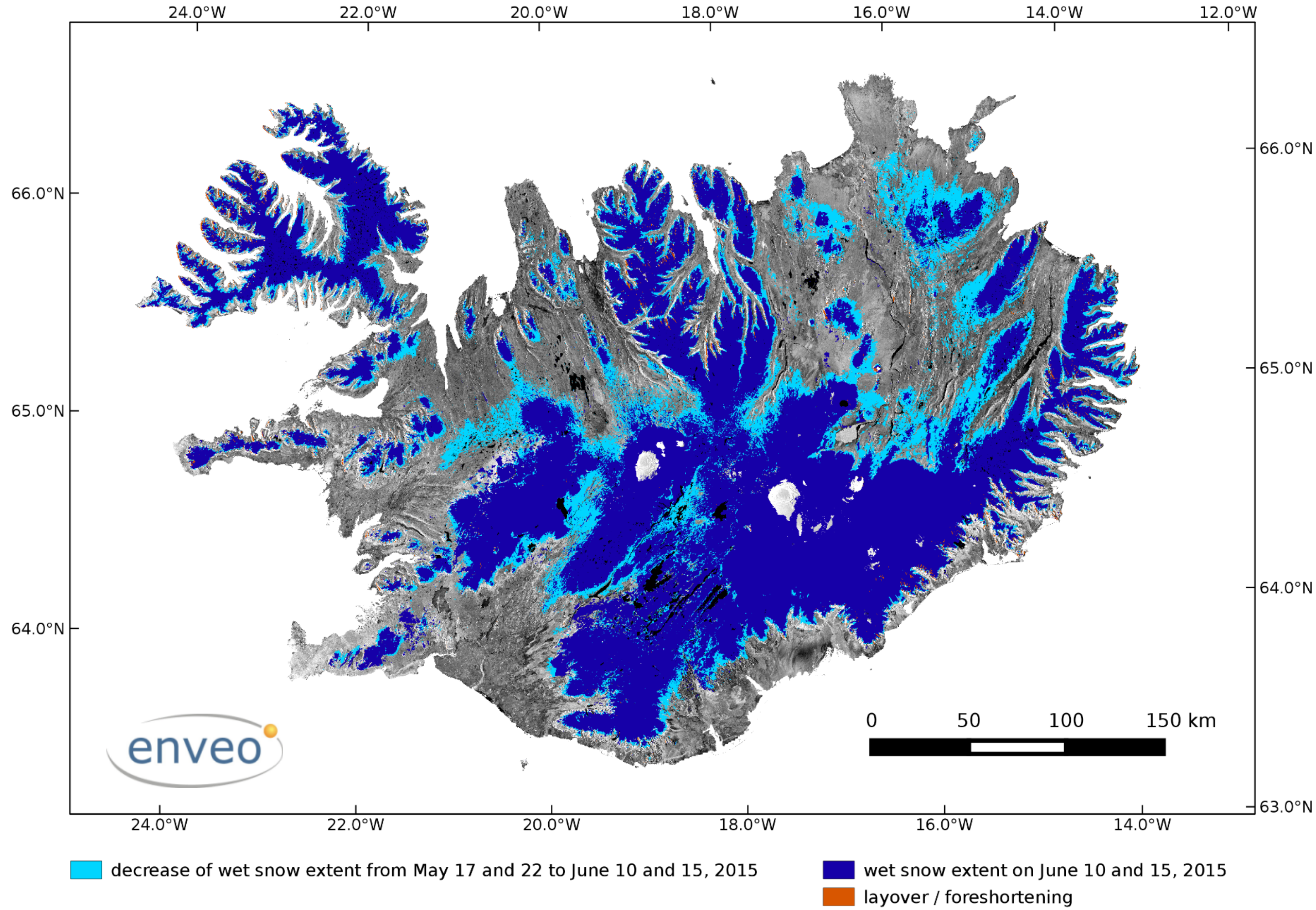
	R_c		
	S1-S	S1-F	AR
LS-S	94.6	5.4	
LS-F	0.2	99.8	
			0.972

Confusion matrix for the classes snow (S) and snow-free, for snow classification based on Landsat (LS) and Sentinel-1 (S1) data. S1 results are shown for snow maps based on . — overall agreement rate ().

Figure courtesy Thomas Nagler

University of Zurich[UZH]

Monitoring melting snow using Sentinel-1



Nagler et al., Remote Sensing, 2016

Figure courtesy Thomas Nagler

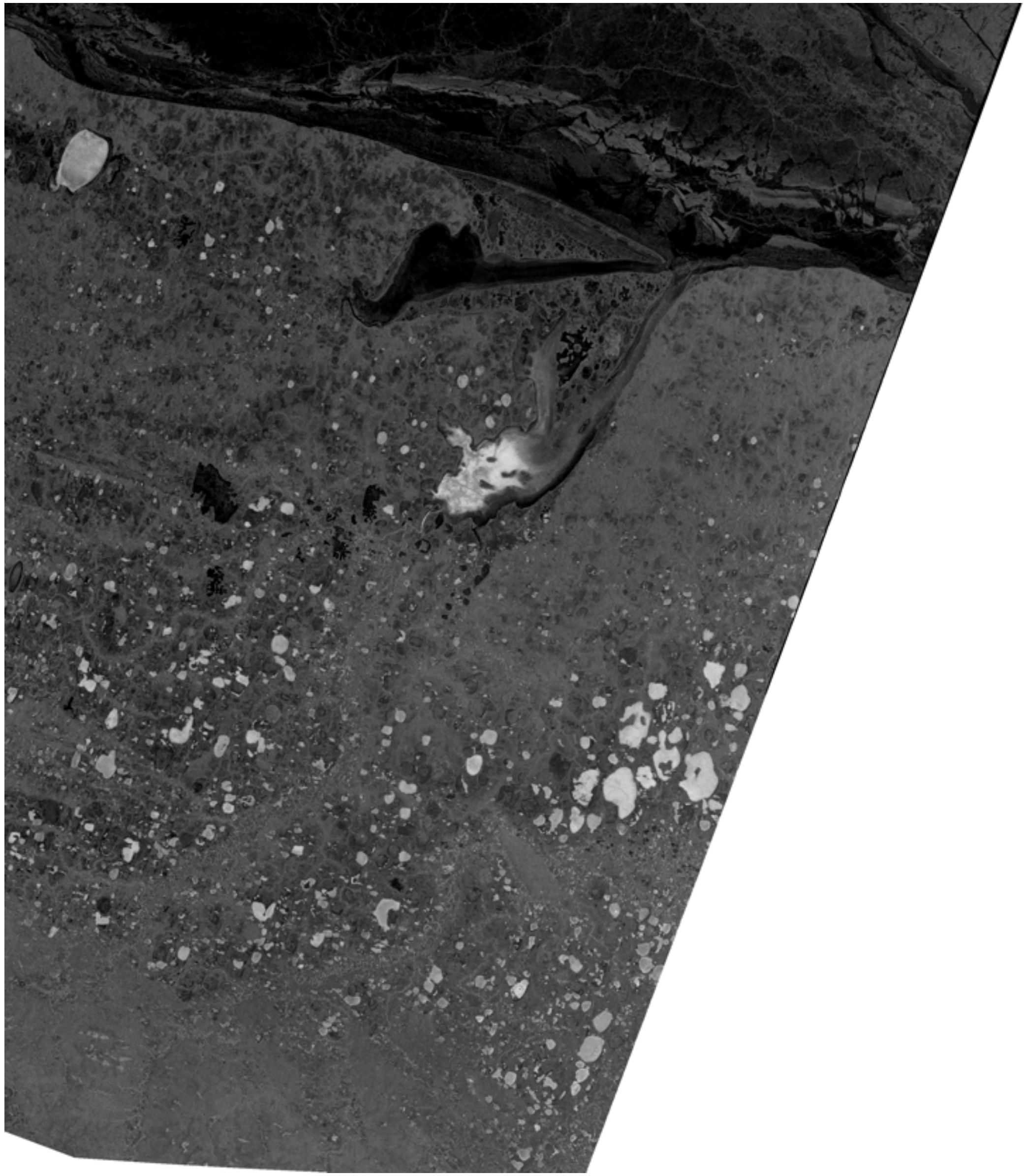
University of Zurich[UZH]

Dept. of Geography / Remote Sensing Laboratories

Kytalyk, Siberia

Sentinel-1 EW HH-pol. Backscatter

20150412



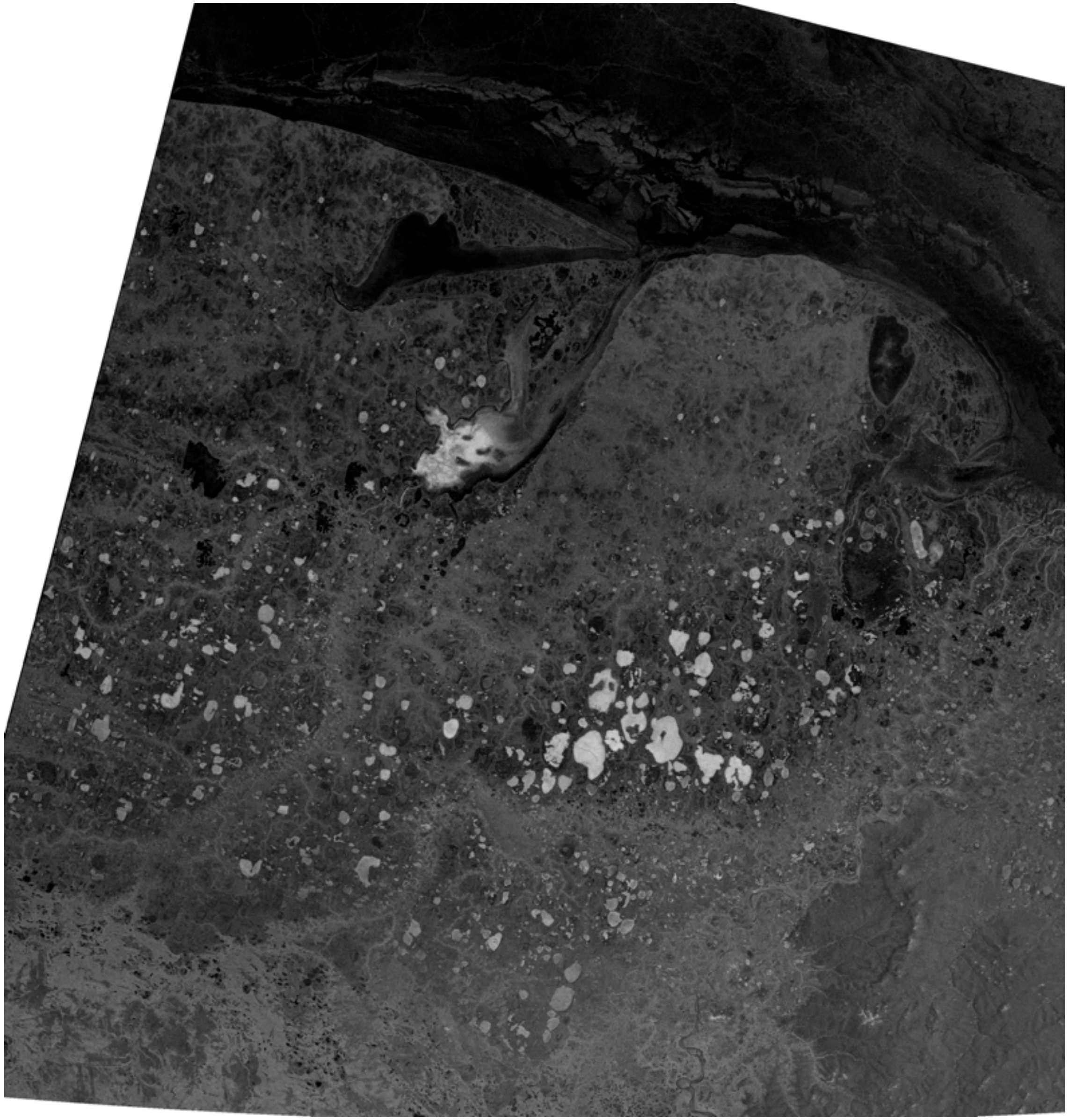
University of Zurich[UZH]

Dept. of Geography / Remote Sensing Laboratories

Kytalyk, Siberia

Sentinel-1 EW HH-pol. Backscatter

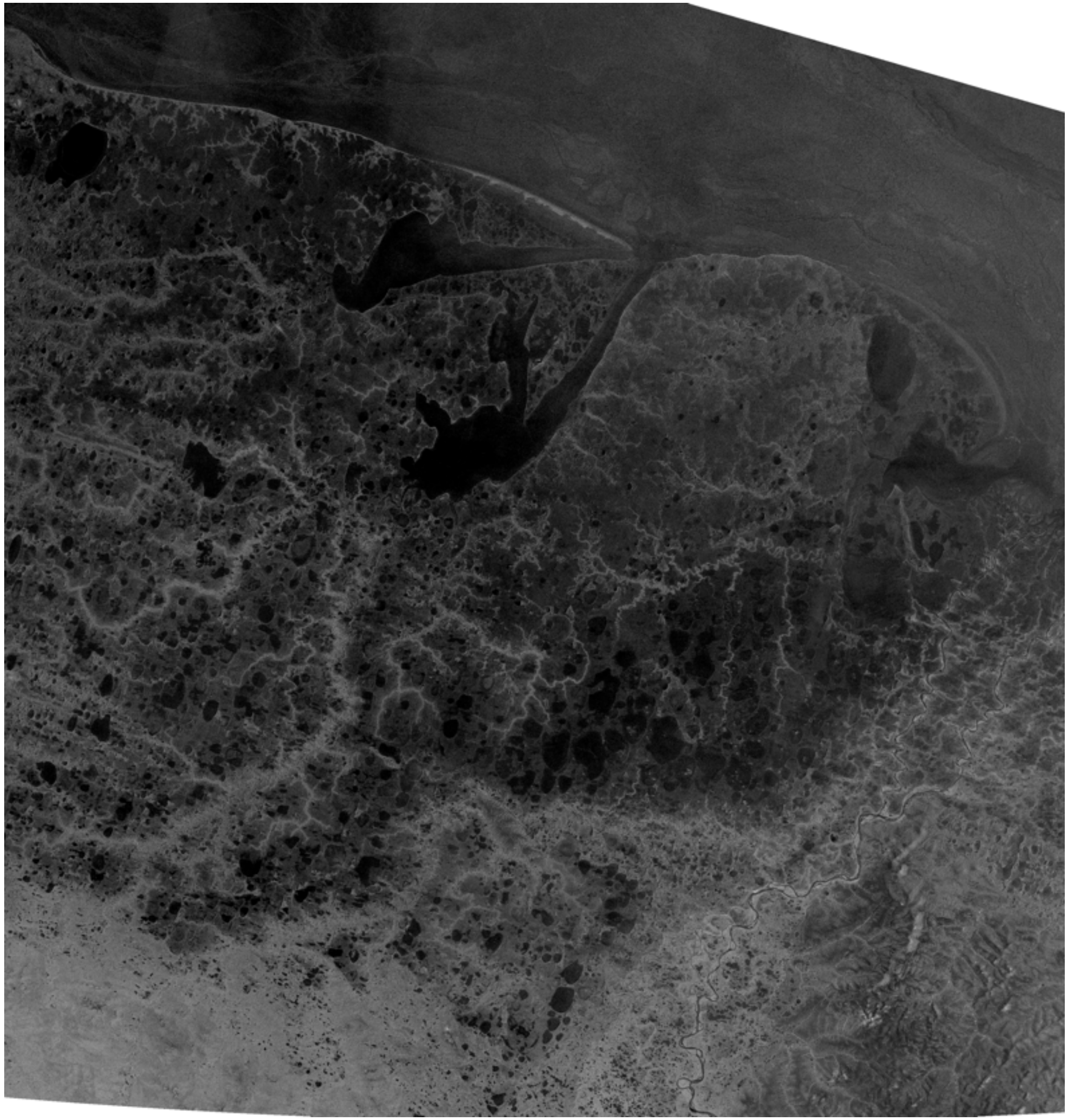
20150527



Kytalyk, Siberia

Sentinel-1 EW HH-pol. Backscatter

20150601



Ground-based sensing

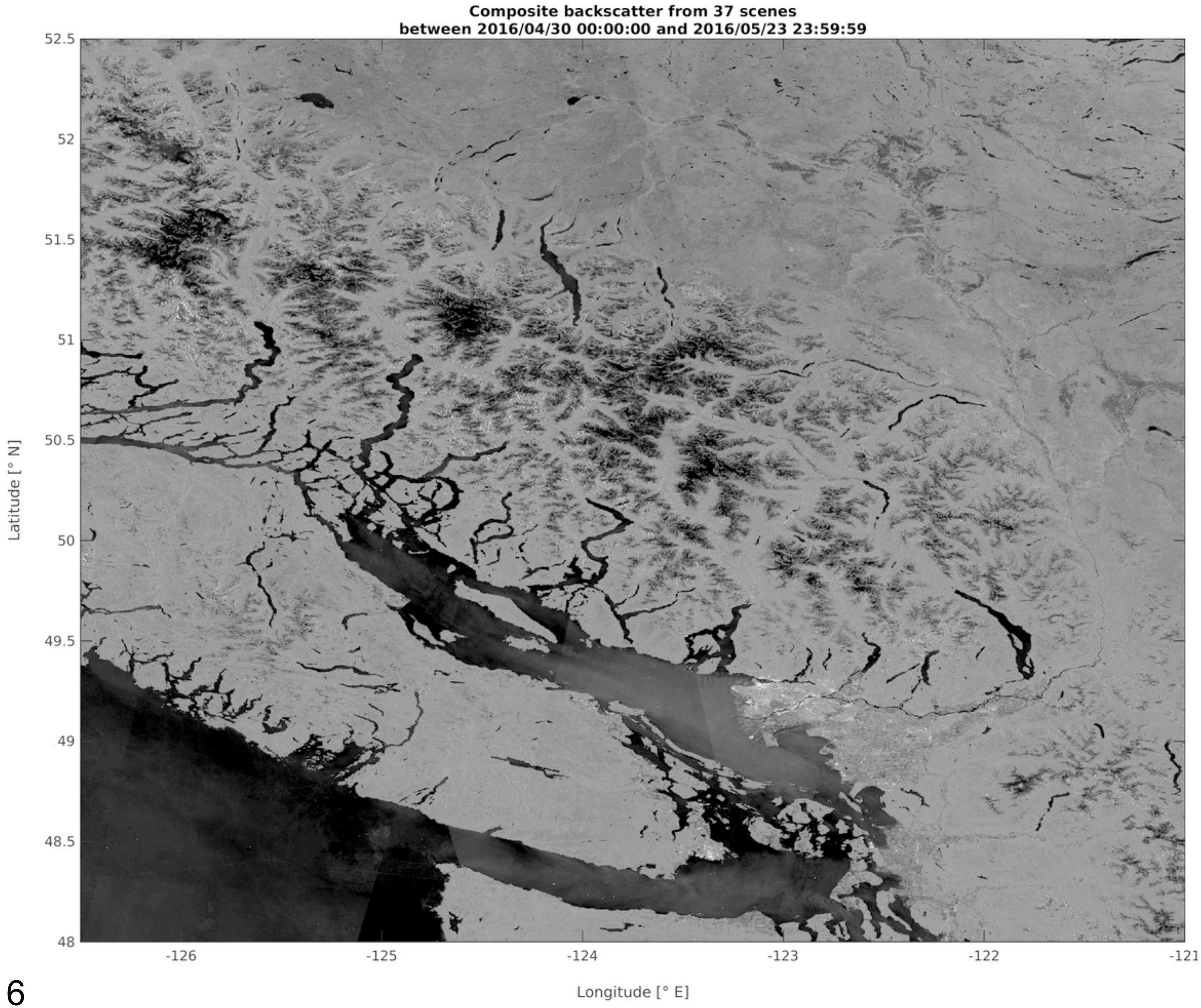
e.g. Phenocam in Kytalyk, Siberia

Movie courtesy G. Ghielmetti, UZH-RSL

Univer
Zurich

Dept. of

Coastal British Columbia Backscatter Composites



S1A IW VV

12 day delta

24 day window

N.B.

Increased dual-pol VV/VH acquisitions in last months)

Jan. – Aug. 2016

Univ
Zuric
Dept.

Ellesmere Island Backscatter Composites

RS2 SCWA
HH

2 day delta

4 day window

N.B.
8 bit radiometry
CDEM

May – Aug. 2015

Univ
Zuric

Dept.

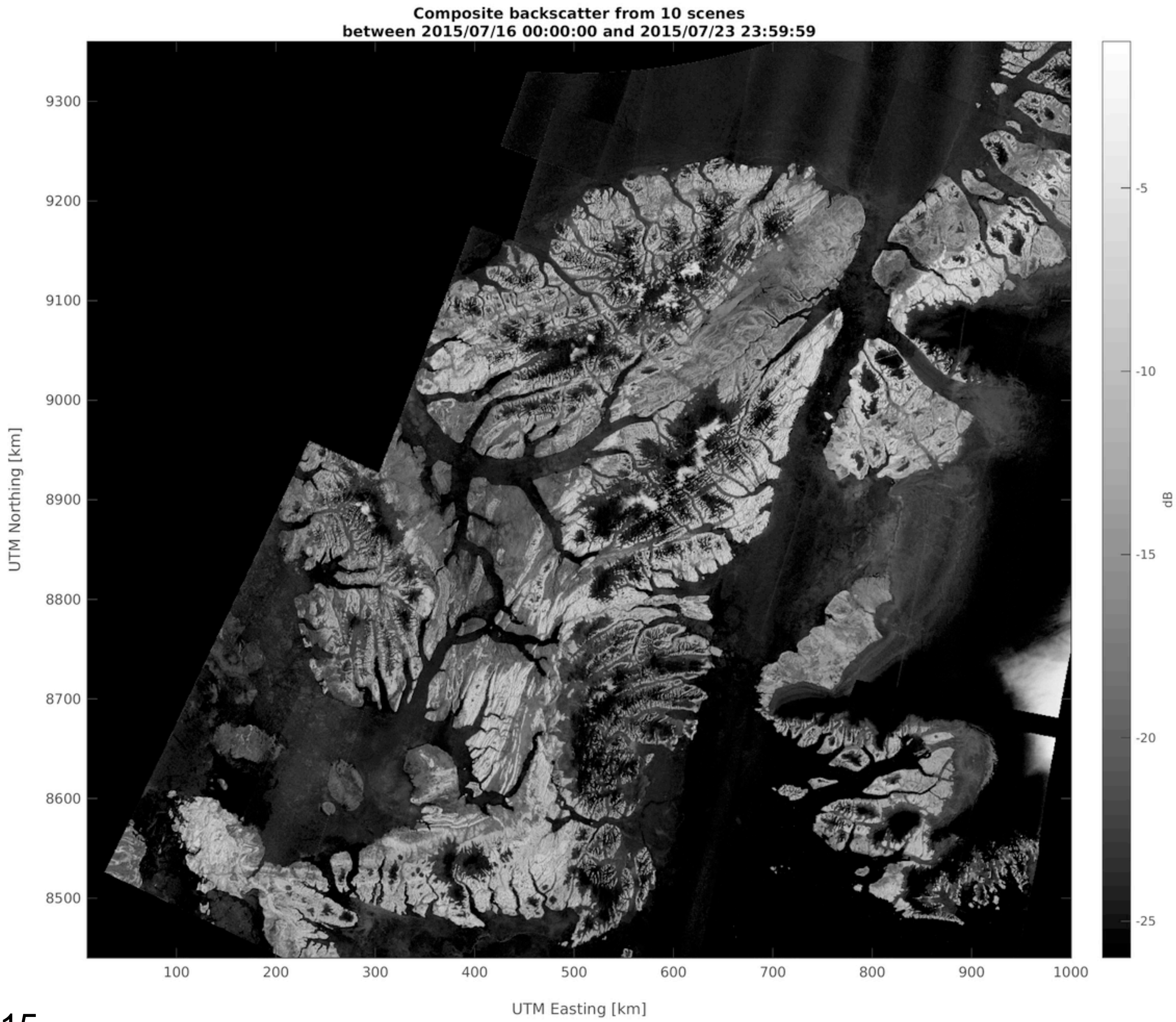
Ellesmere Island Backscatter Composites

RS2 SCWA HV

4 day delta

8 day window

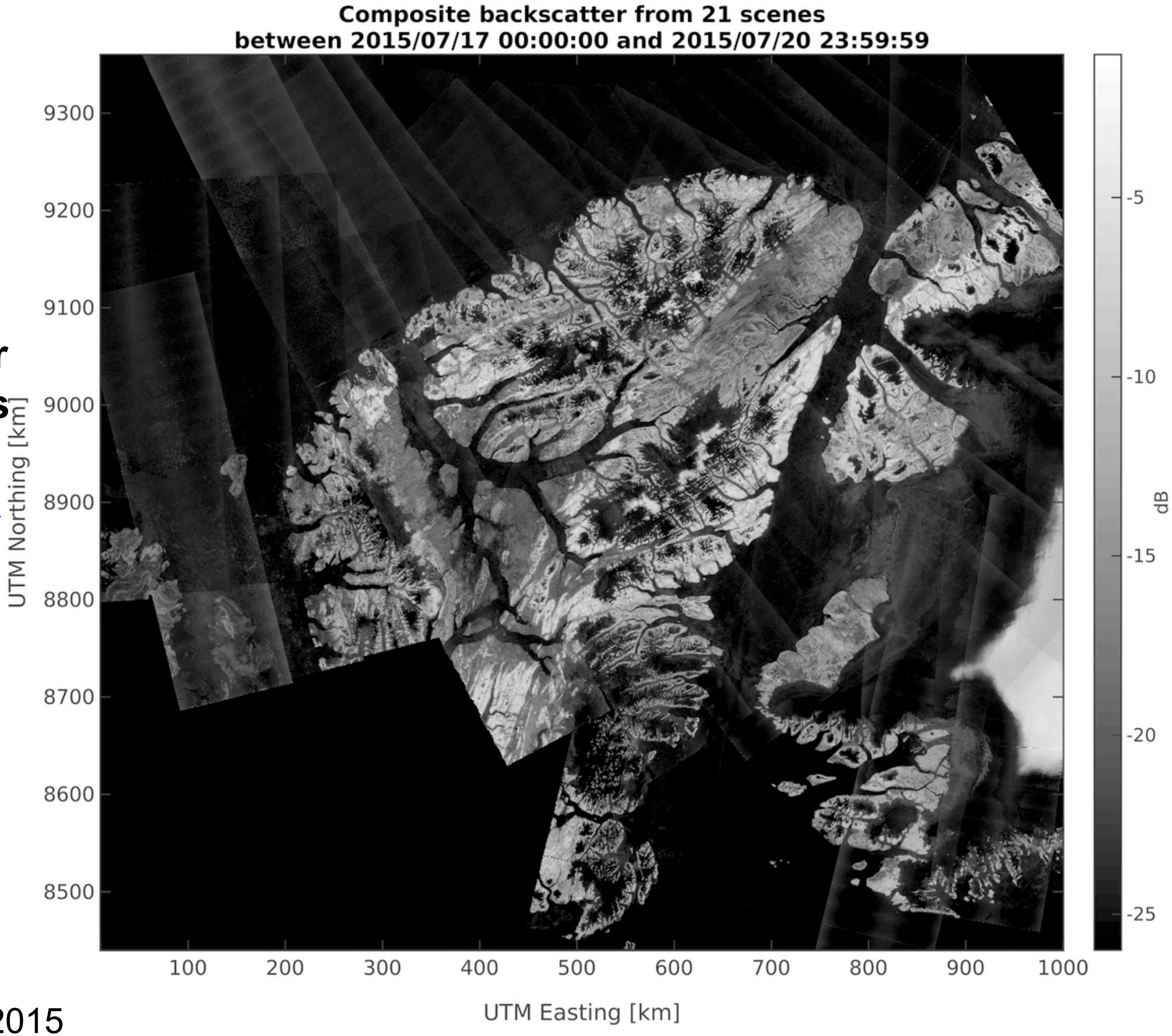
N.B.
8 bit radiometry
CDEM



May – Aug. 2015

Uni
Zuri
Dep

Ellesmere Island Backscatter Composites



S1A EW HV

2 day delta

4 day window

N.B.

HH also available

CDEM

May – Sept. 2015

Contains modified Copernicus Sentinel data (2015)

Universit
Zurich UZH

Dept. of G

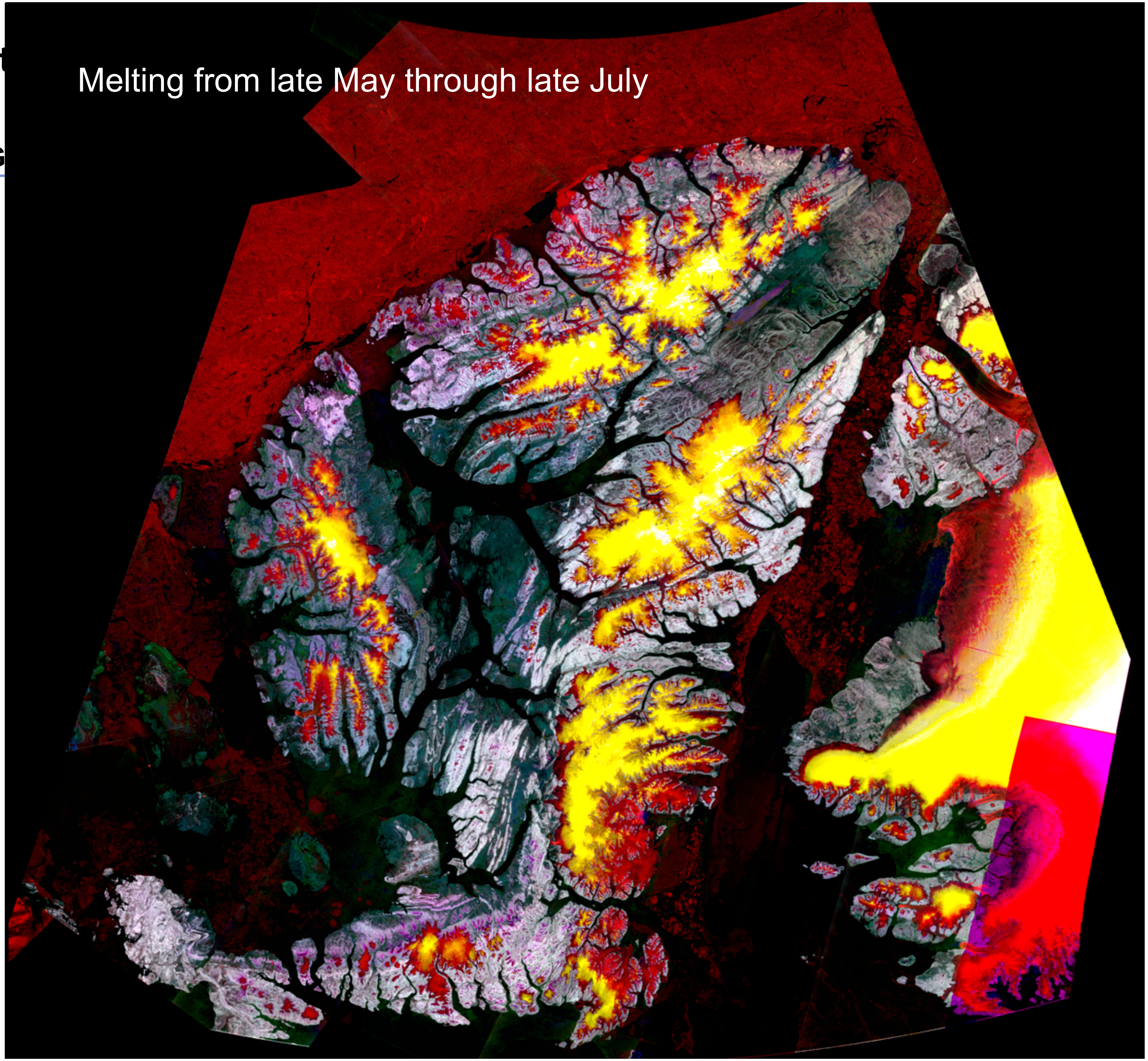
Ellesmere Island, Canada

Sentinel-1 EW **4d**
Composite HV:
May 24-27,
June 29-July 2,
July 23-26

γ_T^0 HV-pol.

-23dB -6dB

Contains modified
Copernicus
Sentinel data (2015)



Universit
Zurich UZH

Dept. of G

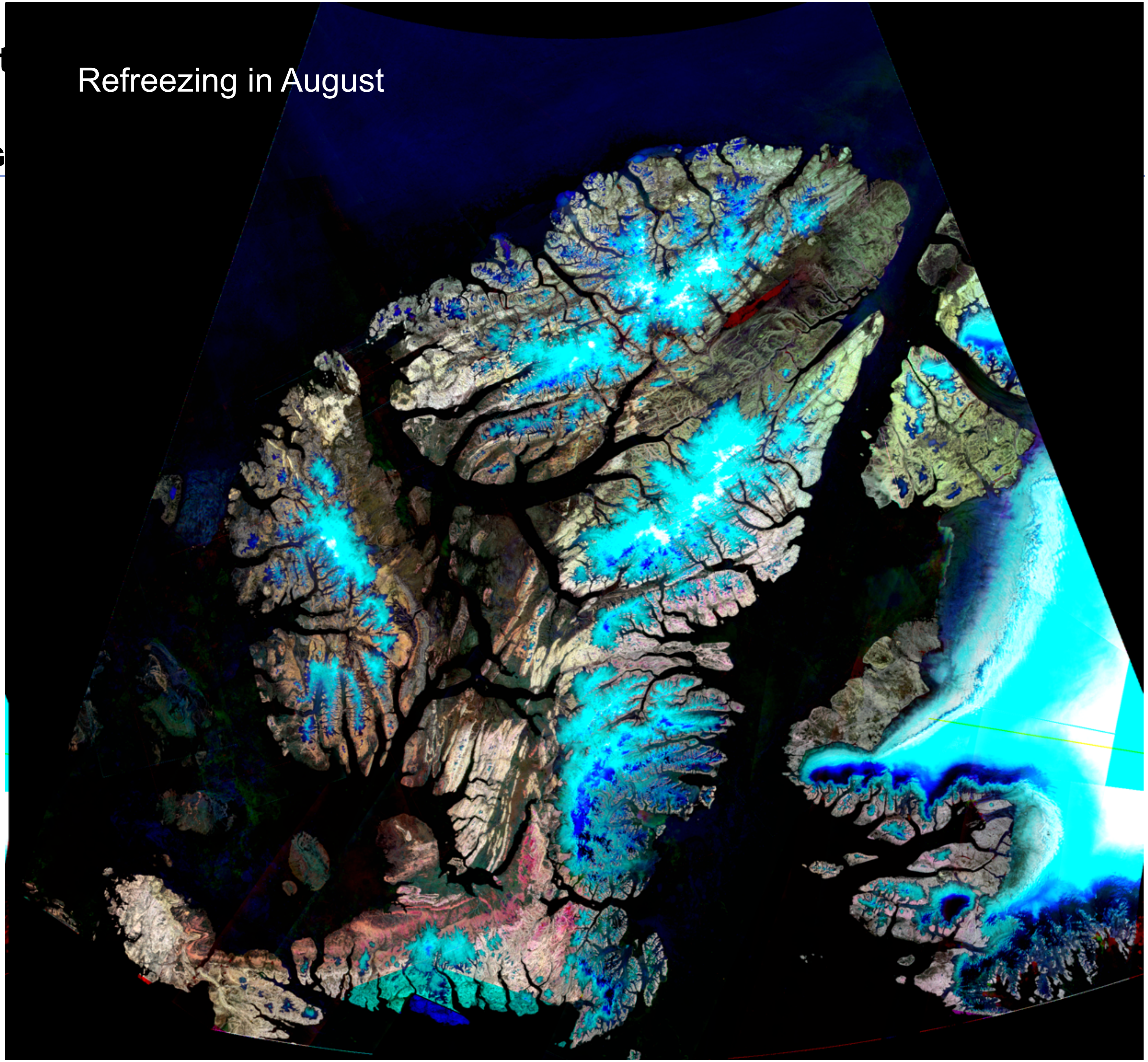
Ellesmere Island, Canada

Sentinel-1 EW **4d**
Composite HV:
July 25-28,
Aug. 12-15,
Aug. 24-27

γ_T^0 HV-pol.

-23dB -6dB

Contains modified Copernicus Sentinel data (2015)



Backscatter Composites

- **Demonstrations of Local Resolution Weighting with Sentinel-1A & Radarsat-2**
  - Geometric and radiometric effects of topography strongly reduced
  - Backscatter composite product properties more homogenous across product, also in presence of terrain

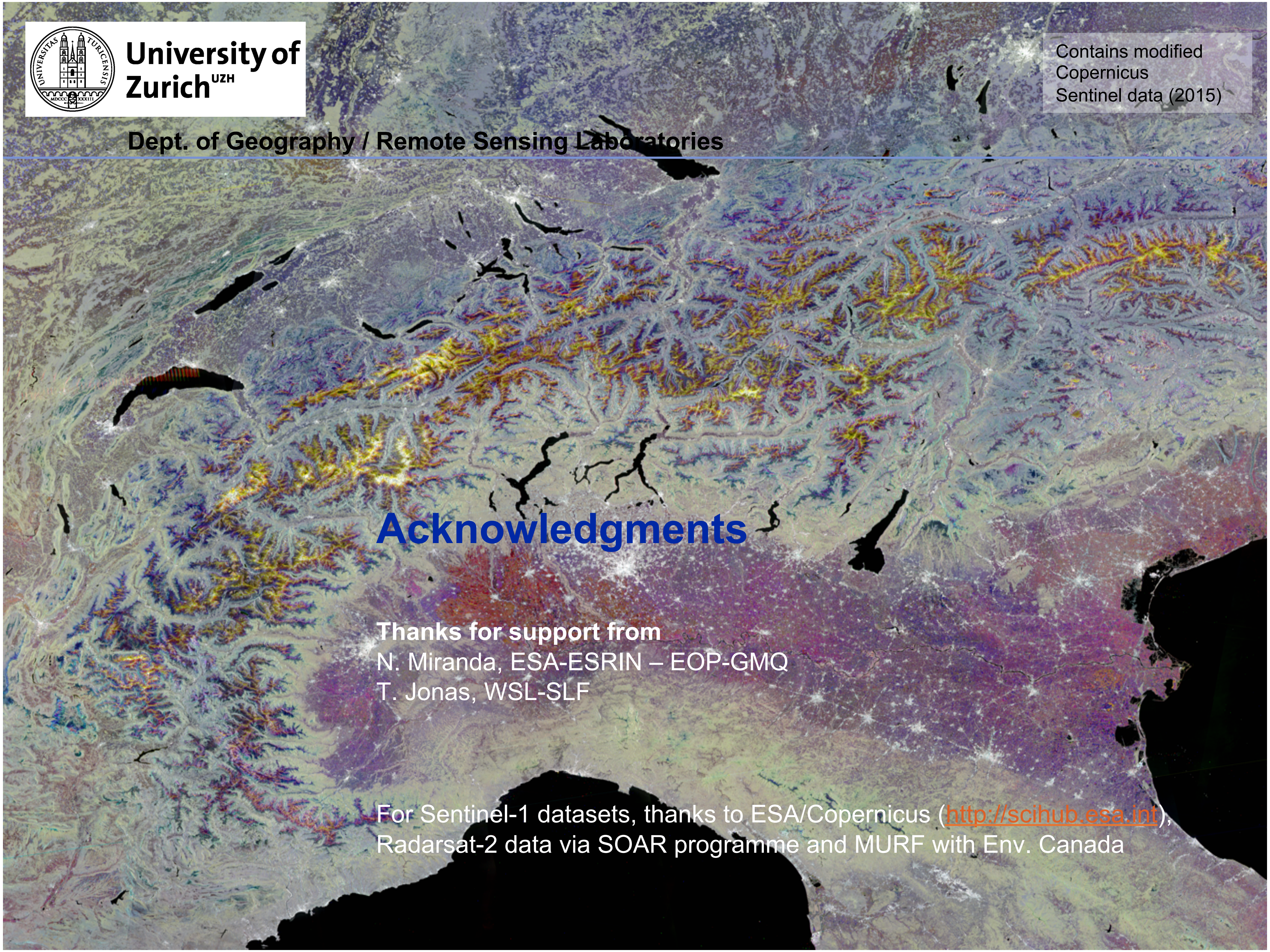
- **Sensor Integration**
  - **Not limited to a single sensor**: Local Resolution Weighting (LRW) useful for integrating multi-track and multi-mode, but also multi-sensor data streams (e.g. S1 + RS2)
  - **Higher time-resolution coming**: Width of time window can be *narrowed* while still supporting full coverage as more data becomes available (S1B opening this month, RCM-1, -2, -3 in 2018?)

- **Importance of Calibration**
  - Composite LRW backscatter stable due to dependable and highly accurate S1A geometric and radiometric calibration

Conclusions

- **Snow wetness clear strong signal in C-band SAR imagery**
- **Snow depth and Snow Water Equivalent (SWE) currently not accessible in single-date C-band SAR data**

- **Series of Sentinel-1 satellites opening a new era of multimodal multi-wavelength data integration**
  - Contributions from other data suppliers (NASA/USGS, CSA, JAXA, DLR, ASI) welcome
    - E.g. SARs: Radarsat-2, Radarsat Constellation Mission, TerraSAR-X, Cosmo-Skymed, PAZ
      - Future: Paz, NiSAR, TanDEM-L
    - E.g. VIS/IR: MODIS, Landsat, Sentinel-2, Sentinel-3



University of Zurich[UZH]

Dept. of Geography / Remote Sensing Laboratories

Contains modified Copernicus Sentinel data (2015)

Acknowledgments

Thanks for support from
N. Miranda, ESA-ESRIN – EOP-GMQ
T. Jonas, WSL-SLF

For Sentinel-1 datasets, thanks to ESA/Copernicus (http://scihub.esa.int),
Radarsat-2 data via SOAR programme and MURF with Env. Canada