→ 6th ESA ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

Snow Mapping and Monitoring

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RSL
measurements | products | policy

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Outline

Remote Sensing of Snow

- 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?

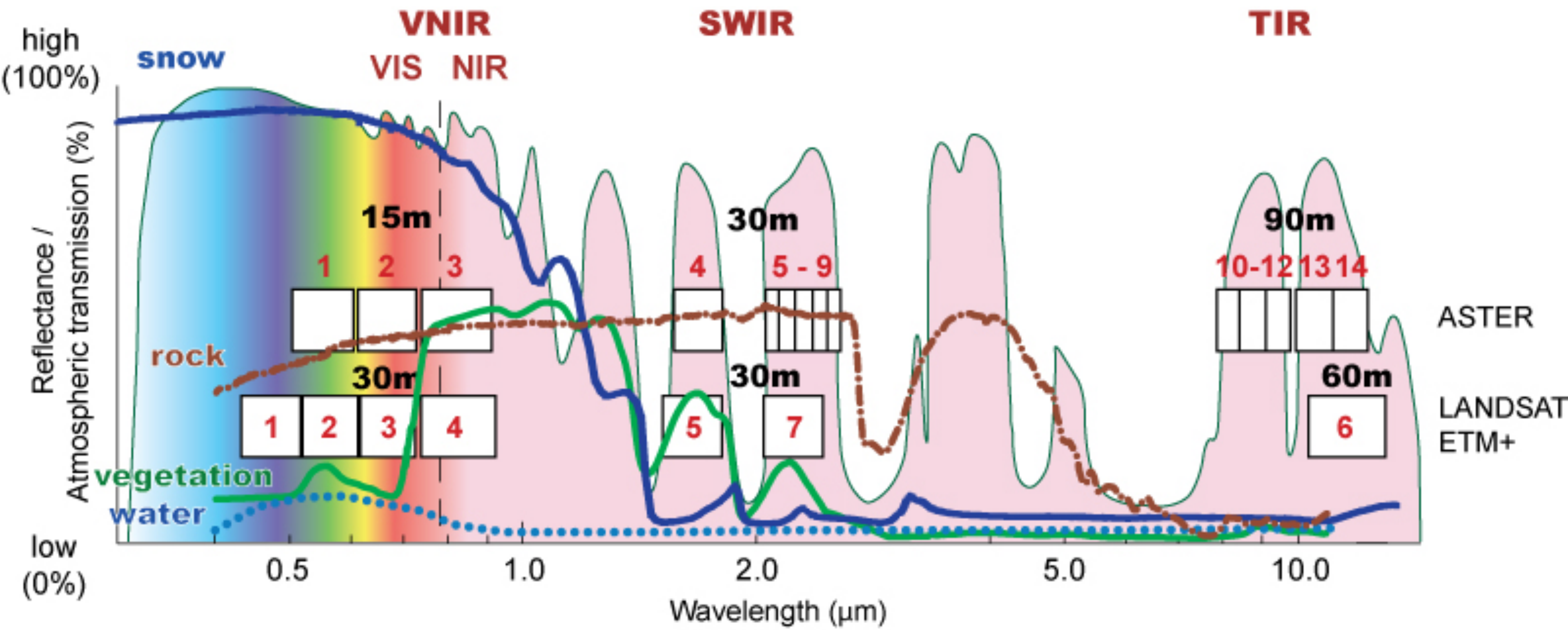
-distorted in presence of steep topography?

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

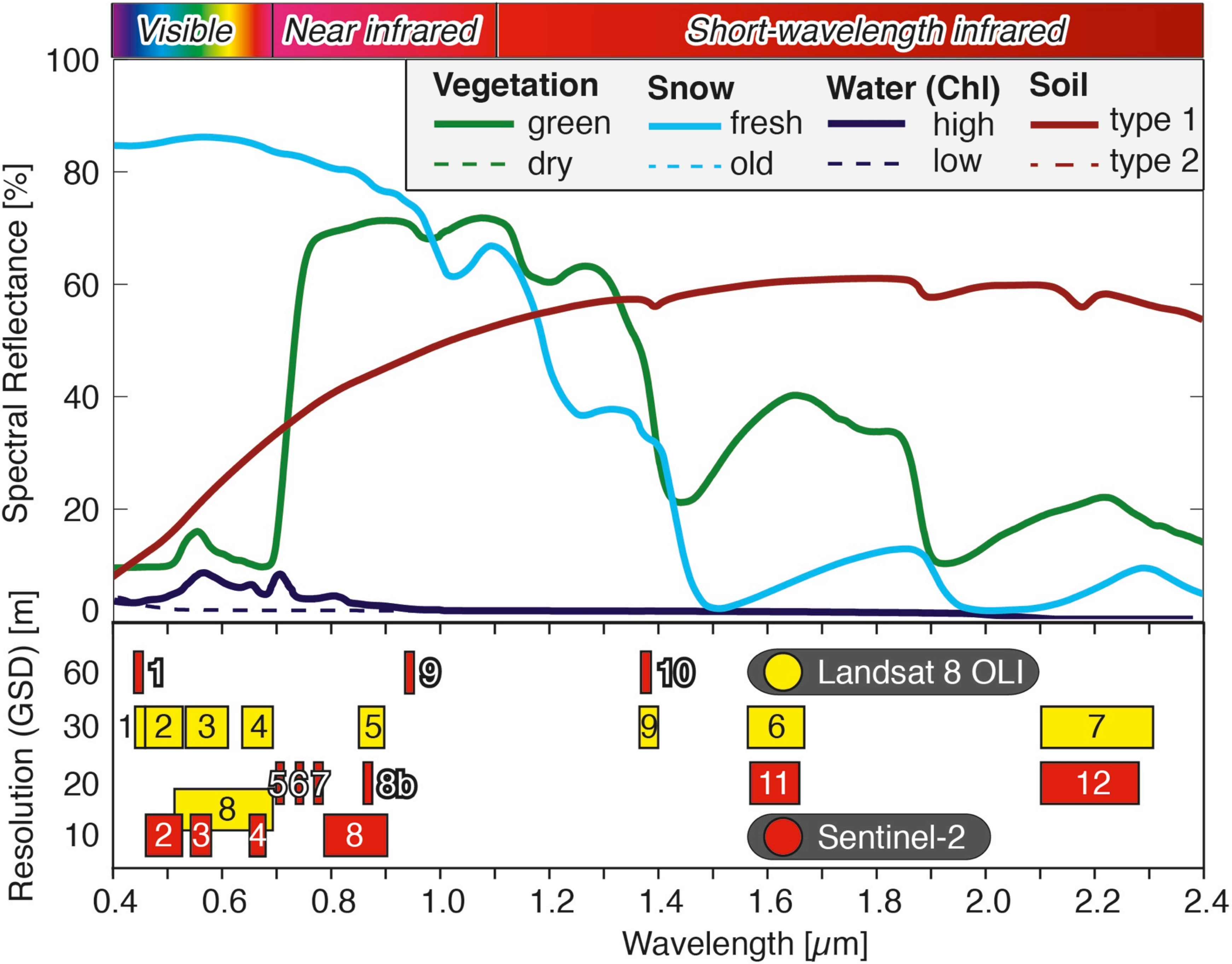
Future: integrate required 'harmonised' measurements, harnessing all strengths?

Visible / Infra-red

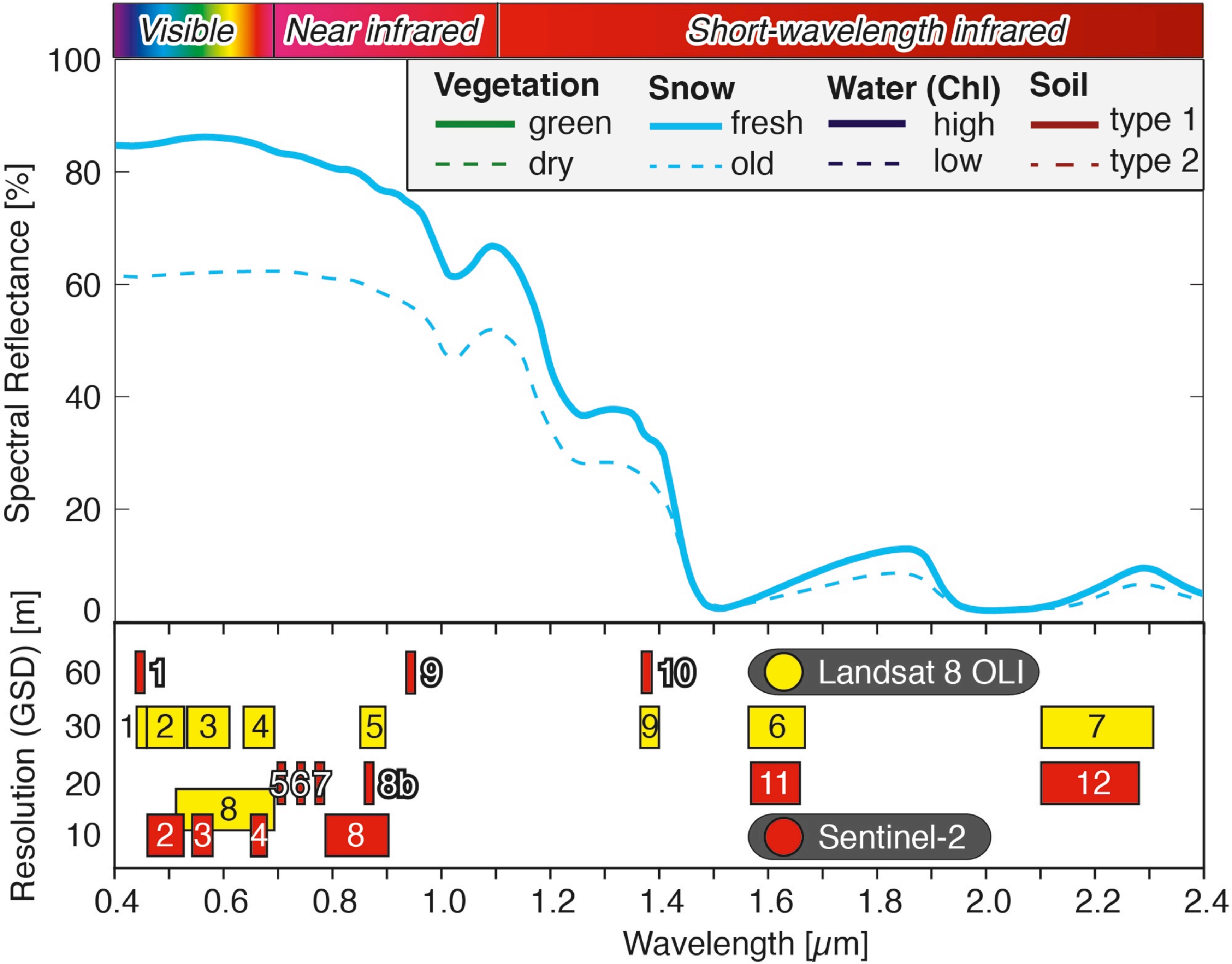
Remote Sensing of Snow: VIS/IR



ESA eduspace



Courtesy
H. Wulf,
UZH-RSL



Courtesy
H. Wulf,
UZH-RSL

Standard Snow Products from optical sensors

MODIS Product Table

- https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table
- http://modis-snow-ice.gsfc.nasa.gov

- Normalised Difference Snow Index (NDSI)
    - NDSI = (TM Band 2 - TM Band 5) / (TM Band 2 + TM Band 5)
    - Adapted thresholds necessary in forests (Dozier & Painter):
        - "A pixel in a clear area is mapped as snow-covered when NDSI>0.4 and TM band 4> 0.11.
        - In a forested area, the pixel is mapped as snow when 0.1 < NDSI < 0.4."

J. Dozier and T. H. Painter, "**Multispectral and Hyperspectral Remote Sensing of Alpine Snow Properties**," Annu. Rev. Earth Planet. Sci., vol. 32, no. 1, pp. 465–494, May 2004.

D. K. Hall, G. A. Riggs, V. V Salomonson, N. E. DiGirolamo, and K. J. Bayr, "**MODIS snow-cover products**," Remote Sens. Environ., vol. 83, no. 1–2, pp. 181–194, Nov. 2002.


Sep 15, 2013

Active Microwave:
Synthetic Aperture Radar

SAR: Backscatter Normalisation Conventions

Radar Cross Section

- For ***point targets***:
- Backscatter σ [dB·m²] is *ratio of scattered to incident power*:

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

- Known: transmitted & received power P_t & P_r
- Derive: incident & scattered power P_i & P_s from P_t & P_r

$$\Rightarrow \sigma = k \cdot \frac{f_2(P_r)}{f_1(P_t)}$$

Radar Equation

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

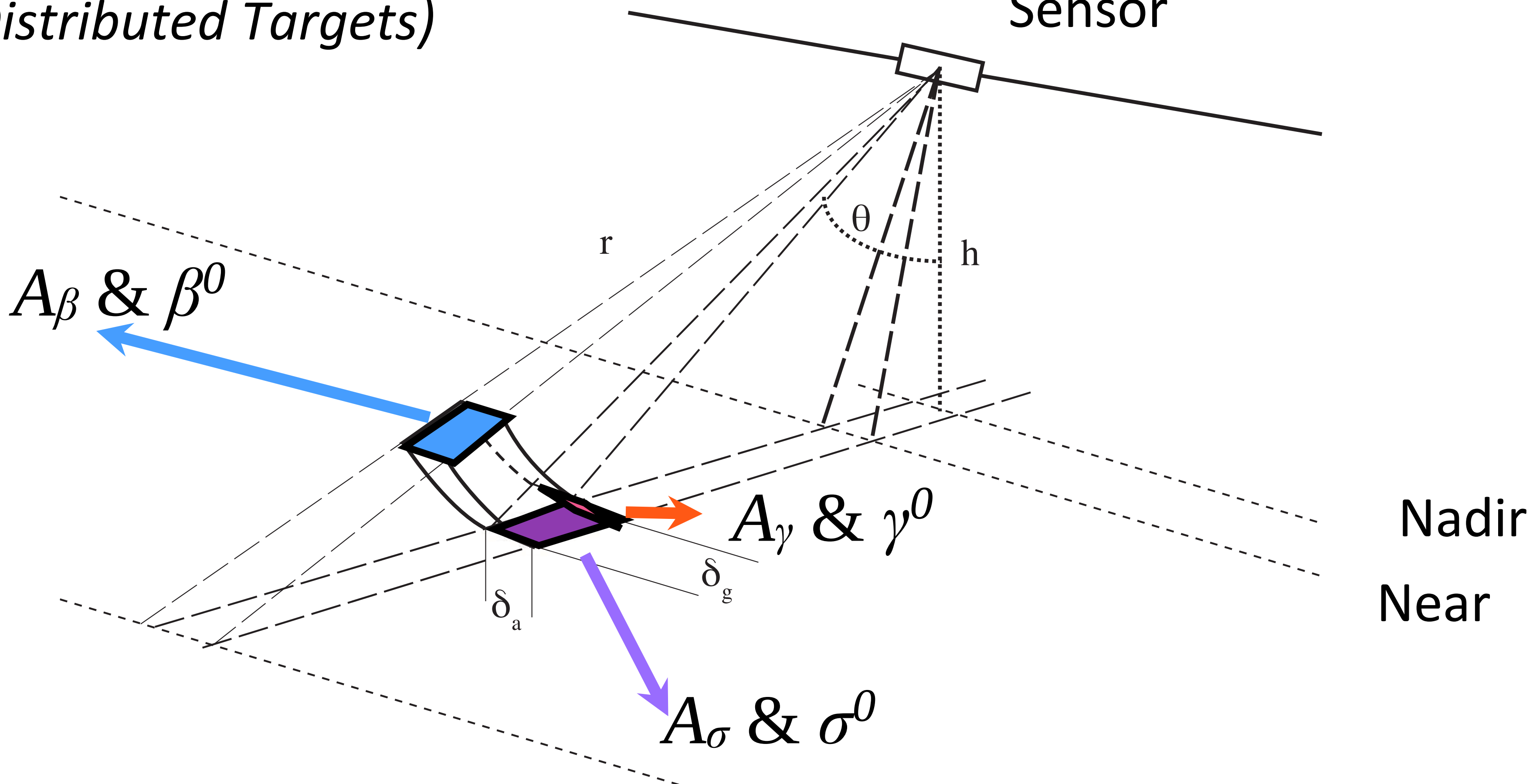
$$\beta^0 = \frac{\sigma}{A_\beta} \qquad \sigma_E^0 = \frac{\sigma}{A_\sigma} \qquad \gamma_E^0 = \frac{\sigma}{A_\gamma}$$

- Known: transmitted & received power P_t & P_r
- Derive: incident & scattered power P_i & P_s from P_t & P_r

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

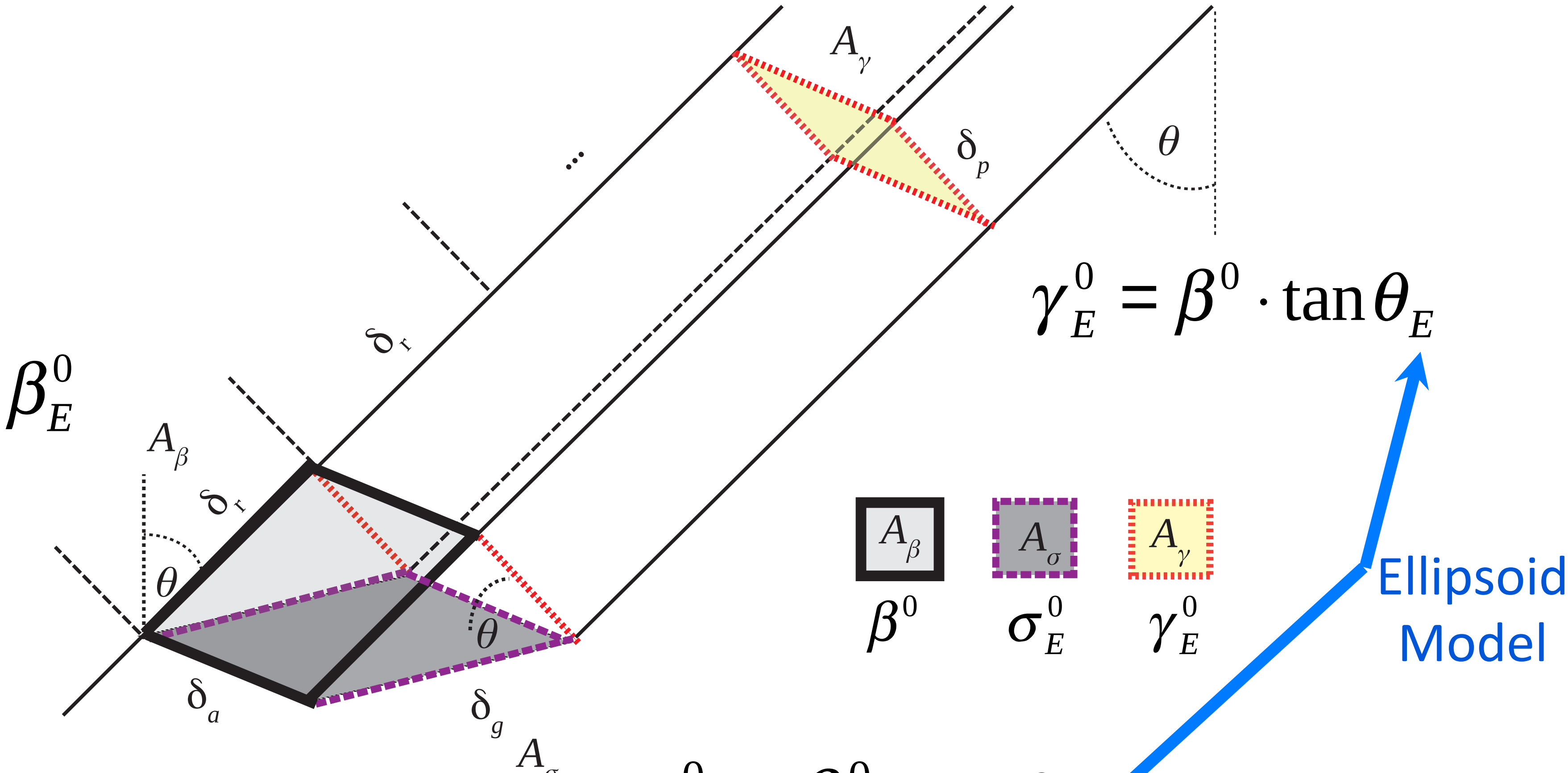
Standard Areas for Normalisation

(Distributed Targets)



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

Ground Illuminated Area

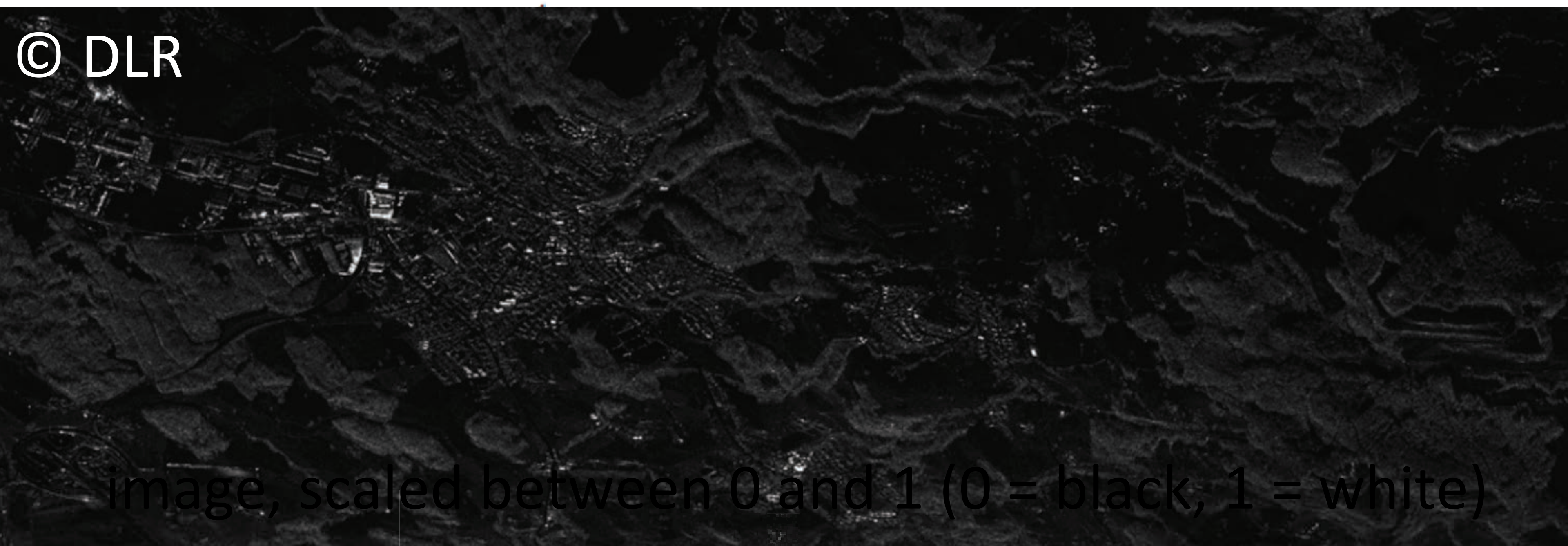


$$\gamma_E^0 = \beta^0 \cdot \tan\theta_E$$

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

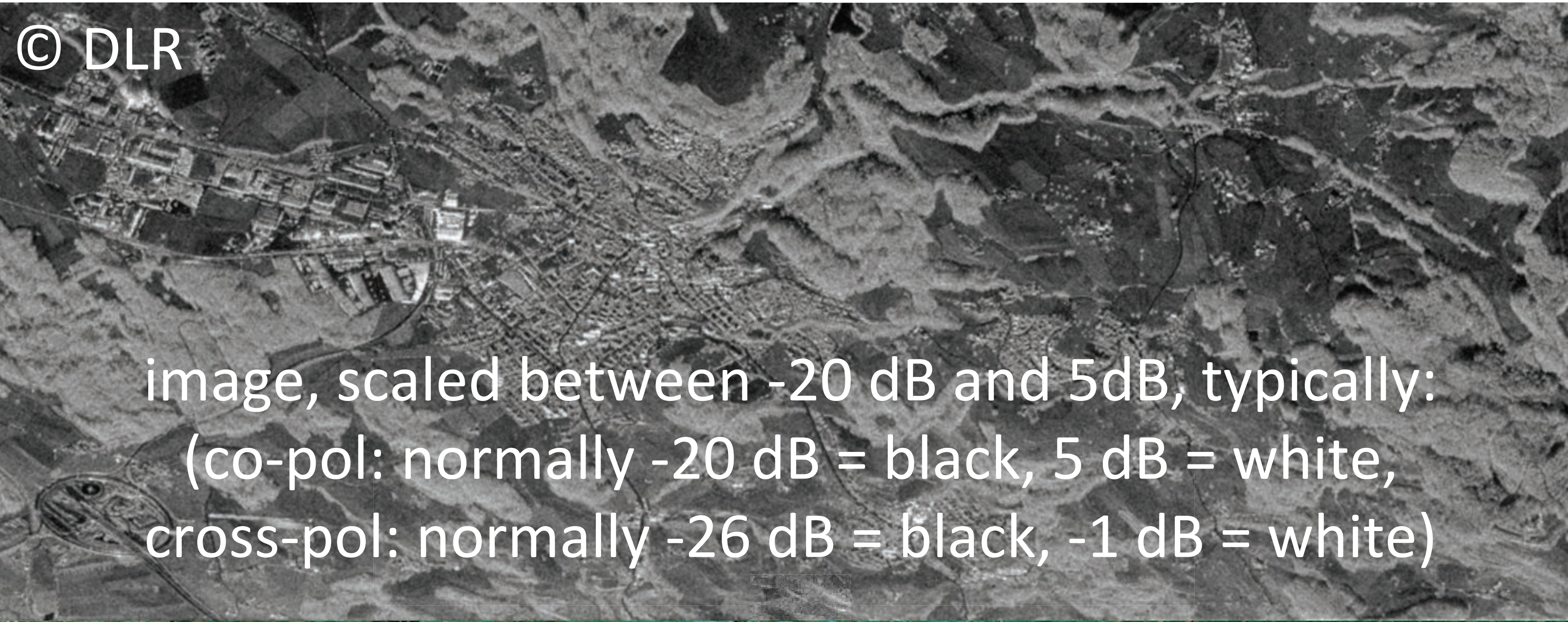
The graphical representation of β^0

- The histogram of β^0 values in a typical SAR image shows very few high values (close to 1), but many very low values (close to 0)



[dB]

- Better would be a histogram like this:



image, scaled between -20 dB and 5dB, typically:
(co-pol: normally -20 dB = black, 5 dB = white,
cross-pol: normally -26 dB = black, -1 dB = white)

dB is a Log Scale

- Calculate the dB (decibel) value of a backscatter coefficient:

$$\beta^0[dB] = 10 \cdot \log_{10}(\beta^0)$$

$$\sigma_E^0[dB] = 10 \cdot \log_{10}(\sigma_E^0)$$

$$\gamma_E^0[dB] = 10 \cdot \log_{10}(\gamma_E^0)$$

$$0 \text{ dB} \leftrightarrow 1.00$$

$$\sim{+3} \text{ dB} \leftrightarrow 2.00$$

$$-20 \text{ dB} \leftrightarrow 0.01$$

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

dB differences, Image *ratios*

- Given two SAR images, image A, and image B, we recover the difference in backscatter between the two images with ***subtraction*** in the *dB* log scale
- Subtraction in the *dB* log scale is equivalent to ***division*** of the radar image digital numbers (*DN*)

$$(\beta_A^0 - \beta_B^0)\ \ [\mathrm{dB}] = 10 \cdot \log_{10}\left(\frac{DN_A}{DN_B}\right)$$

dB *difference*

DN *ratio*

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.

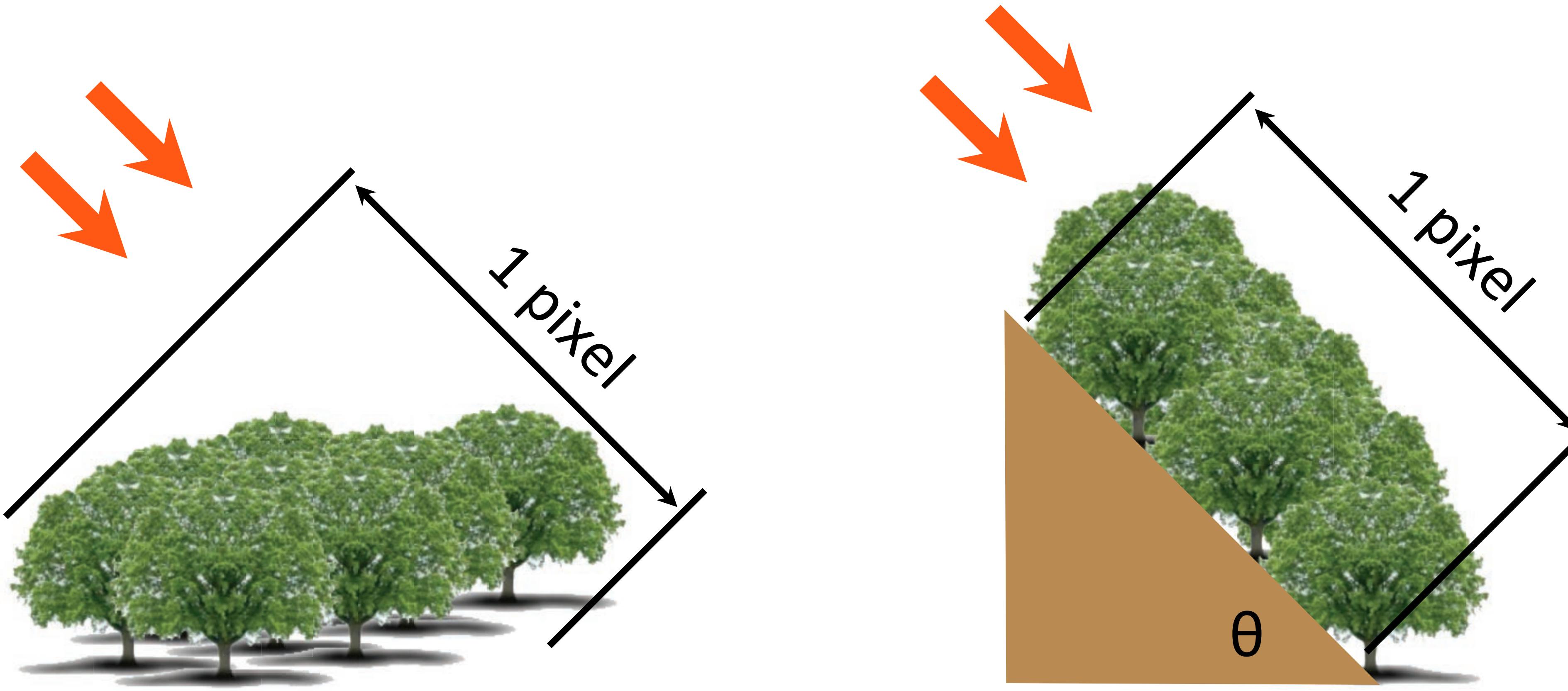
T. Nagler and H. Rott, "**Retrieval of wet snow by means of multitemporal SAR data**," IEEE Trans. Geosci. Remote Sens., vol. 38, no. 2, pp. 754–765, Mar. 2000.

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.

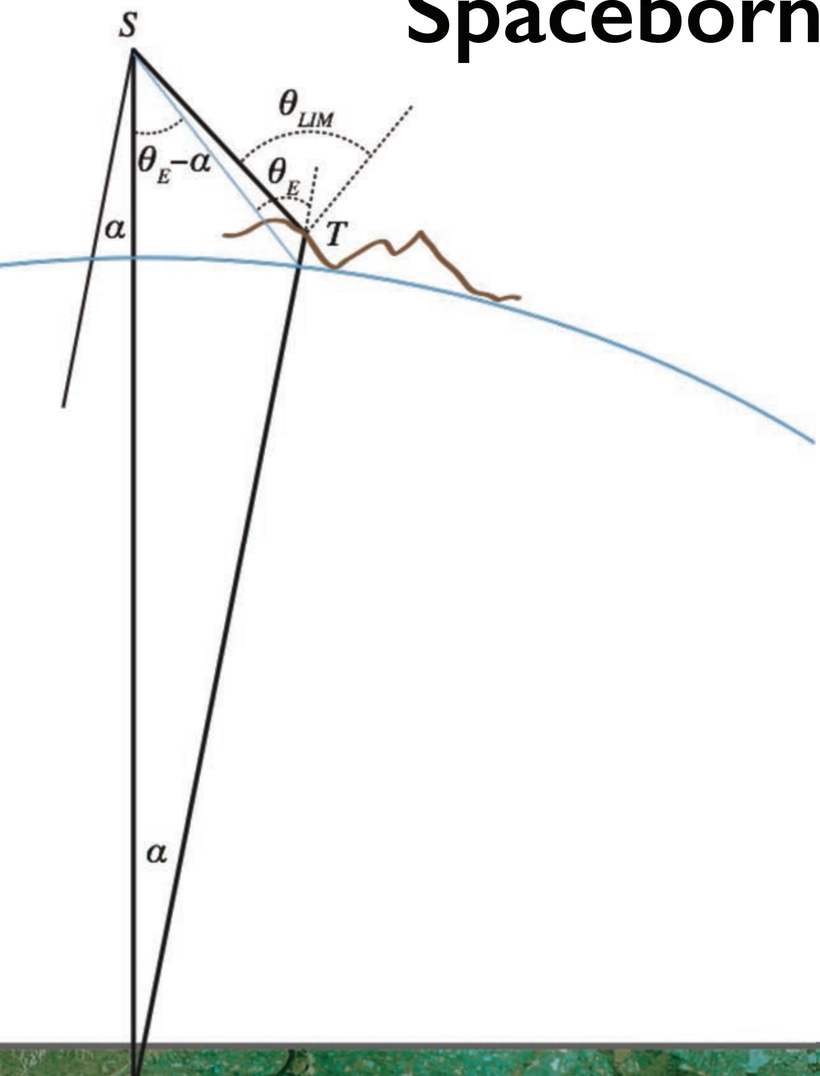
History of snow mapping projects

- **GlobSnow**: SWE for non-Alpine regions using passive microwave & climate stations; Fractional snow extent from ATSR, AATSR, VIIRS – www.globsnow.info
- **PolarView**: Pan-European snow maps at 10d based on ASAR, Radarsat-1, MODIS, AVHRR; specialised products in central Europe & Baltic – www.polarview.org
- **EUMETSAT H-SAF**: Regional passive microwave SWE and optical snow cover fraction – hsaf.meteoam.it
- **SNAPS**: Snow maps for Scandinavia based on combining MODIS and ASAR data and studied wet snow monitoring in the context of avalanche monitoring – www.snaps-project.eu
- **Cryoland**: Regional fractional snow extent based on a combination of MODIS and Radarsat-2 – cryoland.eu
- Summaries of projects: www.snowmonitoring.info

Local Incident Angles θ



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)

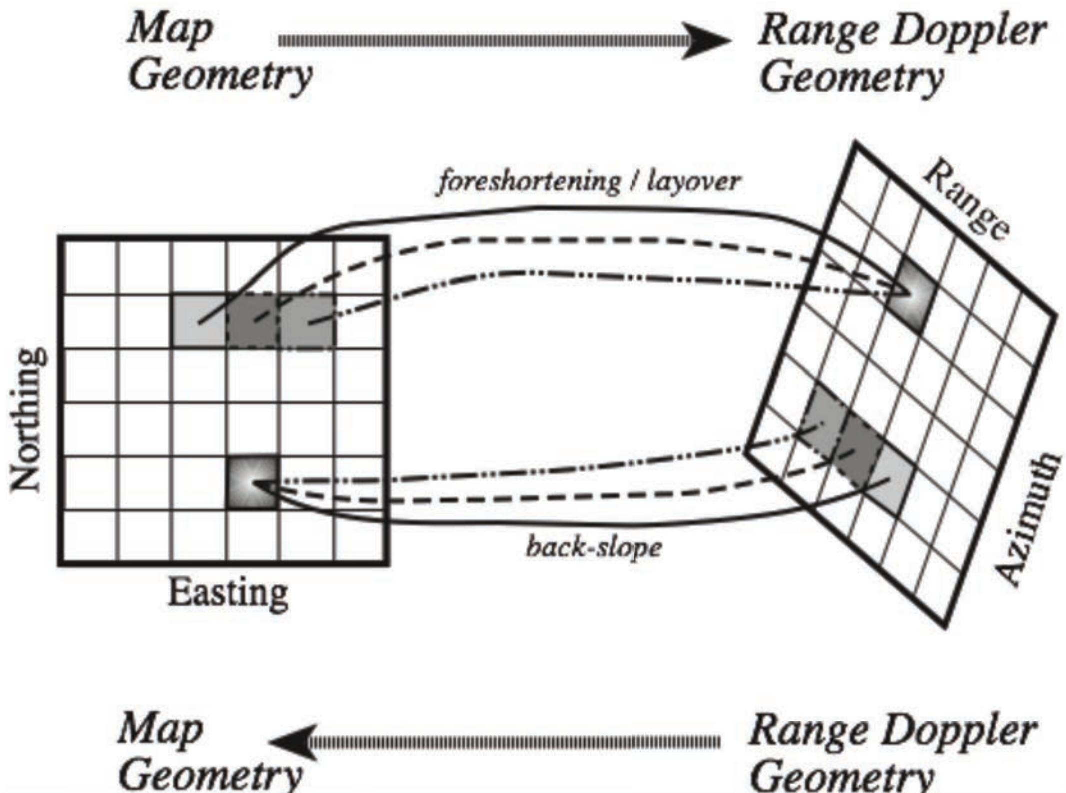
- The most common slope-normalisation methodology found in the literature is fails to account for **non-homomorphic** (one to many correspondence) nature of relationship between Earth coordinates (map geometry) & slant range geometry (native sensor acquisition process)
- Normalisation for local variation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

- 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***

Simulated SAR Image A_γ

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

ASAR WS: April 12, 2010 (Map Geometry)

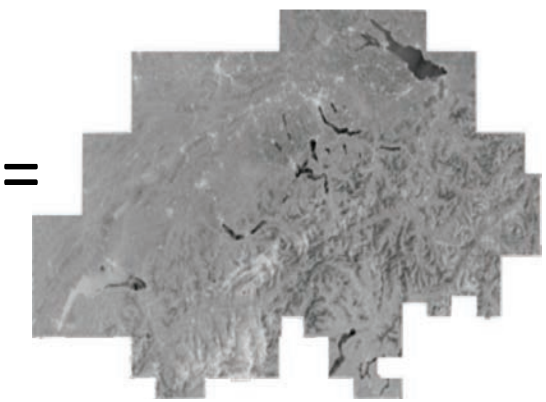
Normalise β^0: divide by simulated image

β^0

/

A_γ / A_β

=



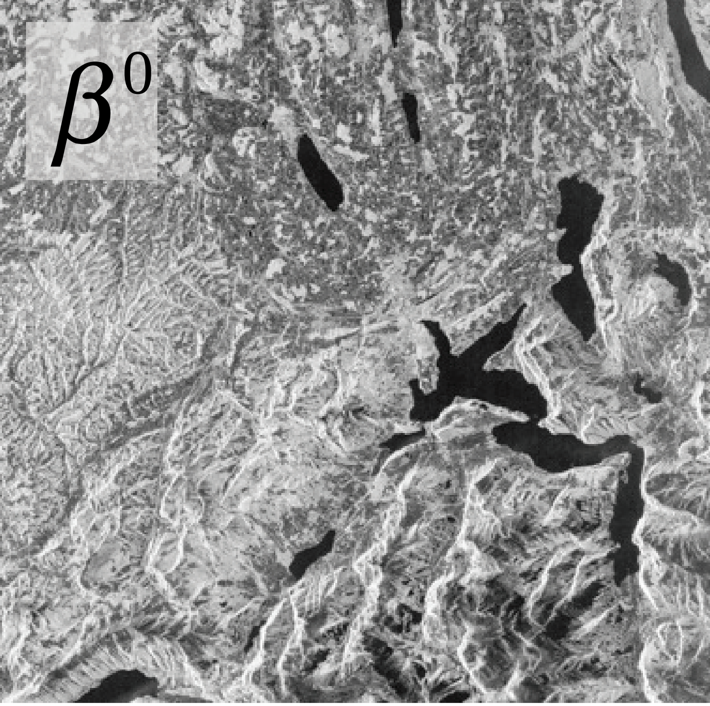
-20dB 5dB

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

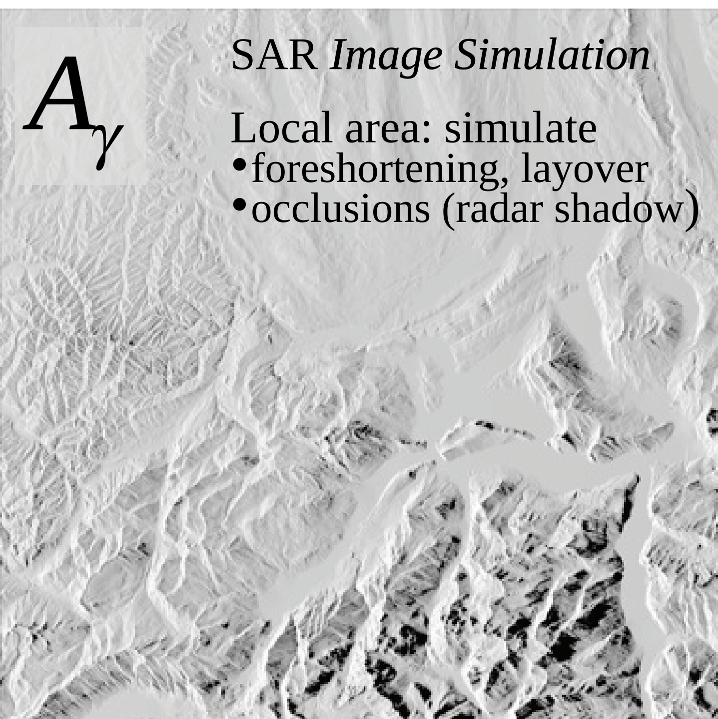
Flattening Radar Backscatter

ALOS PALSAR Fine Beam Dual polarisation (FBD) HV

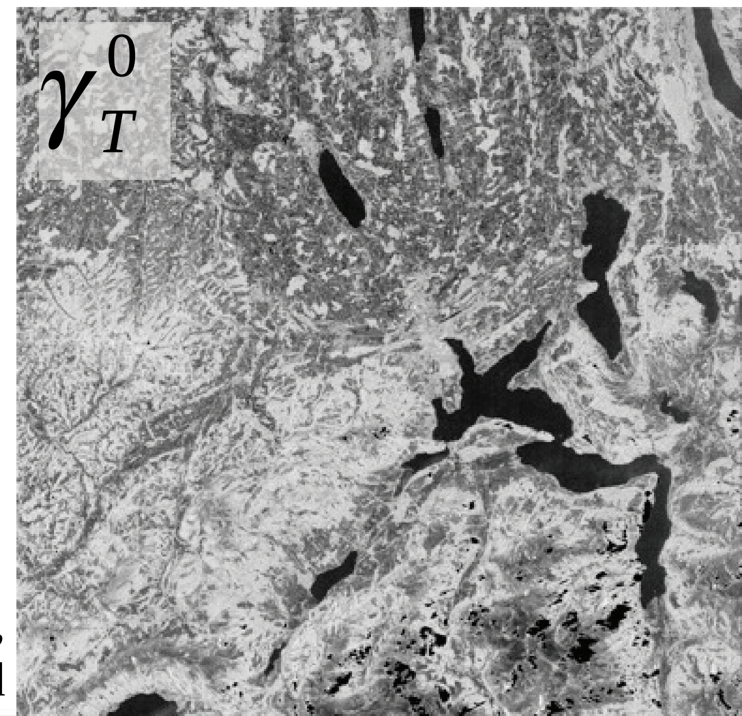
JAXA ALOS PALSAR data via ESA ADEN



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



Terrain-flattened Gamma Nought



Lucerne, Switzerland

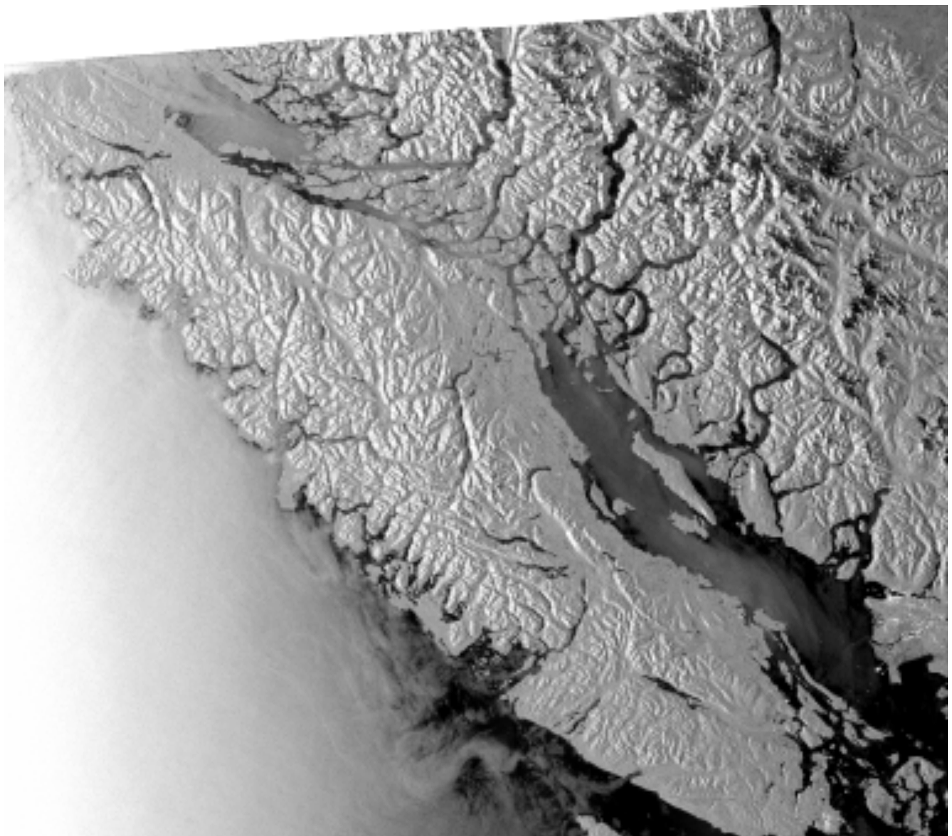
Validation Tests on Terrain-flattening Methodology

ASAR Wide Swath (WS)
Vancouver Island,
British Columbia, Canada

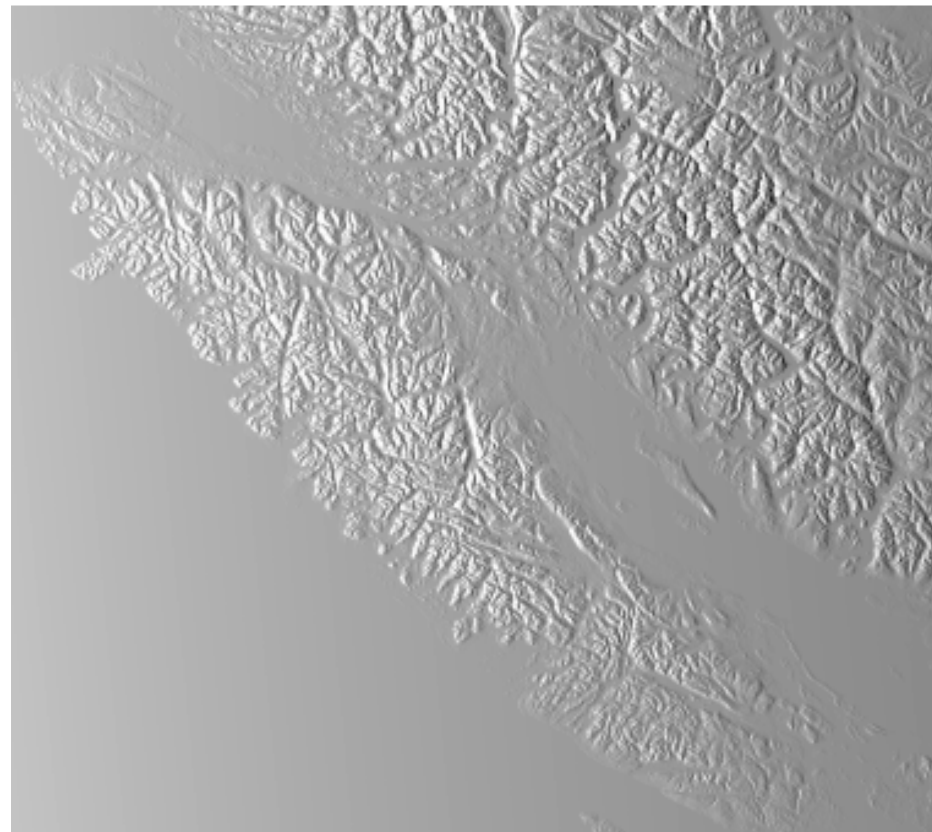
RSL

Vancouver Island, British Columbia, Canada

-20dB 5dB



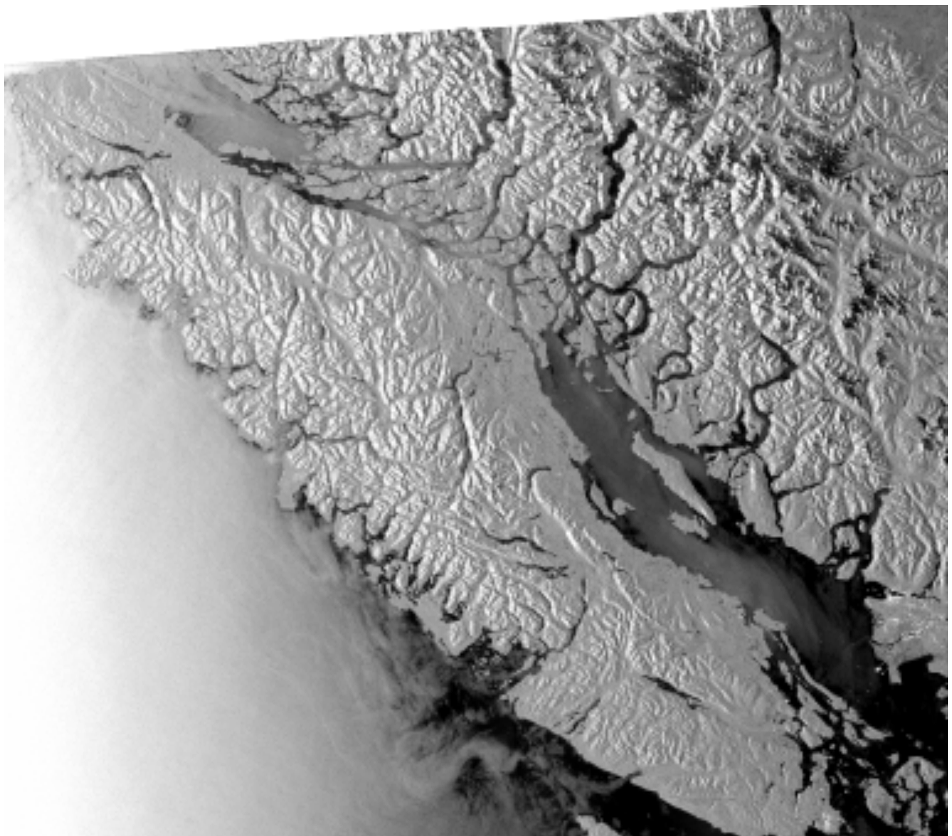
ASAR WSM 2008.09.10 GTC (SRTM3)



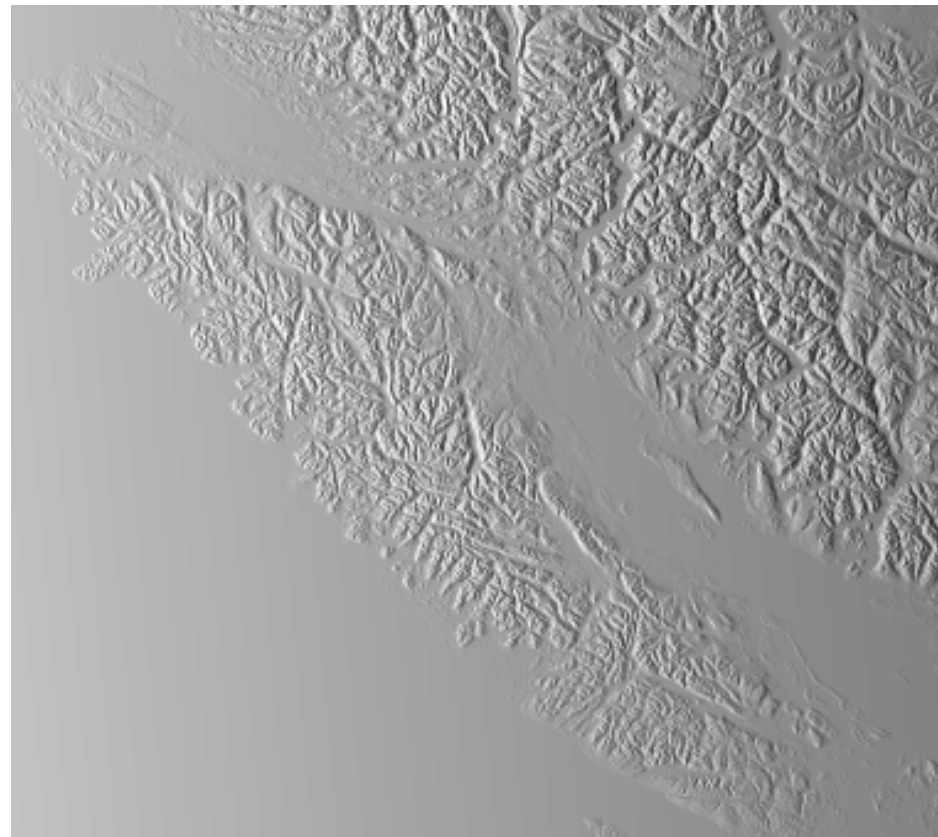
SRTM3 Integrated Contributing Area

Vancouver Island, British Columbia, Canada

-20dB 5dB



ASAR WSM 2008.09.10 GTC (SRTM3)



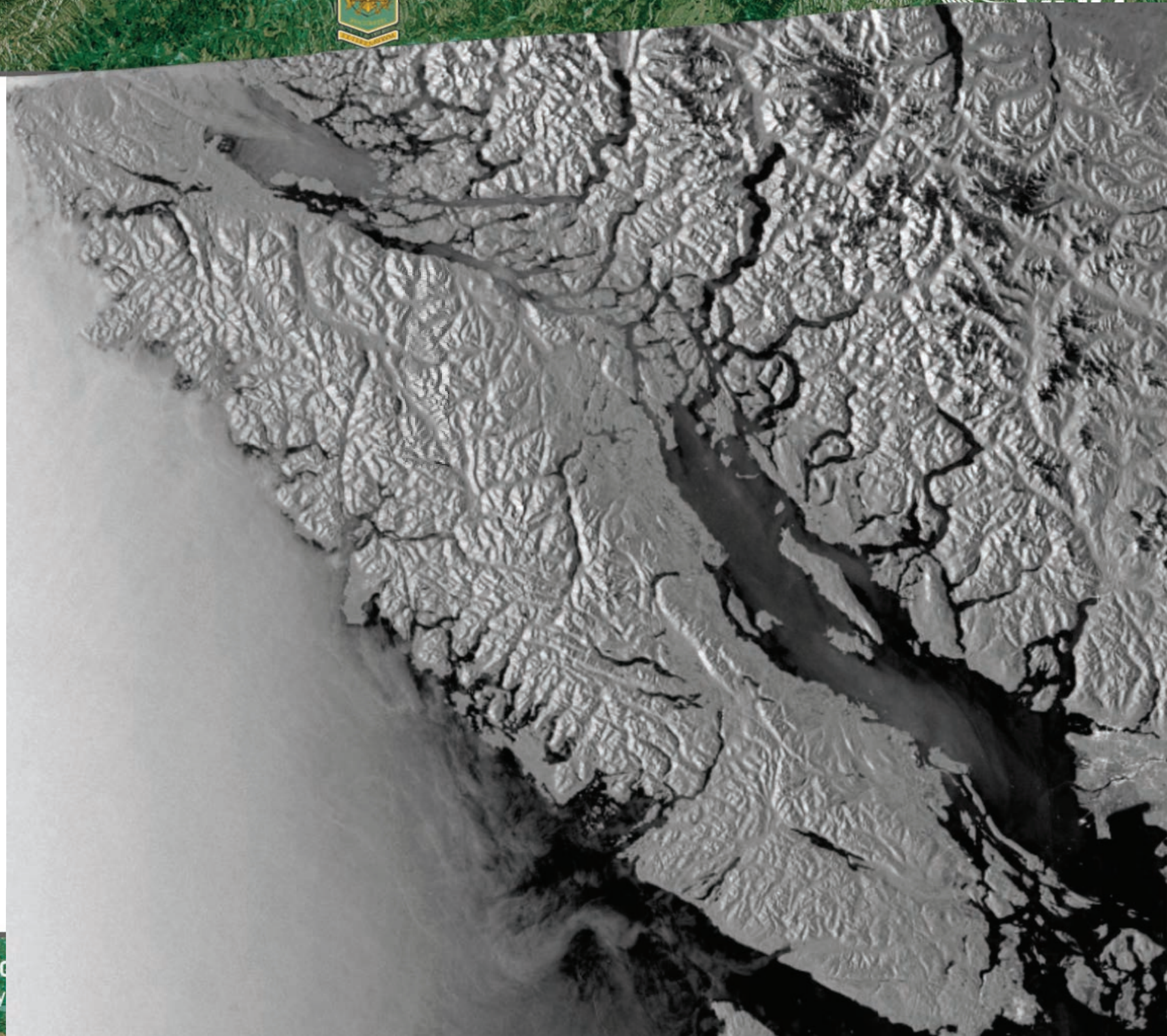
SRTM3 Local Incident-angle Mask

ASAR WSM **GTC**
2008.09.10

SRTM3 DHM

$$\gamma_E^0$$

-20dB 5dB

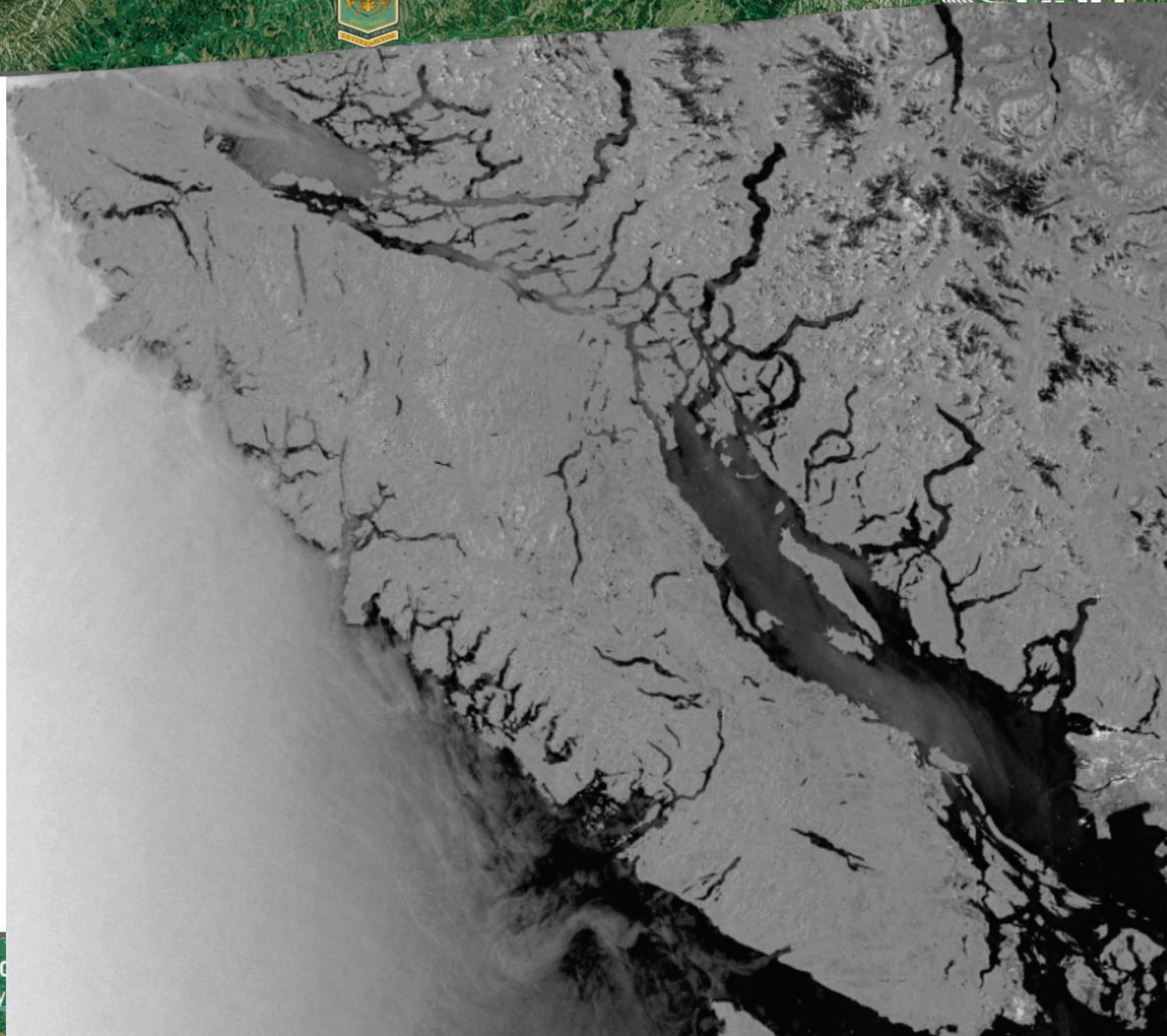


ASAR WSM **RTC**
2008.09.10

SRTM3 DHM

$$\gamma_T^0$$

-20dB 5dB

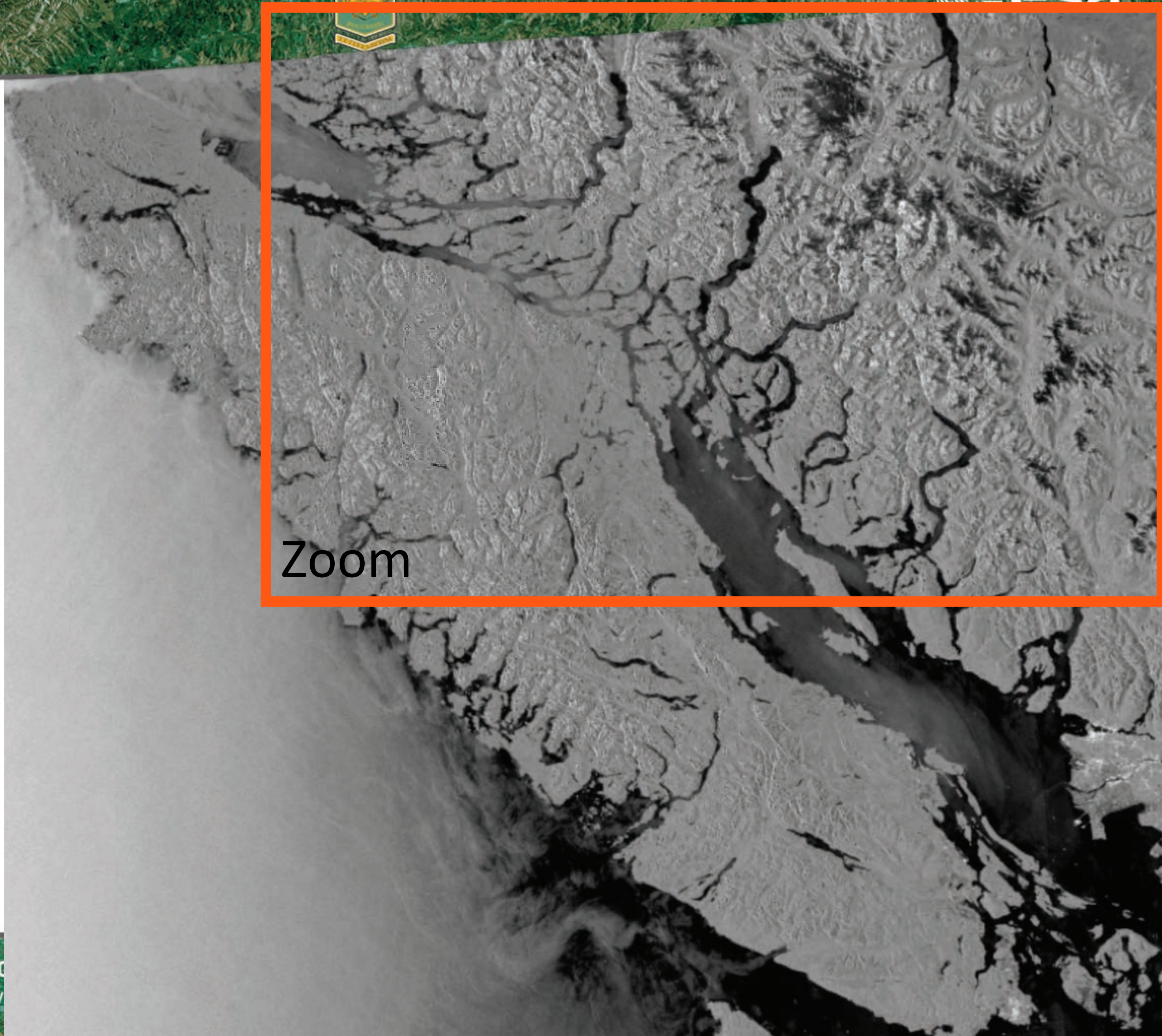


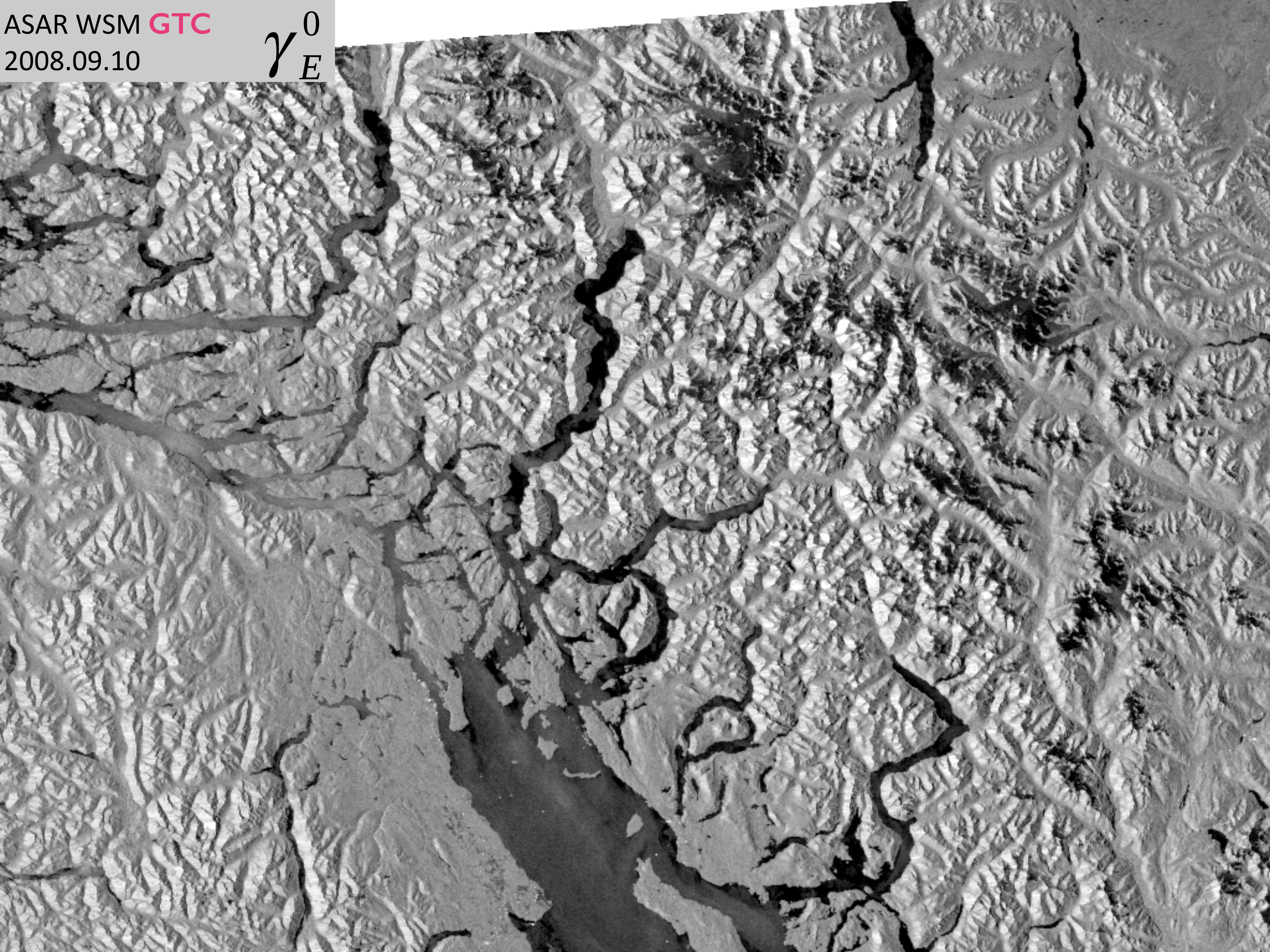
WSM NORLIM
2008.09.10

SRTM3 DHM

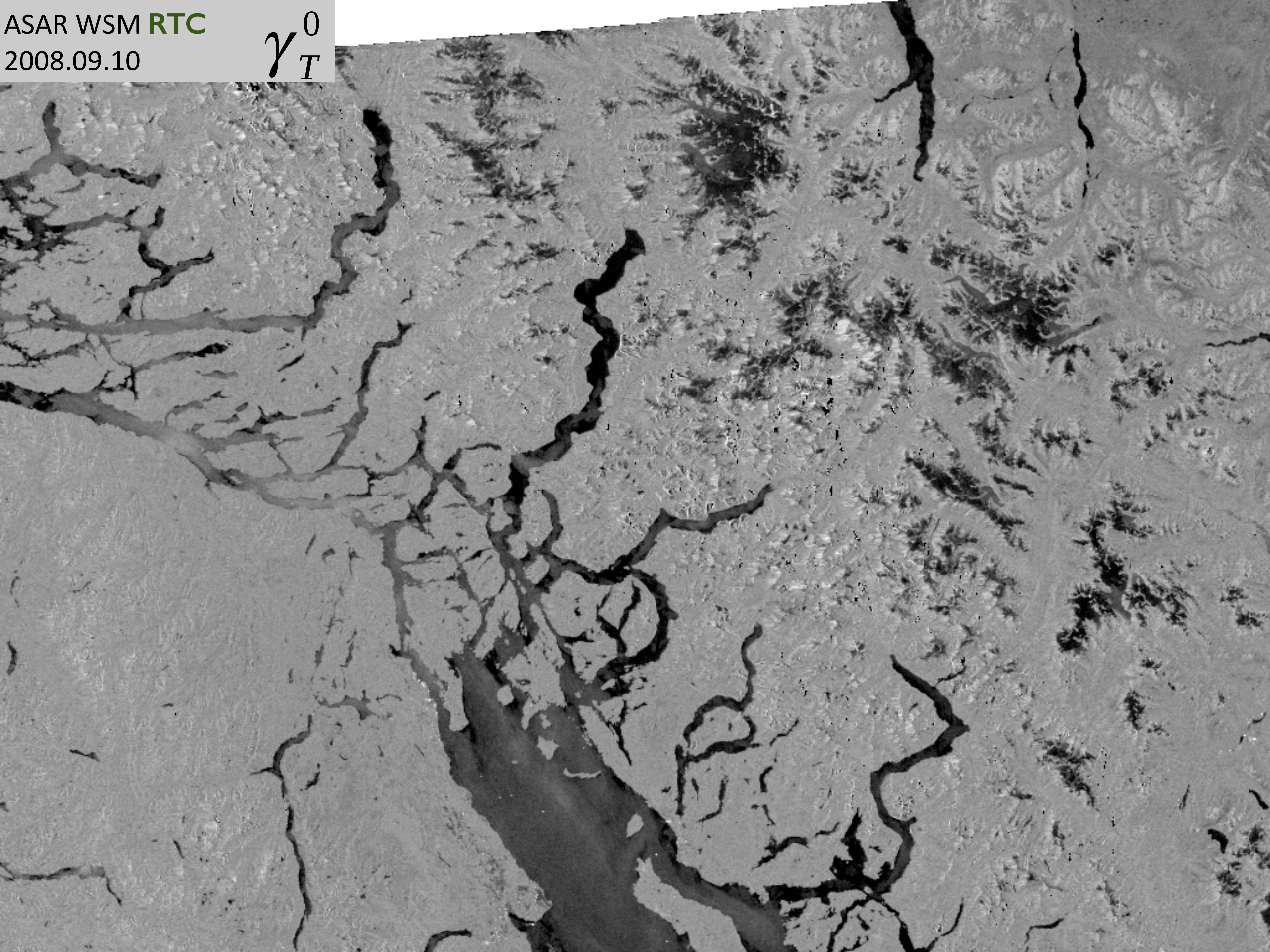
$$\sigma^{0}_{NORLIM}$$

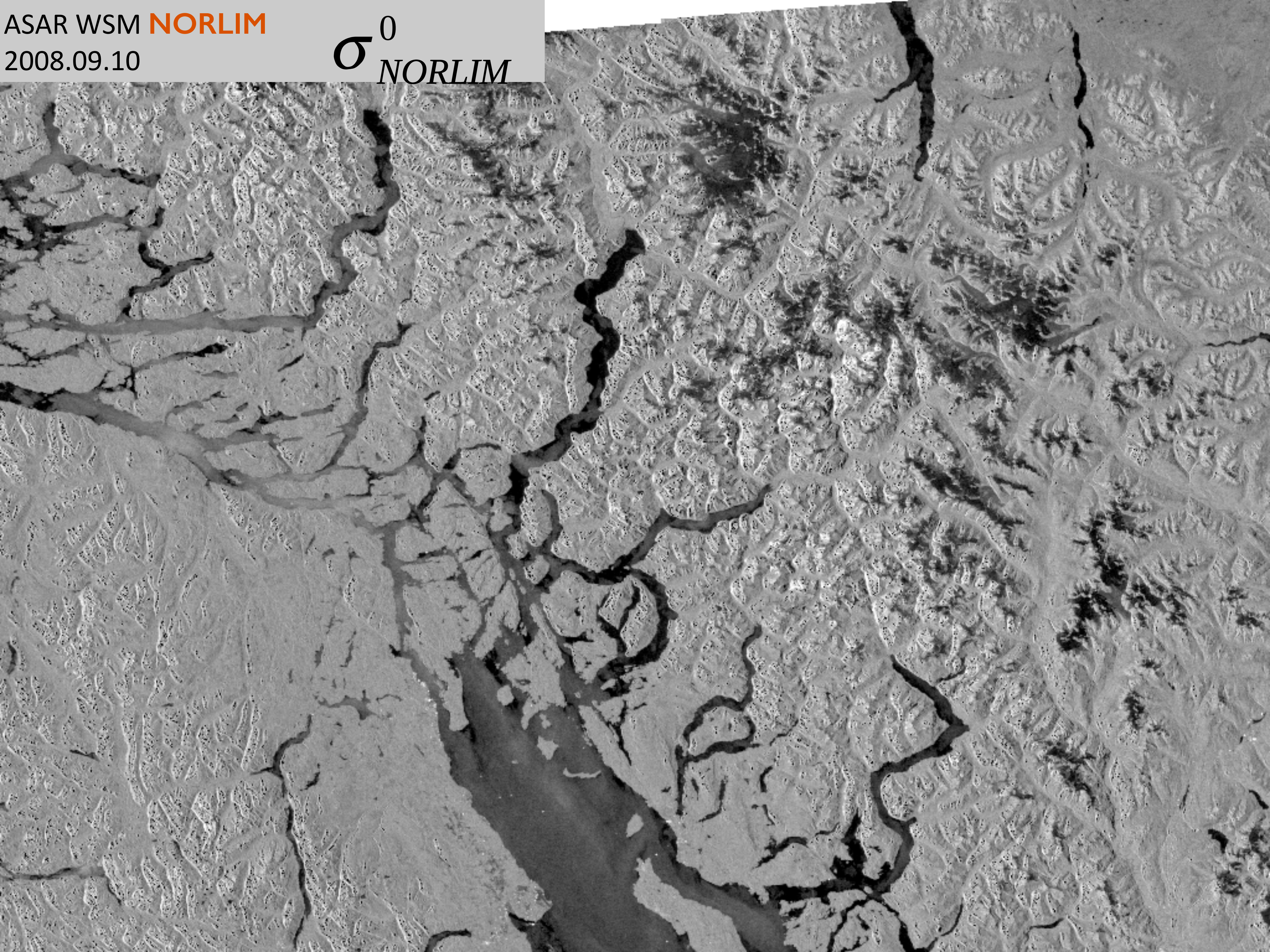
-20dB 5dB





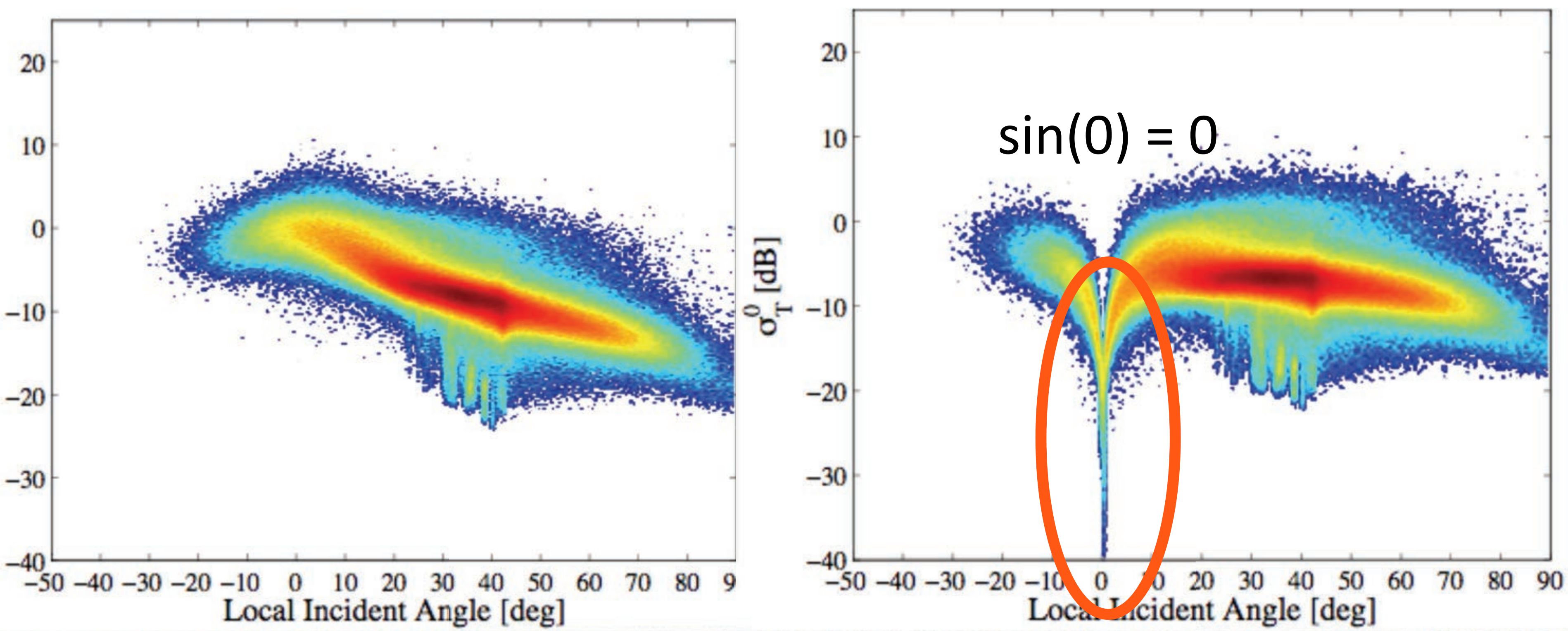
ASAR WSM GTC
2008.09.10
γ_E^0


ASAR WSM RTC
2008.09.10
γ_T^0

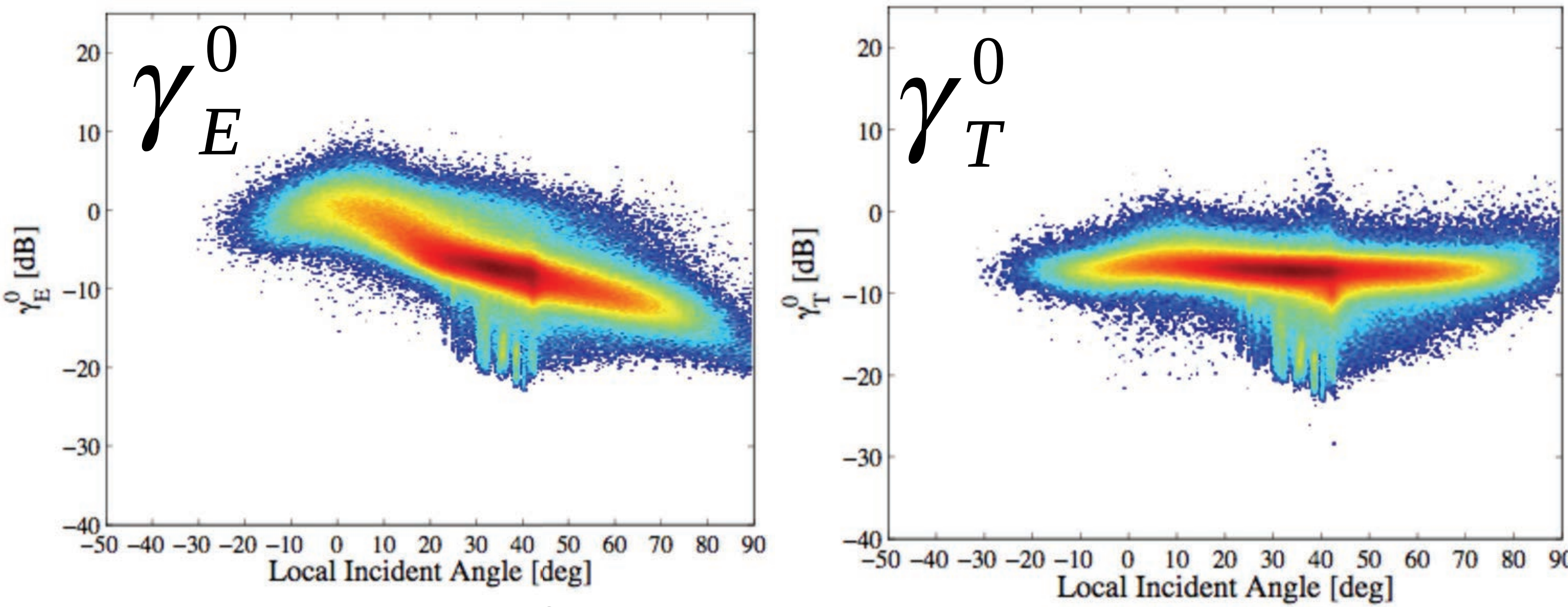

ASAR WSM NORLIM
2008.09.10
σ^0_{NORLIM}

Incident-angle backscatter dependence: before & after NORLIM terrain-correction

σ^0_E σ^0_{NORLIM}

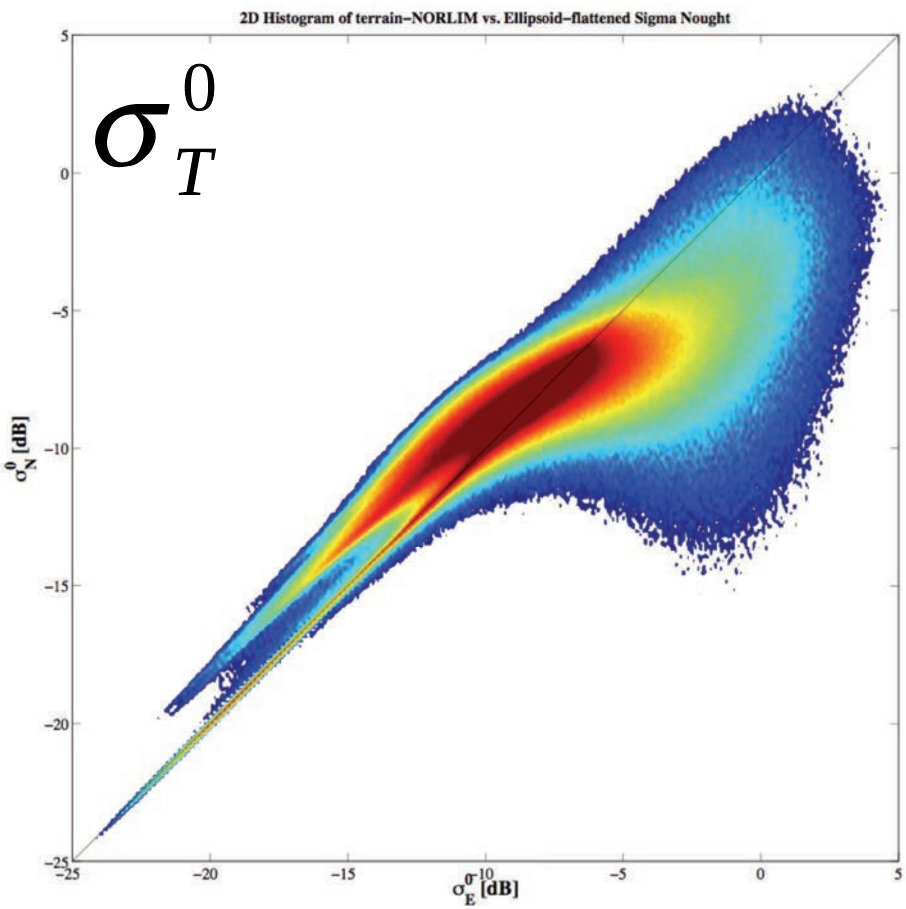


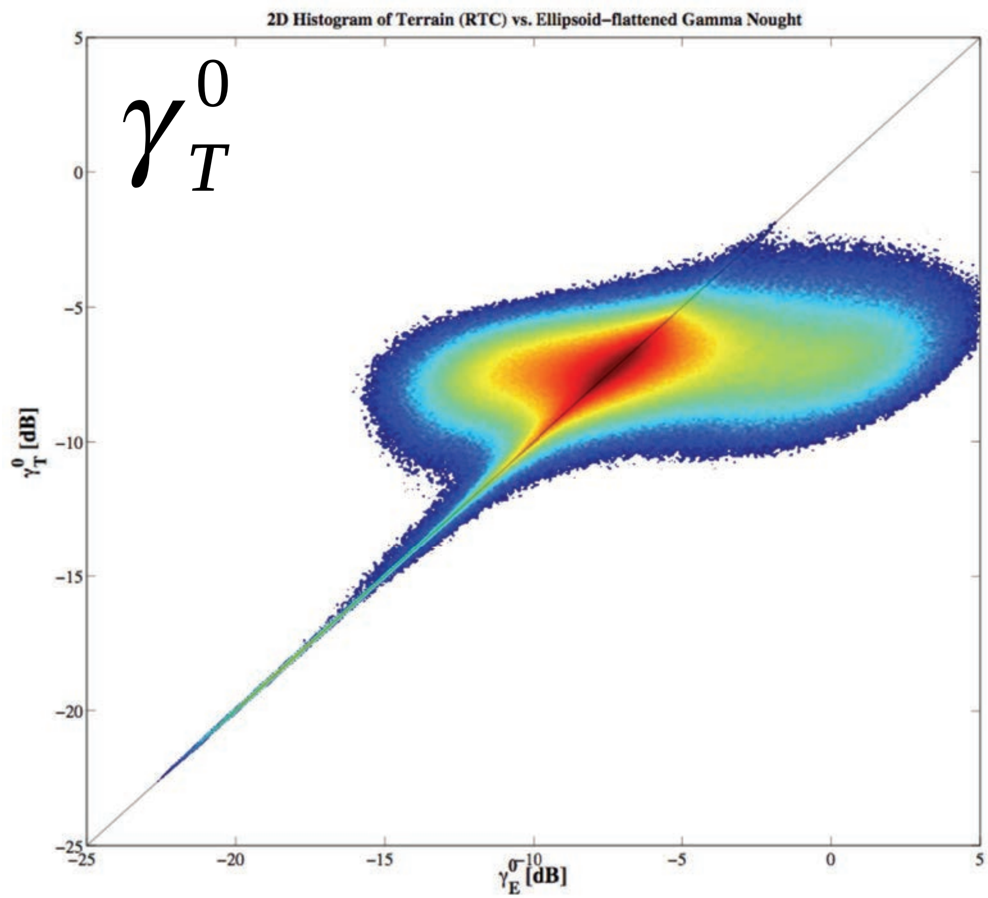
Ellipsoid vs. Terrain-normalised Backscatter



- Incident-angle correlation *flattened* in terrain-corrected gamma nought
- Dataset WSM image of Vancouver Island, BC, Canada:
  - –Ocean & wet snow excluded via 10<h<1900m (same pts as γ_T^0)

Terrain-correction: Angle (NORLIM) vs. Area (RTC)



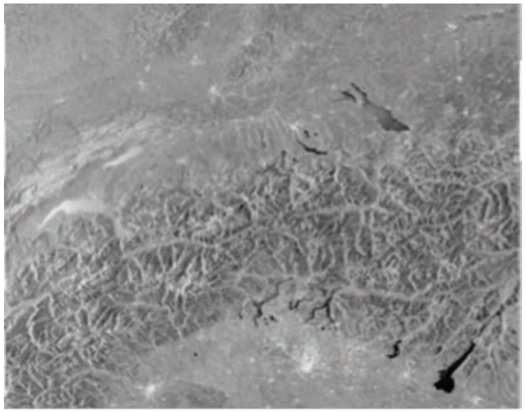


- Identical points in both sets above, using same SRTM3 DHM
- Angle-based σ_T^0 correction subject to singularity at θ=0
- Terrain-flattened gamma γ_T^0 is *significantly flatter*

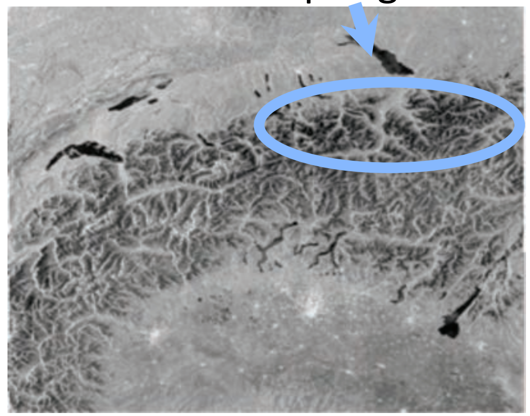
ASAR WSM: Seasonal dependence of snow-melt signature

-20 0 dB

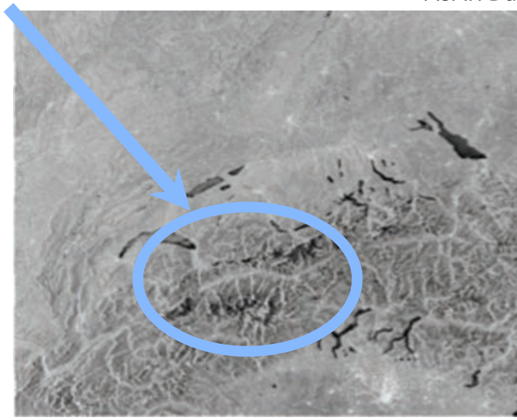
Spring vs. Summer Snow Melt



2006.01.23

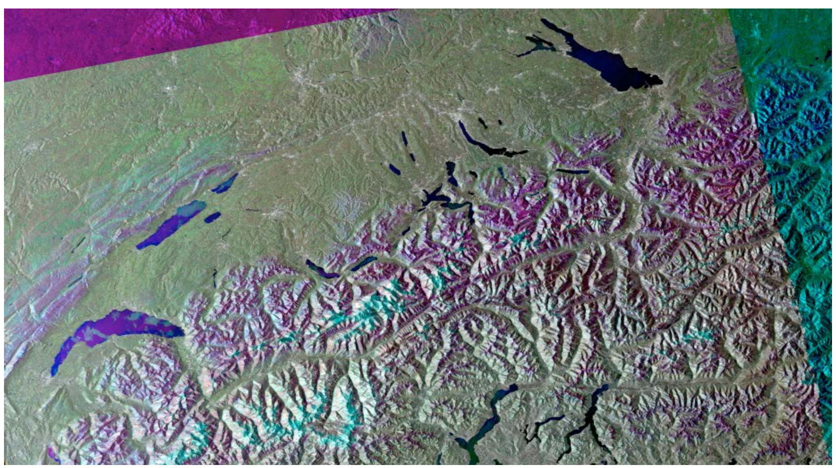


2006.04.03



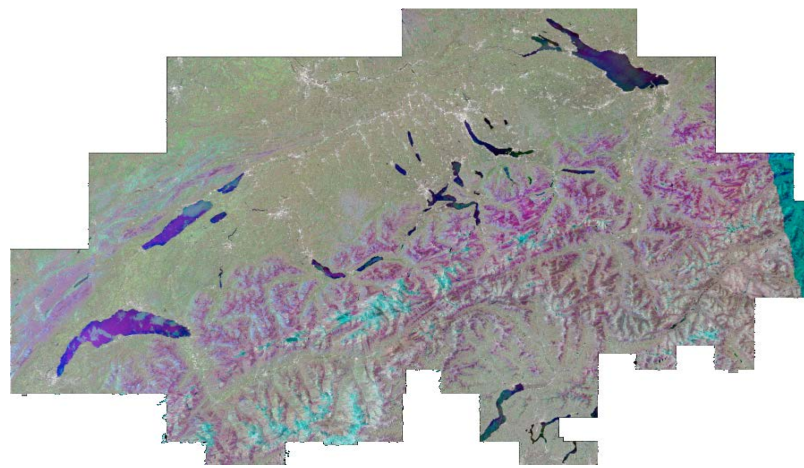
2006.08.05

Ground range radar geometry



Geocoded **T**errain **C**orrected

Mixture of terrain & snow-melt

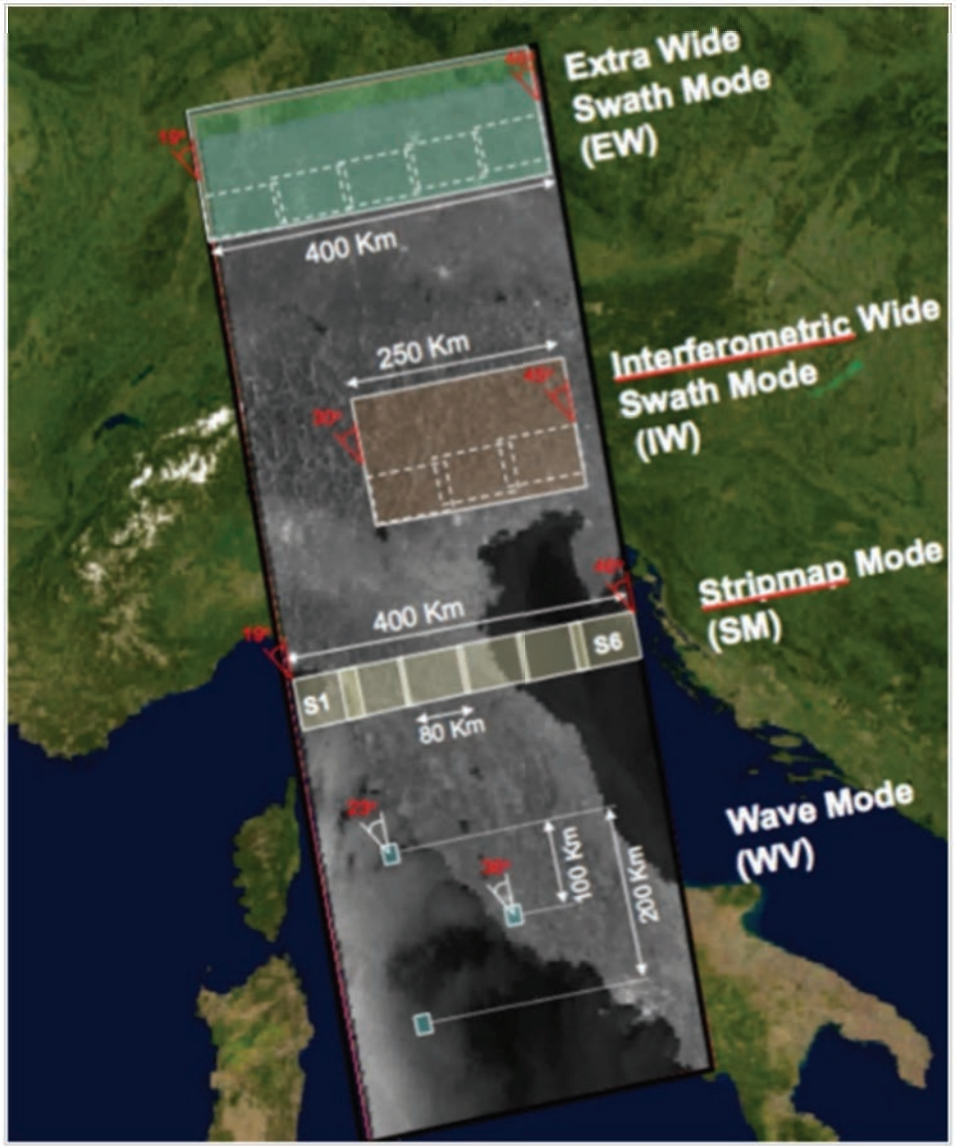


Radiometrically **T**errain **C**orrected

Snow-melt signal

Swiss map coord.

Sentinel-1 Acquisition Modes

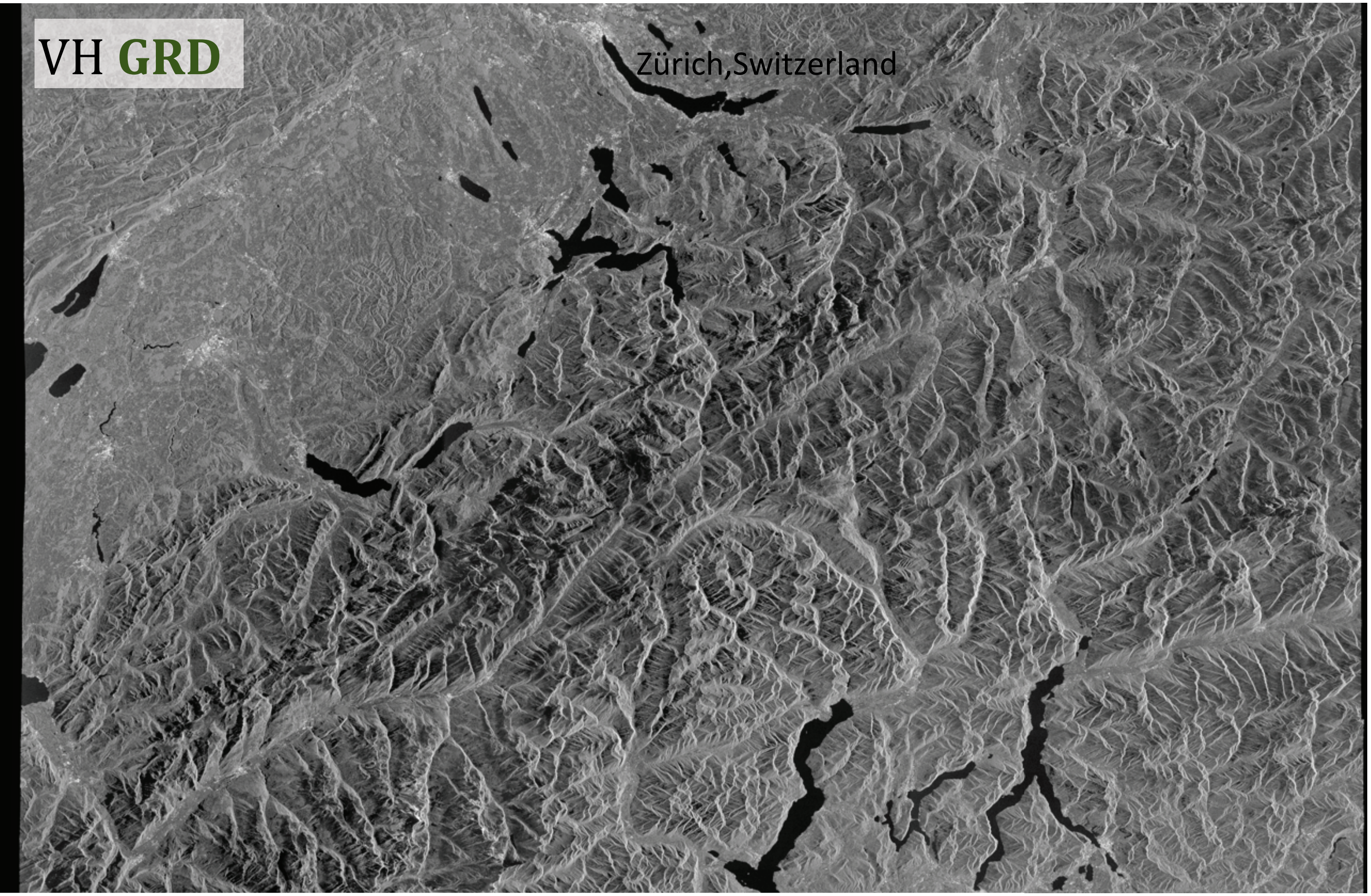


IW is main acquisition mode over land (>80%)

Ensures availability of recent interferometric reference

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

Sentinel-1 IW GRD Product: ***Ground Range Geometry***



2014.10.10 5:34 Desc.

IW GRDH Product

$$\gamma_E^0$$

-26dB -1dB

Sentinel-1 IW GRD Product: *GTC*

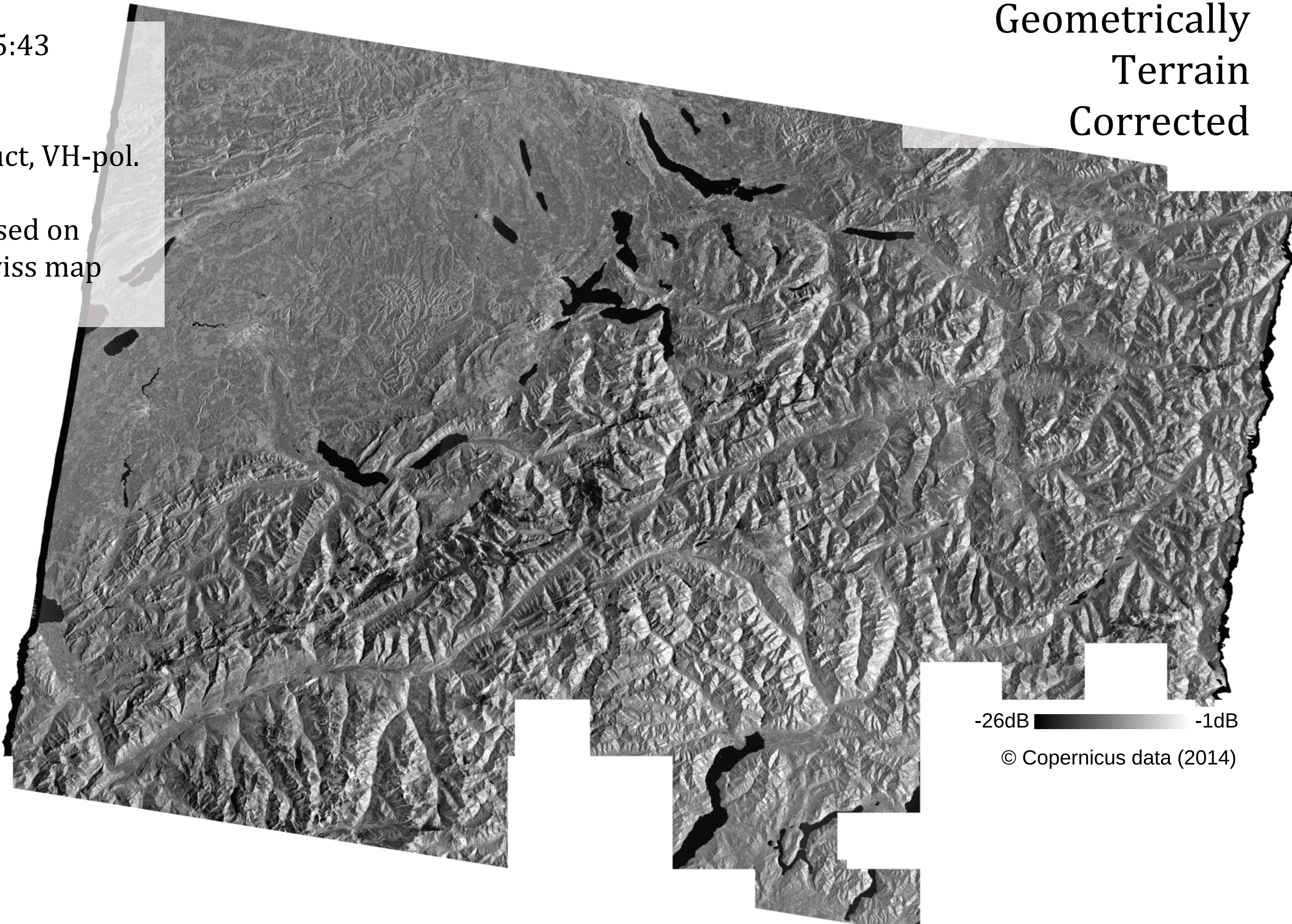
2014.10.10 5:43
Descending

IW GTC Product, VH-pol.

Geocoding based on **DHM25** in Swiss map coordinates

$$\gamma_E^0$$

Geometrically Terrain Corrected



Sentinel-1 IW GRD Product: *RTC*

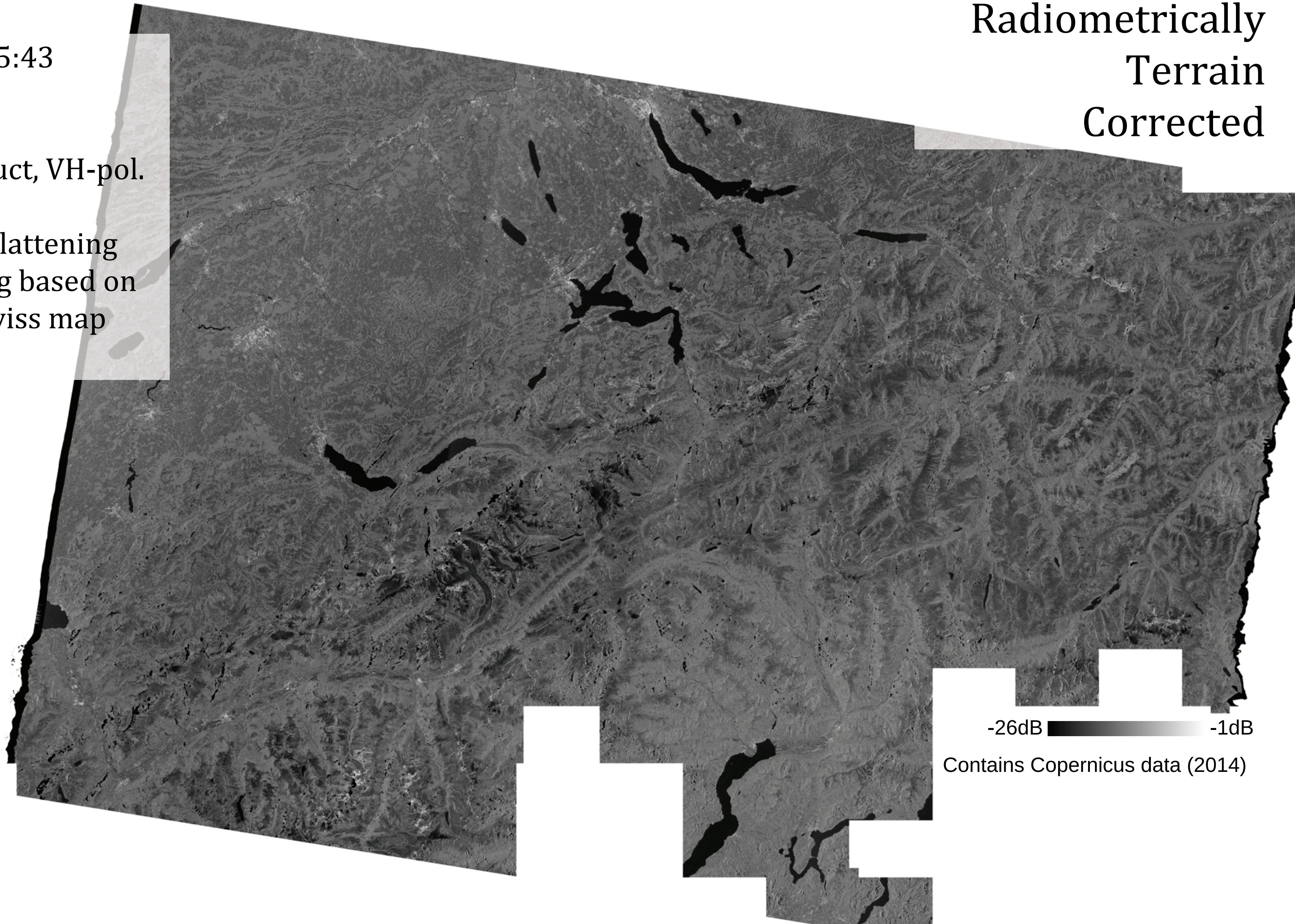
2014.10.10 5:43
Descending

IW RTC Product, VH-pol.

Radiometric flattening and geocoding based on **DHM25** in Swiss map coordinates

$$\gamma_T^0$$

Radiometrically Terrain Corrected



Snow and Dielectric Constant: Attenuation in wet snow

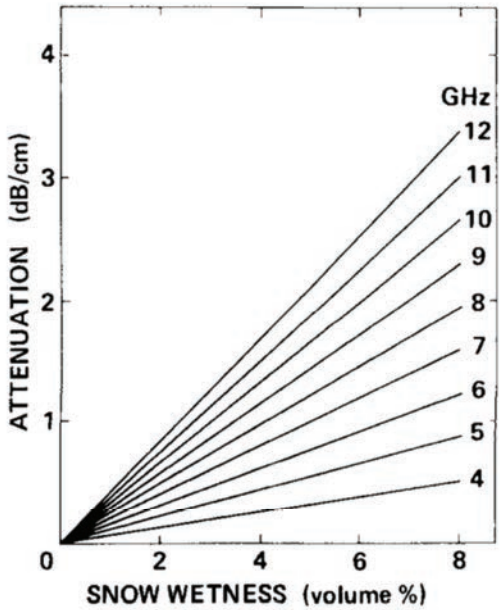
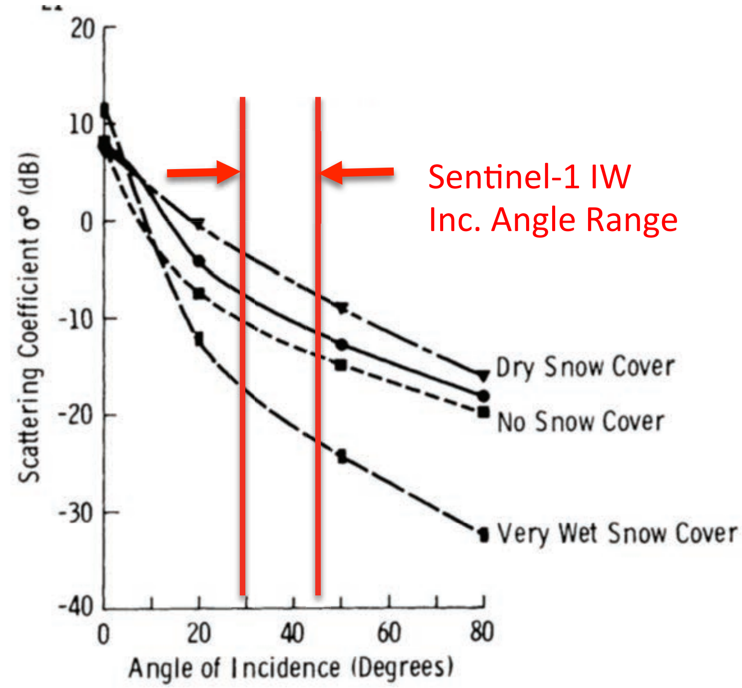


FIG. 5. Variation of attenuation with snow wetness at selected frequencies.



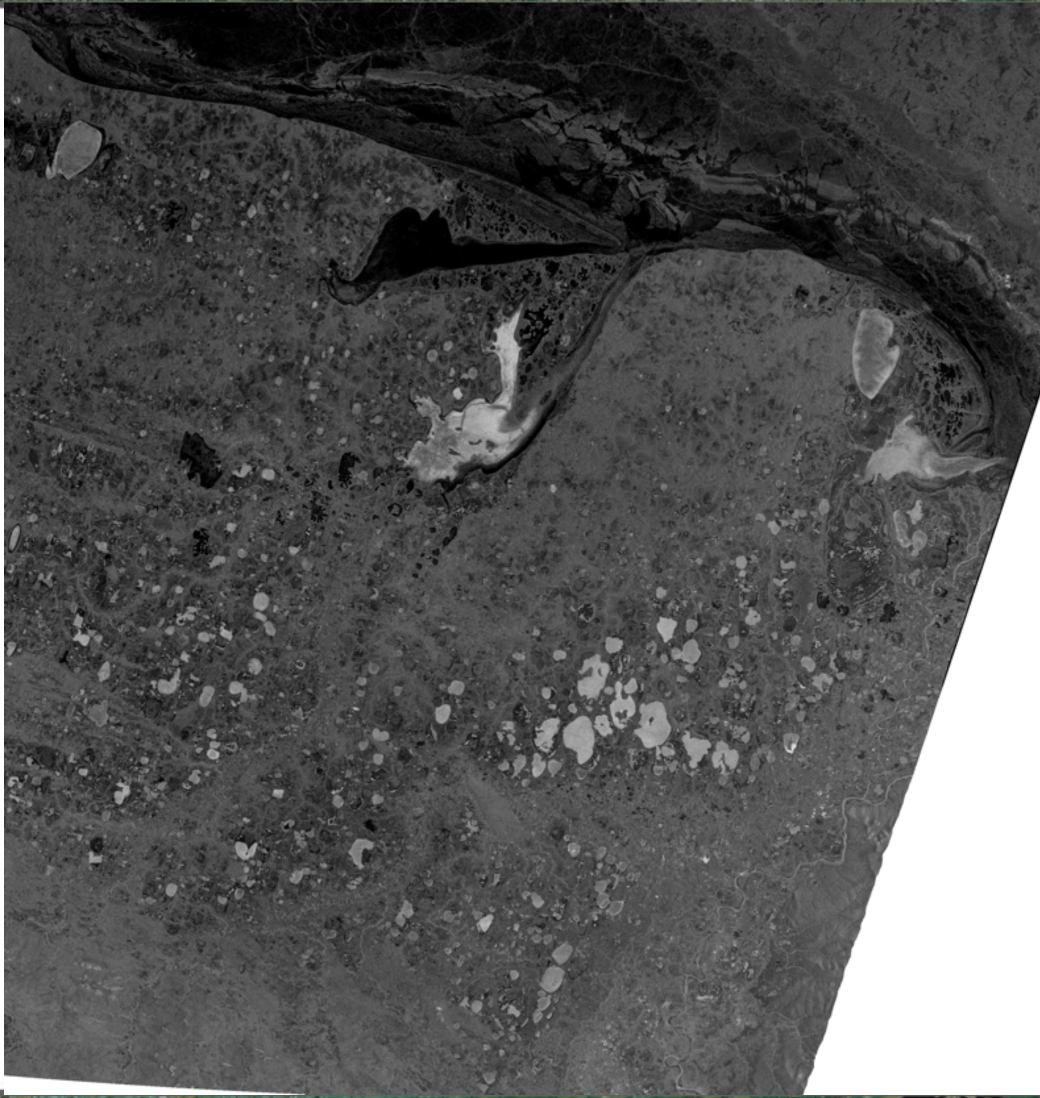
F. T. Ulaby, W. H. Stiles, and M. Abdelrazik, "**Snowcover Influence on Backscattering from Terrain**," IEEE Trans. Geosci. Remote Sens., vol. GE-22, no. 2, pp. 126–133, Mar. 1984.

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.

Kytalyk, Siberia

Sentinel-1 EW HH-pol.
Backscatter

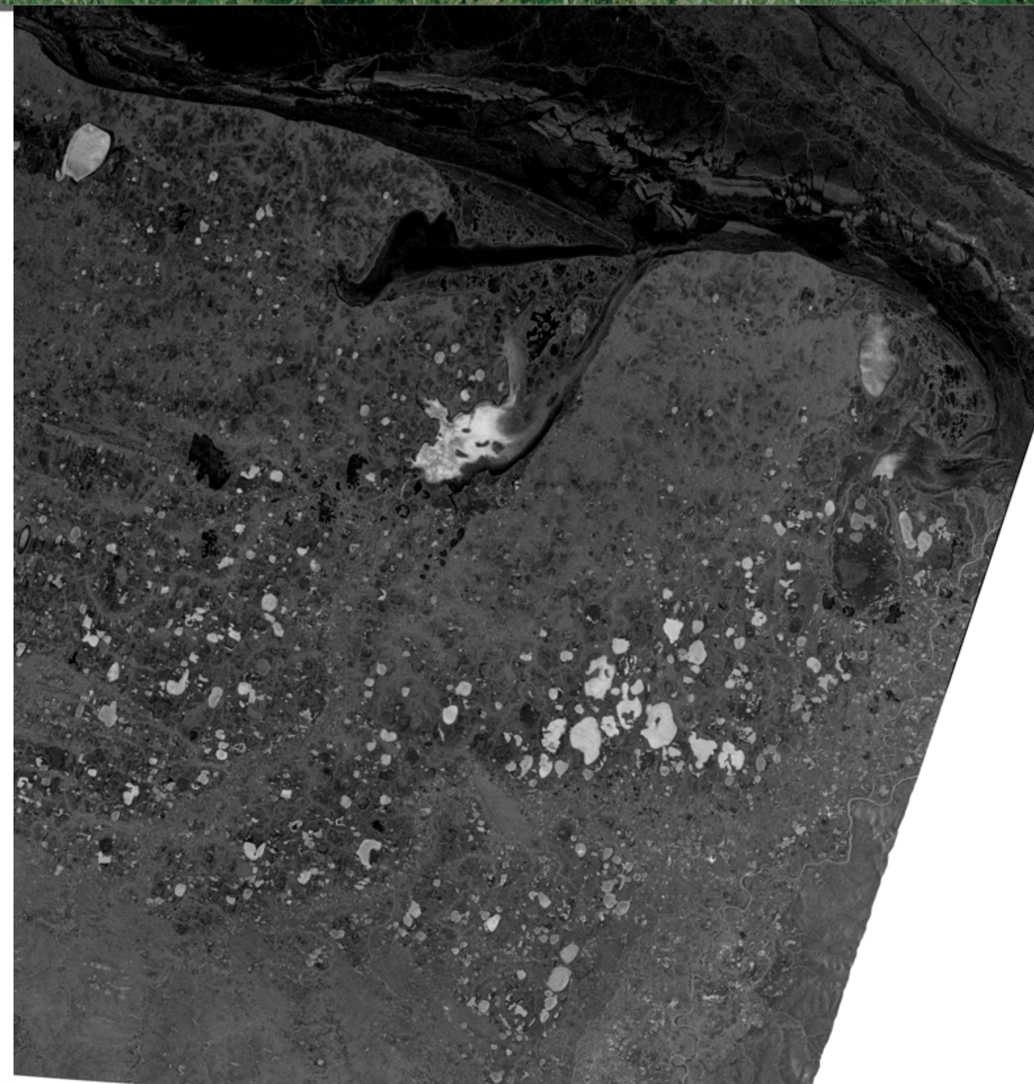
20150101



Kytalyk, Siberia

Sentinel-1 EW HH-pol. Backscatter

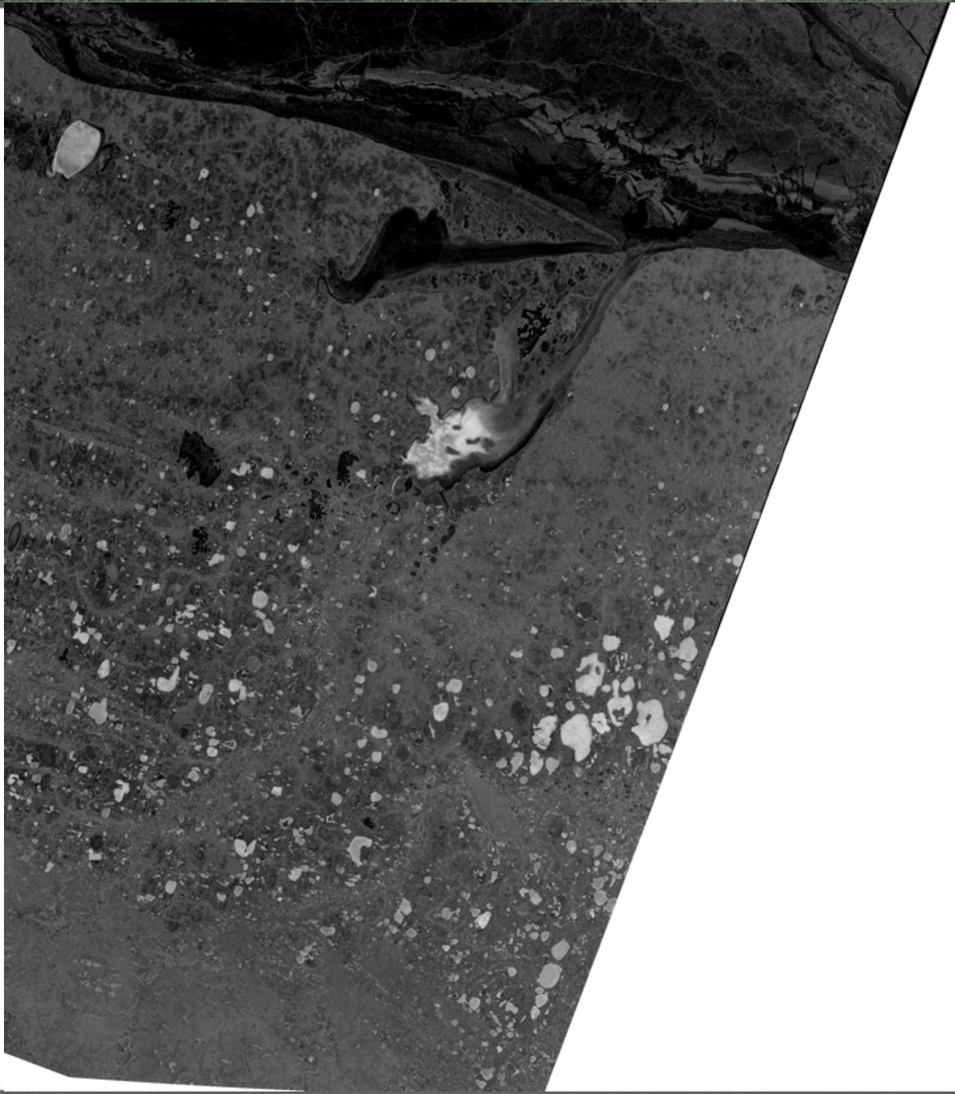
20150314



Kytalyk, Siberia

Sentinel-1 EW HH-pol. Backscatter

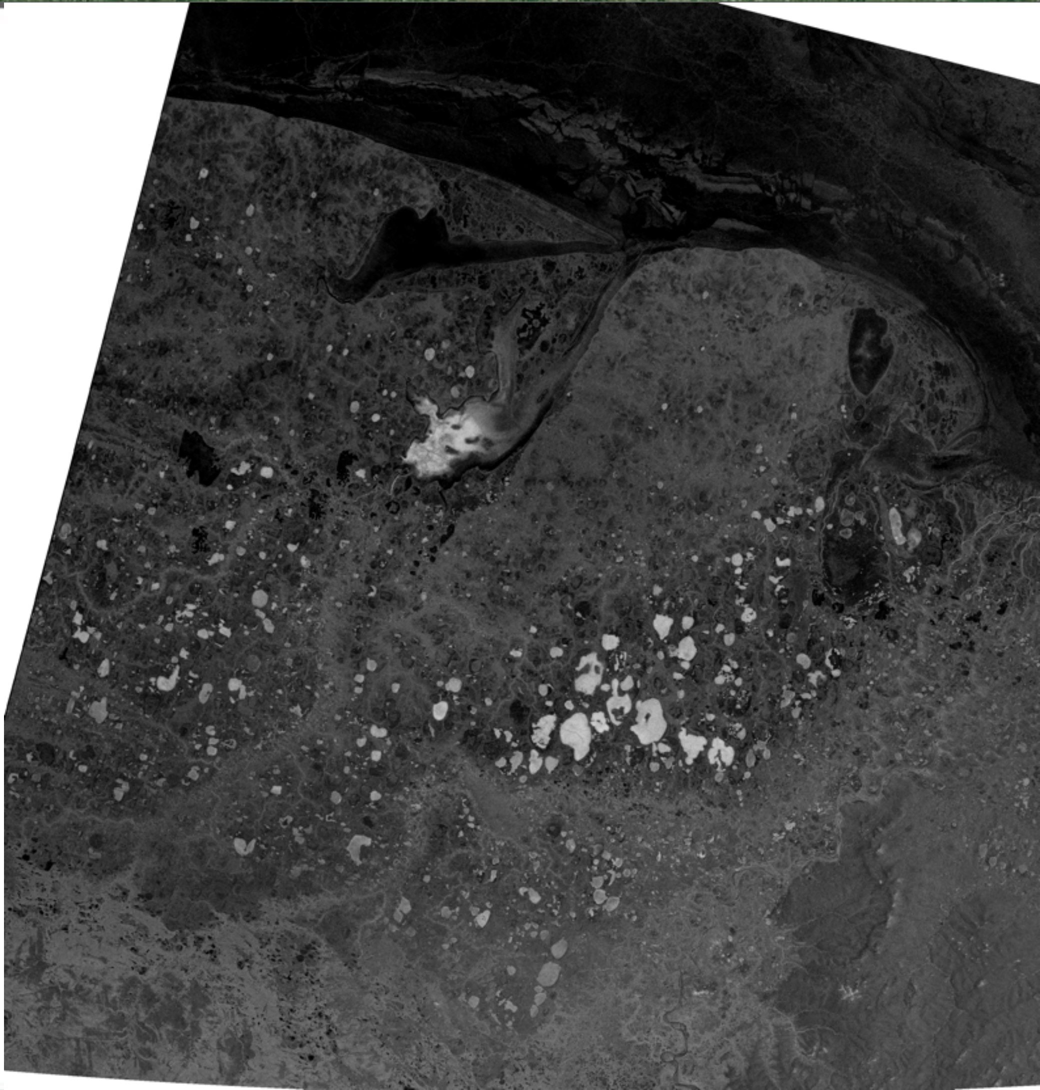
20150412



Kytalyk, Siberia

Sentinel-1 EW HH-pol. Backscatter

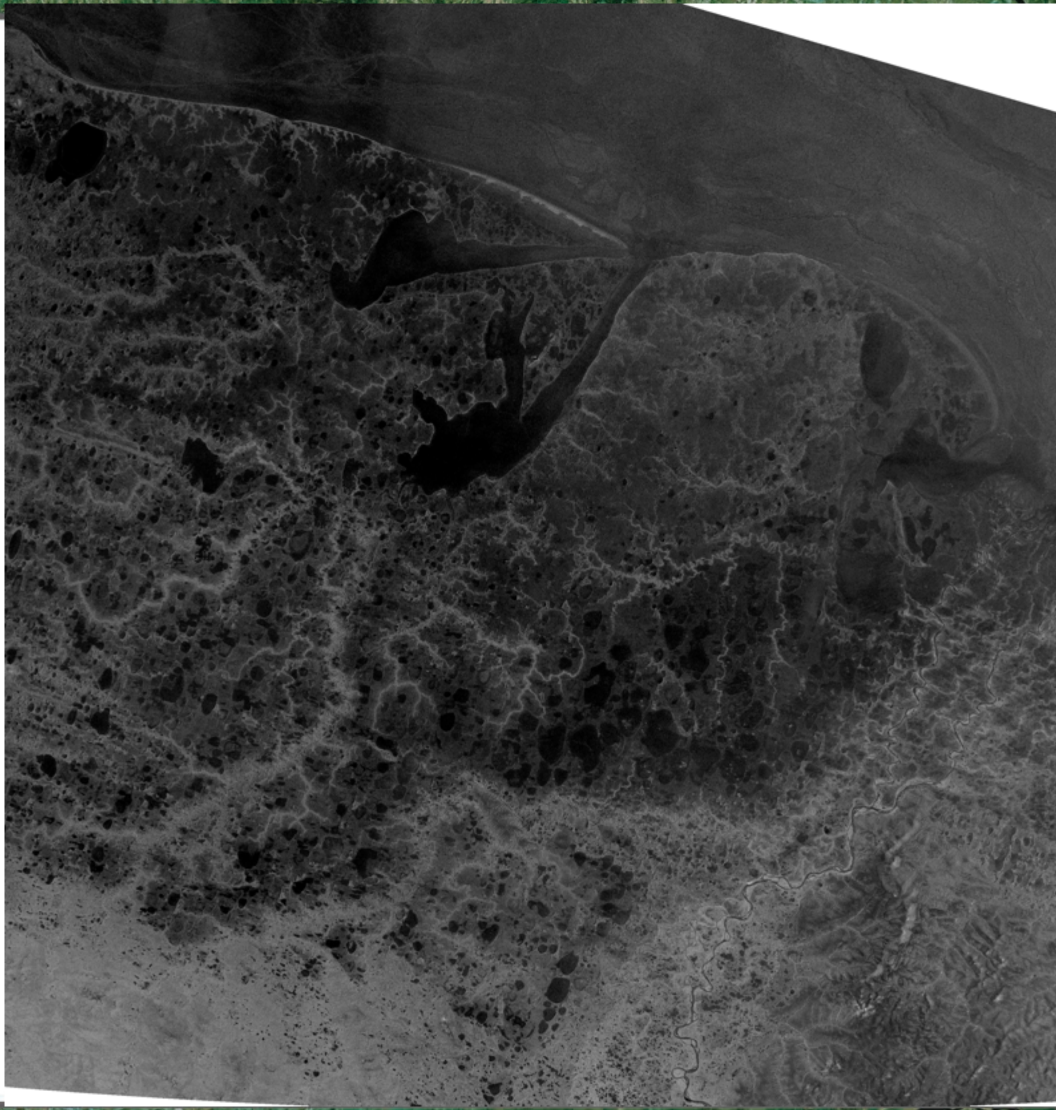
20150527



Kytalyk, Siberia

Sentinel-1 EW HH-pol. Backscatter

20150601



Ground-based sensing

e.g. Phenocam in Kytalyk, Siberia

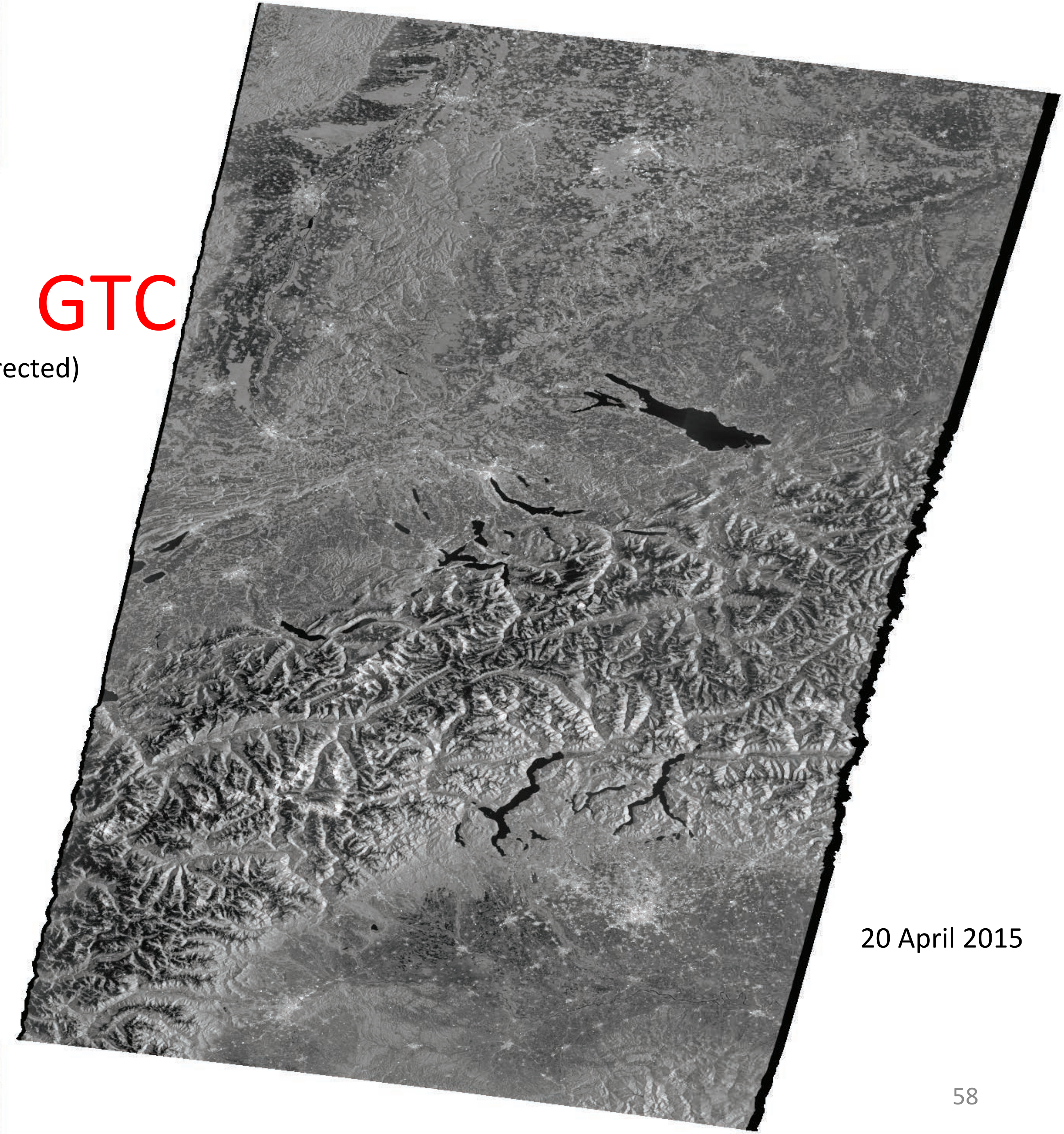
Movie courtesy G. Ghielmetti, UZH-RSL

Sentinel-1A: GTC

(Geometrically Terrain Corrected)

$$\gamma_E^0$$

-26dB -1dB



20 April 2015

Generated automatically from 3 IW GRDH products using SRTM3

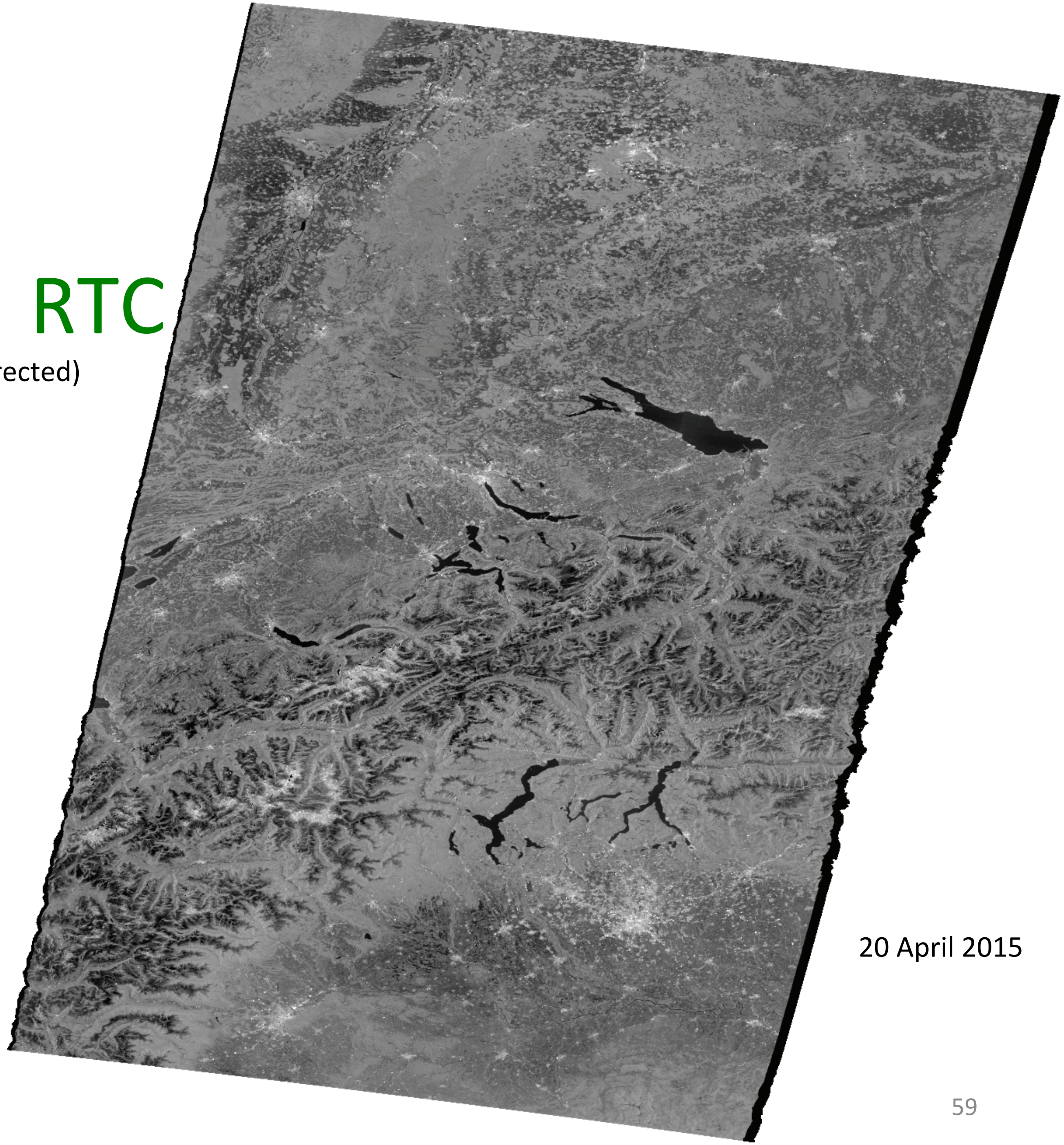
Copernicus Sentinel data (2015)

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)

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.

Satellite SAR instruments, modes, and swaths

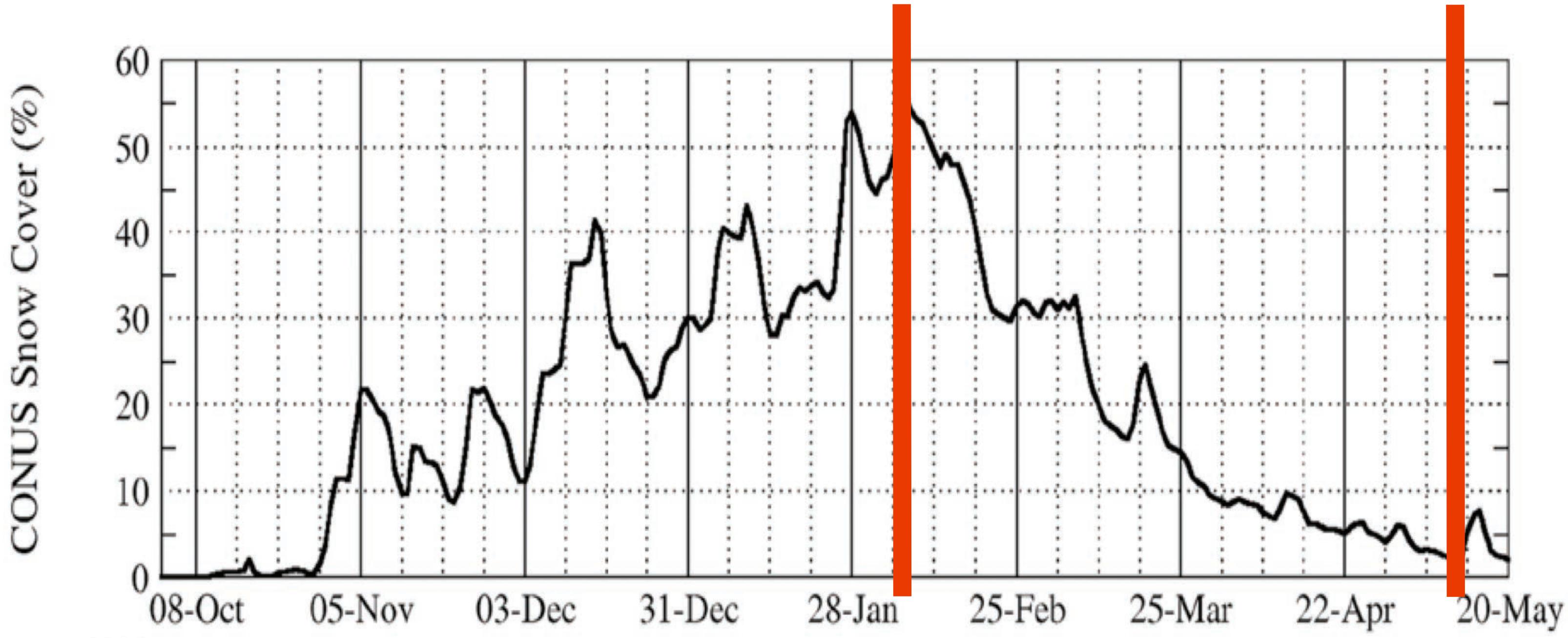
	Satellite Instrument	Orbit Repeat Interval	Mode	Inc. Angle [°]	Swath Width [km]	Available Polarisations
C	ENVISAT ASAR	35d	IM: Image Mode AP: Alternating Polarisation WS: Wide Swath	15 – 45 15 – 45 17 – 44	56-100 56-100 400	Single: HH or VV Dual: HH/HV or VV/VH or HH/VV Single: HH or VV
	Sentinel-1: S1A & S1B	12d	SM: Strip-Map **IW**: Interferometric Wideswath EW: Extra Wideswath	18.3 – 46.7 29.2 – 46 18.2 – 47	up to 100 **250** 400	For all modes: Single-pol.: HH or VV or Dual-pol.: HH/HV or VV/VH
	Radarsat-2	24d	Wide or Wide-Fine SCNA: ScanSAR Narrow A **SCNB**: ScanSAR Narrow B SCWA: ScanSAR Wide A SCWB: ScanSAR Wide B	20 – 45 20 – 39 31 – 47 20 – 49 20 – 46	120-170 300 **300** 500 450	For all these modes: Single-pol.: HH or VV or HV or VH, or Dual-pol.: HH/HV or VV/VH
X	TerraSAR-X: TSX, TDX & PAZ	11d	ScanSAR (SC) Wide ScanSAR (**SC Wide**)	20 – 45 15.6 - 49	100 200-270	Single: HH or VV Single: HH or VV or (HV or VH) N.B. Cross-pol experimental
	Cosmo-Skymed: CSK1- CSK4	16d	ScanSAR Wide Region ScanSAR **Huge Region**	~20 - ~60 ~20 - ~60	100 200	For all modes: HH or VV or HV or VH

Seasonal prioritization of observation windows

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

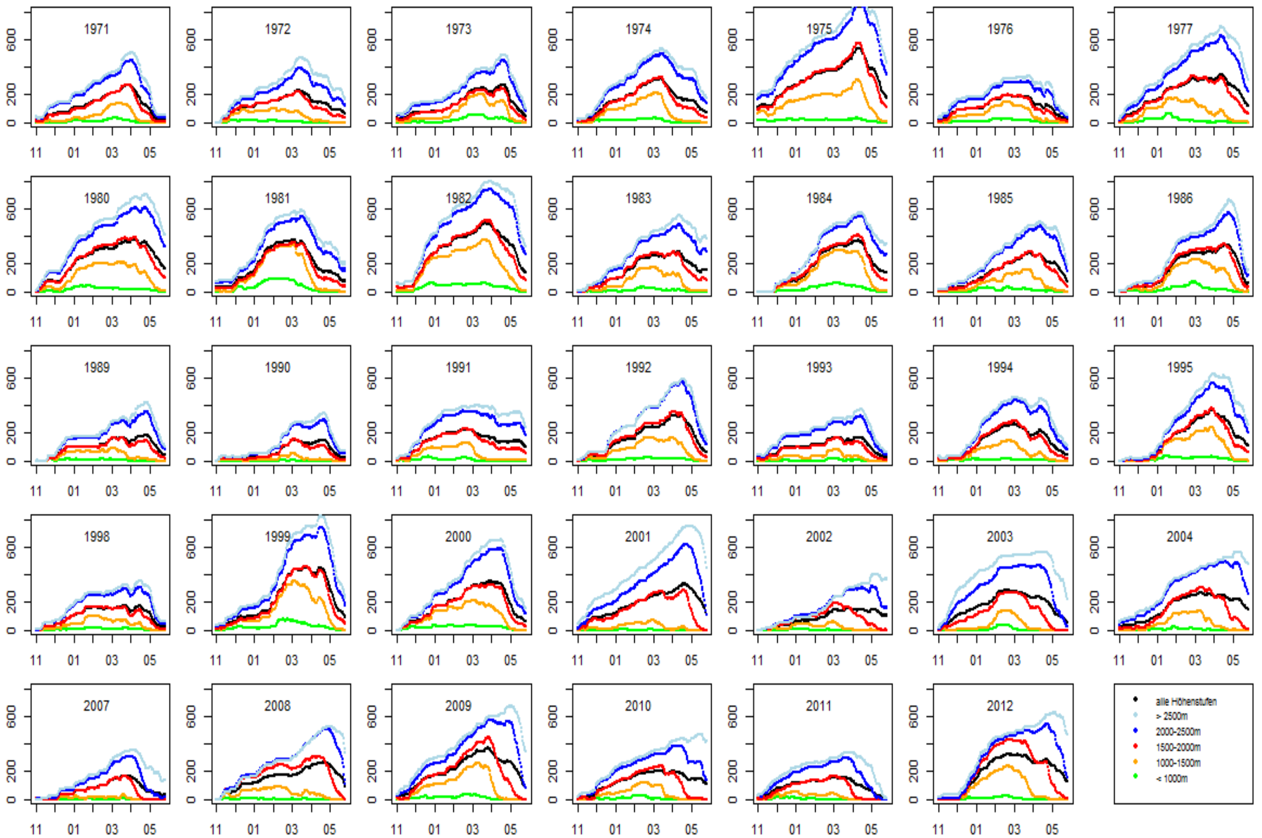


Figure courtesy
Tobias Jonas, SLF

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

Early 2015: Available # of IW GRDH products over Western Alps (Swiss regional neighbourhood)

16d	Sentinel-1A IW GRDH
01.01-01.16	35
01.17-02.01	21
02.02-02.17	29
02.18-03.05	31
03.06-03.21	30
03.22-04.06	44
04.07-04.22	42
04.23-05.08	40
05.09-05.24	34

Two resolution standards for tests:
SRTM (3 seconds) & swissALTI3D (2m)

Resolutions & DEM Quality

Two main RTC processing levels:

SRTM3

- DEM (3 second, ~**90m**), geographic coordinates
- Shuttle C/X-band InSAR, Feb. 2000
- Can serve as "quicklook"
- May be generated anywhere SRTM data is available (~ ***±60° latitude***)

swissALTI3D

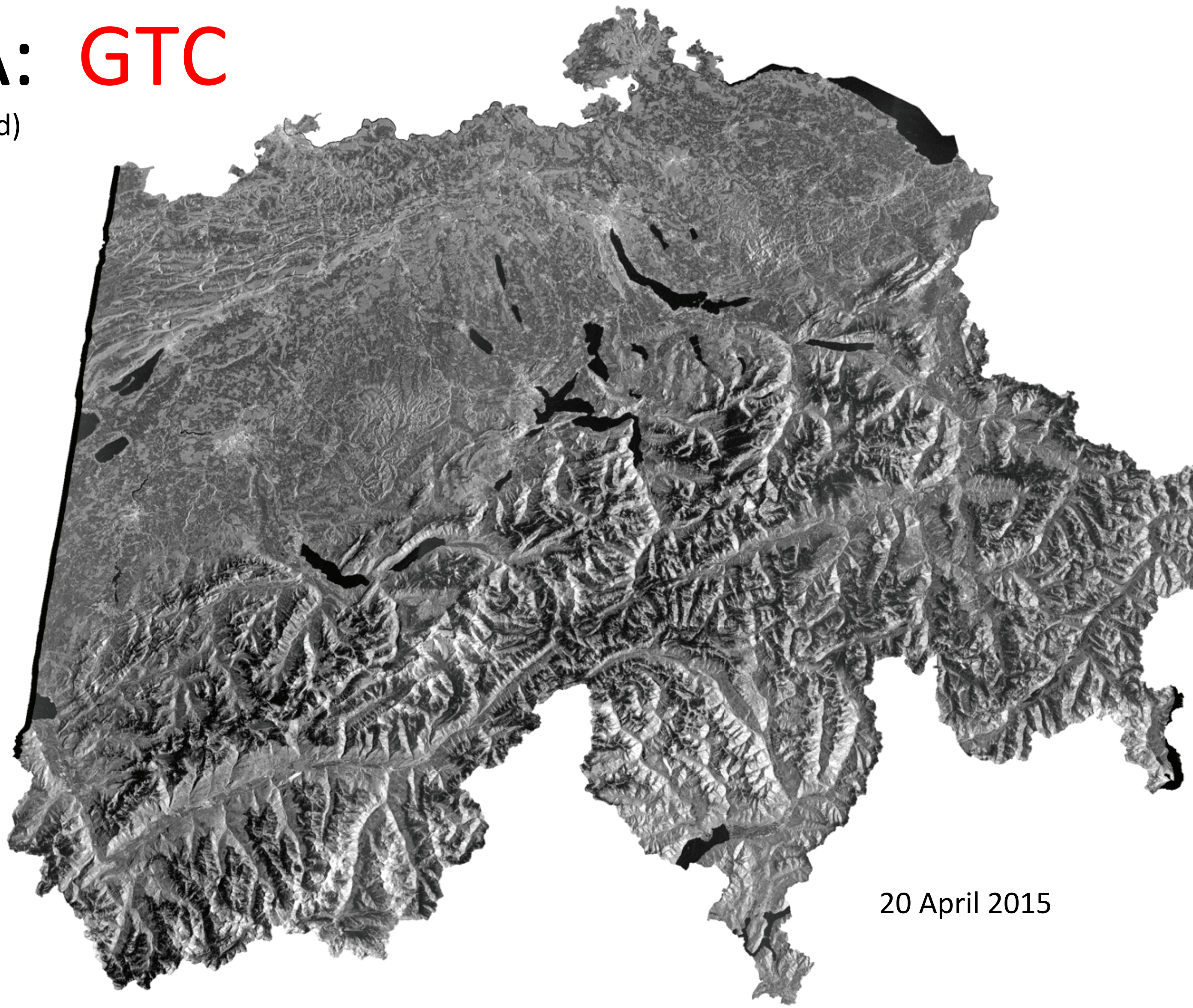
- DEM (2m), Swiss oblique Mercator map grid, ***Swiss territory***
- Airborne Laser Scanning (ALS) & Photogrammetry (above 2000m)
- DEM reduced from 2m to 6m or **10m** resolution for processing
- Higher quality DEM than SRTM allows terrain-flattening at full GRDH resolution
- Often less than full S1A product fully processed

Sentinel-1A: GTC

(Geometrically Terrain Corrected)

$$\gamma_E^0$$

-26dB -1dB



20 April 2015

Generated from 3 IW GRDH products using SwissALTI3D DEM

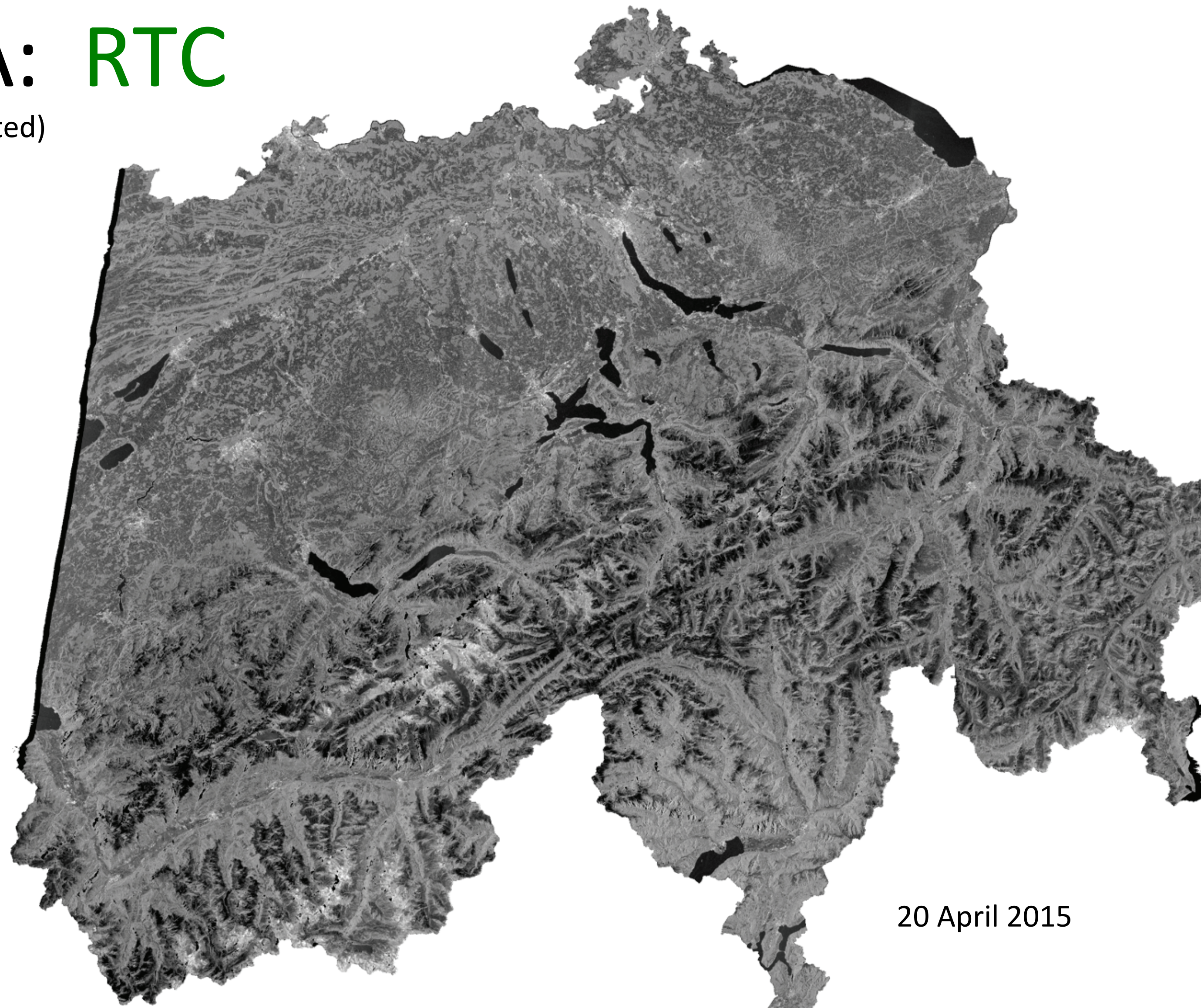
Copernicus Sentinel data (2015)

Sentinel-1A: RTC

(Radiometrically Terrain Corrected)

γ_T^0

-26dB -1dB

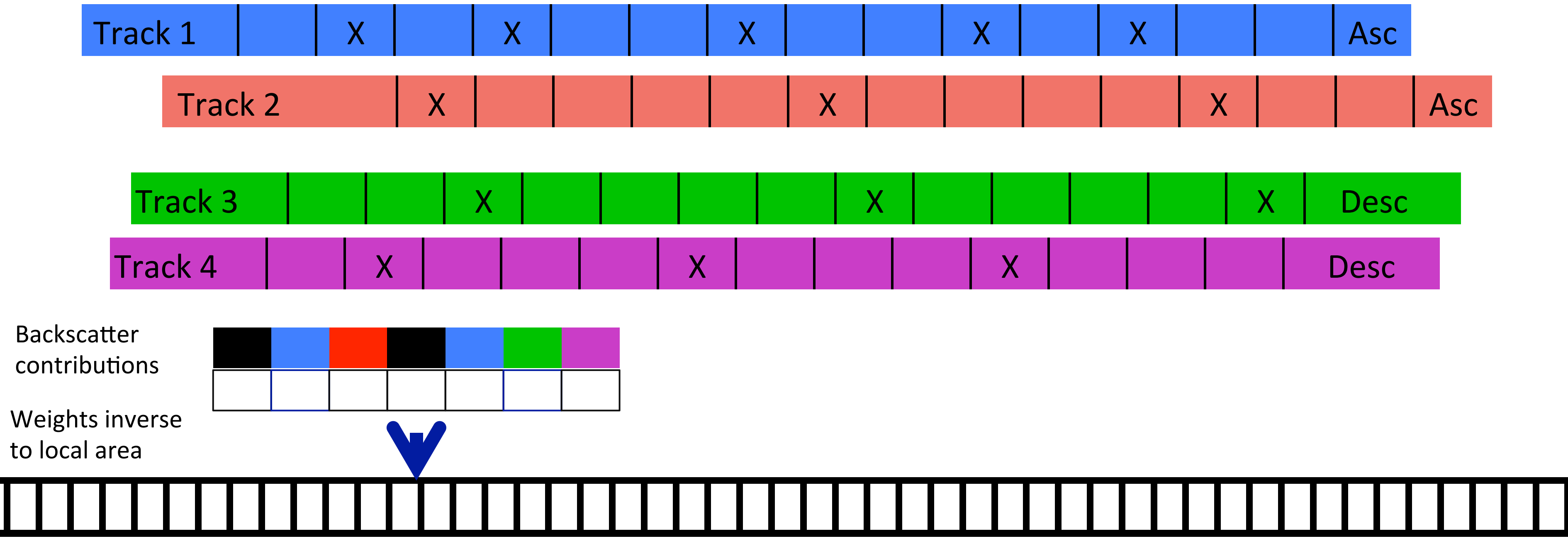


Generated from
3 IW GRDH products using
SwissALTI3D DEM

Contains modified Copernicus Sentinel data (2015)

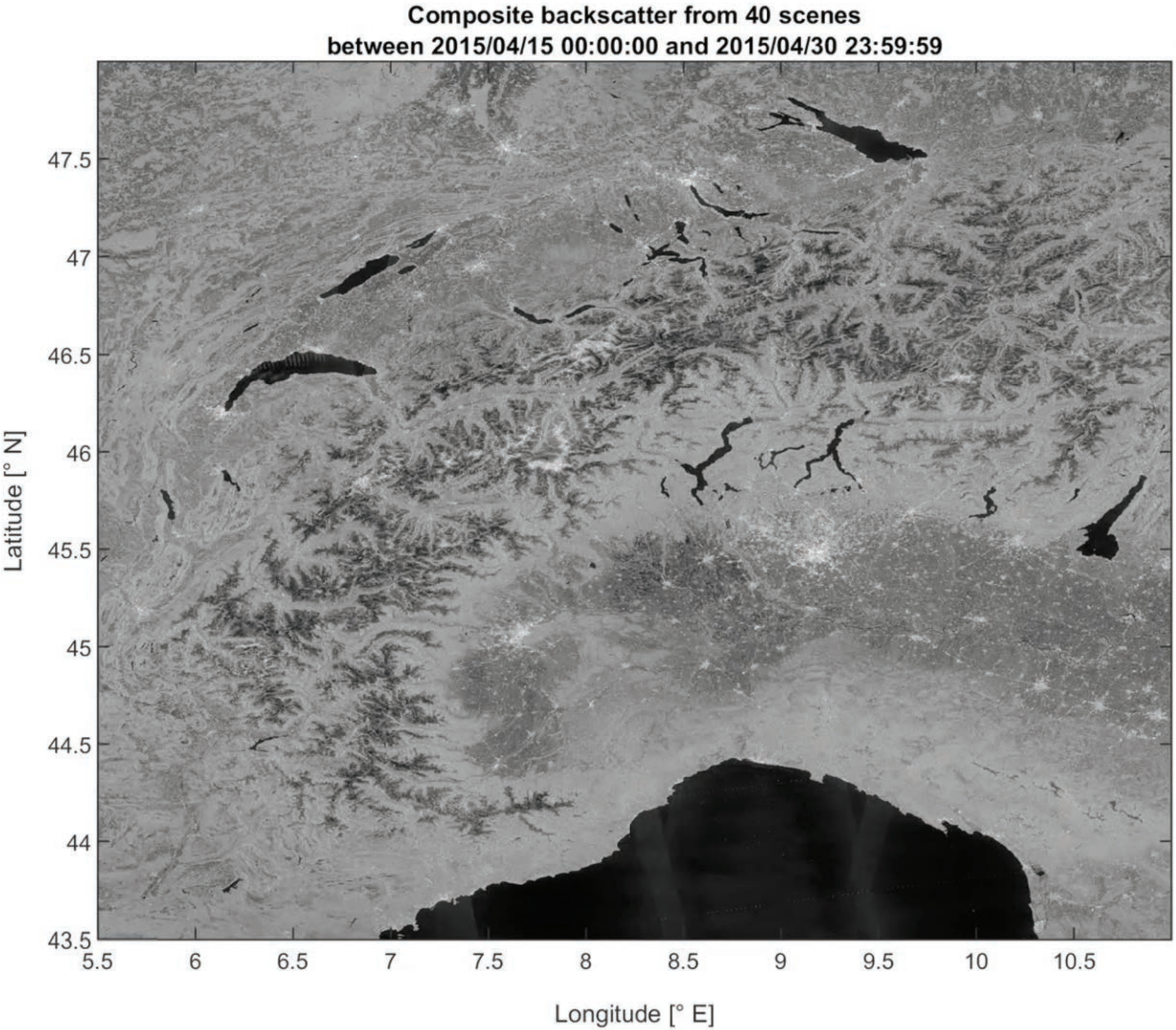
20 April 2015

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
  - **Local resolution weighting** [Small D., Proc. IGARSS 2012]
    - Combine ascending and descending observations to generate composite representing time-window
    - Improved local resolution in composite compared to any single image or even flat areas (!), also lower noise



Movie by UZH
D. Small & C. Rohner
Contains modified Copernicus Sentinel data (2015)

Movie of Eastern Alps Feb-Aug 2015

Composite VH-pol. Backscatter

-26dB -1dB

Movie by UZH
D. Small & C. Rohner
Contains modified Copernicus Sentinel data (2015)

Backscatter Composites

- **First demonstration of Local Resolution Weighting on Sentinel-1A**
  - 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 if more data becomes available (e.g. S1B in 2016, RCM in 2018?)

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

Conclusions

- **Snow wetness can be seen 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 will usher in a new era of multimodal multiwavelength 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