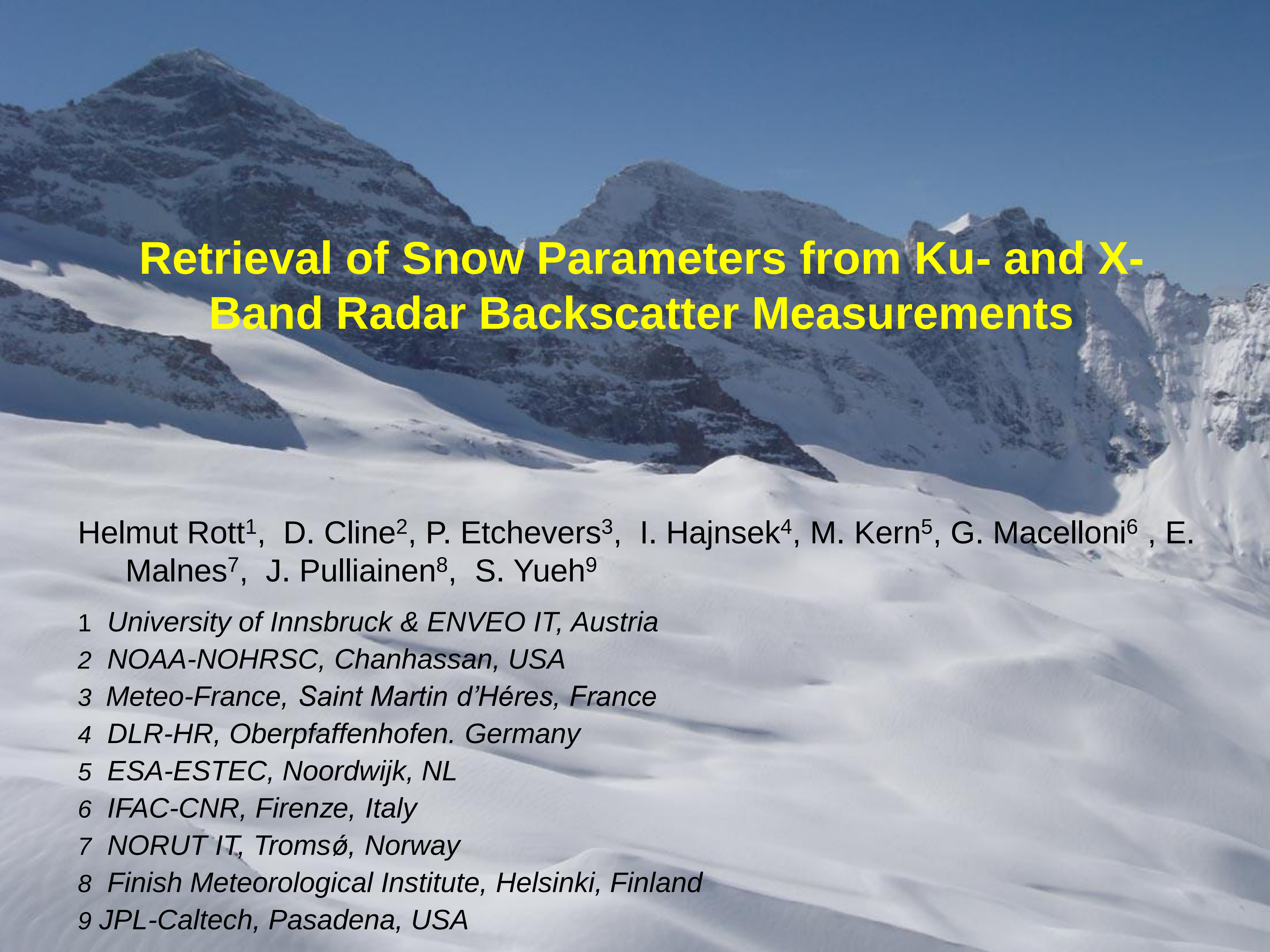

Retrieval of Snow Parameters from Ku- and X-Band Radar Backscatter Measurements

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Outline of Presentation

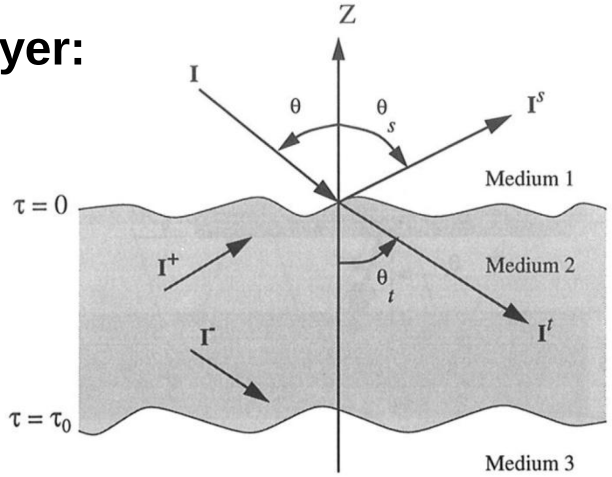
- Radiative transfer formulation for radar backscatter of snow-covered terrain
- Backscatter sensitivity of Ku- and X-band backscatter for SWE over ground
- The inversion problem for retrieving snow mass (SWE) of dry snow over ground and winter snow on glaciers
- Radiative transfer formulation and backscatter sensitivity for snow accumulation on glaciers
- Processing line for SWE retrieval from satellite-based SAR measurements
- Auxiliary data for segmentation and retrieval initialization
- Application example for retrieval algorithm
- Conclusions

RT Transfer for SWE Retrieval

Formulation for scattered intensity of single layer:

$$\mathbf{I}^{S} = \frac{1}{4\pi}\int_{4\pi} \mathbf{S}_{\mathbf{T}}\left(\theta_{S,}\theta;\phi_{S},-\phi\right)\mathbf{I}(\theta,\phi)d\Omega$$

S –Total scattering phase matrix of the layer accounting for scattering at interfaces, in volume, volume-interfaces, and multiple scattering in layer



Second order RT approach:

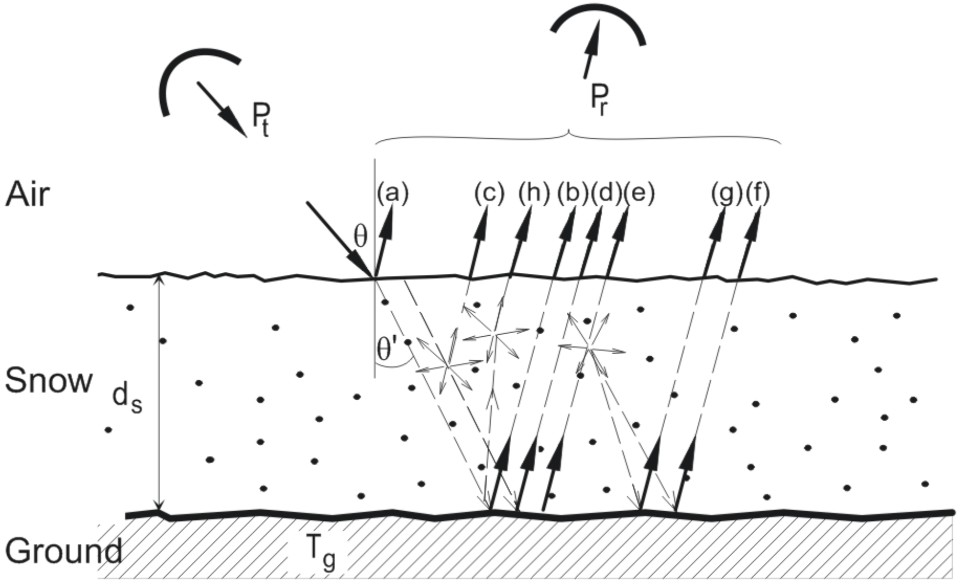
Coherent backscatter terms:

- Direct at interfaces (a), (b)
- Direct volume (c), without multiple

Incoherent backscatter terms:

- Multiple scattering in volume of (c)
- Volume/ground & ground/volume

(ground surface separated in coherent and non-coherent terms)



Semi-empirical RT-Formulation for SWE Retrieval

For iterative retrieval of physical parameters the number of free variables needs to be small, focussing at the main factors (multiple scattering lumped in σ^V)

The basic equation accounts for the *coherent* contributions – Single Layer:

$$\sigma^{t}_{f,pq}(\theta_i) = \sigma^{as}_{f,pq}(\theta_i) + \sigma^{V}_{f,pq}(\theta_t) + \left(\mathrm{T}^{as}_{f}(\theta_t)\right)^2 \left[\frac{\sigma^{G}_{f,pq}(\theta_t)}{L^2_{f,pq}(\theta_t)}\right]$$

One-Way Loss Factor:

$$L(\theta_t) = \exp\left(k_e d_s \sec\theta_t\right) = \exp\left(k'_e\, SWE \sec\theta_t\right)$$

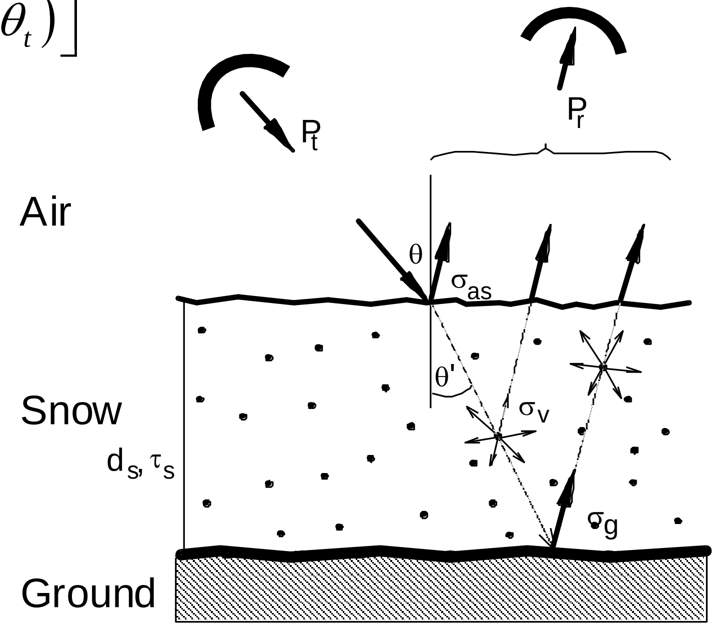
SWE = $\rho_s\, d_s$

Extinction coefficient: $k_e = k_s + k_a$;

Density-normalized: $k'_e = k_e / \rho_s$ $k'_a = k_a / \rho_s$

Volume scattering contribution:

$$\sigma^{V}_{f,pq}(\theta_t) = \mathrm{T}^2_f(\theta_t)\left[\frac{\omega_{f,pq}}{2}\left(1 - \frac{1}{L^2_{f,pq}(\theta_t)}\right)\cos(\theta_t)\right]$$



Scattering

Scattering albedo $\omega = k_s / (k_a + k_s)$

RT-Formulation for SWE Retrieval, Dual-Layer

Semi-empirical RT formulation for dual layer snow model

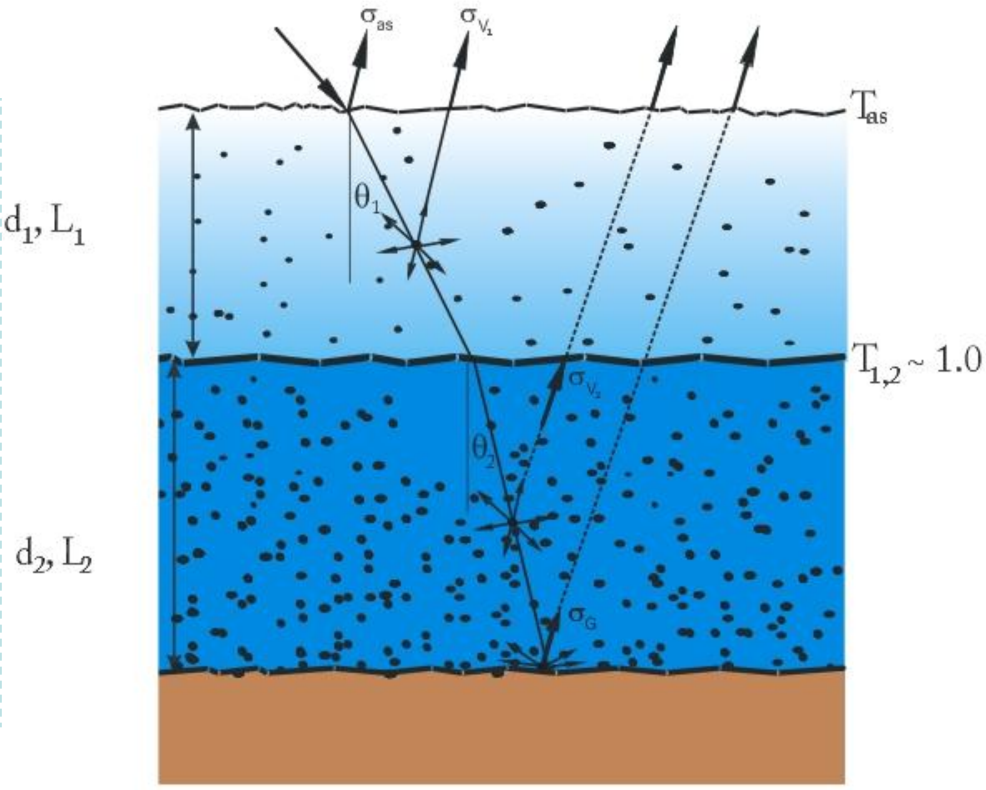
(Multiple interactions not specified, lumped in observed signals)

$$\sigma^{t}_{f,pq}(\theta_i)=\sigma^{as}_{f,pq}(\theta_i)+\sigma^{V1}_{f,pq}(\theta_{t1})+\sigma^{V2}_{f,pq}(\theta_{t2})L_1^2(\theta_1)+\left(\mathrm{T}^{as}_{f}(\theta_{t1})\right)^2\left[\frac{\sigma^{G}_{f,pq}(\theta_t)}{L_1^2(\theta_1)L_2^2(\theta_2)}\right]$$

L – Loss factor

Strategy for inversion:

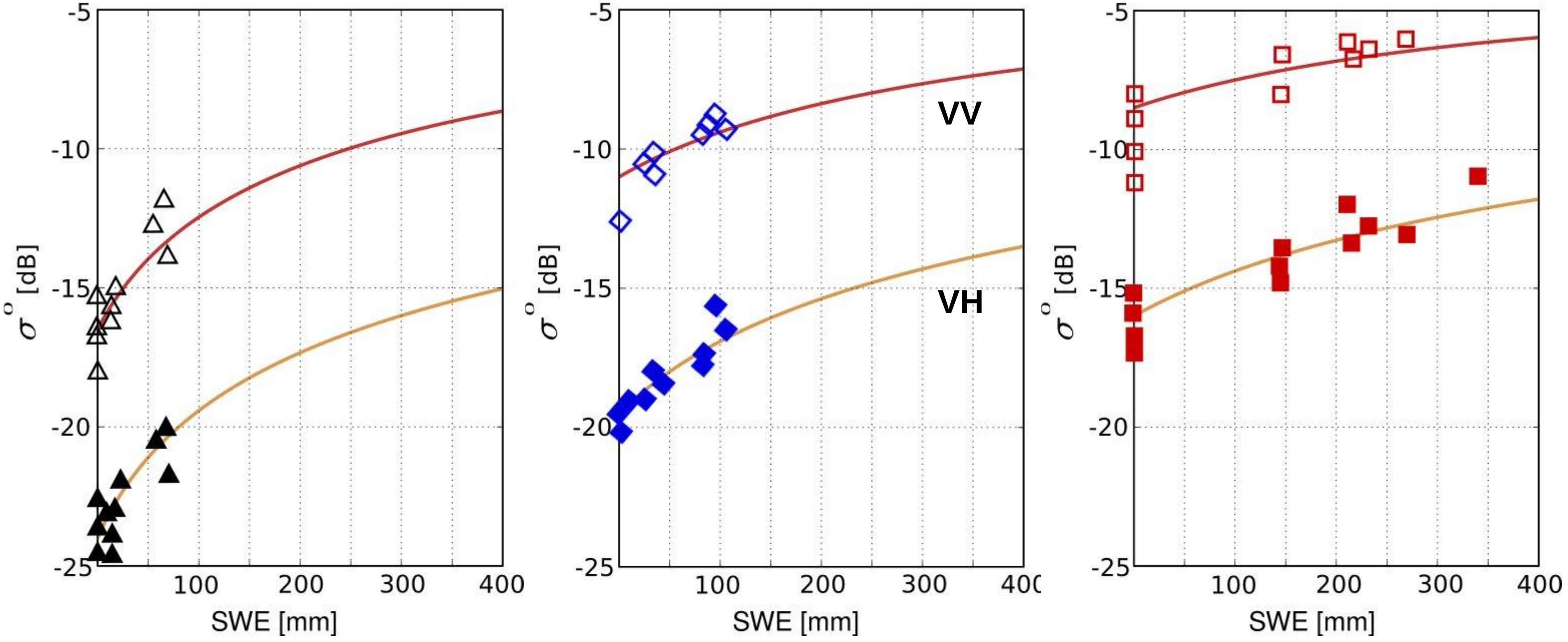
- Layer 1 represents the top snow layer governing the mass and energy fluxes with the atmosphere
- For cold snow Layer 2 properties change slowly by constructive metamorphism of grains → apply snow process model
- Iterate for SWE and ω of Layer 1



Backscatter Sensitivity to SWE – Variations of Volume Scattering Albedo and Background Signal

CLPX-II, Colorado, Winter 2006-07

Rabbit Ears **Oak Creek** **North Park**



PolScat σ° (13.9 GHz) vs. in situ measurements of SWE
Forward computations with RT model, $\omega = 0.80$, $\omega = 0.75$, $\omega = 0.70$

Concept for SWE Retrieval

Inversion of Physical Forward Model

Basic concept: Iterative matching of forward model and backscatter measurements to estimate free state variables

Input data requirements :

- Backscatter forward model
- Land cover data, DEM
- First guess snow parameters (from snow climatology or numerical meteorological data)

Important: Need for reliable and well tested forward model

Advantages
- Physical basis clearly defined
- Widely applicable

Implementation options:

Deterministic
- Very sensitive to noise in measurements and model
- Solution may be non-unique

Statistic
- Unique solution, less sensitive to noise
- Reliable statistical data base on snow parameters needed

Statistical Inversion for Retrieval of SWE

A semi-empirical radiative transfer model with reduced number of free parameters is used. The Nelder-Mead optimization algorithm is applied.

Cost Function:

$$J(x)=\sum_{i=1}^{n}\frac{1}{2\sigma_i^2}\left[\Phi_i\left(x_1,\ldots.,x_q;c_{1i},c_{2i}\ldots..,c_{ri}\right)-Z_i\right]^2+\sum_{j=1}^{q}\frac{1}{2\lambda_j^2}\left(x_j-x_j'\right)^2$$

Free parameters**:**

- SWE
- volume scattering coefficient k_s or scattering albedo ω

Φ_I Forward RT model

Z_i Backscatter Measurement

σ Measurement noise

x_i State variables (1, …., q)

c_i Configuration parameters

λ_i A priori standard deviation

Variational Data Assimilation

$$J(\mathbf{x})=(\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b)+(\mathbf{y}_{obs}-\mathrm{H}[\mathbf{x}])^T\mathbf{R}^{-1}(\mathbf{y}_{obs}-\mathrm{H}[\mathbf{x}]);\ \nabla J(\mathbf{x})\Rightarrow\min$$

Requires background field $\mathbf{x}_b$ and variance (physical snow parameters)

H – transformation operator from state vector **x** to observation vector **y**

Statistical Inversion for Retrieval of SWE

RT model with reduced set of free parameters for iteration

$$\sigma^t_{pq}(\theta_i) = T^2_{pq}(\theta_t)\left[\frac{\omega_{pq}}{2}\cos(\theta_t)\left\{1-\exp\left(\frac{-2k'_e SWE}{\cos\theta_t}\right)\right\} + \sigma^G_{pq}(\theta_t)\exp\left(\frac{-2k'_e SWE}{\cos\theta_t}\right)\right]$$

k'_e – density normalized extinction coefficient

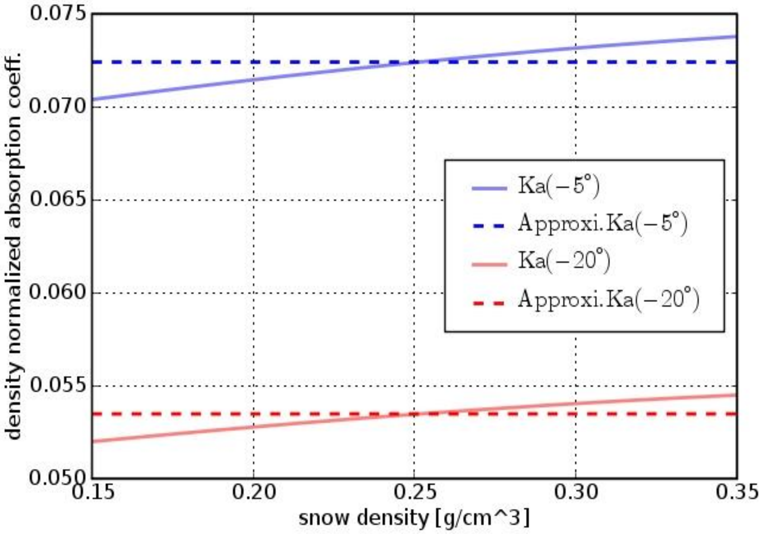
Measurement vector of backscatter :

$$\sigma^t_i = \sum_{i=1}^{4}\left[\frac{\omega_i}{2}\cos\theta_t\left(1-t_i^2\right)+\sigma^G_i t_i^2\right]$$

Transmission coefficient

$$t^2_{i;i=1,2,3,4} = \exp\left(-\frac{2\left(\omega_i + k'_{a,i=1,3}\right)SWE}{\cos\theta_t}\right)$$

k'_a – density normalized absorption coeff.



First guess values (time variable):

SWE (or depth), k_s (f_1), <T>

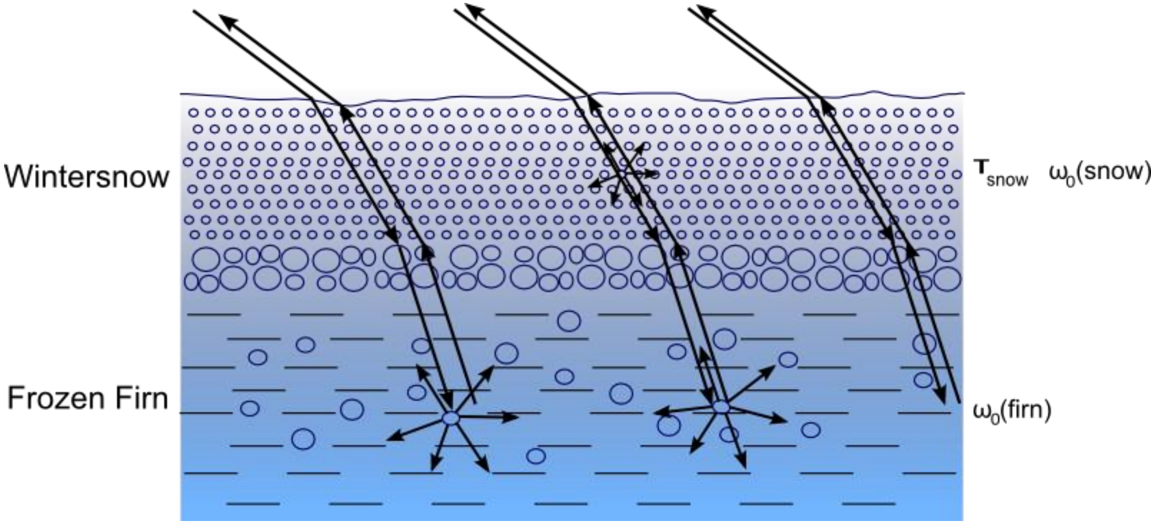
ρ (for estimating dense medium effects)

RT-Formulation for Retrieval of Snow Accumulation on Glaciers

$$\sigma^{t}(\theta_i) = \sigma^{as}(\theta_i) + \sigma^{V}_{WS}(\theta_t) + \mathrm{T}^2(\theta_t)\left\{\sigma^{0}_{FI}(\theta_t) L^{2}_{WS}(\theta_t)\right\}$$

σ^{V}_{WS} - volume scatter by winter snow

$\omega_0(WS) < \omega_0(firn)$

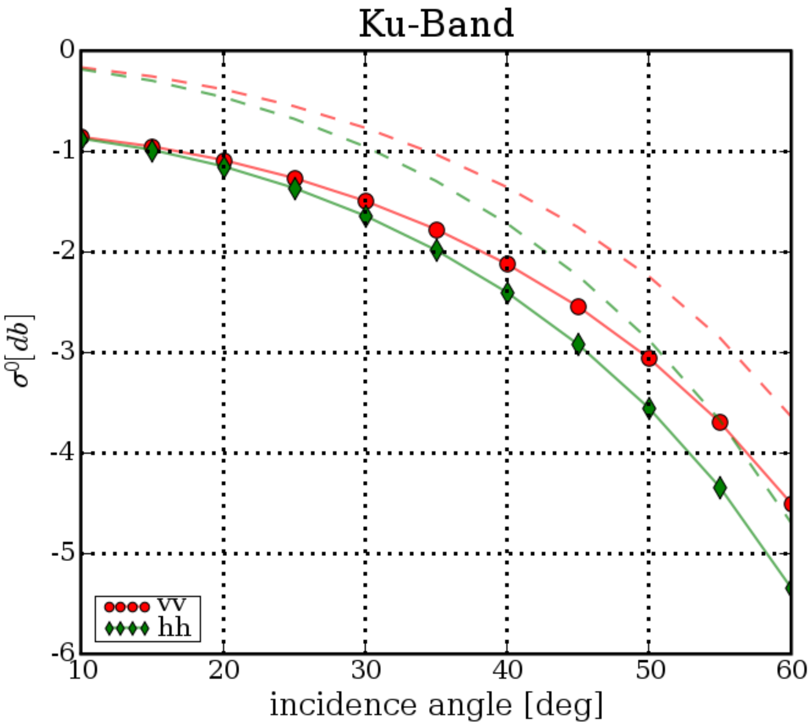


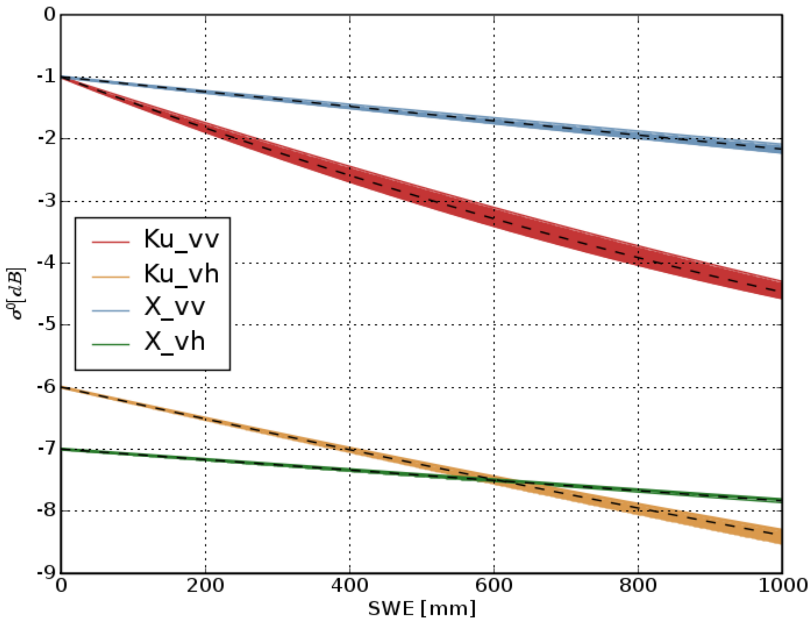
$$L_{WS}(\theta_t) = \exp(k_e d_{WS} \sec\theta_t) = \exp(k'_e\, SWE_{WS} \sec\theta_t)$$

σ_{FI} - backscatter of frozen firn from early autumn period

Iterate for SWE_{WS} by same procedure as for SWE on land

Backscatter Sensitivity to Winter Snow Accumulation in the Percolation Zone of Glaciers





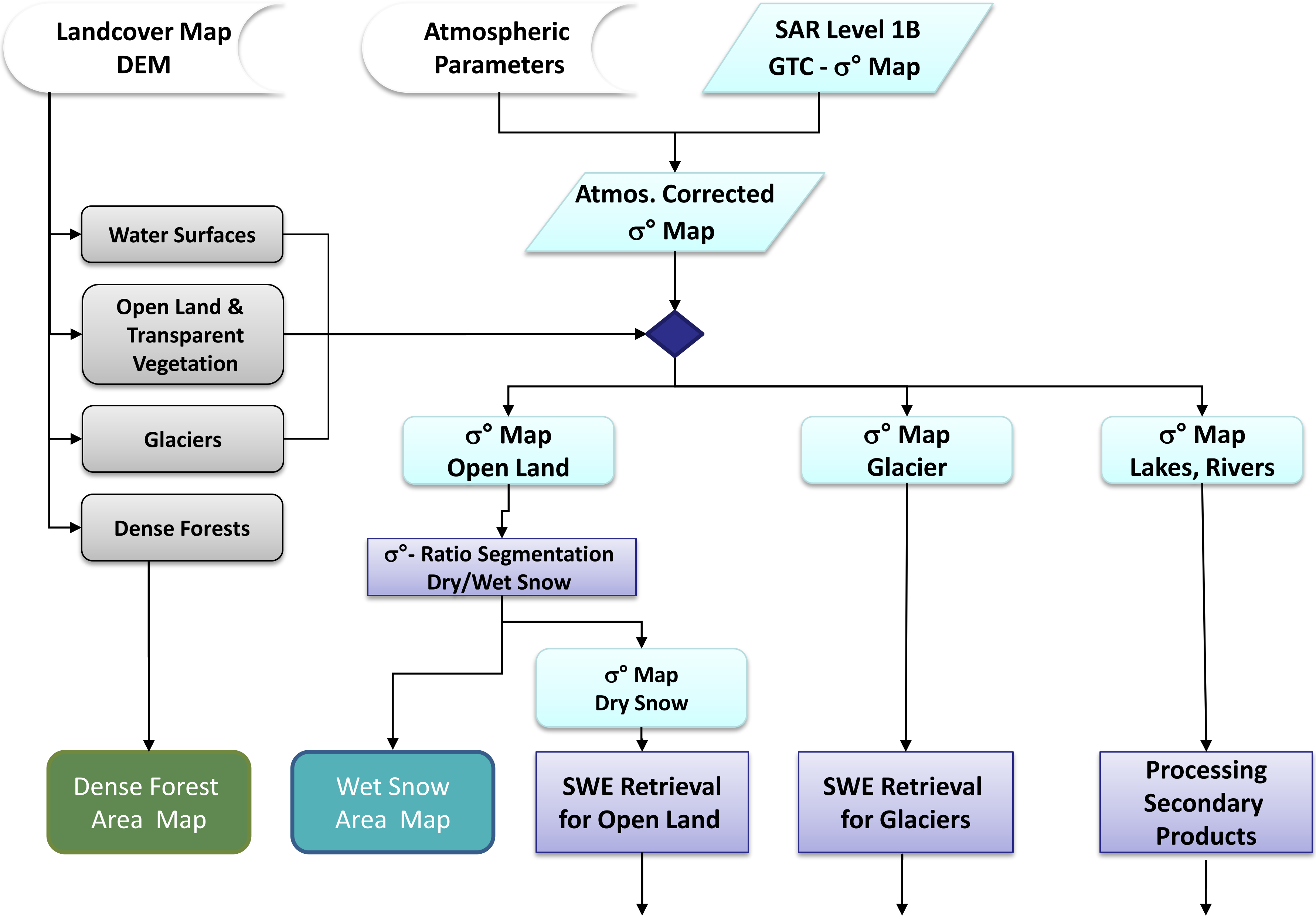
Broken Line – Frozen firn (early autumn)
Full Line – Firn and winter snow

Forward calculation of σ° sensitivity to SWE, starting from σ° observed in early autumn

Winter snow

Equiv. particle radius r = 0.2 mm
Ellipsoid axis ratio = 0.50
Snow density = 300 kg/m^3
Snow depth = 1m

SWE Processing Line – Part 1: Segmentation



Landcover Map
DEM

Atmospheric
Parameters

SAR Level 1B
GTC - σ° Map

Atmos. Corrected
σ° Map

Water Surfaces

Open Land &
Transparent
Vegetation

Glaciers

Dense Forests

σ° Map
Open Land

σ° Map
Glacier

σ° Map
Lakes, Rivers

σ°- Ratio Segmentation
Dry/Wet Snow

σ° Map
Dry Snow

Dense Forest
Area Map

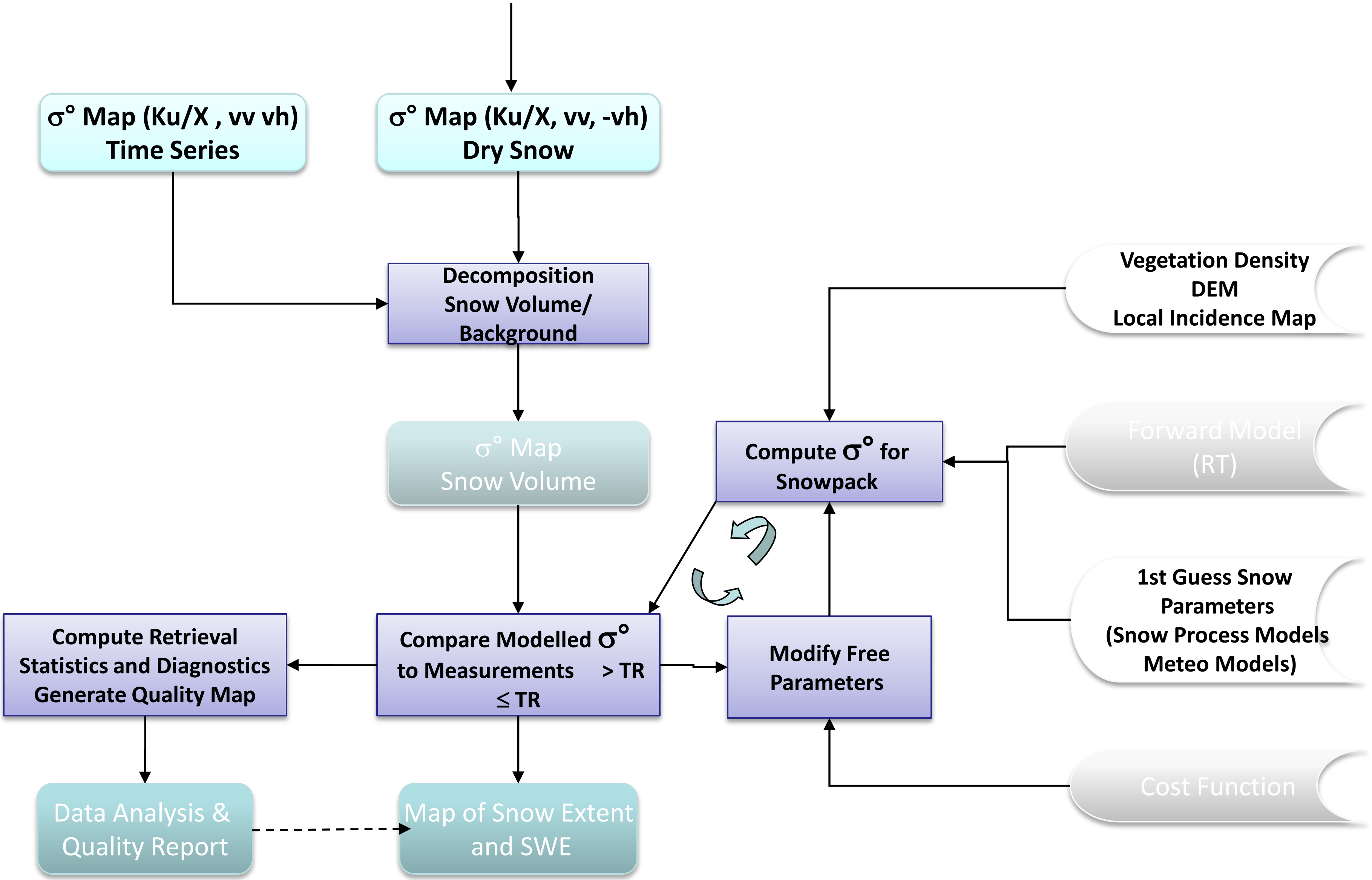
Wet Snow
Area Map

SWE Retrieval
for Open Land

SWE Retrieval
for Glaciers

Processing
Secondary
Products

SWE Processing Line – Part 2: Iterative Retrieval



σ° Map (Ku/X , vv vh)
Time Series

σ° Map (Ku/X, vv, -vh)
Dry Snow

Decomposition
Snow Volume/
Background

σ° Map
Snow Volume

Vegetation Density
DEM
Local Incidence Map

Compute σ° for
Snowpack

Forward Model
(RT)

1st Guess Snow
Parameters
(Snow Process Models
Meteo Models)

Compute Retrieval
Statistics and Diagnostics
Generate Quality Map

Compare Modelled σ°
to Measurements > TR
≤ TR

Modify Free
Parameters

Cost Function

Data Analysis &
Quality Report

Map of Snow Extent
and SWE

Auxiliary Data for SWE Retrieval

- Atmospheric parameters for transmissivity correction (e.g. ECMWF analysis)
- Topography (DEM) – for geocoding and local incidence angle

  SRTM at $\phi < 60°$; ASTER GDEM; national ….
- Vegetation maps

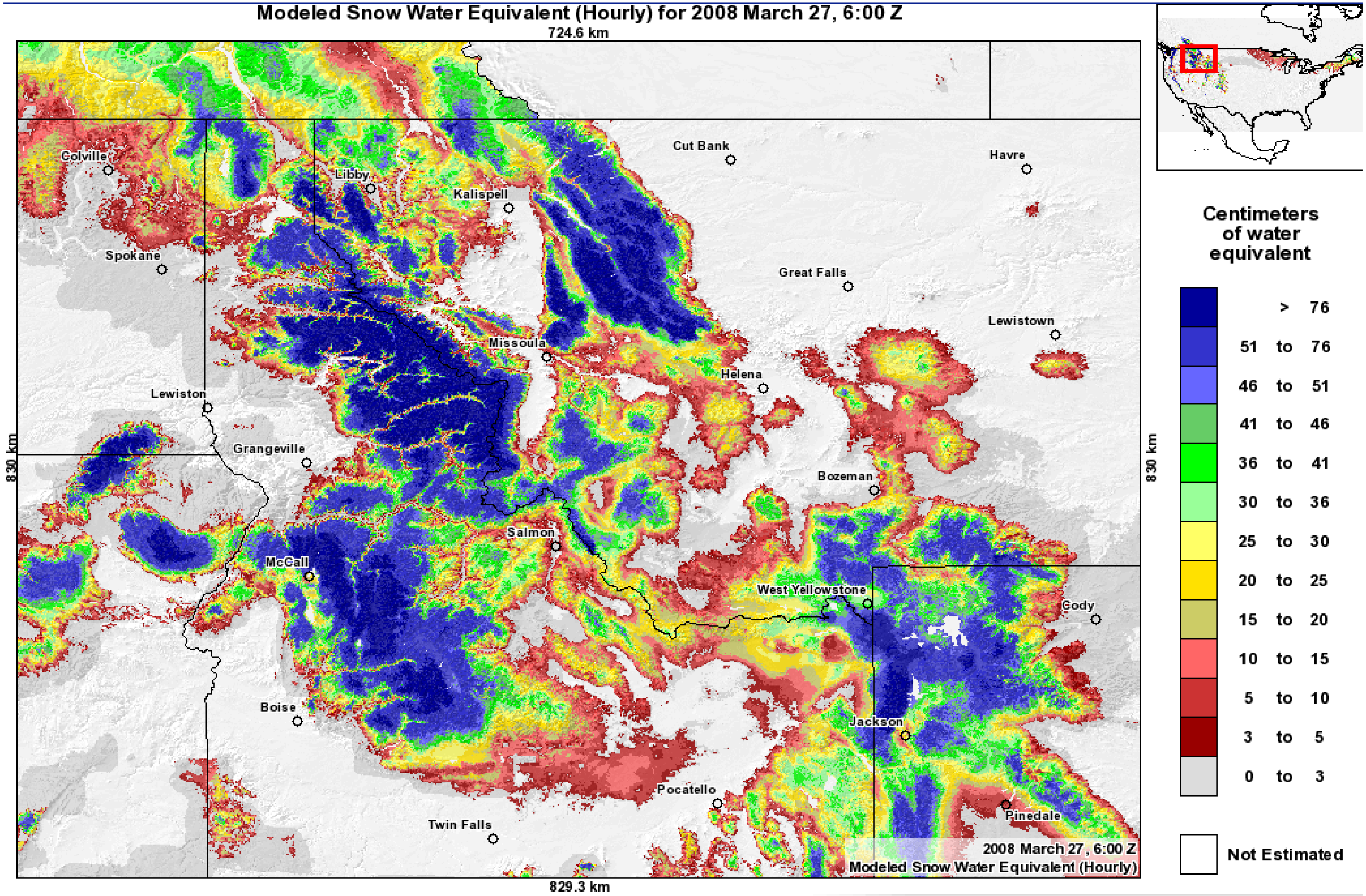
  GlobCover (ESA, 300m), ECOCLIMAP, CORINNE (Europe), …
- Background signature (snow-free case) from the SAR time series
- Snow statistics (climatology)
- 1st guess of snow parameters (e.g. gridded numerical meteo data from GCM and regional models, distributed snow process models, …)
- *For glaciers*: Classification of diagenetic facies

  - Dry snow zone - Percolation zone - Glacier ice zone

  (Classification of facies by means of multi-temporal backscatter ratios)

Option for 1st Guess Data - NOAA Snow Model

Maps on SWE, SD, ρ, <T> in 6 h time steps available



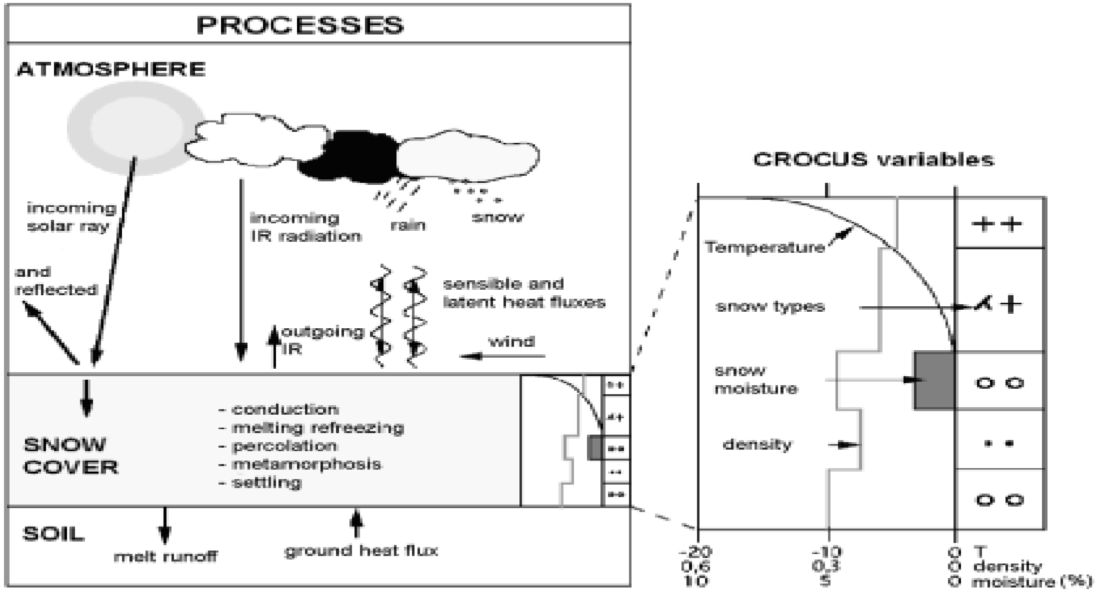
Modeled Snow Water Equivalent (Hourly) for 2008 March 27, 6:00 Z

2008 March 27, 6:00 Z
Modeled Snow Water Equivalent (Hourly)

Option for 1st Guess Data – SAFRAN/CROCUS

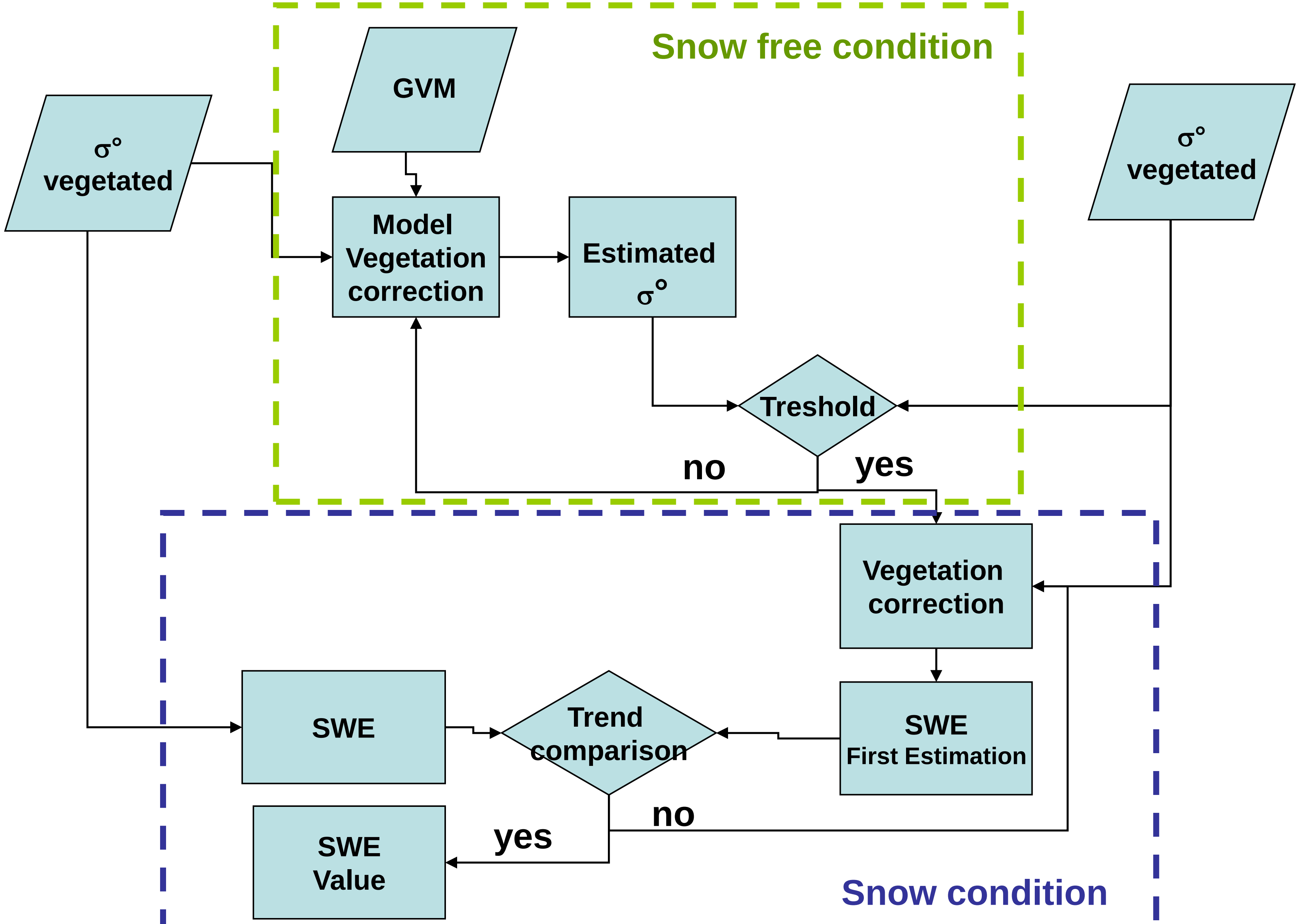
SAFRAN/CROCUS

- SAFRAN delivers the fields of required meteorological input parameters (6 h steps)
- CROCUS computes the snow pack properties (mass, temperature, density, liquid water, layering)

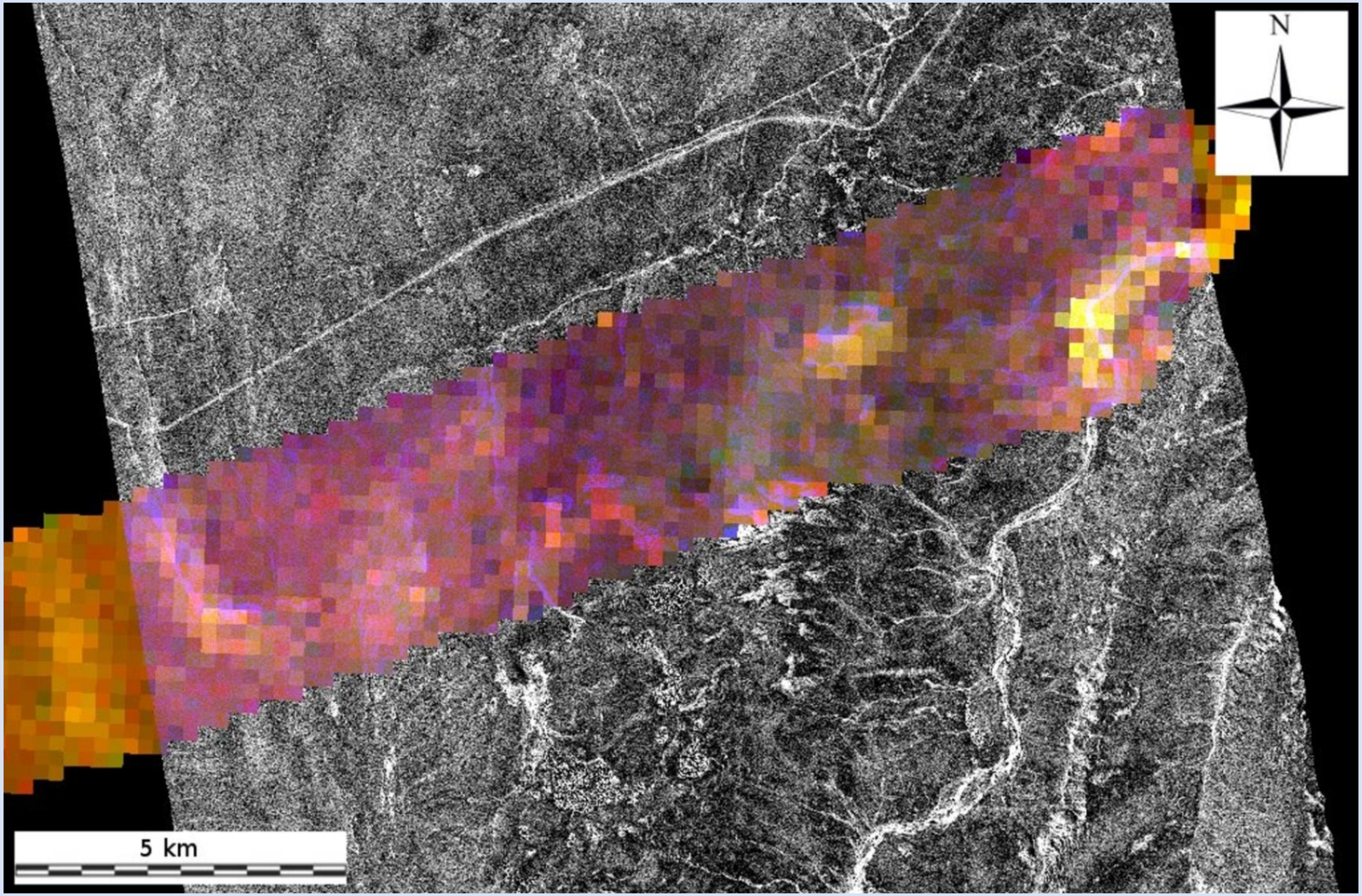


- Computes snowpack mass and properties in semi-distributed manner (elevation zones ∇z = 300 m , 6 orientations, 3 slope classes; local wind effects)
- Operationally used for snow hydrology, avalanche forecasting etc.

Proposed Concept for Correction of Vegetation Effects



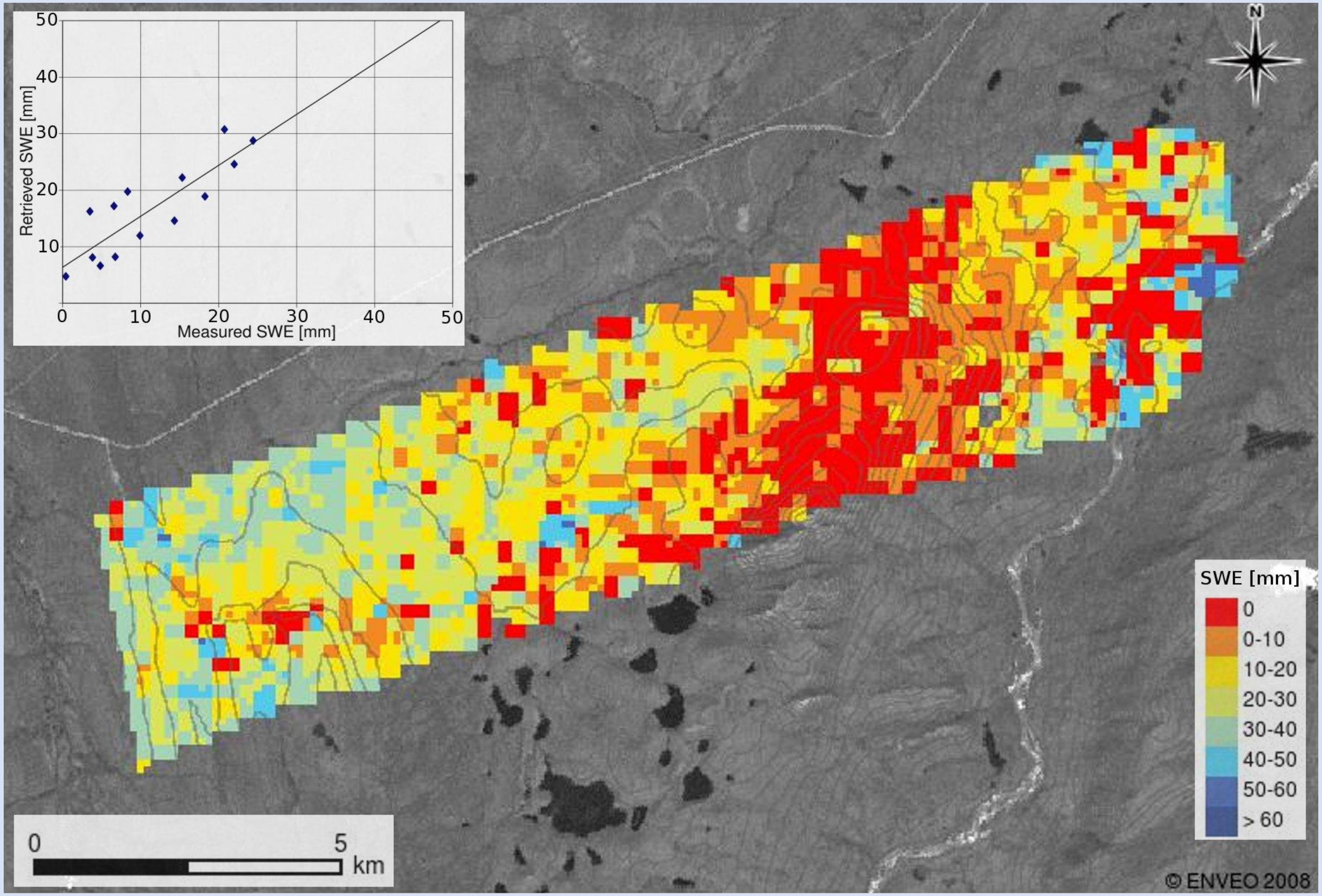
Test of SWE Retrieval Concept



CLPX-II Kuparuk River Study Area, Alaska, February 2008.
Background: TerraSAR-X VV. Colours: Swath of PolScat on TerraSAR-X;
Blue: X-band VV. Red: Ku-band VV. Green: Ku-band VH.

Test of SWE Retrieval Concept

Inset: Comparison of retrieved SWE vs. in-situ data



SWE map for Kuparuk River, Alaska, difference Feb. 2008 –Nov. 2007 from Ku-band VV & VH (PolScat), X-band VV & VH (TerraSAR-X)

Conclusion and Outlook

- Theory and experimental studies confirm the feasibility to apply dual frequency Ku-and X-band SAR measurements for mapping SWE
- Promising candidates for retrieval algorithms are statistical inversion techniques and variational data assimilation (VAR). They are robust and provide unique solutions
- The operator (based on RT model) linking observations (backscatter) to physical snow properties needs to avoid complexity, by still maintaining a realistic representation of the key processes
- Auxiliary data are important for
  - Segmentation (static data)
  - Corrections of vegetation effects, or masking of dense vegetation
  - Initialization of iterative retrieval (time-varying)
- Accounting for spatial and temporal context in the retrieval procedure should help to reduce noise
- For error assessment and validation of retrieval algorithms the acquisition of Ku-and X-band backscatter data over different snow regimes is of high priority