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Time-series fusion of optical and SAR data for snow cover estimation using a Hidden Markov Model

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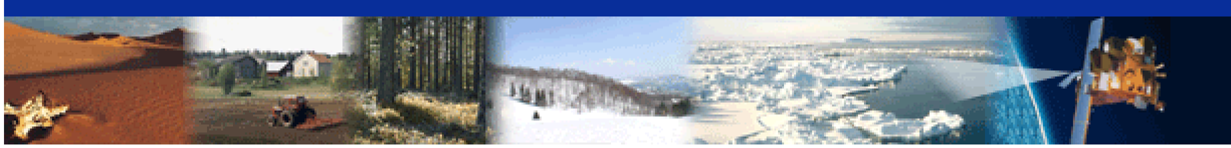
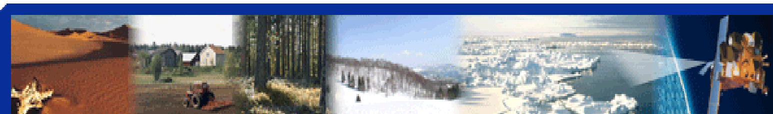


Outline

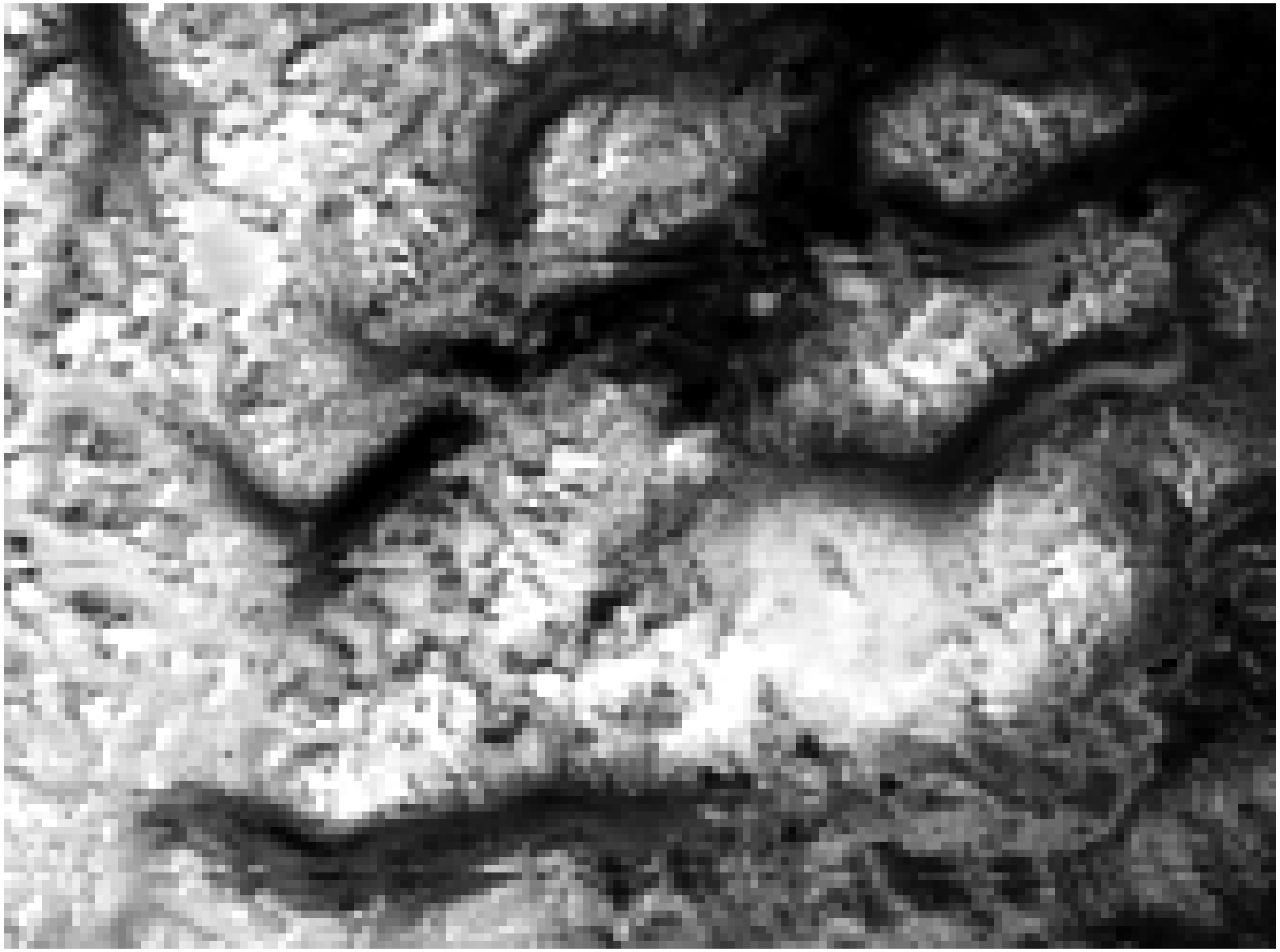
- Background
- Problem
- Solution
- Results

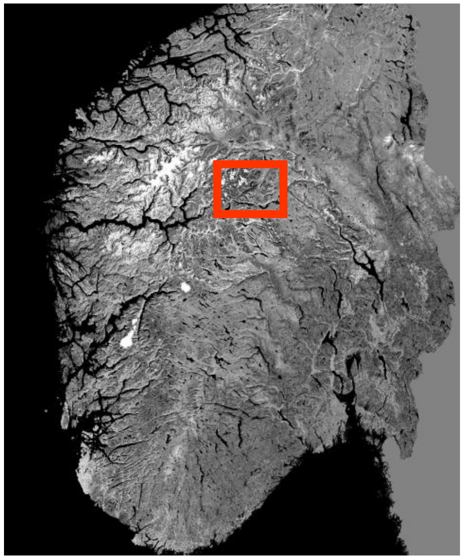


Mapping the snow reserves

- Sources of information:
  - meteorological data
  - field measurements
  - satellite images during the melting season
- Hydrological models
  - estimation of the amount of snow in mountain basins
  - prediction of the level of water reservoirs

Optical data from MODIS



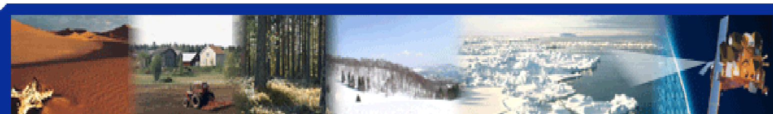


Time: May 10th 2004

Pixel size:
250 × 250 m²

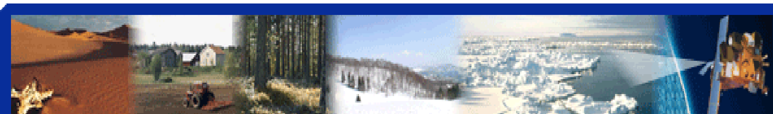
Problem

- Estimate the current Fractional Snow Cover (FSC) per pixel and assess the uncertainty
- Data: Time-series of
  - Optical data (Terra MODIS)
  - Synthetic-aperture radar (SAR) data (ENVISAT ASAR)
- Additional data sources that may be used later:
  - Topographic information
  - Contextual information
  - Field measurements
  - Meteorological data

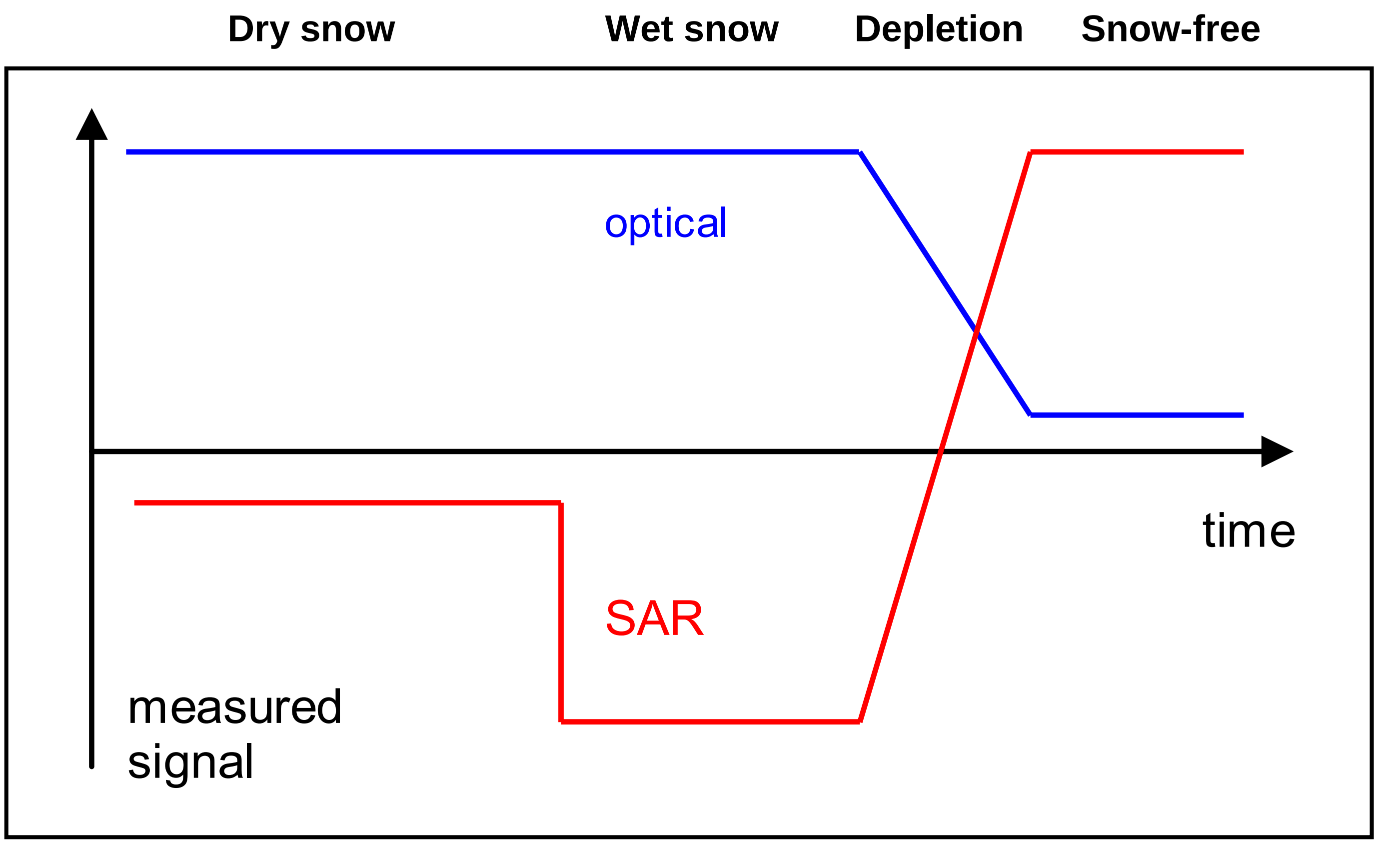


Properties of the data

- Optical data
  - reflectance
  - dominated by effects from photon scattering, transmission and absorption near the snow surface at the snow-grain size
  - limited by cloud cover
- Synthetic-aperture radar (SAR) data
  - backscatter
  - dominated by effects due to dielectric properties of the snow medium as well as snow surface roughness (for wet snow) or a combination of the snow pack structure and the ground below
  - higher variability than reflectance

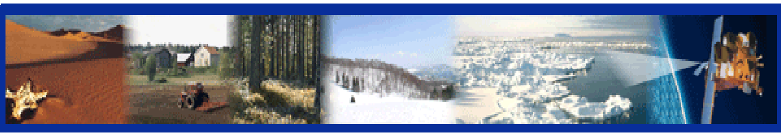


Snow status vs optical reflectance and SAR backscatter



Hidden Markov model - motivation

- Draw inference about an unobservable process through observations from a related process.
- Assume that some prior knowledge about the unobservable process is available.
- Correction errors in single observations is possible by analysis of a sequence of observations in a context. (Filtering)



Hidden Markov model - Example

- X_t - a process with two possible states at time t:
  - R is in her/his office (R is a researcher).
  - R is NOT in her/his office.

  Not always possible to observe X_t at a distance.
- Y_t – a process with two possible states at time t:
  - Light in R's office
  - R's office is dark

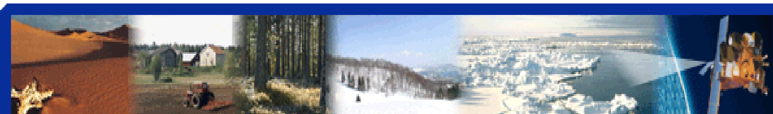
  Y_t is easily observed. Y_t is influenced by X_t:
  Usually light when R is present and dark otherwise
- Can use Y_t to spy on R

Hidden Markov model - Basics

- Two stochastic processes: (X_t, Y_t)
  - X_t not observed
  - Y_t observed
- X_t is a Markov process
  - Given the present state, future states are independent of the past states

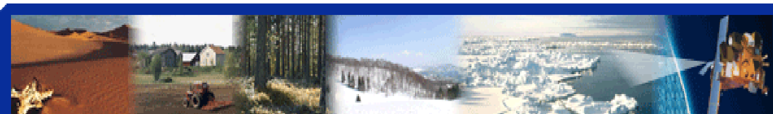
$$\Pr(X_{t+1}=x \mid X_t=x_t,\ldots,X_1=x_1)=\Pr(X_{t+1}=x \mid X_t=x_t)$$

  - Without memory
- In applications:
  - X_t has a constrained behaviour.
  - the distribution of Y_t depends on the state of X_t.
    Then Y_t provides information about X_t.
- Simple models: Given X_t, Y_t is independent of X_s and Y_s, $s \neq t$.



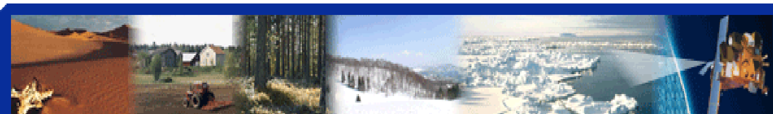
Hidden Markov model
Snow cover estimation

- $X_t = (X_t^c, X_t^w)$ - fractional snow cover, dry/wet snow
  - States:
    - 100% coverage dry snow,
    - 100% coverage wet snow,
    - 99% coverage wet snow,
    - ….
    - Snow free
  - Assume decreasing coverage
  - Transition probabilities depend on prior information about the melting rate
- Y_t^{OPT} – reflectance data
- Y_t^{SAR} – backscatter data



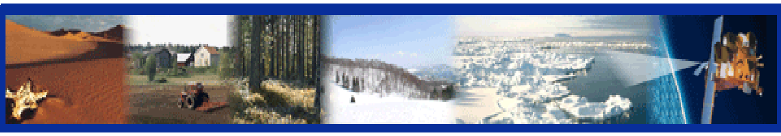
Snow status – Transition probabilities

	Dry	Wet	99%	…	50%	49%	…	1%	Free
Dry	+	+	0	0	0	0	0	0	0
Wet	0	+	+	+	0	0	0	0	0
99%	0	0	+	+	0	0	0	0	0
…									
50%	0	0	0	0	+	+	+	0	0
49%	0	0	0	0	0	+	+	0	0
…									
1%	0	0	0	0	0	0	0	+	+
Free	0	0	0	0	0	0	0	0	1

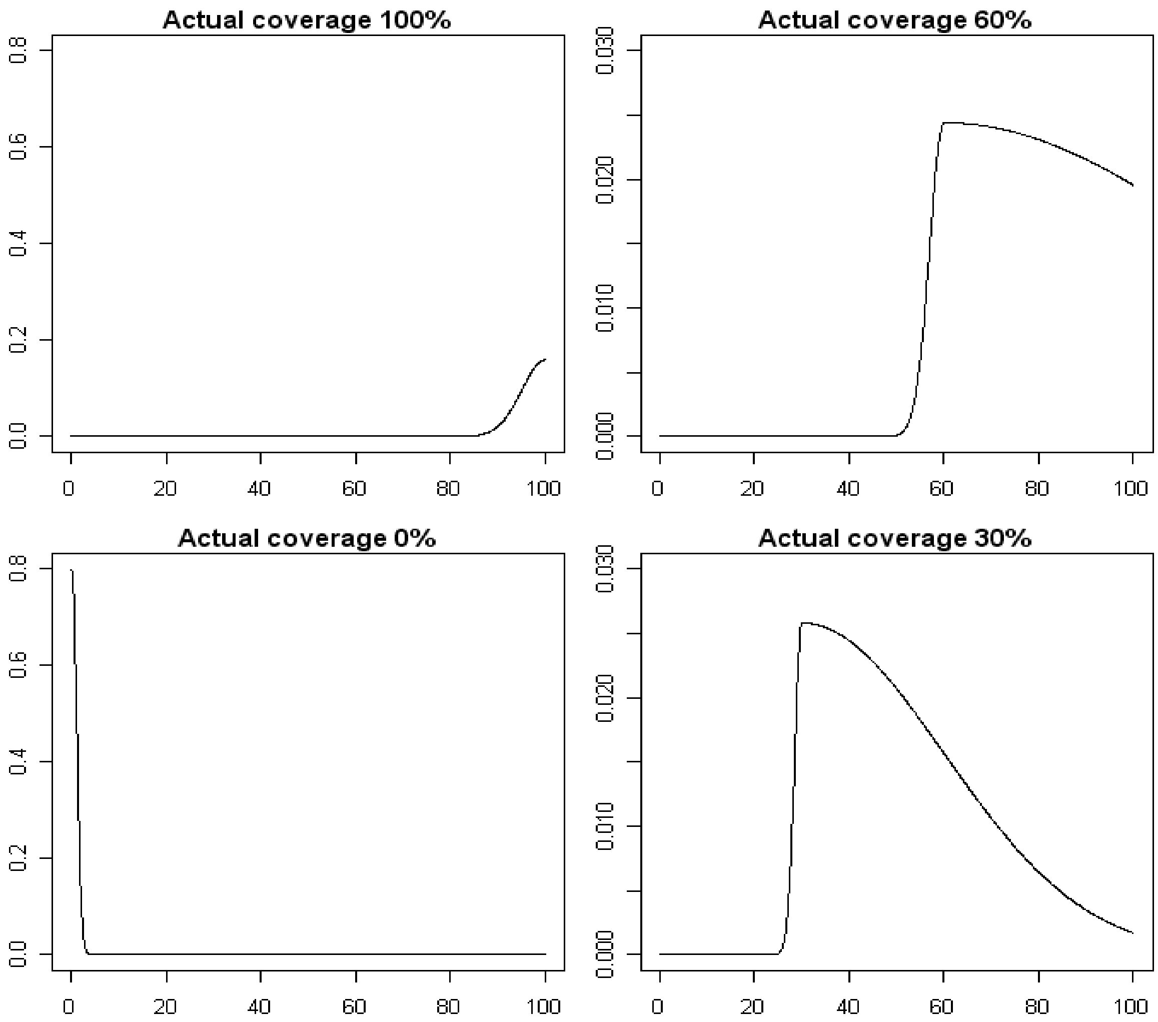


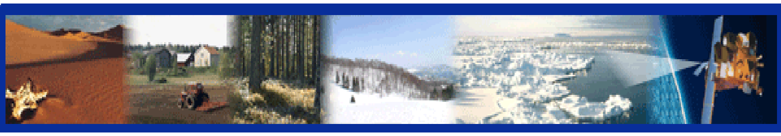
Distribution of optical data - Properties

- Preprocessing:
  - Reflectance data are transformed to snow cover percentages (possibly erroneous).
  - Most cloud pixels are removed from further analysis
- Mode of the distribution = Actual snow cover
- Noise
  - Cloud remains and cloud shadows
  - Temporary snow (not interesting, to be eliminated)



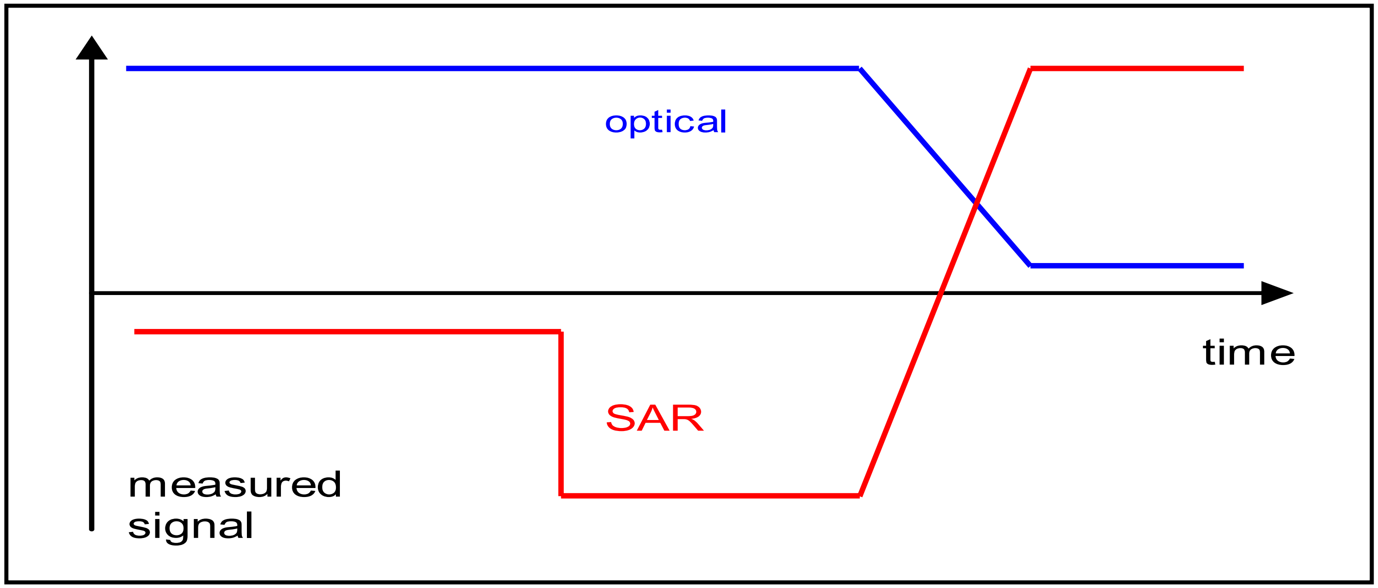
Distribution of optical data - Examples





Distribution of SAR data

- Normal distribution with mean as indicated and state independent standard deviation

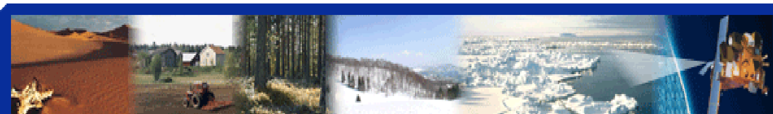


Computations

- Wish to find $E(X_t^c|Y_1,\ldots,Y_t)$, the posterior expectation given the available data up to time t. (c indicates the coverage percentage corresponding to the state of the process)
- The algorithm for computing $Pr(X_t=x|Y_1,\ldots,Y_t)$, the posterior probability, is known.
- The expectation is found through

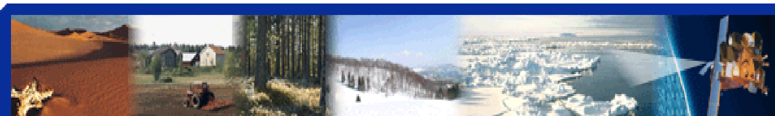
  $$E(X_t^c|Y_1,\ldots,Y_t) = \sum x^c \, Pr(X_t=x|Y_1,\ldots,Y_t),$$

  the sum is taken over all states.



Assessment of uncertainty

- At a given time t, L_t and U_t can be determined such that $Pr(L_t < X_t < U_t | Y_1, \ldots, Y_t) = 95\%$.
- (L_t, U_t) is a Bayesian confidence interval.
- Typically the confidence interval is
  - wide when no observation is available at time t
  - narrow when reflectance (in particular) or backscatter is observed at time t



Remarks

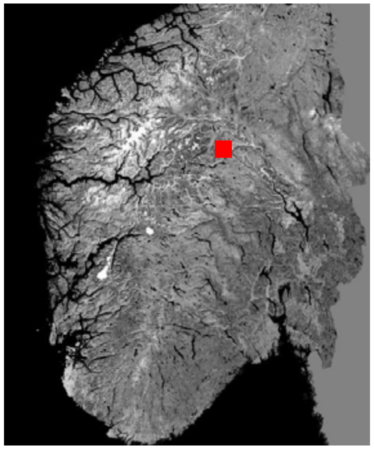
- Alternative approach: Monte Carlo filters
- We do not attempt to find the state sequence

  $x_1,\ldots,x_t$

  that maximises

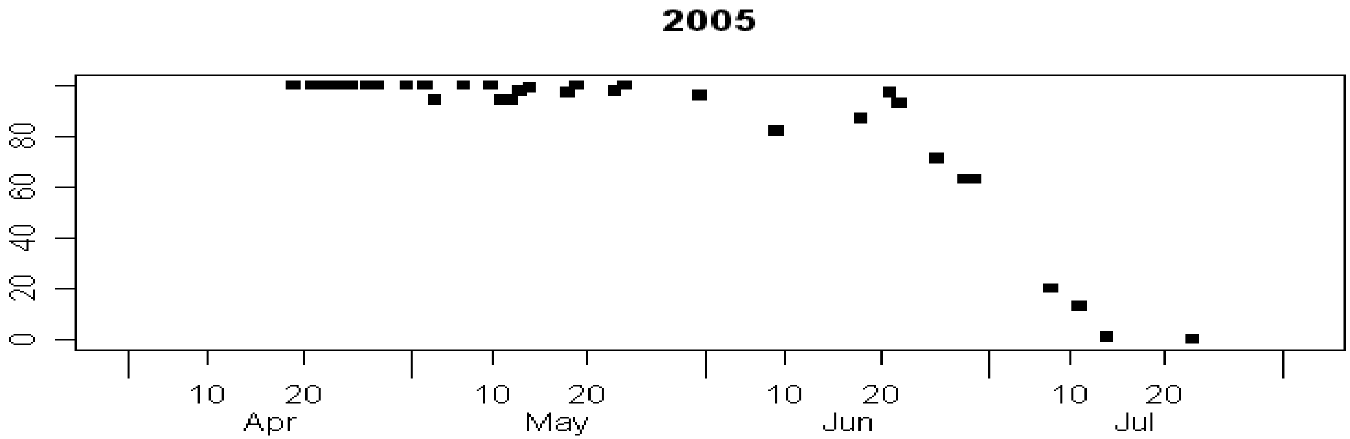
  $Pr(X_1=x_1,\ldots,X_t=x_t|Y_1,\ldots,Y_t)$

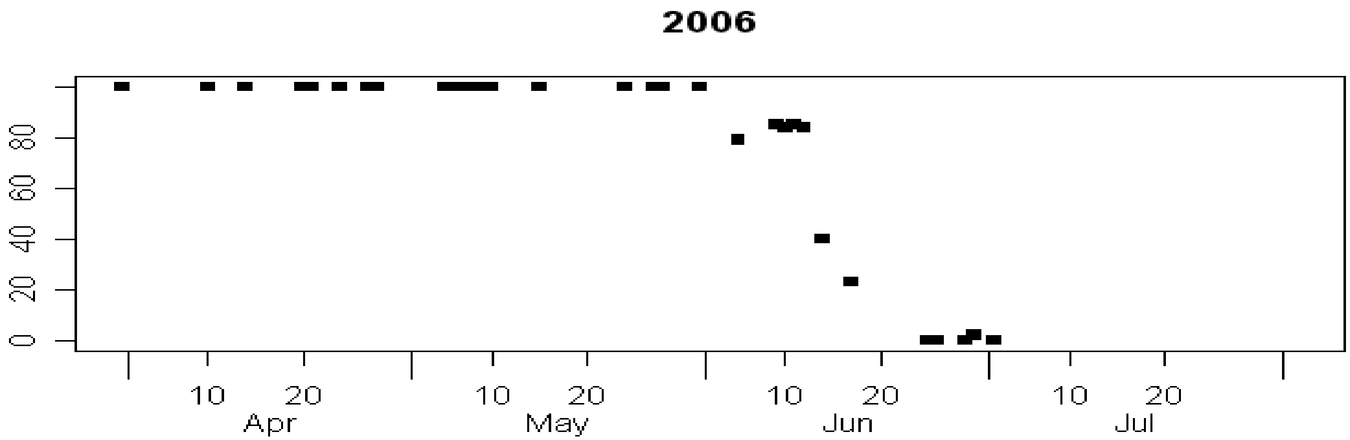
Experimental data



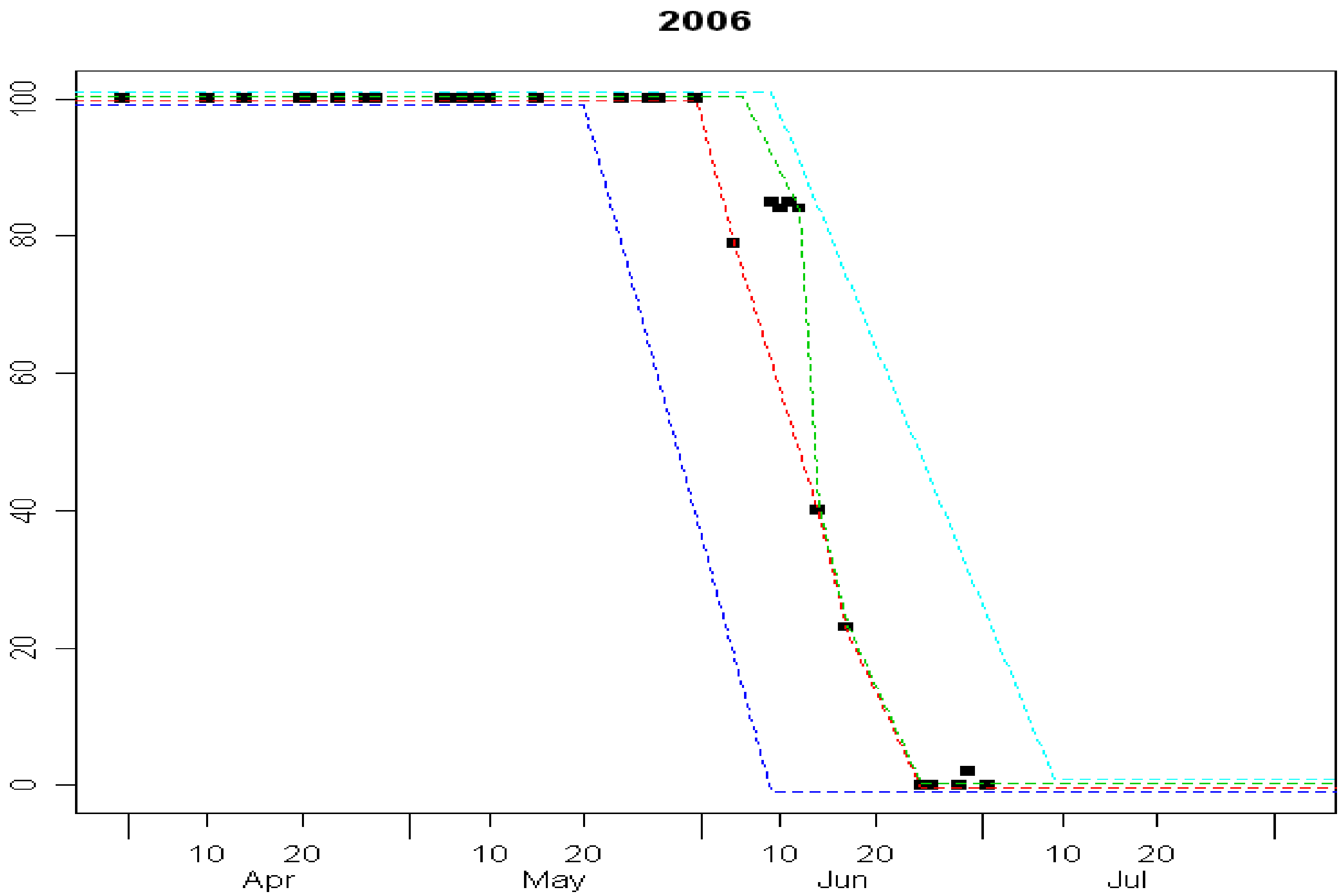
- Site:
  - Valdresflya
  - Flat area
- Period:
  - Melting seasons
  - 2003 – 2006

Optical data

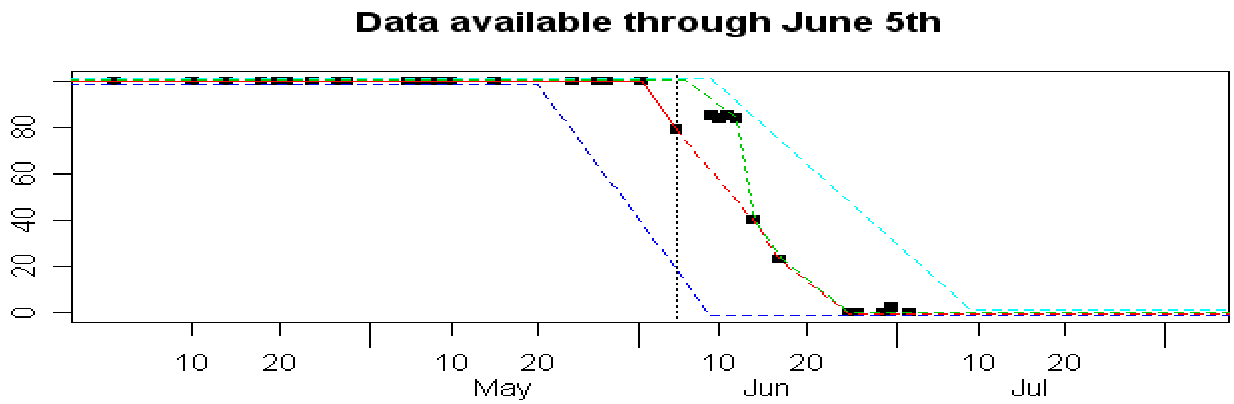


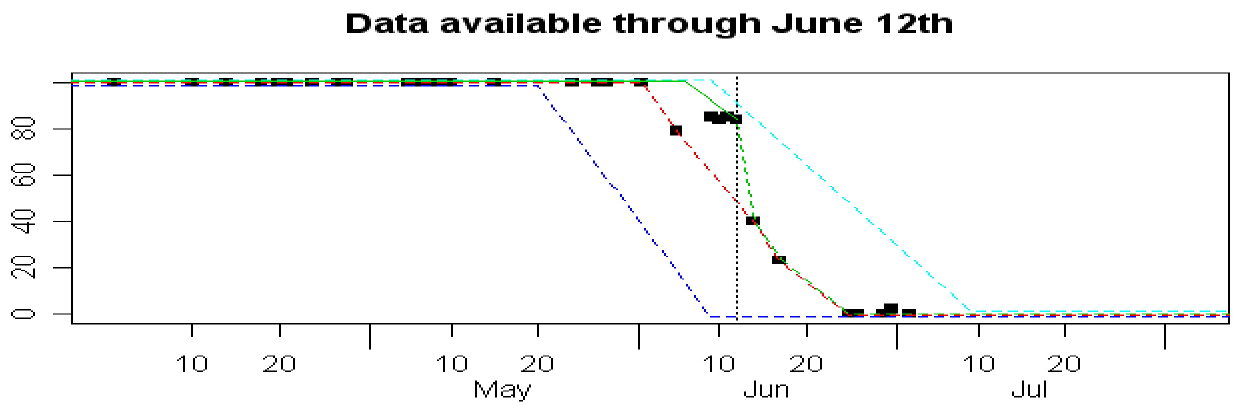


Possible state trajectories

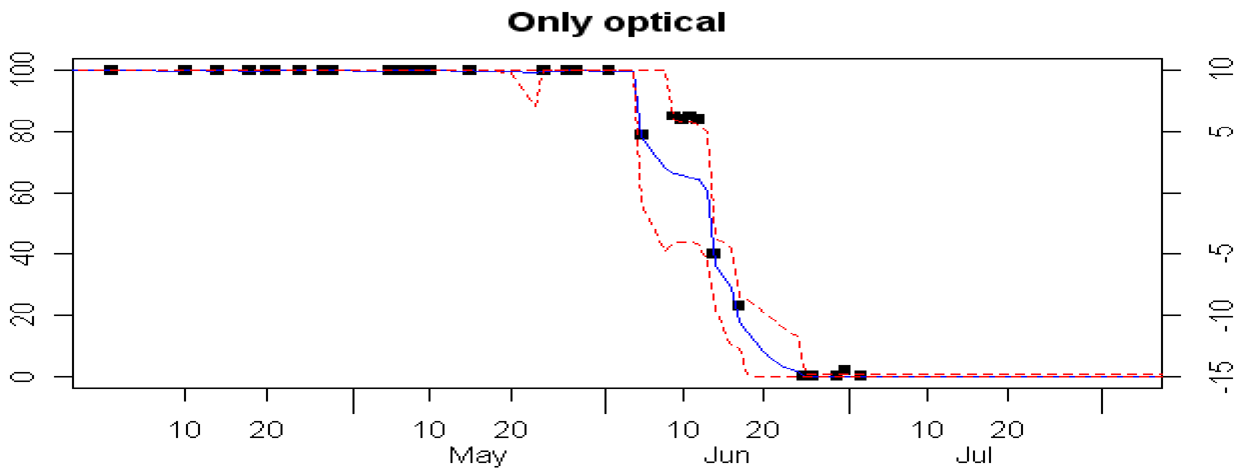


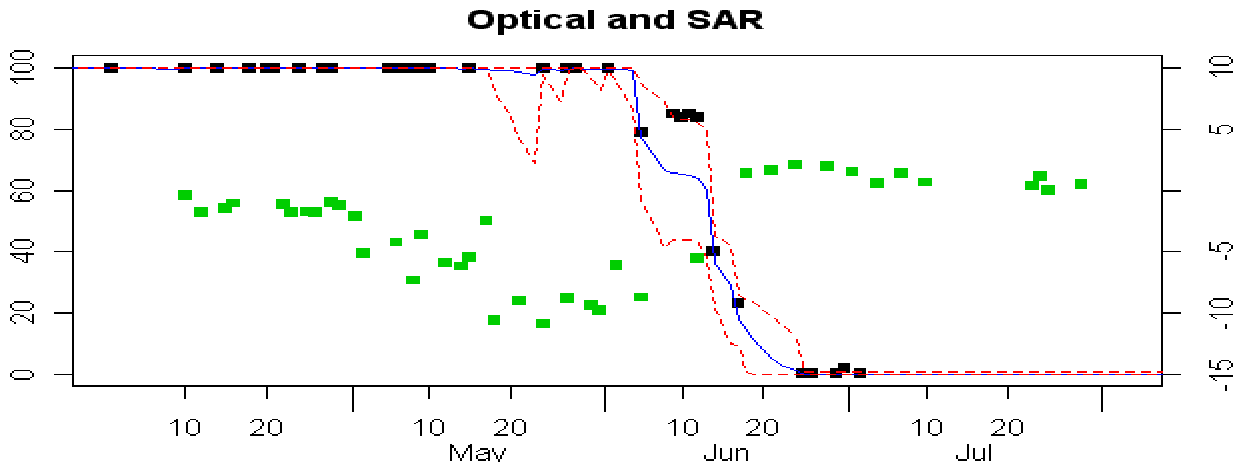
Likely trajectories based on data

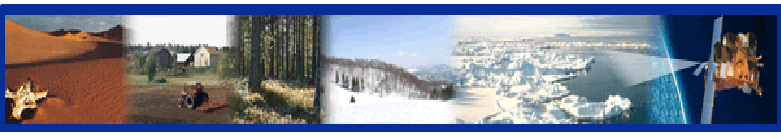




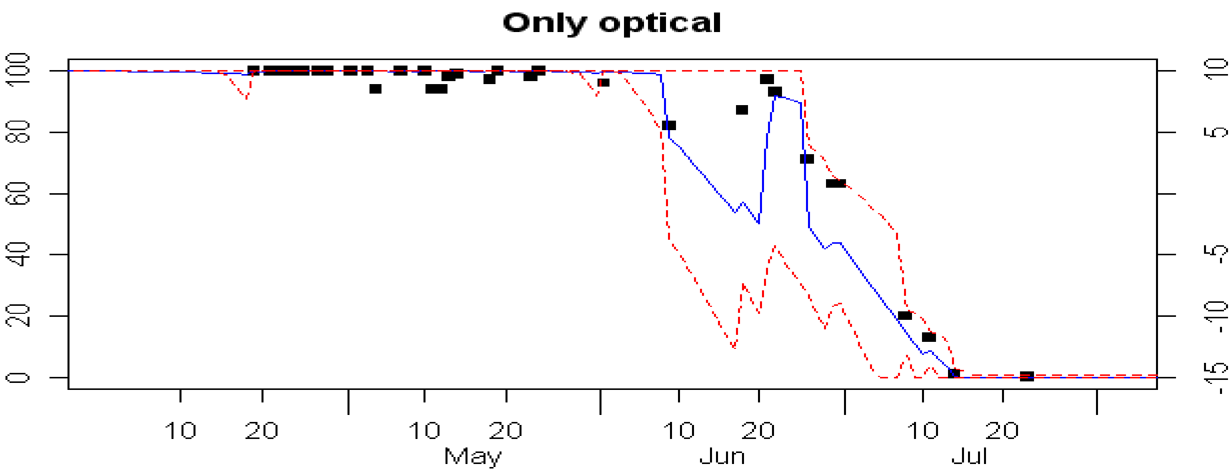
Results 2006

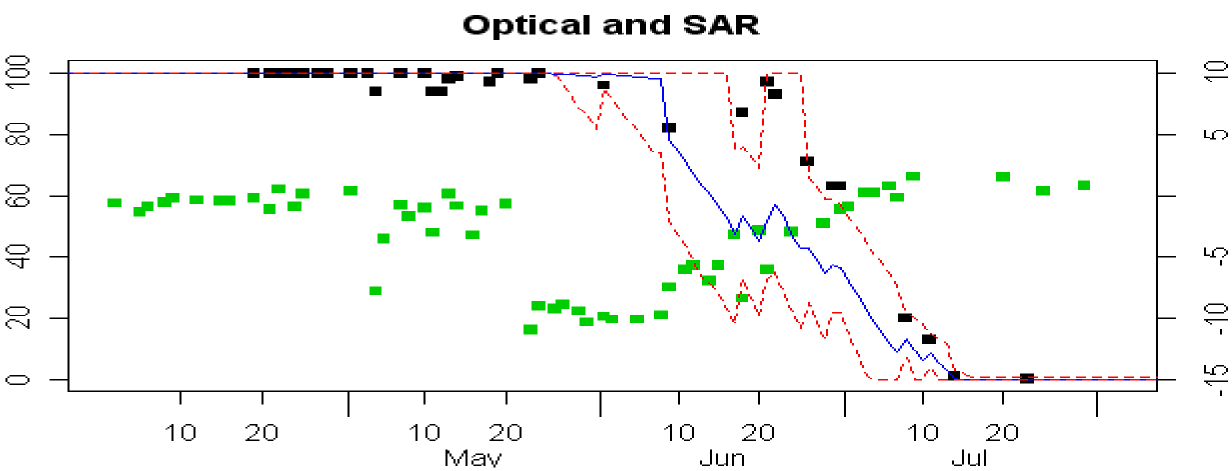


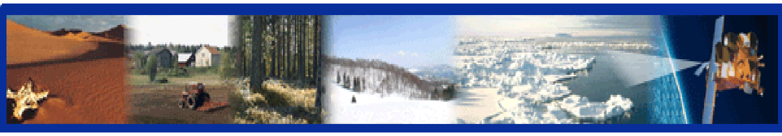




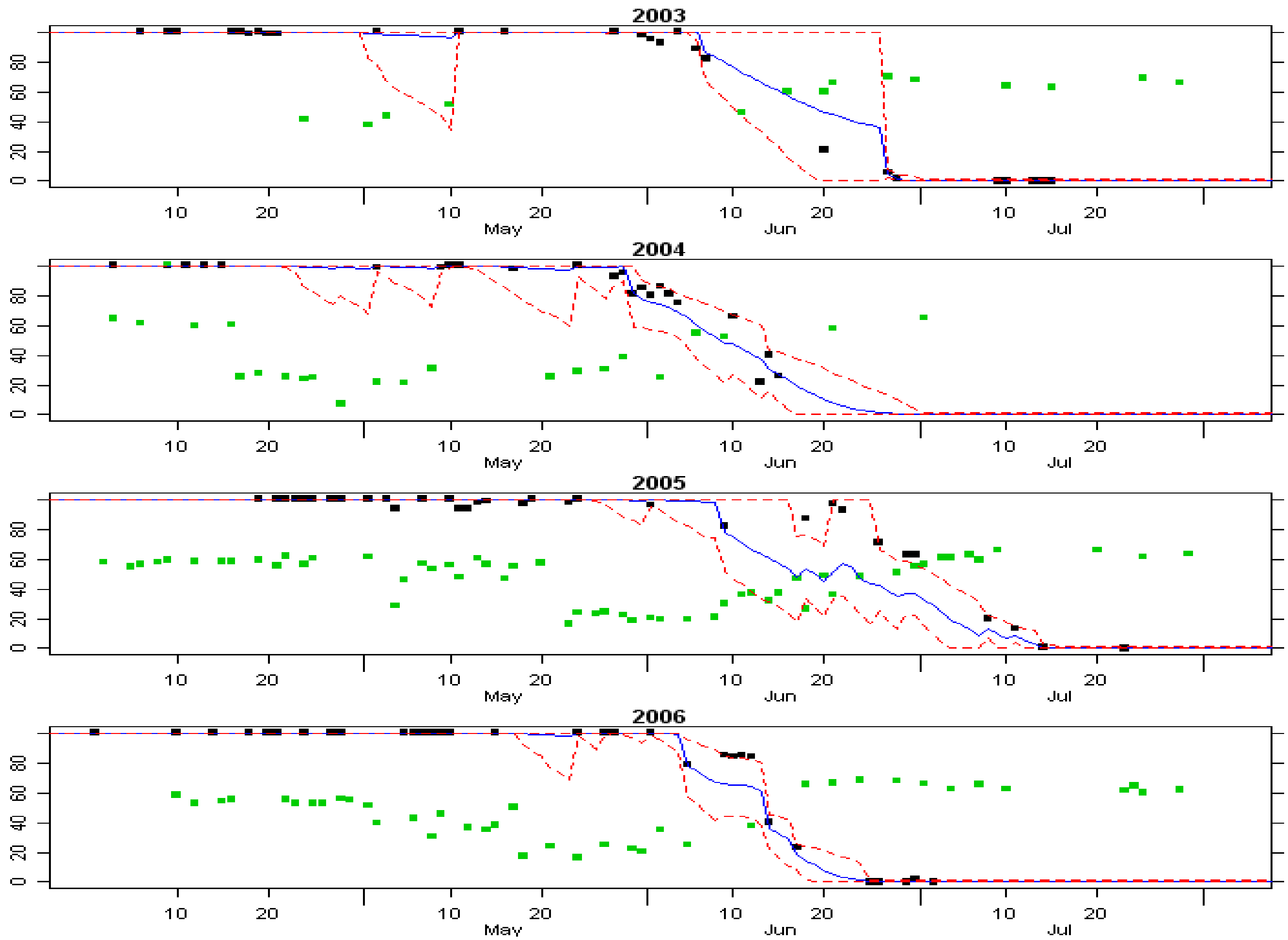
Results 2005







Results 2003 – 2006 (optical and SAR)



Conclusion

- The method estimates the fractional snow cover quite well
- The method is not used in operational snow cover monitoring
- Further work includes experiments in areas with relief.