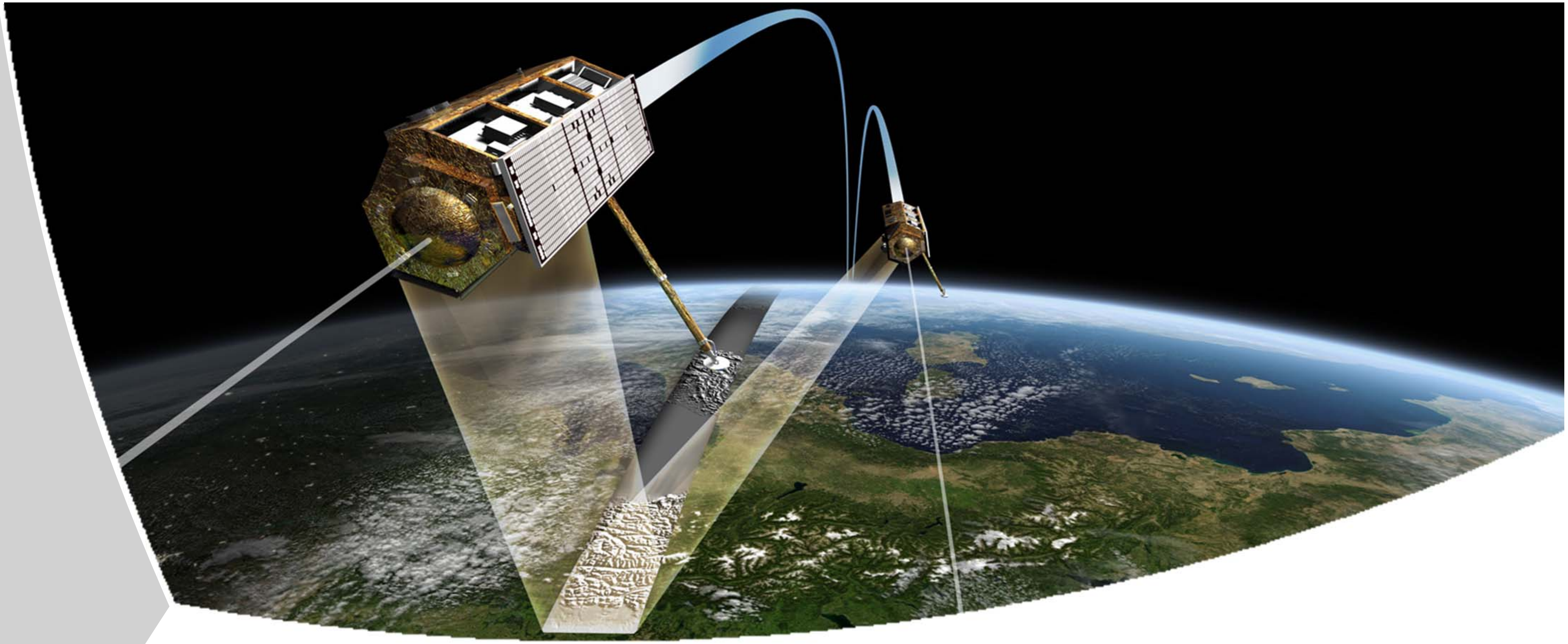


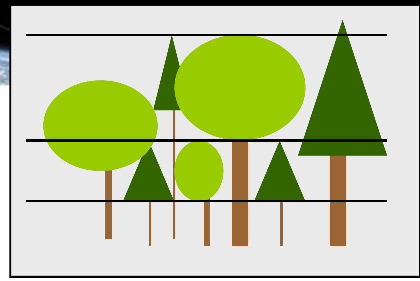
Boreal forest biomass classification with TanDEM-X

Astor Toraño Caicoya[1], Florian Kugler[1], Irena Hajnsek[1,2], Kostas Papathanassiou[1]

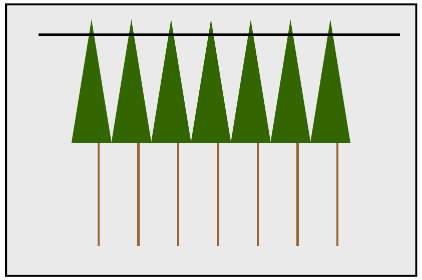
[1] Microwaves and Radar Institute, German Aerospace Center (DLR); [2] ETH Zurich

Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

Biomass Structure in the Boreal Forest

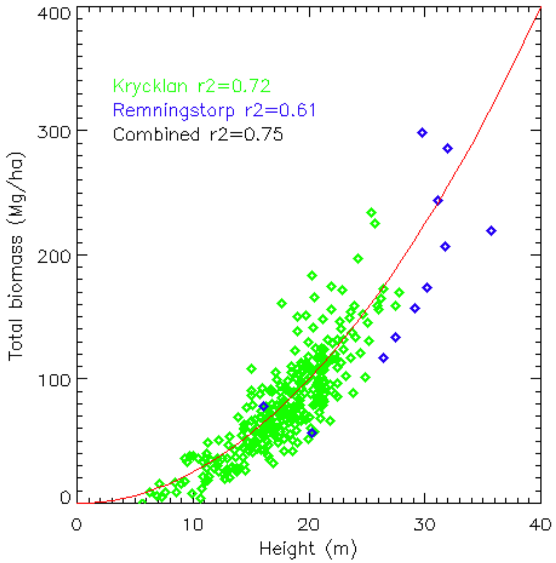


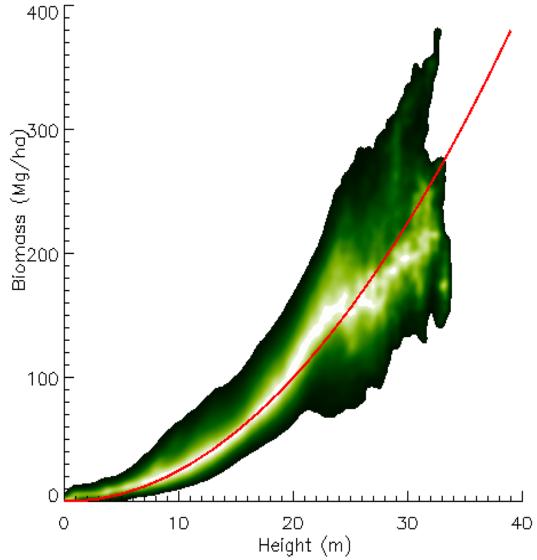
- Forest Above-Ground Biomass can be retrieved from forest height using allometric equations
- Forest structure limits the accuracy of allometric equations



- However boreal forests are characterized by a homogenous structure that optimizes the use of these equations
- Biomass can be estimated with adequate accuracy from height

$$B = 0.25h_v^{\ 2}$$

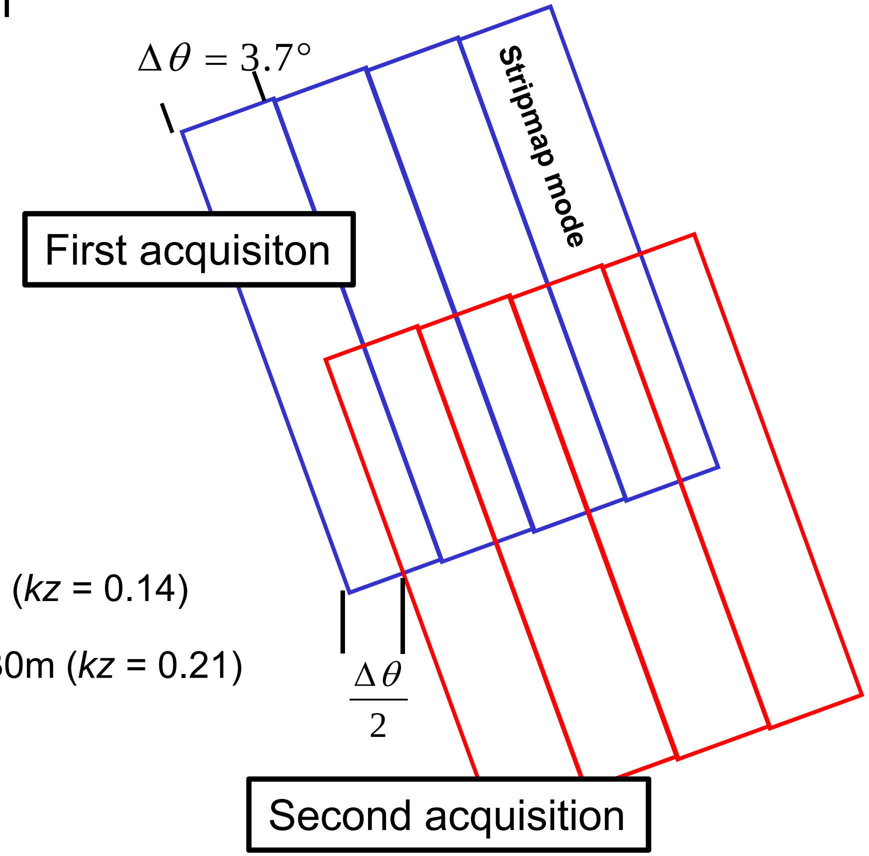




TanDEM-X Operational DEM Mode

Primary mission objective is the generation of a consistent global digital elevation model (DEM)

- Specifications:
  - X-band (3cm wavelength)
  - Bistatic
  - Polarisation: HH
  - Incidence Angle Range: 30° - 48,5°
  - Minimum Height of Ambiguity First acquisition: 45m (*kz* = 0.14)
  - Minimum Height of Ambiguity Second acquisition: 30m (*kz* = 0.21)
  - Stripmap mode: 30 km wide, 50 km long
  - Spatial resolution 6 m x 6m
  - No threshold for seasonality of second acquisition (repetition is arbitrary)



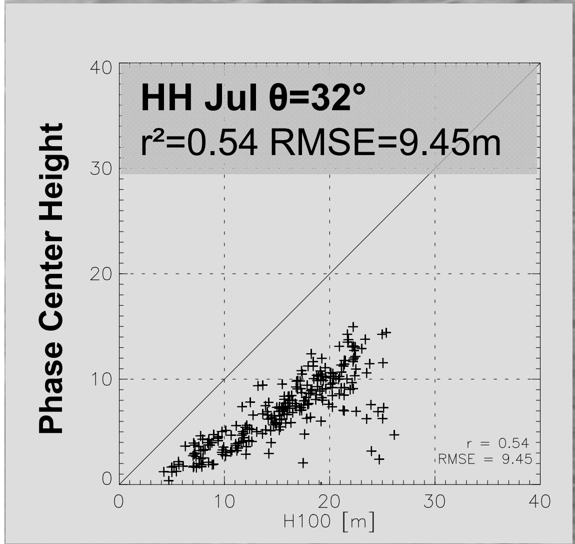
Global DEM acquisitions should be used for biomass classification

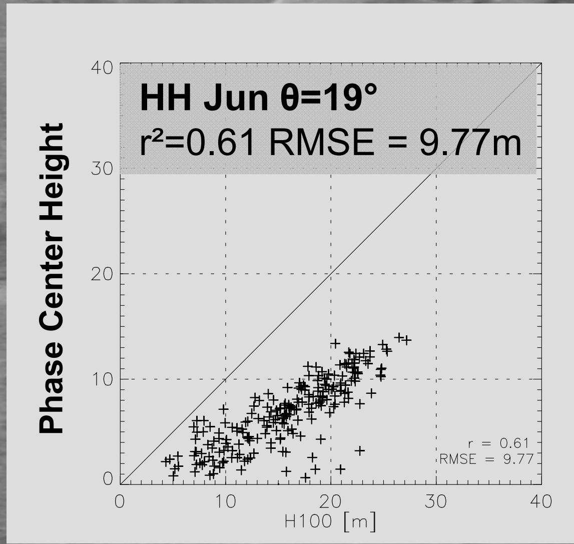
Penetration Depth / Phase Center height in X-band – seasonal differences

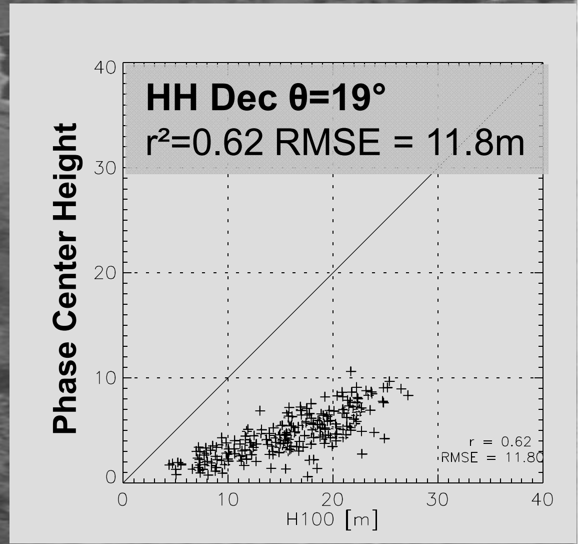
Krycklan

Summer

Winter



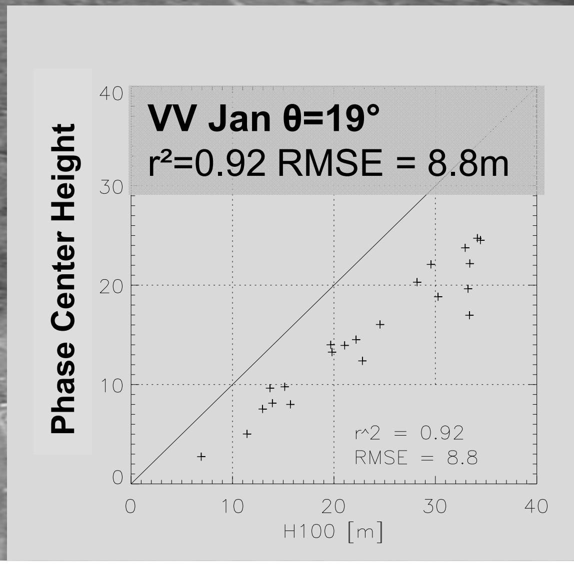


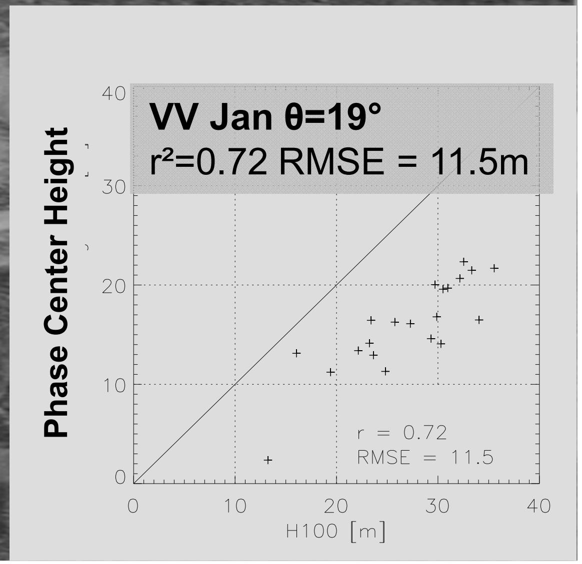


Traunstein

Larger in Winter than in Summer

Phase center height = TDX phase height – Lidar ground phase height





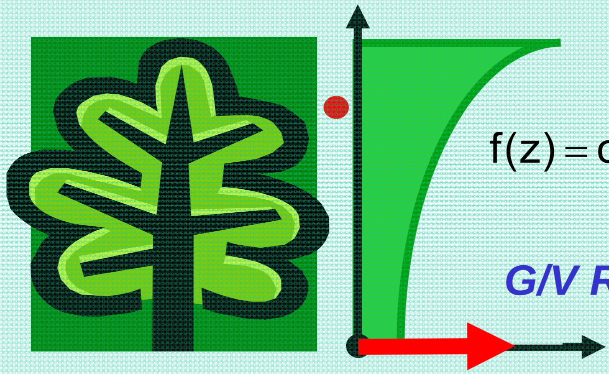
Coherence Modeling

Coherence Calibration

$$\tilde{\gamma}(\vec{w}) = \tilde{\gamma}_{vol}(\vec{w}) \cdot \tilde{\gamma}_{temp}(\vec{w}) \cdot \gamma_{SNR}(\vec{w})$$

$$\gamma_{SNR}(\vec{w}) = \frac{1}{\sqrt{[1+(SNR_{Master}(\vec{w}))^{-1}][(SNR_{Slave}(\vec{w}))^{-1}]}}$$

Random Volume over Ground (RVoG)



Volume Coherence

$$\tilde{\gamma}_V(f(z)) = \frac{\int_0^{h_V} f(z) e^{ik_z z} dz}{\int_0^{h_V} f(z)\, dz}$$

$$f(z) = \sigma_{V0} \exp\left(\frac{2\sigma z}{\cos\theta_0}\right) + m'_G \delta(z - z_0)$$

G/V Ratio $m(\vec{w}) = \frac{m_G(\vec{w})}{m_V(\vec{w}) I_0}$

Vertical Wavenumber $\kappa_z = \frac{\kappa \Delta\theta}{\sin(\theta_0)}$

$$\tilde{\gamma}_{Vol}(\vec{w}) = \exp(i\varphi_0) \frac{\tilde{\gamma}_V + m(\vec{w})}{1 + m(\vec{w})}$$

Unknowns:

volume height	h_V
volume shape factor	σ
G/V Ratio	$m(\vec{w})$
Ground phase	φ_0

Dual Pol

Observables:

$\tilde{\gamma}$ (HH, κ_{z1}), $\tilde{\gamma}$ (VV, κ_{z1})

Assumptions:

$m(\vec{w}_{min}) = 0$

Unknowns:

h_V, σ, $m(\vec{w}_{max})$, φ_0

Single Pol with DTM

Observables:

$\tilde{\gamma}$ ($\vec{w}$, κ_{z1}), DTM(φ_0)

Assumptions:

$m(\vec{w}) = 0$

Unknowns:

h_V, σ

Single Pol

Observables:

$|\tilde{\gamma}(\vec{w})|$

Assumptions:

$m(\vec{w}) = x$, $\sigma = y$

Unknowns:

h_V

Dual Baseline

Observables:

$\tilde{\gamma}$ ($\vec{w}$, κ_{z1}), $\tilde{\gamma}$ ($\vec{w}$, κ_{z2})

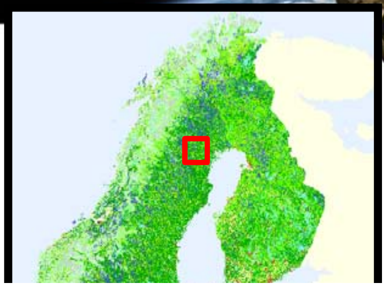
Assumptions:

$m(\vec{w}) = x$ or $\sigma = y$

Unknowns:

h_V, $[m(\vec{w}, \kappa_{z1}), m(\vec{w}, \kappa_{z1})]$ or σ

Test Sites and Data

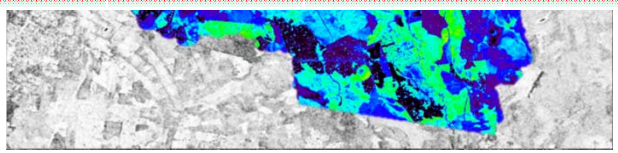


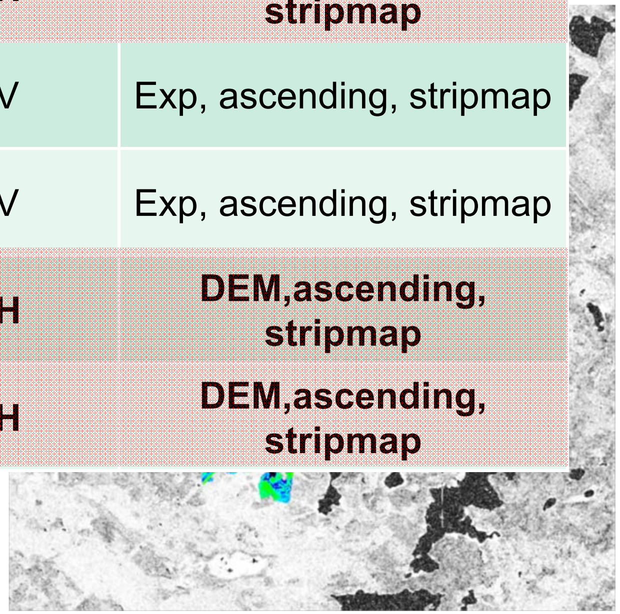
Two boreal forests:

- Krycklan: North Sweden, biomass up to 250Mg/ha
- Remningstorp: Southern Sweden,

Test site	Date	θ [°]	κ_Z [rad/m]	HoA [m]	Polari-sation	Mode
Krycklan	**2011/02/27**	**39°**	**0.14**	**45**	**HH**	**DEM,ascending, stripmap**
Krycklan	**2012/07/28**	**40°**	**0.17**	**38**	**HH**	**DEM,ascending, stripmap**
Krycklan	2011/07/20	40°	0.12	54	VV	Exp, ascending, stripmap
Krycklan	2012/08/19	41°	0.16	39	VV	Exp, ascending, stripmap
Remningstorp	**2011/12/30**	**39°**	**0.10**	**63**	**HH**	**DEM,ascending, stripmap**
Remningstorp	**2012/06/23**	**40°**	**0.19**	**33**	**HH**	**DEM,ascending, stripmap**

– 2 standard DEM bistatic:
- Winter and summer

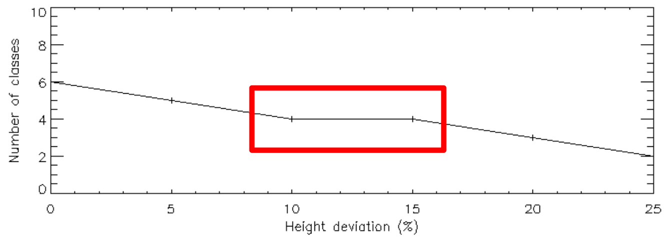




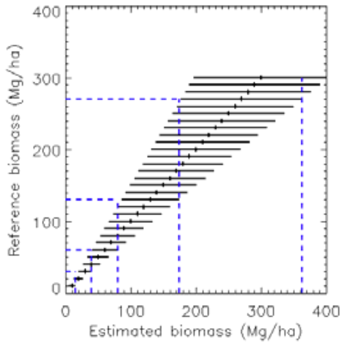
Accuracy Requirements (Performance Analysis)

Coherence → Height → Biomass

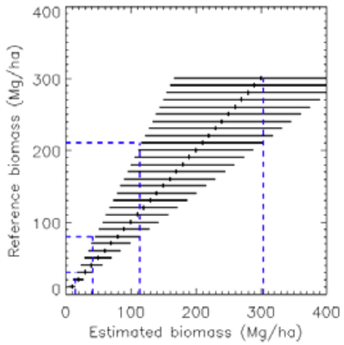
Relative error



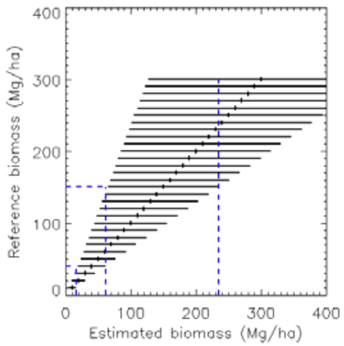
5%



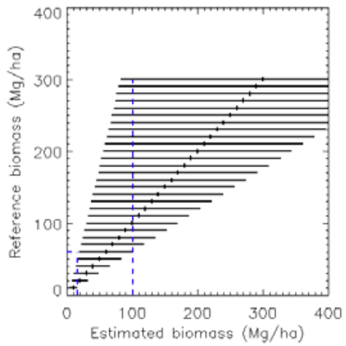
10%

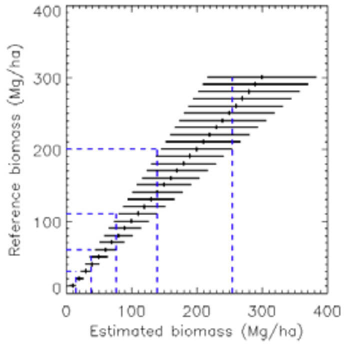


15%



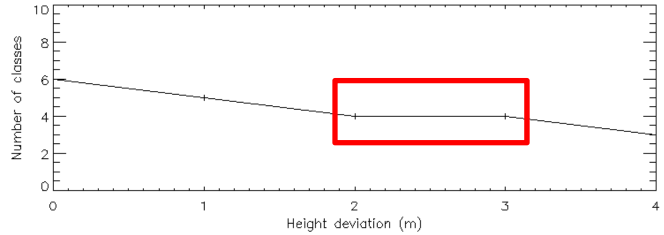
20%



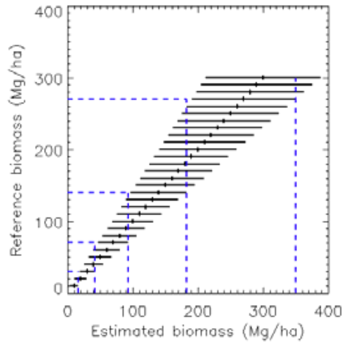


Number of classes for a 90% confidence interval

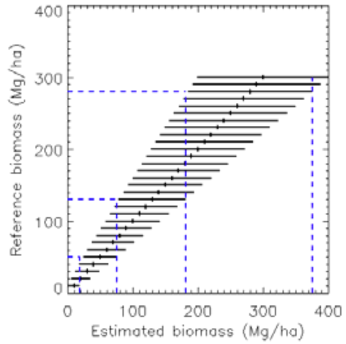
Absolute error



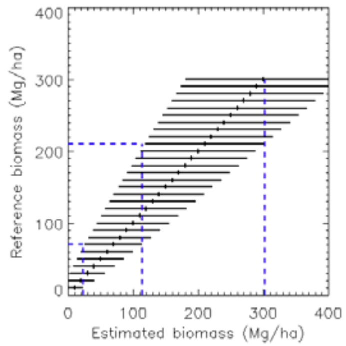
1m



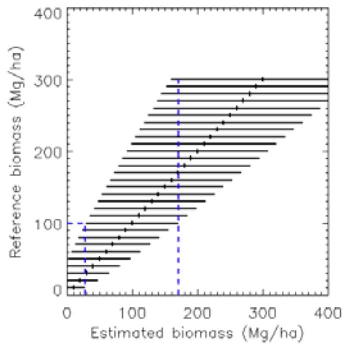
2m



3m

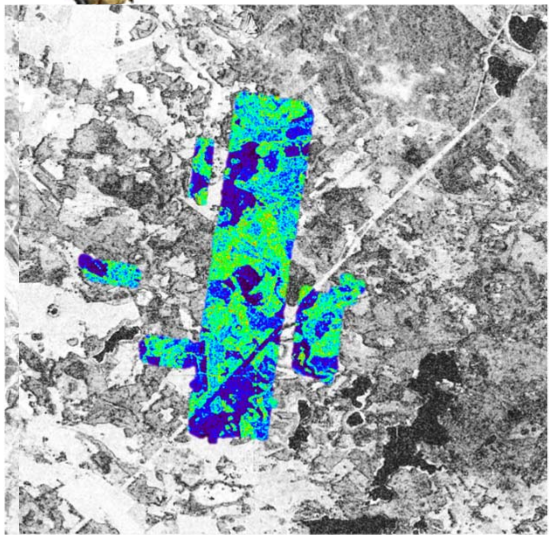


4m



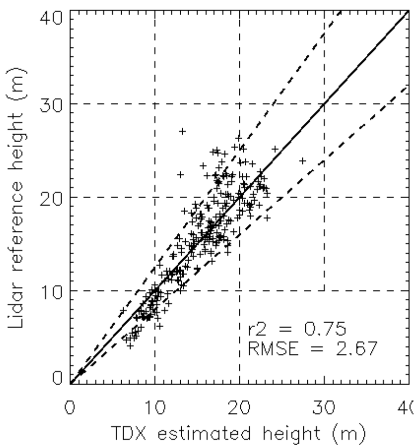
Summer acquisitions: DEM and experimental data

Acquisition	σ = 0.00	σ = 0.05	σ = 0.10	σ = 0.15	σ = 0.20	σ = 0.30
Krycklan 2012/07/28	2.70	2.76	2.67	2.73	2.86	3.69
Krycklan 2011/07/20	3.22	2.76	3.15	3.48	3.87	5.15
Krycklan 2012/08/19	2.78	2.80	2.78	2.97	3.27	4.48
Remningstorp 2012/06/23	4.03	4.00	3.99	3.79	3.70	3.92
Remningstorp 2011/08/20	3.23	3.21	3.16	3.16	3.12	3.66
Remningstorp 2012/08/28	3.57	3.53	3.59	3.52	3.62	4.54

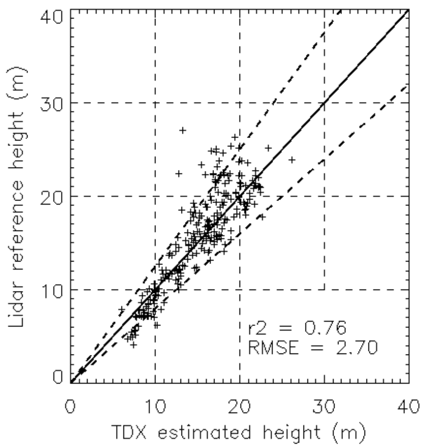


Krycklan 28-07-2012

0.1 dB/m

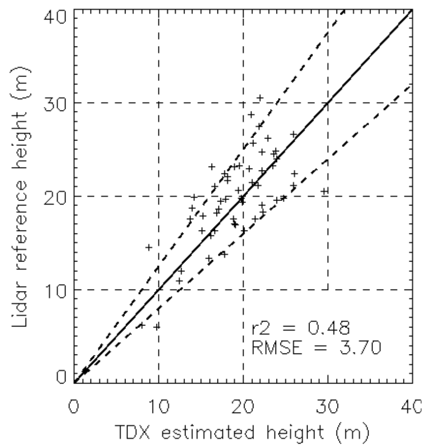


0 dB/m

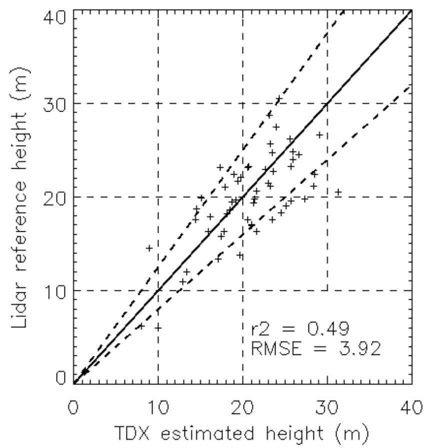


Remningstorp 23-06-2012

0.2 dB/m



0.3 dB/m

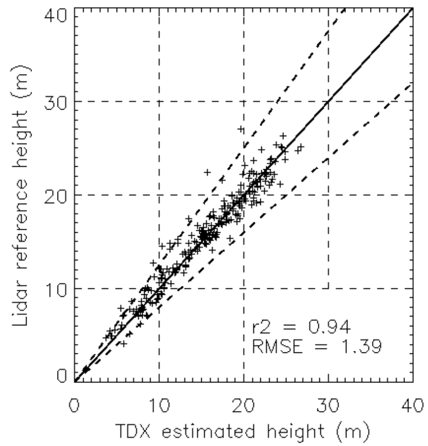


Winter acquisitions: DEM and experimental data

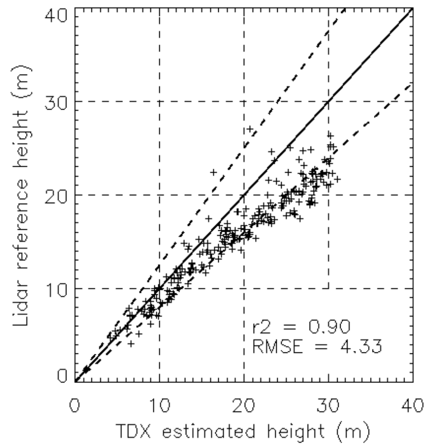
Krycklan

	m= 0.00	m= 0.10	m= 0.25	m= 0.50	m= 1.00	m= 2.00
RMSE for σ = 0.00	2.93	1.91	1.49	1.49	2.44	5.65
RMSE for σ = 0.10	3.13	1.78	1.39	1.46	1.72	4.33
RMSE for σ = 0.20	4.53	2.01	1.42	1.65	1.71	3.63

$\sigma = 0.1$, m=0.25



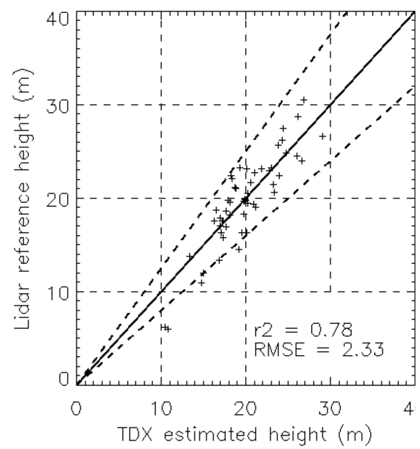
$\sigma = 0.1$ m=2



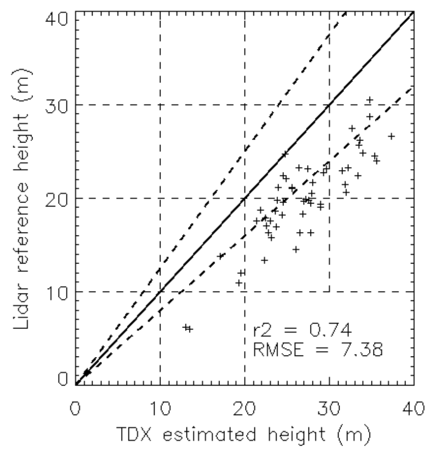
Remningstorp

	m= 0.00	m= 0.10	m= 0.25	m= 0.50	m= 1.00	m= 2.00
RMSE for σ = 0.00	5.63	4.19	3.35	3.13	3.94	7.20
RMSE for σ = 0.10	5.65	3.93	2.86	2.58	2.85	5.19
RMSE for σ = 0.20	7.38	4.10	2.67	2.33	2.50	3.84

$\sigma = 0.2$ m=0.5



$\sigma = 0.2$, m=0



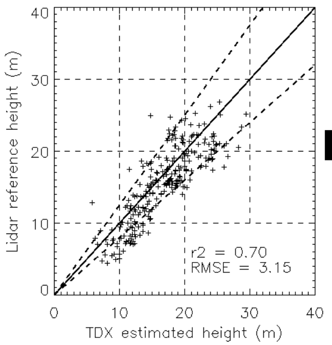
Dual Baseline results: Winter/summer DEM and summer experimental acq.

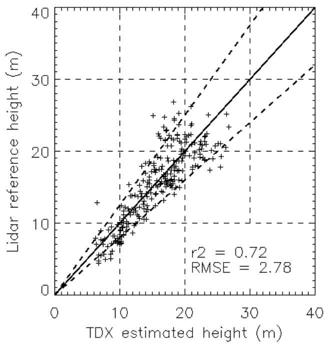
Summer/Summer

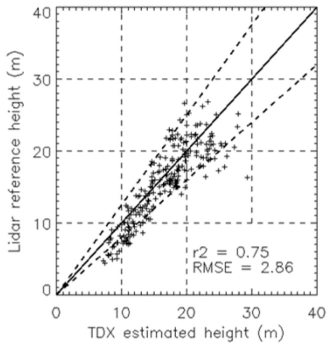
Krycklan

Master

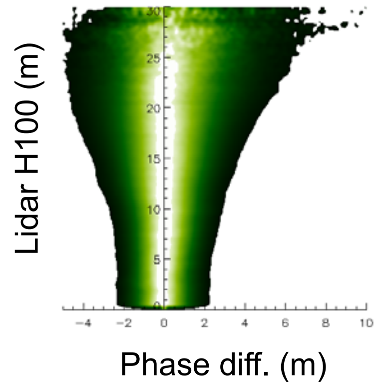
Slave



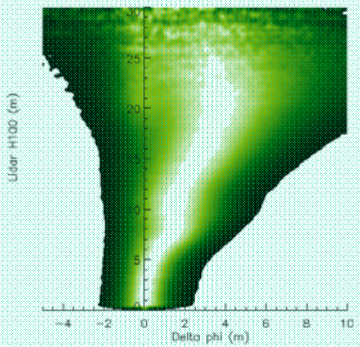


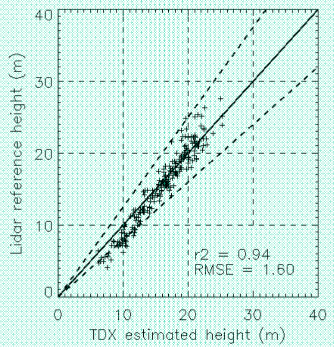


The phase doesn't change



Winter/Summer



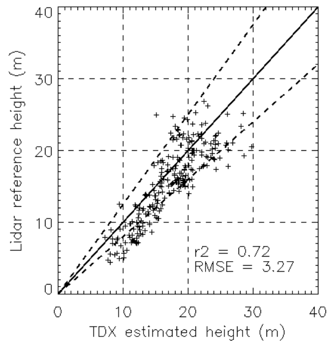


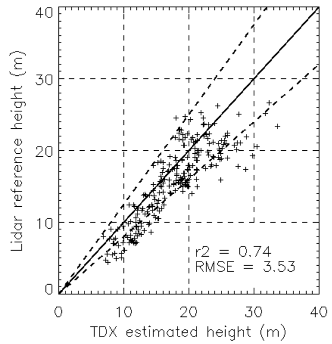
Phase difference related to ground to volume changes

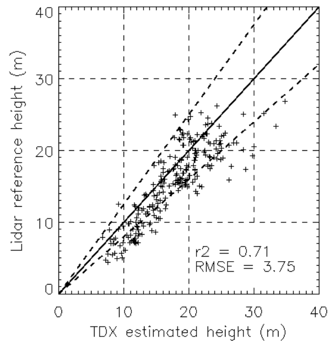
Equal Sigma

Varying Sigma

Delta phi Sigma



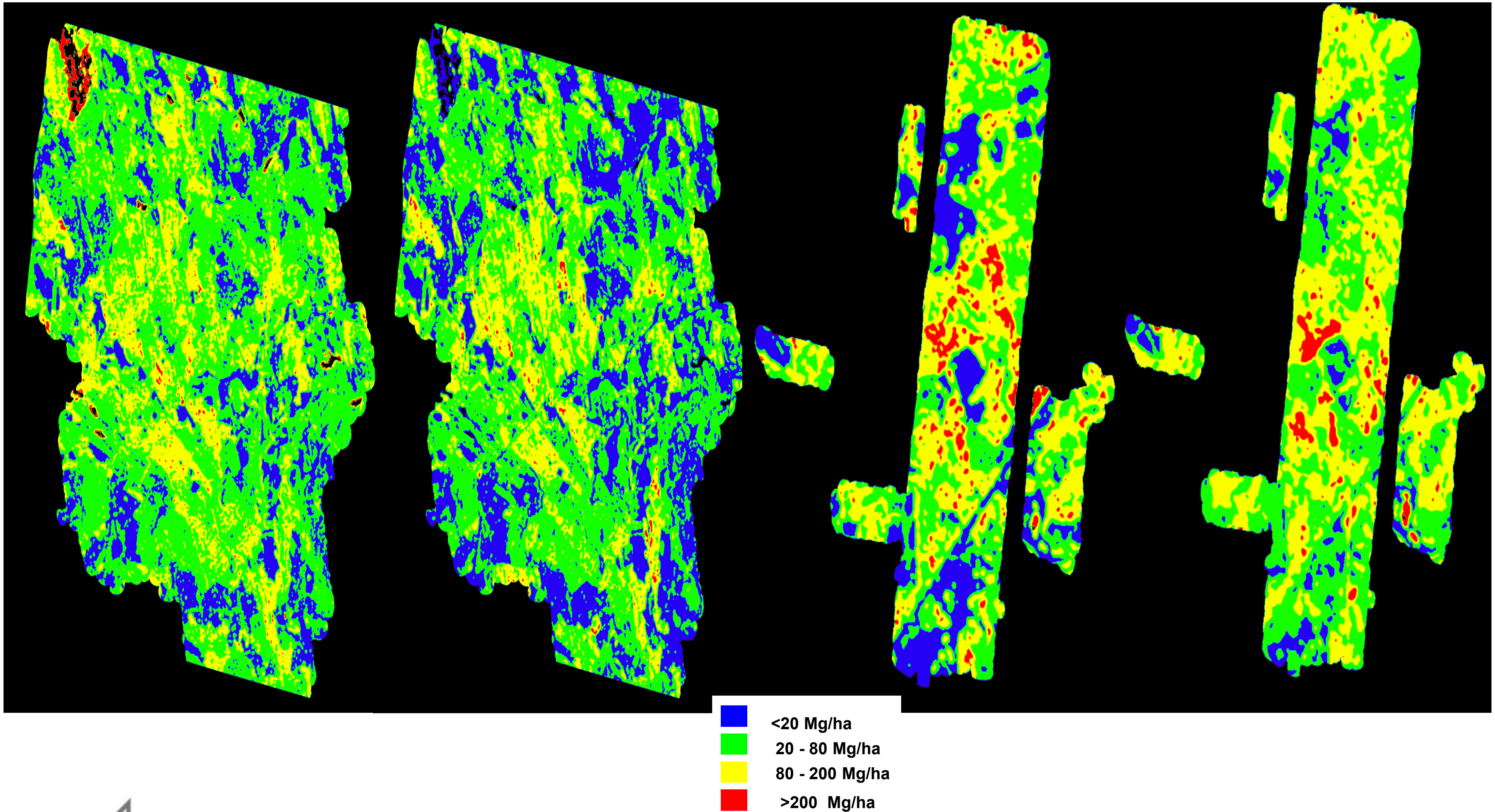




Biomass classification results single baseline

Krycklan | Remningstorp

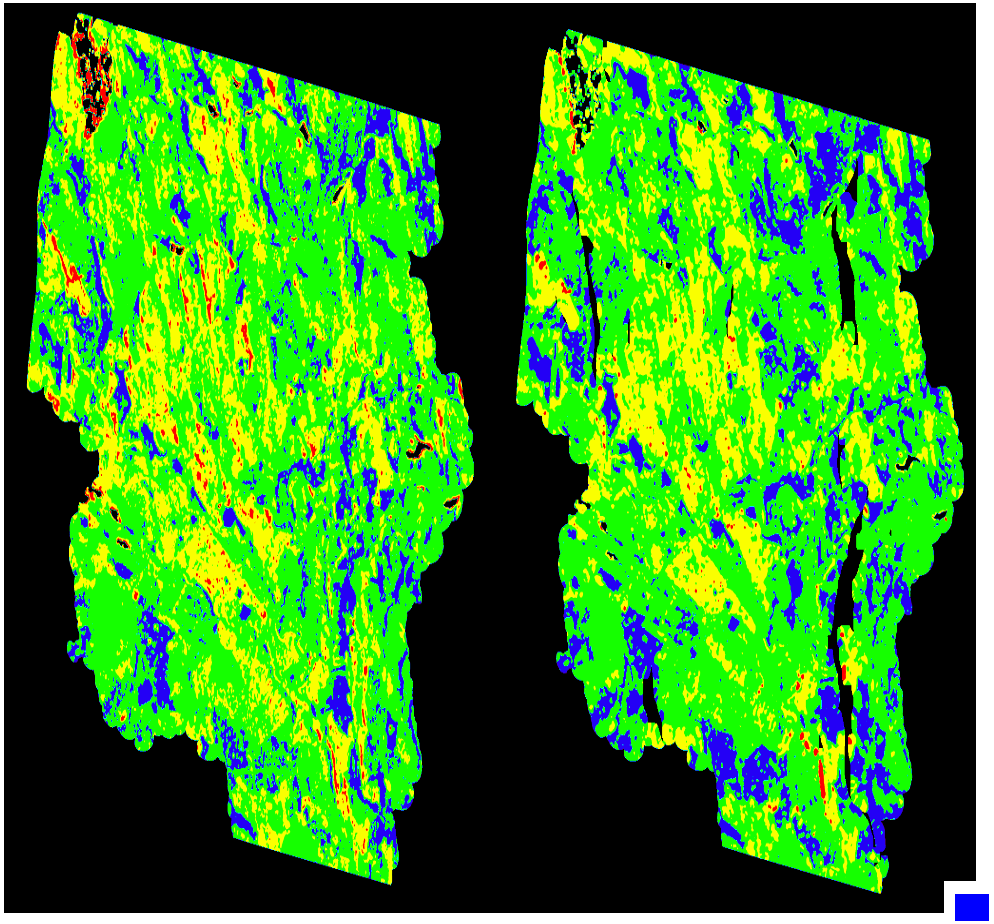
Summer | Winter | Summer | Winter

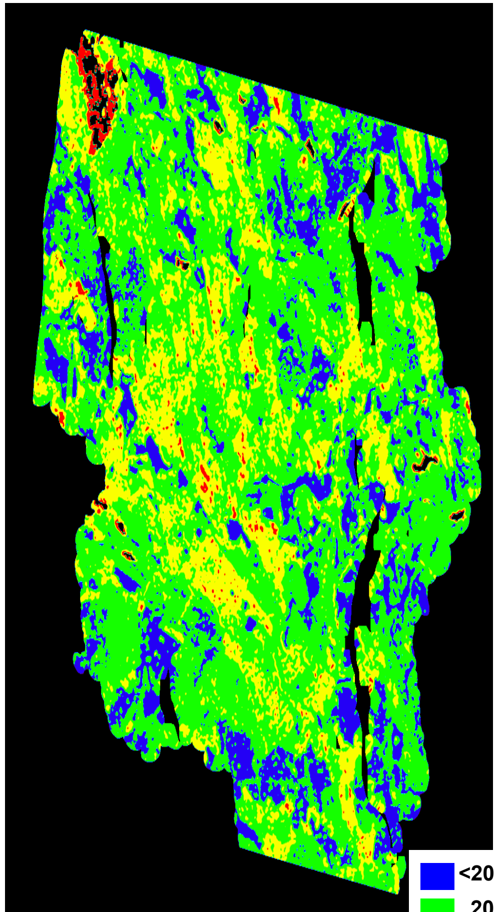


Biomass classification results: dual baseline

Krycklan

Summer/Summer Winter/Summer Winter/Summer – 5 classes



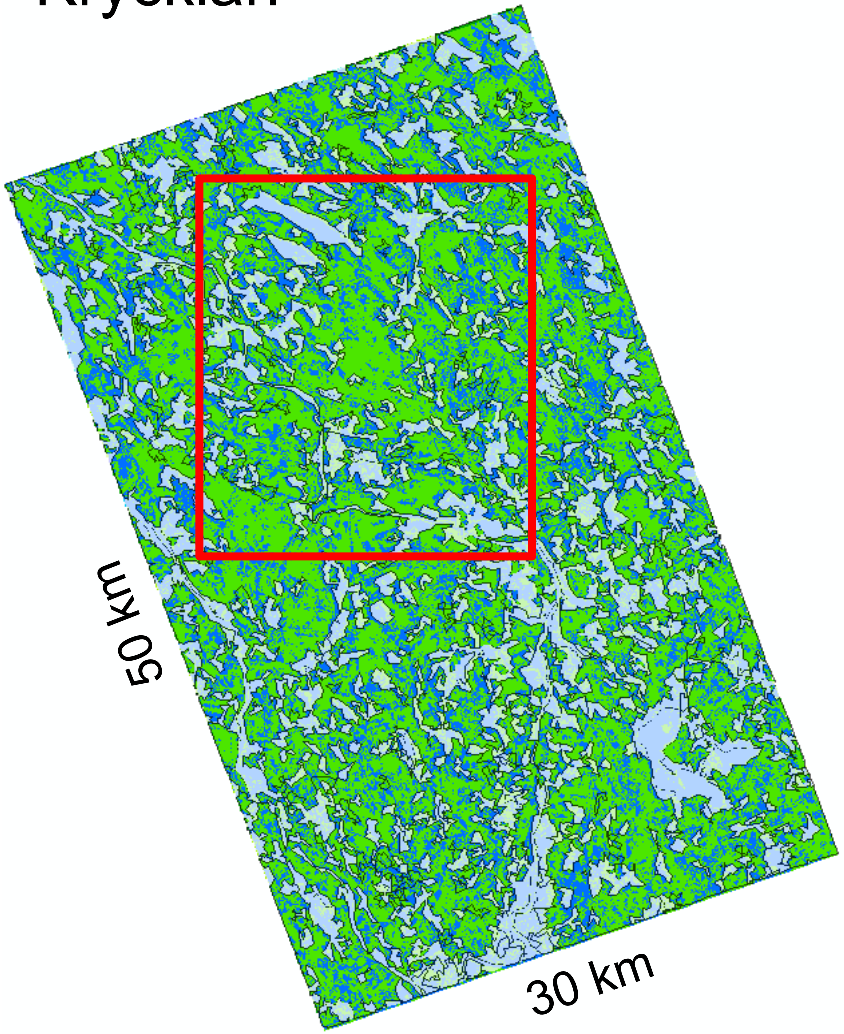


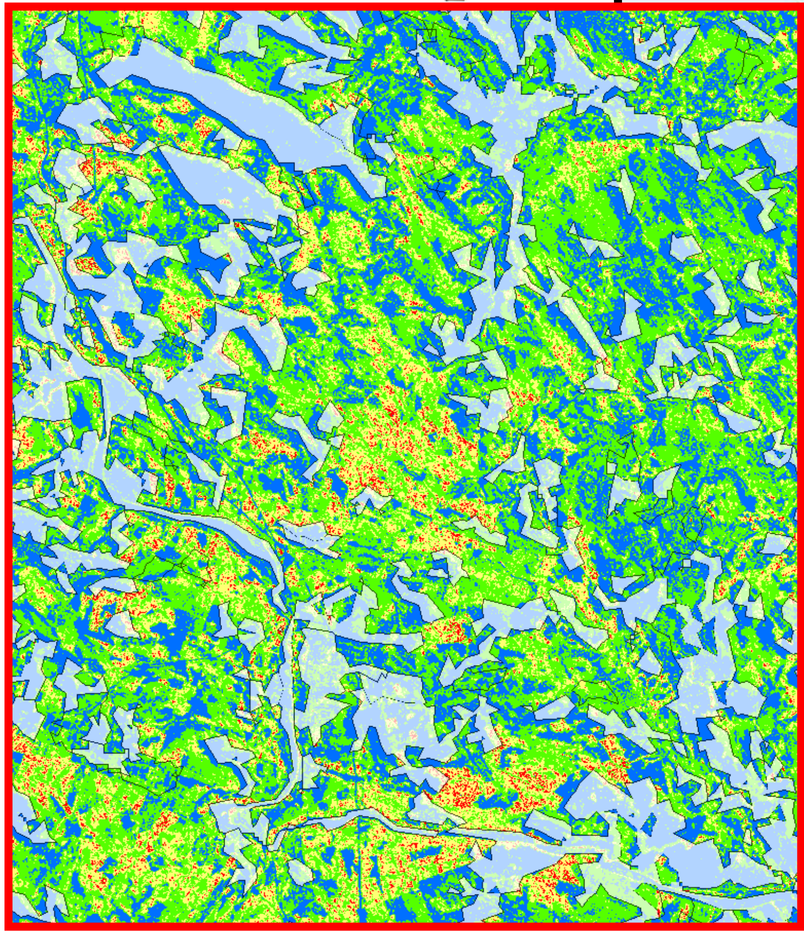
- <20 Mg/ha
- 20 - 80 Mg/ha
- 80 - 200 Mg/ha
- >200 Mg/ha

- <20 Mg/ha
- 20 - 80Mg/ha
- 80 - 160 Mg/ha
- 160 - 250 Mg/ha
- >250 Mg/ha

CORINE Classification Evaluation

Krycklan





- <10 Mg/ha
- 10 - 50 Mg/ha
- 50 - 150 Mg/ha
- >150 Mg/ha

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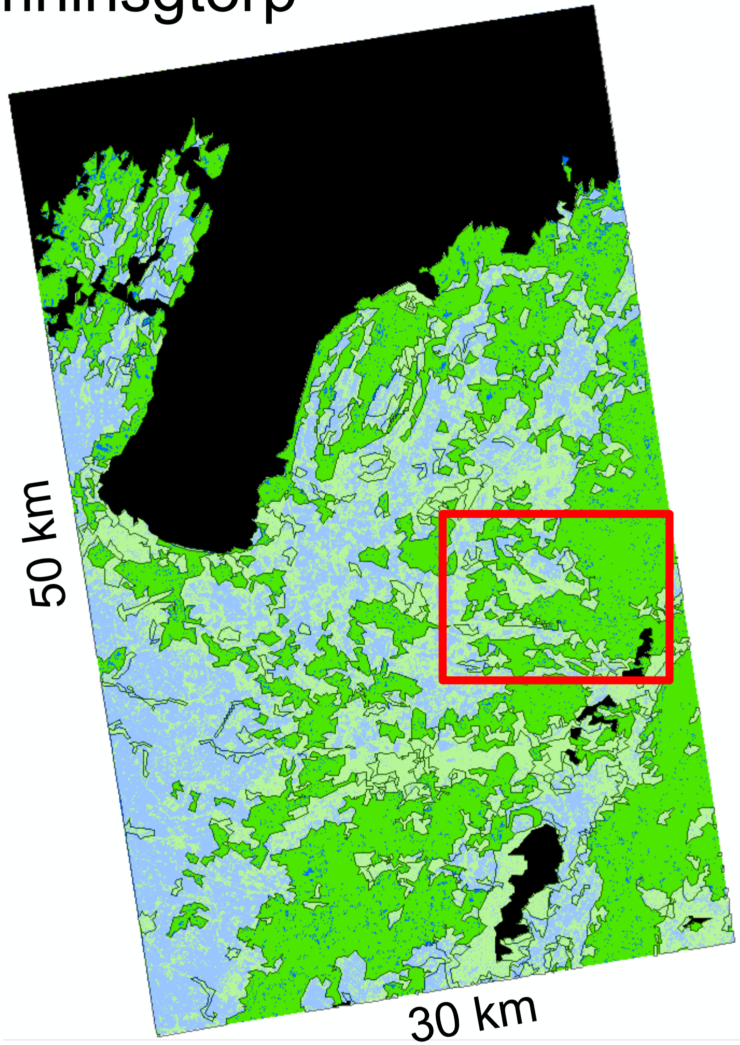
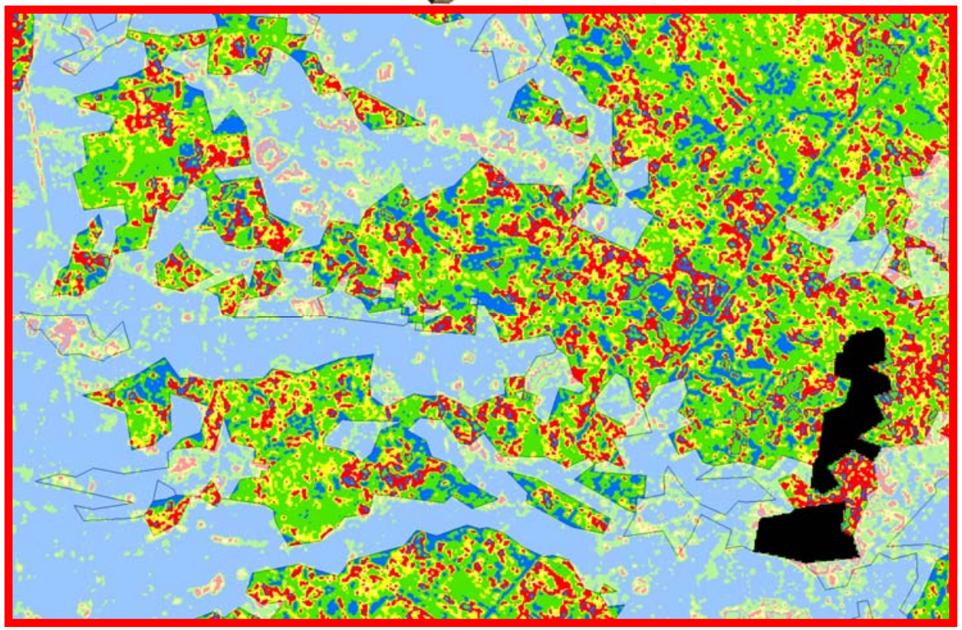
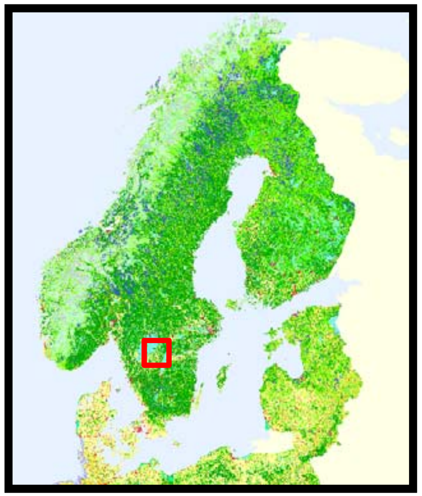
CORINE Classification Evaluation

Remninsgtorp

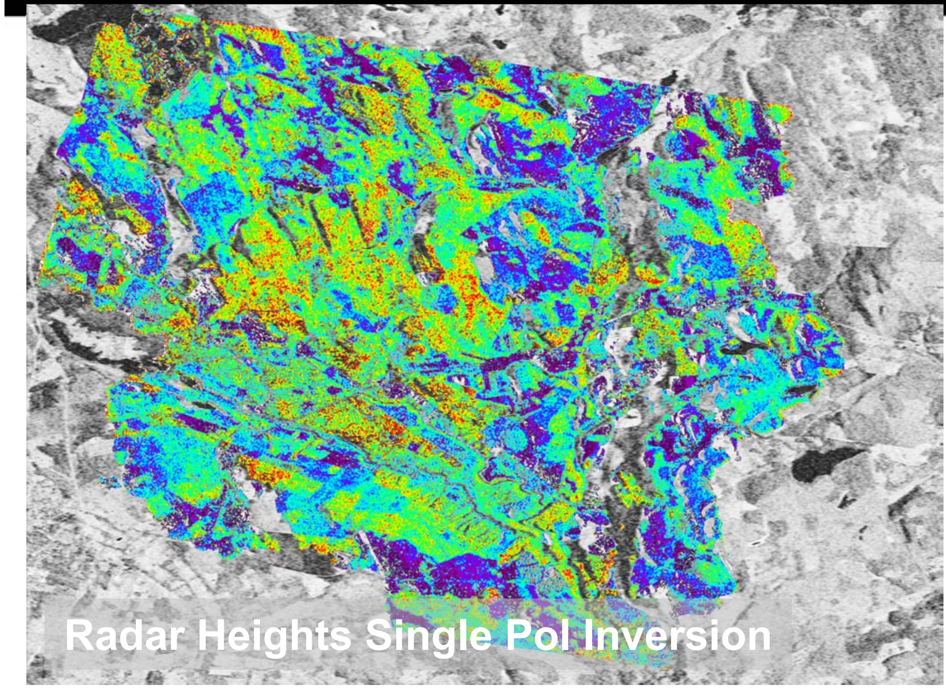


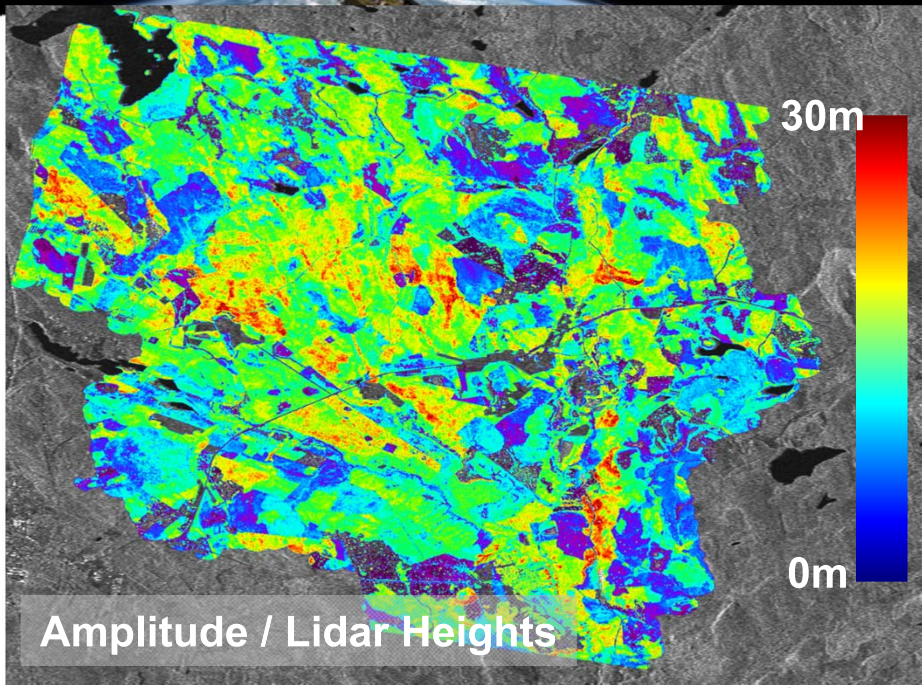




- <10 Mg/ha
- 10 - 50 Mg/ha
- 50 - 150 Mg/ha
- >150 Mg/ha

Height inversion improvements: DMT and polarizations

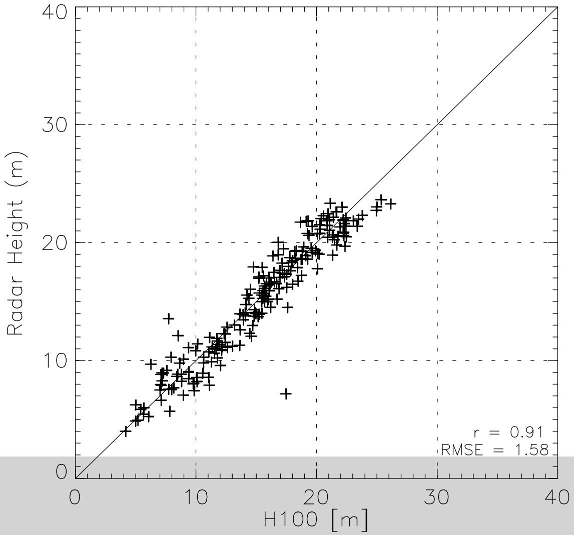




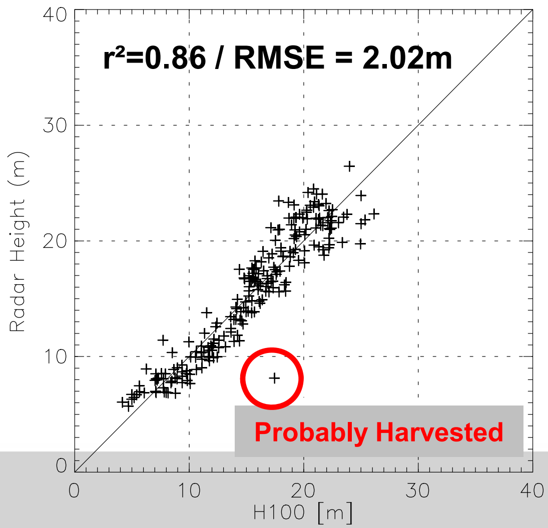
Slide 15

The use of the ground phase information reduces the height error

1 Pol + DTM



2 Pol



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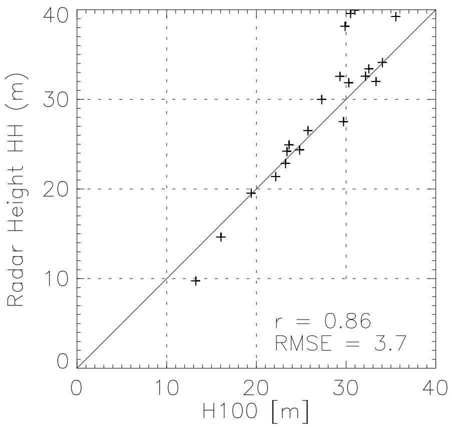
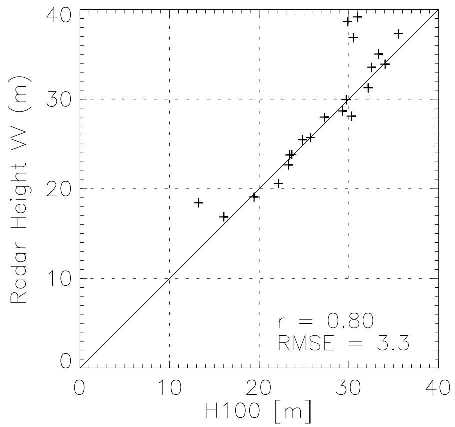
Conclusions

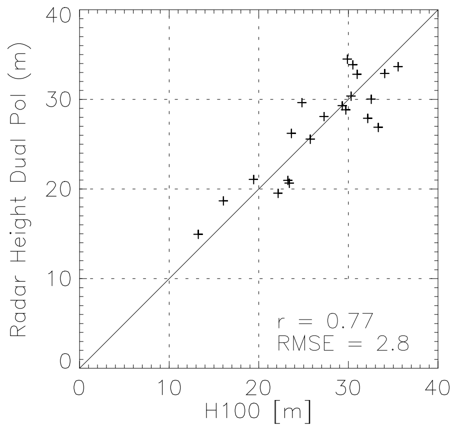
- The TDX standard acquisition mode has a high potential for forest biomass classification in the boreal region
- Model based height estimations allow to compensate environmental, weather, seasonal and geometrical variations.
- Single baseline, single pol acquisitions do no allow to explore all the degrees of freedom provided by the model in the absence of a DTM
  - Winter acquisitions show a better height estimation with a correct ground to volume ratio assumption
  - Four biomass classes can be distinguished until 200 Mg/ha for a single baseline case
  - Five biomass classes can be distinguished if the height error is lower than 10%
- Two baselines allow the estimation of an extra parameter when there is a sufficient phase difference (winter-summer case)
- Performance increases with the availability of DTMs or a second polarizations
- The obtained classification maps can improve thematic mapping in forested areas as provided by the European Thematic Map CORINE

Mawas Single Baseline Temporal Evolution

Traunstein Dual pol (09/01/2012)

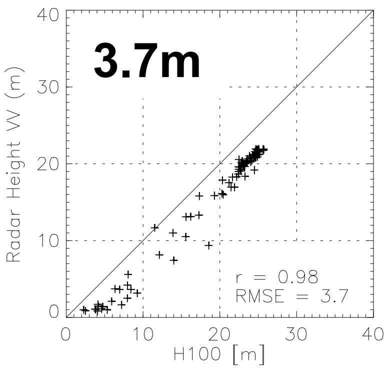




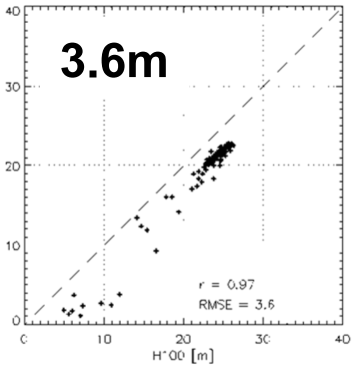


Mawas Rain Season

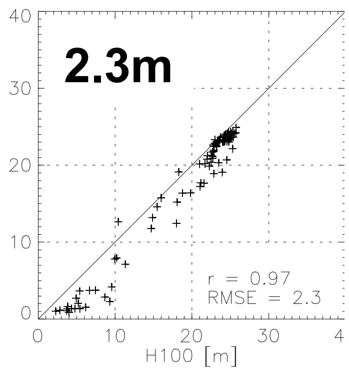
25.August 2011



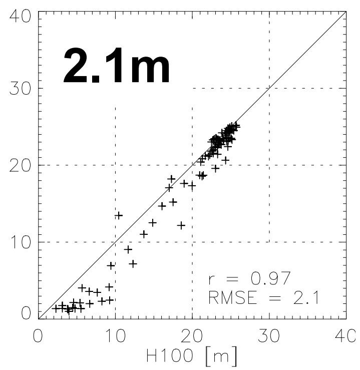
4. September 2011



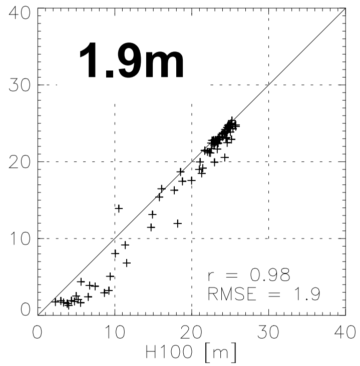
13. December 2011



24.December 2011

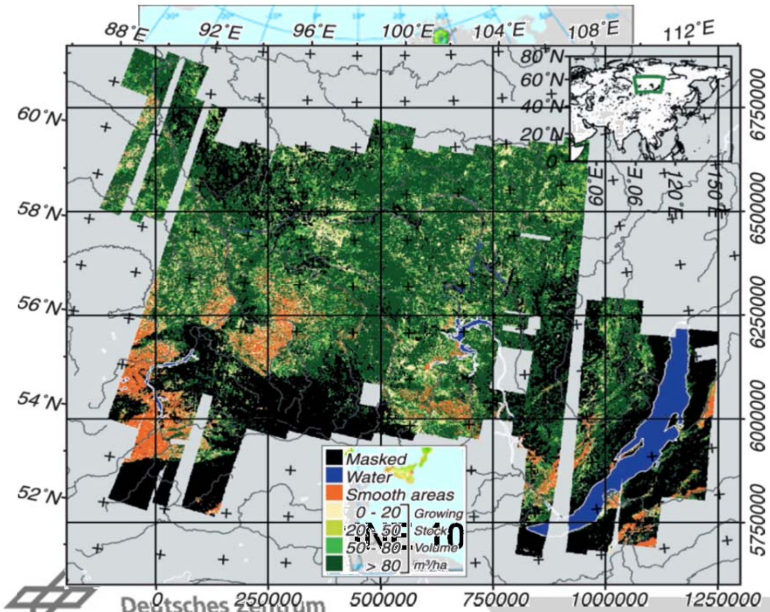


4. January 2012



Boreal Forest Biomass

- Boreal forests contain 1/3 world biomass.
- Biomass stock is well known, however there is a lack of periodic information.
- Rate of biomass change (e.g. fire) is critical for carbon cycles assessment. Very high percentage of carbon is stored in the soil and is highly affected by land cover changes.
- Periodic and systematic land cover classifications, as well as, biomass estimations are highly needed.



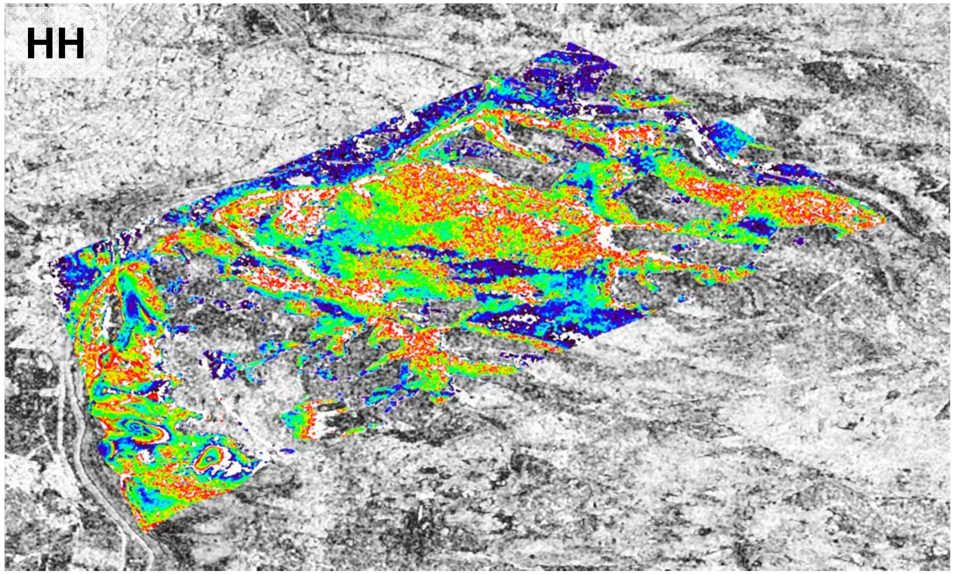
Existing classifications:

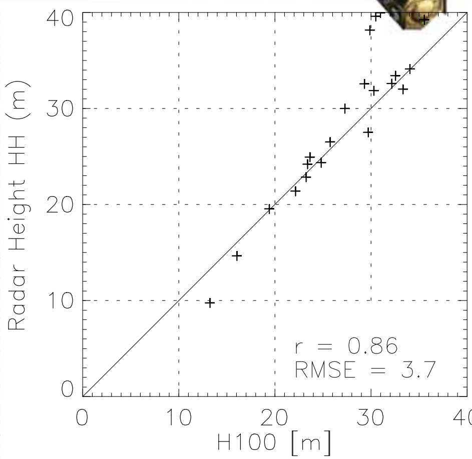
- Mainly based on optical systems
- Generally not updated.
- Qualitative classifications

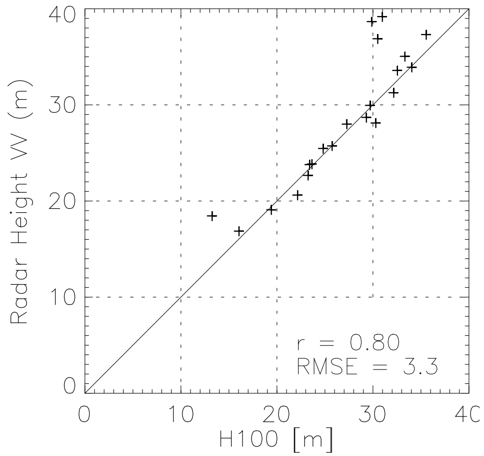
CORINE: Europe 100x100 m
SIBERIA Project:

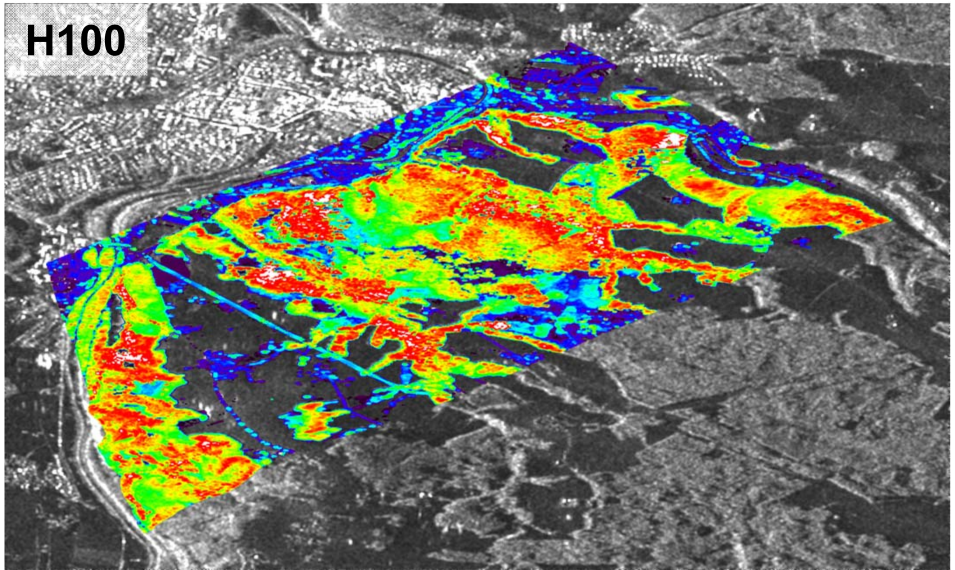
- Coherence and backscattering
- From ERS and JERS 900000 km2 in 50x50m
- Classes: Bare soil, sparse shrub, forest (1-20, 21-50, 51-80, >80 T/ha)

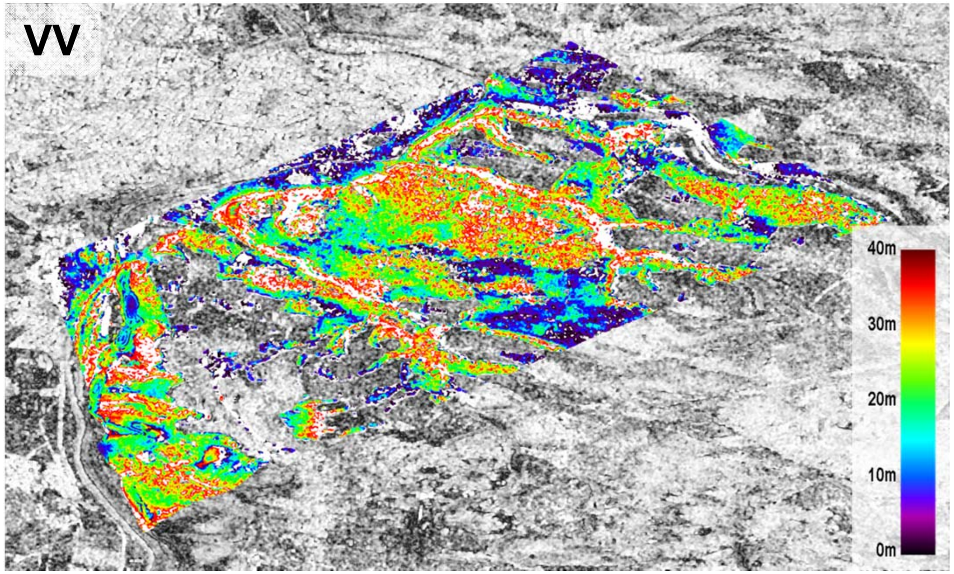
Traunstein 09.01.2012 Single Pol Forest Height



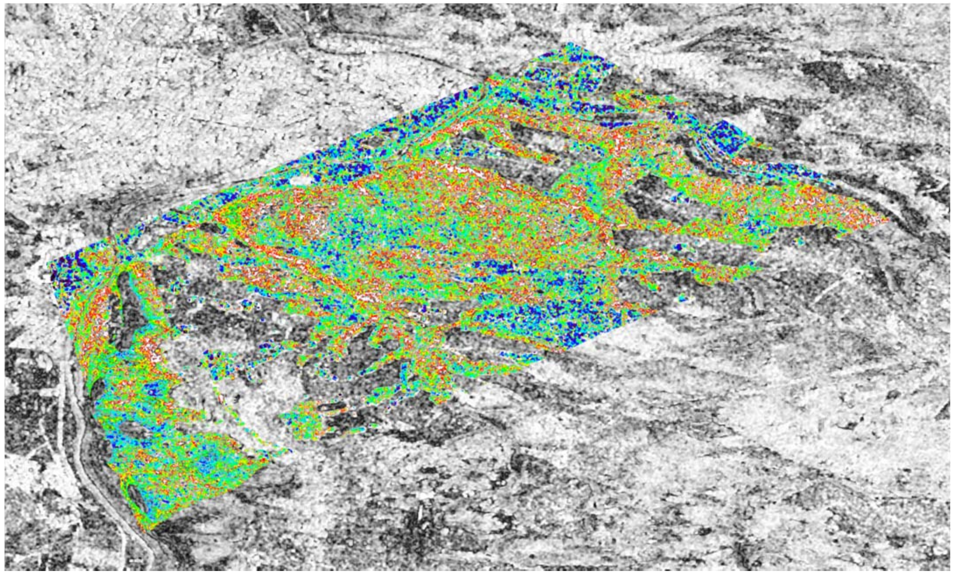


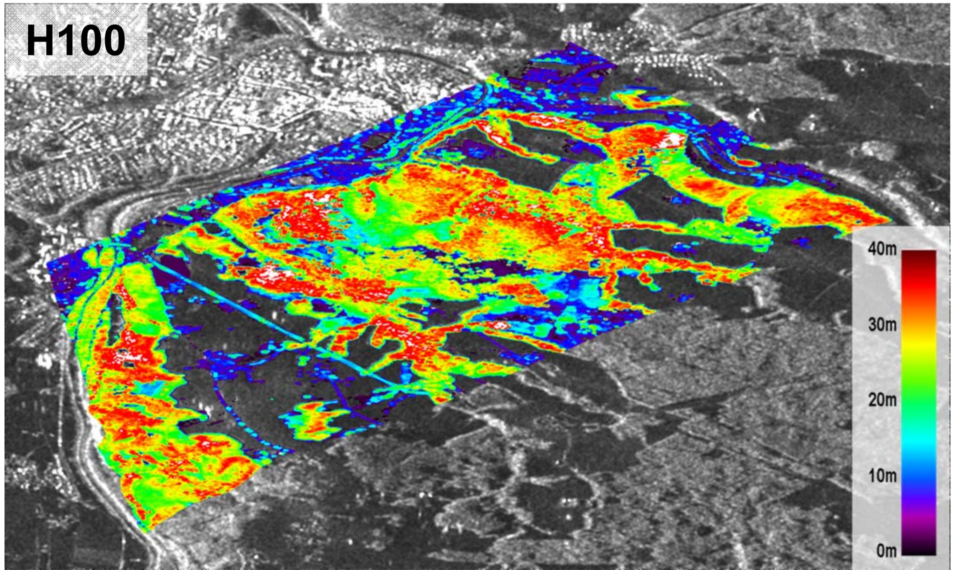


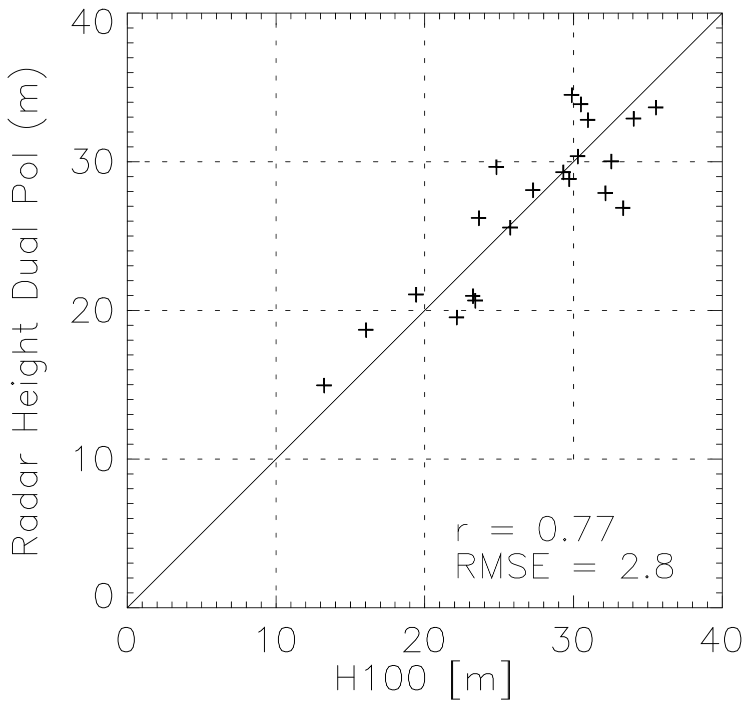




Traunstein 09.01.2012 Dual Pol Forest Height







20% - 25 % of the points can not be inverted.
These points are not within the solution space of the model
The Coherence region is to small due to the decreasing ground spectrum visible with increasing forest height

Coherence Modeling

$$\tilde{\gamma} = \tilde{\gamma}_{vol} \cdot \tilde{\gamma}_{temp} \cdot \gamma_{SNR}$$

Noise Correction

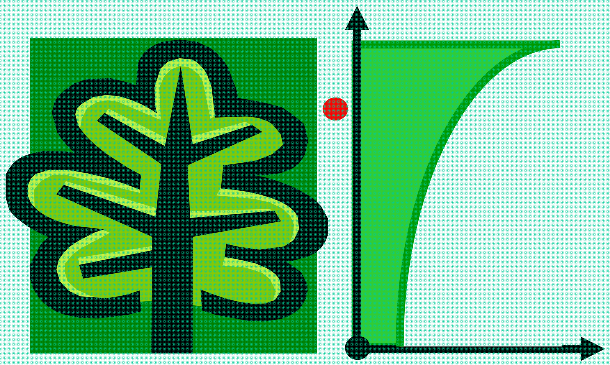
$$P_{Master/Slave} = Signal\ Power\ of\ Master/Slave$$

$$\gamma_{SNR}^{HH/VV} = \frac{1}{\sqrt{[1+(SNR_{Master}^{HH/VV})^{-1}][(SNR_{Slave}^{HH/VV})^{-1}]}}$$

$$SNR_{Master/Slave}^{HH/VV} = \frac{P_{Master/Slave}^{HH/VV} - NESZ_{Master/Slave}^{HH/VV}}{NESZ_{Master/Slave}^{HH/VV}} \quad \gamma_{vol}$$

$$\tilde{\gamma}_{vol} = \tilde{\gamma} / \gamma_{SNR}$$

Random Volume over Ground (RVoG)



$$\tilde{\gamma}_{vol}(HH) = \exp(ik_z z_0)\tilde{\gamma}_V$$

$$\tilde{\gamma}_V = \exp(i\phi_0)\frac{\int_0^{h_V} e^{\frac{2\sigma z'}{\cos(\theta_0)}} e^{ik_z z'} dz'}{\int_0^{h_V} e^{\frac{2\sigma z'}{\cos(\theta_0)}} dz'}$$

Unknowns: Volume coherence(γ_{vol}) , volume height(h_{vol}), volume shape factor (σ) and vertical wave number (k_z)

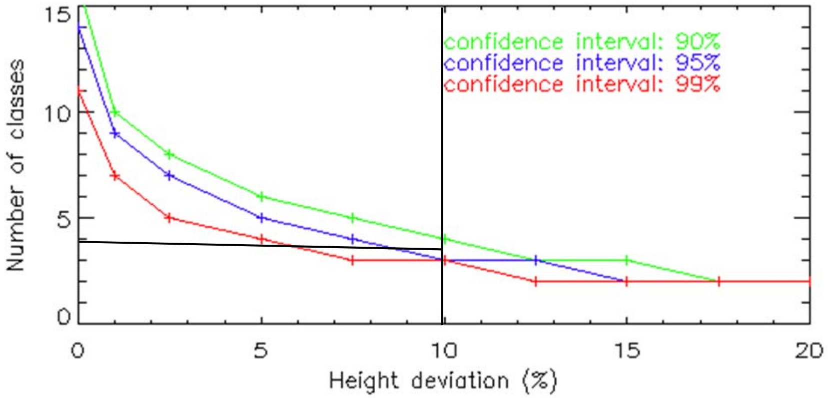
$$\min_{h_V} \left\| \, |\tilde{\gamma}| - |\tilde{\gamma}_{V_0}(h_V | \kappa_z, \sigma = const)| \, \right\|$$

Biomass Classification Performance

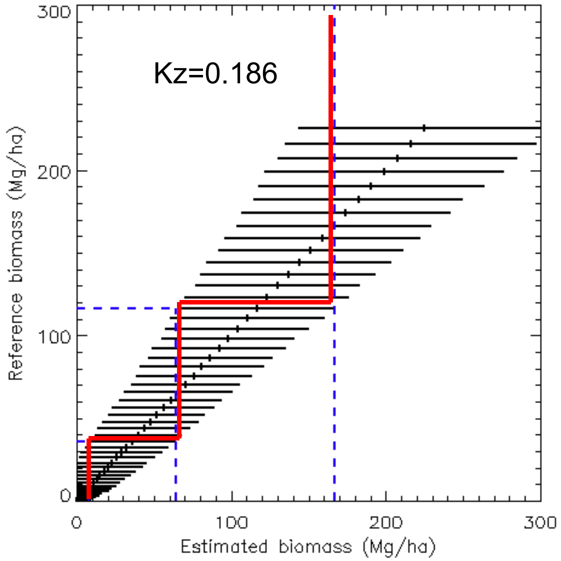
Coherence → Height → Biomass

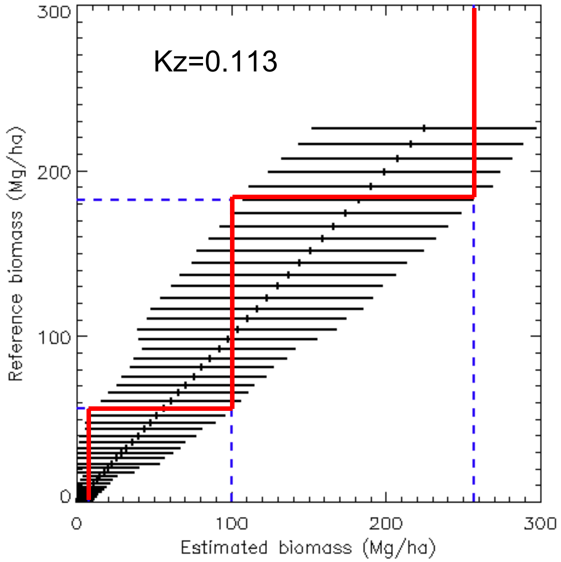
- Classification performance depends on two deviation sources:
  - Height estimation from coherence
  - Biomass estimation from Height

$$\Delta B_{tot} = \frac{\partial B}{\partial h_v}\Delta h_v + \Delta B \quad ; \quad B = 0.25 h_v^2 \quad ; \quad \Delta B_{tot} = 0.5 H \Delta h_v + \Delta B$$

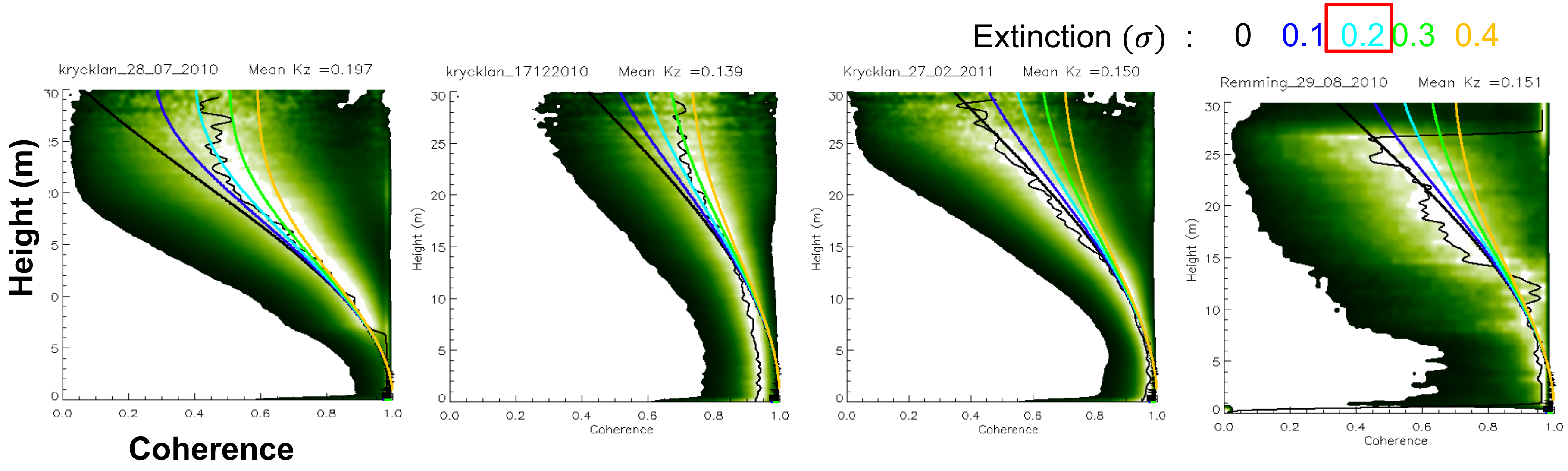


- Four biomass classes are chosen:
  - <10 Mg/ha
  - 10-50
  - 50-150
  - >150



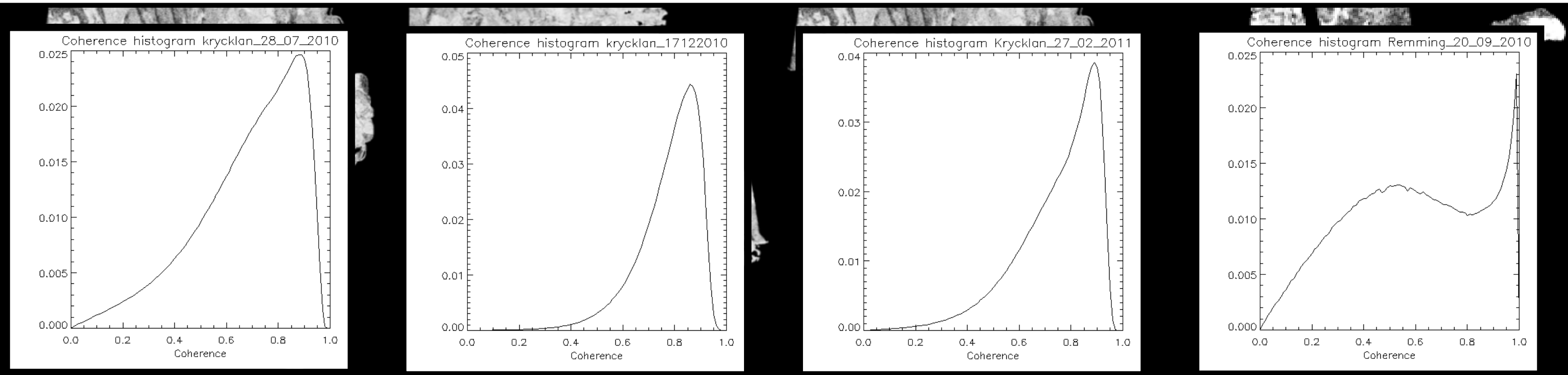


Test Sites and Data



– Optimum fixed extinction = 0.2 dB/m

– This Extinction value is lower than expected for X-band due to significant ground contribution.

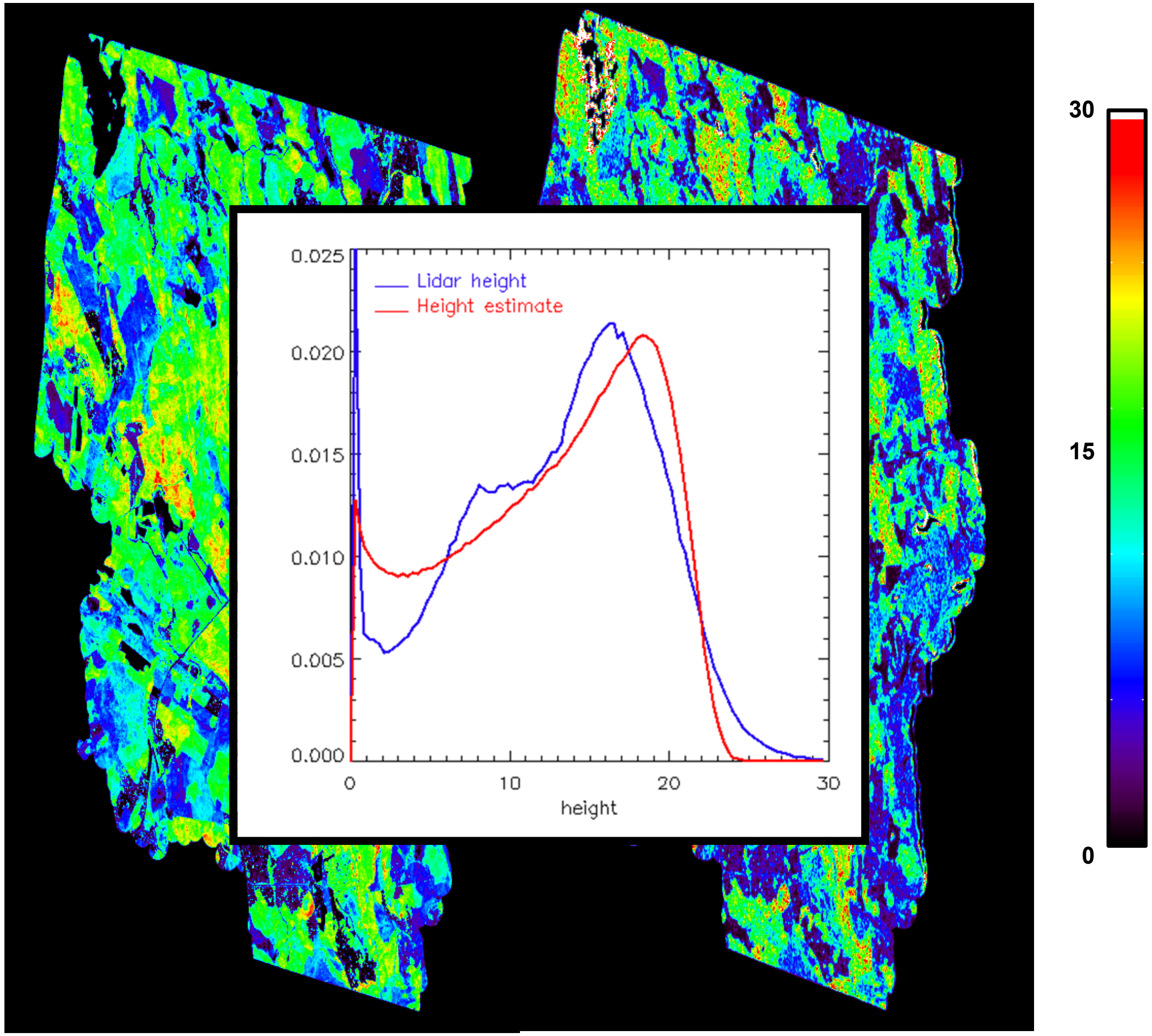


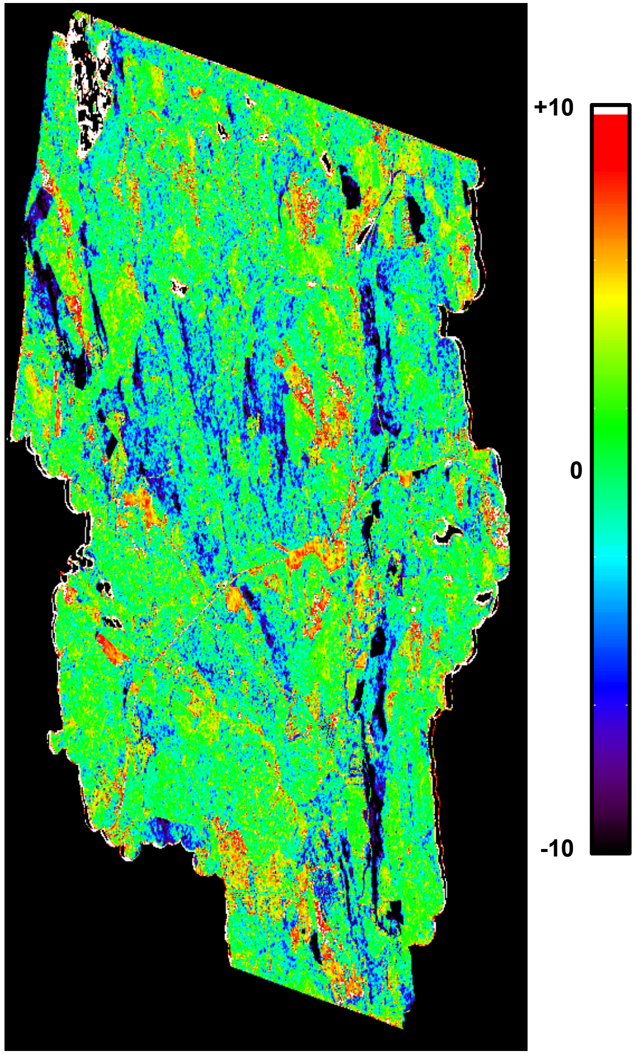
Height Inversion, Krycklan - 28-07-2010

Lidar Height

Estimated height

Difference (Estimate - LiDAR))





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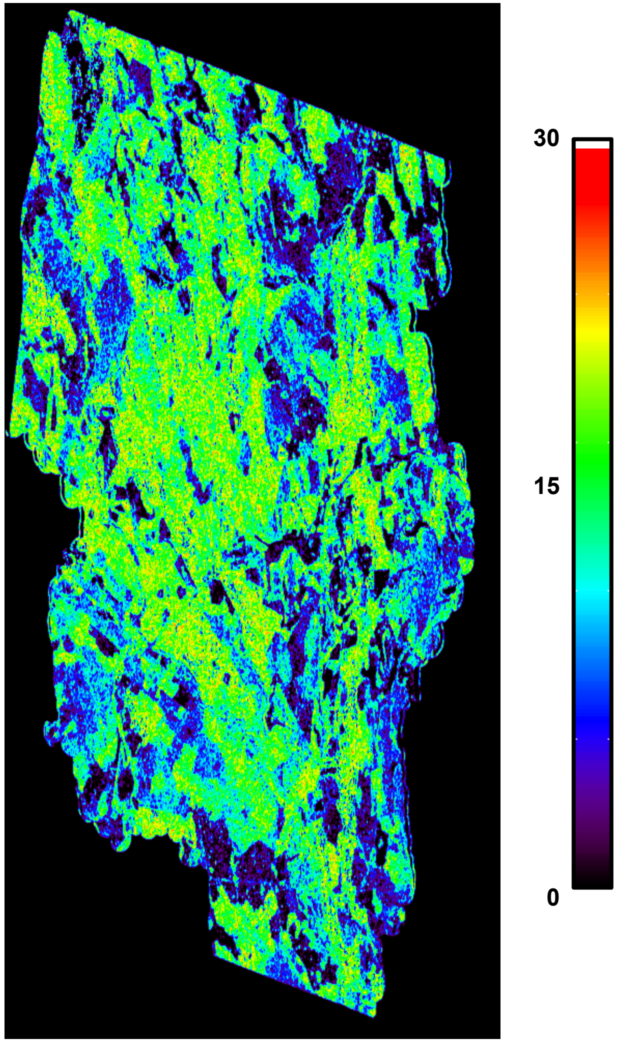
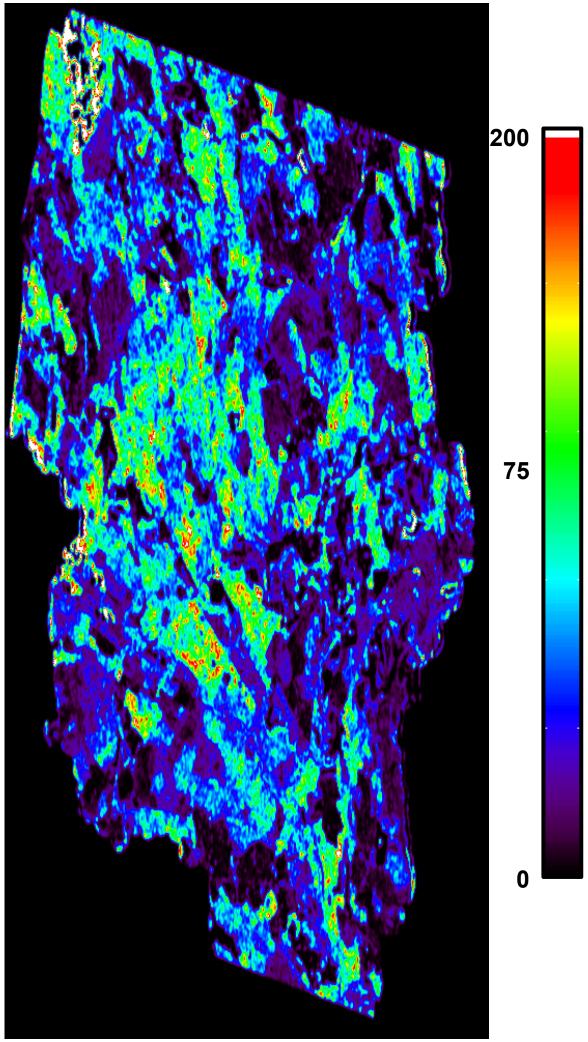
Biomass Classification, Krycklan - 28-07-2010

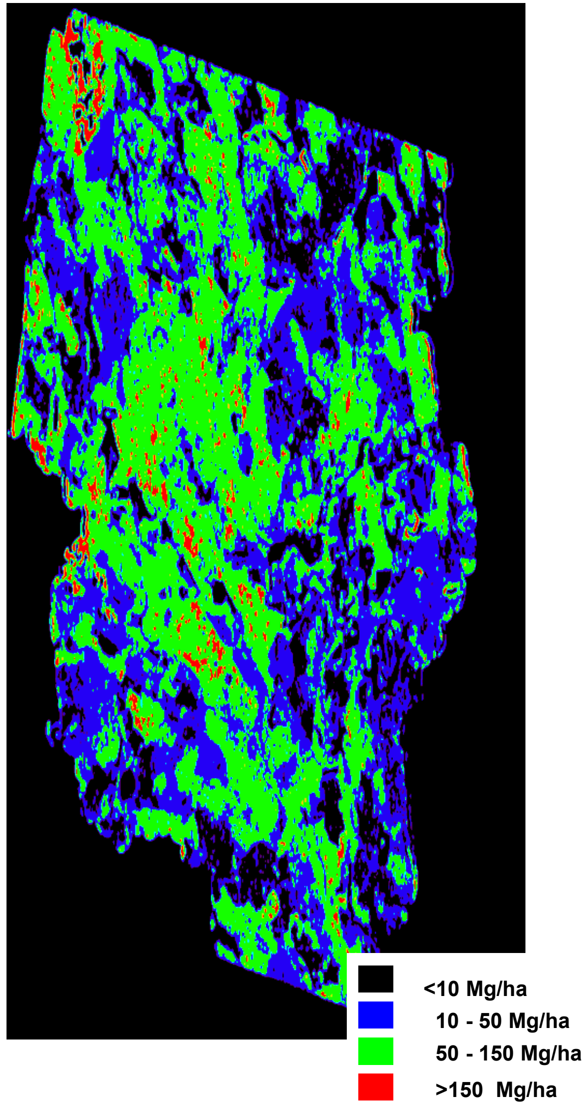
Height Inversion



Biomass estimation



Biomass classification



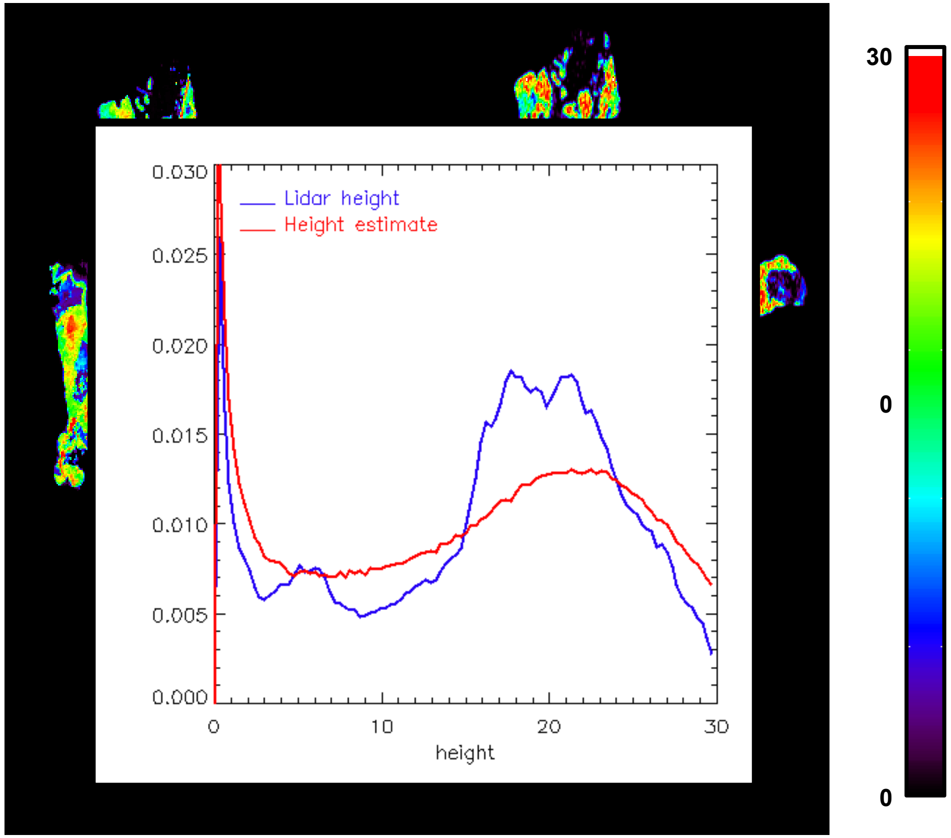
$$B = 0.25 h_v^{\ 2}$$

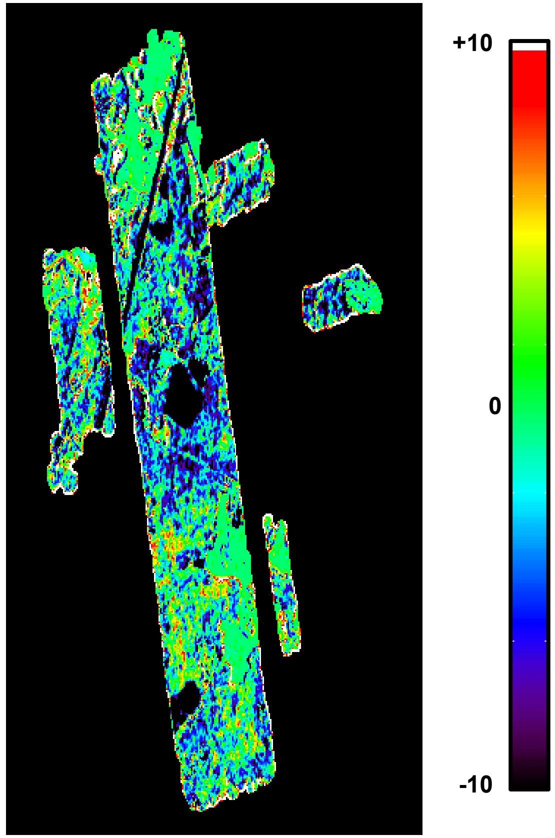
Height Inversion, Remningstorp 29-08-2010

Lidar Height

Estimated height

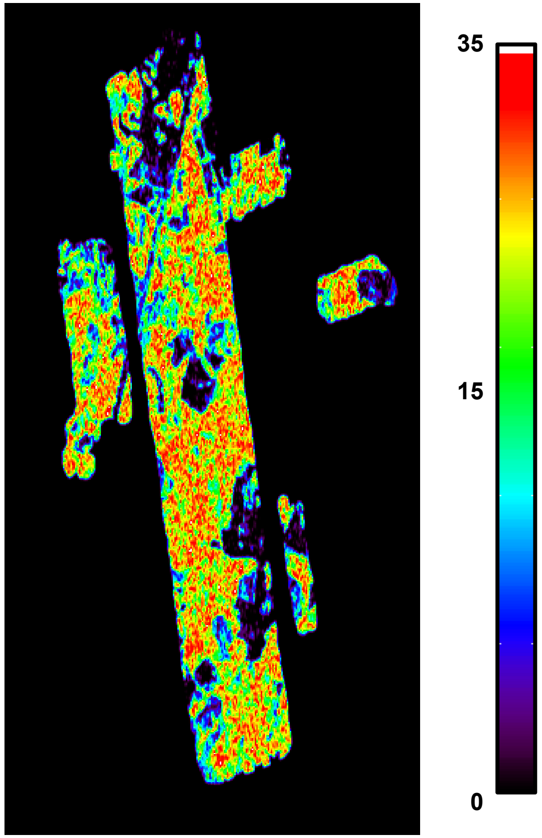
Difference (Estimate - LiDAR)



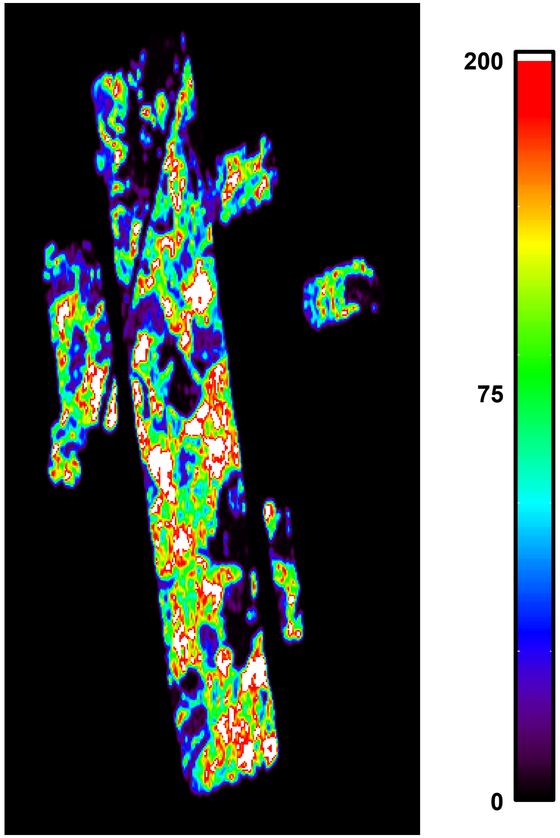


Biomass Classification , Remningstorp 29-08-2010

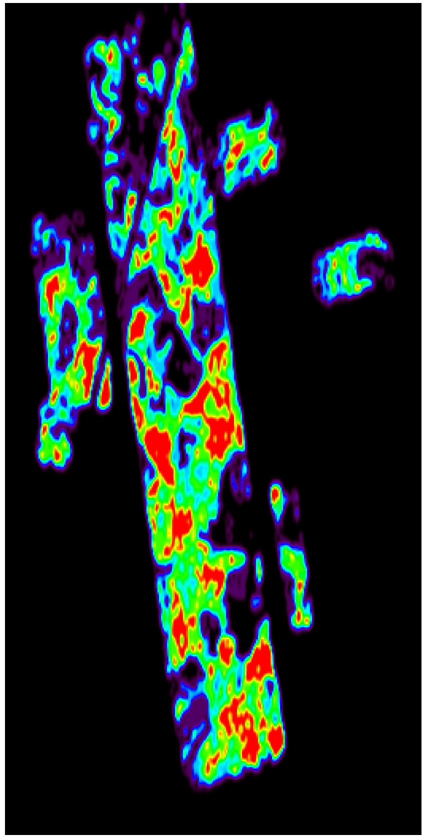
Height Inversion



Biomass estimation



Biomass classification

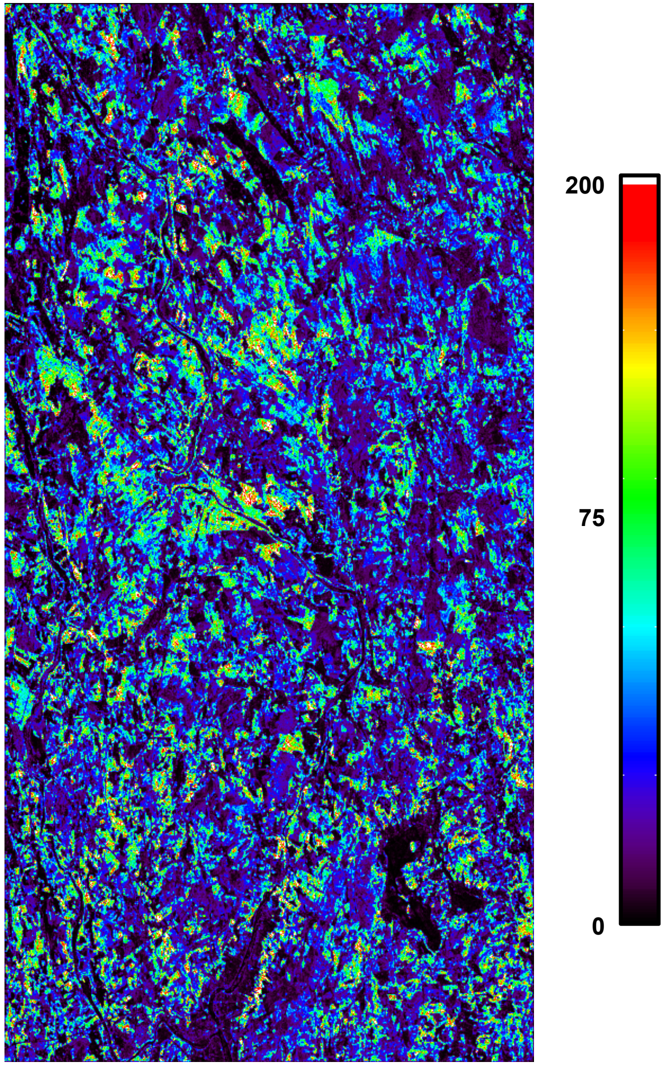


$$B = 0.25 h_v^{\ 2}$$

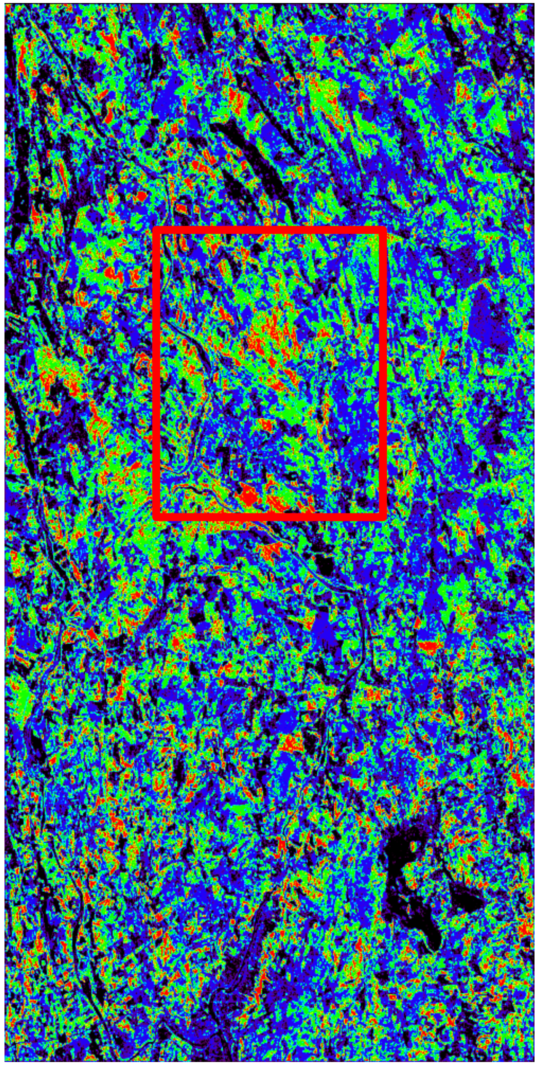
- <10 Mg/ha
- 10 - 50 Mg/ha
- 50 - 150 Mg/ha
- >150 Mg/ha

Standard DEM Acquisition Krycklan 27-02-2011

Biomass

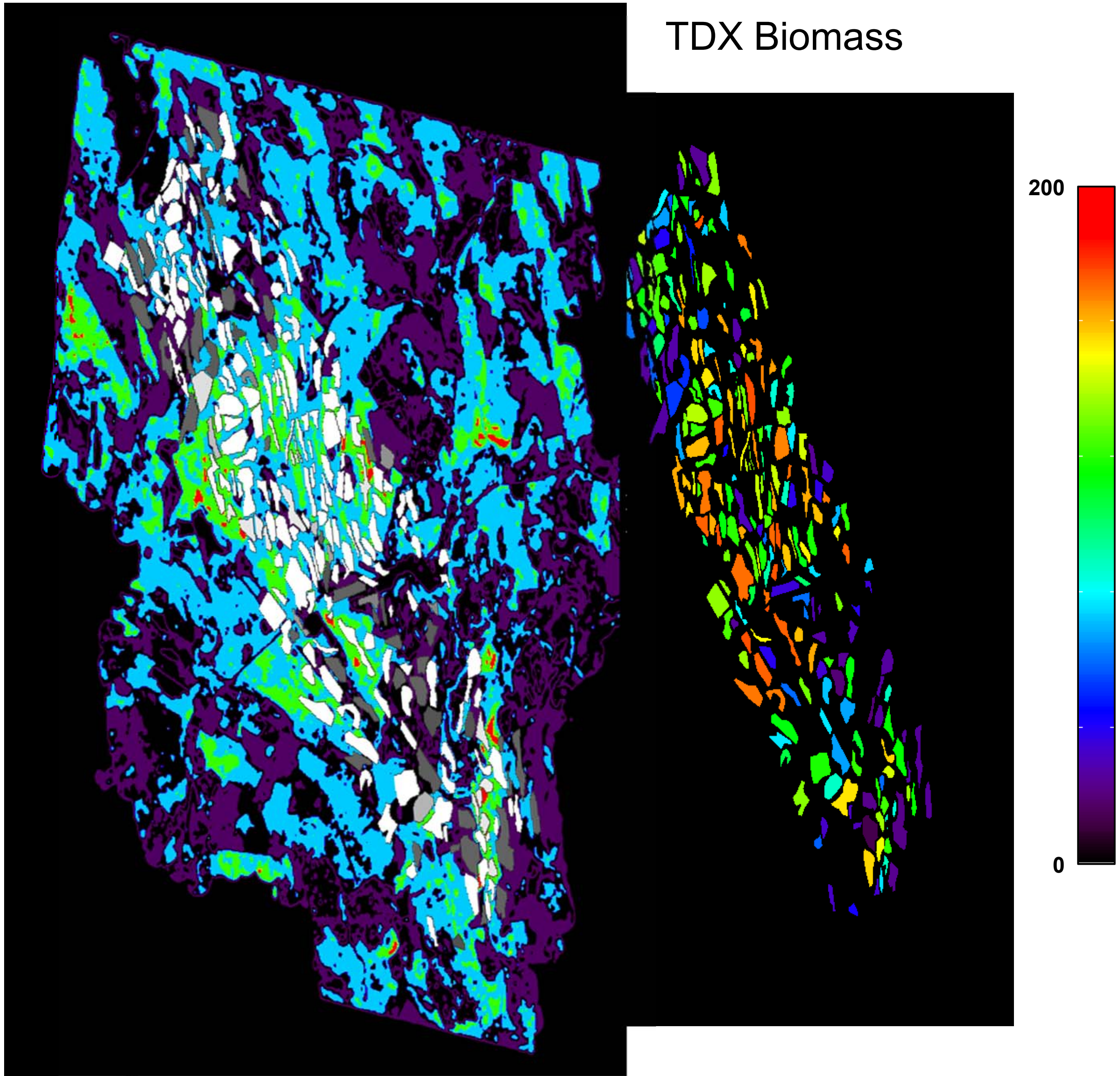


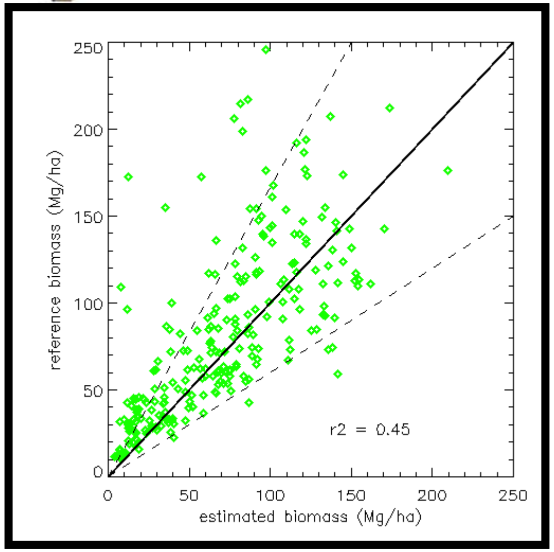
Biomass Classification

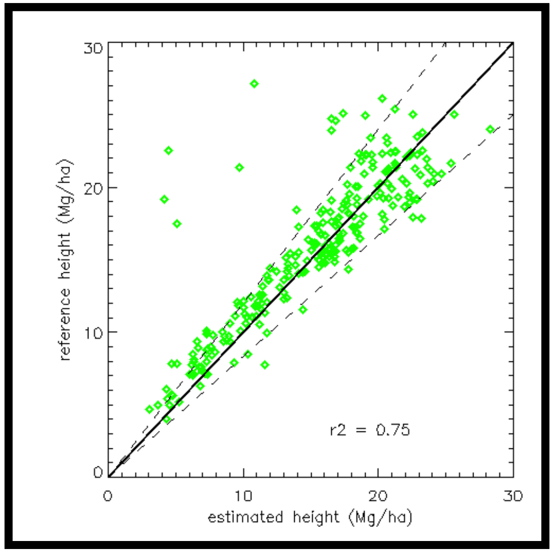


- <10 Mg/ha
- 10 - 50 Mg/ha
- 50 - 150 Mg/ha
- >150 Mg/ha

Biomass Validation in Pre-defined Stands

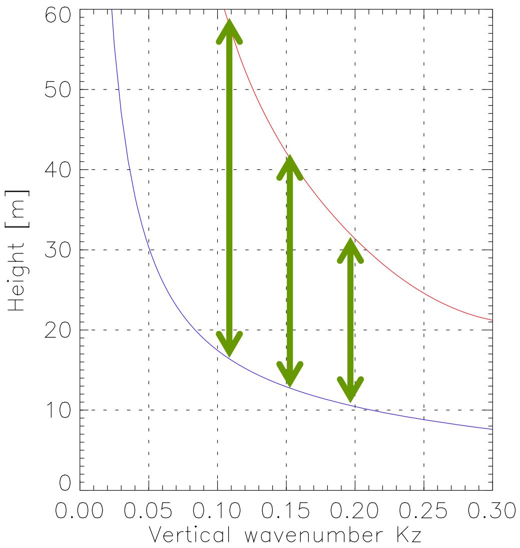


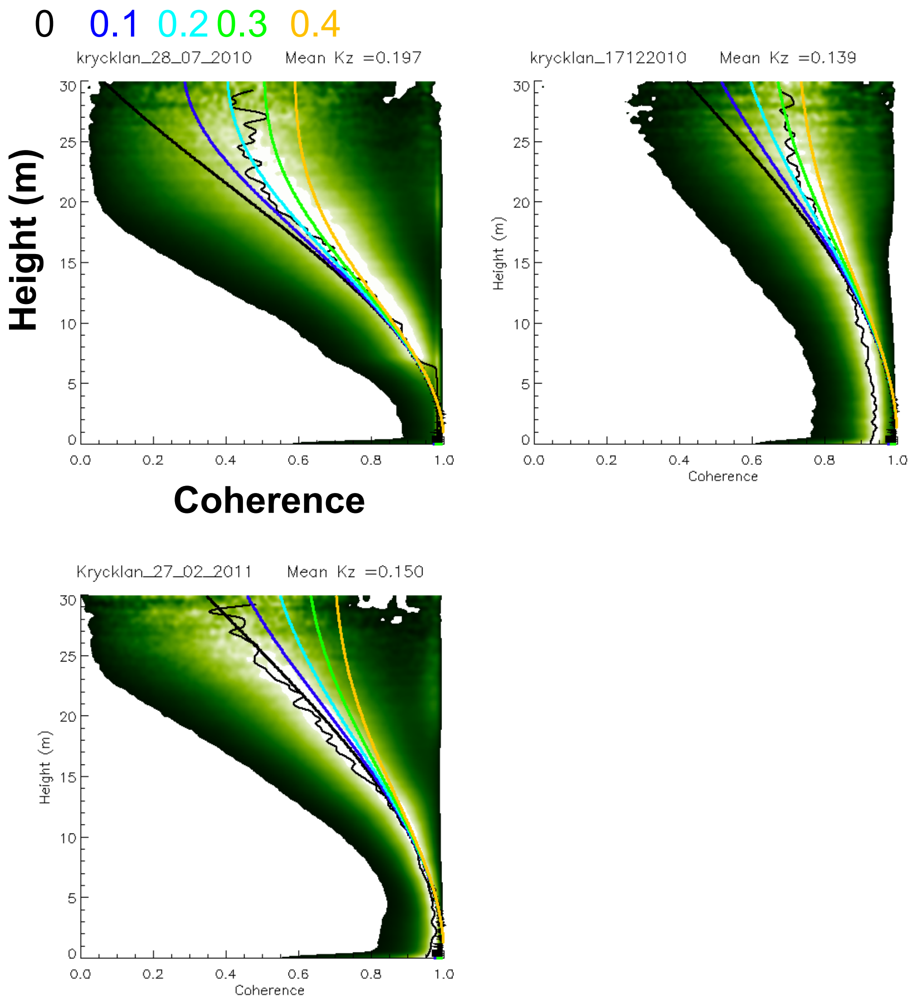




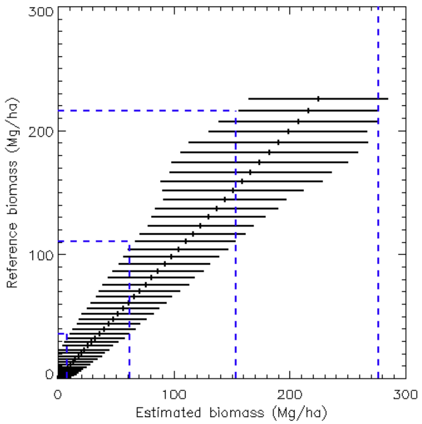
Height Estimation Performance, Kz and seasonality

- Height estimation accuracy is limited by the baseline (Kz).
- Winter acquisitions show higher penetrations, i.e. lower extinction values

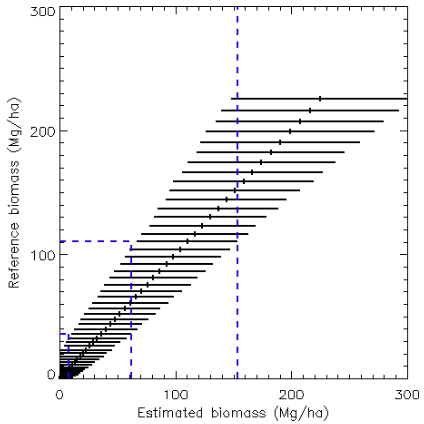




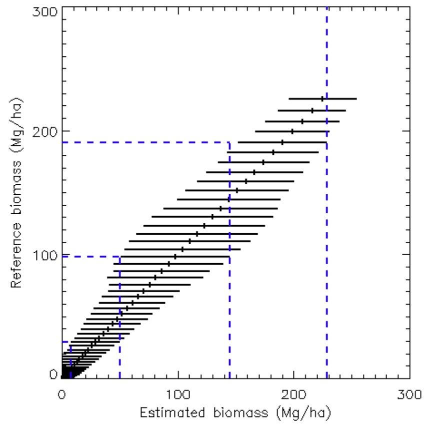
One baseline does not cover all possible heights!



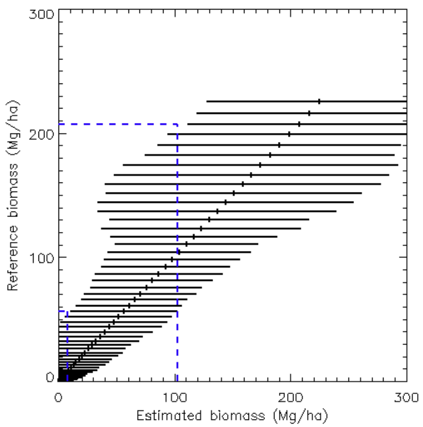
300
200
100
0
0
100
200
300
Reference biomass (Mg/ha)
Estimated biomass (Mg/ha)



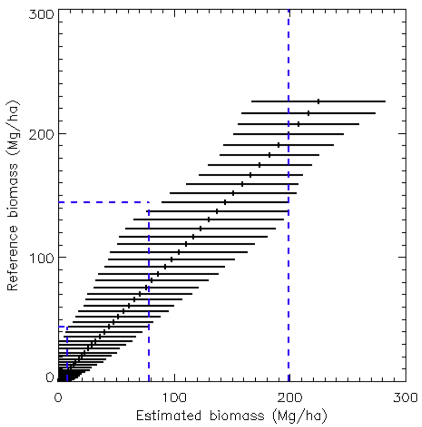
300
200
100
0
0
100
200
300
Reference biomass (Mg/ha)
Estimated biomass (Mg/ha)



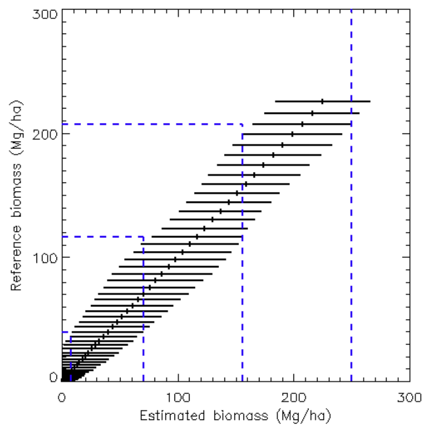
300
200
100
0
0
100
200
300
Reference biomass (Mg/ha)
Estimated biomass (Mg/ha)



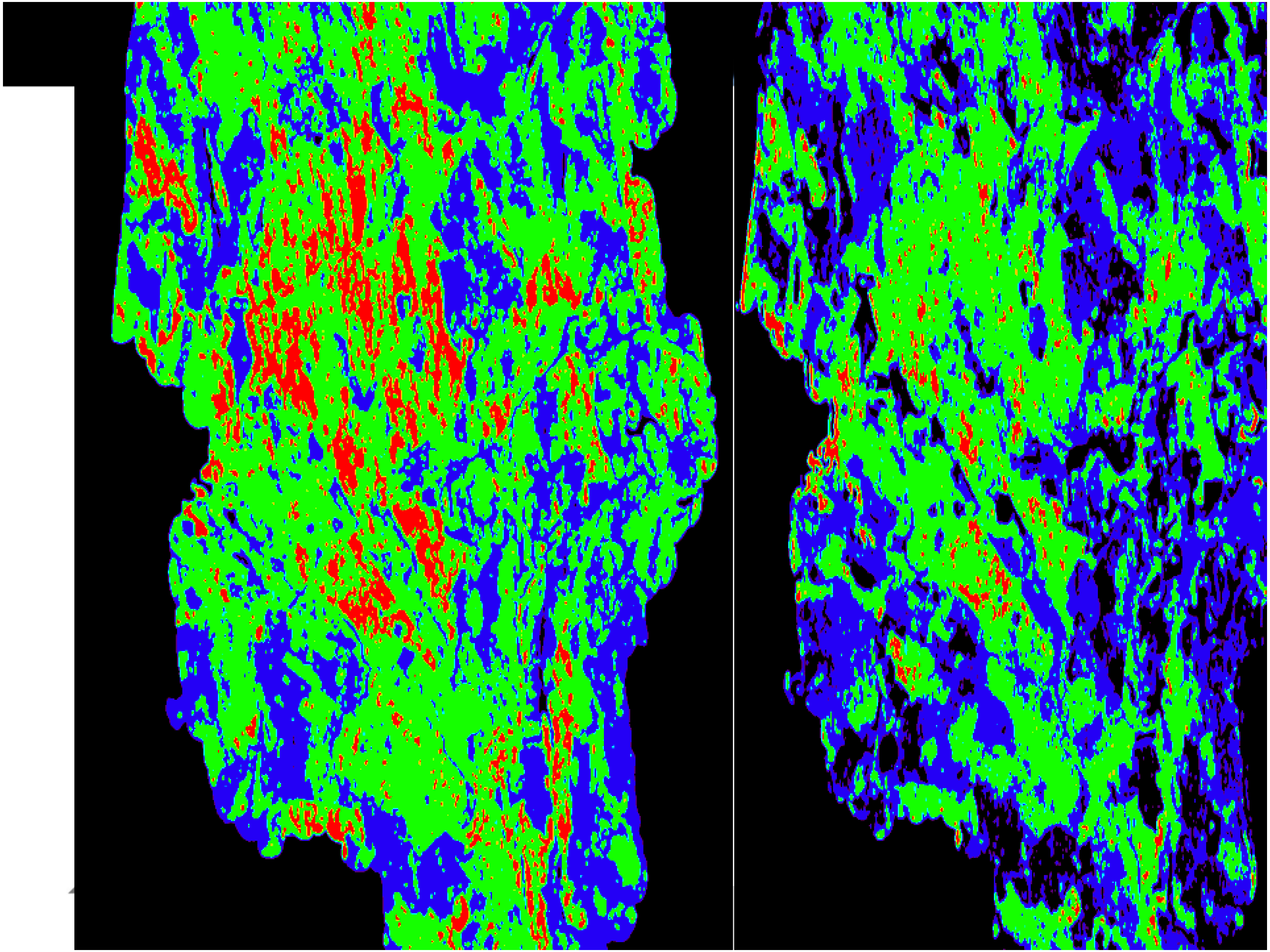
300
200
100
0
0
100
200
300
Reference biomass (Mg/ha)
Estimated biomass (Mg/ha)

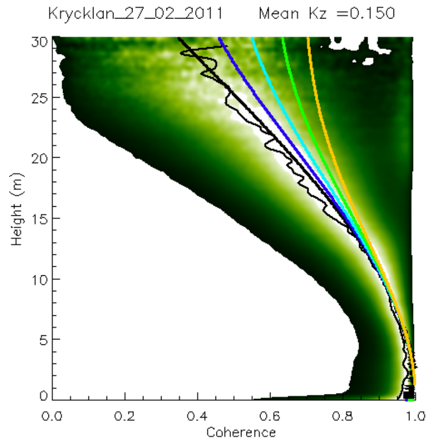


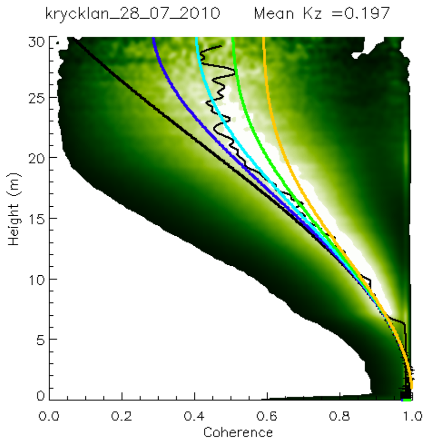
300
200
100
0
0
100
200
300
Reference biomass (Mg/ha)
Estimated biomass (Mg/ha)

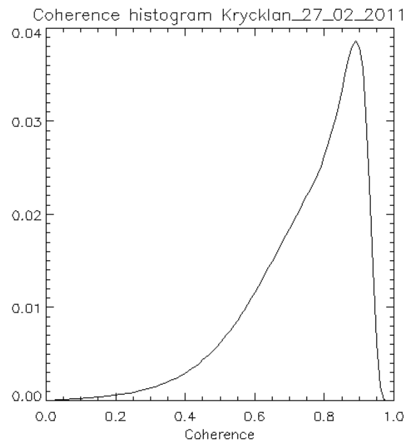


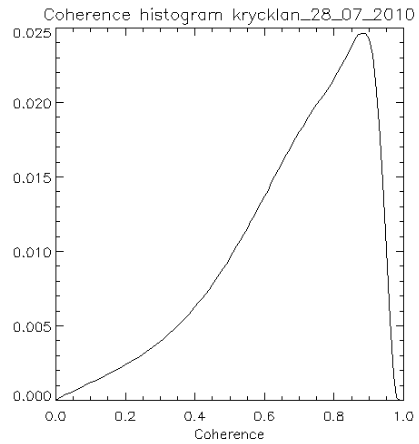
300
200
100
0
0
100
200
300
Reference biomass (Mg/ha)
Estimated biomass (Mg/ha)

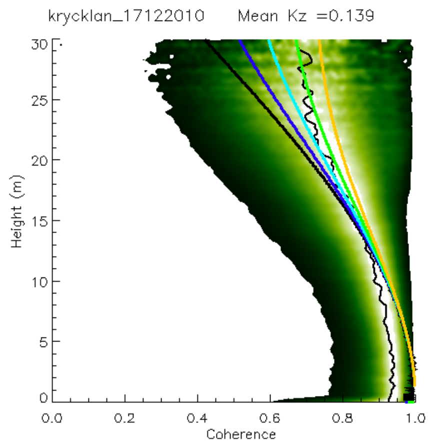


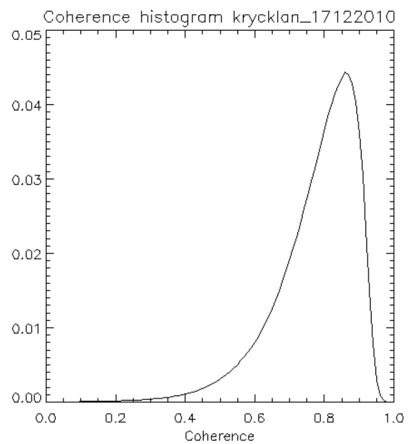

Krycklan_27_02_2011 Mean Kz =0.150
Height (m)
Coherence

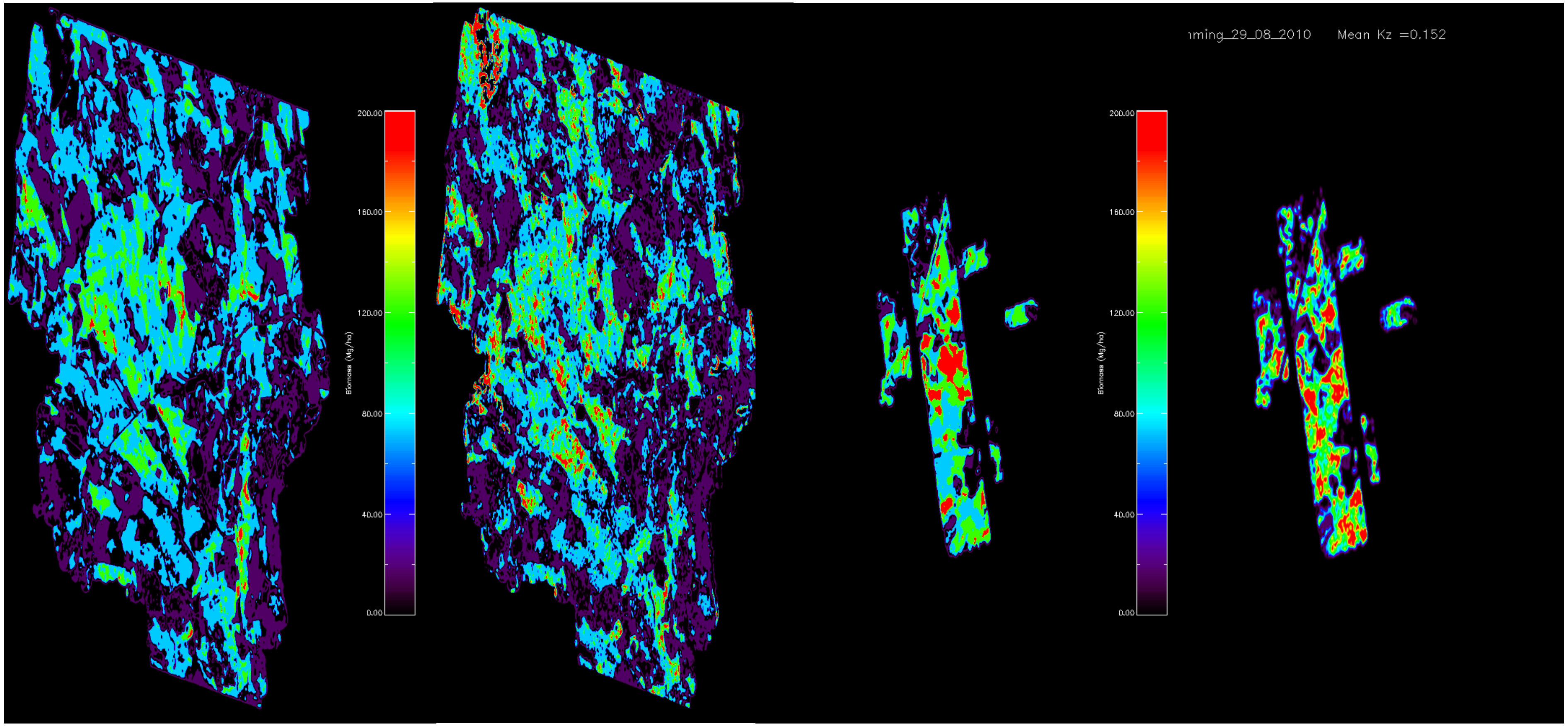

krycklan_28_07_2010 Mean Kz =0.197
Height (m)
Coherence

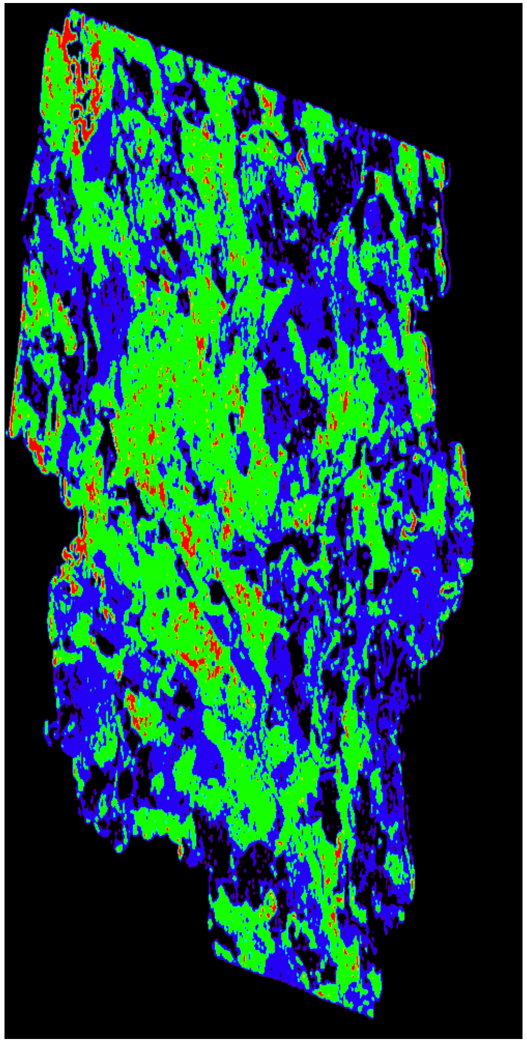

Coherence histogram Krycklan_27_02_2011
Coherence

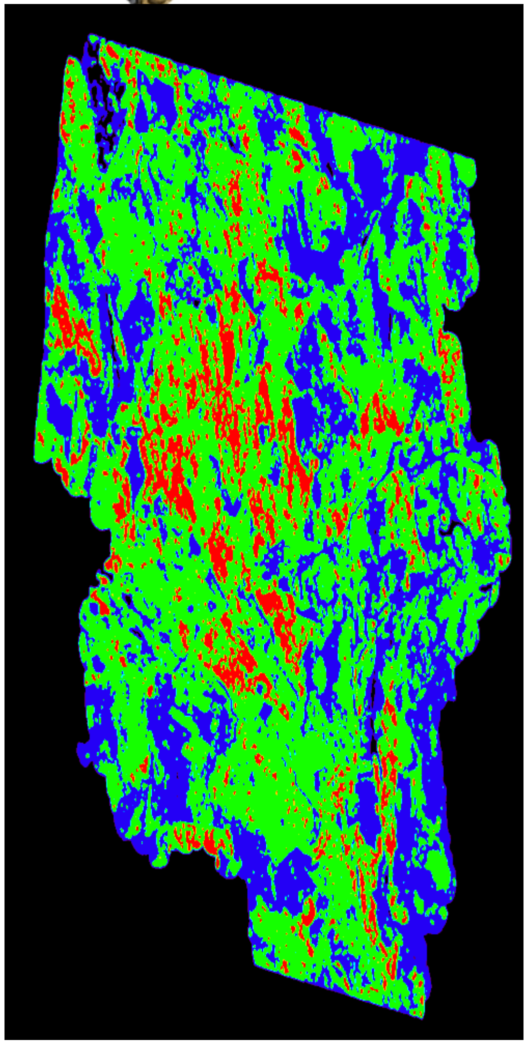

Coherence histogram krycklan_28_07_2010
Coherence


krycklan_17122010 Mean Kz =0.139
Height (m)
Coherence

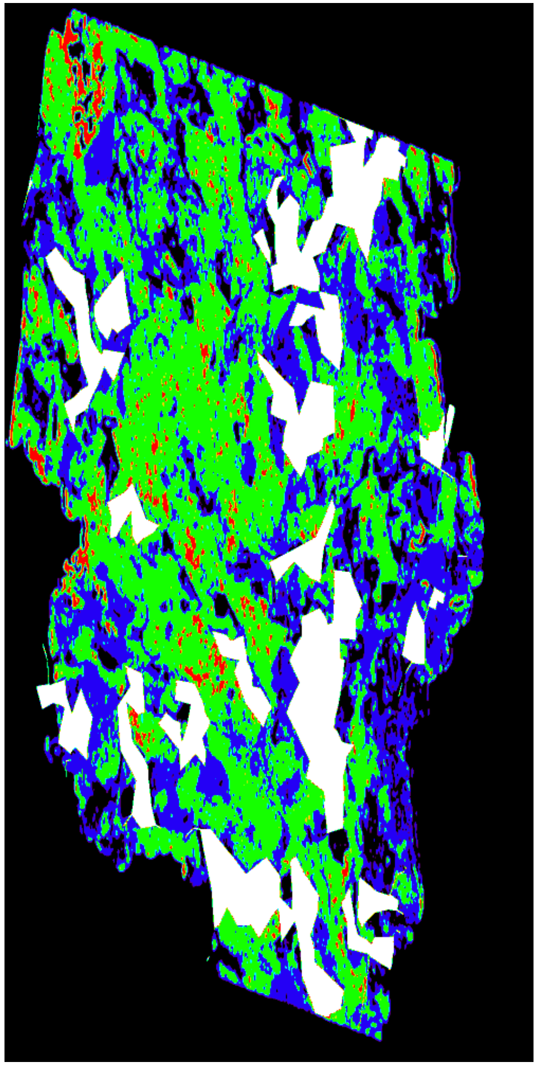

Coherence histogram krycklan_17122010
Coherence


ıming_29_08_2010 Mean Kz =0.152
200.00
160.00
120.00
80.00
40.00
0.00
Biomass (Mg/ha)

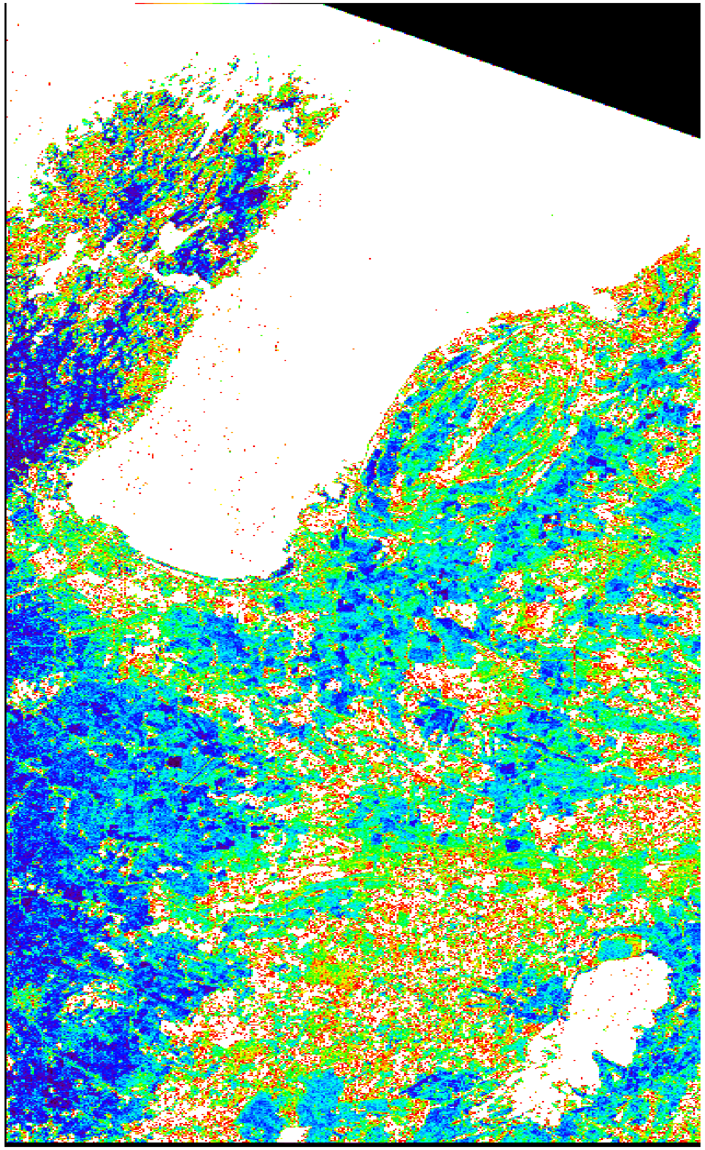




Krycklan



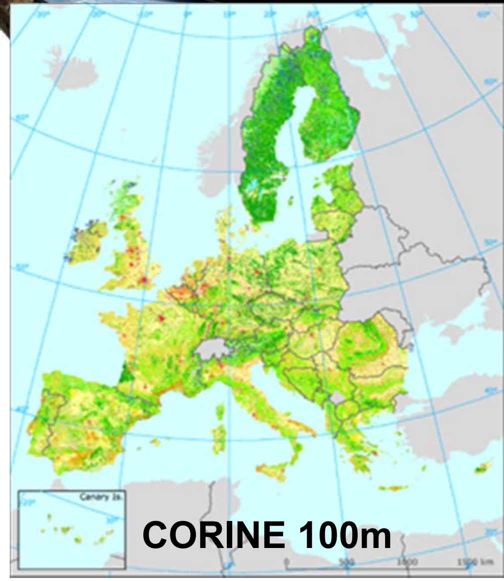
Remningstorp

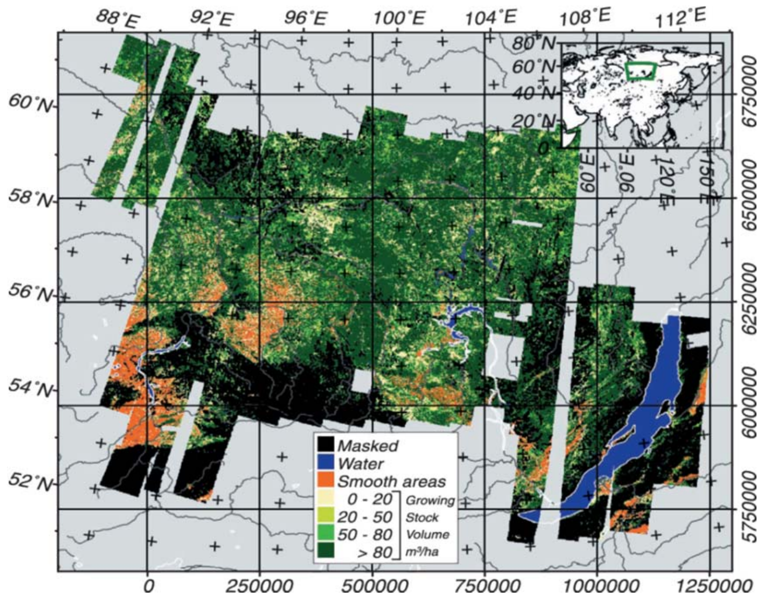


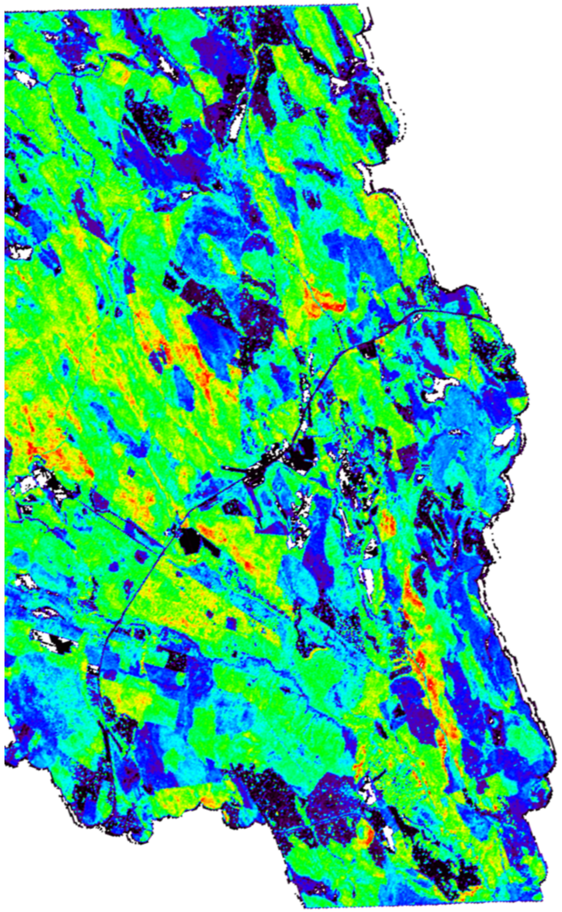
Forest classifications in the boreal region

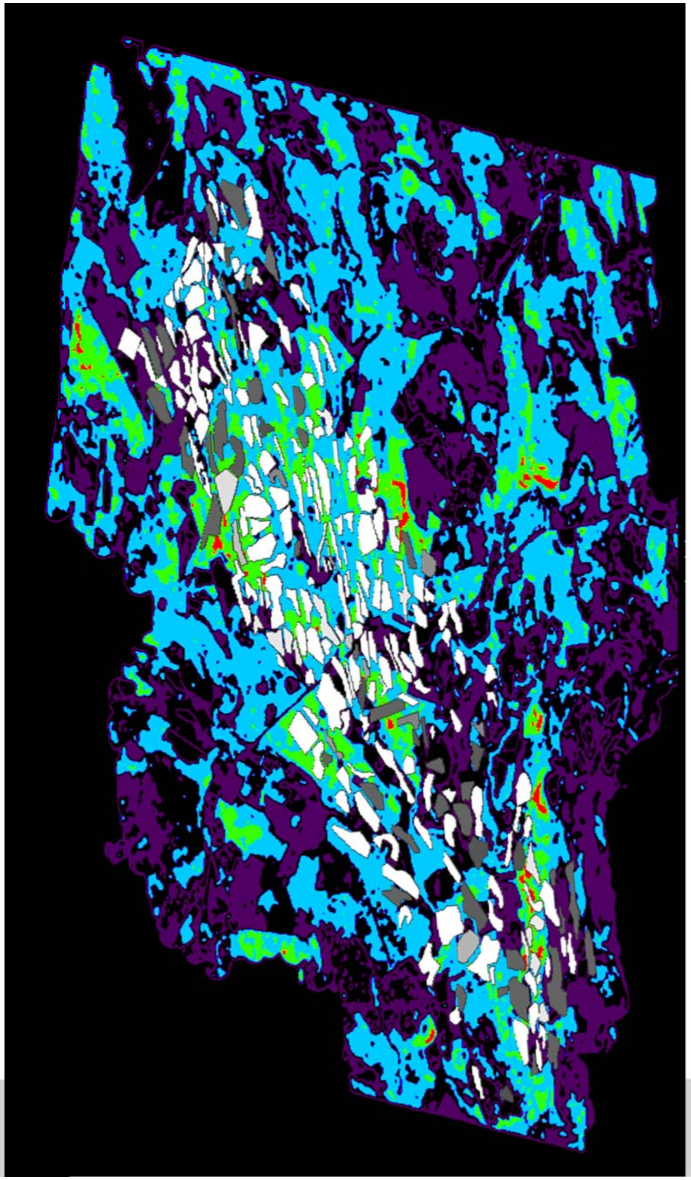
Existing classifications:

- Mainly based on optical systems.
    - Qualitative classifications
- Different classifications for each region
    - Corine thematic mapping in Europe (100 * 100 m spatial resoltuion)
- There is a need for quantitative and standard classifications for the boreal biome
- SAR classification: SIBERIA project
    - Coherence and backscattering
    - From ERS and JERS 900000 km2 in 50x50m
    - Classes: Bare soil, sparse shrub, forest (1-20, 21-50, 51-80, >80 T/ha)

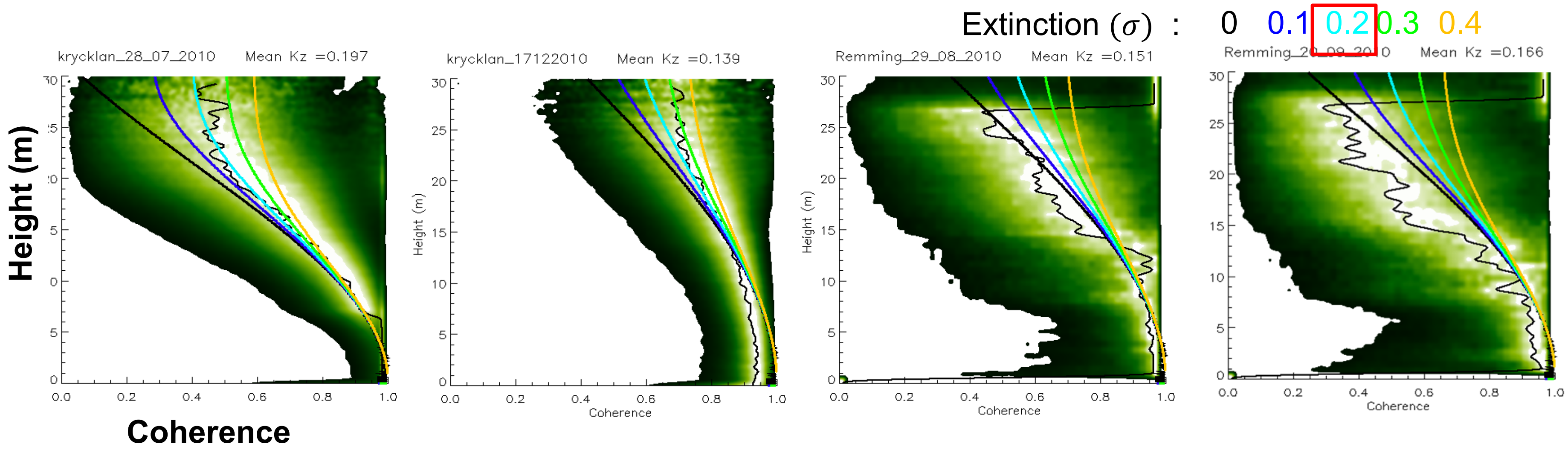








Coherence Modelling



- Optimum fixed extinction = 0.2 dB/m
- This Extinction value is lower than expected for X-band due to significant ground contribution.
- Extinction values decrease in winter