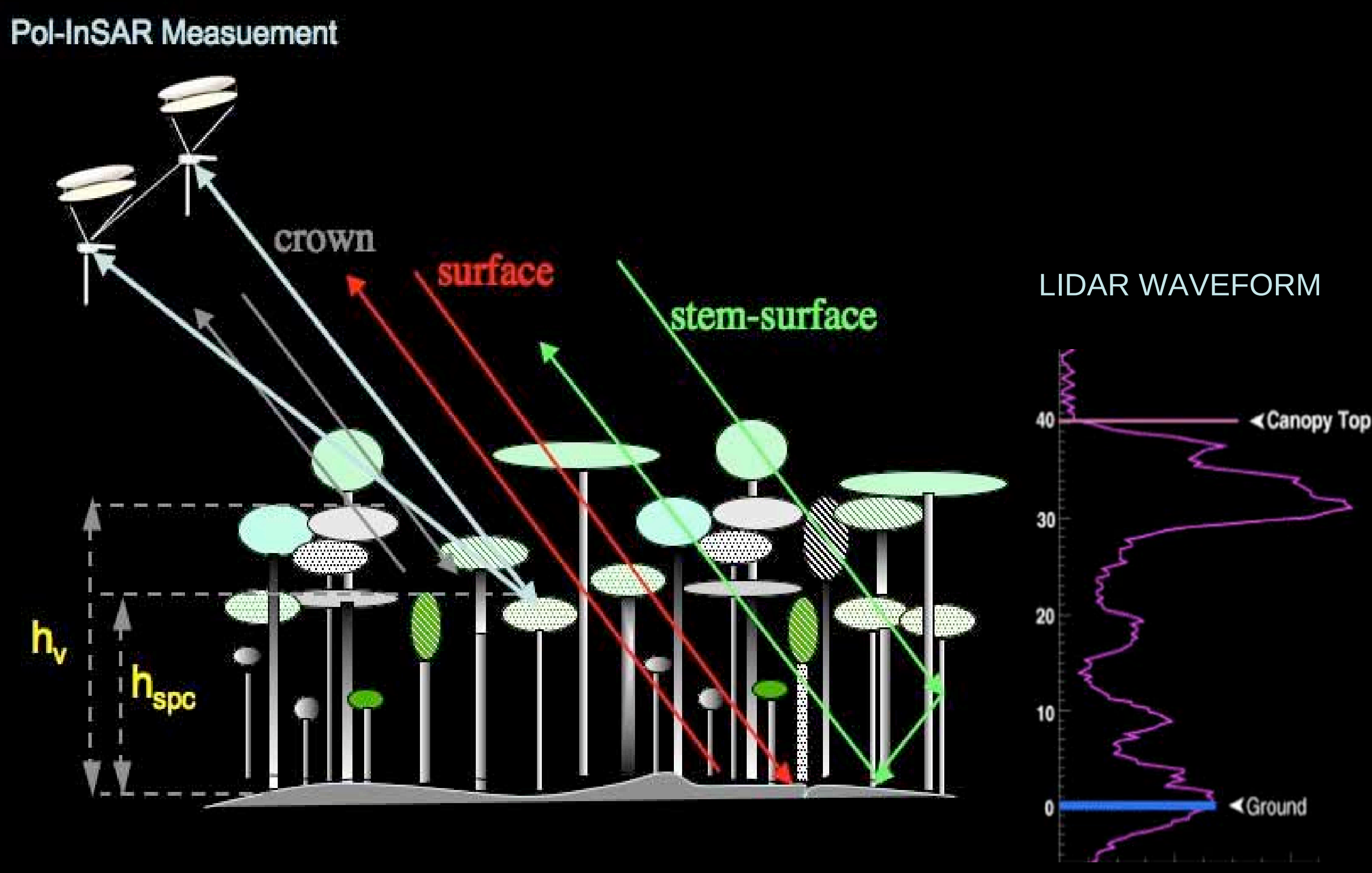
Radar Polarimetry & InSAR Measurements of Forest Structure & Biomass

S. Saatchi, R. Treuhaft, P. Siqueira, J. Kellndorfer,
M. Simard, K. Sarabandi, K. Papathanassiou, J. Ranson, S. Hensley

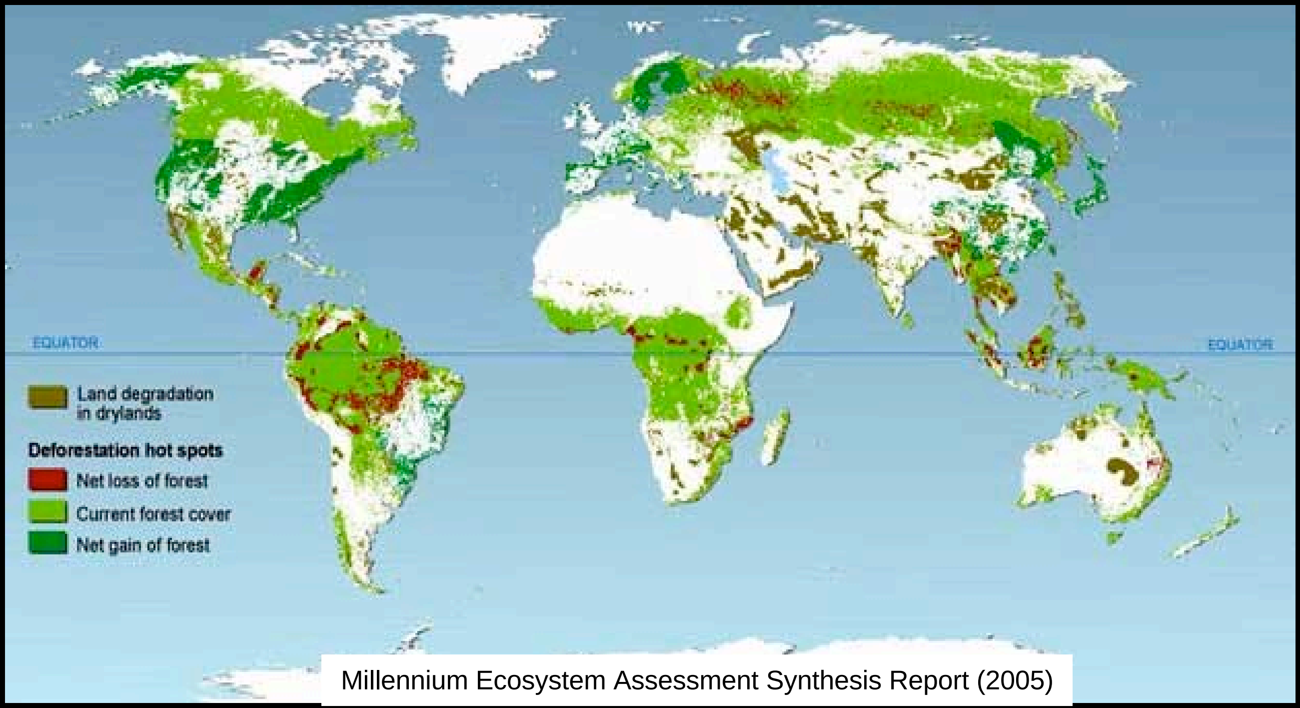


Carbon Stock and Dynamics

Uncertainty in the magnitude of carbon emissions from land use changes is 62% of the estimated input (1.6 petagrams)

The map shows areas with a canopy cover of at least 40% by woody plants taller than 5 meters

The carbon implications of these dramatic changes are poorly quantified



Millennium Ecosystem Assessment Synthesis Report (2005)

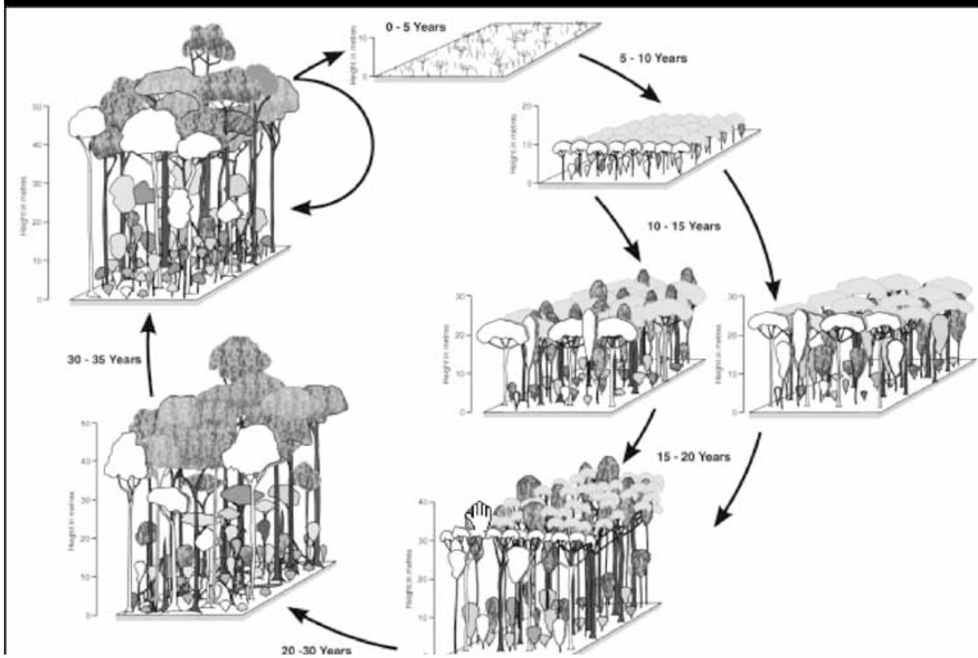
- **From 1990 to 2000, the global area of temperate forest increased by almost 3 million hectares per year**

- **From 1980-2000 deforestation in the tropics occurred at an average rate exceeding 12 million hectares per year**

- **Quantifying the resulting changes in forest carbon storage is key to reducing uncertainties in the global carbon budget**

Carbon Stock and Dynamics

What is there?



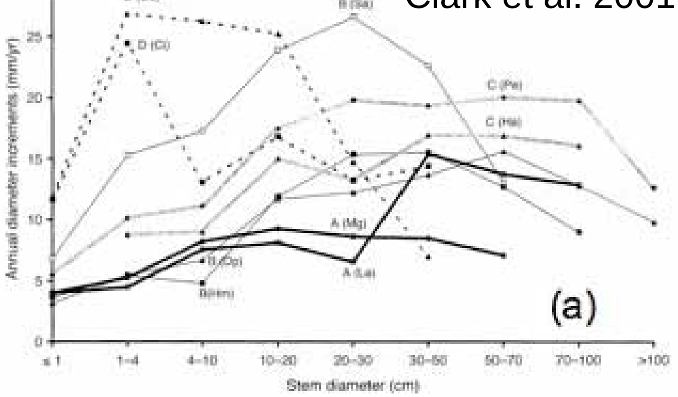
How does it change?

A complex mixture of tree species, diameter, height, canopy structure, and disturbance & recovery patterns define biomass

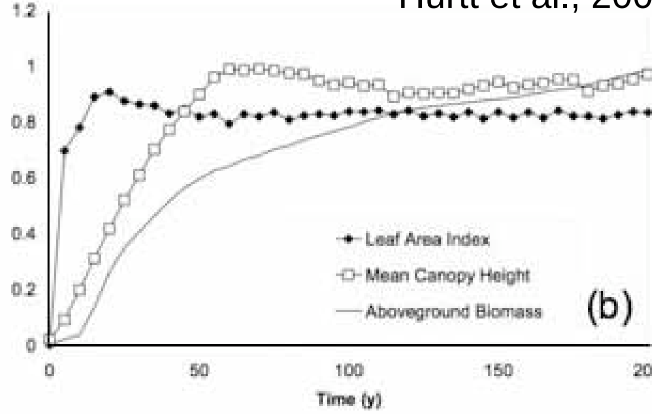
Average height and leaf area saturate in most tropical forests after 50-100 years but diameter, basal area,maximum height continue changing

Both aboveground biomass and its structural changes are needed to capture tropical forest carbon dynamics

Ground data from La Selva
Clark et al. 2001



ED Model over La Selva
Hurtt et al., 2003

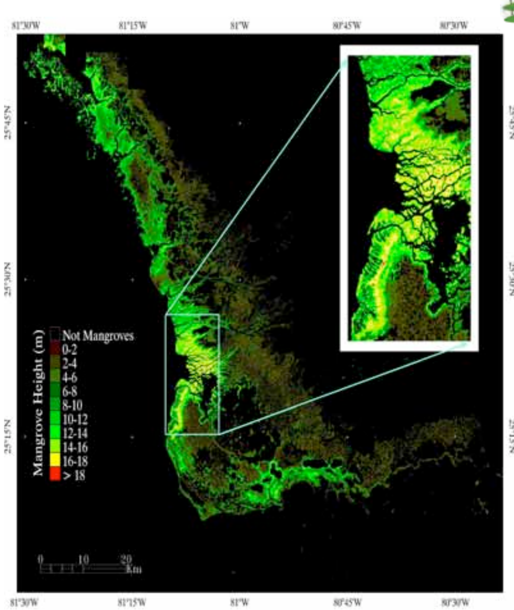


Starting Point

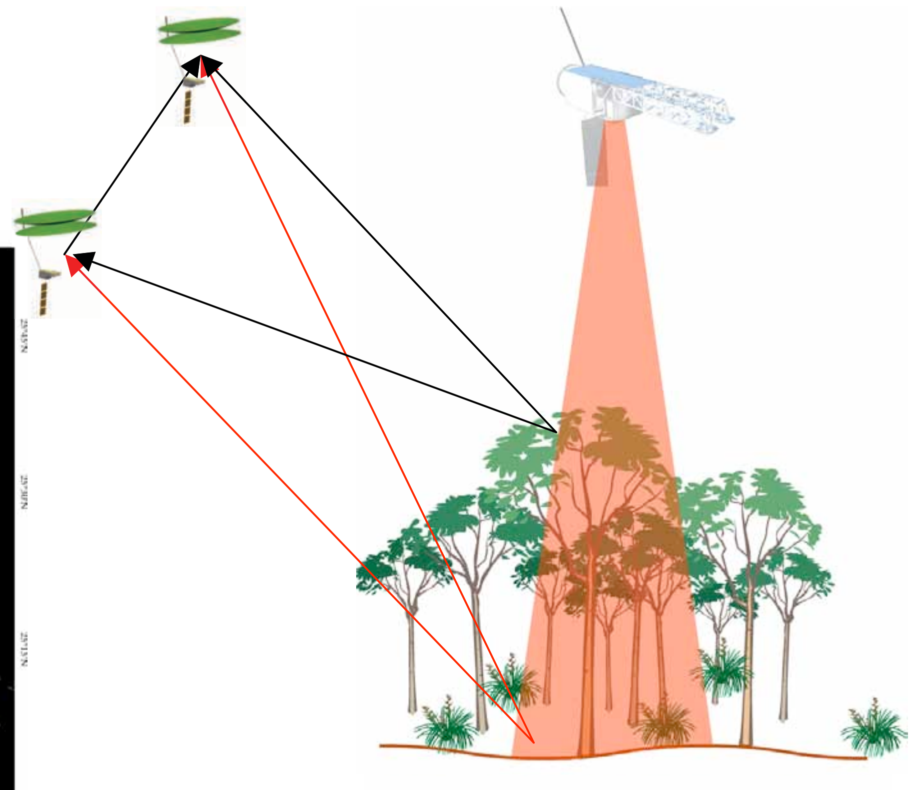
Polarimetric & InSAR Measurements:
Imaging Average Height & Biomass

Multi-beam Lidar Measurements:
Sampling forest height & vertical profile

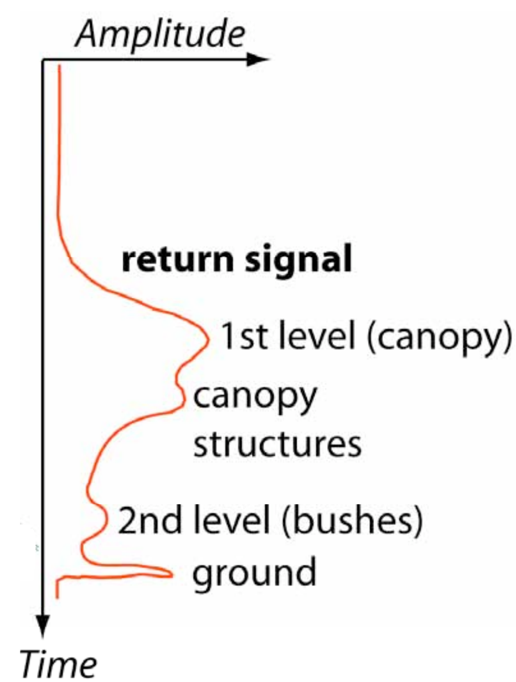
FUSION



Polarimetric SAR and
Finite Baseline InSAR



Multibeam LIDAR



Outline

- How do Polarimetric & InSAR measurements meet science requirements?
- What are the main scenarios for InSAR & Lidar data fusion?
- What are the main questions for discussion or study?

Aboveground Forest Biomass

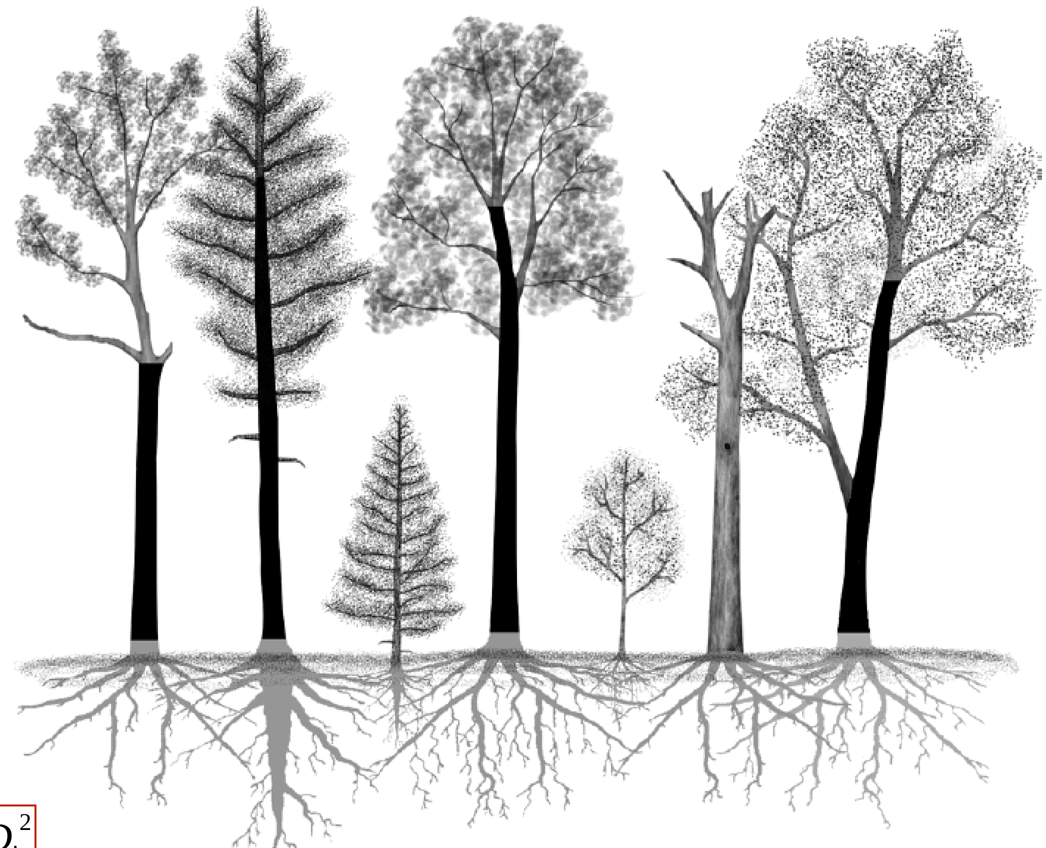
$$AGB = \frac{1}{A}\sum_i AGB_i$$

$$AGB = \frac{1}{A}\sum_i \frac{\pi D_i^2}{4} H_i W_i$$

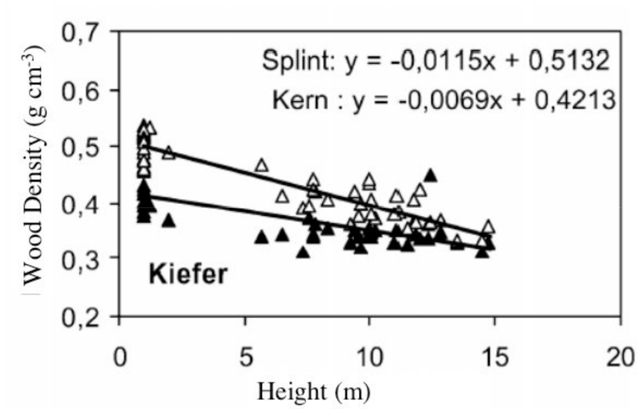
$$Vol = \frac{1}{A}\sum_i \frac{\pi D_i^2}{4} H_i$$

$$BA = \frac{1}{A}\sum_i \frac{\pi D_i^2}{4}$$

A: Area sampled
D: Diameter at Breast Height, DBH
H: Tree Height
W: Wood Density (species dependent)



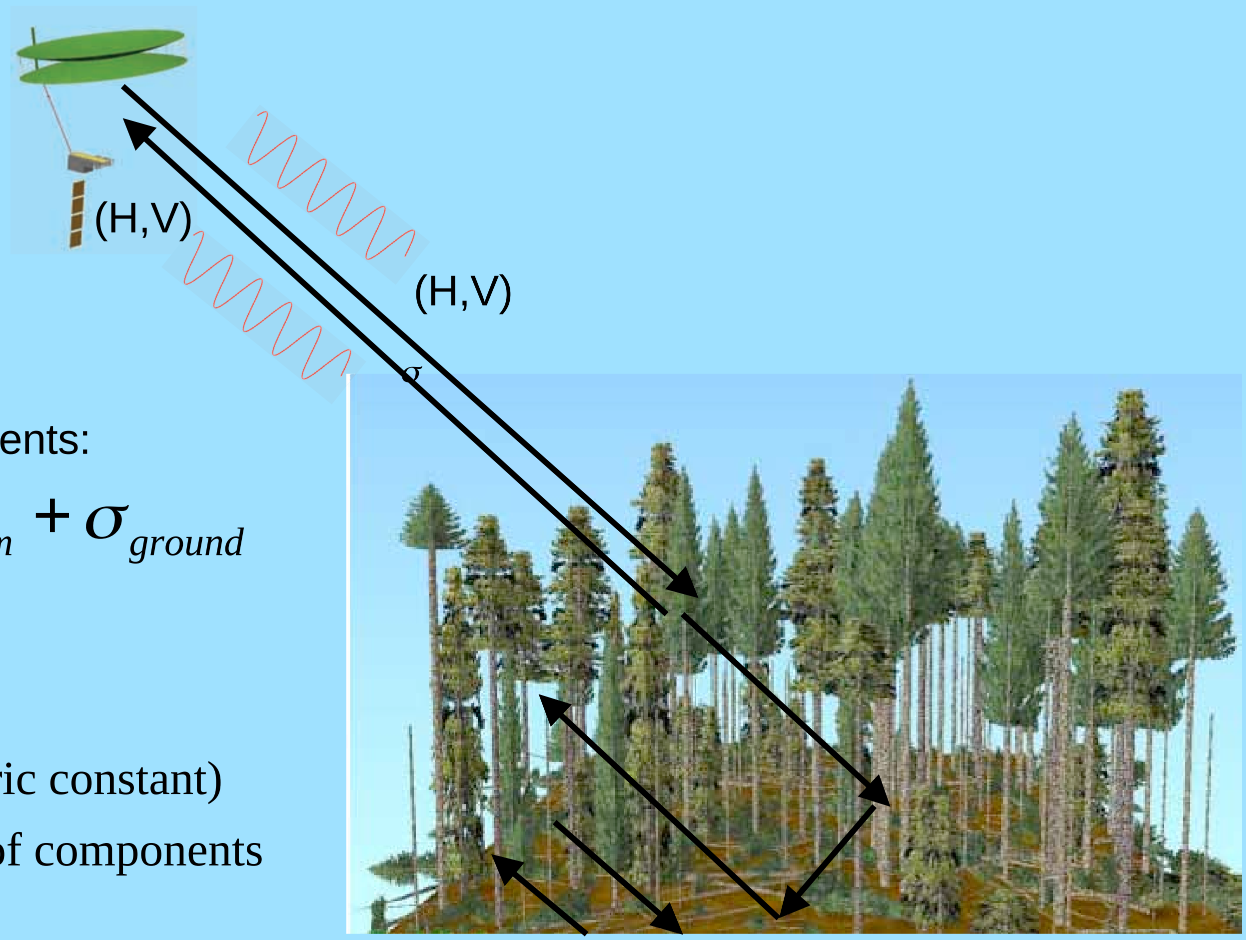
Allometry: $AGB_i = 42.7 - 12.8 \times D_i + 1.24 \times D_i^2$



Ground Measurements:
Statistical Sampling of structure plus allometry (limited in spatial & temporal coverage)

Satellite Measurements:
1. measurement of structure & use of allometry
2. Direct measurement of aboveground biomass (no limitation in spatial and temporal coverage)

Radar Backscatter Measurements



Backscatter Measurements:

$$\sigma_{(H,V)} = \sigma_{crown} + \sigma_{stem} + \sigma_{ground}$$

$\sigma_{(H,V)} = f(vol, W_d, \Omega)$

vol : forest volume (size)

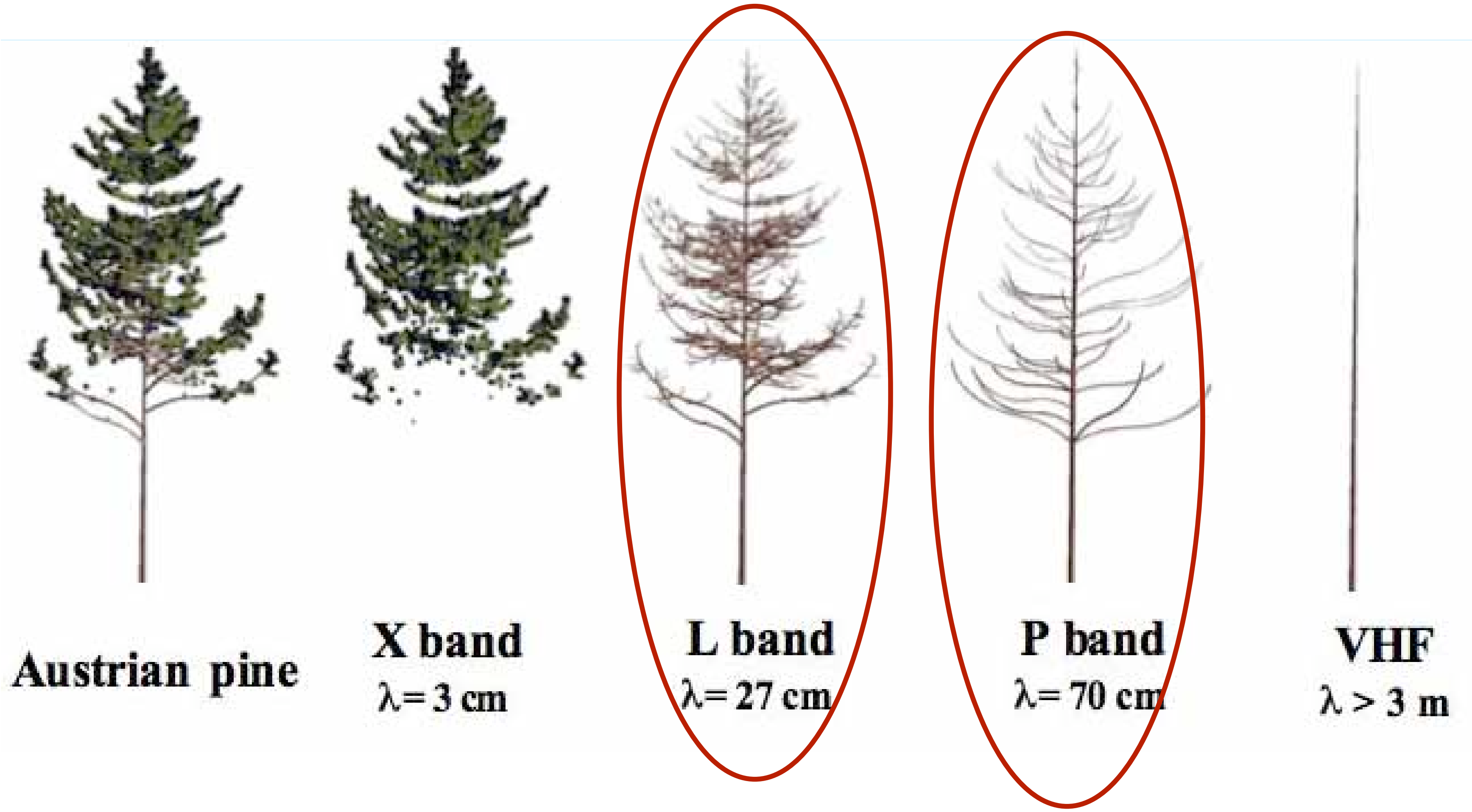
W_d : wood density (dielectric constant)

Ω : shape and orientation of components

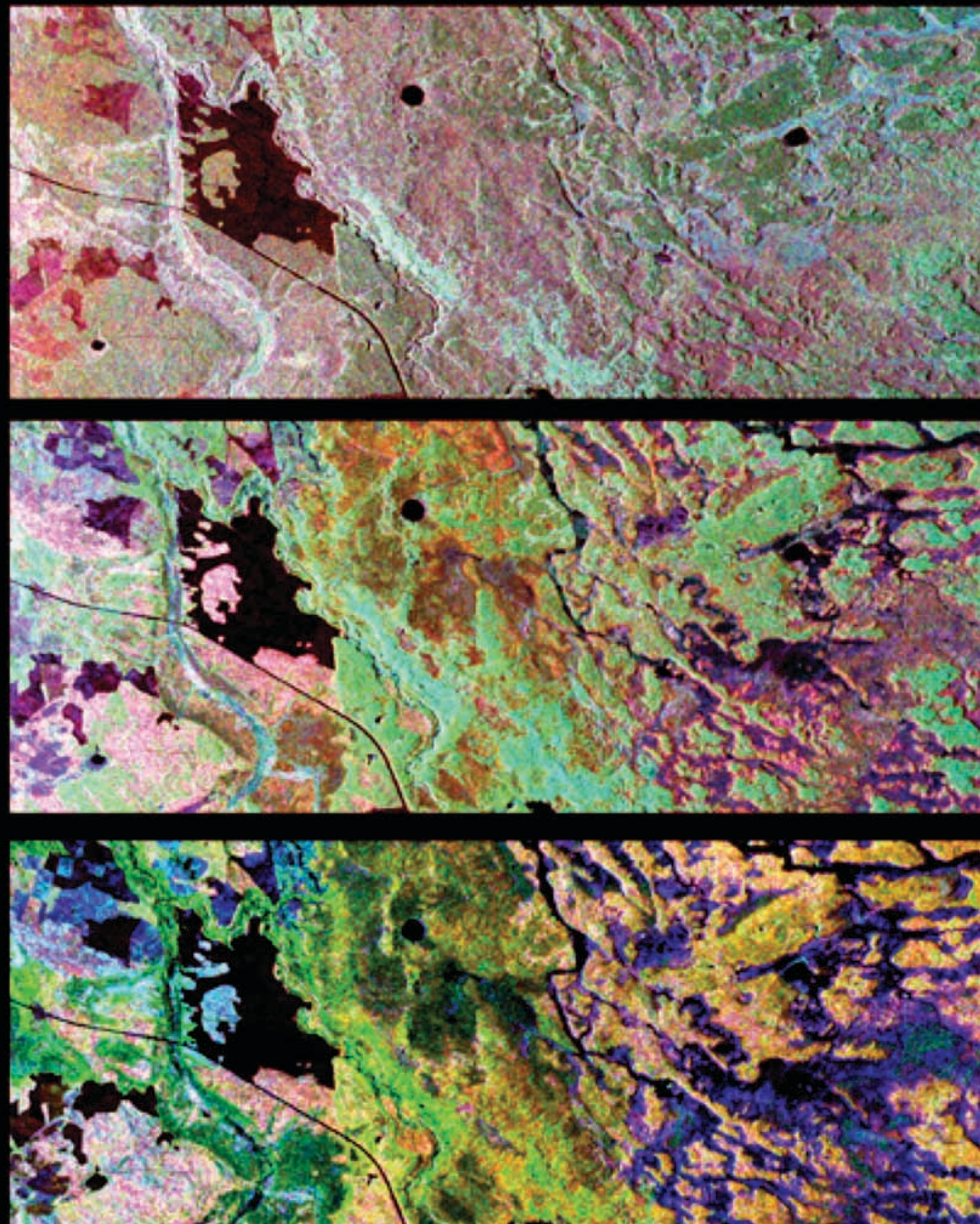
Measurement Variables: Frequency, Angle, Polarization

high spatial resolution, seasonal to annual revisit time, all time capability

Why L-band or P-band Radar?



HH, HV, VV



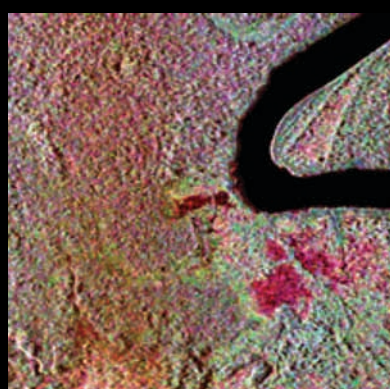
C-band

L-band

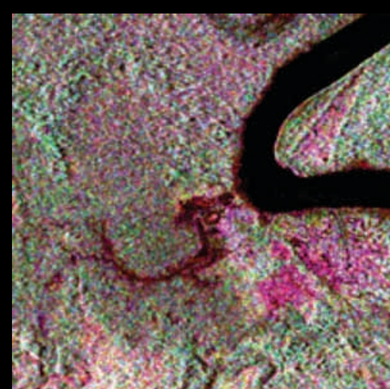
P-band

Radar Backscatter Images at HH, HV, and VV polarizations over boreal forests of Canada (1995)

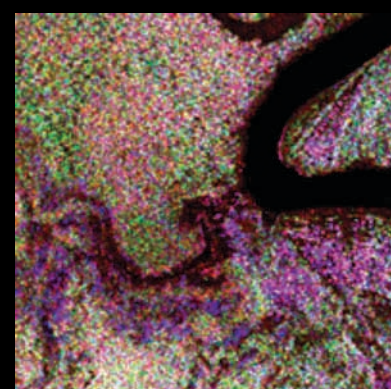
Radar Backscatter Measurements over Tropical Forests



C-band



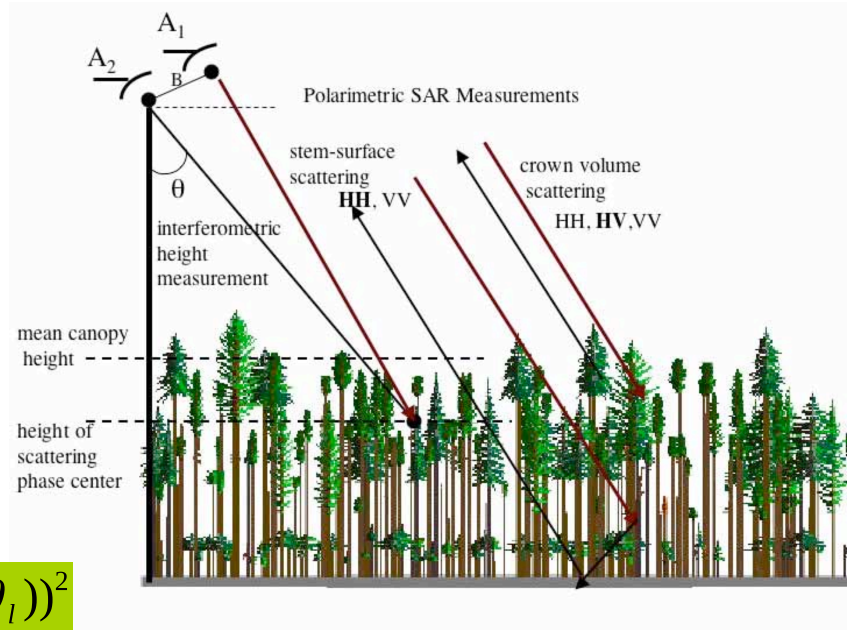
L-band



P-band

Biomass Algorithms

Algorithms are almost mature:
1. Empirical (regression models)
2. Semi-empirical models
3. Physically-based models



A semi-empirical algorithm
(Saatchi et al., 2007)

$$Log(W_s) = a_0 + a_1\sigma^0_{HV}\sin(\theta_0 - \theta_l) + a_2(\sigma^0_{HV}\sin(\theta_0 - \theta_l))^2 + b_1\sigma^0_{HH}\cos(\theta_0 - \theta_l) + b_2(\sigma^0_{HH}\cos(\theta_0 - \theta_l))^2 + c_1\sigma^0_{VV}\cos(\theta_0 - \theta_l) + c_2(\sigma^0_{VV}\cos(\theta_0 - \theta_l))^2$$

Works in complex terrains:

$$\cos\theta_l = \sin\alpha\sin\theta_0\cos(\gamma - \gamma_s) + \cos\alpha\cos\theta_0$$

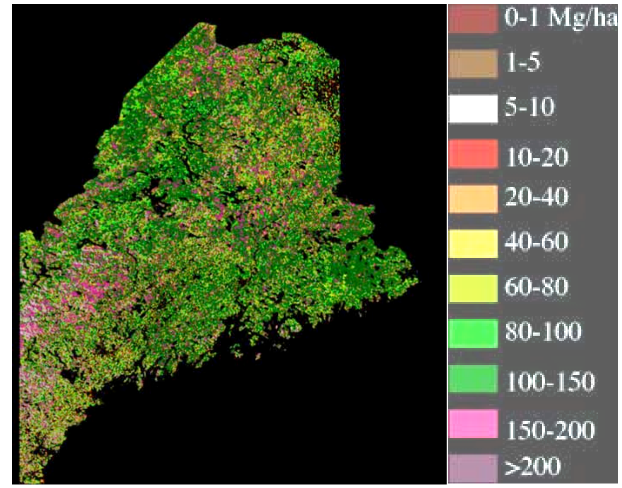
Where α is the local slope, γ is the azimuth angle of the radar illumination direction and γ_s is the aspect angle at the local slope.

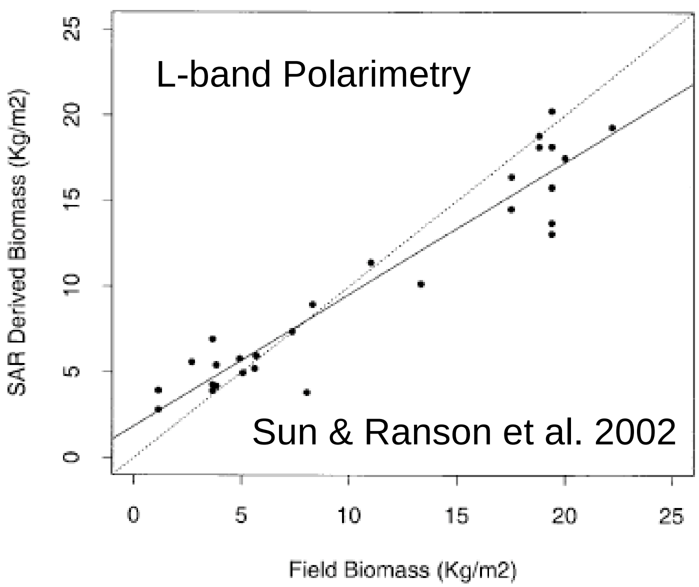
Forest Type	a_0	a_1	a_2	b_1	b_2	c_1	c_2
Terra Firme	21.34	2.11	0.035	-1.34	-0.11	-0.56	0.042

Radar Backscatter Derived Biomass
Boreal Forests

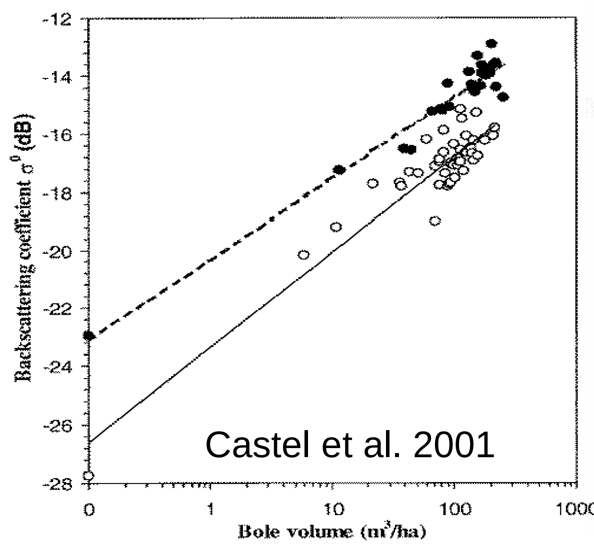
AIRSAR Channels	*Crown Biomass Accuracy*	*Stem Biomass Accuracy*	*Total Biomass Accuracy*
PHH, PHV, LHV, CHV	**95%**	**90%**	**91%**
PHH, PHV, PVV	**76%**	**92%**	**89%**
LHH, LHV, LVV	**93%**	**86%**	**87%**
CHH,CHV,CVV	**56%**	**23%**	**32%**
LHH,CHH,CVV	**68%**	**65%**	**63%**

Saatchi et al. 2000



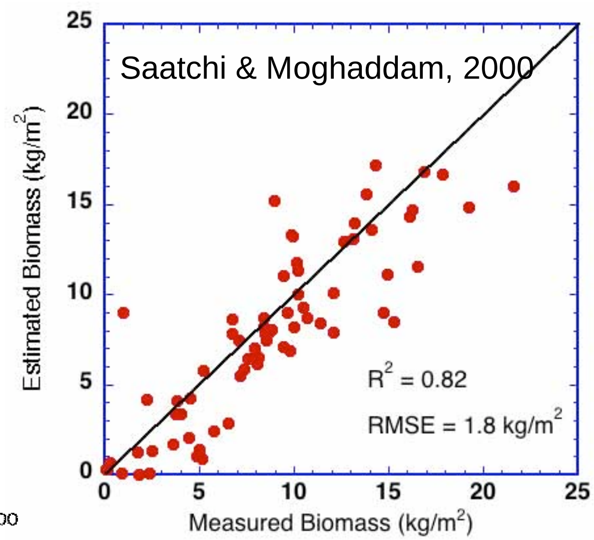


R^2=0.91, RSE=18.1 Mg/ha

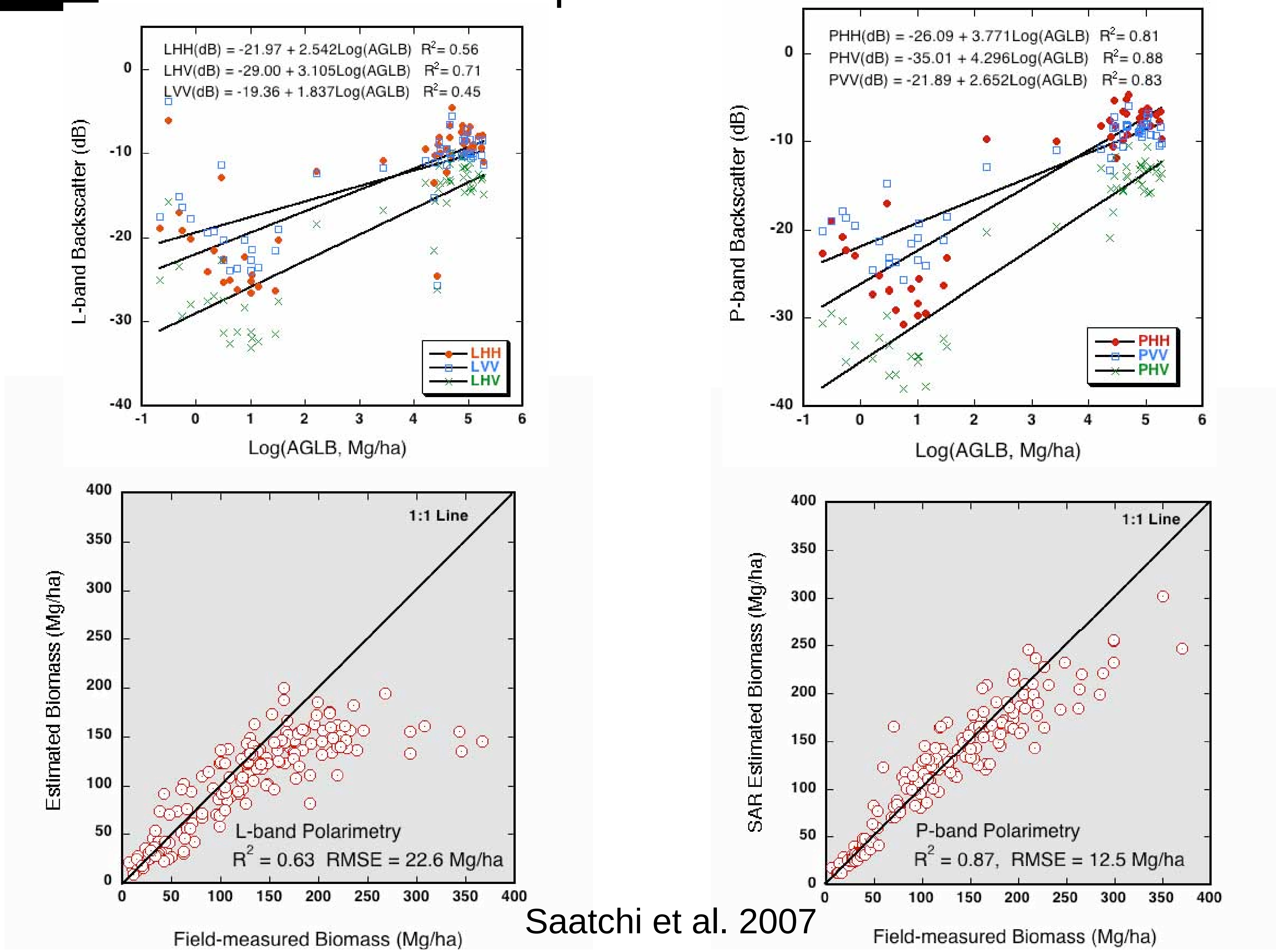


Landes : L-HV AIRSAR σ^0 = 1,2*Ln(vol) - 20 R^2 = 0.94

○ Lozère : L-HV SIR-C σ^0 = 1,4*Ln(vol) - 23 R^2 = 0.86

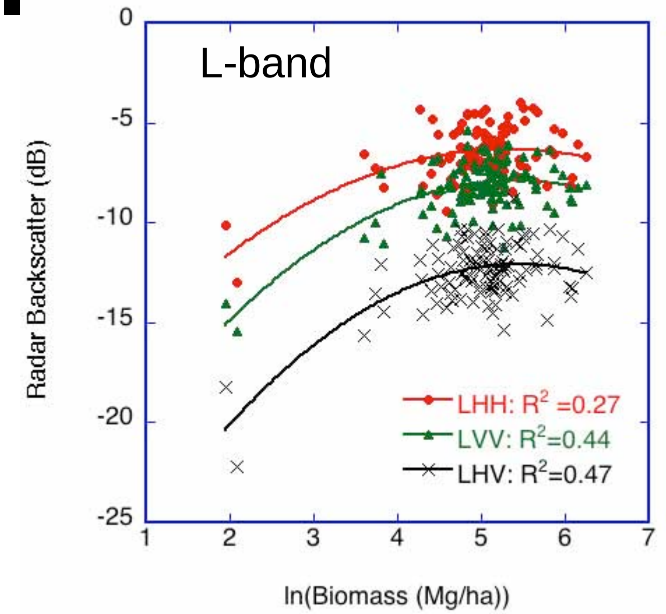


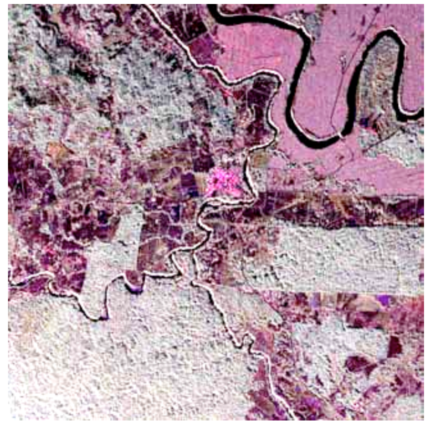
Radar Backscatter Derived Biomass Temperate Forest



Saatchi et al. 2007

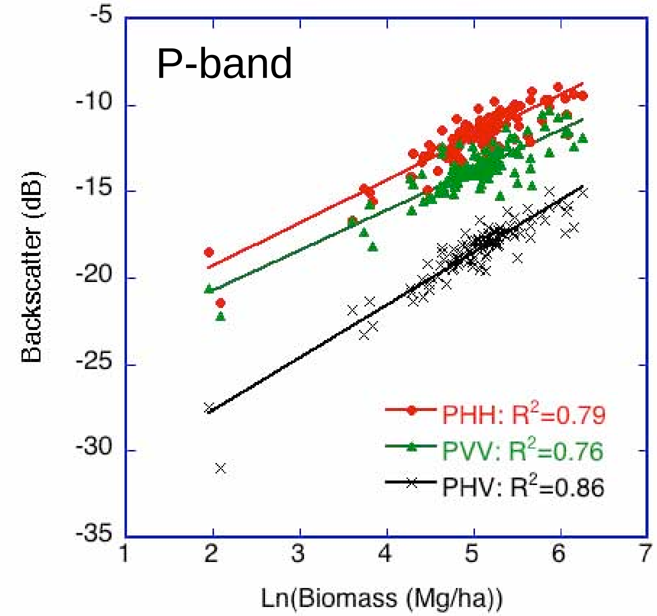
Radar Backscatter Derived Biomass
Tropical Forest

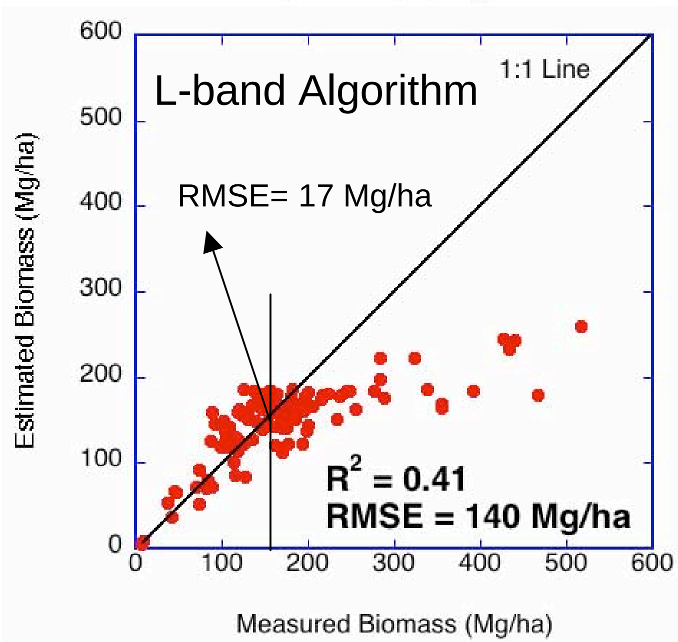


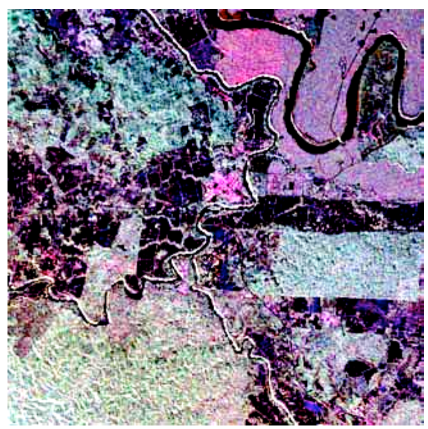


Polarimetric L-band

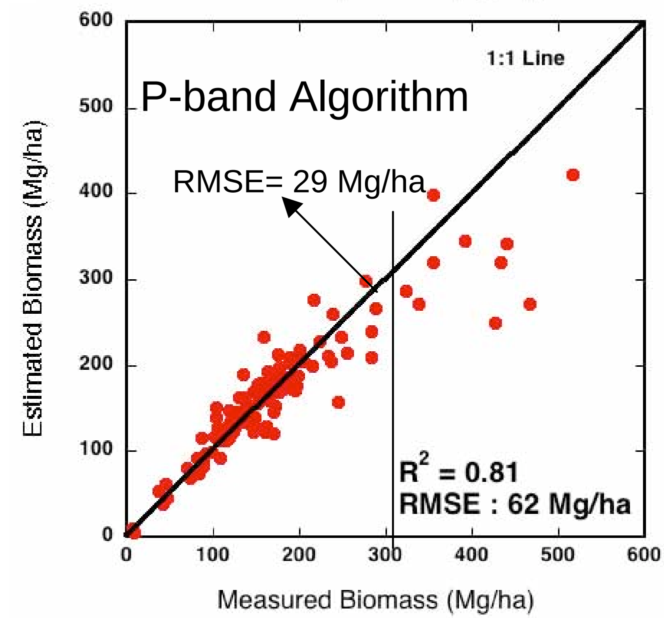
AIRSAR Campaign over
La Selva Biological Station
Costa Rica, March 2004



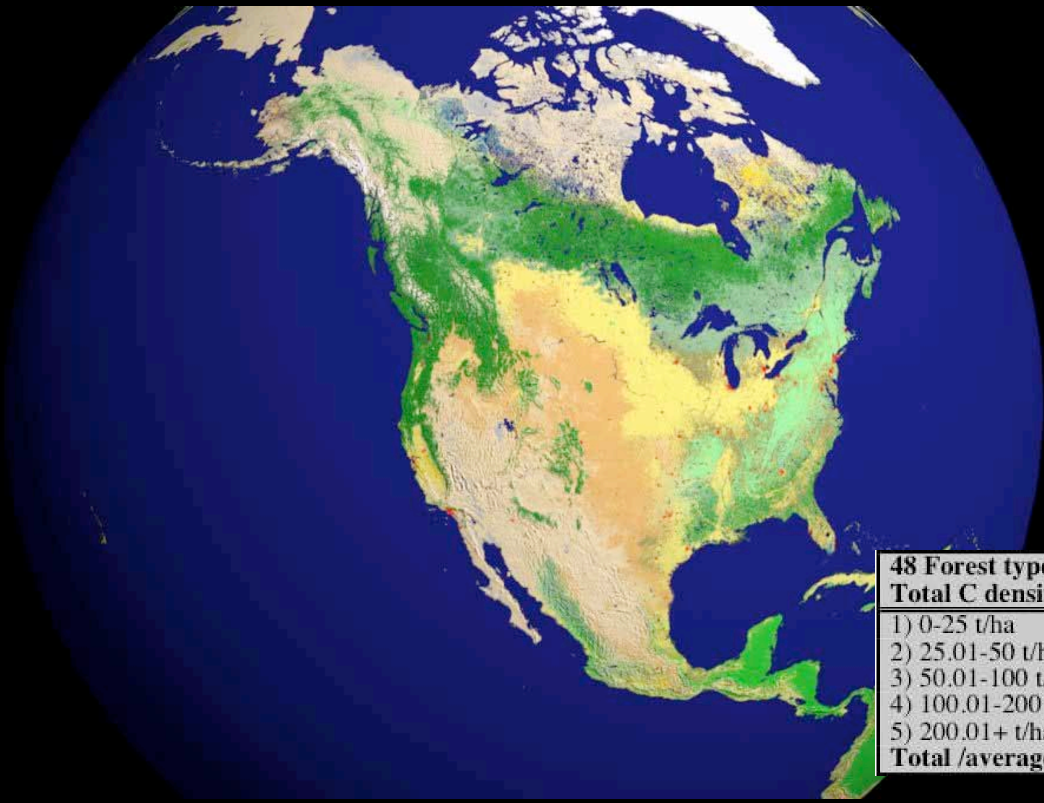


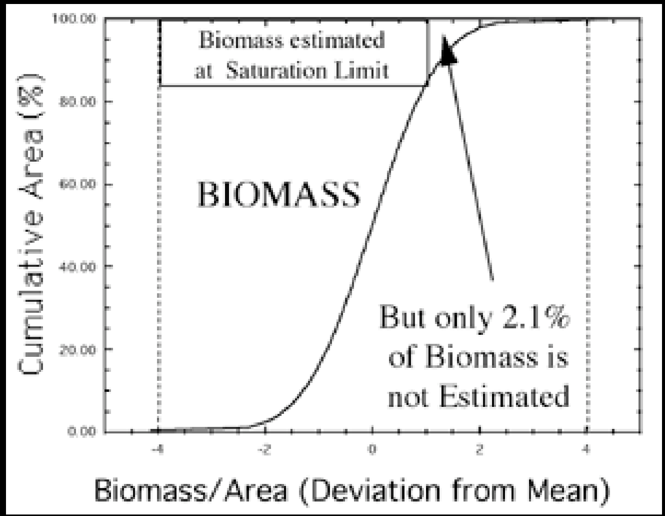


Polarimetric P-band



Global Biomass from L-band Polarimetric Measurements only



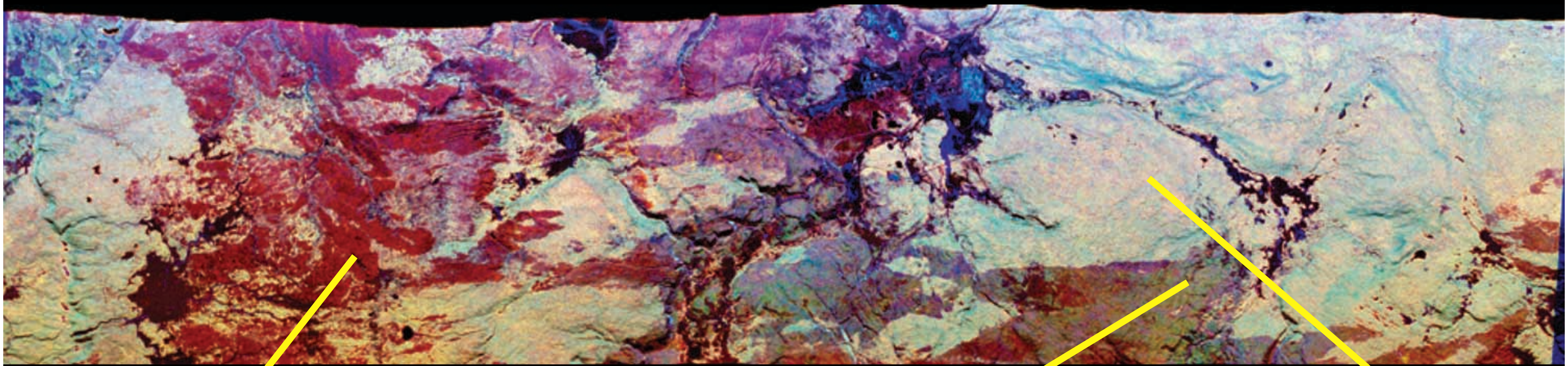


48 Forest types Total C density	Forestland Area_kha	Percent of total forestland	Timberland area_kha	Growth C tph
1) 0-25 t/ha	72,012	28.62%	44,008	0.00
2) 25.01-50 t/ha	55,771	22.17%	46,640	0.94
3) 50.01-100 t/ha	86,023	34.19%	78,729	1.30
4) 100.01-200 t/ha	32,641	12.97%	29,092	1.38
5) 200.01+ t/ha	5,111	2.03%	3,948	1.84
Total /average	251,558		202,416	0.78

Biomass Stock over Northern Boreal & temperate Forests up to 200 Mg/ha with required 10-20% accuracy.
Tropical secondary forests up to 150 Mg/ha with required 10% accuracy.
Other structural measurements: canopy roughness from texture analysis, and canopy fuel load.

Mapping Disturbance and Recovery

Yellowstone National Park



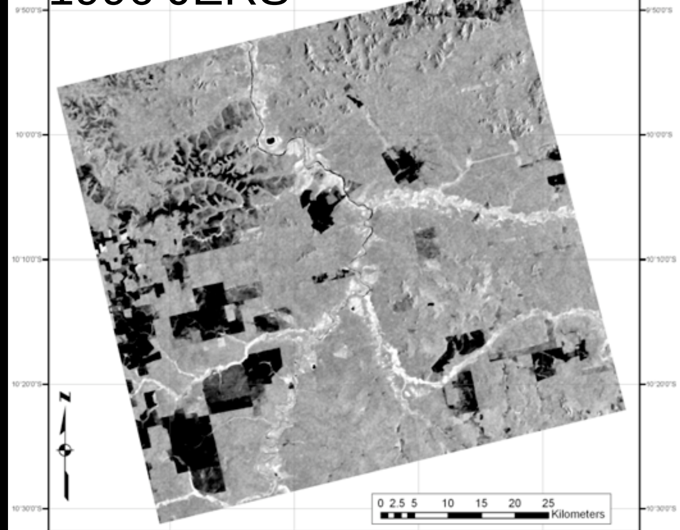
2003 Burn

1988 Burn

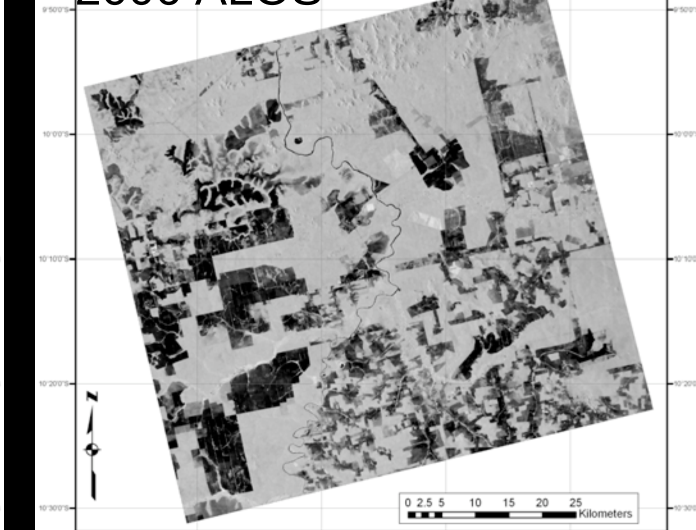
Pine Beatle Disease

Mapping of Disturbance and Recovery
Amazon Example

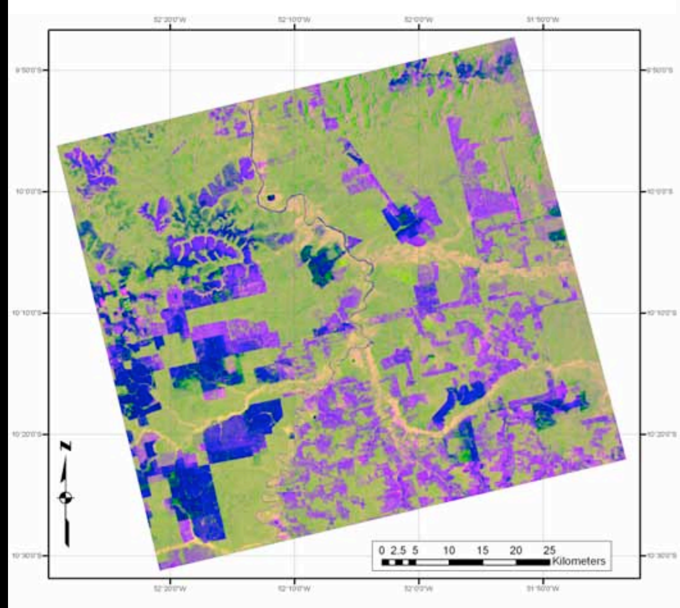
1996 JERS



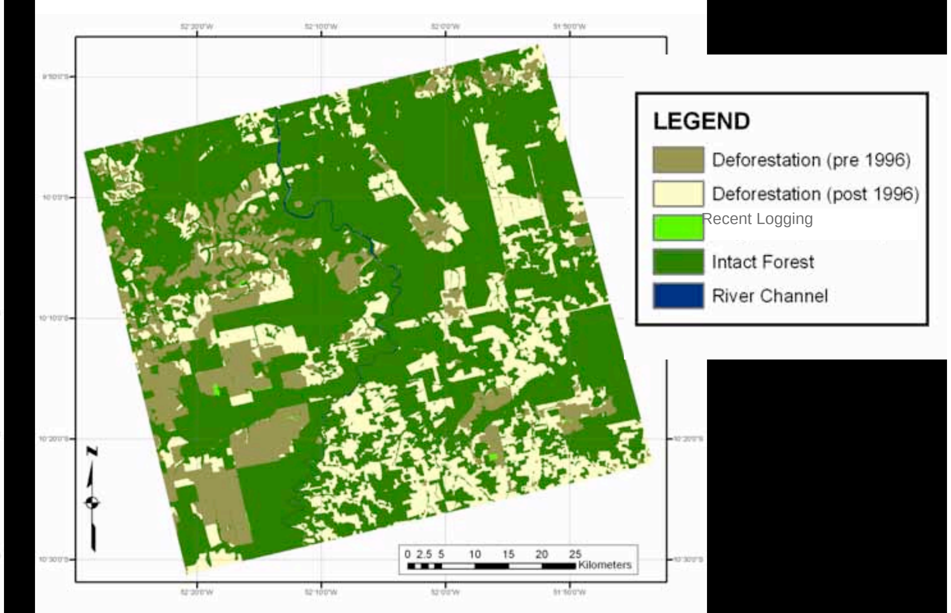
2006 ALOS



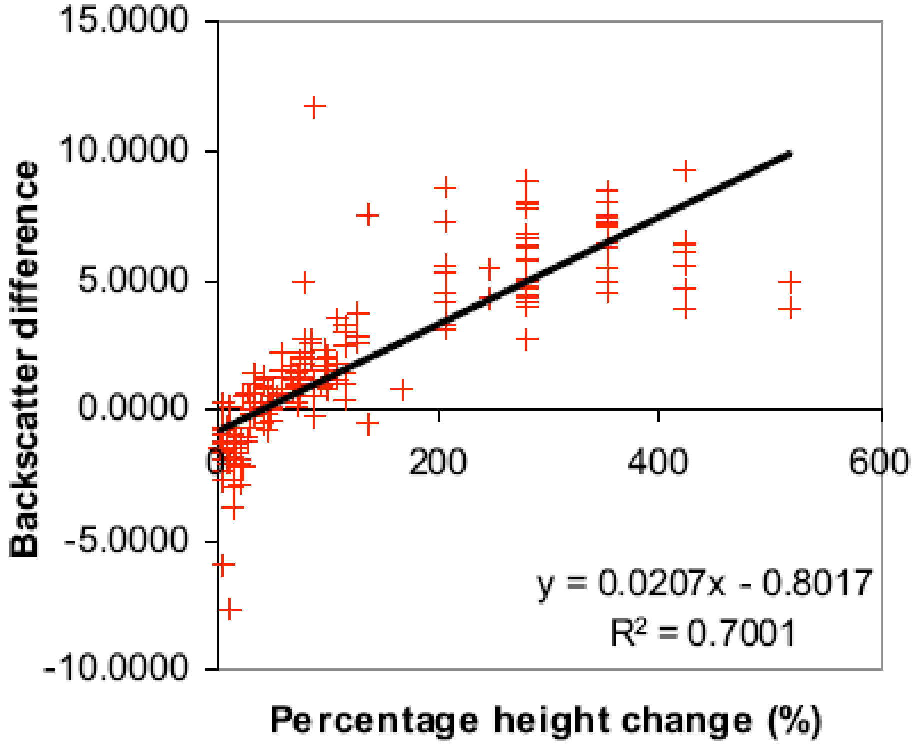
2006/1996 Color Composite

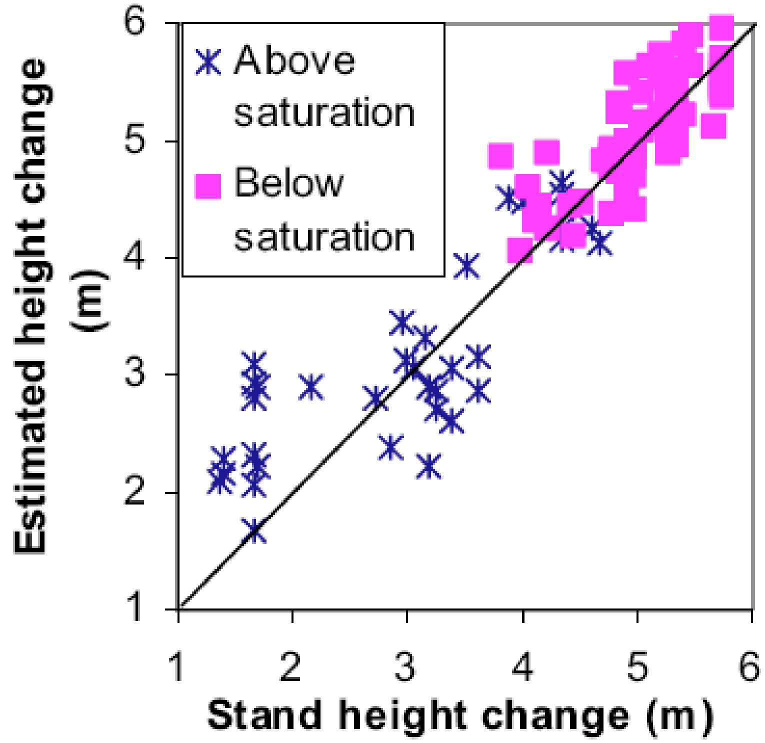


Radar Change Detection



Monitoring Biomass Change





	RMSE	PRMSE(%)	R^2
Percentage height change (%)	46.27	9.00	0.88
Percentage volume change (%)	7.77	8.86	0.94
Height change (m)	0.45	10.27	0.87
Volume change (m)	16.91	15.98	0.46

Estimate of change in height between 1991 and 2000 using change in L-band (HV) backscatter
Rowland et al. 2003.

Summary

Polarimetric Backscatter Measurements of Forest Biomass and Changes (L-band SAR)

1. Estimate of Global Forest Aboveground Biomass
   - Boreal Forest (+/- 10% accuracy)
   - Temperate Forest (+/- 10-20% accuracy)
   - Tropical Forest (AGB<150 Mg/ha, (+/- 10% accuracy)
   - 25 m with 8 looks (products at 100 m resolution)
2. Disturbance & Recovery
   - Secondary regeneration in all ecosystems
   - Mapping disturbance (fire, deforestation, hurricane, flooding)
   - Biomass change (~5 Mg/ha/yr in boreal & temperate forests)
3. What is to be done:
   - Improve the state of algorithms for three ecosystems
   - Develop fusion approach with lidar sampling of height or biomass
   - Improve algorithms for quantitative measurements of disturbance & recovery
   - Evaluate the outcome in terms of residual errors in biomass or structure

InSAR Measurements

$\Delta\phi$: phase difference between antenna A1 and A2 :

From Geometry :

$$h_v + h_g = H - \rho\cos\theta$$

$$h_v = H - h_g - \boxed{\rho\cos\left(\sin^{-1}\left(\frac{\lambda\Delta\phi}{4\pi B}\right)\right)}$$

h_v : vegetation height weighted by density)

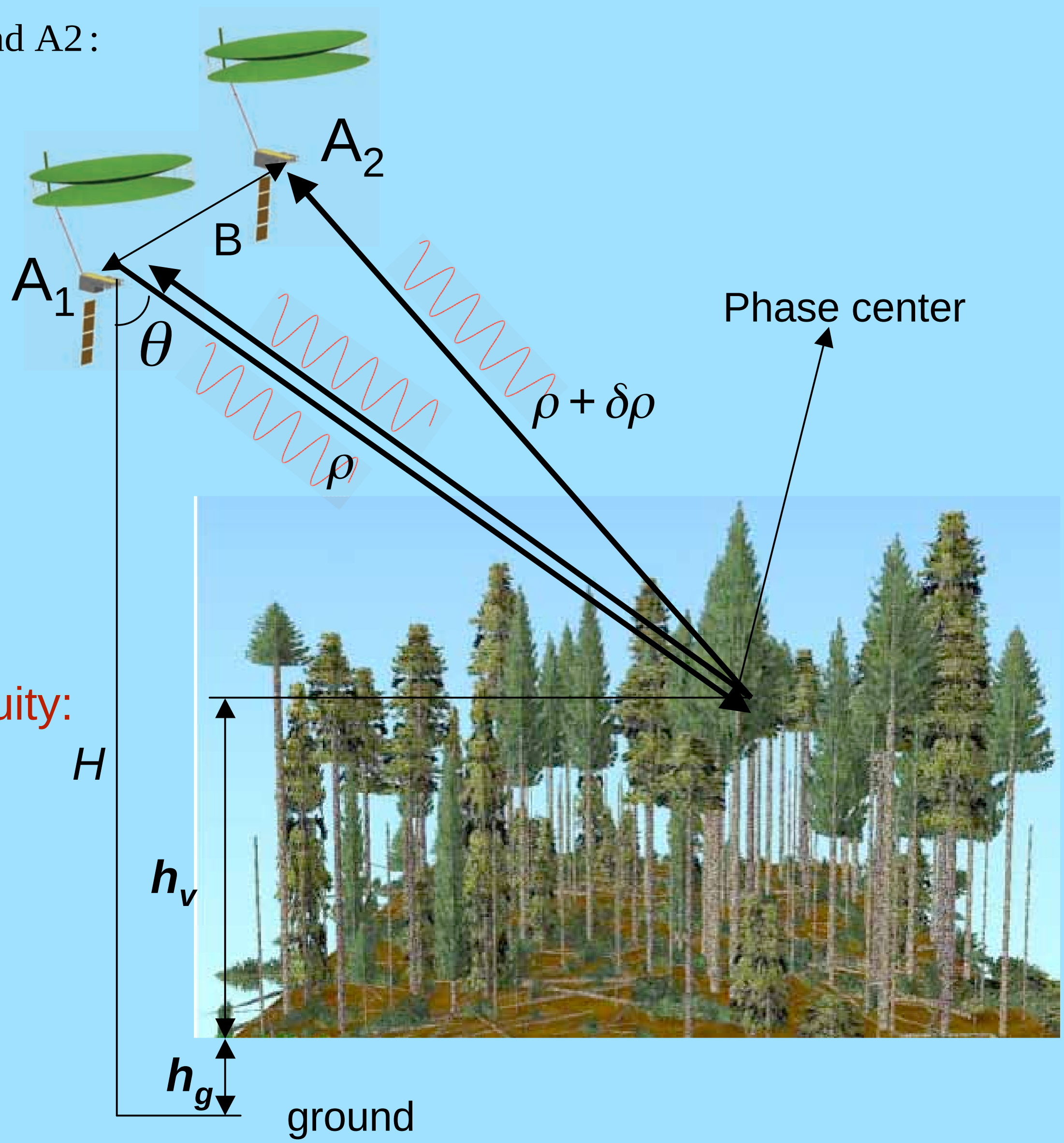
h_g : ground height (unknown!)

Measurement Variables:
Polarization, Baseline, Frequency

Removing single observation ambiguity:

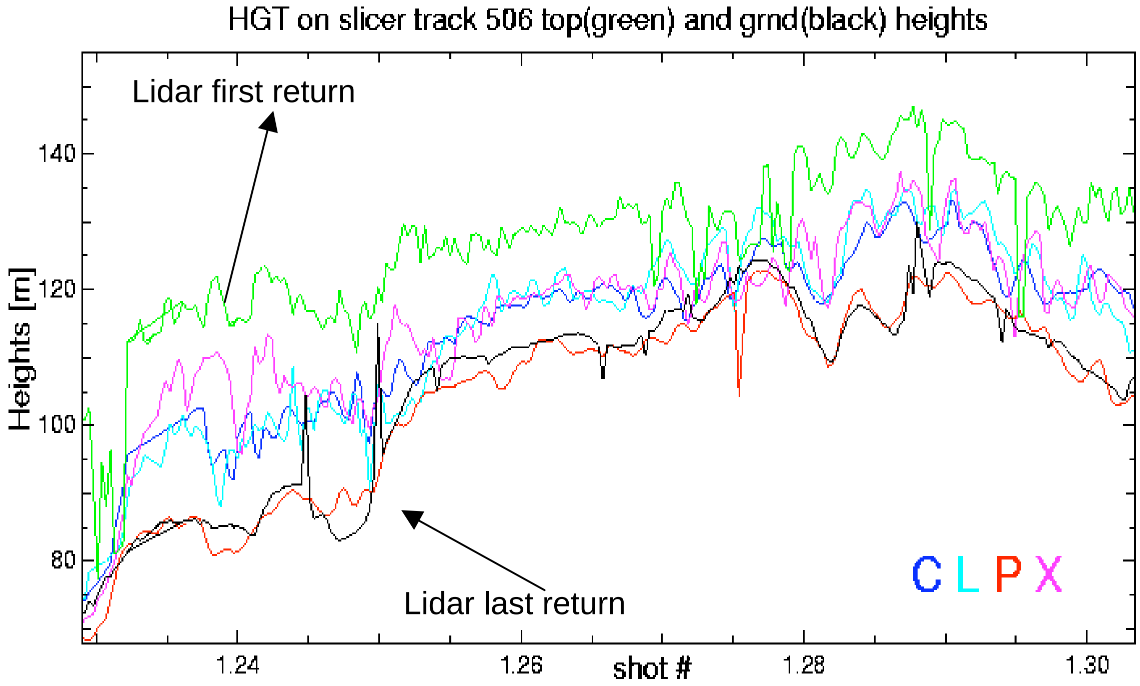
Add external calibration:
ground topography
Field or Lidar measurements

Add additional InSAR observations:
InSAR obs at multiple pol (Pol-InSAR)
Multiple baselines
Multiple frequencies



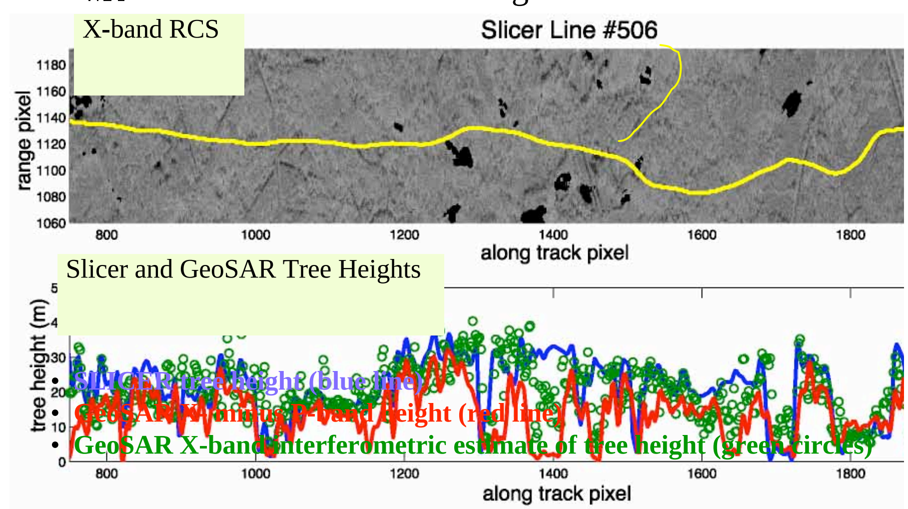
Use of Interferometry for Estimating Vegetation Height

L-, C-, and X-band all penetrate into the canopy about the same distance. P-band phase center is at the canopy base



Comparison between LIDAR

and Radar Height Estimates

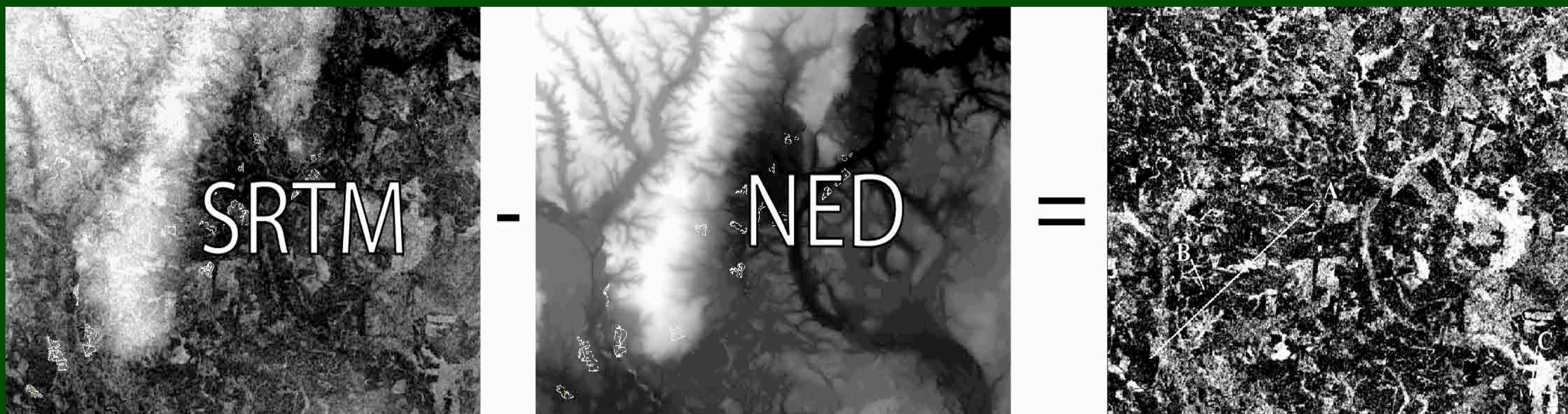


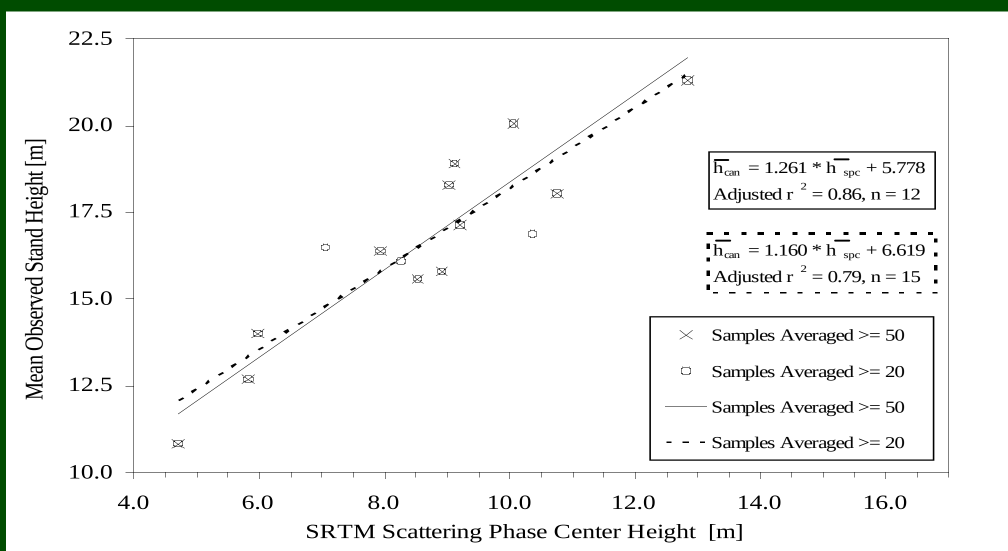
Siquiera et al. 2006

InSAR Measurements Options:

1. Single Frequency, single pol.
2. Polarimetirc InSAR
3. Multiple baseline
4. Multiple Frequency

Pilot Studies for SRTM Height Retrieval: Georgia

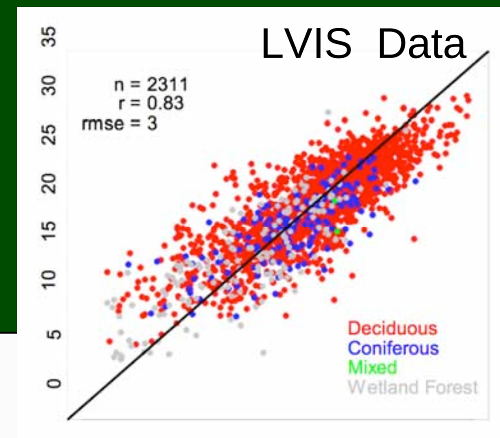


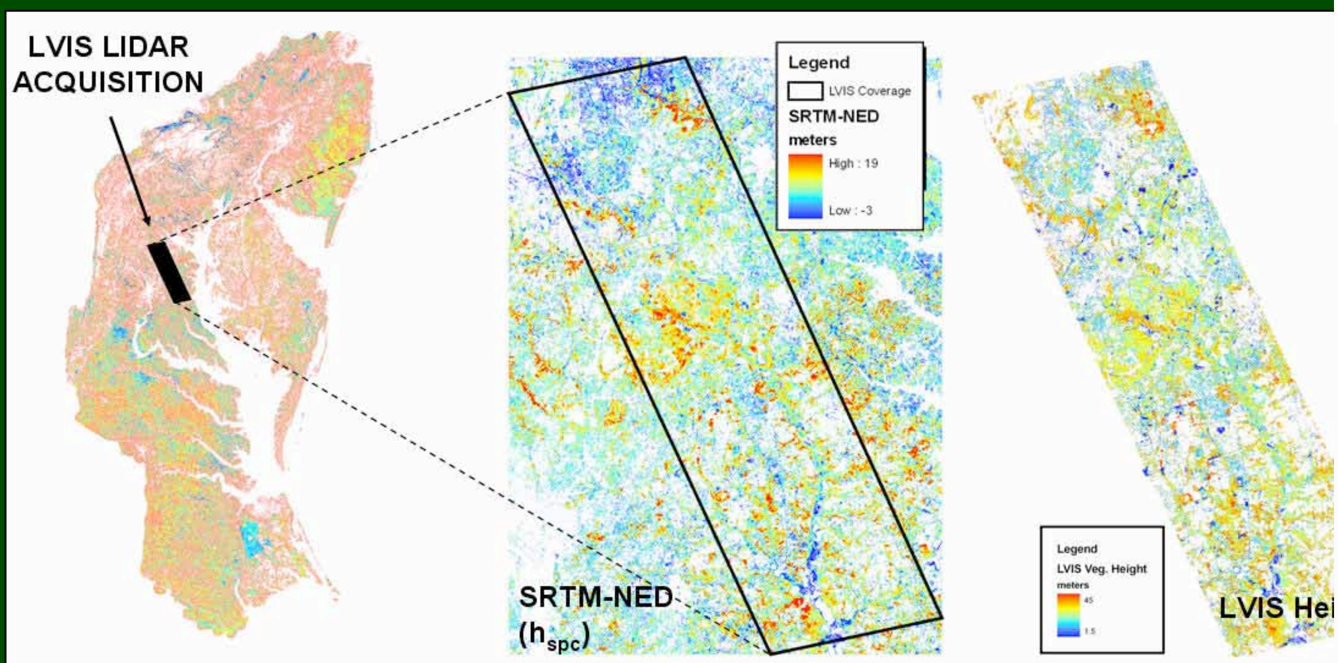


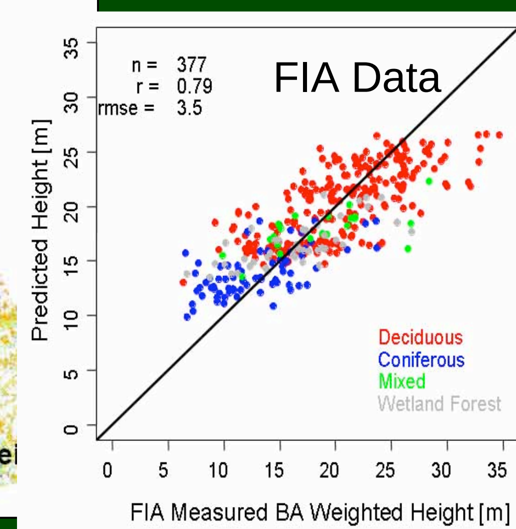
- Kellndorfer, J.M., W.S. Walker and L.E. Pierce, M.C Dobson, J. Fites, C. Hunsaker, J. Vona, M. Clutter, "***Vegetation height derivation from Shuttle Radar Topography Mission and National Elevation data sets.***" Remote Sensing of Environment, Vol. 93, No. 3, 339-358, 2004.

Pilot Research: Lidar as a Reference Data Source

- LVIS Data were used as a source for reference heights to develop models with the NBCD 2000 predictor layers
- The model was applied in the entire mapping zone 60
- Validated with FIA plot-based height measurements across the zone



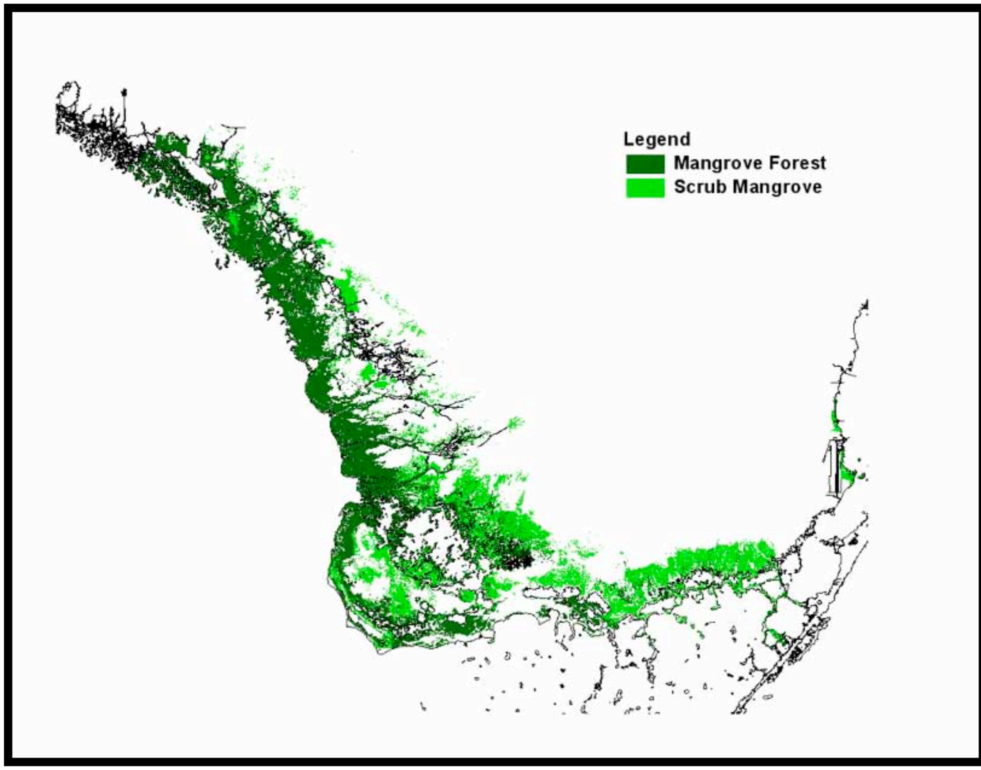




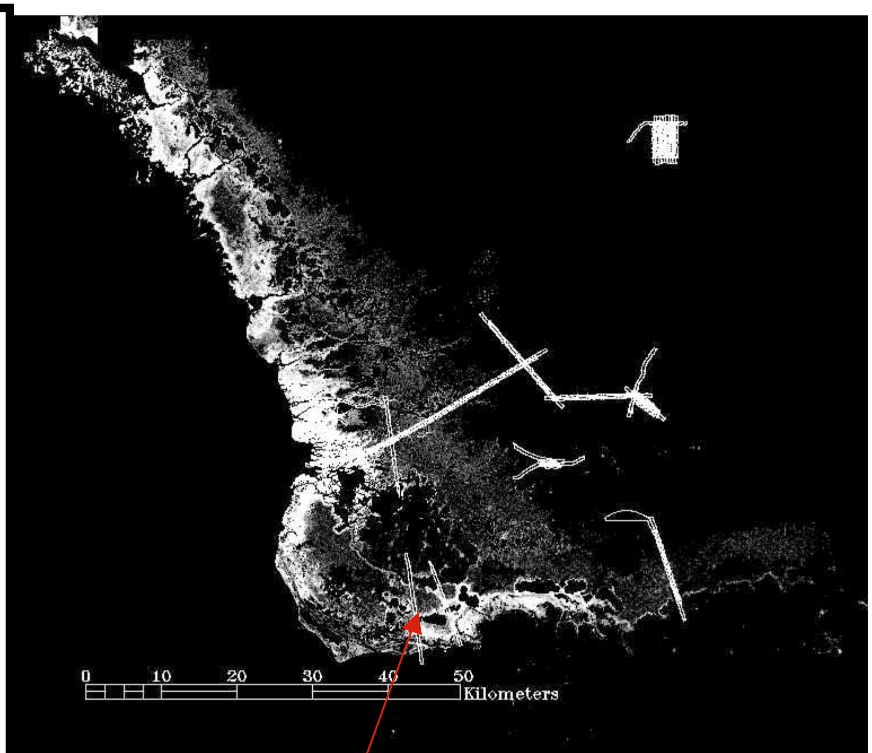
Mangrove Biome Example

Combining SRTM Ht. Data with Lidar

Everglades National Park



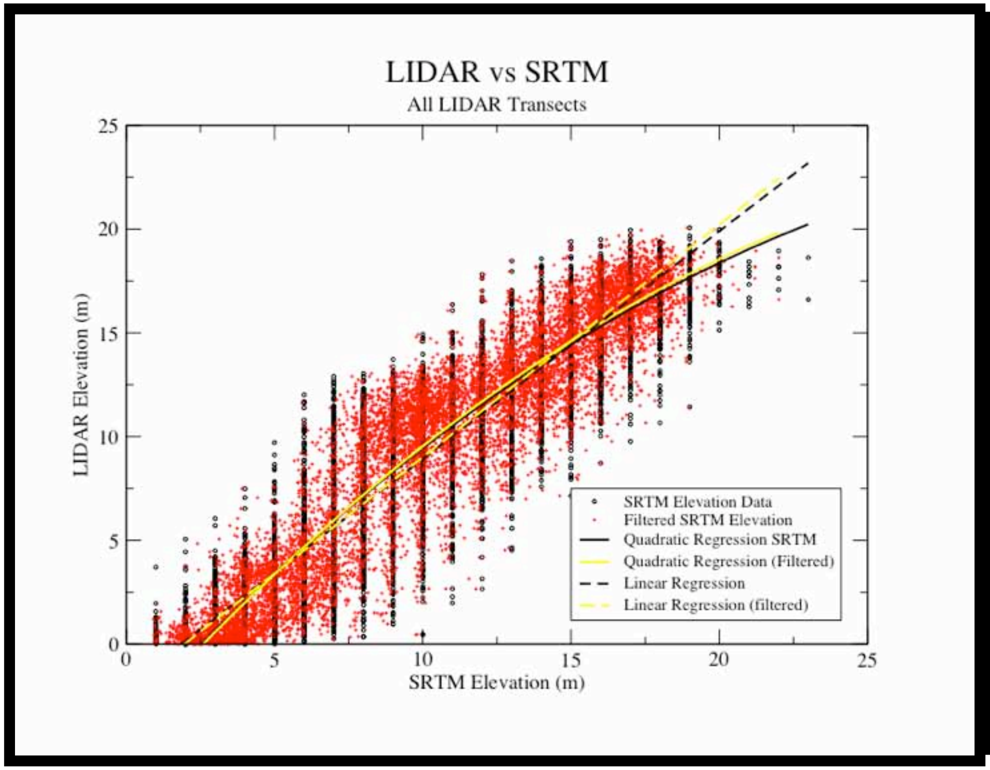
SRTM Ht. map with lidar tracks overlaid

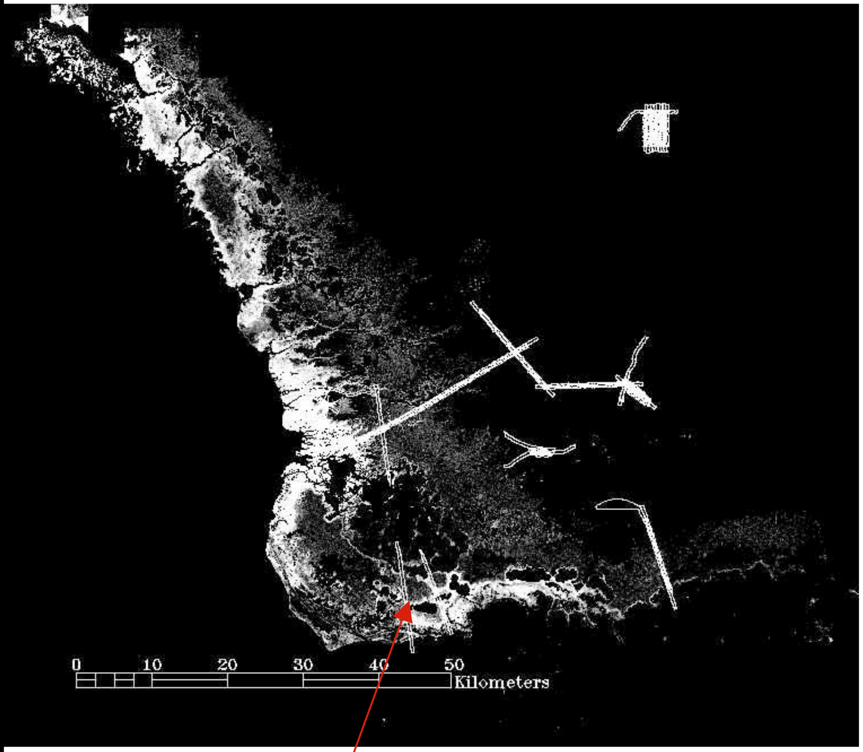


Single ICEsat Transect

Mangrove Biome Example
Combining SRTM Ht. Data with Lidar

Everglades National Park

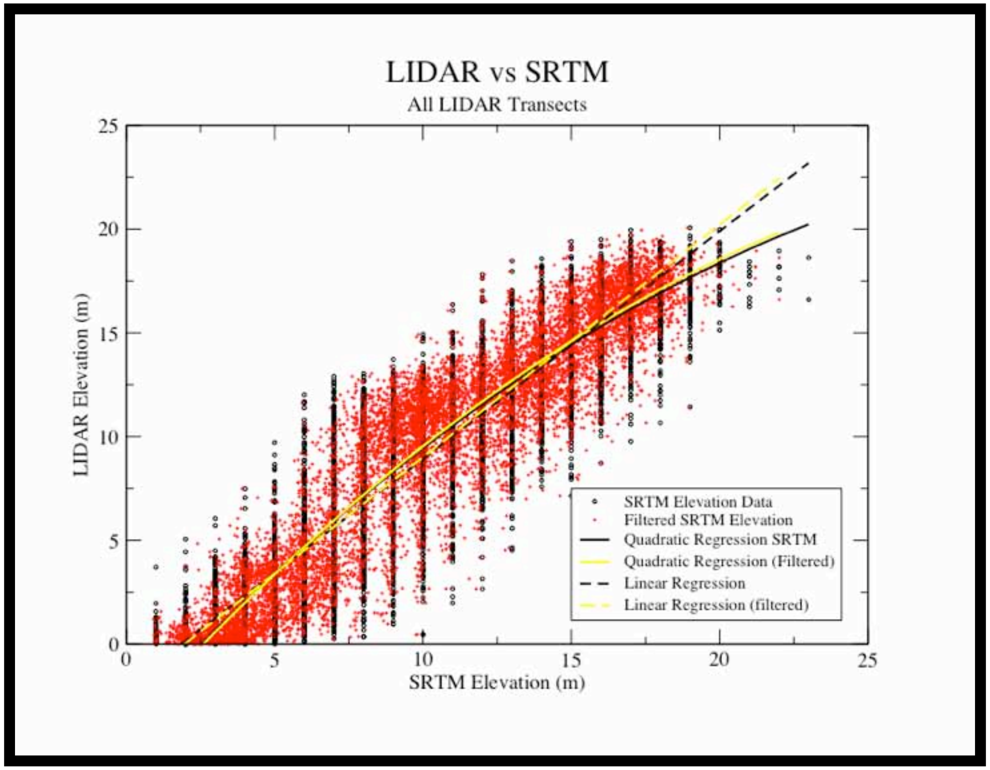




Single ICEsat Transect

SRTM-derived Ht. error is ~ 2m per 30m pixel

Mangrove Biome Example
Biomass maps derived from SRTM Ht. Data



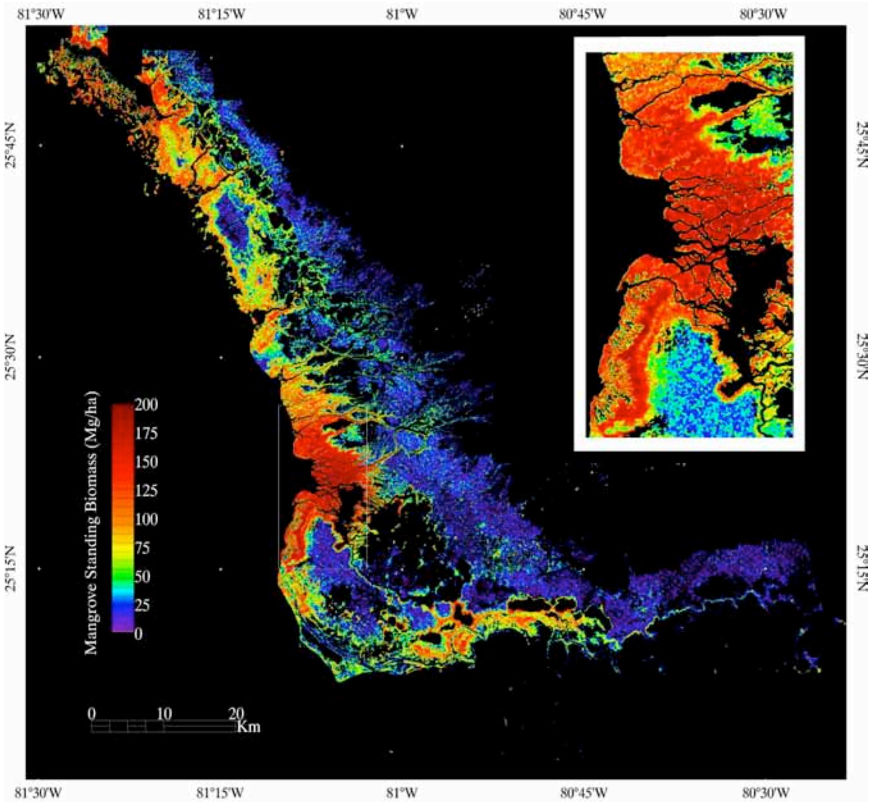
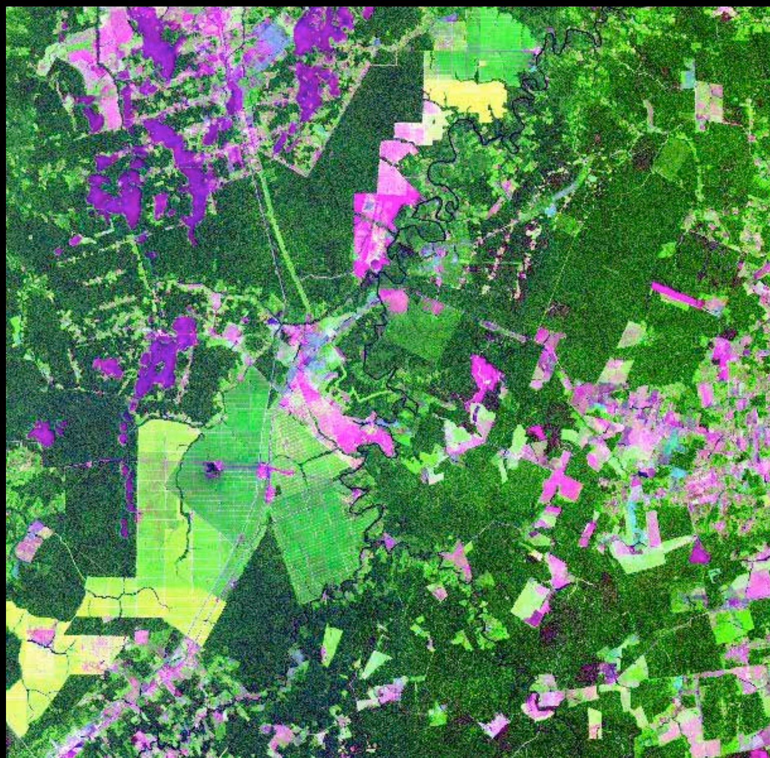


Figure 3: Biomass Map built using SRTM mean tree height estimate and biomass-height regression obtained from field data. We estimated the total biomass contained in Mangrove Forest of the ENP to 5.6Mt.

Marc Simard et al., "Mapping Height and Biomass of Mangrove Forests in Everglades National Park with SRTM Elevation Data", *Photogrammetric Engineering and Remote Sensing*, SRTM special issue, April 2006

Measurement of Vegetation Height from InSAR
Amazon Forest

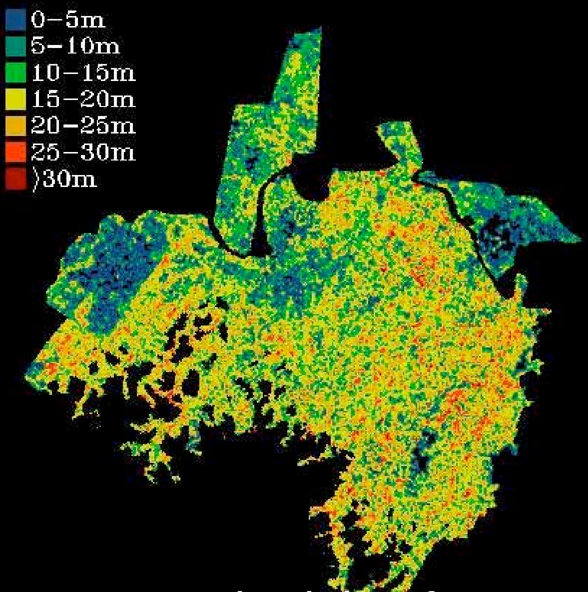


Landsat TM

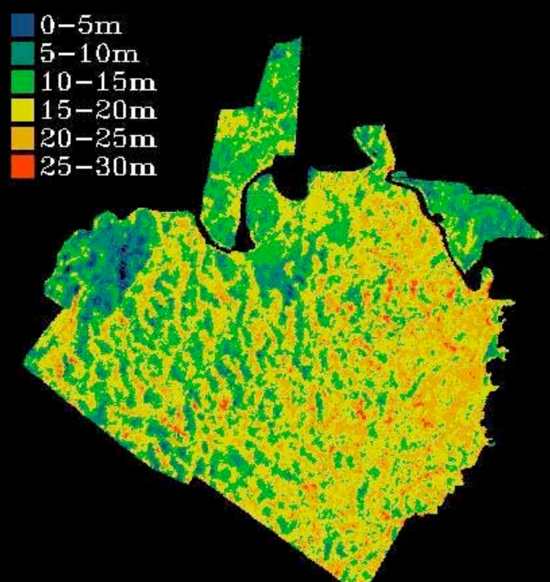
SRTM derived Height

Saatchi et.al. 2007

Vegetation height derived from InSAR over La Selva Biological Station.

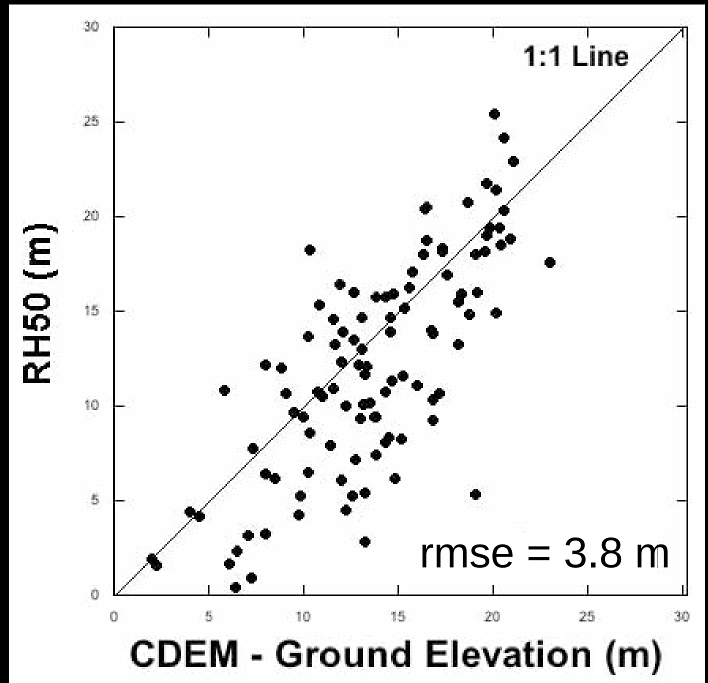


LVIS RH50 (Height of 50% energy)

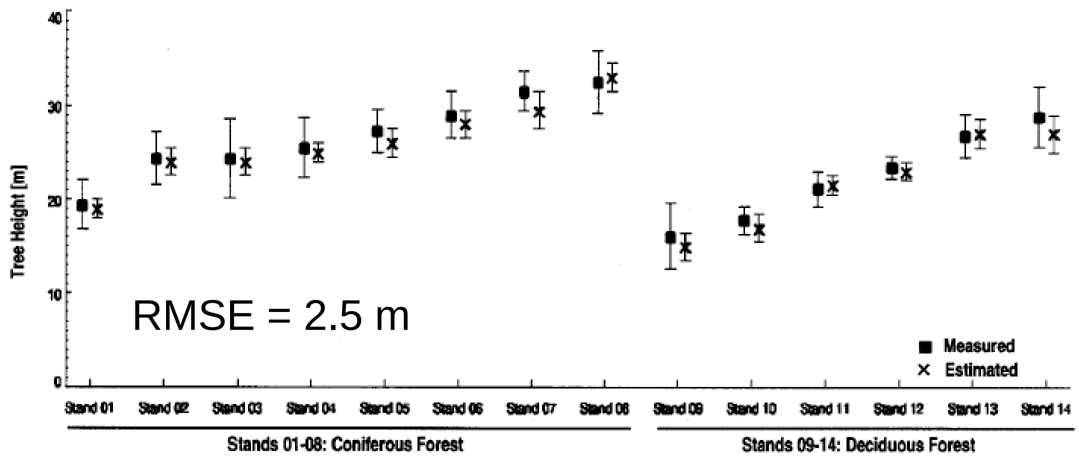


InSAR Average Height

InSAR derived vegetation height
Weighted by forest density is
Highly correlated with height at
50% energy of lidar waveform

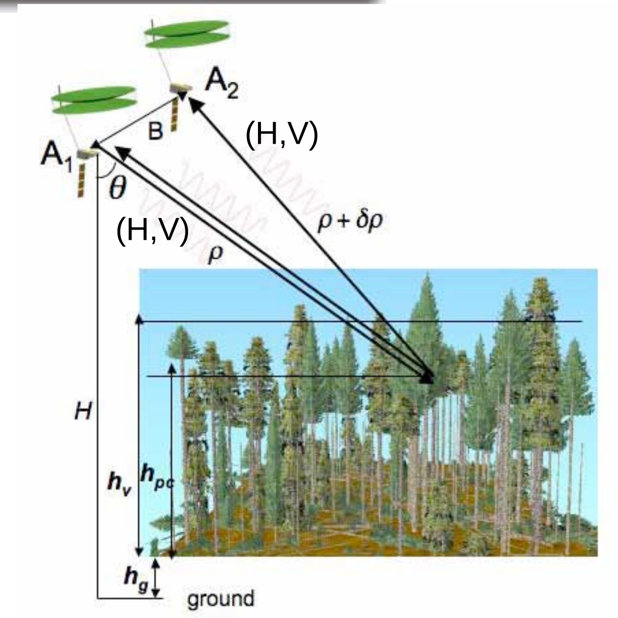


Removing Single-Observation Ambiguity: Pol-InSAR



Airborne, L-band

Papathanassiou and Cloude 2001

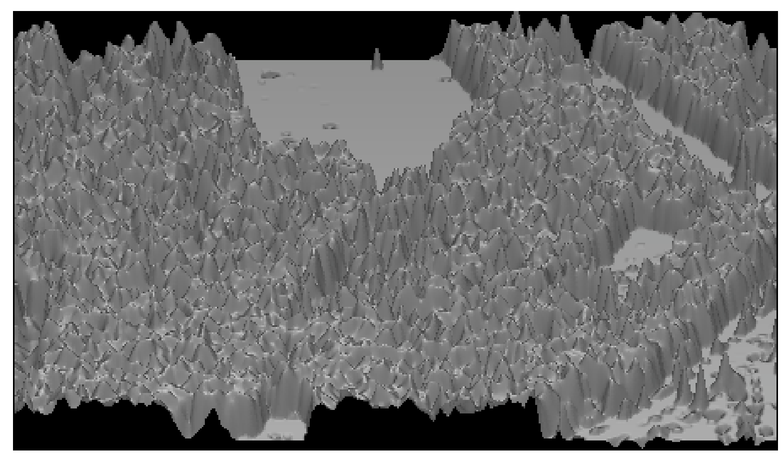


$$\gamma = e^{i\phi_0} \frac{\int_0^{h_v} f(z) e^{ik_z z} dz}{\int_0^{h_v} f(z) dz}$$

ϕ_0 = ground phase

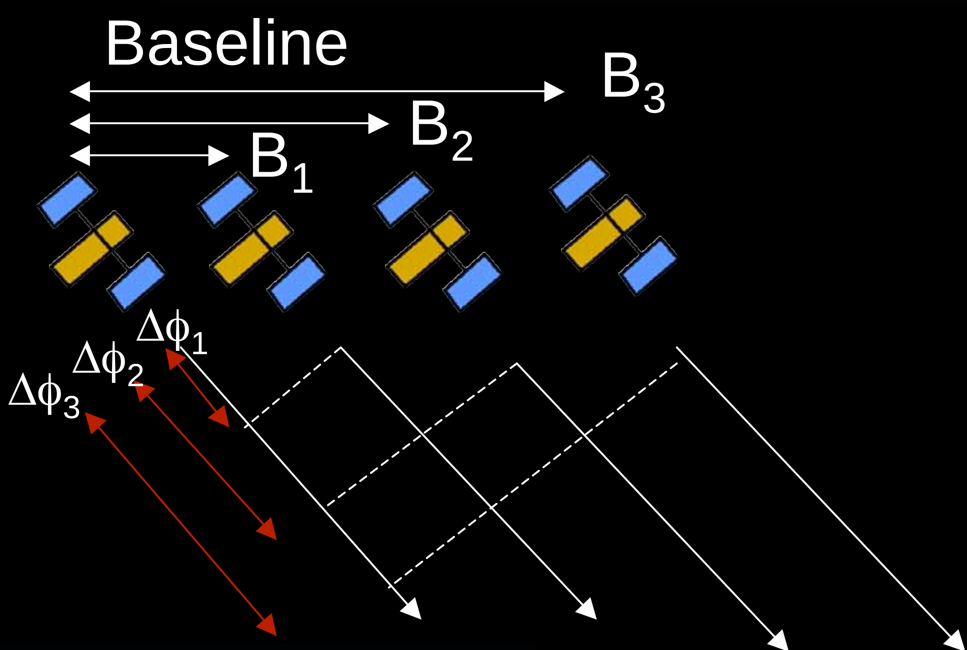
$f(z)$ = vertical profile as seen by radar

$$\begin{bmatrix} h_v \\ \phi_0 \\ \alpha(H,V) \\ \mu_s(H,V) \end{bmatrix} = [M]^{-1} \begin{bmatrix} \gamma_{HH} \\ \gamma_{HV} \\ \gamma_{VV} \end{bmatrix}$$

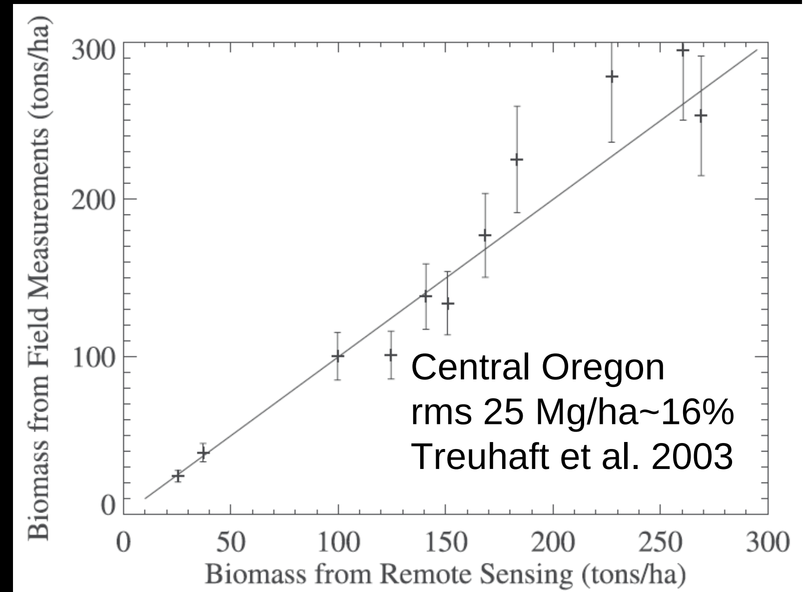


Perspective View of Forest Height

Removing Single-Observation Ambiguity: Multiple Baselines

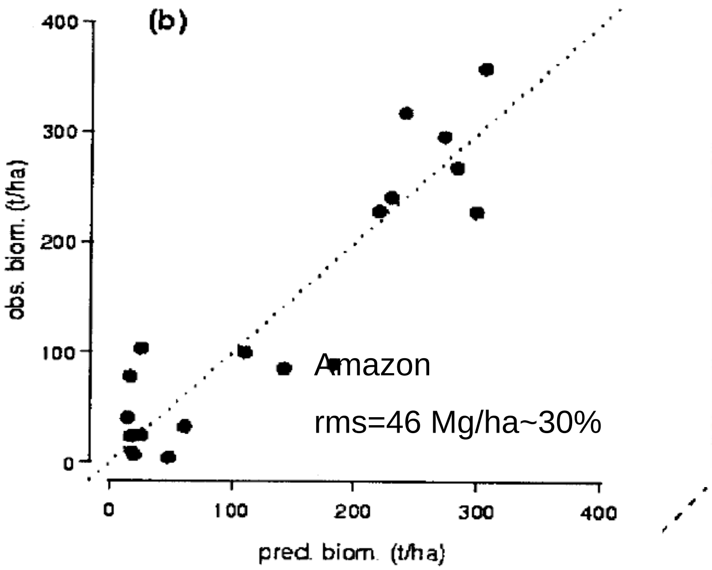


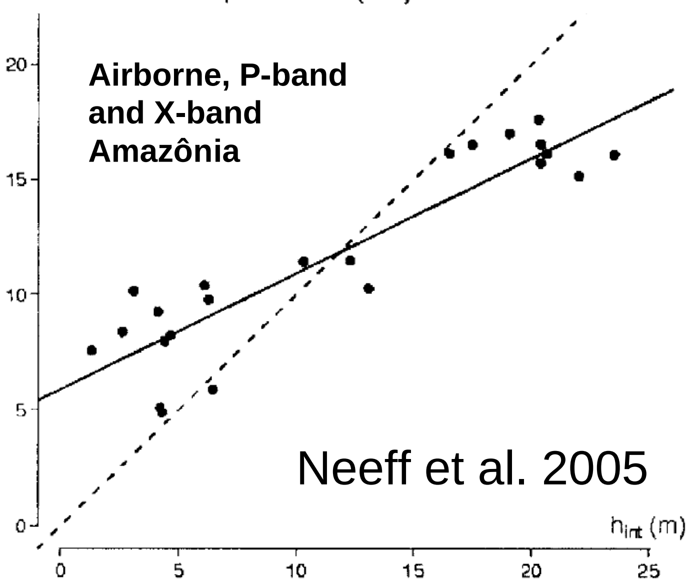
$$h_v = H - h_g - \rho \cos\left(\sin^{-1}\left(\frac{\lambda\Delta\phi}{4\pi B}\right)\right)$$



Removing Single-Observation Ambiguity: Multiple Frequencies

Tropical Forest

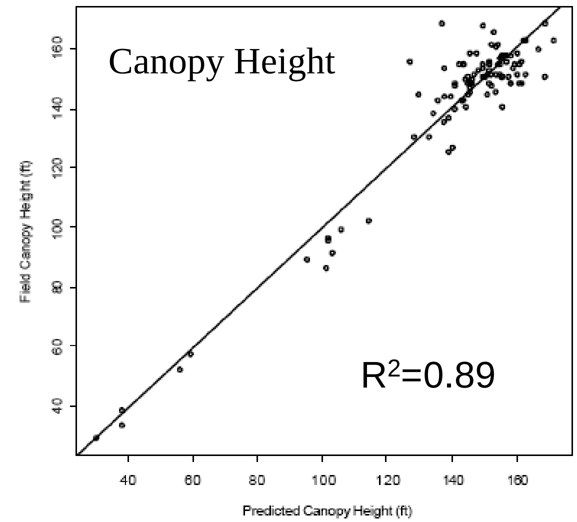


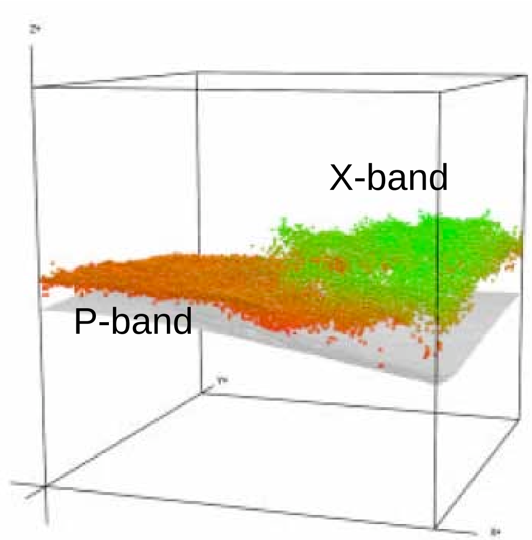


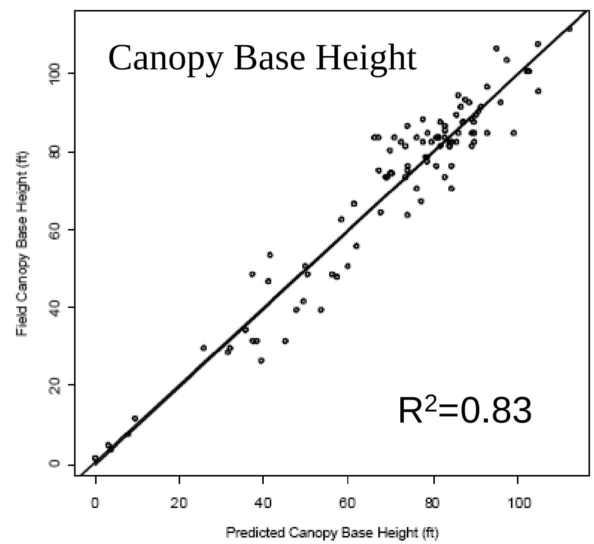
Temperate Forest

Andersen, et al. 2004

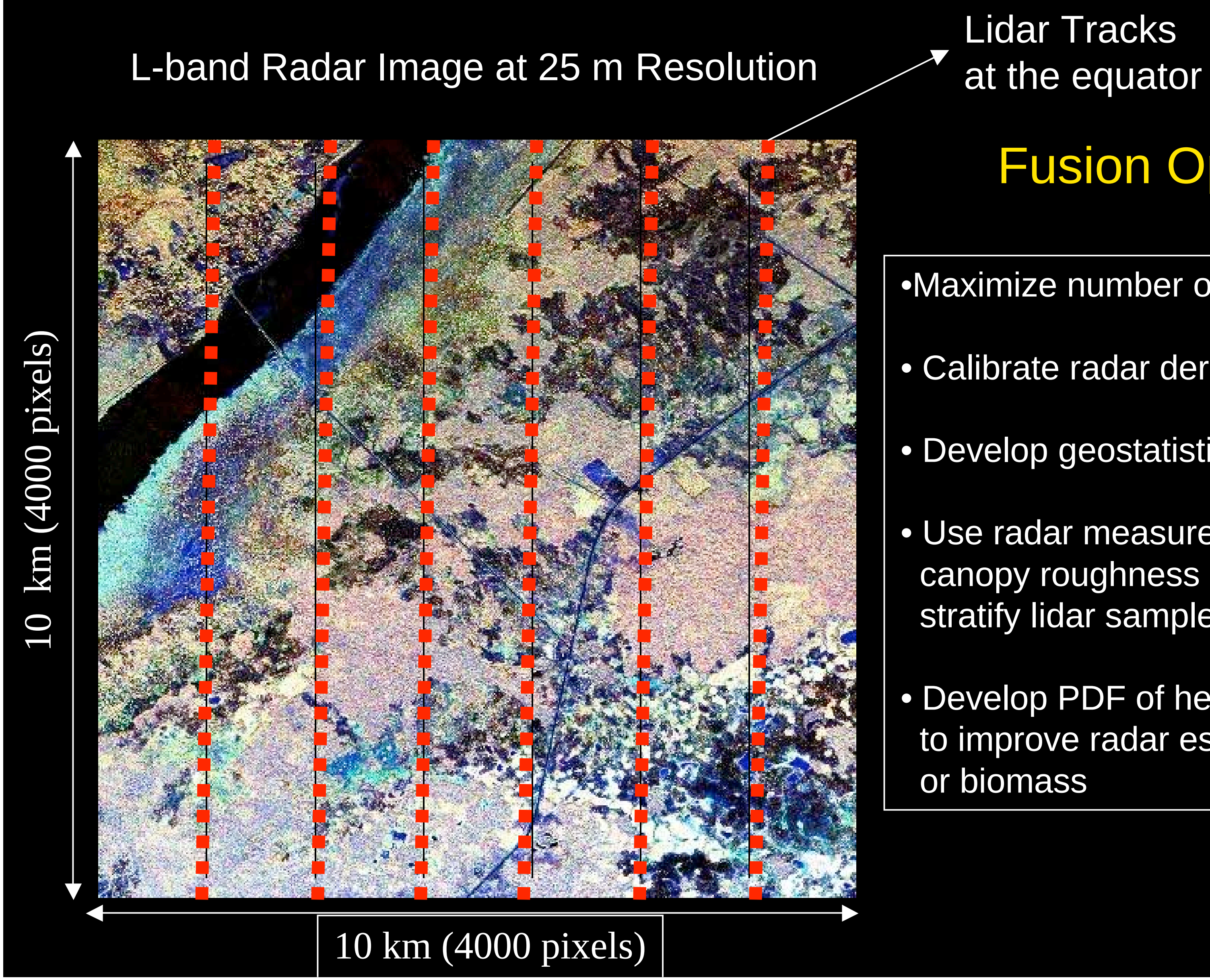
Capital State Forest,
Washington USA







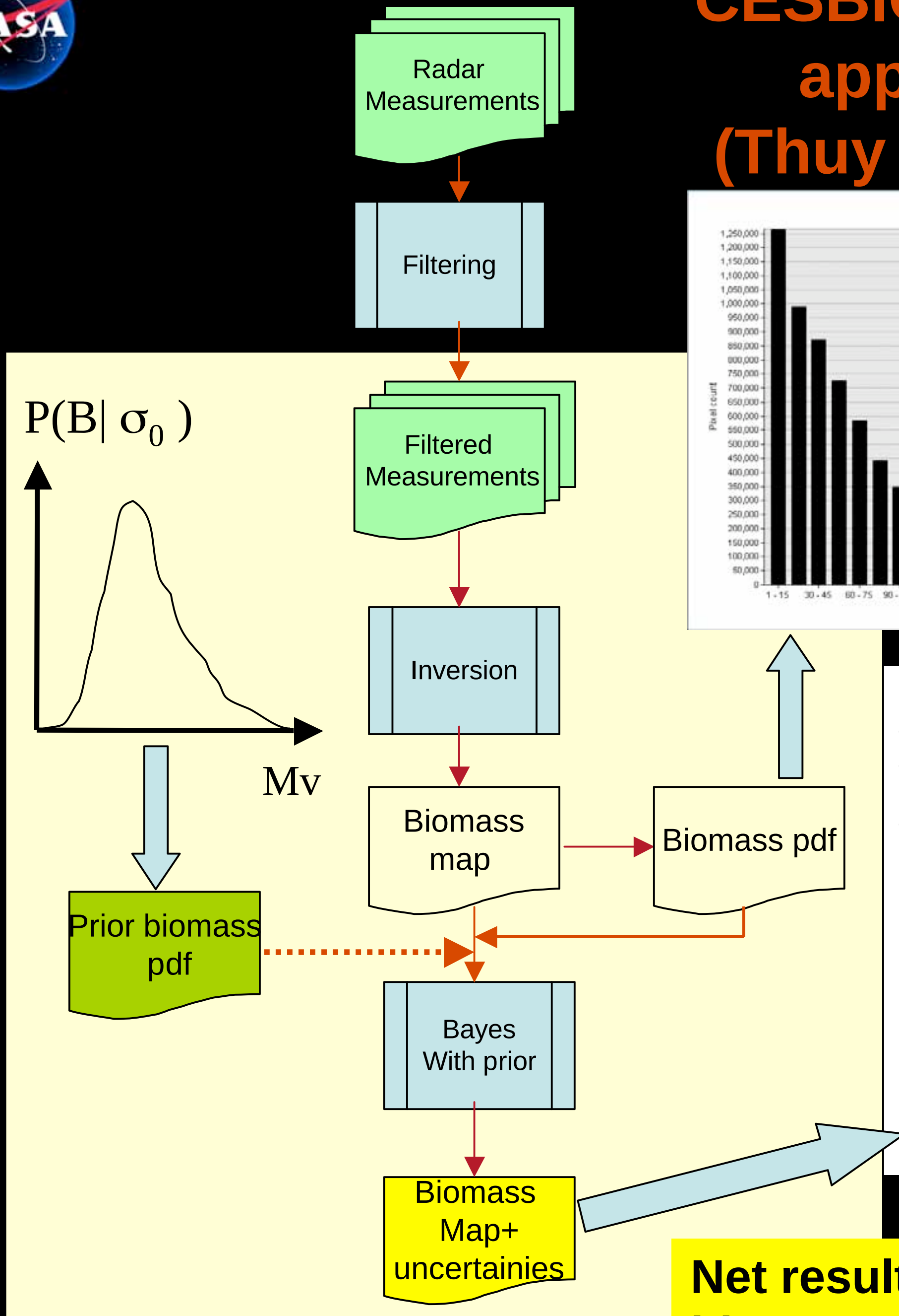
Radar & Lidar Fusion

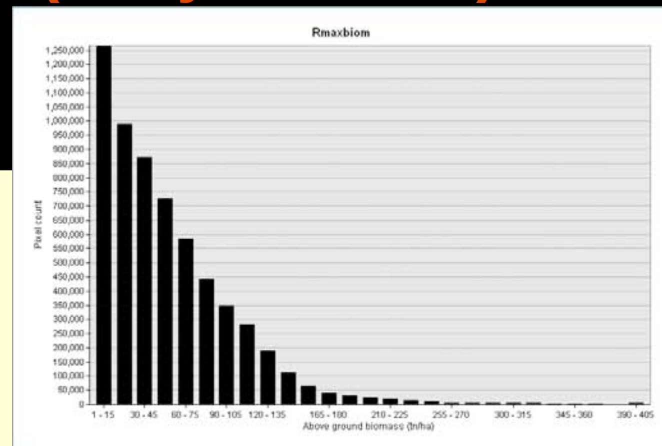


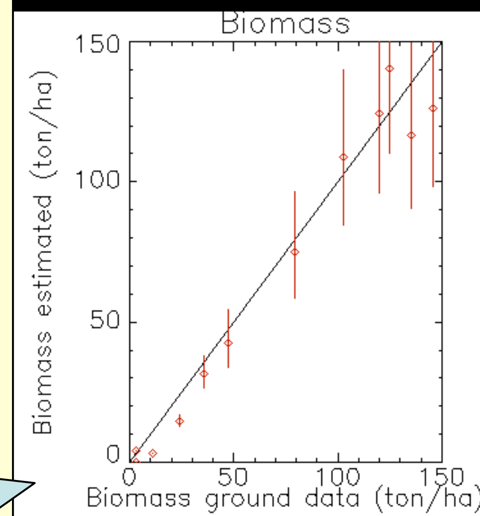
Fusion Options

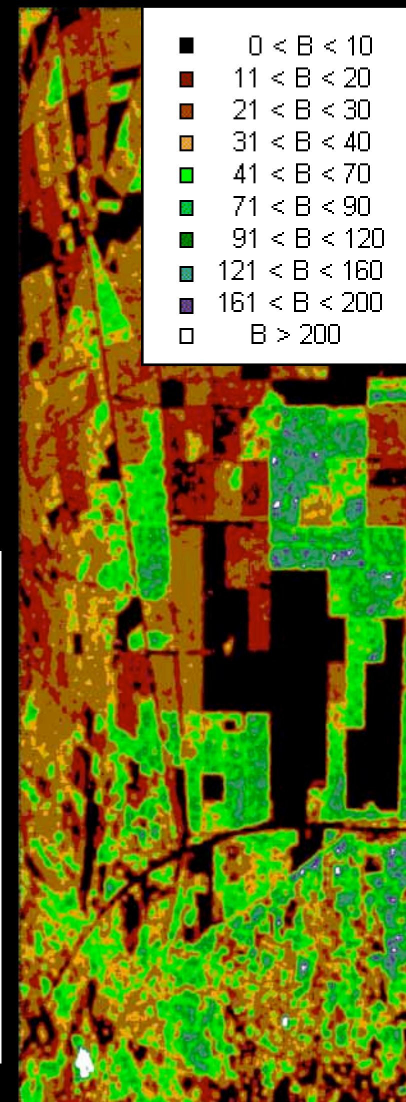
- Maximize number of Lidar samples
- Calibrate radar derived height by Lidar
- Develop geostatistical fusion
- Use radar measurements of height canopy roughness (texture) to stratify lidar samples
- Develop PDF of height or biomass to improve radar estimates of height or biomass

CESBIO group's approach (Thuy Le Toan)



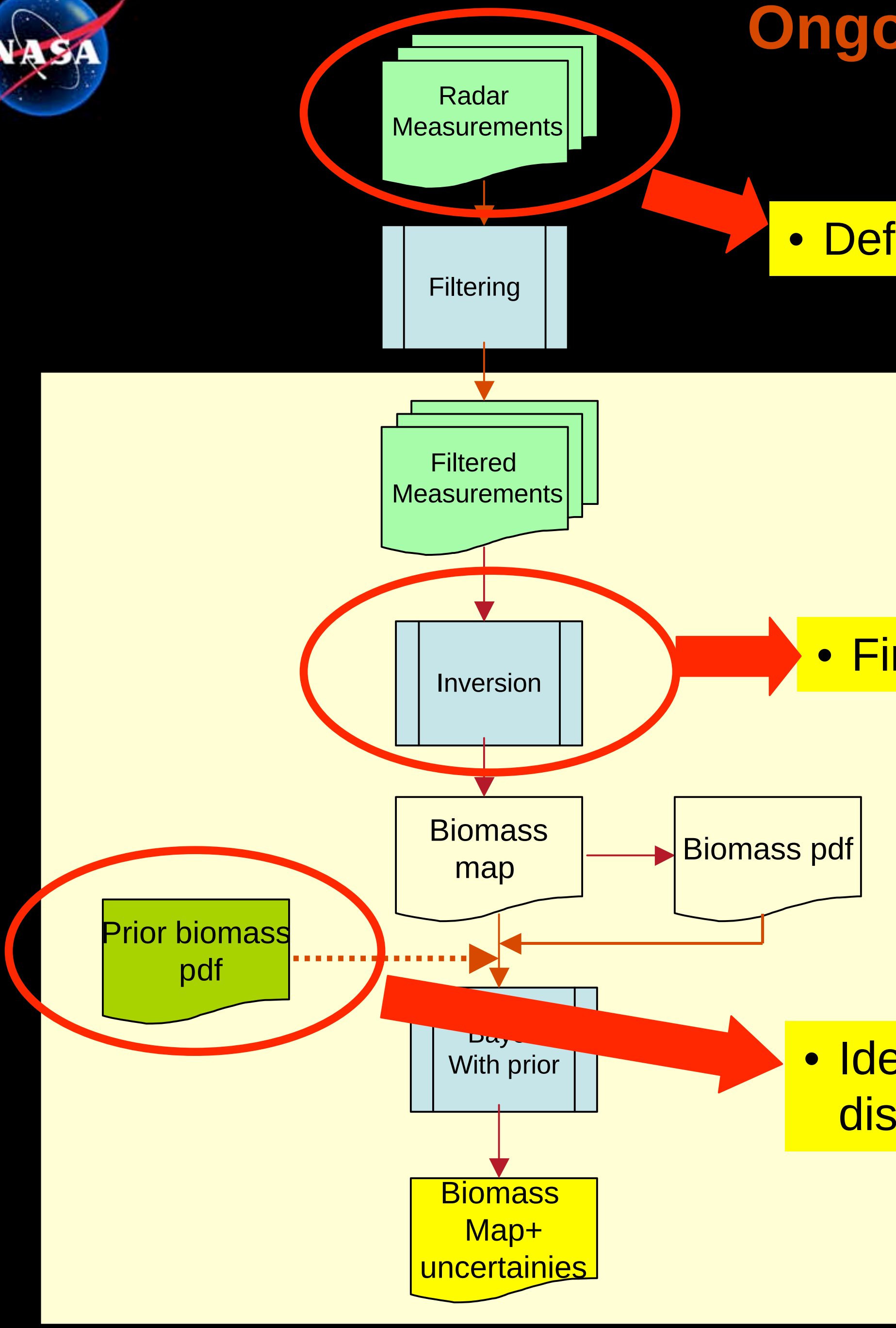






Net result is improvement in biomass estimates by up to 35%

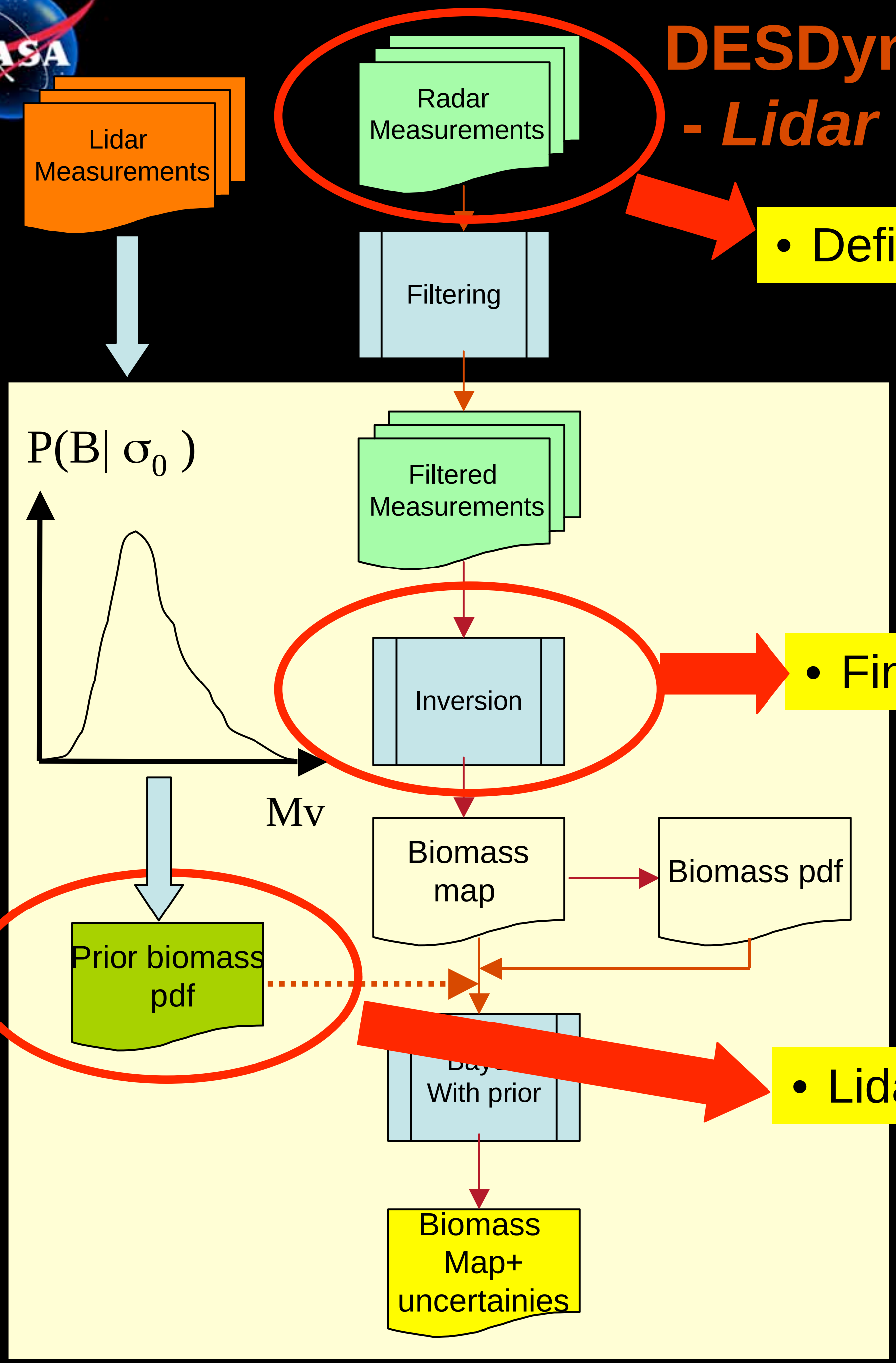
Ongoing research at CESBIO



- Defining the right set of radar measurements
- Fine-tuning the inversion algorithms
- Identifying the best source for a priori distributions of biomass (or tree ht.)

DESDynI Relevance

- Lidar data used to calibrate Radar



- Defining the right set of radar measurements
- Fine-tuning the inversion algorithms
- Lidar as the source for the a priori pdf
- ***General Approach could be used for both Biomass and Tree Ht. estimates***

Chave et al. 2003

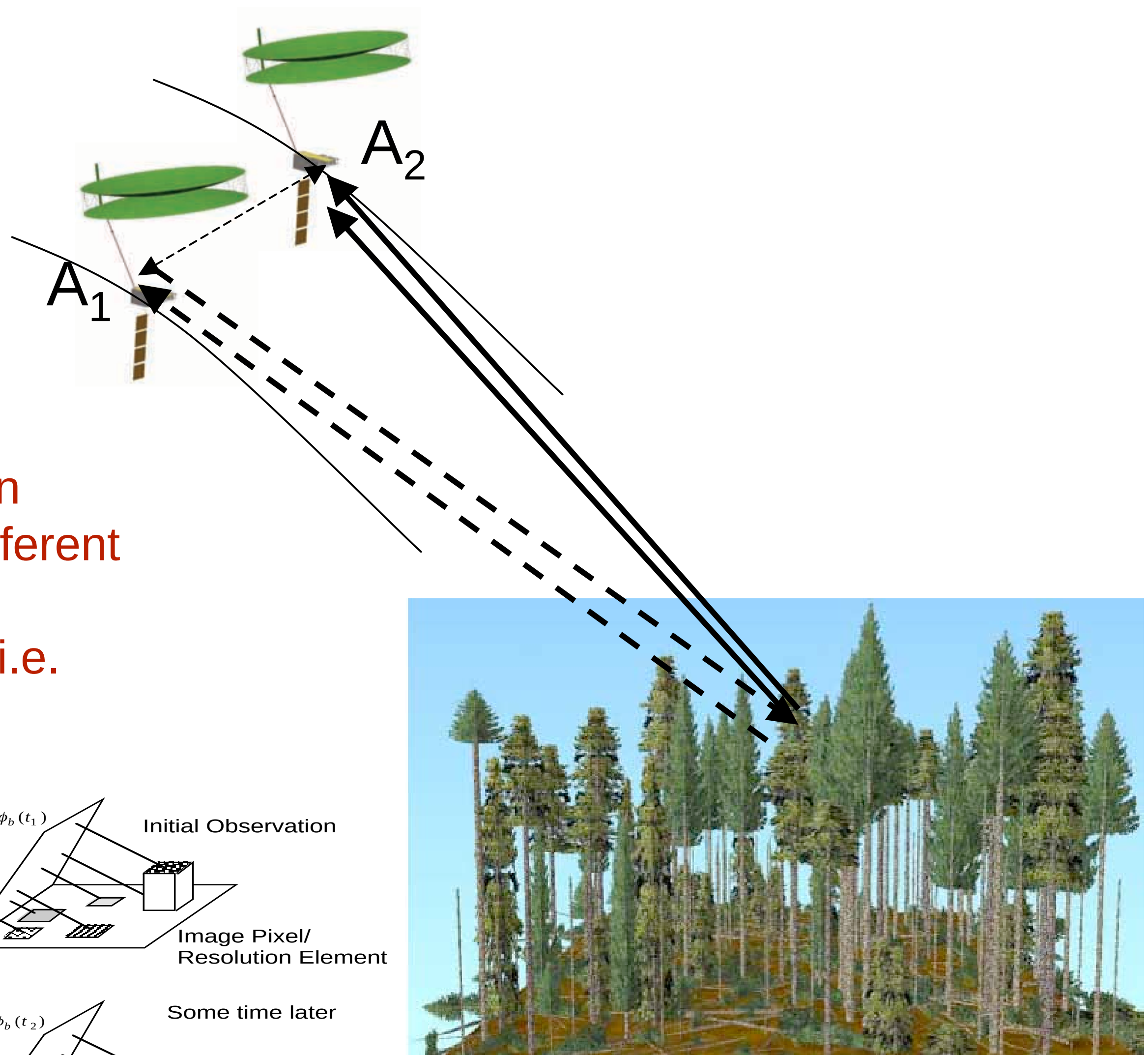
BCI (Panama) 50 ha (500 m x 1000 m) plot data

Subplot size	Number of subplots	CI95	95% CI (in Mg ha^{-1}) from one 1-ha plot	Minimal number of subplots* (Mg ha^{-1})
10 × 10	5000	17.4	123	481
10 × 20	2500	18.7	132	279
20 × 20	1250	20.0	142	160
20 × 50	500	21.4	151	73
50 × 50	200	20.1	142	26
50 × 100	100	22.4	158	16
100 × 100	50	23.5	166	9

*Minimal number of subplots required to know the mean biomass with 20% error (±10%) within the 95% confidence interval.

Number of samples from Lidar Shots

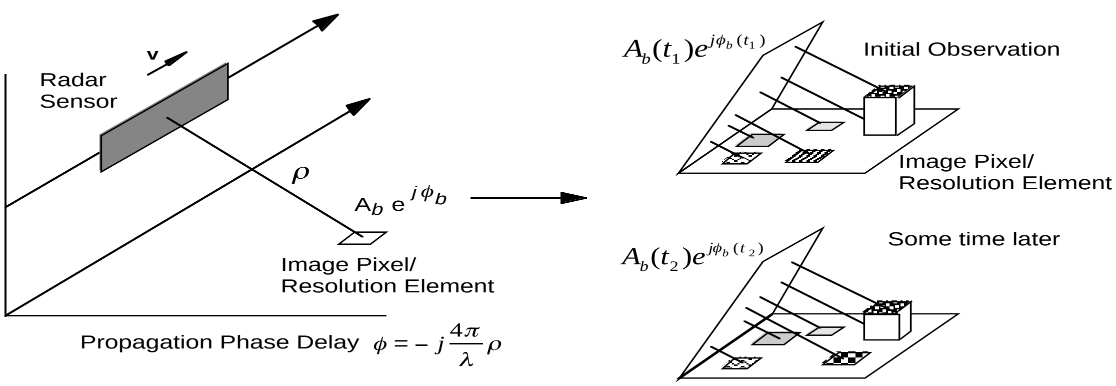
DESDynI InSAR Measurements



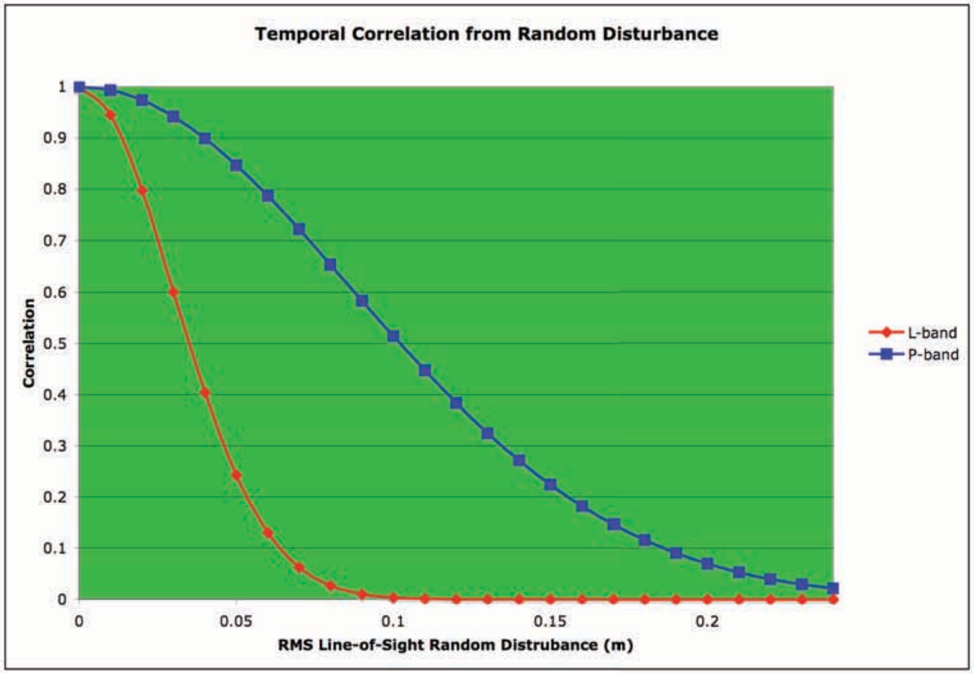
Repeat Pass Interferometry

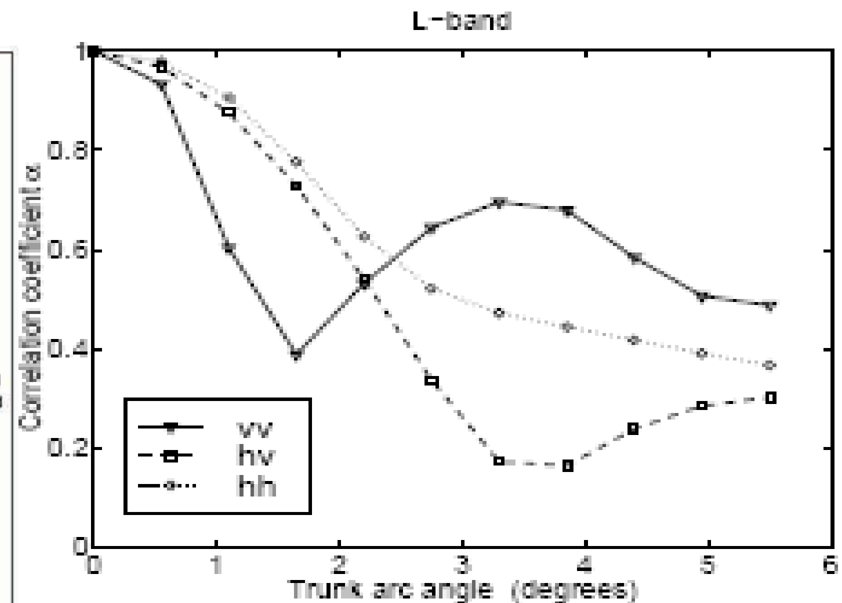
Achilles' Heel:
Temporal Decorrelation:

Motion of scatterers within the resolution cell from one observation to the next will lead to randomly different coherent backscatter phase from one image to another, i.e. "temporal" decorrelation.



Temporal Decorrelation





Wind Strength

The impact of Soil & Canopy Moisture is Small compared to the wind strength

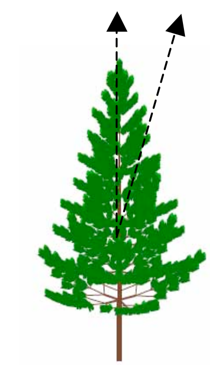
Wind-still Condition

The basis of comparison

Wind-blown Condition

Moderate wind:

trunk arc angle 5.5 degrees



Wind-blown Condition

Strong wind:

trunk arc angle 11 degrees

Temporal Decorrelation

The simplest measure of structure is vegetation height and may be related to the correlation by

$$h_v \approx \sqrt{\frac{24}{k_z^2}\left(1-|\gamma_{vol}|\right)}$$

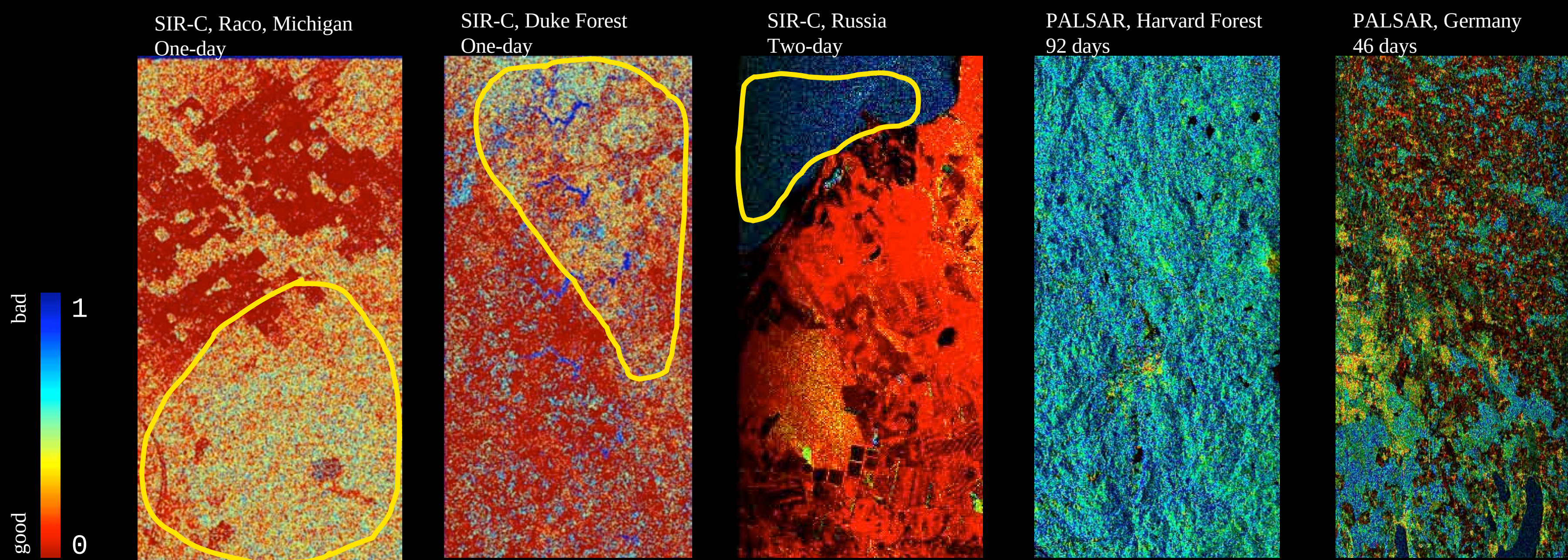
Where γ_{vol} is the volumetric correlation, a component of the observed interferometric correlation

$$\gamma_{obs} = \gamma_{vol}\gamma_{SNR}\gamma_{geom}\gamma_{temp}$$

γ_{vol} is determined by removing the other effects of interferometric decorrelation.

$$\gamma_{vol} = \frac{\gamma_{obs}}{\gamma_{SNR}\gamma_{geom}\gamma_{temp}} = f(h_v)$$

Temporal Decorrelation occurs when the observed electric field changes between passes of the interferometer.
Single-pass interferometry does not experience temporal decorrelation
Temporal Decorrelation has the effect of causing an overestimation of vegetation heights.

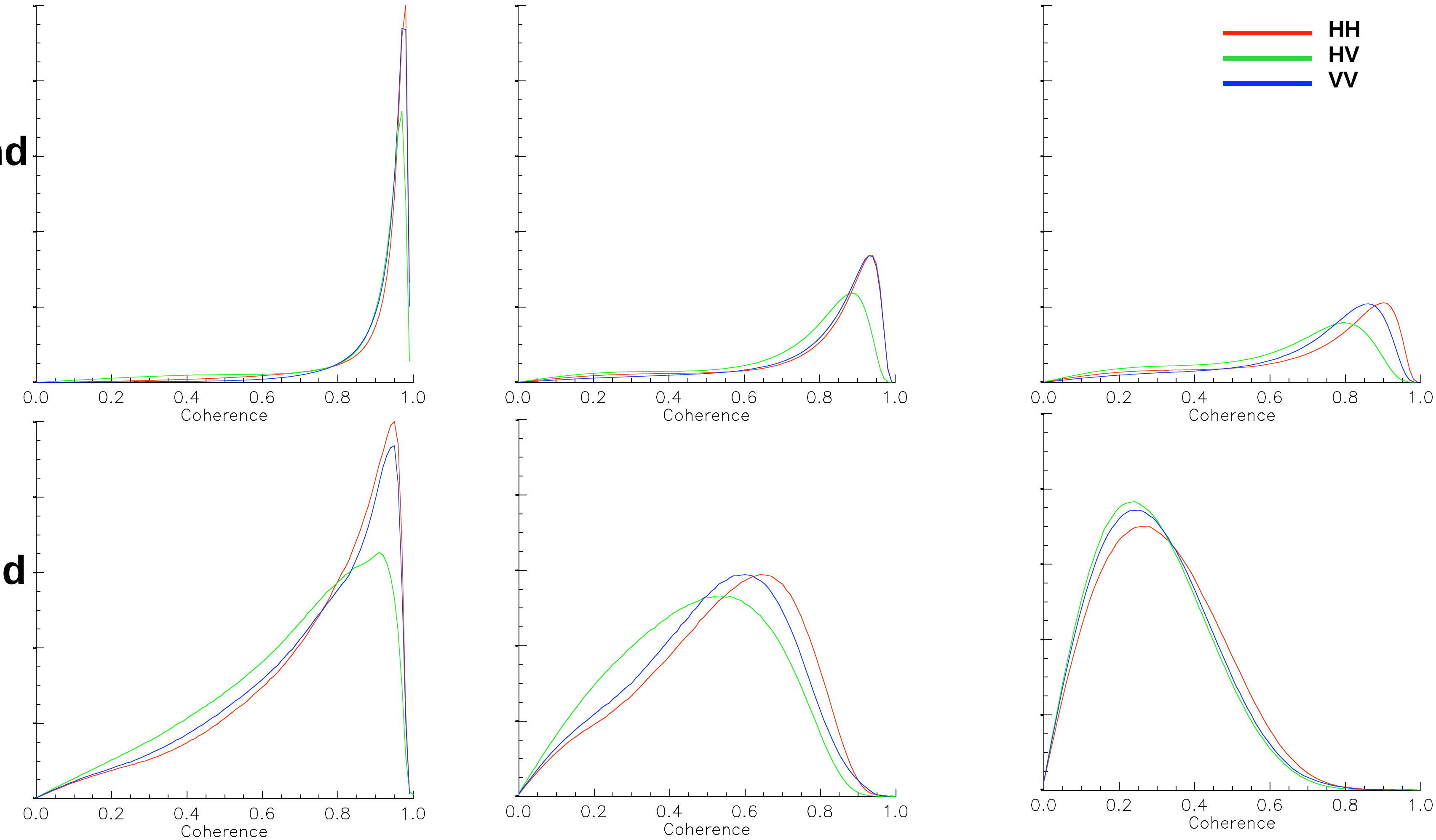


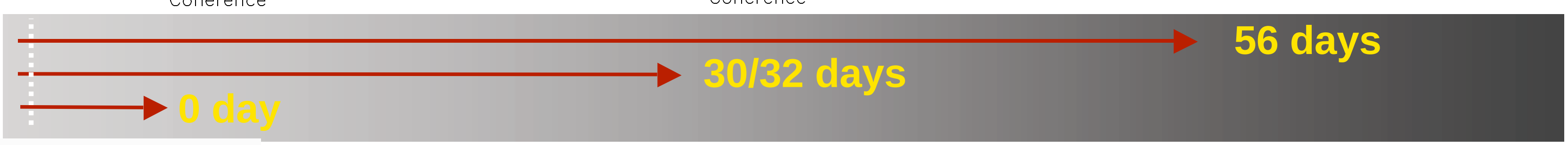
Temporal Decorrelation at P & L-band

Test Site: Remingstorp, Sweden

P-band

L-band





Papathanassiou, et al. 2007

Temporal Decorrelation

What to do?!

1. Single-pass interferometry does not experience temporal decorrelation (see GeoSAR and AIRSAR). A Tandem-X and/or a Tandem-L mission should work extremely well for estimating vertical structure.

   Can one satellite be used instead of two?

2. Polarimetric Interferometry (PolInSAR) may be more robust to temporal decorrelation because the relative phase between polarizations for each observation is a more accurate measurement than the phase between observations.

3. Reduce repeat-times as short as possible.
   - one possible scenario for achieving global coverage: perform 3-day repeats in pairs. At the end of each pair, shift the Right Ascension of the Ascending Node. Such a strategy could achieve a global data set in ~3 months.

SAR-derived Measurement of Forest Height and Biomass

Breakout Charge:

1. Defining the right set of radar measurements
   - Backscatter Measurements (polarization, resolution, temporal & spatial coverage)
   - InSAR Measurements (baseline, polarization, temporal repeat-pass, coverage)
   - Sampling Lidar within radar coverage
2. Fine-tuning the available algorithms
   - Polarimetric algorithms for different forests
   - Minimizing the effects of temporal decorrelation
   - Taking into account varying topography
   - Combining polarization diversity with interferometry
3. Fusion Algorithms
   - A priori pdf-based approach
   - Direct height calibration
   - Lidar waveform integration