Profiling LiDAR for Regional Forest Inventories

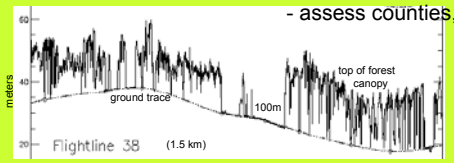
Dr. Ross Nelson
Biospheric Sciences Branch
Code 614.4, NASA-GSFC
301-614-6632
Ross.F.Nelson@nasa.gov

<u>Objective</u>: Develop a complete system of airborne LiDAR hardware, software field procedures, and robust statistical techniques designed to estimate above-ground forest carbon regionally, real-time, anywhere in the world.






Features:
- inexpensive (35k), off-the-shelf hardware – **laser rangefinder, diff. GPS, CCD video camera, VCR, laptop**
- transportable, one operator, bolts onto aircraft found worldwide – **Cessna, Bell JetRanger, Twin Otter**
- LiDAR profiler, a sampling tool to collect sub-meter forest height, height variability, and crown closure measures along linear transects 10s – 1000s of kilometers long
- assess counties, states, provinces, ecoregions





<u>Structure of the profiling LiDAR talk</u>:

- Introduction to lasers

- Using airborne lasers as regional sampling tools for forest measurement, inventory, and monitoring

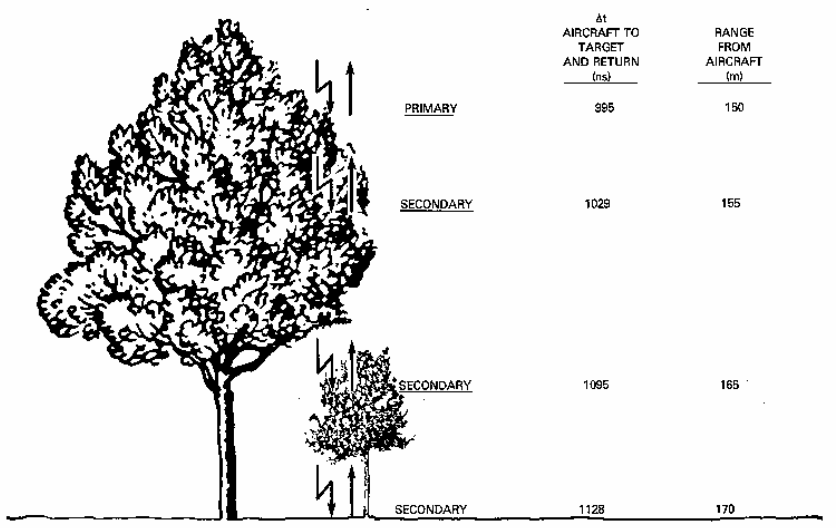
- Estimating natural resources in Delaware, merchantable volume, biomass, impervious surface area

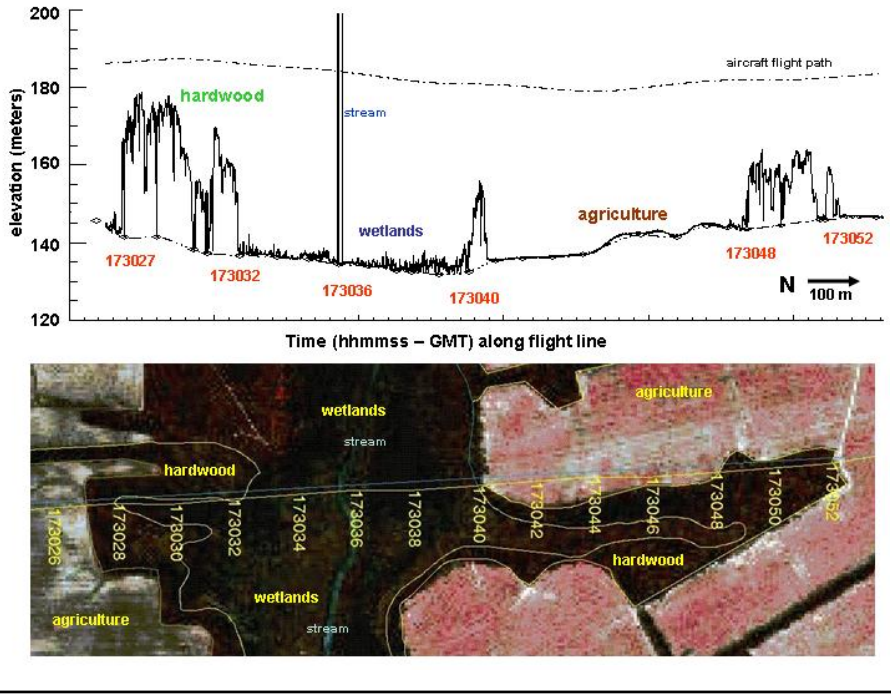
- Quebec – ground/PALS/GLAS

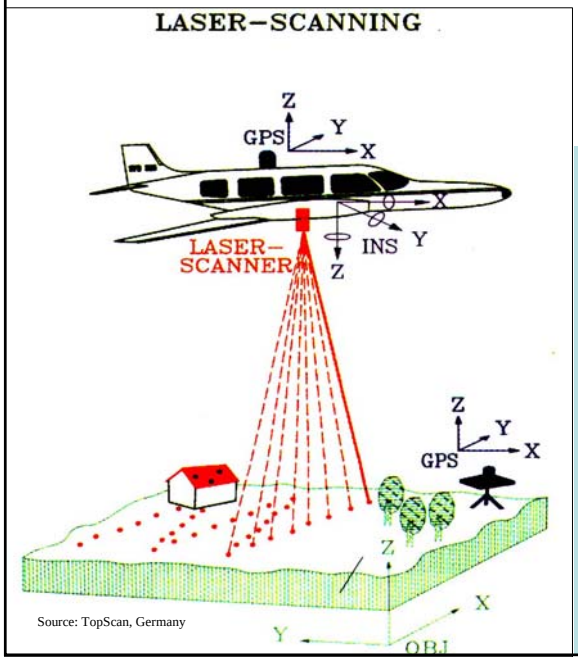
-Other studies:
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PRIMARY
SECONDARY
SECONDARY
SECONDARY
AT AIRCRAFT TO TARGET AND RETURN (ns)
RANGE FROM AIRCRAFT (nm)
995
150
1029
155
1095
165
1128
170

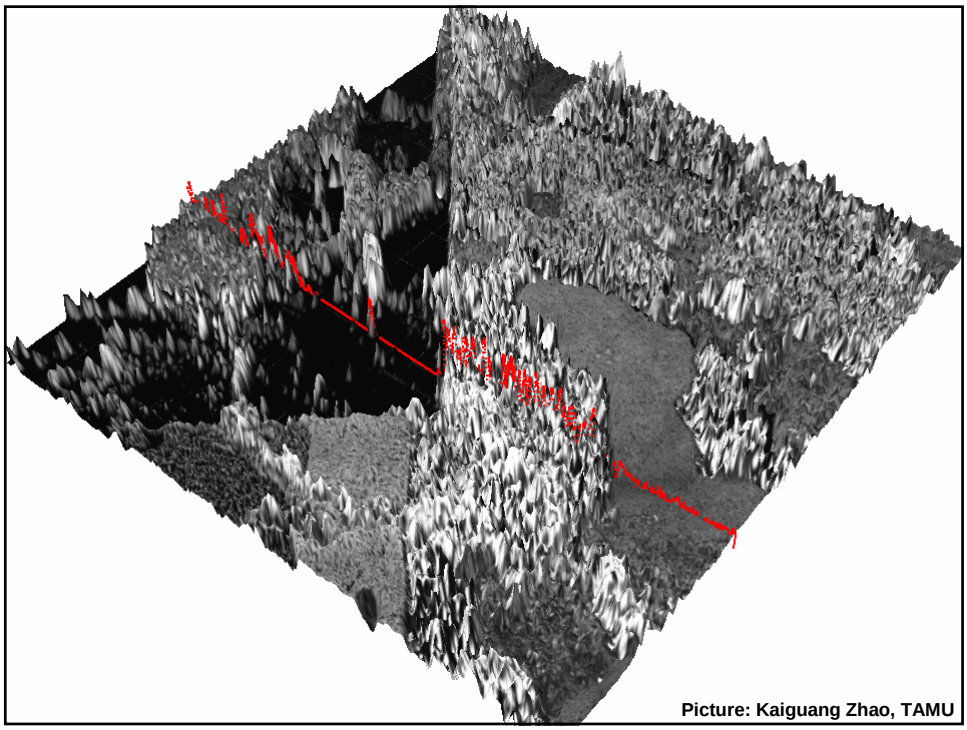

elevation (meters)
200
180
160
140
120
aircraft flight path
hardwood
stream
wetlands
agriculture
173027
173032
173036
173040
173048
173052
N
100 m
Time (hhmmss – GMT) along flight line
wetlands
stream
agriculture
hardwood
173026
173028
173030
173032
173034
173036
173038
173040
173042
173044
173046
173048
173050
173052
hardwood
wetlands
stream
agriculture



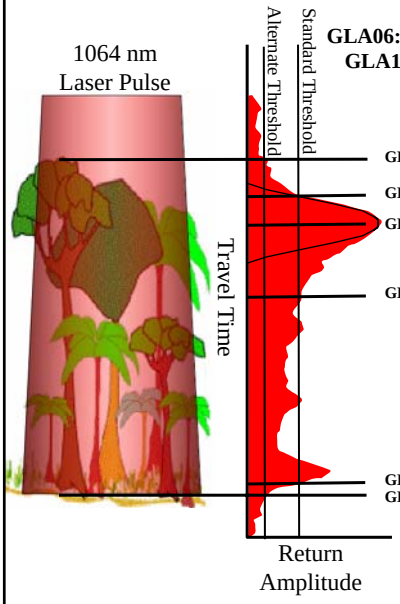
Source: TopScan, Germany

Typical ”laser parameters” in our projects

- Ranging from plane
- Measurements of canopy and ground
- Typical parameters:
  - 10,000-33,000 pulses per sec. (state of the art: 100,000 hz)
  - First and last pulse reflection
  - 15-25 cm ”footprint” diameter
  - 1-5 pulses per m^2
  - 300-500 m swath width
  - Accuracy (x,y) of 20-30 cm


Picture: Kaiguang Zhao, TAMU

GLAS Waveform Range Offsets & Elevations



GLA06: standard products using ice sheet algorithms & parameters
GLA14: alternate products using land algorithms & parameters

Range offsets are with respect to i_refRng

GLA14: i_SigBegOff offset to highest signal alternate threshold crossing

GLA06: i_SigBegOff offset to highest signal standard threshold crossing

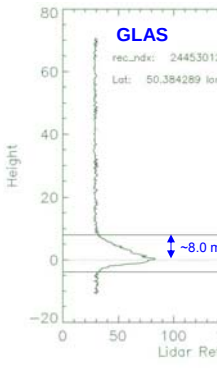
GLA06: i_isRngOff offset to center of Gaussian fit to largest peak
= **GLA06: i_elev** geolocated elevation corresponding to ice sheet range

GLA14: i_ldRngOff offset to centroid of signal from alternate beginning to end
= **GLA14: i_elev** geolocated elevation corresponding to land range

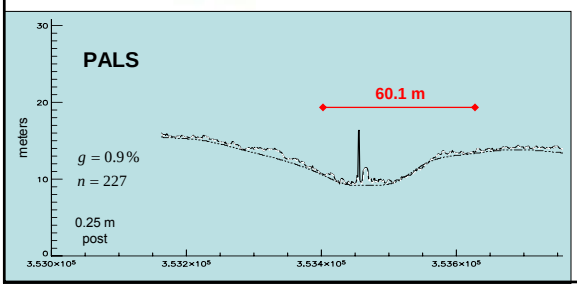
GLA06: i_SigEndOff offset to lowest signal standard threshold crossing
GLA14: i_SigEndOff offset to lowest signal alternate threshold crossing

GLA06: i_refRng & GLA14: i_refRng
Distance calculated from the time between the peak of the transmit pulse and the last bin of the received pulse waveform (farthest bin from the spacecraft)

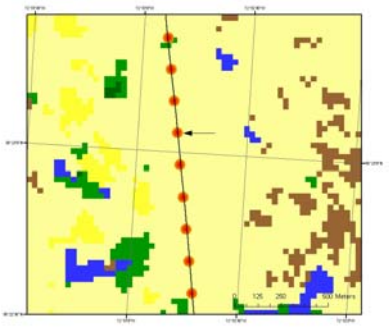
Low Shrub – E. Chibougamau, QC

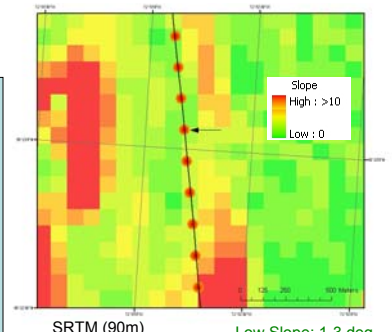


(m)	GLAS	PALS
$\bar{h}_a$	5.2	0.4
$\bar{h}_{qa}$	5.3	0.9
$\bar{h}_{max}$	8.8	7.2



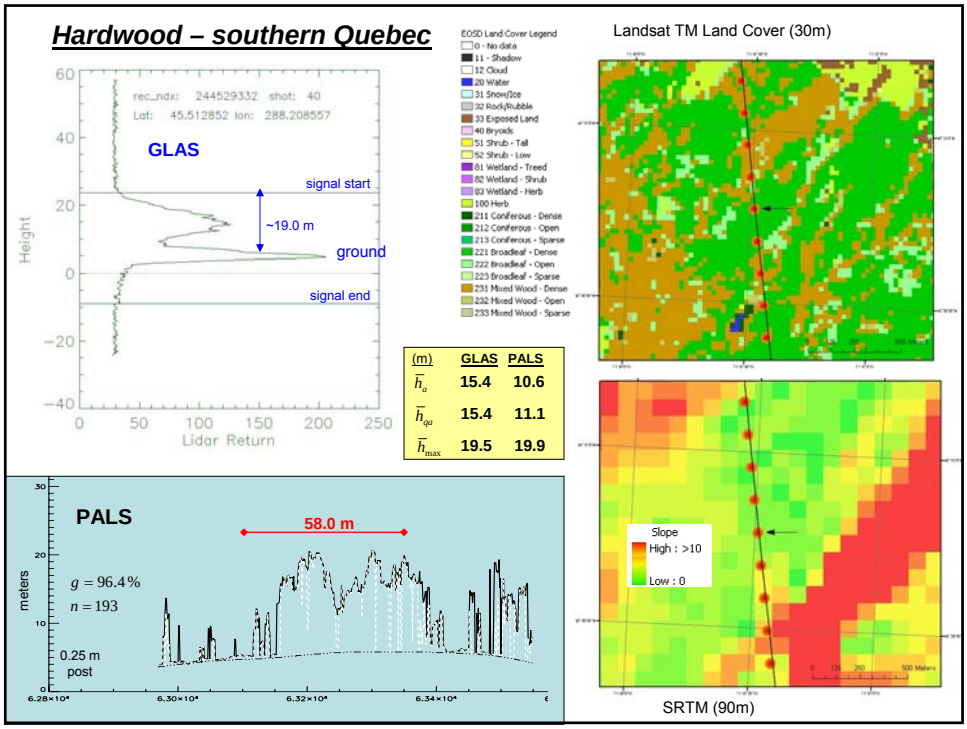
Landsat TM Land Cover (30m)





SRTM (90m)

Low Slope: 1-3 deg.



So there's all sorts of LiDARs (Light Detection and Ranging) out there:

PALS:

first return
first/last return
multi-stop
waveform

x **small footprint (<1m)** **large footprint (>5m)** x **profiling** **scanning**

LiDARs associated with vegetation or natural resource measurement and assessment tend to work in the near-infrared (e.g., 1.064 um) or green (0.532 um) due to

1. physics associated with laser construction,
2. reflectivity of vegetation in these wavelengths.



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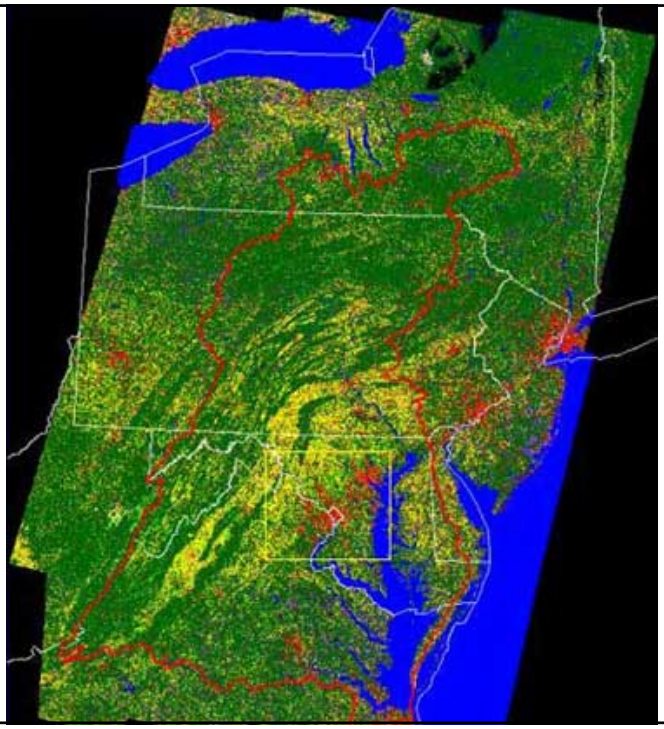
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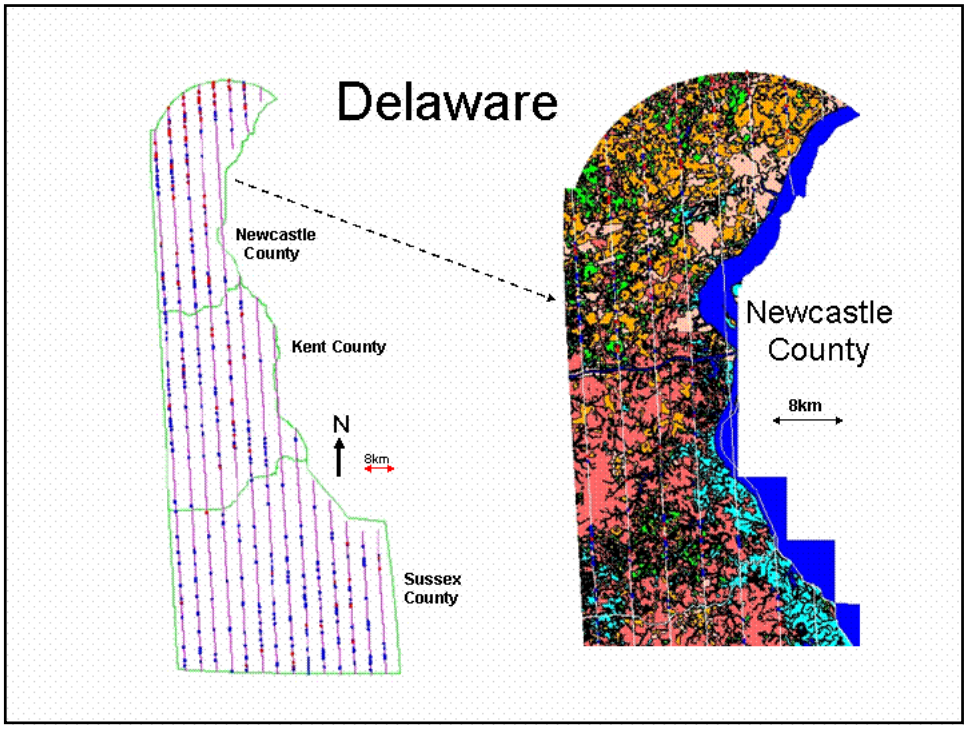
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Ok, we've collected laser forest canopy heights along flight lines systematically arrayed across our study area of interest.
We know biomass ~ height.

How do we predict regional biomass from the laser heights?

We need coincident ground and laser measurements.
2 ways to get these coincident measurements:

1. **Fly the mission, then locate sections of flight line on the ground and measure biomass.**
   or
2. **Fly over existing ground plots.**

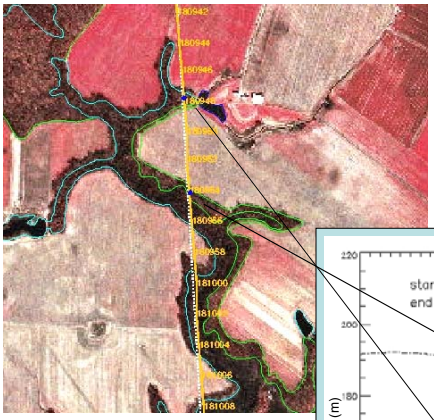
Bottom Line: No matter what laser system you employ - you have to tie those laser heights to the ground, i.e., someone has to hug trees.



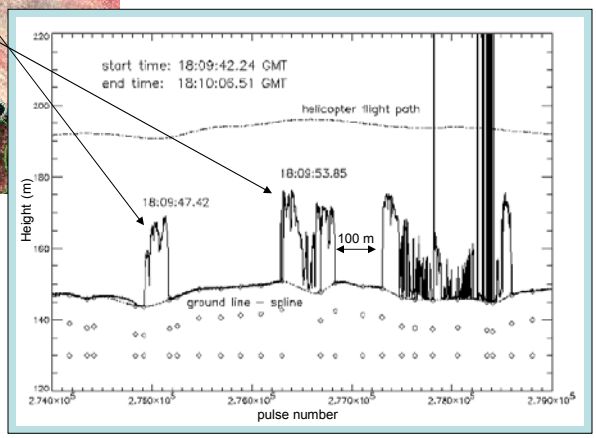
Chibougamau, Quebec (50°N) – 5.5 t/ha

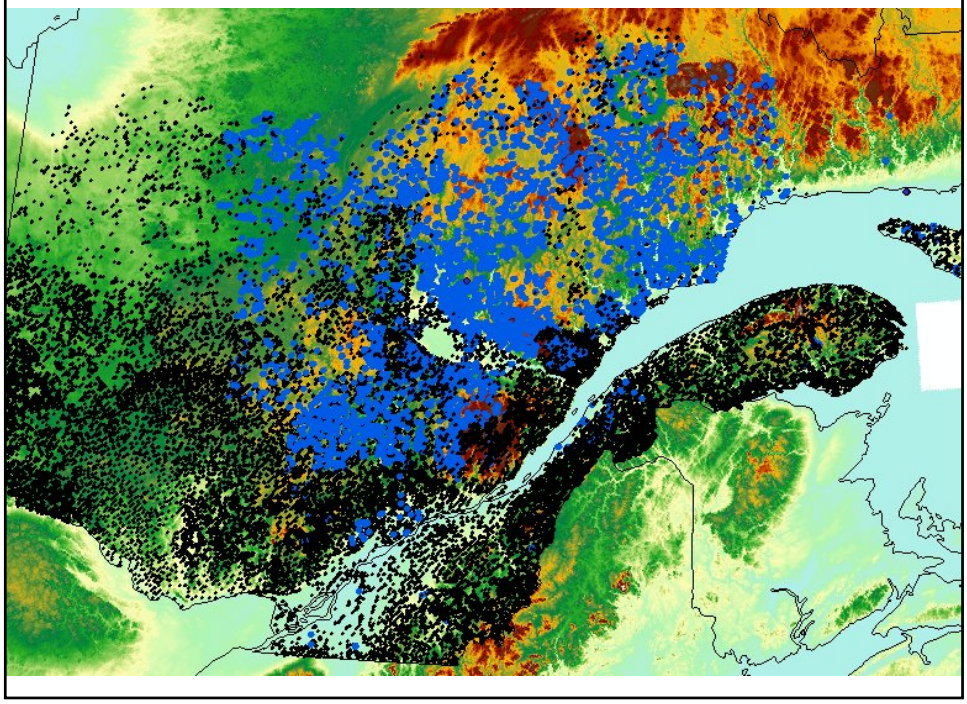
PALS Data

Segment of flightline 18,
Delaware, June 2000









Regressions – no stratification:

merchantable volume (m^3) = 11.60 (h_{qc}) – 17.0 R^2 = 0.68

total above-ground dry biomass (mt) = 9.070 (h_{qc}) – 1.897 R^2 = 0.66

Regressions – stratified:

merchantable volume (m^3):

hardwood/mixed:	mv = 11.3(h_{qa}) – 10.7	R^2 = 0.42
conifer:	mv = 10.9(h_a) + 17.5(s_a) -58.9	R^2 = 0.58
wetlands:	mv = 27.0(h_{qc}) – 3.2(c) + 0.3	R^2 = 0.85
ag/resid/urb:	mv = 12.6(h_{qc}) – 0.9(c) – 9.4	R^2 = 0.84

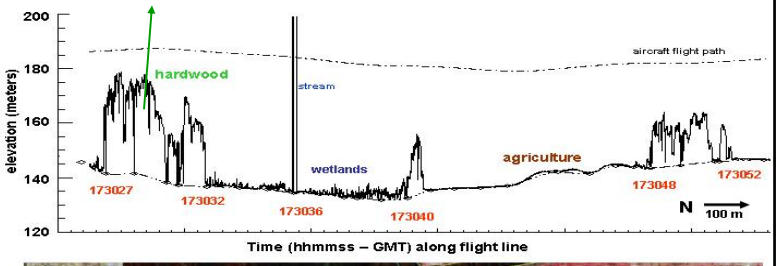
total above-ground dry biomass (mt):

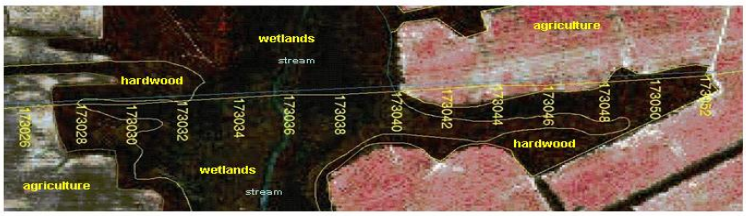
hardwood/mixed:	tagdb = 6.5(h_{qc}) + 1.0(c) – 40.0	R^2 = 0.29
conifer:	tagdb = 10.0(h_{qa}) – 5.6	R^2 = 0.44
wetlands:	tagdb = 16.8(h_c) – 1.4(c) +2.1	R^2 = 0.95
ag/resid/urb:	tagdb = 8.3(h_{qc}) – 4.1	R^2 = 0.76

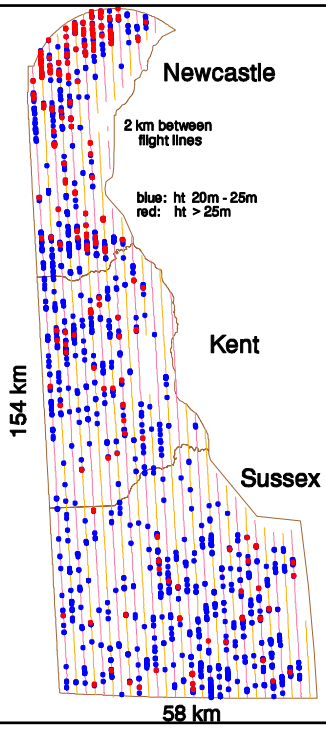
$$\hat{b}_{ijk} = a_i \left[\sum_{s=1}^{n_{ijk}} \left(w_{ijks} \right) \left(\hat{b}'_{ijks} \right) \right] \left[\frac{\sum_{s=1}^{n_{ijk}} l_{ijks}}{\sum_{j=1}^{8} \sum_{s=1}^{n_{ijk}} l_{ijks}} \right] = \begin{pmatrix} \text{area in} \\ \text{county } i \end{pmatrix} \begin{bmatrix} \text{average biomass / ha} \\ \text{in county } i, \text{ stratum } j, \\ \text{flightline } k \end{bmatrix} \begin{bmatrix} \text{an estimate, for flightline } k, \\ \text{of proportion of stratum } j \\ \text{in county } i \end{bmatrix}$$

total biomass (tons) in county *i*, stratum *j*, on flight line *k*

$$\hat{b}'_{ijks} = (10.09)(\bar{h}_{qc}) - 23.04$$







-Use Line Intercept Sampling techniques to compile biomass estimates as a function of laser heights

sample unit = the flight line

-If you stratify (satellite or GIS landcover maps), then your sample units are those flight lines which intercept the stratum.

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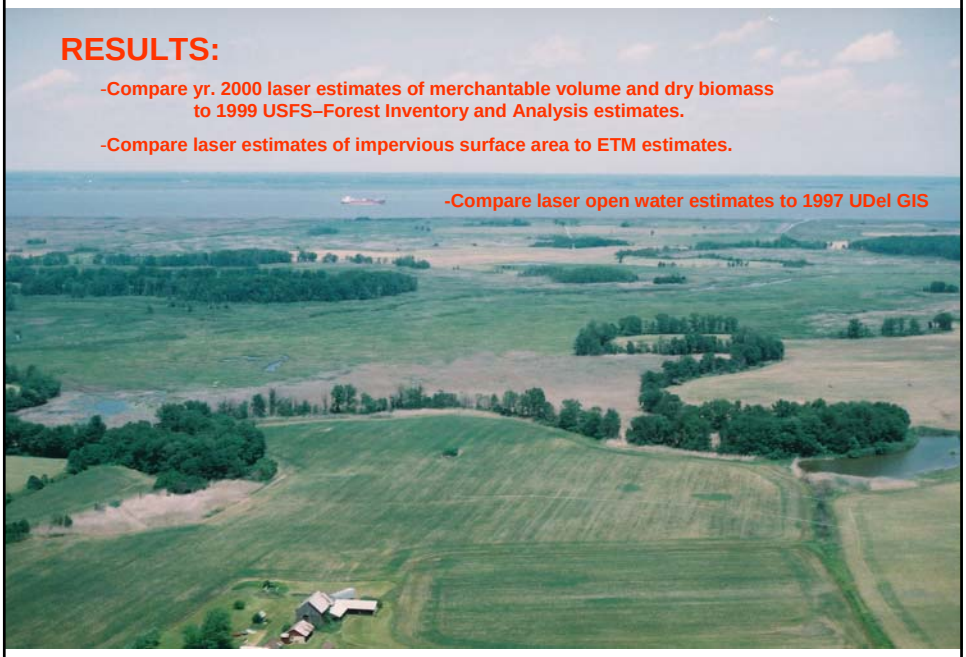
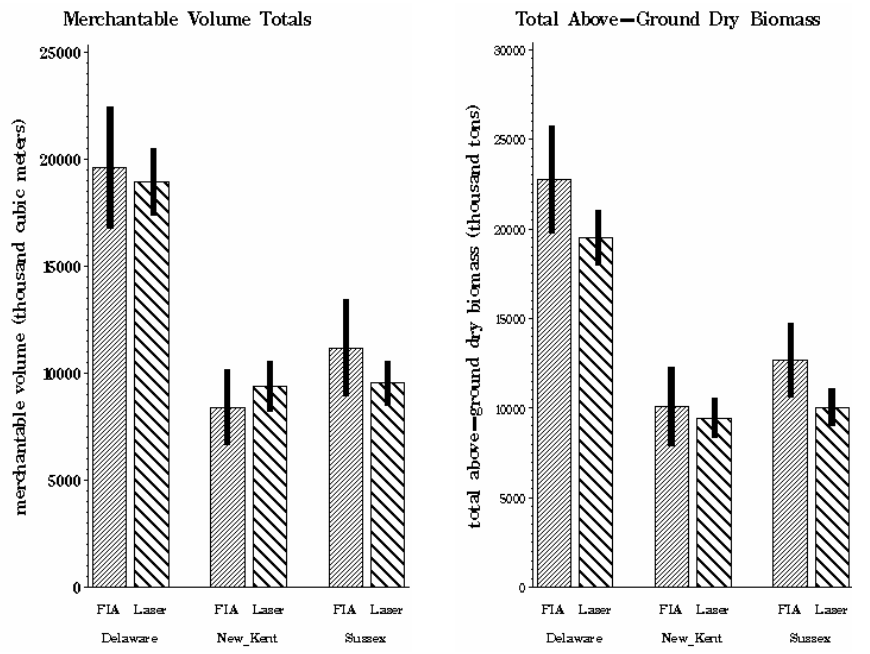


Table 1. Percent difference between USFS-FIA and airborne laser estimates total merchantable volume and total above-ground dry biomass,by county and state. Non-stratified and stratified results for Models 1 and 2 are compared to USFS-FIA estimates. Model 1 is parametric; model 2 is developed using nonparametric techniques.

dependent variable	*model*	*stratification*	***difference (%)****		
			New/Kent	***Sussex***	***Delaware***
Merchantable Volume	*1*	*no*	*-23.5*	*-7.5 ‡*	*-14.4 ‡*
		yes	*-17.6 ‡*	*4.9 ‡*	*-4.8 ‡*
	2	*no*	*-9.6 ‡*	*7.7 ‡*	*0.3 ‡*
		yes	*-9.6 ‡*	*14.5 ‡*	*4.2 ‡*
Total Above-Ground Dry Biomass	*1*	*no*	*12.5 ‡*	*18.8*	*16.0*
		yes	*7.4 ‡*	*22.0*	*15.5*
	2	*no*	*15.7 ‡*	*22.7*	*19.6*
		yes	*8.3 ‡*	*21.1*	*15.4*

** [(FIA-laser)/FIA] x 100. Negative percentages indicate a laser overestimate.*
‡ Laser estimate is within ±2 standard errors of the USFS-FIA estimate.

Stratified Linear Models, nonparametric:



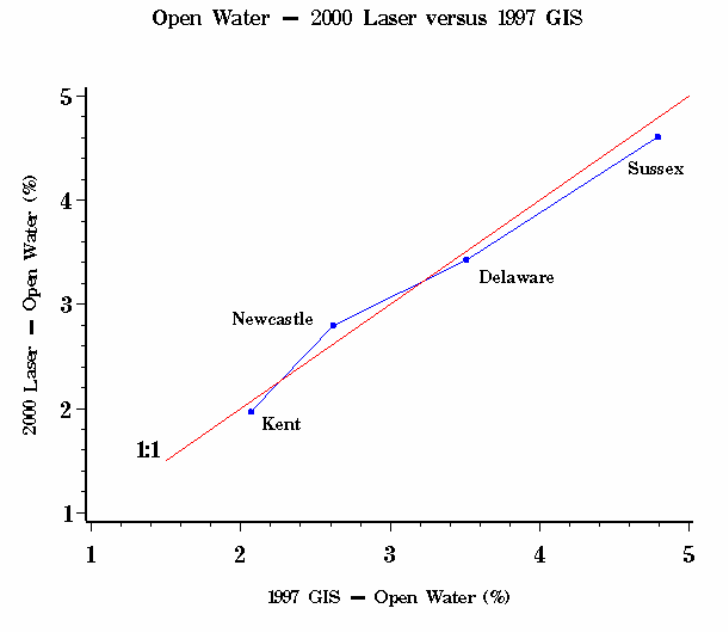
Impervious Surface and Open Water Area

- Airborne laser measurements + video record can be used to measure crossing distances.
- [(roof distance)/(total distance)] [area] = area under roof
- Estimate area under roof, asphalt/concrete, water.

Laser Transect Surface Report,
by County and for the State (percent)

	Newcastle	Kent	Sussex	Delaware
Forest	27.92	26.85	33.66	30.40
SEE	0.71	0.50	0.39	0.31
Nonforest	58.26	67.83	58.92	61.42
SEE	0.58	0.53	0.37	0.28
Pervious Subt:	86.18	94.68	92.58	91.82
SEE	0.25	0.39	0.24	0.13
Roof	3.45	1.13	1.04	1.59
SEE	0.05	0.08	0.06	0.02
Asphalt/Concr:	7.57	2.21	1.77	3.16
SEE	0.11	0.12	0.09	0.05
Imperv. Subt:	11.02	3.35	2.82	4.75
SEE	0.15	0.15	0.12	0.06
Water	2.80	1.97	4.61	3.43
SEE	0.21	0.37	0.22	0.12
TOTAL:	100.00	100.00	100.00	100.00
Imperv. Subt:	8.76	3.50	3.88	4.90

(from Smith et al. 2003)



Assessing Wildlife Habitat – Delmarva Fox Squirrel

- Airborne lasers can be used to locate and estimate the extent of wildlife habitat *IF* that habitat is related to forest structure.
- Delmarva fox squirrels inhabit tall, dense forests with an open understory.
- Lasers measure tree height and canopy closure, no understory information.





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QCLP – Quebec Carbon LiDAR Project

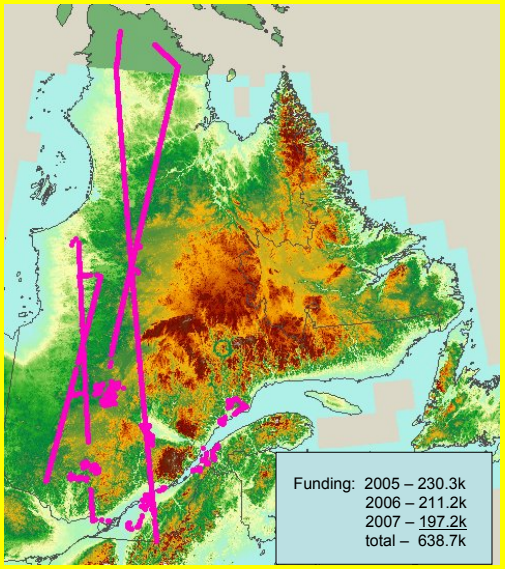
"A Realistic Analysis of the Variability of Carbon Estimates Using Airborne and Space LiDAR"

NASA-HQ early Mid-Project Review, April 8, 2005

The QCLP Team:

- **Ross Nelson – NASA/GSFC**
- **Dan Kimes – NASA/GSFC**
- **Hank Margolis – Laval Univ.**
- **Jonathan Boudreau – Laval Univ.**
- **André Beaudoin – CFS**
- **Chhun-Huor Ung – CFS**
- **Tim Gregoire – Yale Univ.**
- **Erik Næsset – Nor. Univ. Life Sci.**
- **Terje Gobakken – Nor. Univ. Life Sci.**
- **Göran Ståhl – Swed. Univ of Ag. Sci.**





Funding: 2005 – 230.3k
2006 – 211.2k
2007 – 197.2k
total – 638.7k

Quebec Inventory: André, Dan, Hank, Huor, Luc, Philippe, Jonathan, Ross



Responsible for

(1) provide ground reference data – MNRQ, ECOLEAP plots,
(2) process Quebec stratification map – TM map,
(3) acquire PALS data over ground plots and GLAS flight lines,
(4) develop predictive equations relating ground-PALS and PALS-GLAS,
(5) process GLAS data to estimate volume, biomass carbon, for the province, by cover type.

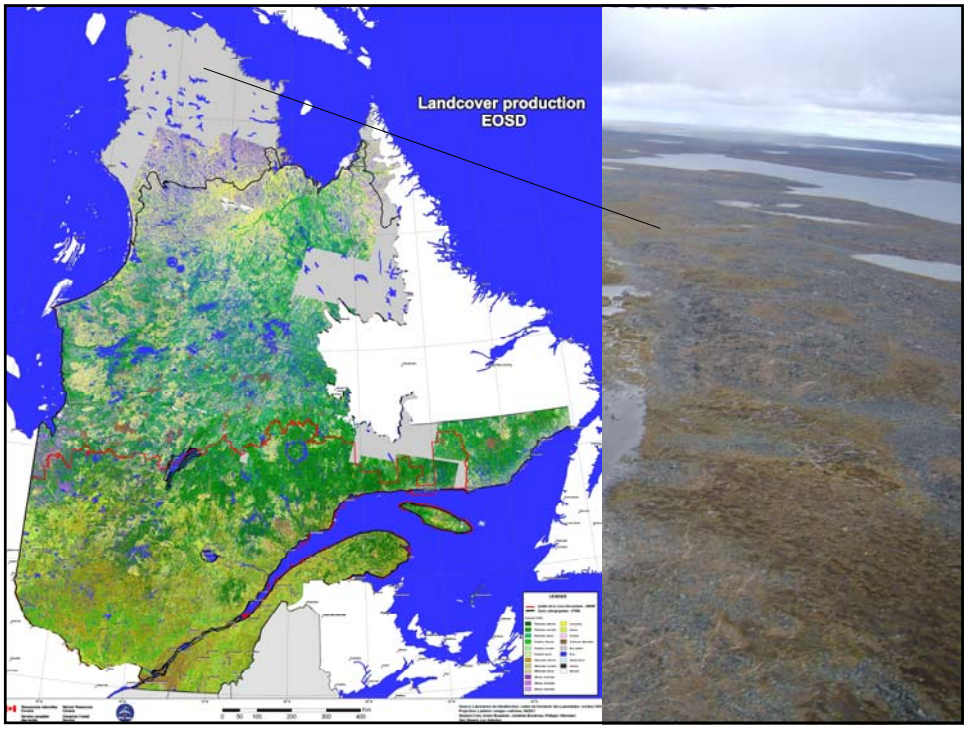
$b_{PALS} = f(ht, cc)_{GLAS}$

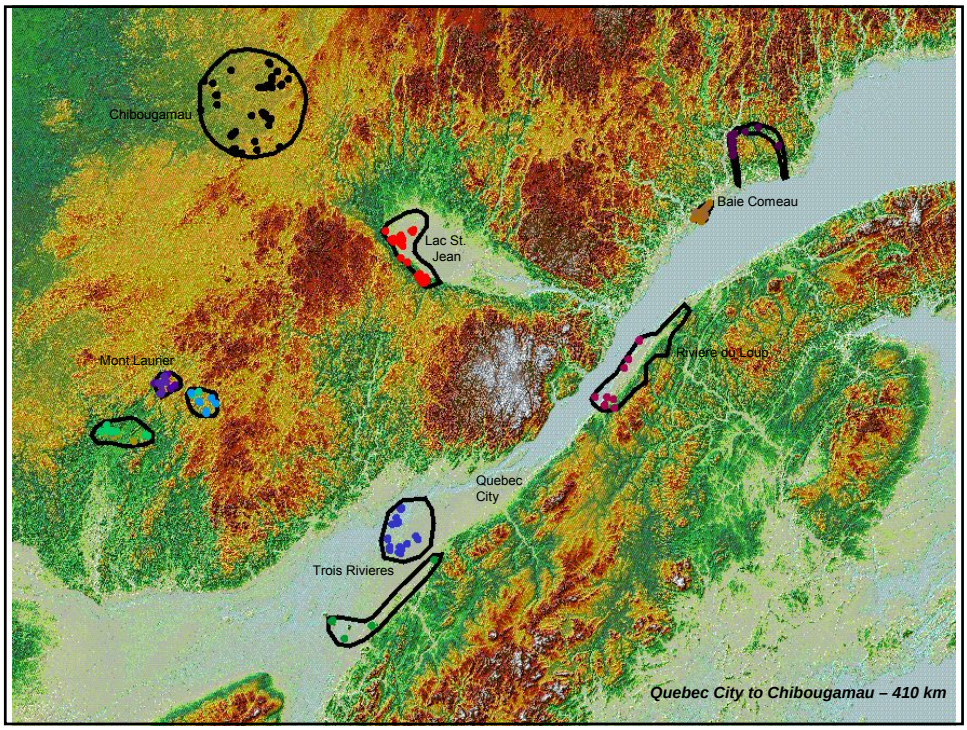


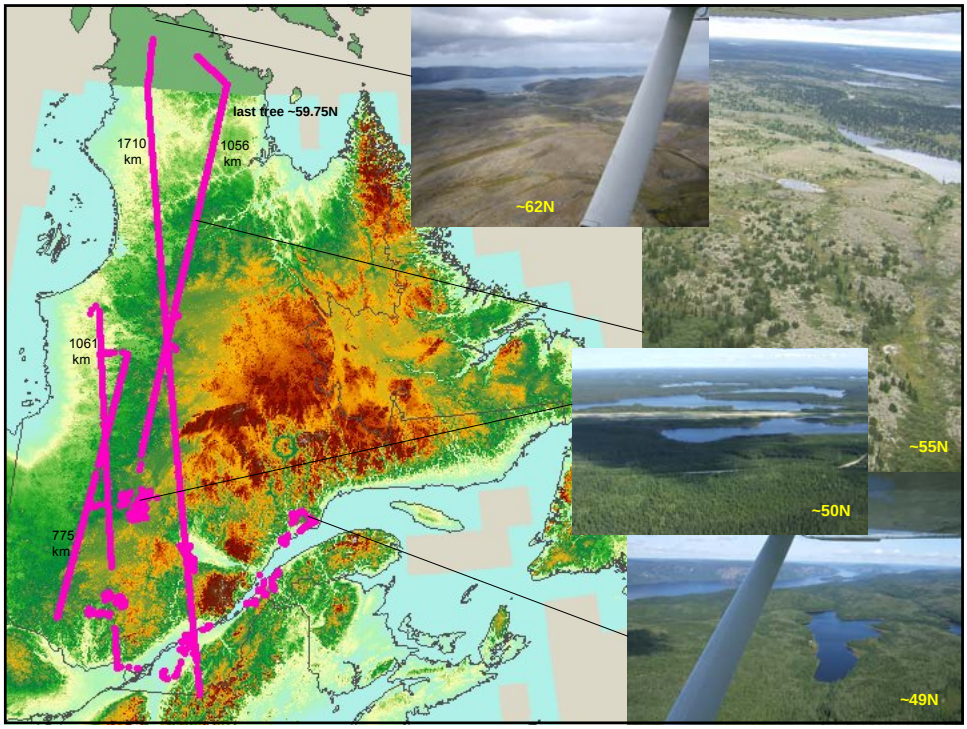
Radisson – 6.7 t/ha

$b_{ground} = f(ht, cc)_{PALS}$




Landcover production
EOSD


Chibougamau
Lac St.
Jean
Baie Comeau
Mont Laurier
Riviere du Loup
Quebec
City
Trois Rivieres
Quebec City to Chibougamau – 410 km



A work in progress….

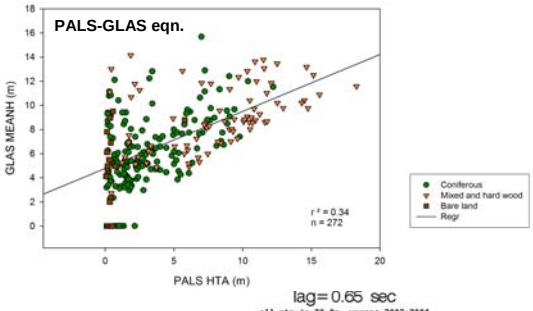


$b_{PALS} = f(ht, cc)_{GLAS}$

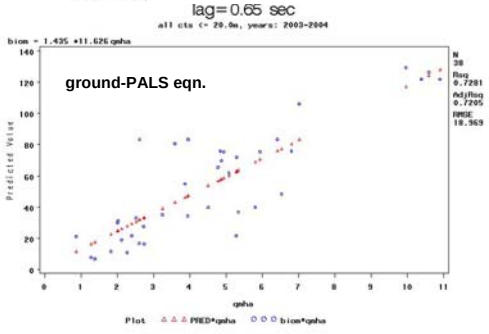


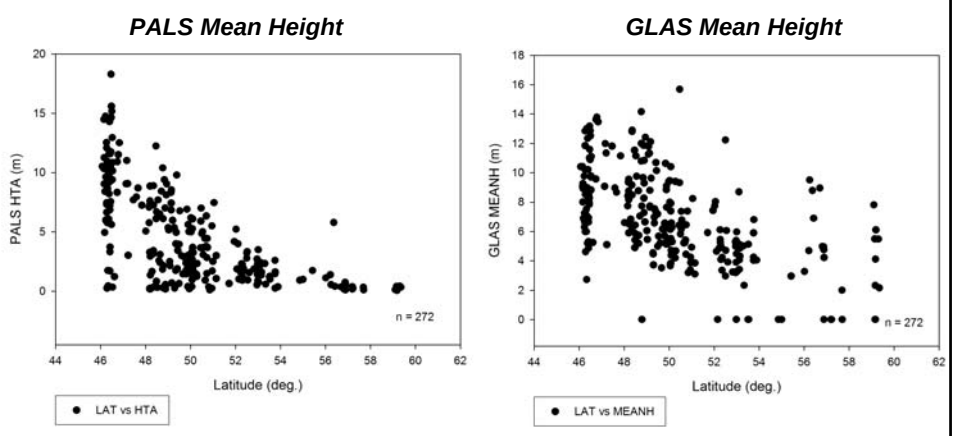
$b_{ground} = f(ht, cc)_{PALS}$



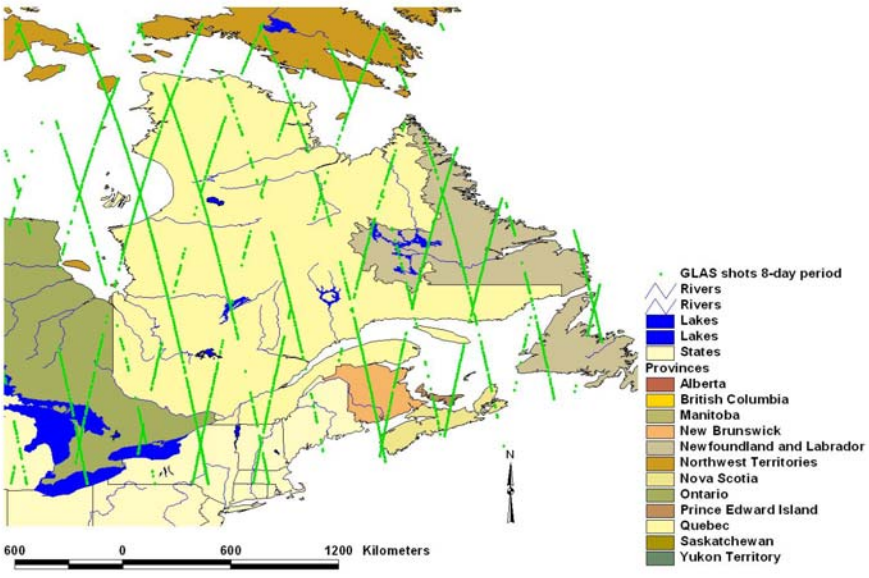


lag = 0.65 sec





PALS & GLAS Heights x Latitude



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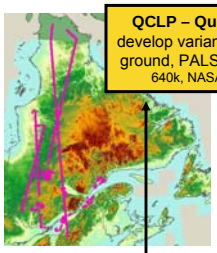
- Summary

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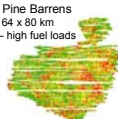
PALS Program:



Profiling & Scanning LiDARs for Biomass & C-Estimation –
PALS-scanning LiDAR comparison for national forest inventory
870k, Skogforst (Norwegian Forestry Institute), 2005-2008. GSFC funding – 300k, FY06,07



QCLP – Quebec LiDAR Program -
develop variance estimators that include ground, PALS, and satellite laser errors
640k, NASA-HQ-Code Y, 2005-2007



NJ Pine Barrens
64 x 80 km
red – high fuel loads

Mapping Forest Fuels – NJ Pine Barrens -
US Forest Service, Global Change Program,
25k + flight, 2004-2006

national forest inventory

statistical development

fuels - fire risk

automation

Real-time Regional Carbon Measurement –
develop an on-the-fly C-estimation system
Texas A&M Univ.-PhD cand.
87k, NASA-HQ-Code Y
2005-2007

RaDAR/LiDAR Synergy –
determine if BioSAR/PALS data, considered jointly, improves biomass estimates
263k, NASA-HQ-Code Y, 2004-2005

sensor fusion

PALS Profiler
60k, GSFC-DDF, y2000

carbon change

commercialization

climate change

DOE STTR -
Univ. Idaho & AquilaVision, Inc.
2004, not funded

DOE SBIR, Phase 2 –
Zimmerman Associates, Inc.
PALS commercialized as part of RaDAR/LiDAR biomass estimation system

Circumpolar Boreal Forest Measurements -
acquire 12-20 transboreal LiDAR flight lines globally in 2005-2010 to estimate C amount and location. Establish "pre-climate change" baseline (albeit a bit late).
funding: piecemeal, w/Ehime University and Norwegian University of Life Sciences

Ehime Prefecture (SW Japan) Carbon Study -
Ehime University, Matsuyama -
2005,2007 PALS overflights to estimate Prefecture carbon change, ~5000 km².
travel+flights, 2005-2007

completed
ongoing



Structure of the profiling LiDAR talk:

- Introduction to lasers

- Using airborne lasers as regional sampling tools
  for forest measurement, inventory, and monitoring

- Estimating natural resources in Delaware,
  merchantable volume, biomass,
  impervious surface area

- Quebec – ground/PALS/GLAS

-Other studies:
  Hedmark, Norway – profiler vs. scanner
  Circumpolar boreal transects as baselines
  for climate change

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Summary:

1. Tree heights and crown closure are related to the amount of wood on the ground. Airborne lasers measure both.

2. Laser heights + robust inventory design = laser-based regional inventory tool.

3. Possibility of using satellite lasers for continental/global studies, but GLAS waveform data difficult to machine process.

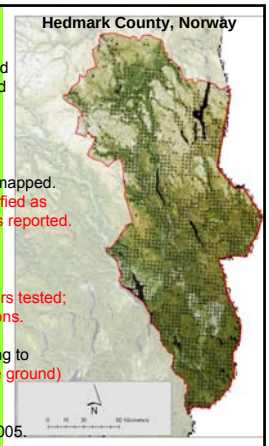
4. Possibility of automating profiling laser (PALS) for near-real-time forest inventory.

5. Japanese and US scientists are cobbling together a collection of circumpolar trans-boreal flight lines to establish a "pre-climate change" baseline for vegetation structure in early 2000's.
   - big hole in central/western Canada and Alaska
   - bigger hole in Scandinavia, northern Europe, and Russia/Siberia

7. Completely biased opinions:
   • Airborne lasers will play an integral roll in regional/national inventories.
   • Norway, Sweden, Finland are currently the world's leader wrt utilization of laser technology for local and regional forest measurement.



Profiling LiDAR Studies



1. PALS built (30k) and flown over Delaware (30k); basic LiDAR sampling procedure developed to estimate forest volume, biomass, carbon, and impervious surface area. Results compared to USFS-Forest Inventory and Analysis estimates:
   - PALS merchantable volume within 10% at county level, within 1% at state level.
   - PALS total dry biomass within 21% at county level, within 16% at state level.

2. Wildlife habitat assessment – Delmarva fox squirrel (DFS, an endangered species) habitat mapped.
   - 78% of areas mapped by PALS as >20m tall, >80% crown closure, >120m long were identified as suited to the DFS (blue and red dots); areal estimates of potential habitat and patch statistics reported.

3. QCLP: Quebec LiDAR Project – variance estimators tested, multiple sources of variability identified, regression error included in variance estimates.
   - Regression error adds 1 – 1.5 t/ha to SEs of LiDAR-based biomass estimates. Estimators tested; SRS estimator most accurate. Systematic fls ≥2 km apart act as independent observations.

4. USFS Pine Barrens Study – map forest fuels and identify areas in need of prescribed burning to mitigate risk of crown fire. Procedure developed to assess understory fuel load (1-4m above ground) using PALS.

5. RaDAR/LiDAR Synergy – BioSAR/PALS data collected over Weyerhaeuser stands 2003, 2005. Data analyzed to assess repeatability and utility for biomass/carbon estimation.
   - RaDAR/LiDAR results from Arizona ponderosa pine study – scanning LiDAR explained over 80% of forest biomass variation, RaDAR added little/no predictive information.

PALS Publications

1. Nelson, R., G. Parker, and M. Hom. 2003. A Portable Airborne Laser System for Forest Inventory. *Photogrammetric Engineering and Remote Sensing* 69(3): 267-273. [ASPRS 1st place award for best practical paper, 2003]
2. Nelson, R., M. Valenti, A. Short, and C. Keller. 2003. A Multiple Resource Inventory of Delaware Using Airborne Laser Data. *BioScience* 53(10): 981-992.
3. Nelson, R., A. Short, and M. Valenti. 2004. Measuring Biomass and Carbon in Delaware Using an Airborne Profiling LiDAR. *Scandinavian Journal of Forest Research* 19: 500-511.
4. Nelson, R., C. Keller, and M. Ratnaswamy. 2005. Locating and Estimating the Extent of Delmarva Fox Squirrel Habitat Using an Airborne LiDAR Profiler. *Remote Sensing of Environment* 96(3-4): 292-301.