AARHUS UNIVERSITET

8. May 2013

EFFECT OF SCANNING ANGLE ON VEGETATION METRICS DERIVED FROM A NATIONWIDE AIRBORNE LASER SCANNING ACQUISITION

Alessandro Montaghi

Department of Agroecology
Aarhus University, Denmark

Håkan Olsson

Section of Forest Remote Sensing
Department of Forest Resource Management,
Swedish University of Agricultural Sciences, Sweden

Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

SLU Umeå campus

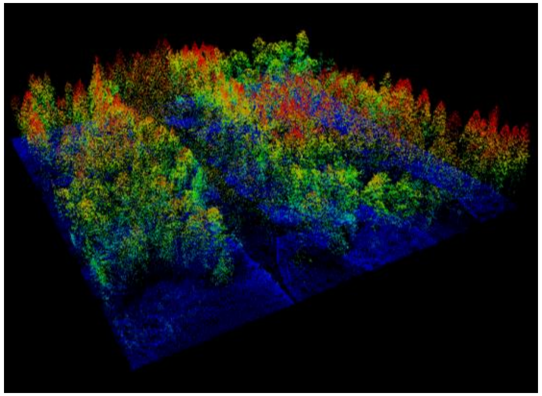
Department of Forest Resource Management (110 Full-time employees)

Sections of
- Forest Remote Sensing
- Forest Planning
- Forest Inventory and Statistics
- Landscape Analysis

FOREST REMOTE SENSING SECTION (*SKOGLIG FJÄRRANALYS*)

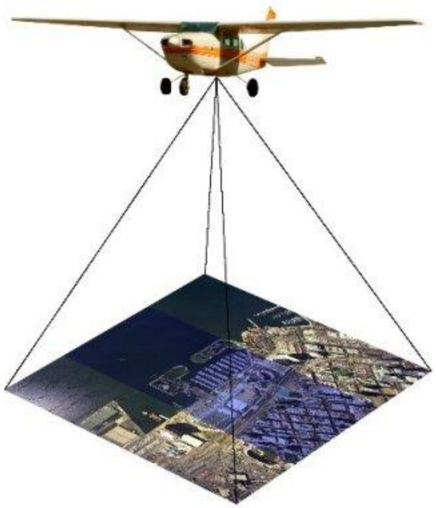
The section conducts research regarding the remote sensing of forests and vegetation, and applies research results to environmental analysis.

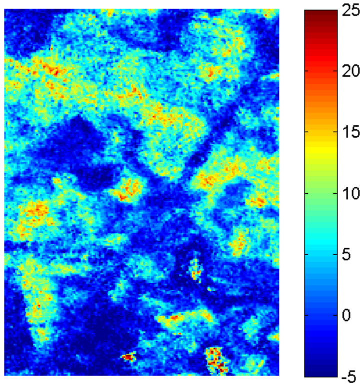
Total around 20 people, including
1 Professor, 3 Assistant Professors, 3 Senior researchers, 1 Lecturer,
5 Research Engineers/Assistants, & 6 PhD students



LiDAR

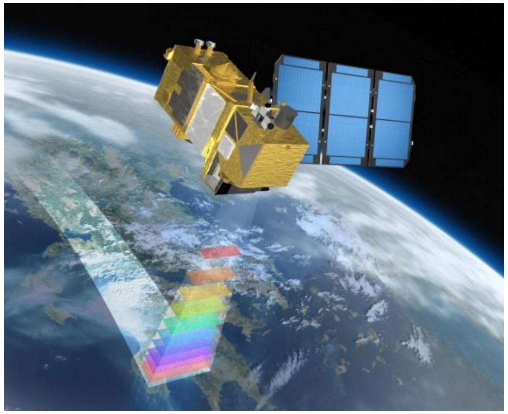
Digital photogrammetry





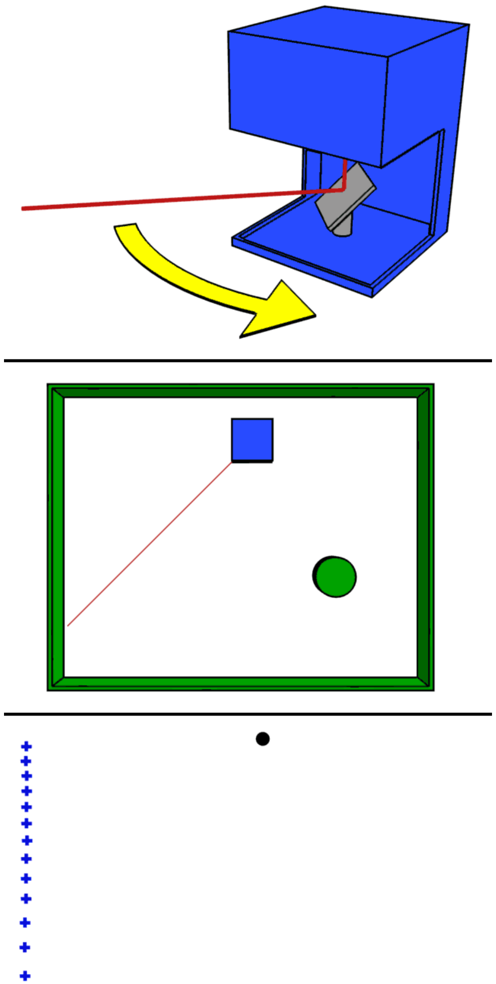
RADAR

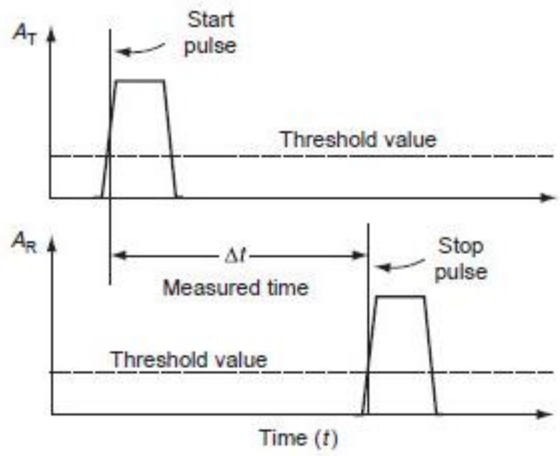
Optical satellite



LIDAR BASIC PRINCIPLE

LiDAR (*Light Detection and Ranging*) systems can emit pulses at rates > 200,000 pulses per second referred to as pulse repetition frequency. A pulse of laser light travels at *c*, the speed of light (3 x 108 ms^{-1}). LiDAR technology is based on the accurate measurement of the laser pulse travel time from the transmitter to the target and back to the receiver. The traveling time of a pulse of light, *t*, is:

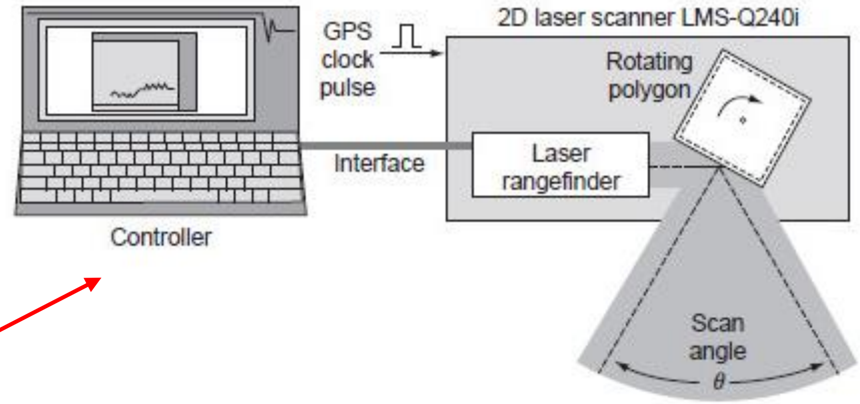




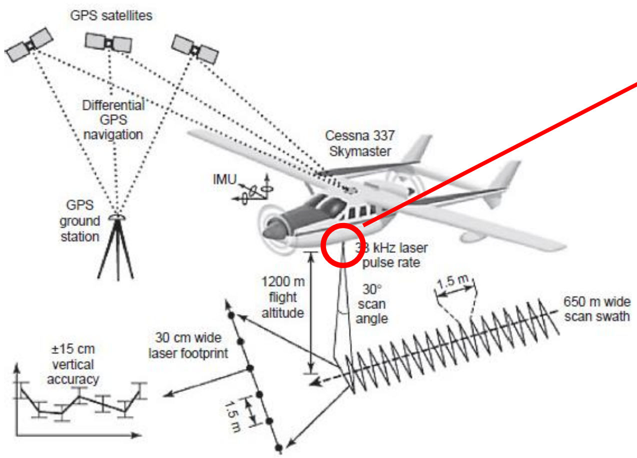
$$t = 2\,\frac{R}{c}$$

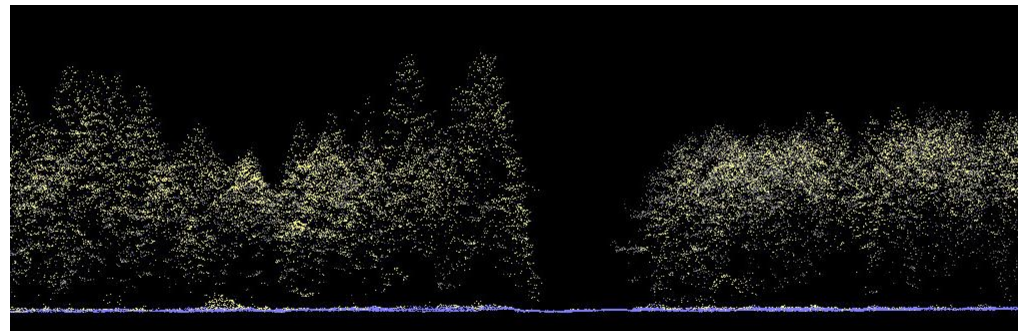
Where *R* is the range (distance) between the LiDAR sensor and the object. The range, R can be determined by rearranging the equation:

$$R = \frac{1}{2}t * c$$



AIRBORNE LASER SCANNER





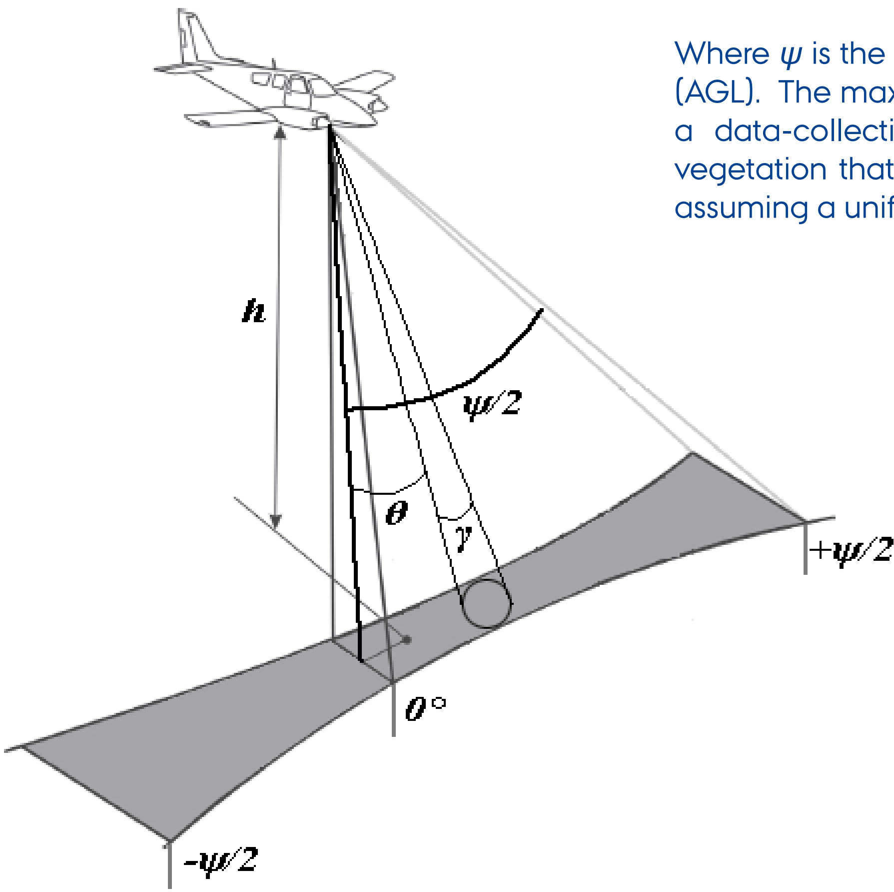
449628.46	6244026.59	0.47	1	1	1	0	0	42	-29	3	1	479827.443325	18944	23040	22784
449628.55	6244033.12	0.30	2	1	1	0	0	42	-28	3	1	479827.443421	20480	24832	24832
449628.75	6244046.31	0.37	3	1	1	0	0	42	-26	3	1	479827.443616	20224	24576	24064
449628.81	6244049.63	0.44	1	1	1	0	0	42	-25	3	1	479827.443666	19712	23552	23296
449628.81	6244049.88	0.39	5	1	1	0	0	42	-25	3	1	479827.443671	20480	24064	23808
449628.81	6244050.66	0.30	1	1	1	0	0	50	-25	3	1	479827.443683	20992	24320	24064
449628.96	6244060.67	0.38	2	1	1	0	0	42	-23	3	1	479827.443837	20736	24320	24320
449629.18	6244075.61	0.39	2	1	1	0	0	42	-21	3	1	479827.444074	19968	24064	23808
449629.24	6244078.72	0.47	4	1	1	0	0	42	-20	3	1	479827.444124	22016	25600	25344
449629.24	6244078.96	0.41	8	1	1	0	0	42	-20	3	1	479827.444128	20992	24320	24320
449629.23	6244079.19	0.34	4	1	1	0	0	42	-20	3	1	479827.444132	20736	24320	24064
449629.29	6244082.54	0.43	5	1	1	0	0	42	-19	3	1	479827.444187	20224	24064	23808
449629.29	6244082.77	0.35	1	1	1	0	0	42	-19	3	1	479827.444191	18944	22784	22528
449629.29	6244083.04	0.38	1	1	1	0	0	42	-19	3	1	479827.444195	19200	23296	23040
449629.34	6244085.60	0.45	2	1	1	0	0	42	-19	3	1	479827.444236	19456	23808	23296
449629.33	6244085.83	0.39	4	1	1	0	0	42	-19	3	1	479827.444241	19456	23552	23296
449629.34	6244086.33	0.35	1	1	1	0	0	42	-19	3	1	479827.444249	19712	24064	23808

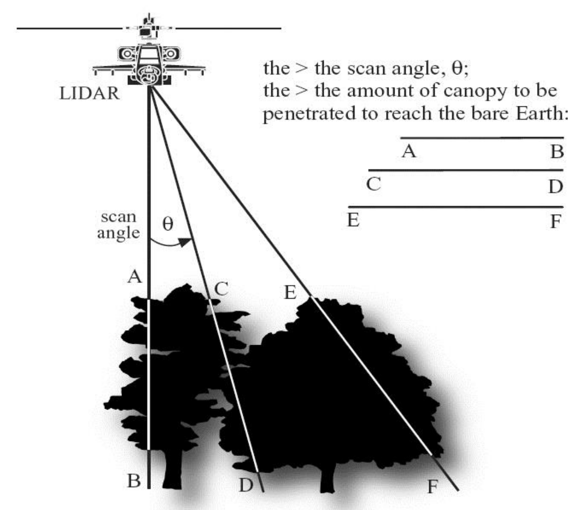
SCANNING ANGLE

The across-track swath width (sw) is given by:

$$\text{sw} = 2h\, tan\frac{\psi}{2}$$

Where ψ is the "total opening angle" (typically 14°-60°) and h is the flying height (AGL). The maximum off-nadir scan angle can be adjusted to meet the needs of a data-collection mission. The greater the scan angle off-nadir, the more vegetation that will have to be penetrated to receive a pulse from the ground assuming a uniform canopy.

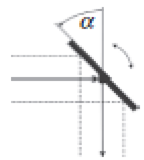
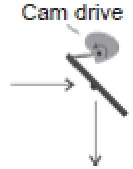
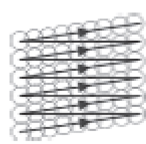
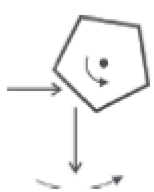
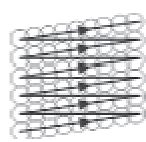
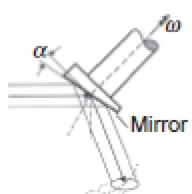
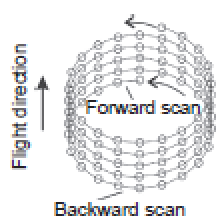


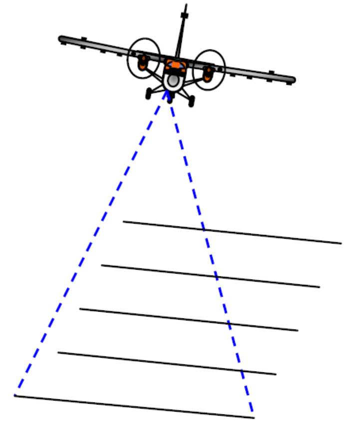


c. Impact of increased scan angle.

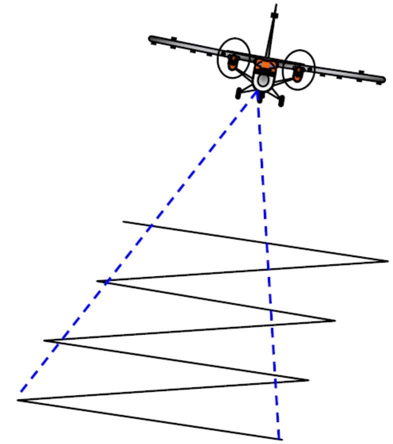
SCANNING PATTERNS

Overview of Mirror Scanners

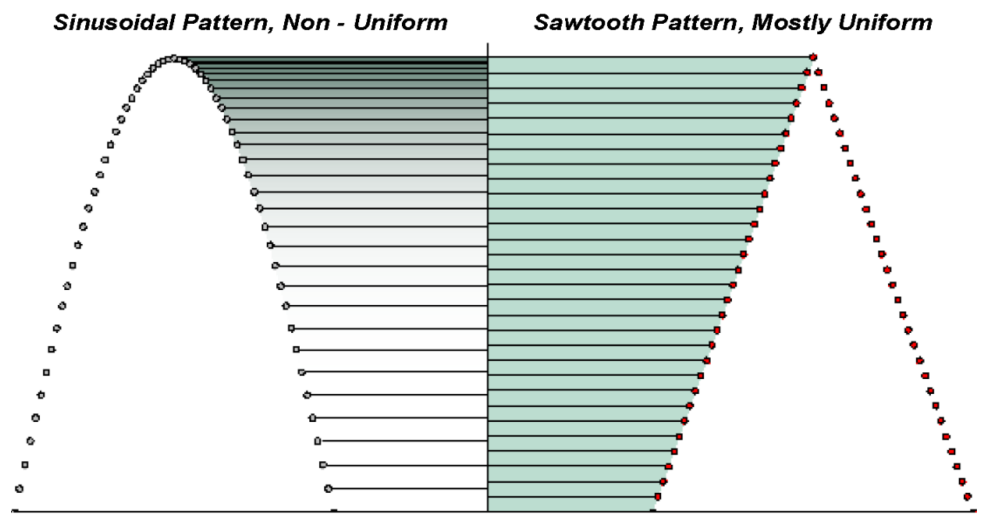
Name	Principle	Scanning Pattern
Oscillating mirror scanner		
Oscillating mirror scanner with cam drive		
Polygon scanner		
Palmer scanner		



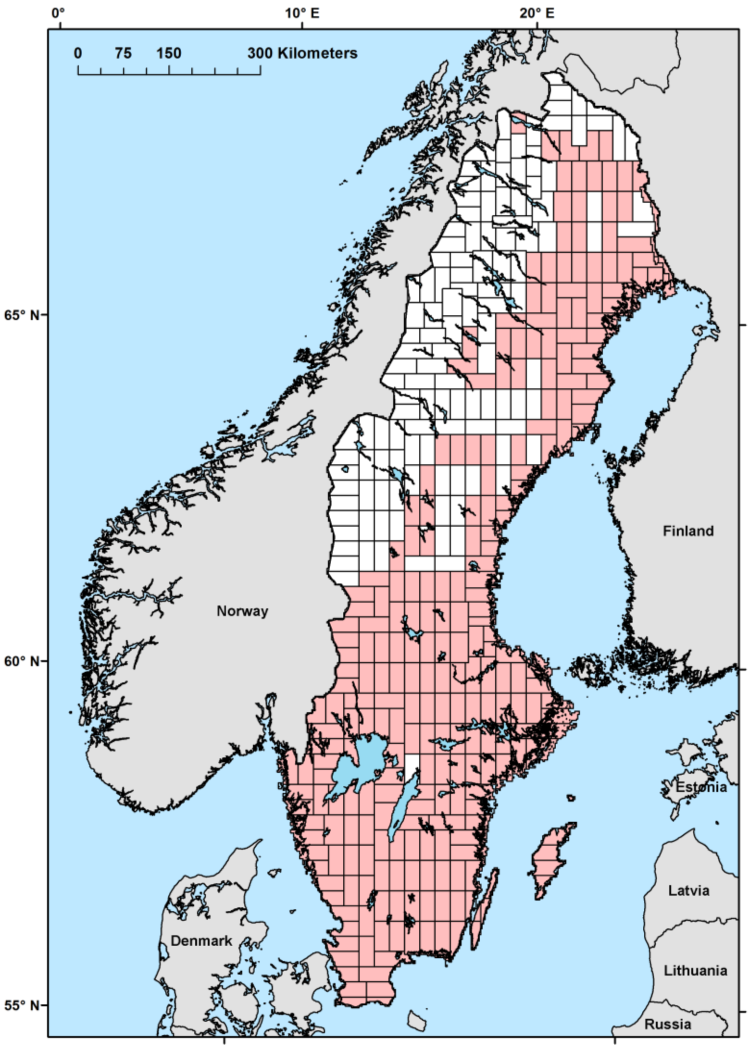
constant-velocity
rotating polygon mirror



oscillating mirror scan mechanism
(seems to be more popular
for airborne lidar systems)



THE NEW SWEDISH NATIONWIDE ELEVATION MODEL (IN SWEDISH: *NY NATIONELL HÖJDMODELL*)

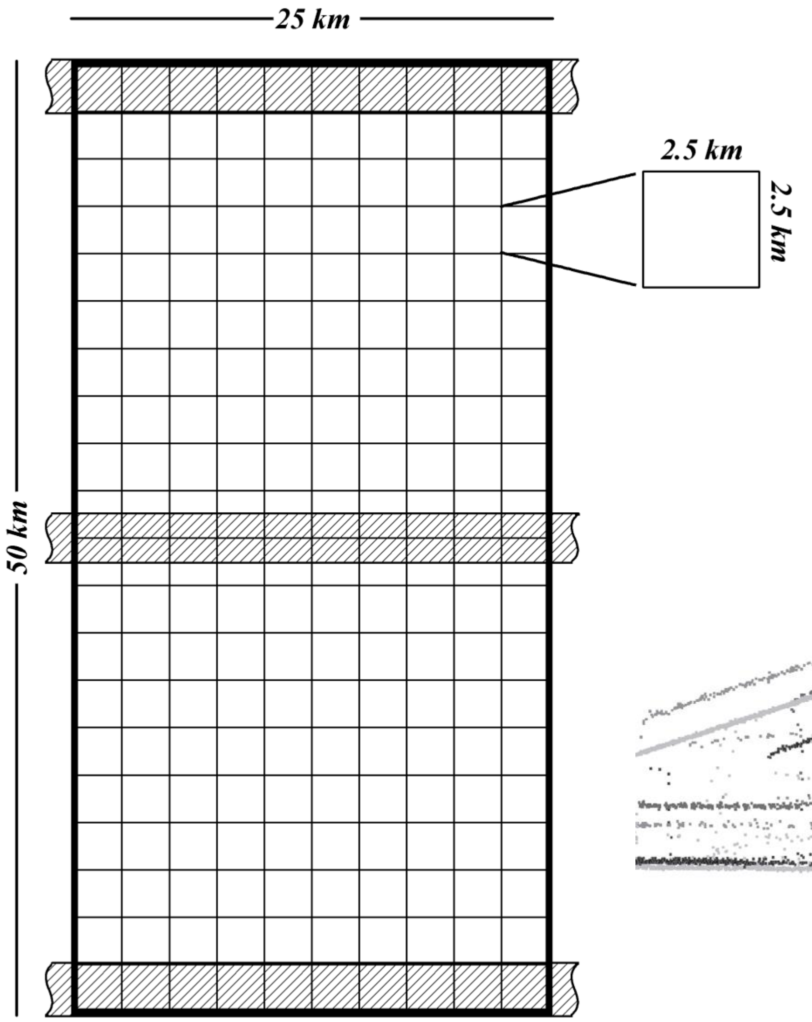


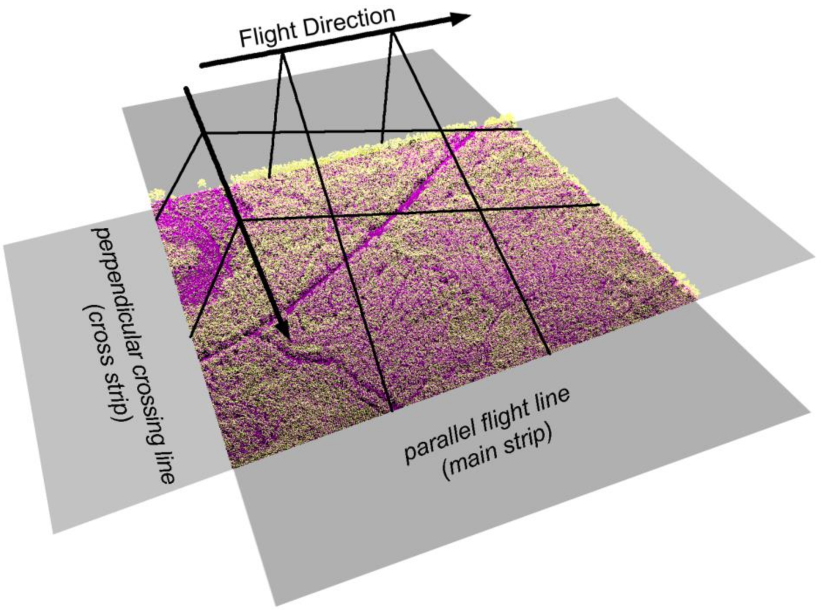
The new Swedish Nationwide Elevation Model in numbers and facts:

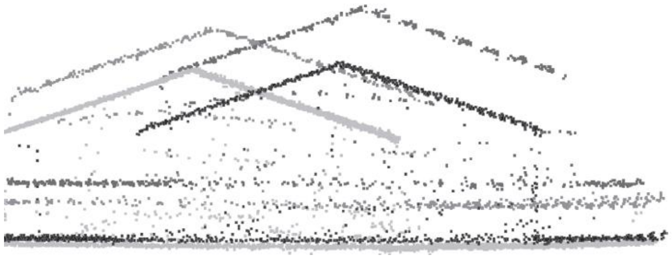
- Produce a Digital Elevation Model (DEM) with high and known accuracy for entire Sweden (450,000 km^2, the fourth largest country in Europe).
- Seven years project (started July 2009), including about 4 years for scanning.
- A total of about four hundred scanning areas, with a size of 25 km by 50 km (1250 km^2), will be collected with a nominal density of 0.5 points per square meter (in single flight lines) and with a footprint on the ground of 0.5 meters.
- Each scanning area, twenty-one parallel flight lines were flown with a nominal overlap of 20%, in addition to three perpendicular crossing lines. The cross strips were located in the top, middle, and bottom within the block, along the small side.
- Delivery data: available approximately 6 months after scan of the actual area.
- The output is a raster grid of 2 m by 2 m pixel resolution, delivered in blocks of 2.5 km by 2.5 km.

LANTMÄTERIET

THE NEW SWEDISH NATIONWIDE ELEVATION MODEL (IN SWEDISH: *NY NATIONELL HÖJDMODELL*)

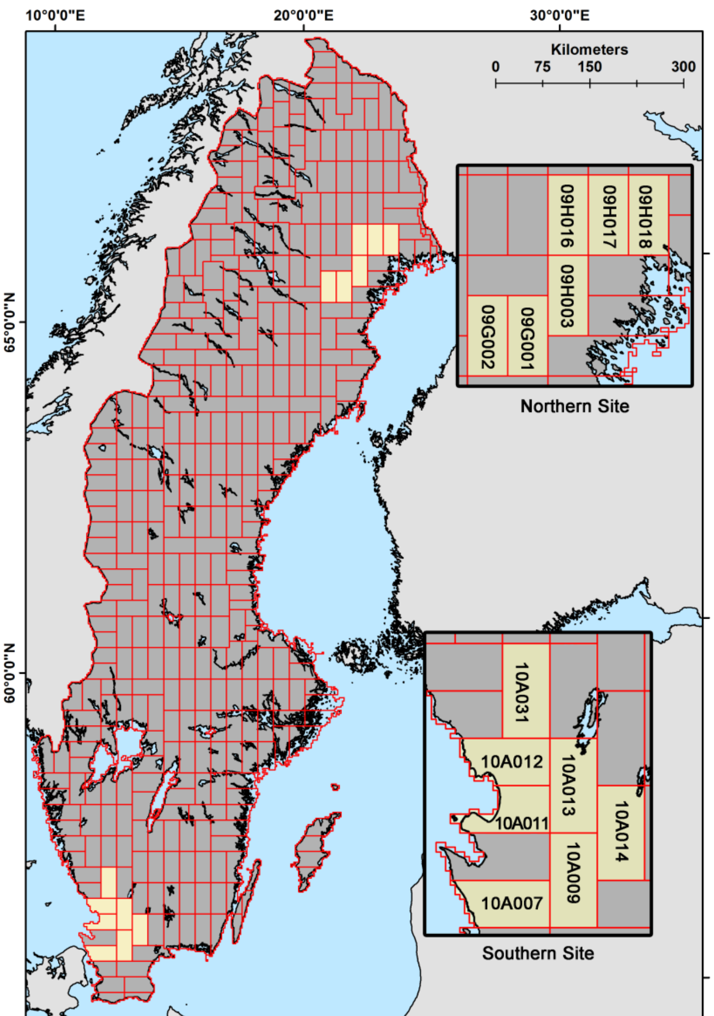






This flight line arrangement with two different directions was designed to allow the strip adjustment techniques, based on sensor parameter calibration, necessary to create a seamless final product.

STUDY AREAS

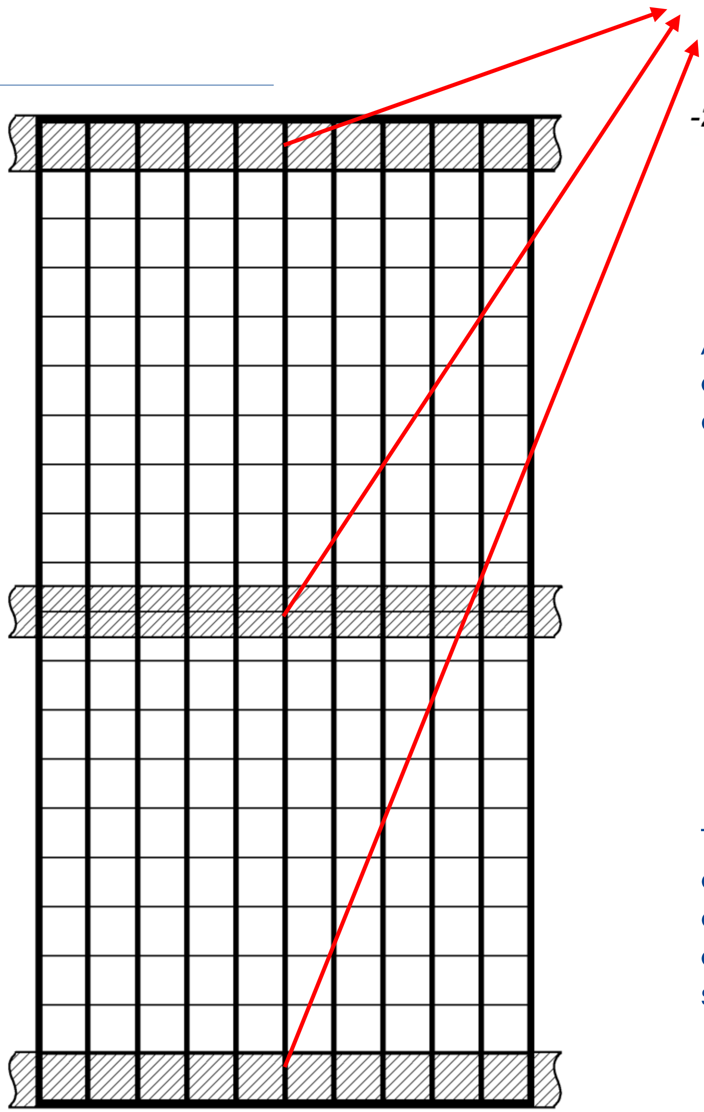


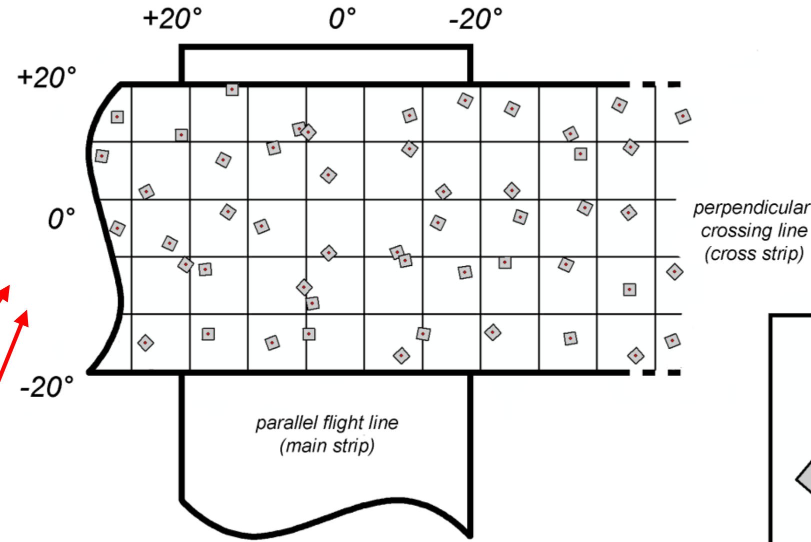
The study was conducted within two sites in Sweden. The first study site (approximately 7,500 km^2) was located in boreal forest in the northern part of Sweden with a central point of Lat. N 65° 50', Lon. E 21° 43'. The topography ranged from 0 to 590 m above sea level (a.s.l.). The second study site (8,162 km^2) was situated in hemi-boreal forest in the southern part of Sweden with a central point of Lat. N 56° 27', Lon. E 13° 35' and topography ranging from 0 to 290 m a.s.l.

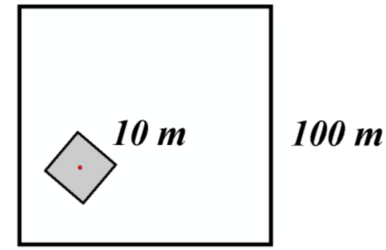
Airborne Laser Scanning (ALS) survey configurations for each scanning areas for the Northern and Southern site.

	Scanning area	sensor	Interval date(s) of survey (DD-MM-YYYY)	Flying height (m a.g.l.)	Flying speed (knots)	Pulse frequency (kHz)	Scanning frequency (Hz)	Point density (points per square meters)	Scanning angle (degrees)
Northern site	09G001	ALS60	24-08-2009/16-09-2009	2391	146	102.4	39.4	0.5	±20
	09G002	ALS60	13-08-2009/21-09-2009	2533	142	102.4	39.4	0.5	±20
	09H003	ALS60	21-08-2009/10-09-2009	2318	144	102.4	39.4	0.5	±20
	09H016	ALS60	27-08-2009/23-09-2009	2328	142	102.4	39.4	0.5	±20
	09H018	ALS60	21-09-2009/27-09-2009	2307	138	102.4	39.4	0.5	±20
	09H017	ALS50-II	14-08-2009/14-09-2009	2300	134	102.4	39.4	0.5	±20
Southern site	10A012	ALS60	12-04-2010/14-04-2010	2259	129	104.1	39.4	0.6	±20
	10A014	ALS60	02-04-2010/01-07-2010	2275	135	104.1	39.4	0.6	±20
	10A031	ALS60	19-04-2010/02-06-2010	2317	140	104.1	39.4	0.6	±20
	10A007	ALS50-II	03-04-2010/12-04-2010	2215	139	104.1	39.4	0.6	±20
	10A009	ALS50-II	13-04-2010/15-04-2010	2252	138	104.1	39.4	0.6	±20
	10A011	ALS50-II	03-04-2010/11-04-2010	2217	137	104.1	39.4	0.6	±20
	10A013	ALS50-II	15-04-2010/27-05-2010	2300	137	104.1	39.4	0.6	±20

DESIGN OF EXPERIMENT



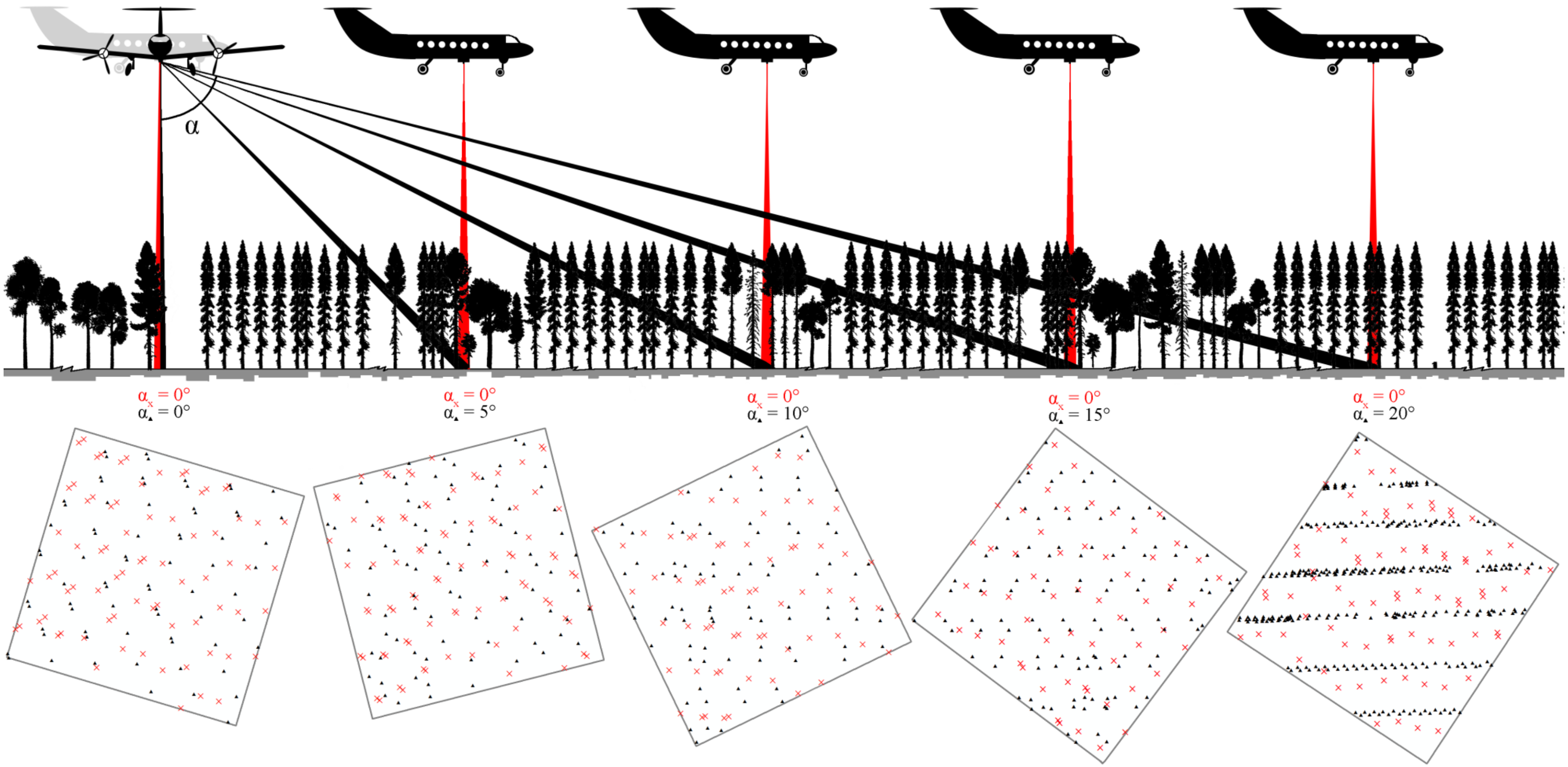




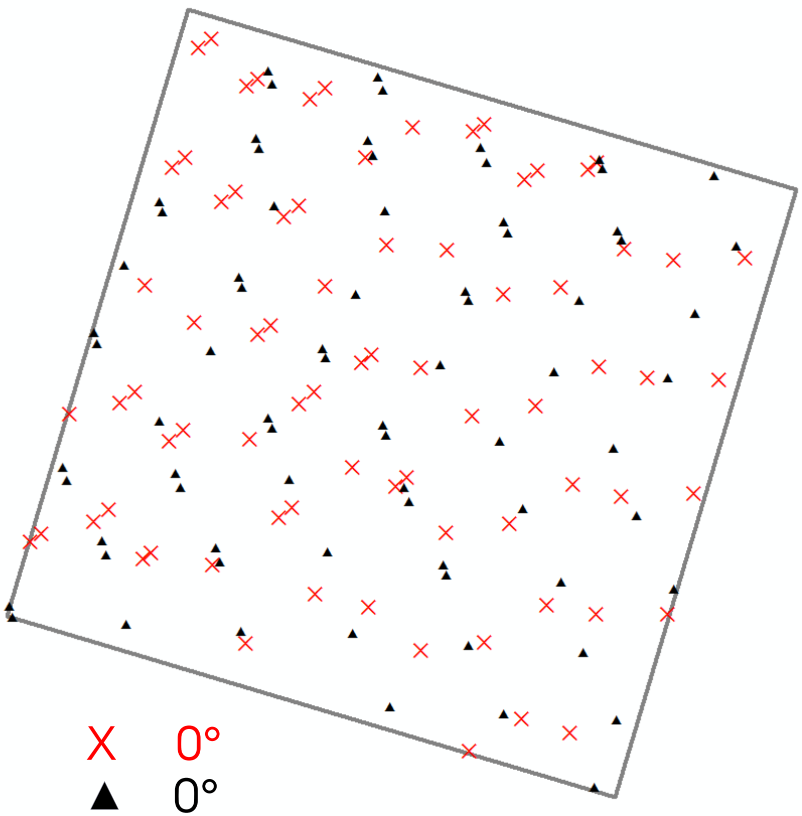
A grid with 100 x 100 m cells was laid over each crossing between main and crossing strips, and in each grid cell a random sample point was created. For each point, a square of 10 m by 10 m was created with random orientation.

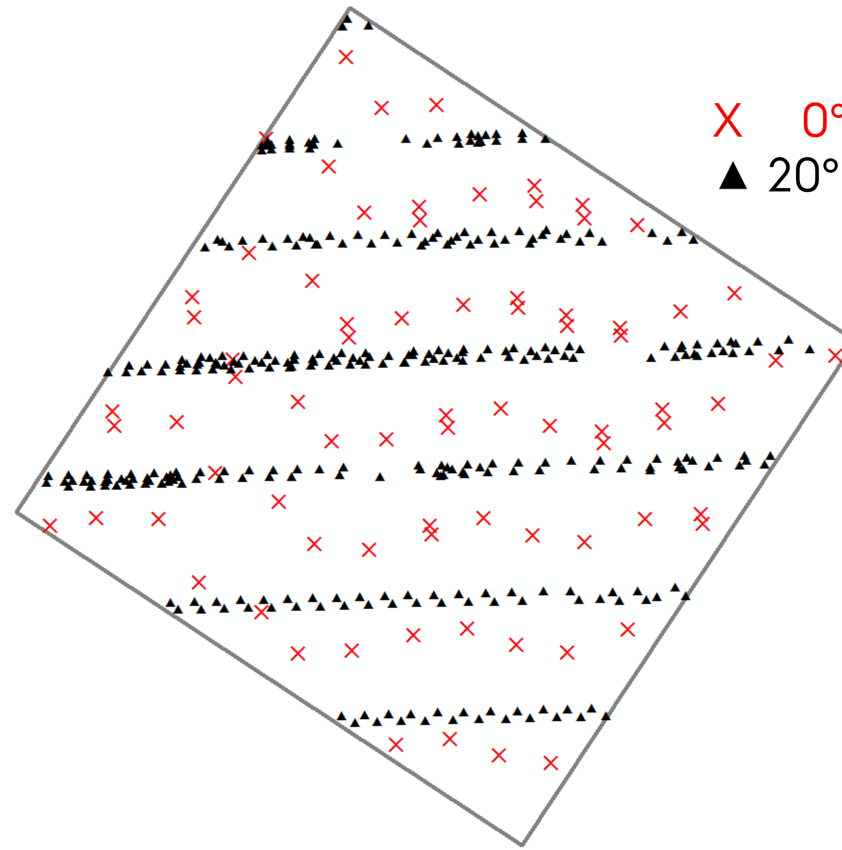
- Only those samples belonging entirely within forested areas were considered.
- Samples were rejected if the returns had scanning angles other than zero degrees for the perpendicular crossing lines and if all returns did not have the same scanning angle for the parallel flight line.
- samples were rejected if the data survey for the perpendicular crossing lines and parallel flight lines was not carried out on the same day.

These criteria reduced the number of samples to 1,309 for the northern site and 1,001 for the southern site, with each sample flown with two different acquisitions: one with a scanning angle of 0 degrees (cross strips) and the other with an absolute scanning angle ranging from 0 to ≤ 20 degrees (main strips).


α
$\alpha_x = 0°$
$\alpha_▲ = 0°$
$\alpha_x = 0°$
$\alpha_▲ = 5°$
$\alpha_x = 0°$
$\alpha_▲ = 10°$
$\alpha_x = 0°$
$\alpha_▲ = 15°$
$\alpha_x = 0°$
$\alpha_▲ = 20°$

Using sinusoidal distribution, the distance between each point near nadir and on the edge of the swath are different. The point spacing is minimal at the center of the swath (at nadir) and increases toward the edges of the scan line since the oscillating mirror moves fastest in the center of the swath and slower at the edges. The result is that the space between each laser point near nadir and the space between each laser point at the edge of the swath are different.





STATISTICAL ANALYSIS

A non-parametric Wilcoxon signed-rank test was employed to determine whether individual metrics were statistically significant inside each scanning angle class. The following hypotheses were tested for each ALS metric:

H_0: No difference exists between metrics derived from a scanning angle of 0 degrees and metrics derived from an absolute scanning angle ranging from 0 to 20 degrees;

H_a: A difference exists between metrics derived from a scanning angle of 0 degrees and metrics derived from an absolute scanning angle ranging from 0 to 20 degrees.

If the test results were significant ($p < 0.05$), then H_0 was rejected and the alternative hypothesis was accepted. Accepting the alternative hypothesis indicated that the scanning angle had an influence on the repeatability of the ALS metric used for describing the forest structure.

$$MAD = \frac{1}{n}\sum_{j=1}^{n} |y_{|k°|,j} - y_{0°,j}|$$

Mean Absolute Difference

$$RMSD = \frac{\sqrt{(y_{|k°|,j} - y_{0°,j})^2}}{n}$$

Root-Mean-Square Difference

where $y|k°|,j$ is the ALS metric value (y) derived from the main strips and having an absolute scanning angle (k) ranging from nadir to 20 degrees in plot-j, $y0°,j$ is the value of the metric (y) from the scanning angle at nadir in plot-j belonging to the cross strips, and n is the number of plots.

Both the MAD and RMSD can range from 0 to positive infinity, with a value of 0 corresponding to the ideal ($\Sigma y|k°|,j = \Sigma y0°,j$).

Plot-level Wilcoxon signed-rank test for the Northern Site. Pairwise scanning angle classes were created based on comparison of two metrics: one metric acquired at 0° from cross-strips and the second metric acquired at an (absolute) scanning angle (*k*, where *k*=0,1,2…20) from main strips. Class names are given as 0-*k*.

Survey interval: 21-08-09 to 26-09-09		Scanning Angle classes (angles expressed in degrees and in absolute value)																				
		0-0	0-1	0-2	0-3	0-4	0-5	0-6	0-7	0-8	0-9	0-10	0-11	0-12	0-13	0-14	0-15	0-16	0-17	0-18	0-19	0-20
Point density metrics	All returns (≥ 0 m)						**		***	***	***	***	***	***	***	***	***	***	***	***	***	***
	Ground returns (= 0 m)						**		*	*	*	**	*	**		.	***	***	***	***	***	***
	All canopy returns (> 0 m)						.	.	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	Understory returns (> 0 m to < 2 m)				.				*		**	***	***	***	***	***	***	***	***	***	***	***
	Canopy returns (≥ 2 m)						.	*	***	***	***	***	***	***	***	***	***	***	***	***	***	***
Distributional metrics	Mean of height (m)													*	*		.	**			**	.
	Modal of height (m)									*				.	*			*				
	Standard Deviation of height (m)																		*			
	Median Absolute Deviation (m)										.							.			*	
	Average Absolute Deviation (m)																		**			
	Interquartile Range (m)																	*	.			
	Skewness			.																		
	Kurtosis							.			*		*			.		*			.	
Height metrics	10th percentile (m)														*	.		*	*	*	*	**
	25th percentile (m)																	**			*	*
	50th percentile (m)				.							.		**			*	*			*	
	75th percentile (m)				.					.				*		.		.				
	80th percentile (m)									.												
	90th percentile (m)	*									.					.				**		
	95th percentile (m)																**		.	*		
	99th percentile (m)																**	.	***	***		
	Maximum height (m)												.				**		***	***		
Layer density metrics	Cumulative Density of layer 1 (%)							.					*				*				***	*
	Cumulative Density of layer 2 (%)															*						
	Cumulative Density of layer 3 (%)													*			.	*	*			
	Stratified Density of layer 1 (%)											*					.	*				
	Stratified Density of layer 2 (%)			*				*						*			*	**	*	.	*	
	Stratified Density of layer 3 (%)			.				*				.		**			*	***	*	.	***	.
Structural descriptor metrics	Understory ratio (%)			.							**	***	***	***	***	***	***	***	***	***	***	***
	Vegetation ratio (%)		**					.		**	.	**	***	***	***	***	***	***	***	***	***	***
	Canopy Relief ratio index (%)			.							*											
	Point Height Diversity index (%)		*									.	.	**	.	.	*	**	***		**	.
	n. of plot	78	77	55	59	67	68	67	53	59	49	67	72	65	67	57	65	73	52	59	41	59

Significance levels: *** p-value < 0.001; ** p-value < 0.01; * p-value < 0.05; . p-value < 0.1; blank space = not significant.

AARHUS UNIVERSITET

Plot-level Wilcoxon signed-rank test for the Southern Site. Pairwise scanning angle classes were created based on comparison of two metrics: one metric acquired at 0° from cross-strips and the second metric acquired at an (absolute) scanning angle (*k*, where *k*=0,1,2…20) from main strips. Class names are given as 0-*k*.

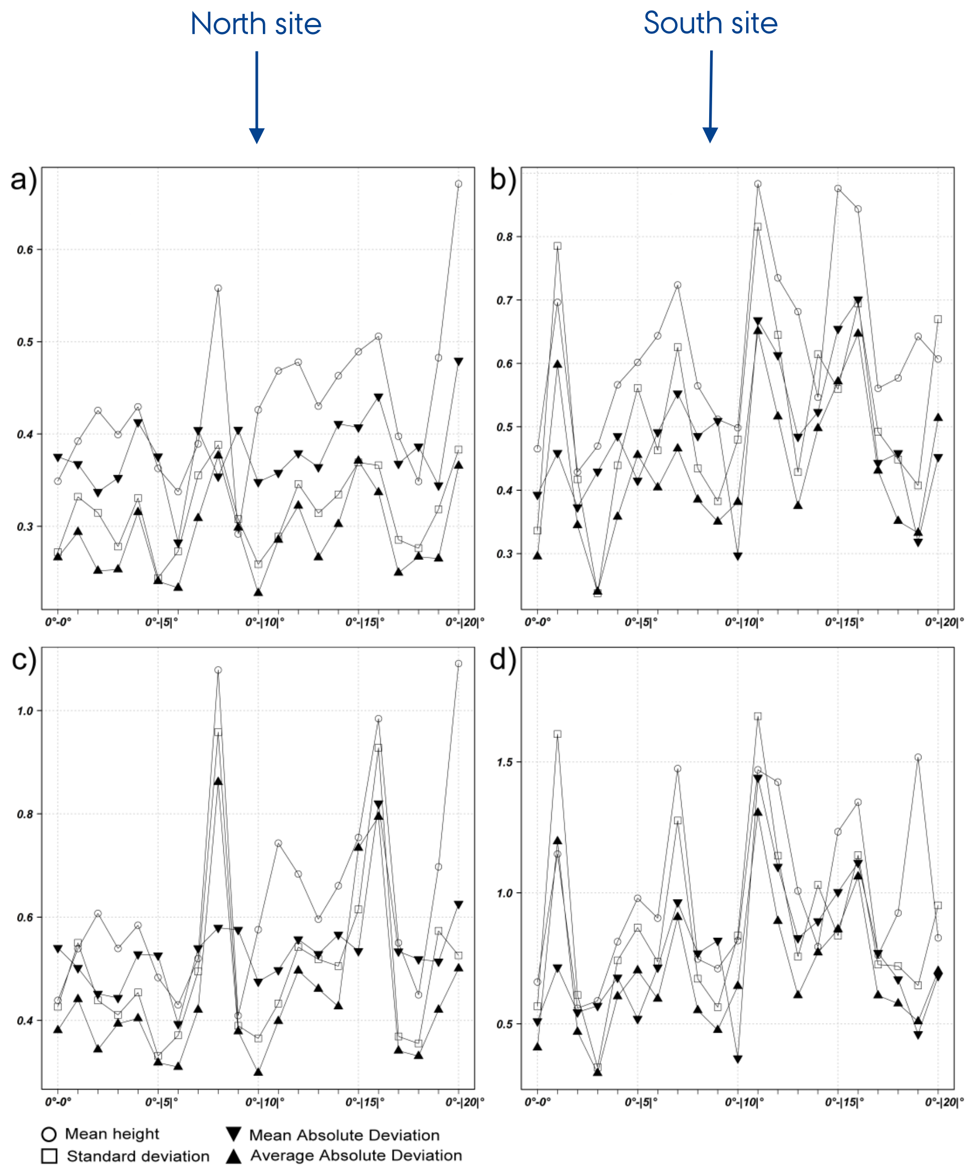
Survey interval: 02-04-2010 to 01-07-2010		Scanning Angle classes (angles expressed in degrees and in absolute value)																				
		0-0	0-1	0-2	0-3	0-4	0-5	0-6	0-7	0-8	0-9	0-10	0-11	0-12	0-13	0-14	0-15	0-16	0-17	0-18	0-19	0-20
Point density metrics	All returns (≥ 0 m)							*	*	***	***	**	***	***	***	***	***	***	***	***	***	***
	Ground returns (= 0 m)	*		*											*	**	**	***	***	***	***	***
	All canopy returns (> 0 m)							*	***	***	***	***	***	***	***	***	***	***	***	***	***	***
	Understory returns (> 0 m to < 2 m)		*							**	**	***	***	***	***	***	***	***	***	***	***	***
	Canopy returns (≥ 2 m)							*	***	***	***	**	***	***	***	***	***	***	***	***	***	***
Distributional metrics	Mean of height (m)					.					*		.	*	**	*	*					**
	Modal of height (m)															.						
	Standard Deviation of height (m)					.							.			.	.					
	Median Absolute Deviation (m)												*	*							.	
	Average Absolute Deviation (m)	.								*			.		.	.			.		*	
	Interquartile Range (m)									*			*						*		*	.
	Skewness	*	*													**						**
	Kurtosis									.	*		*			***		.		**		***
Height metrics	10th percentile (m)	.										.	.	*	**	*	*				*	*
	25th percentile (m)												**	*	*	.			*		*	**
	50th percentile (m)		*								.		*		*		*			.		.
	75th percentile (m)											.		**	***							
	80th percentile (m)							.						.	*							
	90th percentile (m)								*						.							
	95th percentile (m)			*																		
	99th percentile (m)			.										*						*		
	Maximum height (m)													**						*		
Layer density metrics	Cumulative Density of layer 1 (%)		.			.										.			*	.		
	Cumulative Density of layer 2 (%)				.						.				*							
	Cumulative Density of layer 3 (%)					*								*	*							
	Stratified Density of layer 1 (%)				.				.					*	.		**			.	.	.
	Stratified Density of layer 2 (%)		.								*				*							
	Stratified Density of layer 3 (%)				.	.					**		*	*	**					*		
Structural descriptor metrics	Understory ratio (%)		*							**	**	***	***	***	***	***	***	***	***	***	***	***
	Vegetation ratio (%)						*		***		**		***	***	***	***	**	**	***	***	***	***
	Canopy Relief ratio index (%)	.	.											.		**						*
	Point Height Diversity index (%)					.			.				*	*	.	.	.			.	*	.
	n. of plot	57	46	57	37	44	55	52	37	46	54	36	47	57	50	57	42	50	43	45	41	48

Significance levels: *** p-value < 0.001; ** p-value < 0.01; * p-value < 0.05; . p-value < 0.1; blank space = not significant.

Distributional metrics

MAD
Mean Absolute Difference
a) and b)

RMSD
Root-Mean-Square Difference
c) and d)



AARHUS UNIVERSITET

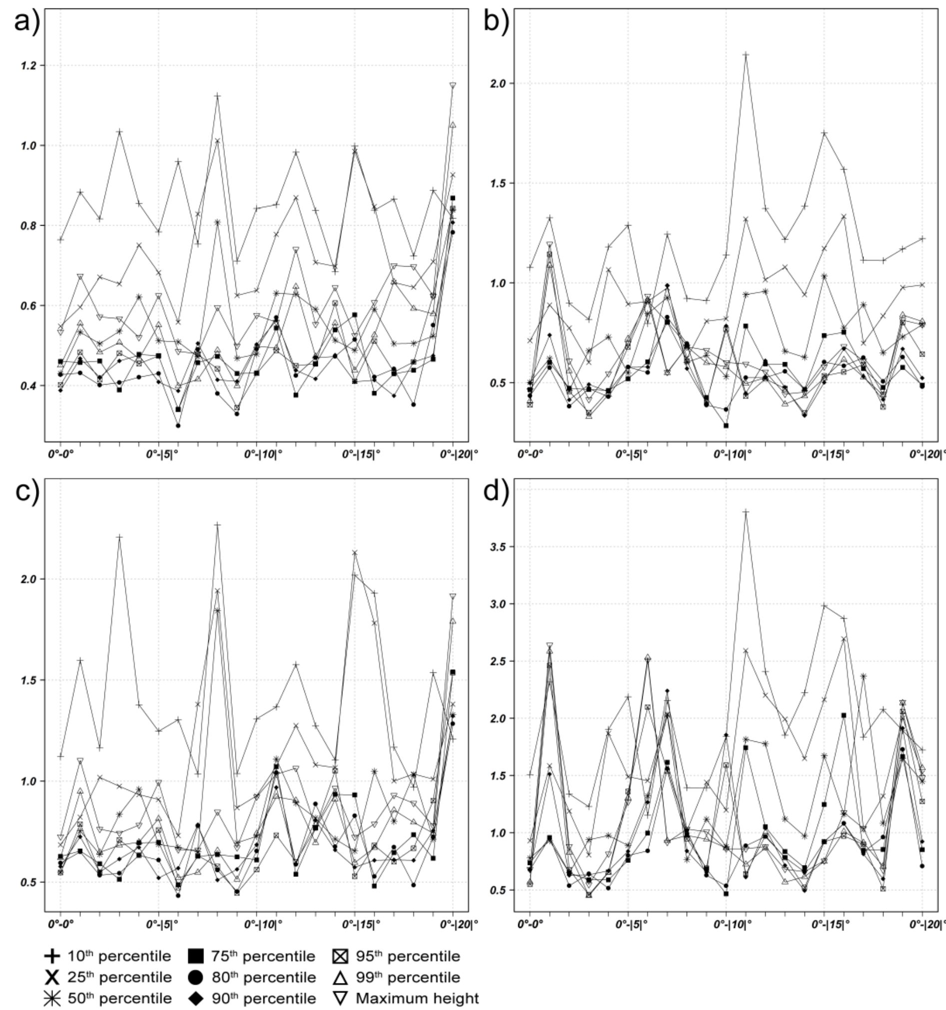
Height metrics

MAD
Mean Absolute Difference
a) and b)

RMSD
Root-Mean-Square Difference
c) and d)

North site

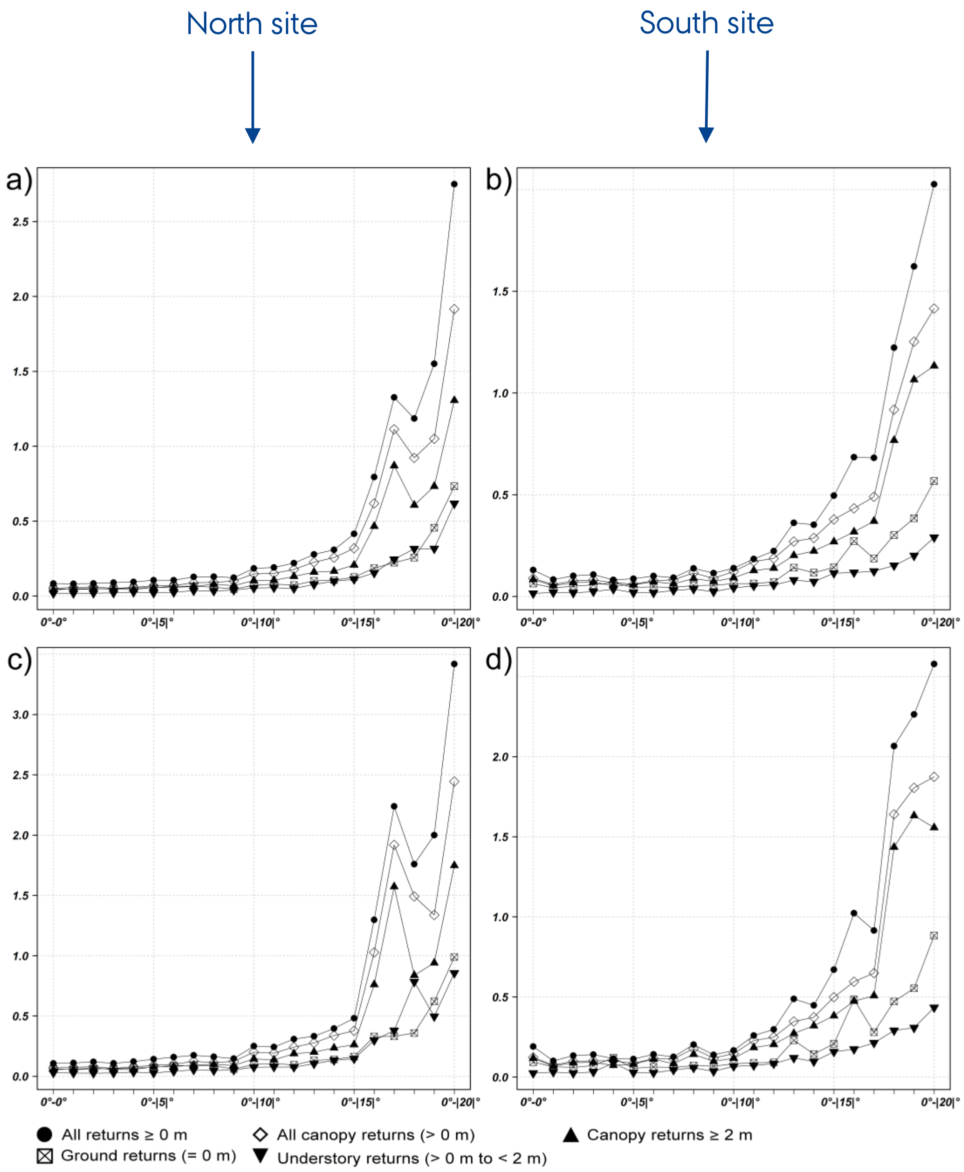
South site



Structural descriptor metrics

MAD
Mean Absolute Difference
a) and b)

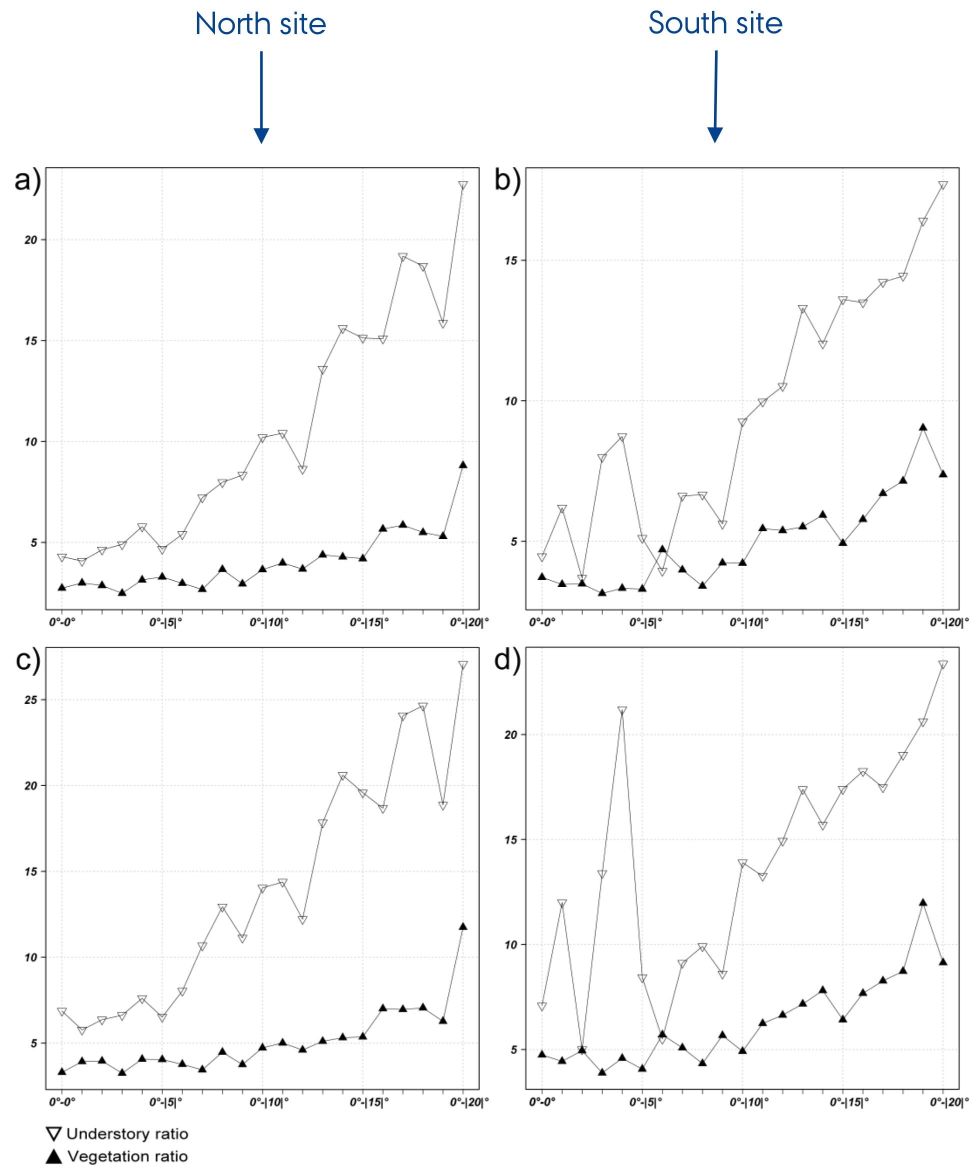
RMSD
Root-Mean-Square Difference
c) and d)



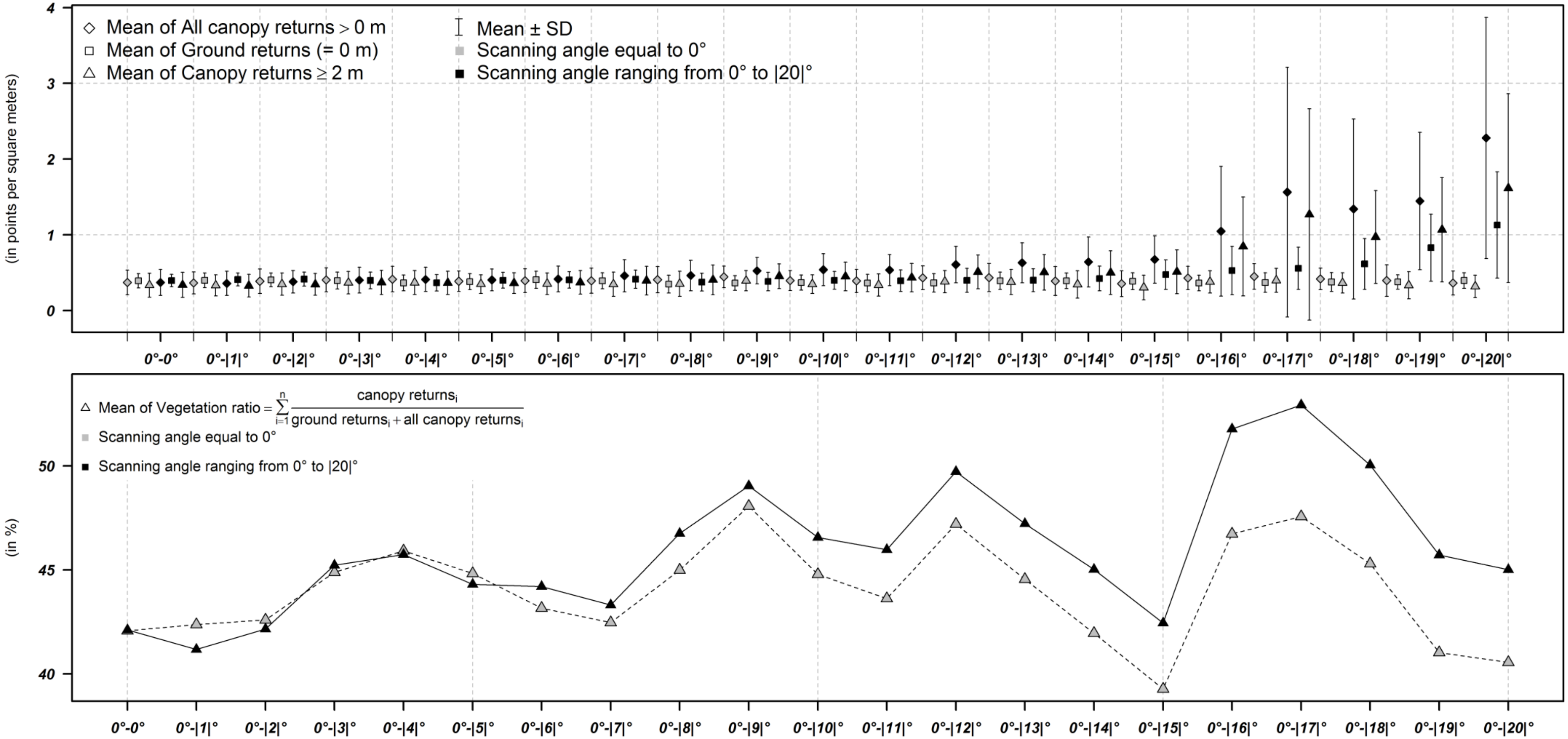
Point density metrics

MAD
Mean Absolute Difference
a) and b)

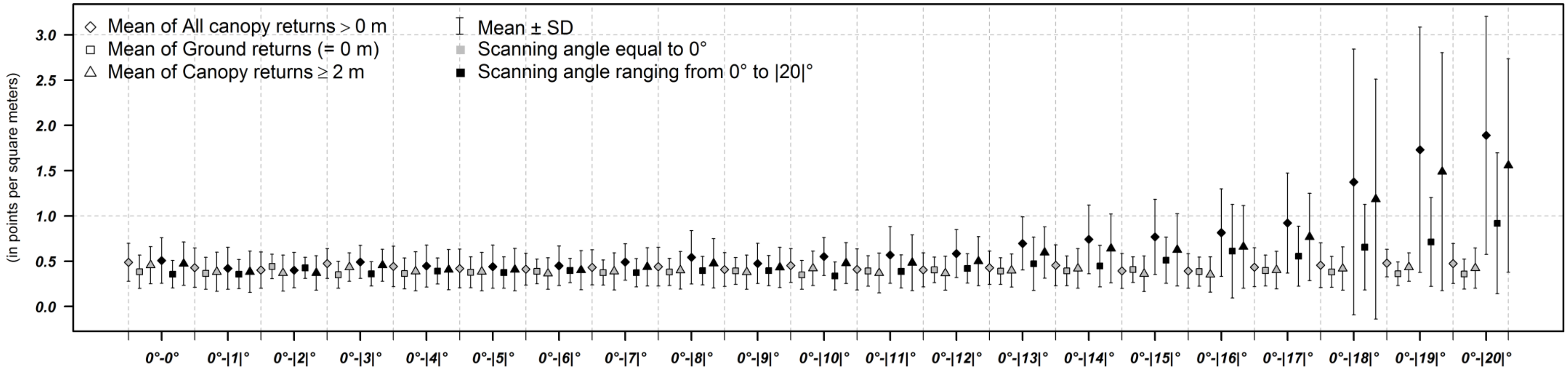
RMSD
Root-Mean-Square Difference
c) and d)

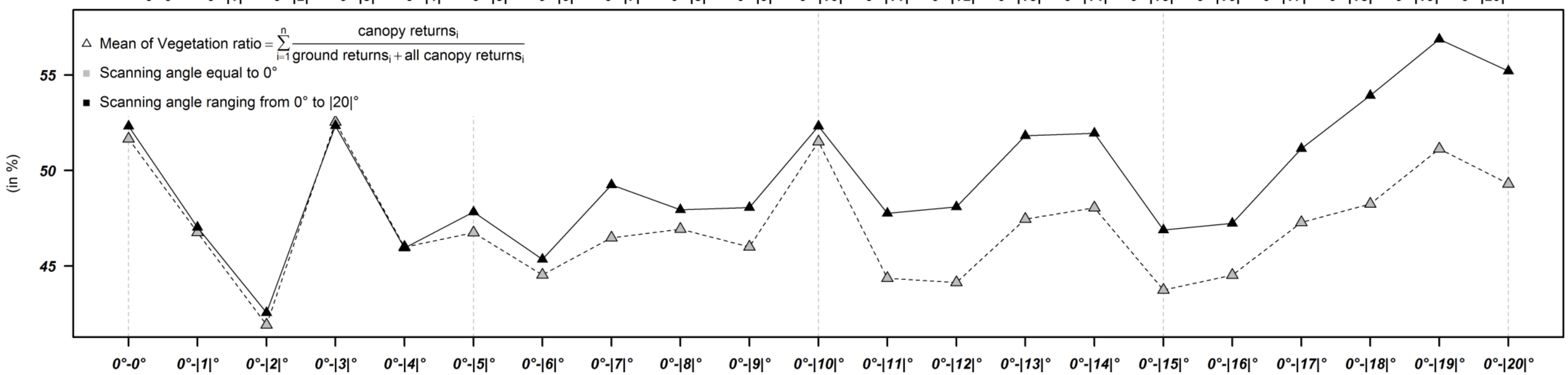


North site – Vegetation ratio



South site – Vegetation ratio





remarks

- that there was a scanning angle influence on the point density metrics and also on Understory and Vegetation ratio for both the northern and southern study sites;
- the Understory ratio and the Vegetation ratio were stable for scanning angles up to about 10 degrees off-nadir;
- with an off-nadir incident angle each laser beam passes a longer distance through the canopy and therefore the probability is higher that the light is reflected from the canopy;
- The difference in point density from nadir to large scanning angles is related to the sinusoidal scanning pattern where the distance between each point near nadir and on the edge of the swath are different;
- The increment of standard deviation in the higher scanning angle classes may also be related to the influence of the pulse power to detect canopy elements. A pulse frequency emitted at 100 kHz, as used in this study, returns data with more "noise" and it is more appropriate for detecting the upper part of the canopy, because laser pulses emitted at that frequency did not penetrate as deeply into the canopy;
- the Understory ratio and the Vegetation ratio were stable for scanning angles up to about 10 degrees off-nadir;
- the results presented here show that care must be taken when considering forest change detection when using ALS-derived vegetation metrics, especially forest density metrics (e.g., Vegetation ratio and Understory ratio). The difference in the magnitude of the changes may be confused with apparent differences at coincident survey times due at an off-nadir scanning angle effect.