



WOOLPERT

ARCHITECTURE | ENGINEERING | GEOSPATIAL

UAS-based Lidar: Performance comparison of Four Lidar systems

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AFB80 Committee Summer 2019 Meeting – July 22-24, 2019 Daytona Beach, FL

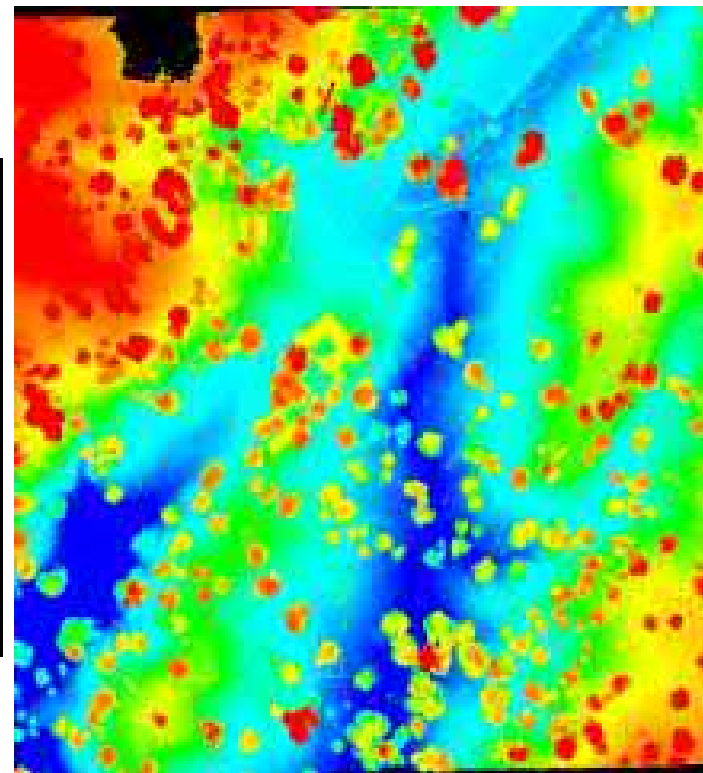
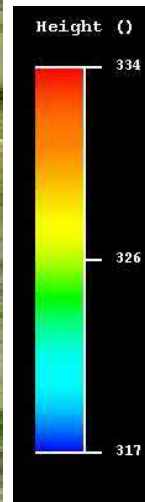
The background of the slide is a blue-tinted aerial photograph of a testing field. The field is marked with a grid of white lines, and several tall, thin poles are visible in the distance. The overall scene is a technical or industrial setting.

The Project

- Woolpert was contracted by CSU-Fresno Foundation to acquire data over their testing field using UAS-based imagery and lidar
- Woolpert flew eBee X RTK UAS for imagery and four lidar systems
- I will brief you on our analysis of the data

CSU Testing site, North of Fresno California

400x400 meter



An aerial photograph of a multi-lane highway interchange, overlaid with a semi-transparent blue filter. The road lines and overpasses are clearly visible, leading towards a horizon with several tall utility poles. The overall tone is monochromatic blue.

The Digital Imaging Technology

We deployed Sensefly eBee X with RTK/PPK Capability

eBee X
Fixed-Wing Drone



senseFly S.O.D.A. 3D
Mapping Camera

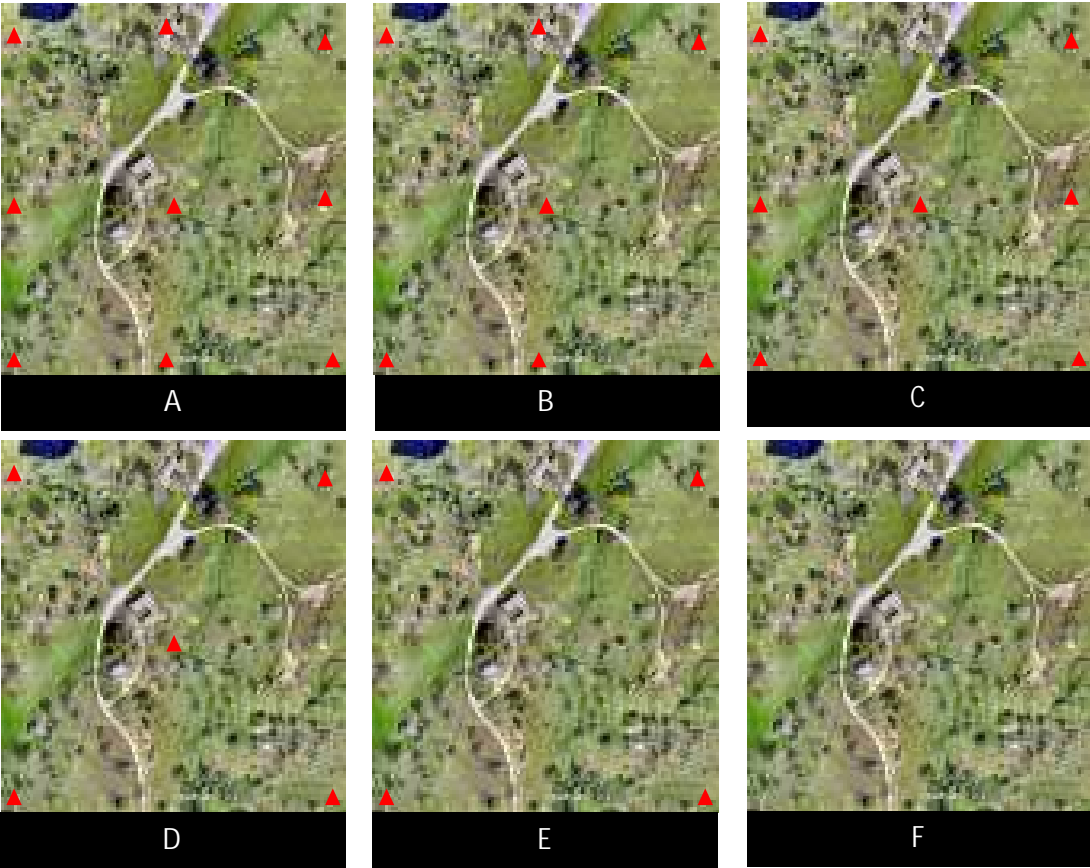


CSU Testing Site

- 81 Targeted GCPs
- Surveyed to accuracy of:
 - Vertical one-sigma = 0.3-cm
 - Horizontal one-sigma = 1.0-cm
- Woolpert was provided with 40 check points for the analysis



Ground Controls and Accuracy – The eBee X Evaluation



Accuracy Term	Residual Values (m)			Delta Z after Z-bias Removed (m)
	Error in Easting (m)	Error in Northing (m)	Error in Elevation (m)	
Mean Error	-0.008	0.003	-0.053	0.000
Standard Deviation (StDEV)	0.013	0.013	0.030	0.030
Root Mean Squares Error (RMSE _{array})	0.015	0.013	0.061	0.029
Radial RMSE	0.020			
NSSDA Horiz Accuracy at 95% accuracy Level	0.035			
NSSDA Vert Accuracy at 95% accuracy Level	0.119			
NSSDA Vert Accuracy at 95% accuracy Level after z-bias removal	0.058			



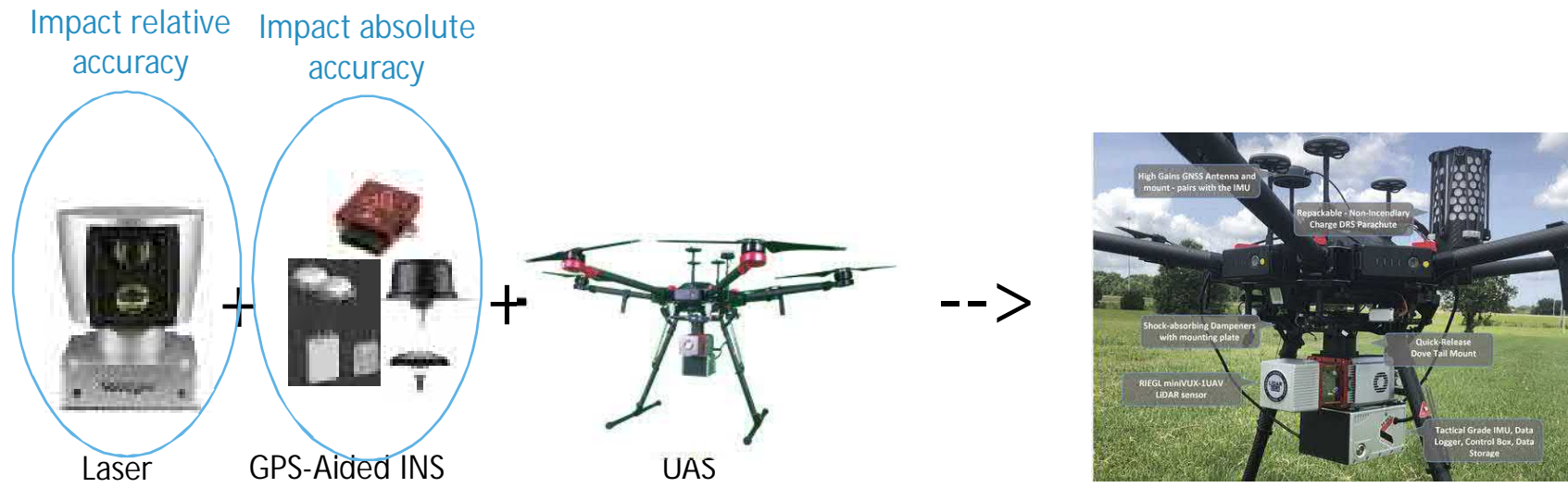
Accuracy Term	Processing Scenario					
	A	B	C	D	E	F
Number of GCPs in AT	9	7	7	5	4	0
Number of Check Points	30	32	32	34	35	39
RMSE E (m)	0.015	0.011	0.017	0.016	0.015	0.016
RMSE N (m)	0.013	0.016	0.013	0.015	0.015	0.017
Radial RMSE N,E (m)	0.020	0.020	0.021	0.022	0.021	0.023
RMSE Elev. (m)	0.029	0.029	0.031	0.032	0.032	0.030
Horizontal Accuracy at 95% (m)	0.035	0.034	0.037	0.037	0.037	0.040
Vertical Accuracy at 95% (m)	0.058	0.057	0.061	0.062	0.062	0.060



The image is a blue-tinted aerial photograph of a complex highway interchange. The roads are multi-laned and feature white dashed and solid lane markings. Several overpasses and ramps are visible, connecting different levels of the highway. In the background, there are several tall, thin utility poles or light towers. The overall scene is rendered in a monochromatic blue color scheme, giving it a technical and futuristic appearance. The text 'The Lidar Technology' is centered over the image in a white, sans-serif font.

The Lidar Technology

Anatomy Of a UAS-based Lidar System



Images courtesy, Lidar USA, DJI, and VECTORNAV



Dynamics governing putting Lidar system on a drone

- Has to be light weight
 - Limited physical size and weight impact its performance
 - Lower power laser
 - Lower performance GPS and IMU
- Has to be affordable to fly it on a small drone over a small size project
 - Low cost lidar means degraded performance
 - Low cost lidar means lower quality laser, GPS, and IMU
 - Lower quality sub-systems means lower quality points cloud

We deployed four Lidar systems

leased from Lidar USA through a contract with MODUS

Velodyne Lidar

HDL-32E




KEY FEATURES

- 128 Channels
- 47° FOV (vertical)
- Range up to 300m (for calibrated)
- 10° Resolution
- 100m/100m Range
- Up to 1.3M Points per Second
- 200° Horizontal FOV
- 40° x 300° Vertical FOV
- Low Power Consumption
- Rugged Design




Velodyne Lidar

Puck LITE




REVOLUTION 60




KEY FEATURES


- 6 Channels
- Max Range 100m
- Range Accuracy 1cm (100m)
- Field of View (FOV) 60° x 60° (2D)
- Range Resolution (Vertical) 2°
- Field of View (Horizontal) 60°
- Range Resolution (Horizontal) 0.5° - 1°
- Range Rate 1m - 20m
- Integrated Software for Easy Monitoring and Configuration



REOLINK VUX




Snoopy miniVUX



KEY FEATURES

- Max. Range (Horizontal) 100m
- Max. Measuring Height 100m
- Max. Range (Vertical) 30%
- Max. Range (Vertical) 200m
- Max. Range (Vertical) 40%
- Max. Range (Vertical) 40m (400m)
- Max. Number of Scans per Hour 1

Minimum Range 3m
Accuracy 15mm
Precision 12mm



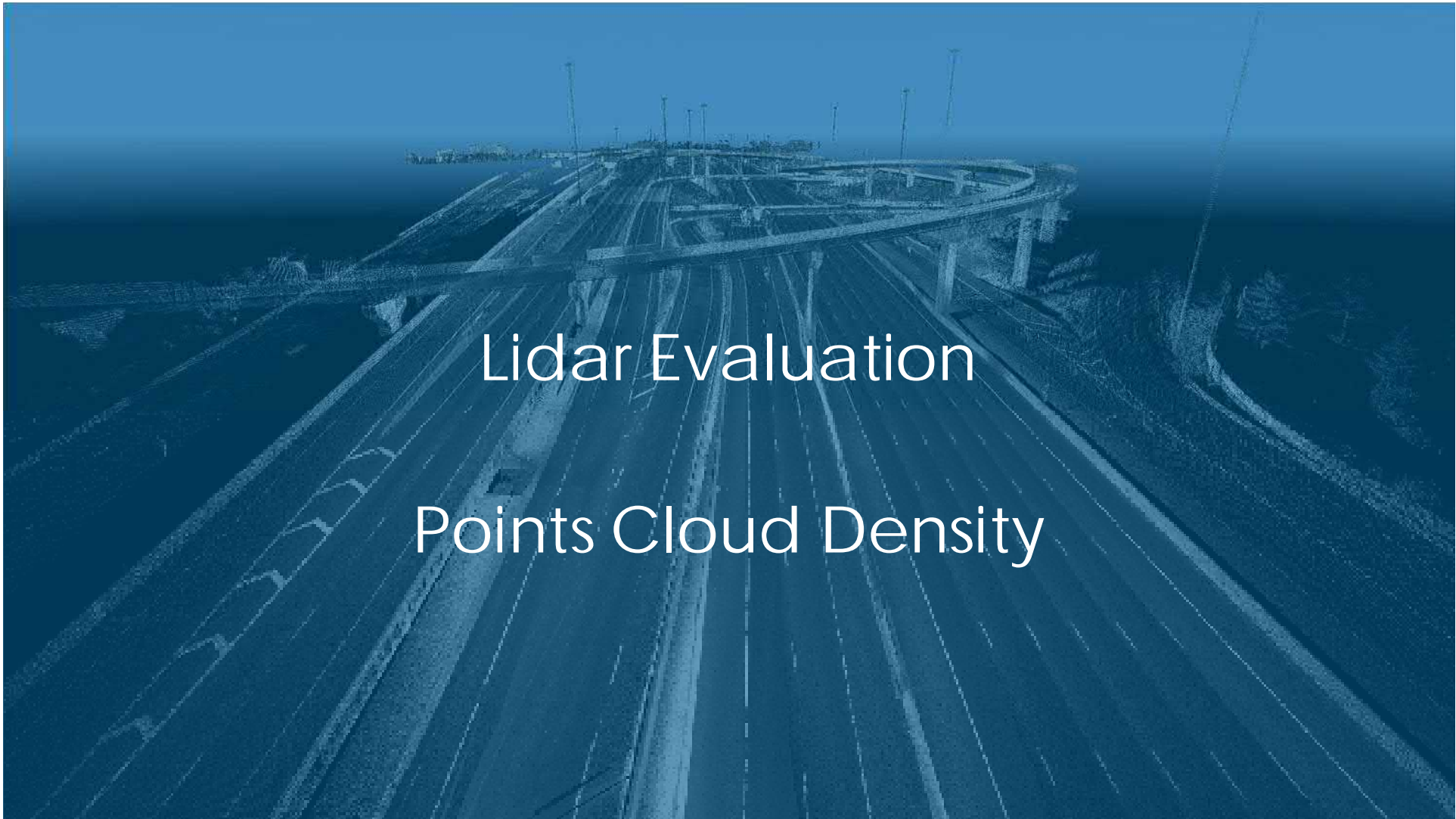
Quanergy M8



Model	Model
Max. Range	100m (Horizontal)
Max. Measuring Height	100m
Max. Range (Vertical)	30%
Max. Range (Vertical)	200m
Max. Range (Vertical)	40%
Max. Range (Vertical)	40m (400m)
Max. Number of Scans per Hour	1
Minimum Range	3m
Accuracy	15mm
Precision	12mm

MODUS

LIDAR USA



Lidar Evaluation

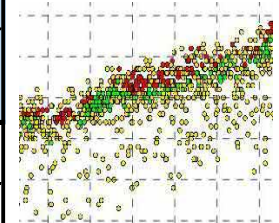
Points Cloud Density

Points Density, standard processing

Sensor	Ground ONLY		All Classes (pts/m2)	
	Density (pts/m2)	Nominal Point Spacing (m)	Density (pts/m2)	Nominal Point Spacing (m)
MiniVUX	7.6	0.36	155	0.08
Quanergy_M8	9.6	0.32	570	0.04
Velodyne HDL32	7.5	0.365	521	0.04
Velodyne VLP16	4.7	0.461	305	0.06

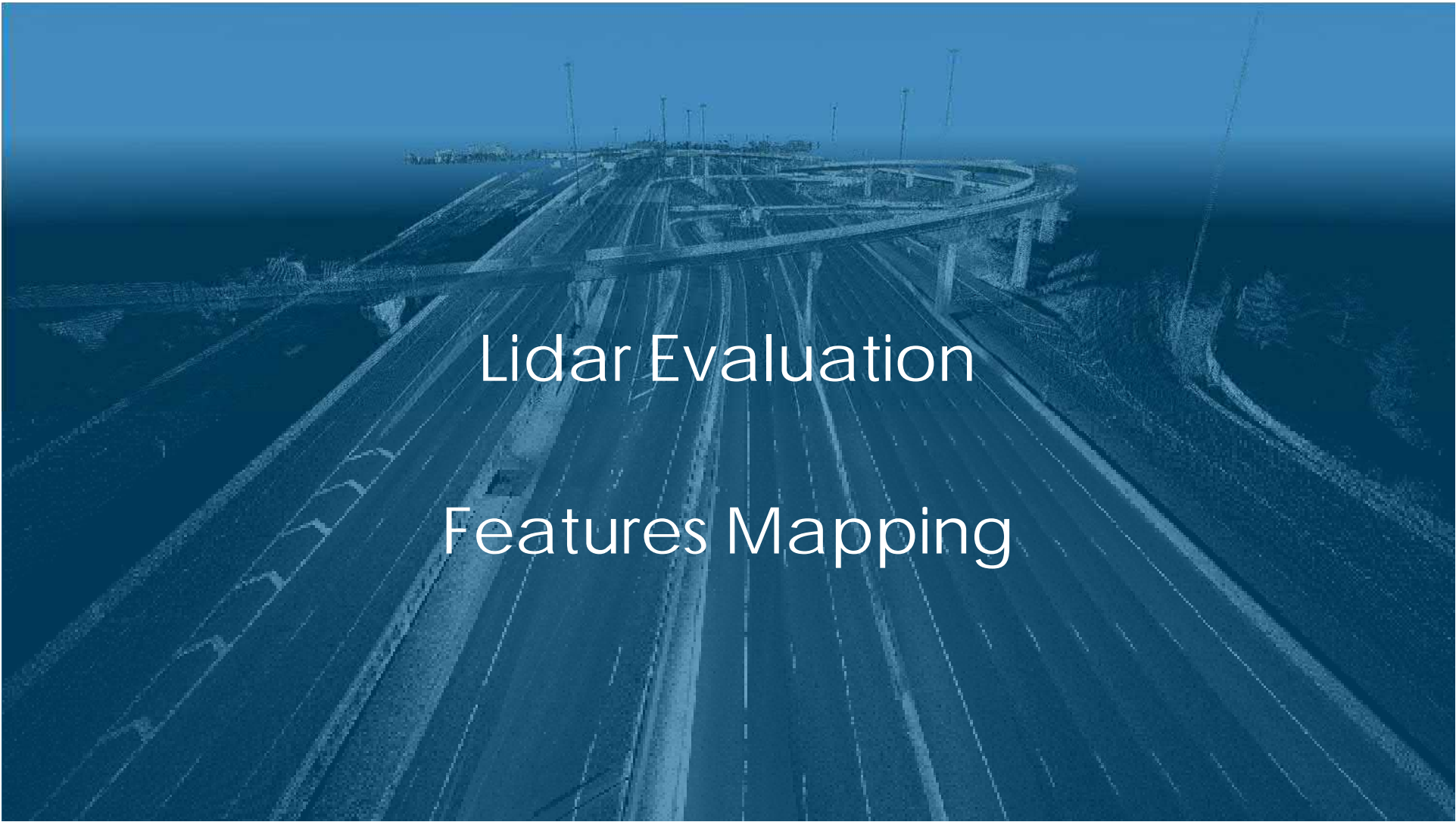
Points Density, after allowing some noisy points**

Sensor	Ground ONLY		All Classes (pts/m2)	
	Density (pts/m2)	Nominal Point Spacing (m)	Density (pts/m2)	Nominal Point Spacing (m)
MiniVUX	42	0.15	155	0.08
Quanergy_M8	76	0.12	570	0.04
Velodyne HDL32	56	0.13	521	0.04
Velodyne VLP16	18	0.23	305	0.06



** Used "Classify above ground" routine





Lidar Evaluation
Features Mapping



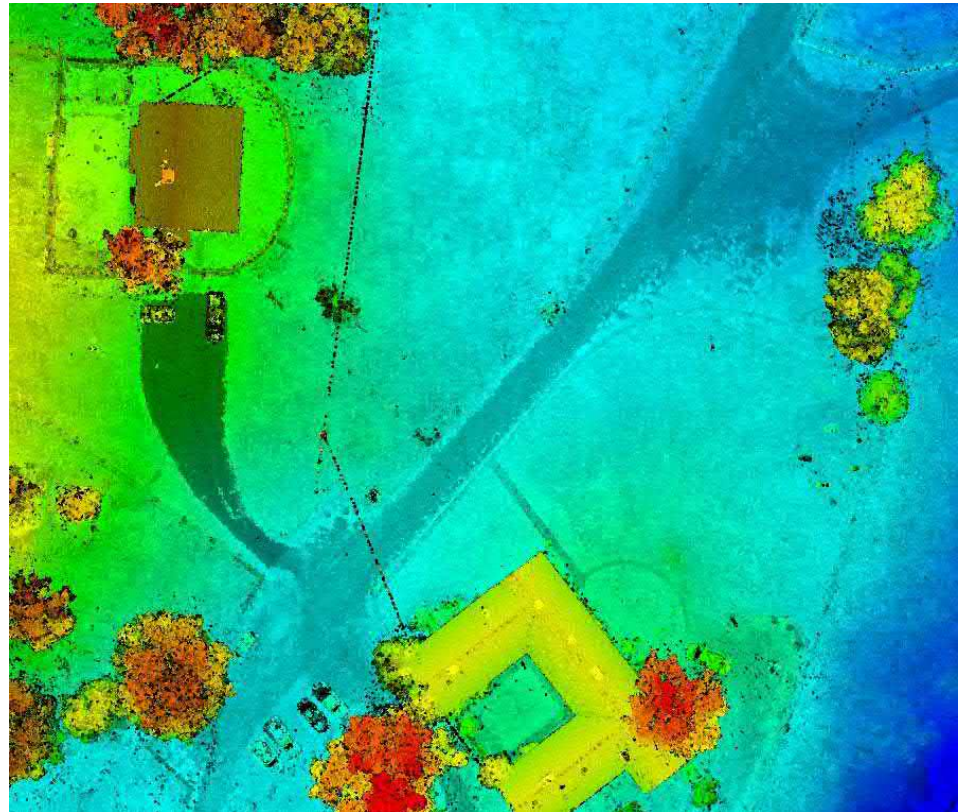
Lidar Evaluation

Riegl Mini VUX

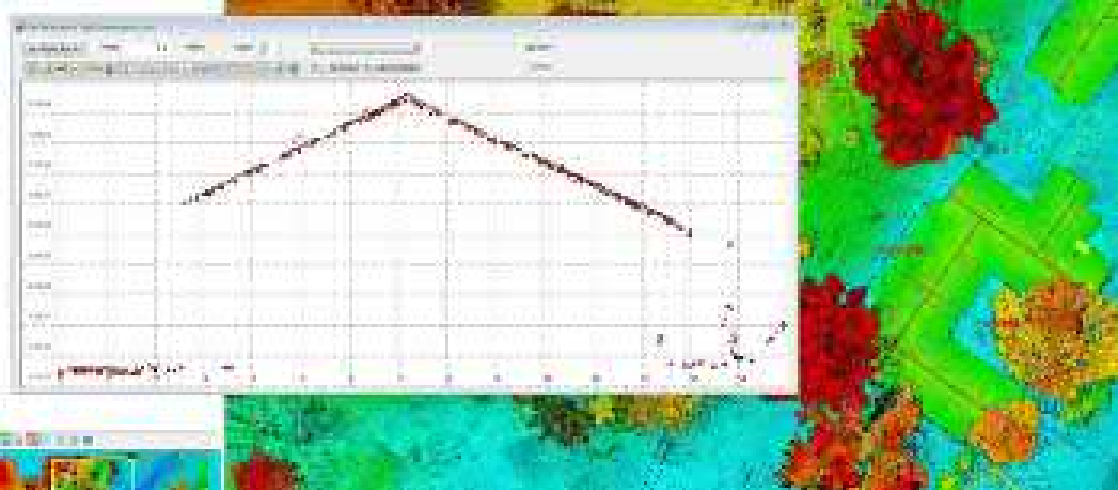
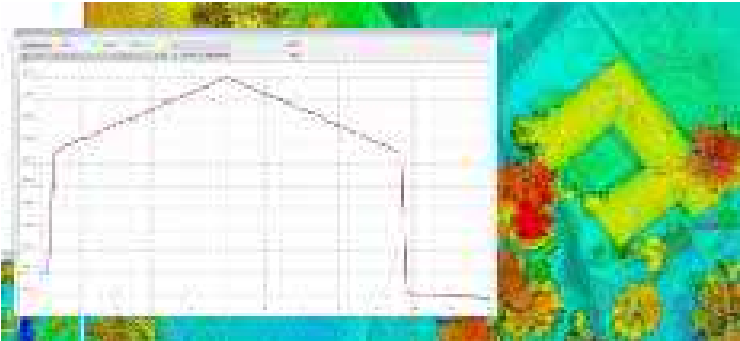
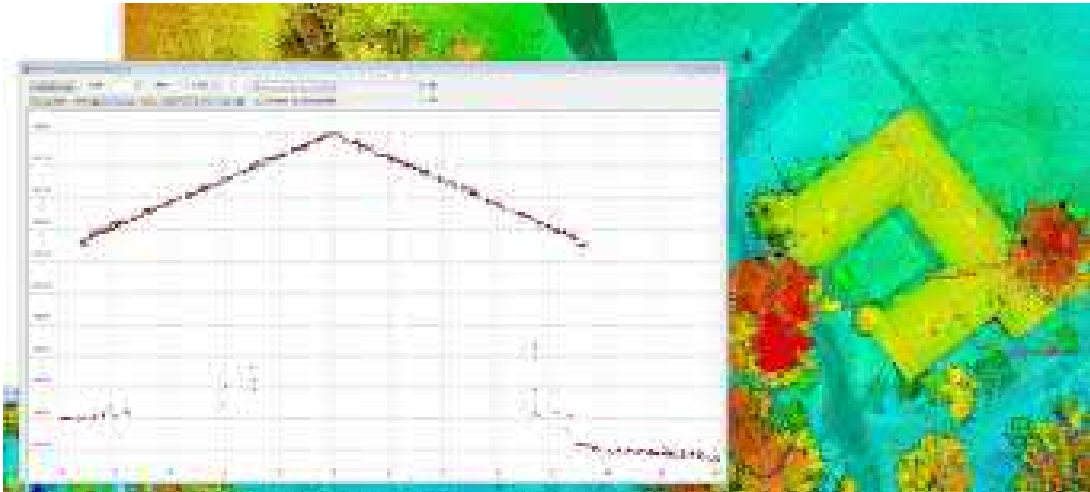
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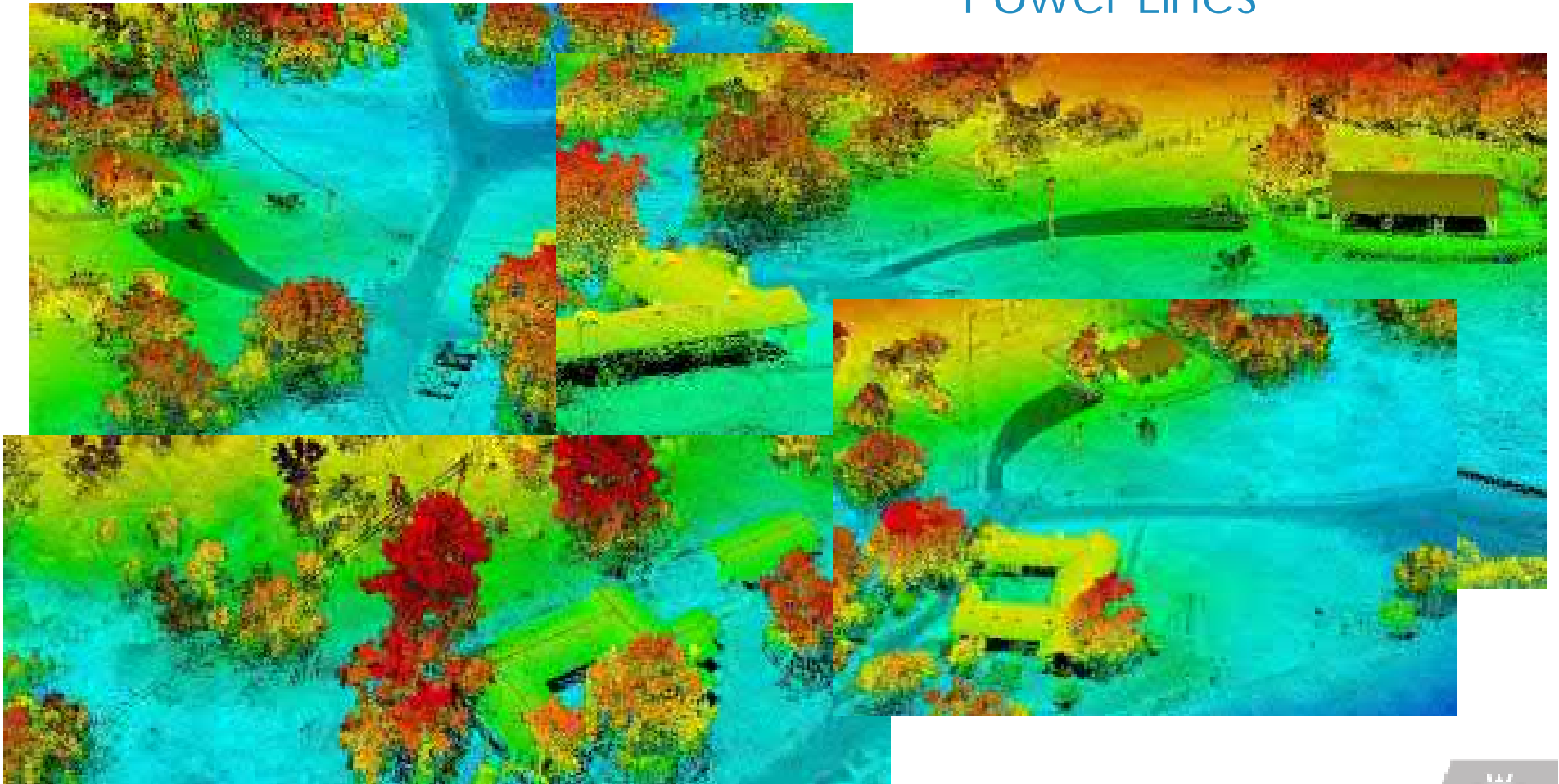
Intensity Quality



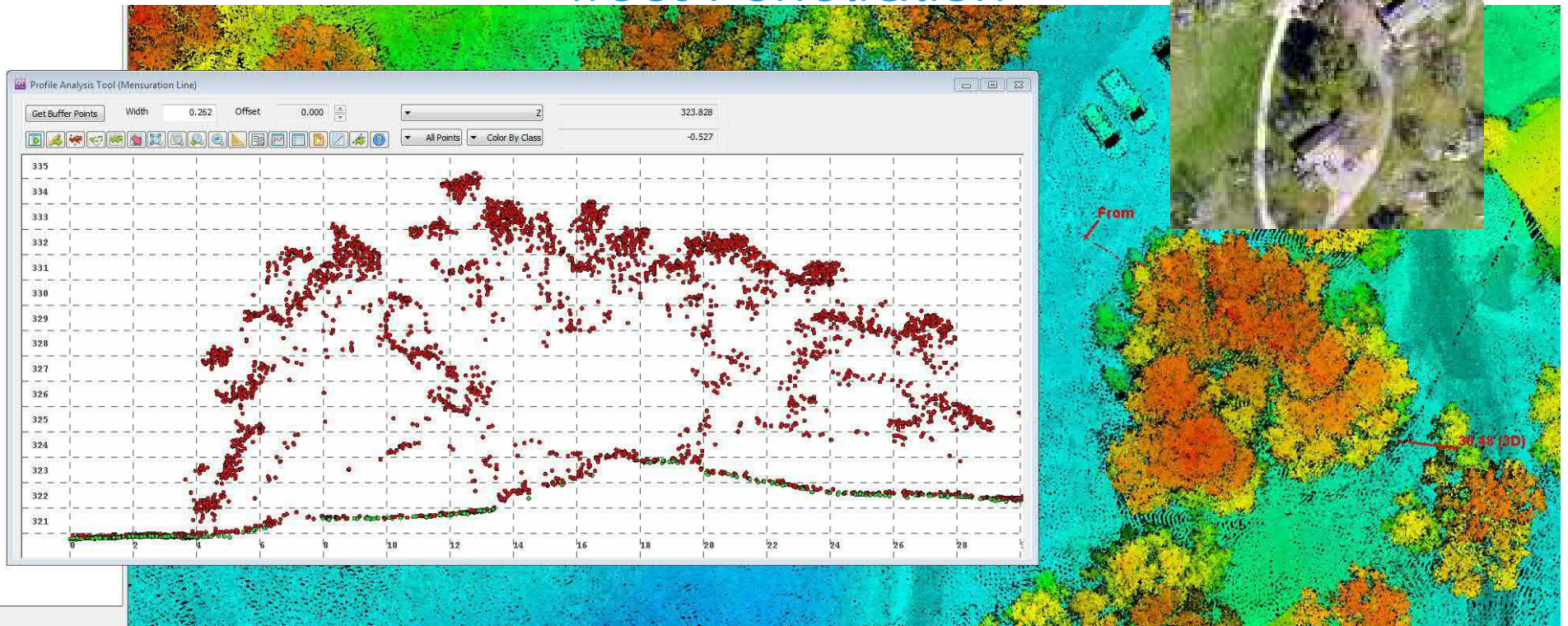
Roofs



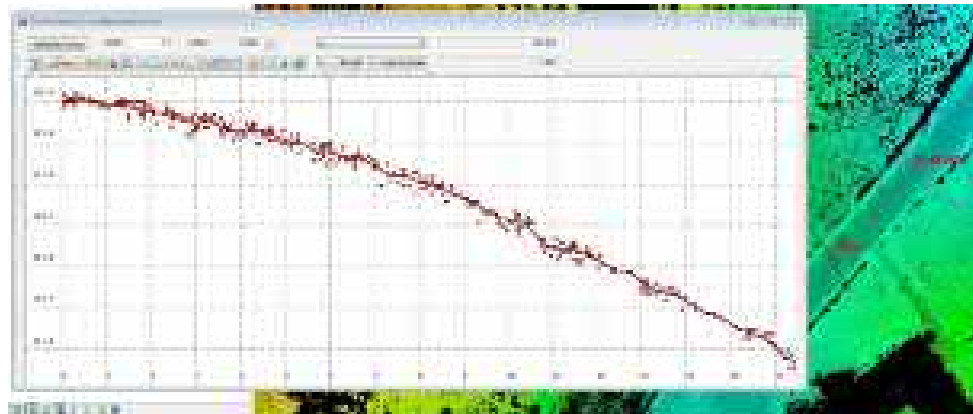
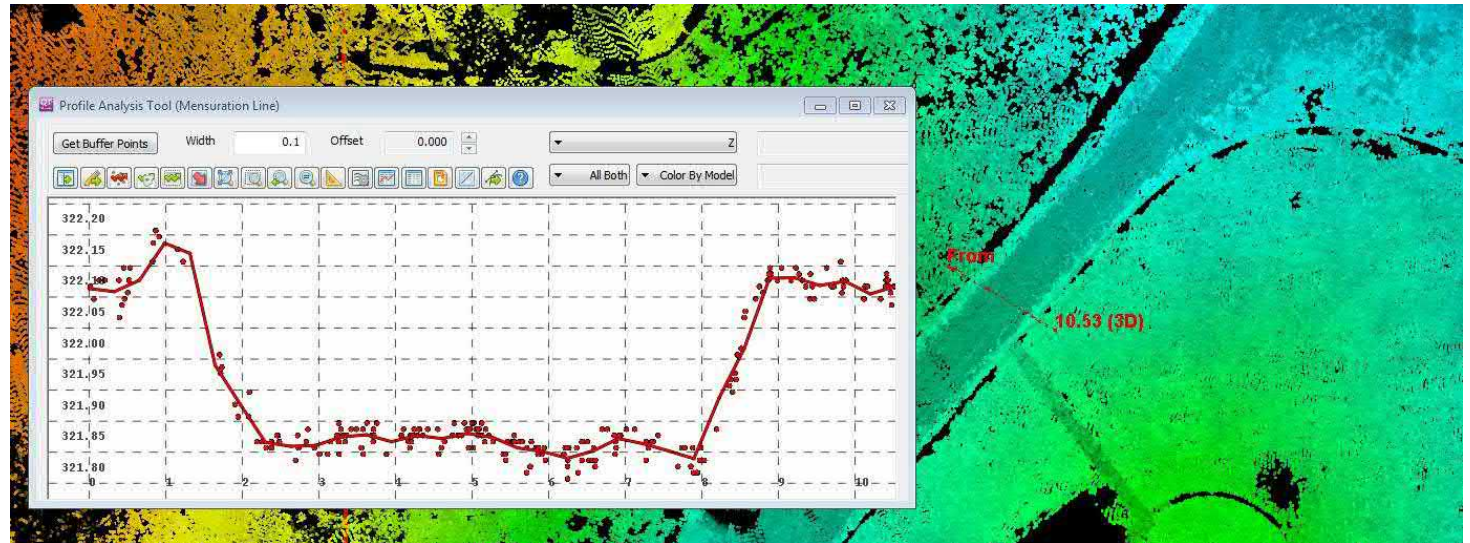
Power Lines



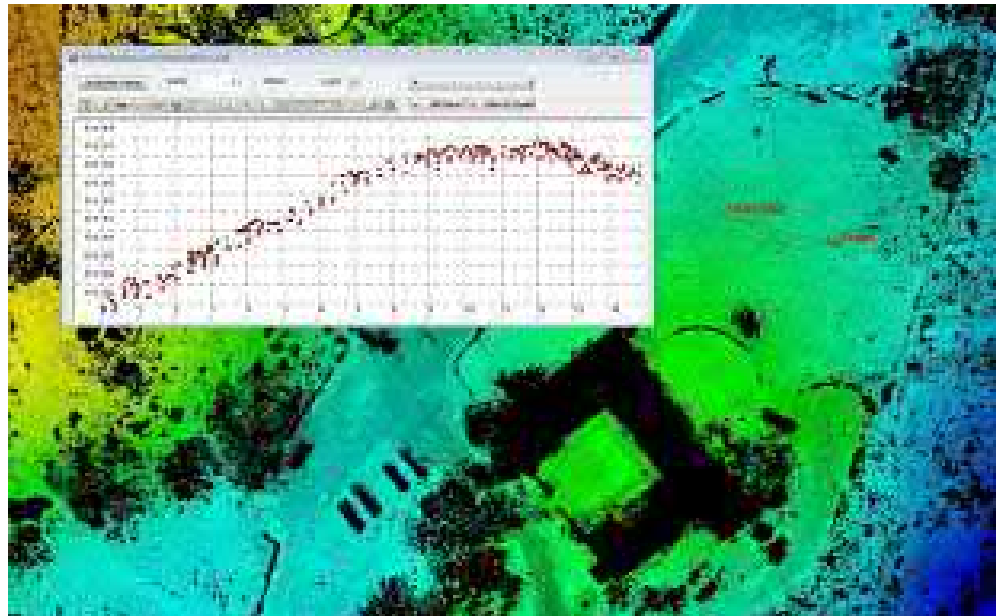
Trees Penetration

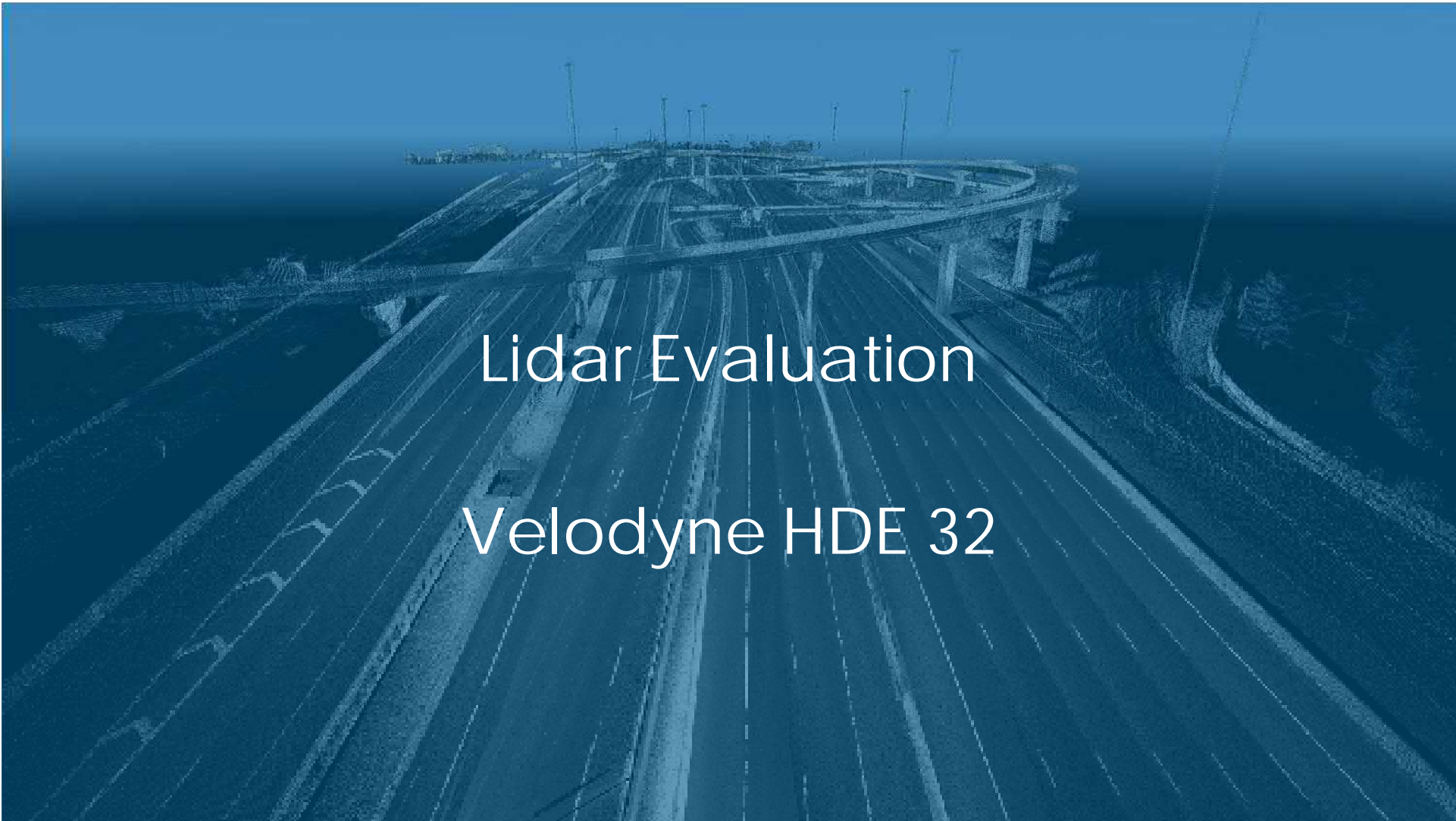


Road Profiles



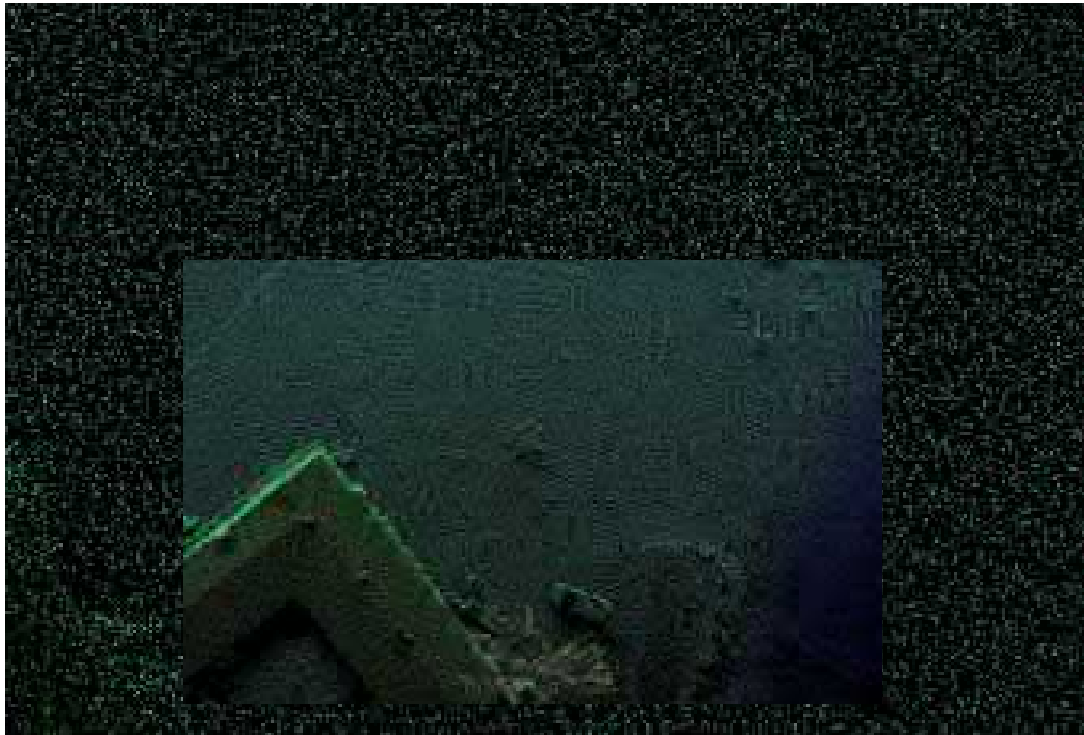
Grassy Ground





Lidar Evaluation
Velodyne HDE 32

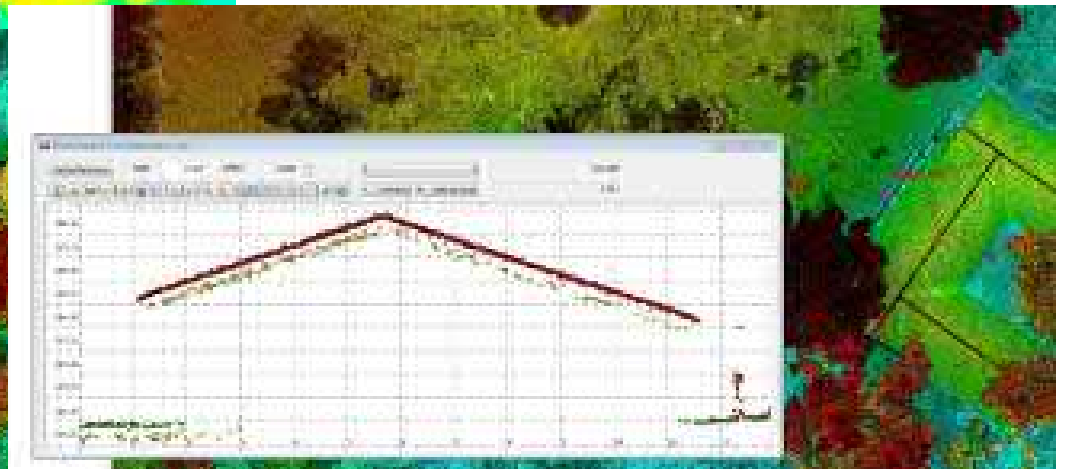
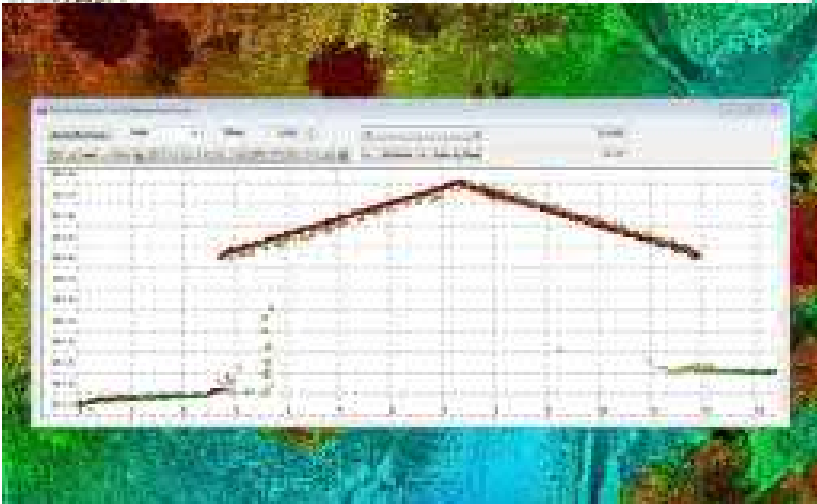
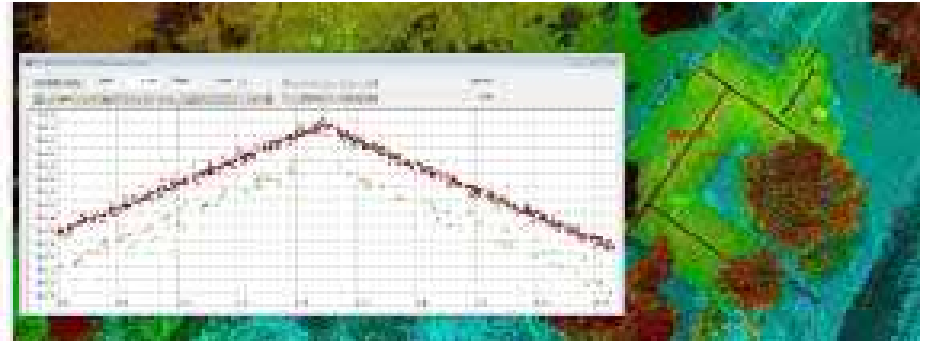
Scan Pattern



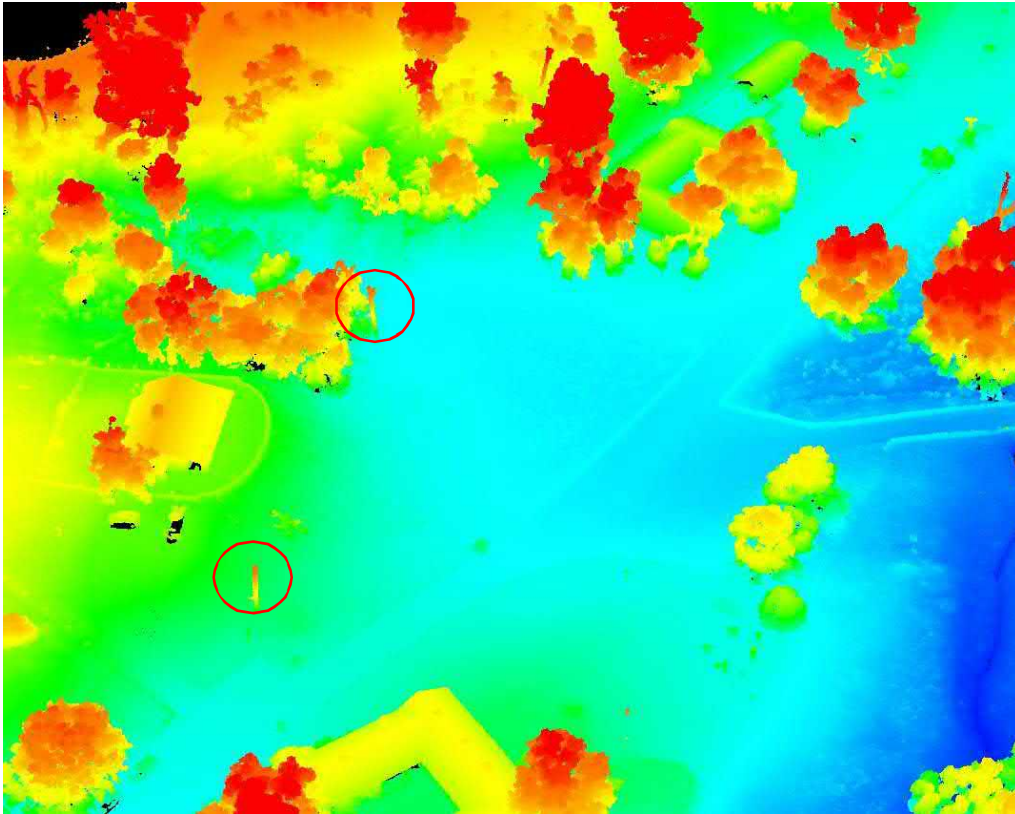
Intensity Quality



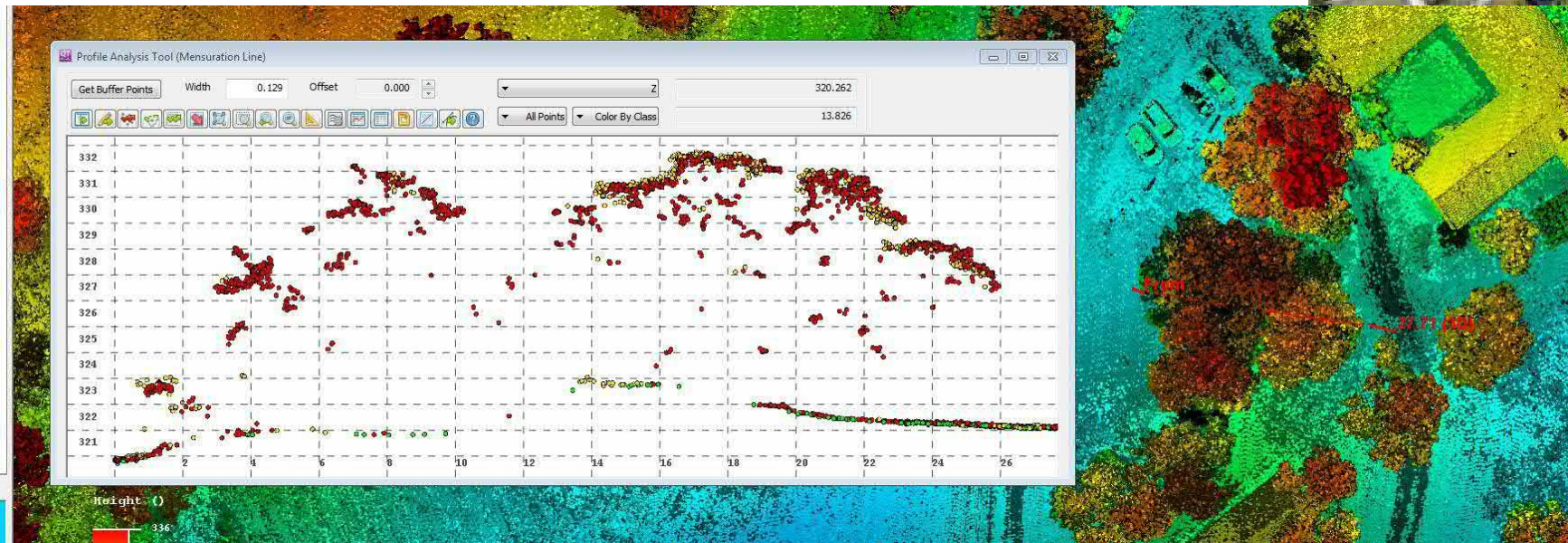
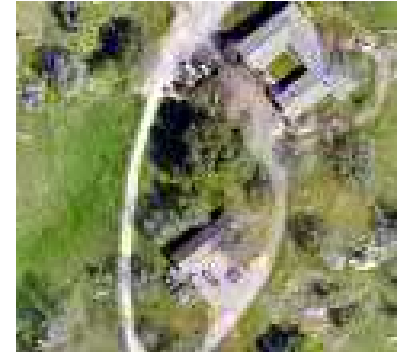
Roofs



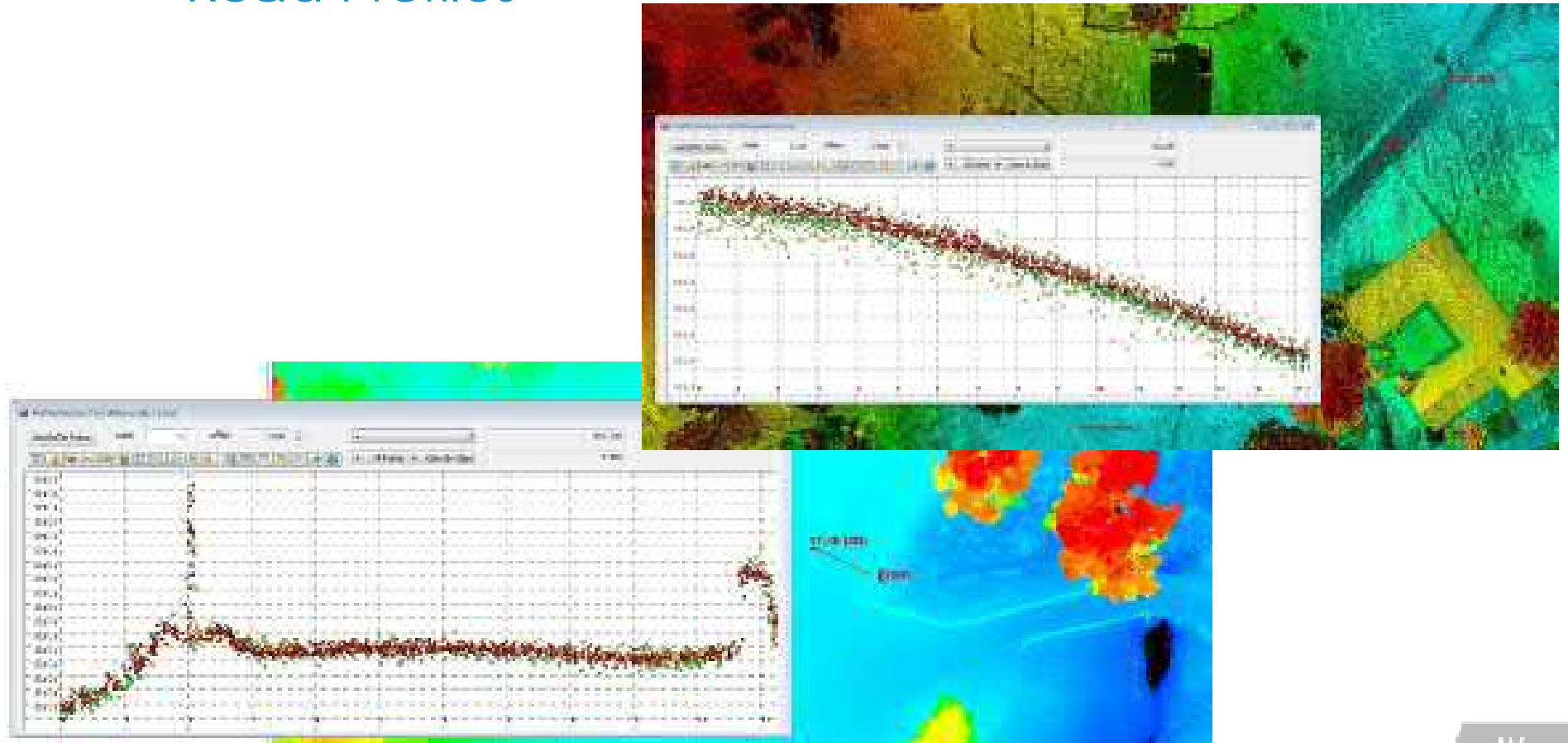
Missing Power Lines



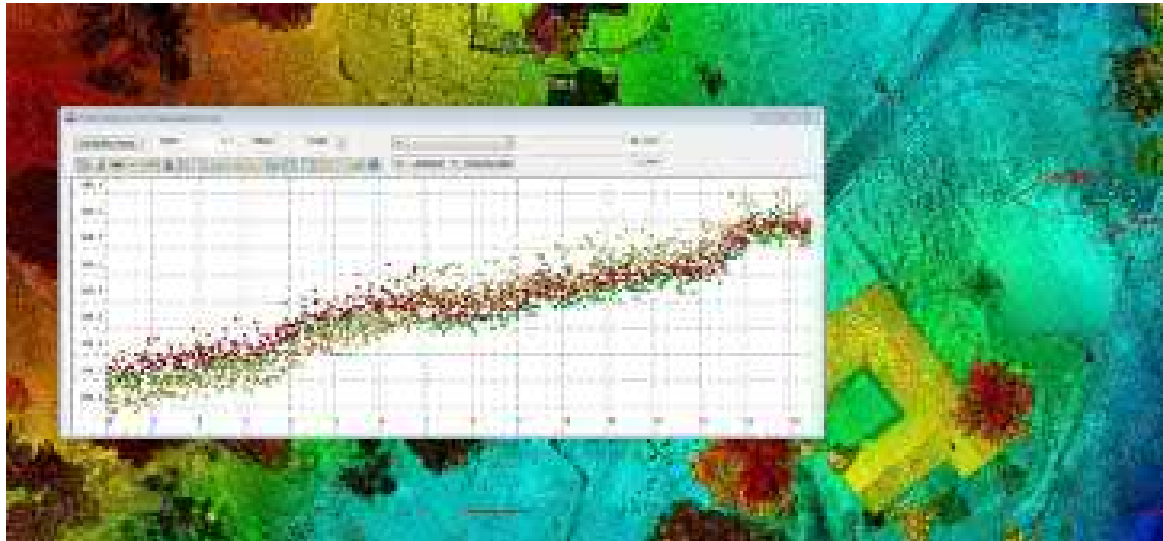
Trees Penetration



Road Profiles



Grassy Ground

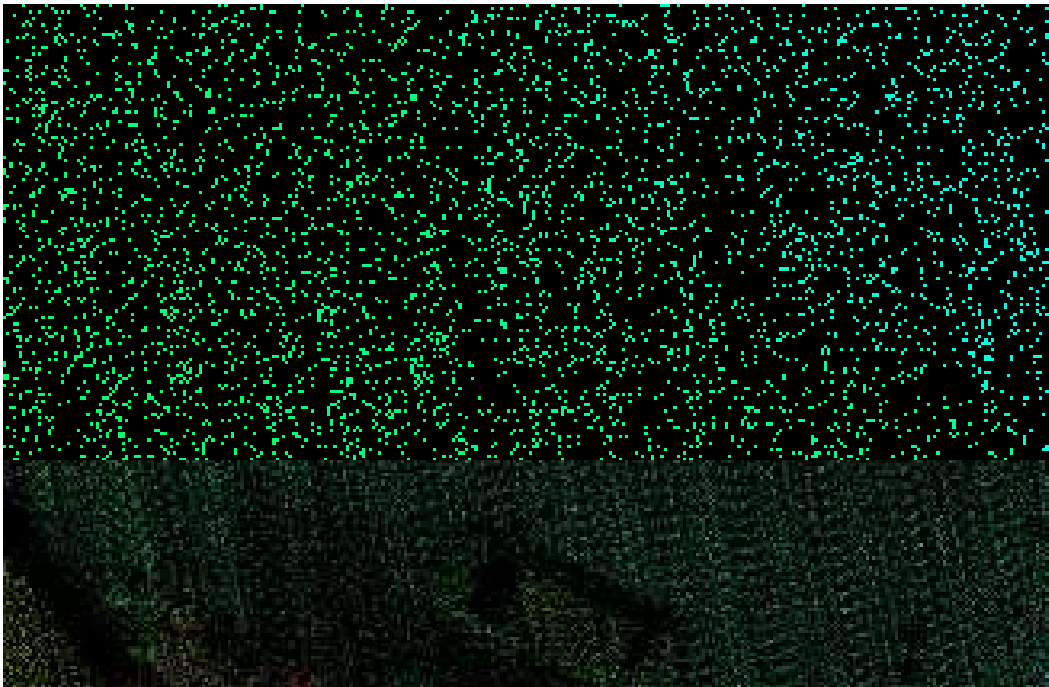




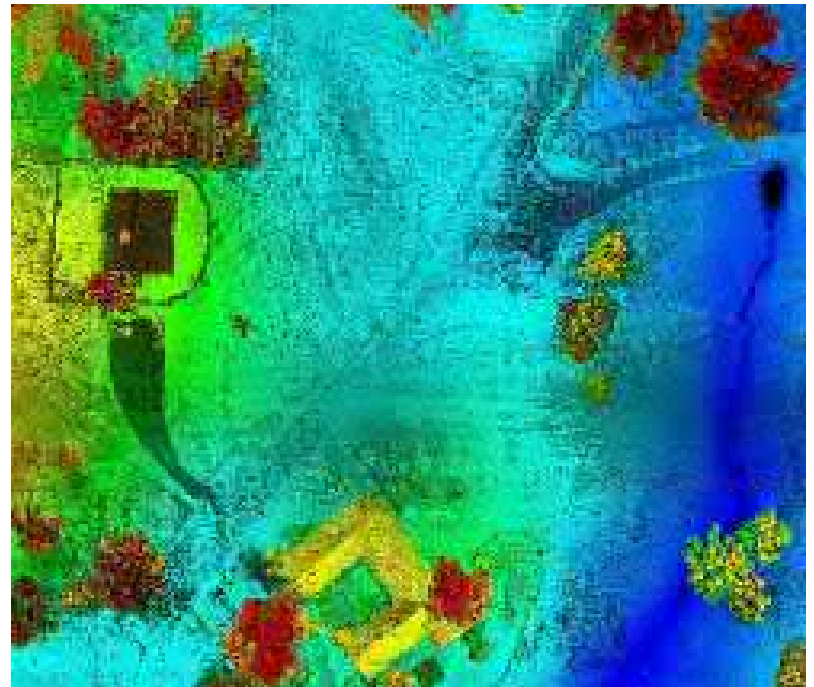
Lidar Evaluation

Velodyne VLP16

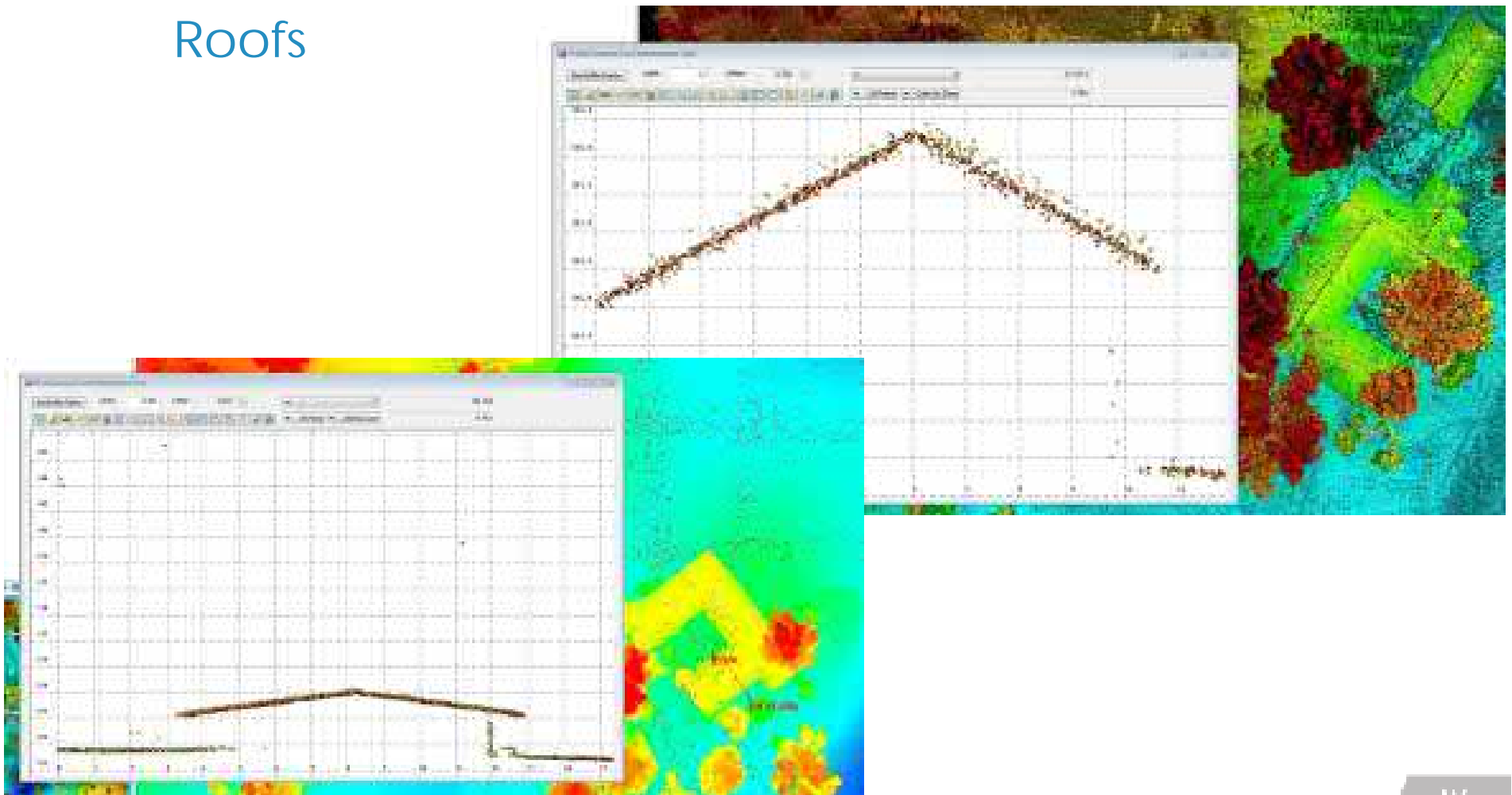
Scan Pattern



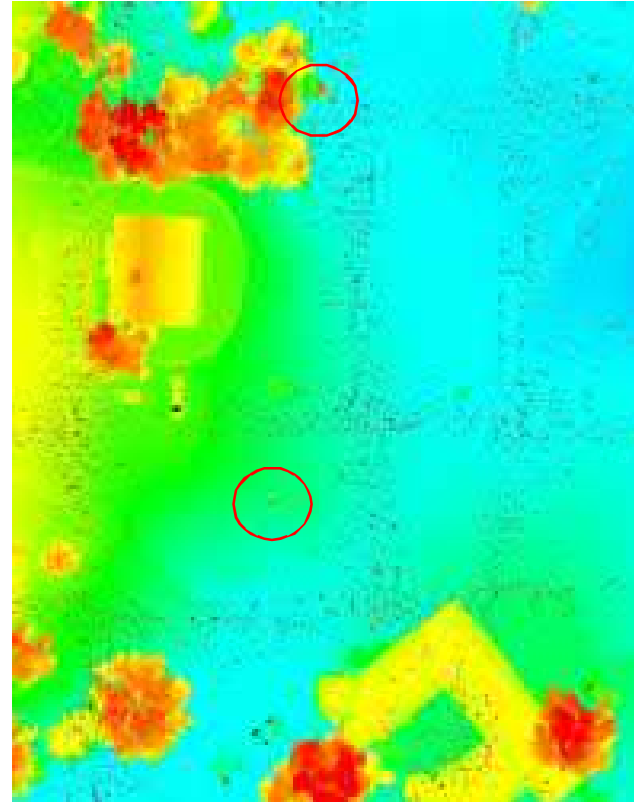
Intensity Quality



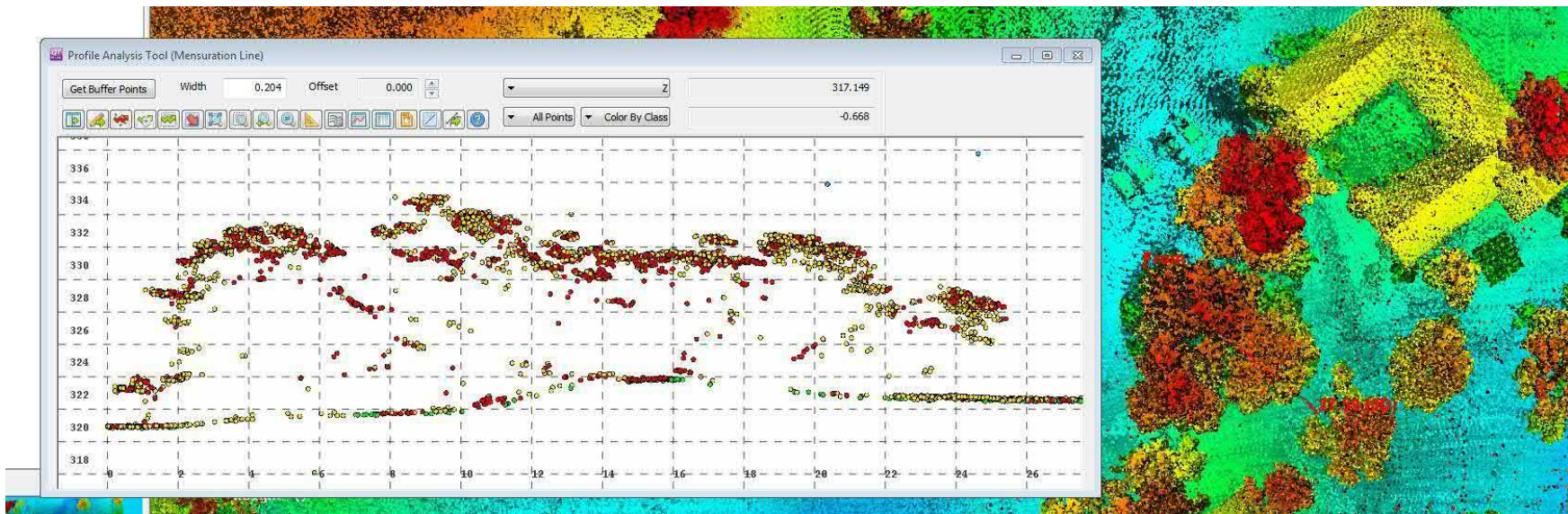
Roofs



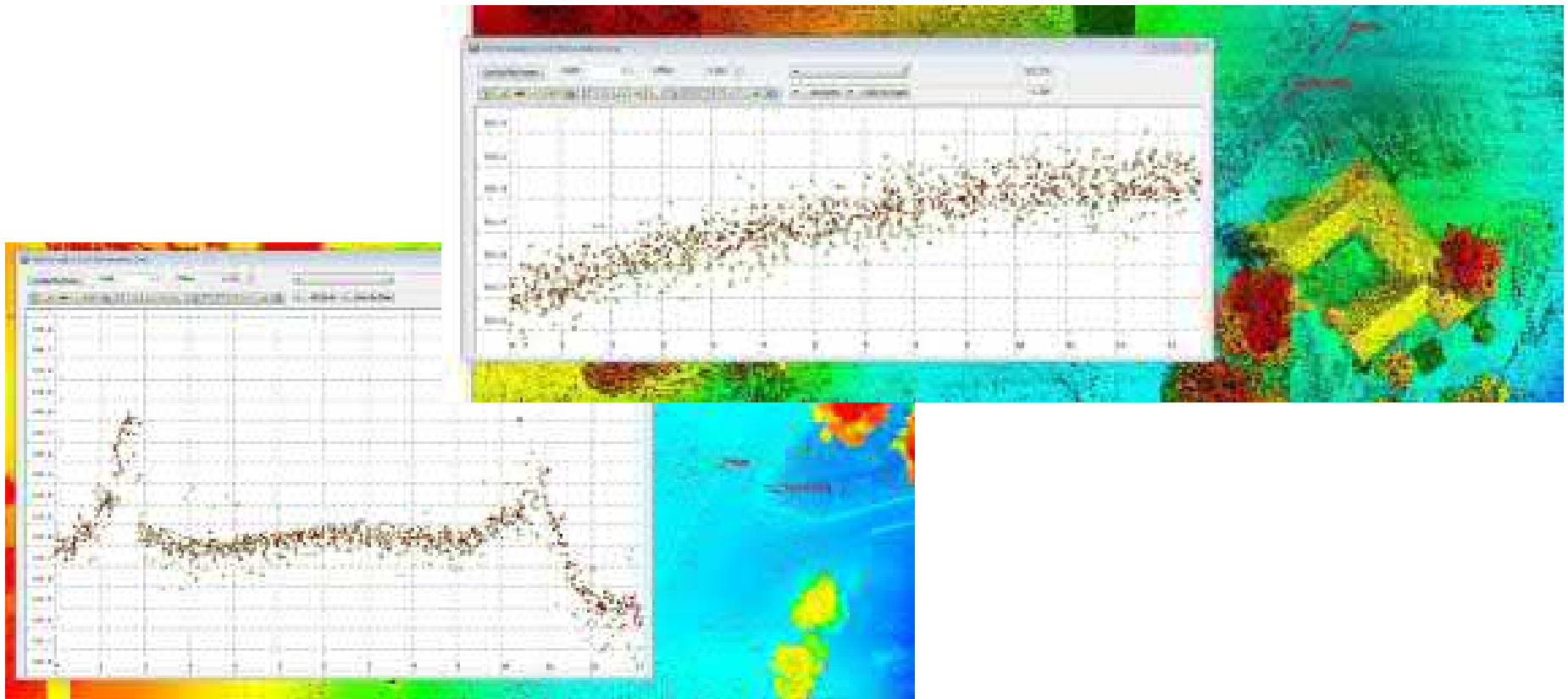
Missing Power Lines



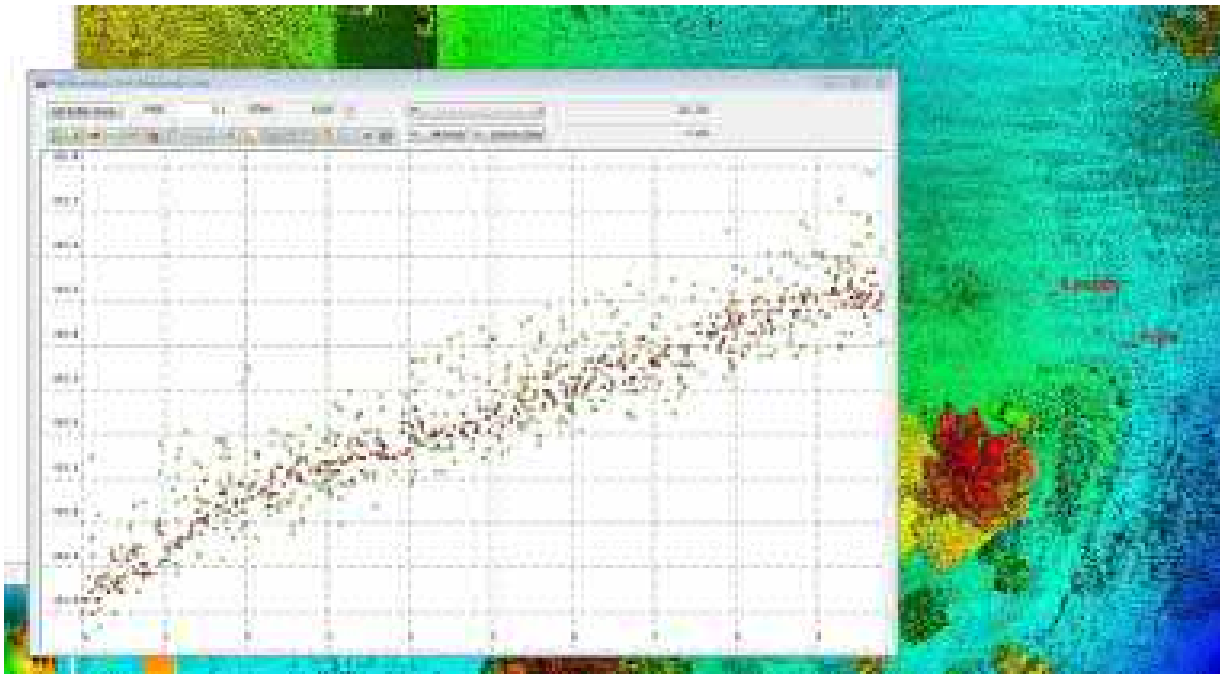
Trees Penetration



Road Profiles



Grassy Ground

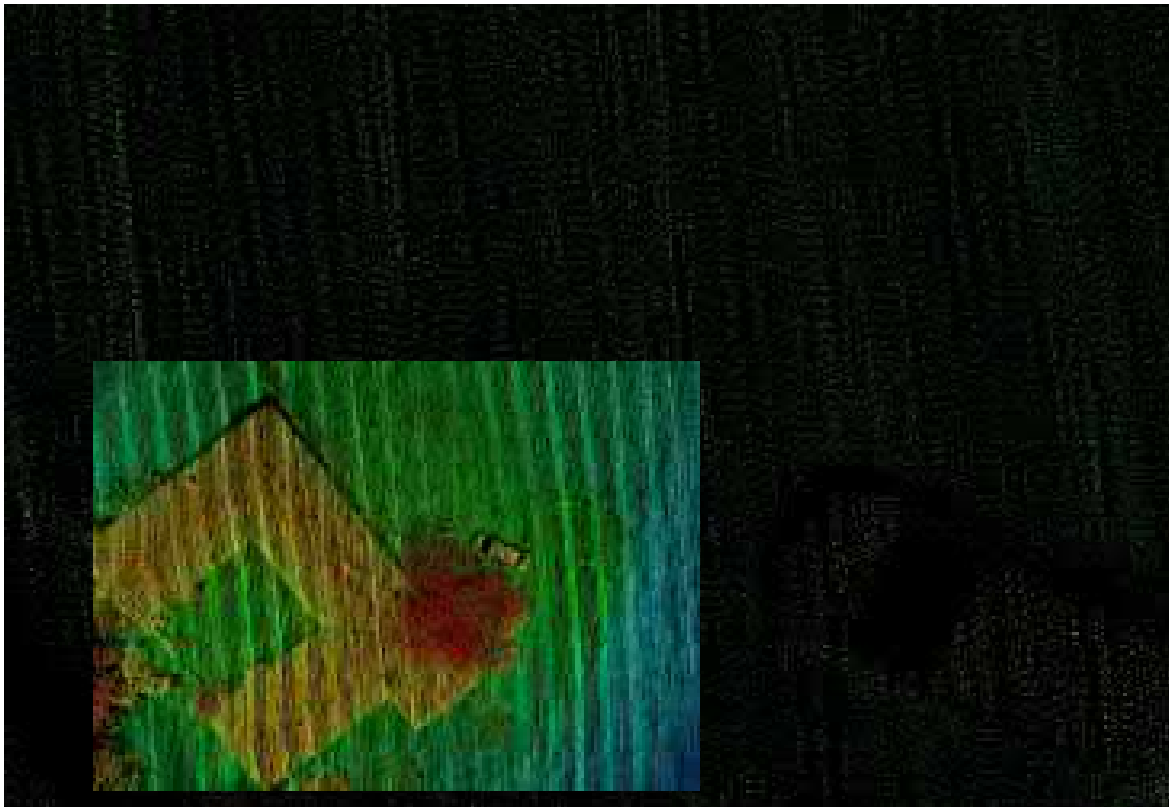




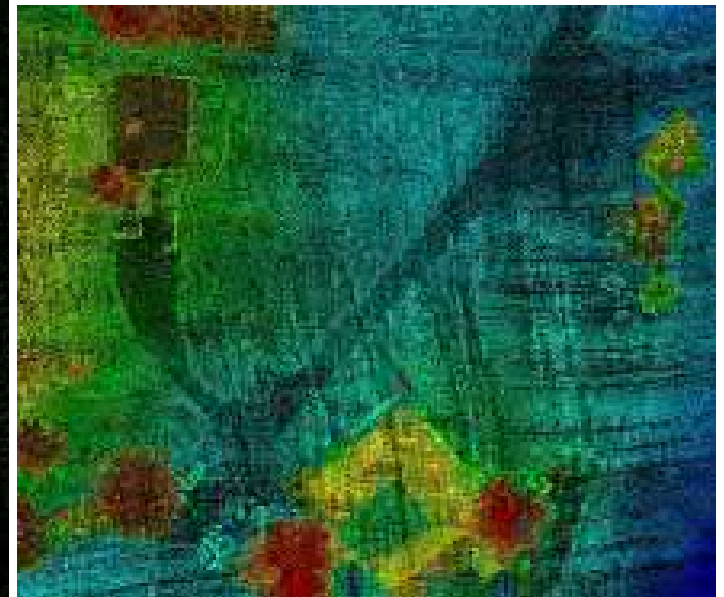
Lidar Evaluation

Quenergy M8

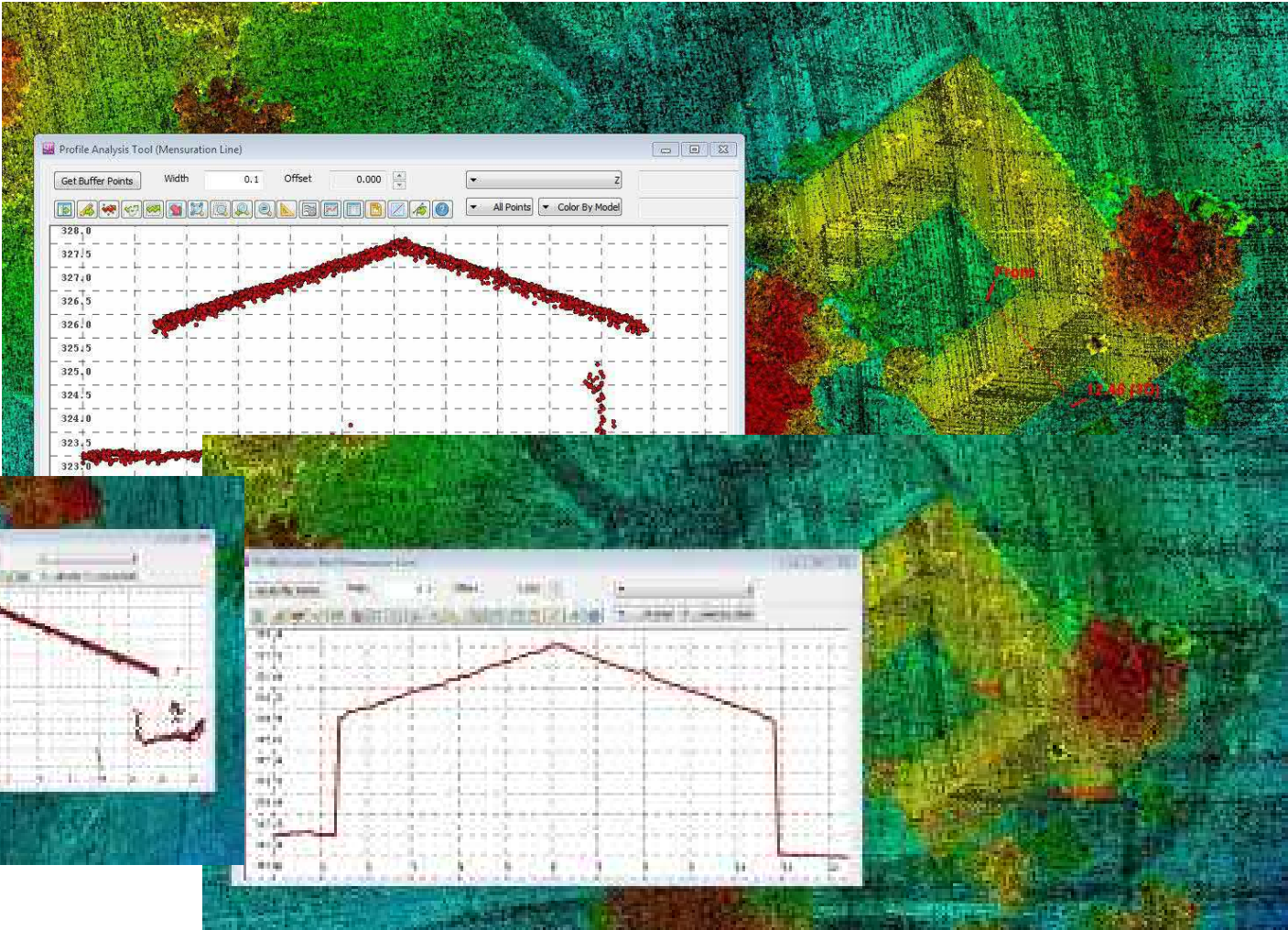
Scan Pattern



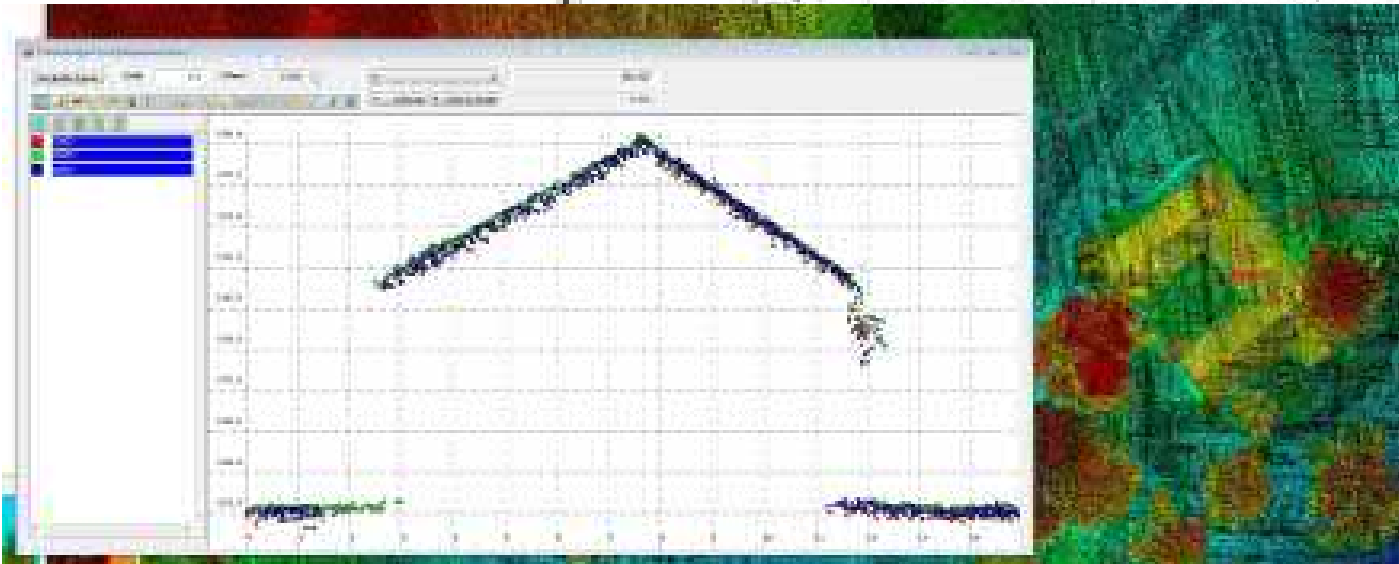
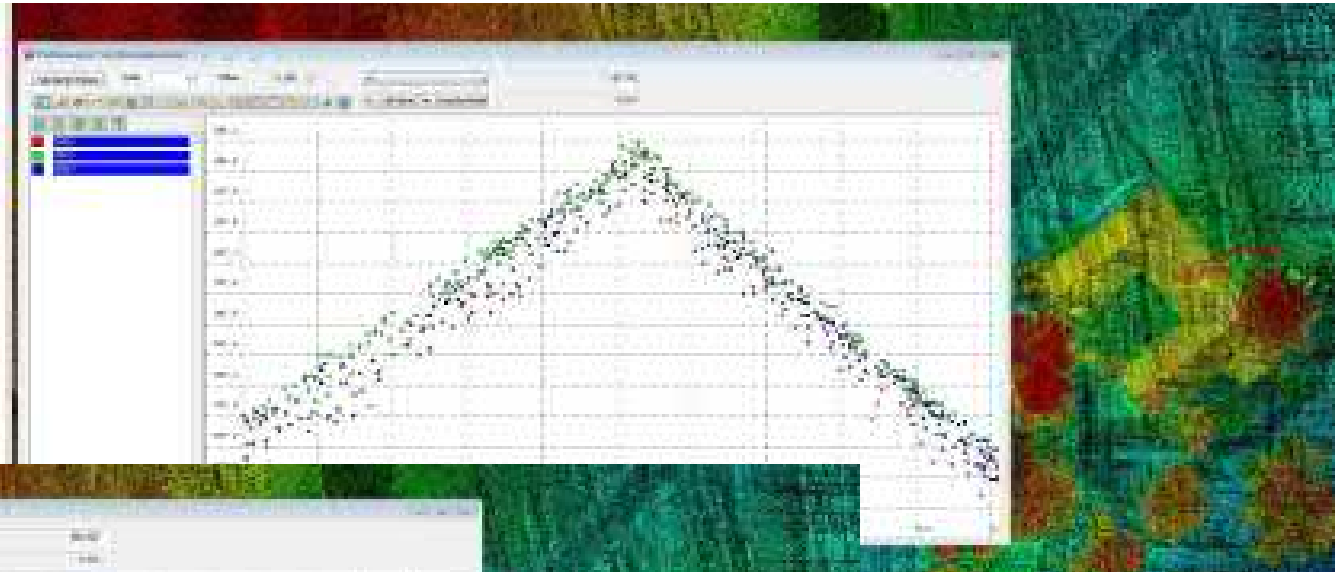
Intensity Quality



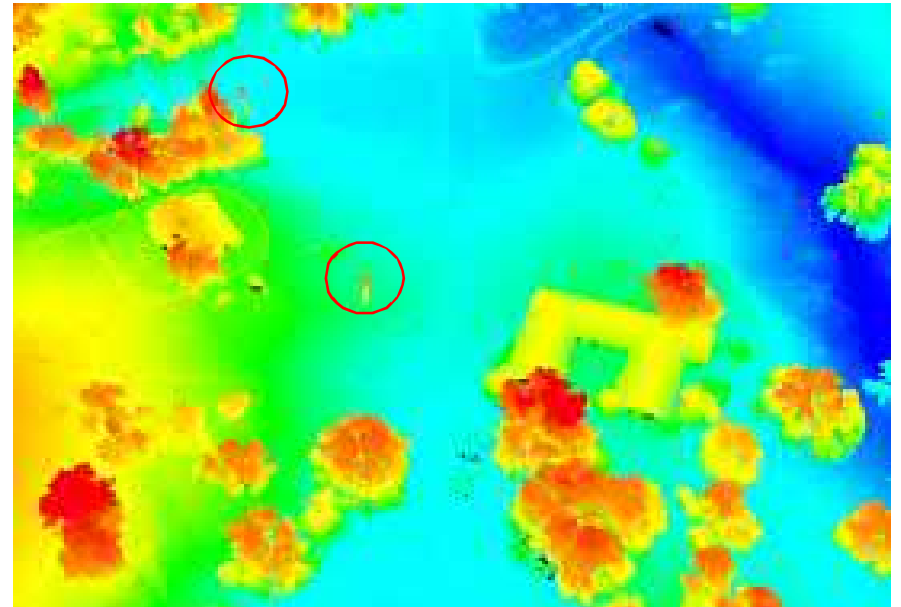
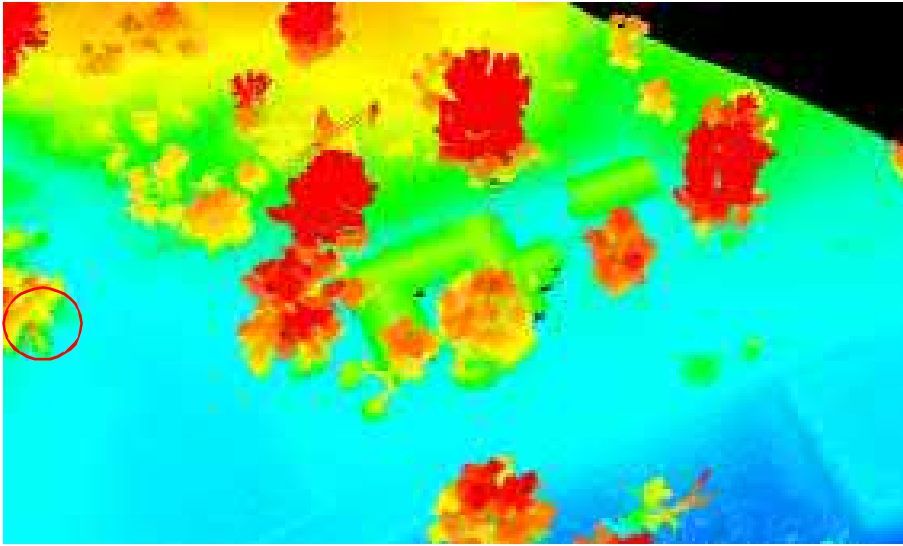
Roofs - Classification



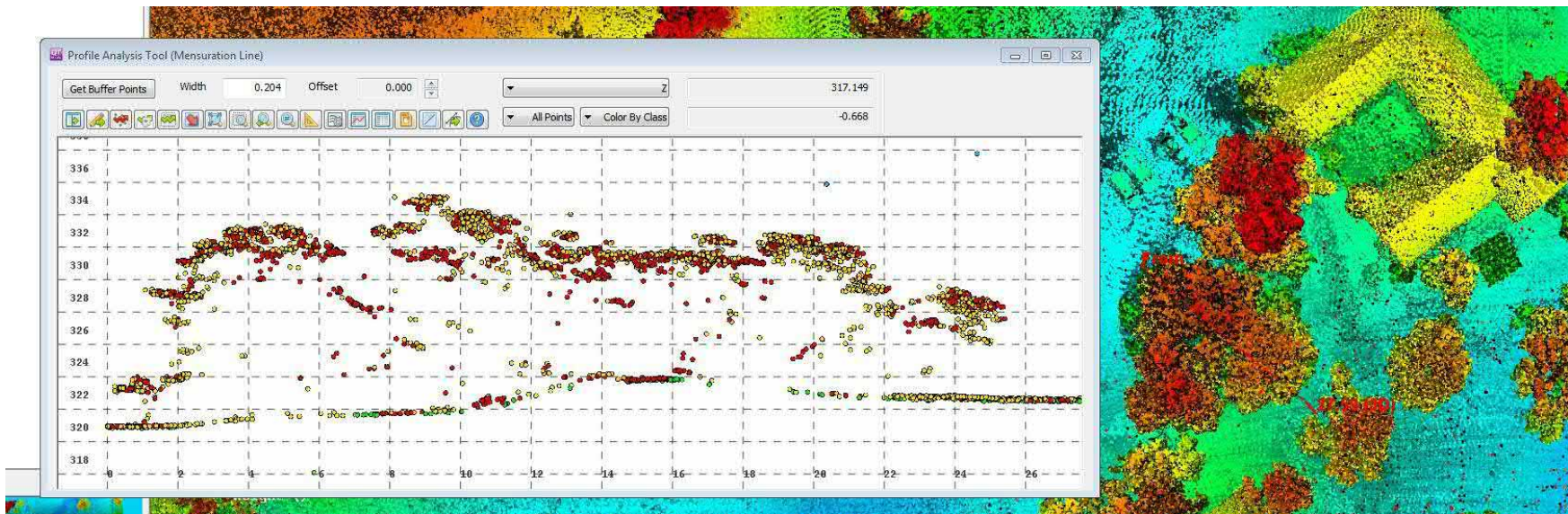
Roofs 3 lines registration



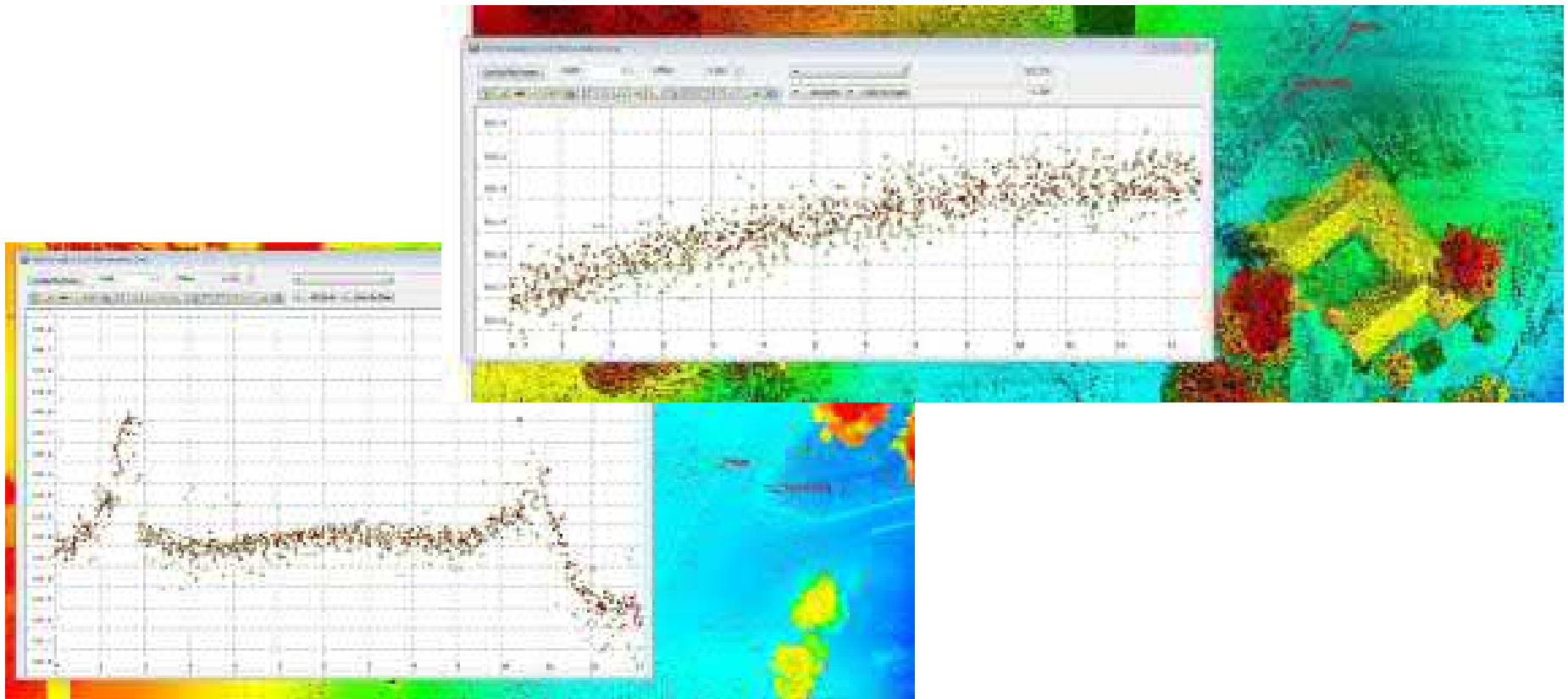
Missing Power Lines



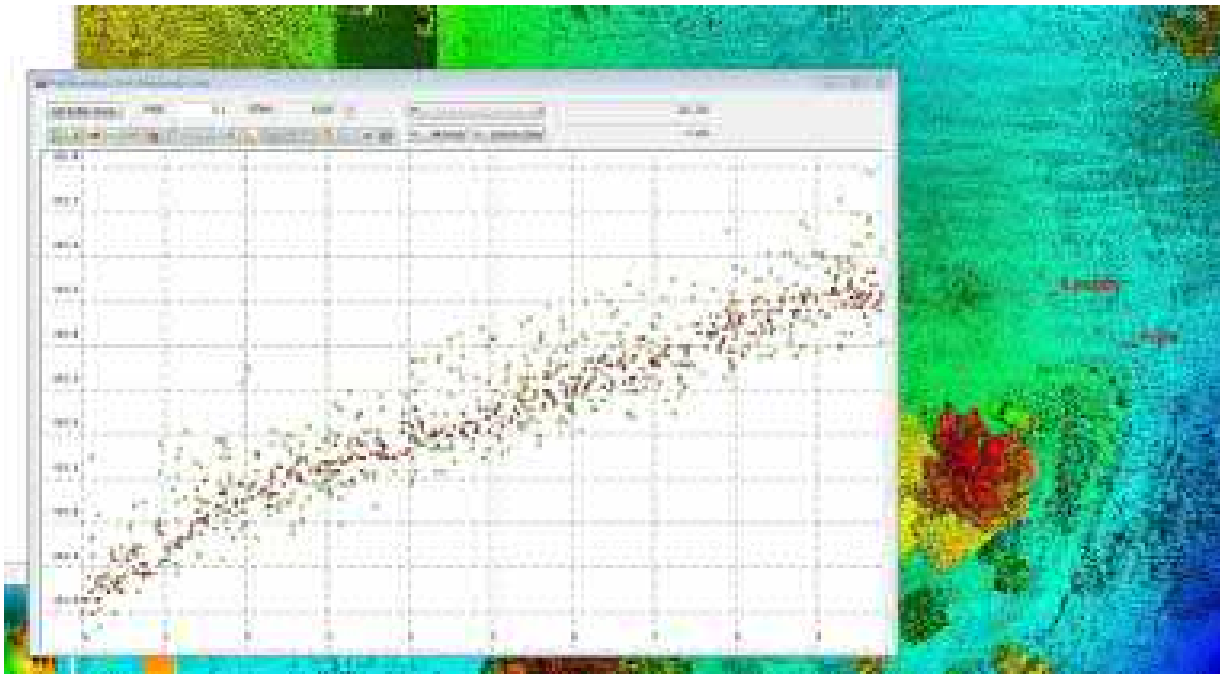
Trees Penetration



Road Profiles



Grassy Ground





Lidar Evaluation
Vertical Accuracy

AQ1

Accuracy Evaluation using 40 check points

Accuracy Term	Velodyne HDL 32E	Velodyne HDL VLP16	Riegl MiniVUX	Quenergy M8
Average (m)	0.000	0.000	0.000	0.000
Minimum (m)	-0.162	-0.138	-0.093	-0.128
Maximum (m)	0.149	0.100	0.071	0.052
StDEV (m)	0.082	0.054	0.038	0.042
RMSE _v (m)	0.081	0.054	0.038	0.042
Accuracy at 95% (m)	0.159	0.105	0.074	0.082

An aerial photograph of a complex highway interchange with multiple overpasses and ramps, overlaid with a semi-transparent blue filter. The perspective is from a high angle looking down the length of the highway.

The Wrong and Right Practices In Geospatial Data Accuracy Verification

Statement of the problem:

- We quantify products accuracy ignoring the errors in the surveyed check points
- Our surveying techniques are approximating the datum, i.e. producing pseudo datum
- Currently, we are evaluation the closeness of data to the pseudo datum and not the datum

Current practice:

Product accuracy = Errors in fitting products to
check points

Correct practice:

Product accuracy = Errors in fitting products to
check points + check points accuracy



Why So

Long ago, geospatial products and mapping technologies were less accurate:

- Ortho imagery produced with low resolution, DOQQ is 1 meter GSD
- Maps were produced with small scale
- Therefore, errors in control/check points were usually ignored as it was considered negligible

Why Now

- Geospatial products today are very accurate
- We are heading toward more accurate datum in 2022
- Drone are collecting imagery with 1-cm GSD and producing highly accurate products
- Lidar is providing accuracy in the range of 1.5 to 10 cm
- ASPRS standards support high accuracy
- We just can not continue our wrongful practice



How should we express product accuracy?

Photogrammetry:

Aerial Triangulation Accuracy = The fit to the GCPs + the accuracy of the GCPs

Ortho Accuracy = The fit to check points + the accuracy of the GCPs

Lidar:

Lidar Accuracy = The fit to check points + the accuracy of the GCPs



Example

- Surveyed check points are used to verify ortho and DSM accuracy.
- The check points was surveyed using RTK techniques with horizontal accuracy of RMSE = 2-cm and vertical accuracy of RMSE = 3-cm

Ortho QC using the check points resulted in $RMSE_{xy} = 2.5\text{-cm}$

DSM QC resulted in $RMSE_z = 2.7\text{-cm}$

Final Ortho Accuracy = 2.5-cm + 2-cm (vectors arithmetic should be used here)

Final DSM Accuracy = 2.7-cm + 3-cm (vectors arithmetic should be used here)

Currently, the ortho is labeled with 2.5-cm accuracy and the DSM with 2.7-cm accuracy



An aerial photograph of a multi-lane highway interchange, overlaid with a semi-transparent blue filter. The perspective is from an elevated position looking down the road. Several support pillars for an overpass are visible in the distance.

Thank you!



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The Best of All Worlds: Data Fusion and the Hybrid DSM

Aerial Lidar + MMS + UAS



Aerial Lidar:

Points Density: up to 30 pts/m²
Accuracy(v) RMSE = 6 to 15 cm



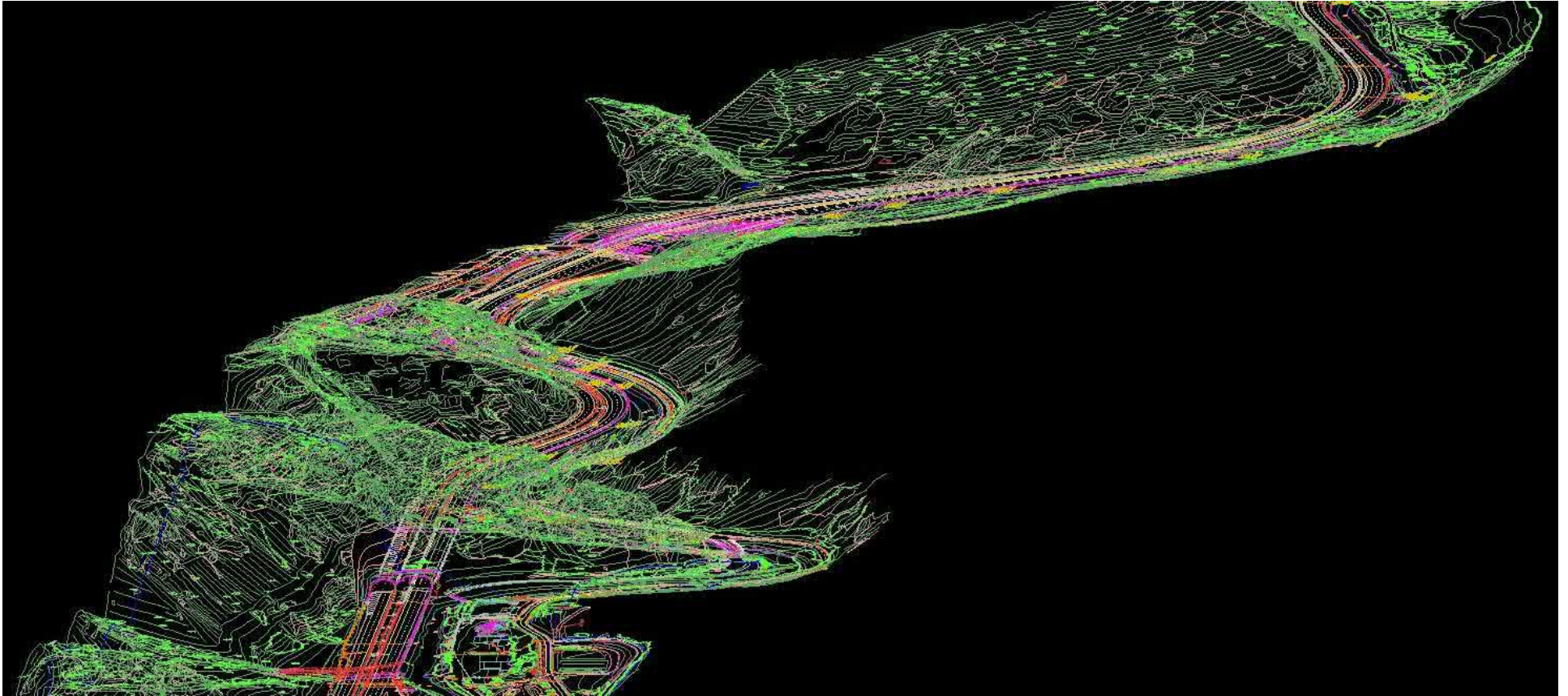
MMS:

Points Density: 2,000 to 6,000 pts/m²
Accuracy(v) RMSE = 1.5 cm



UAS:

Points Density: 40 to 1000 pts/m²
Accuracy(v) RMSE = 5 to 15 cm



Integrated Surfaces

Collect, digitize and attribute all elements of the project

Advantages of Point Clouds from UAS Imagery

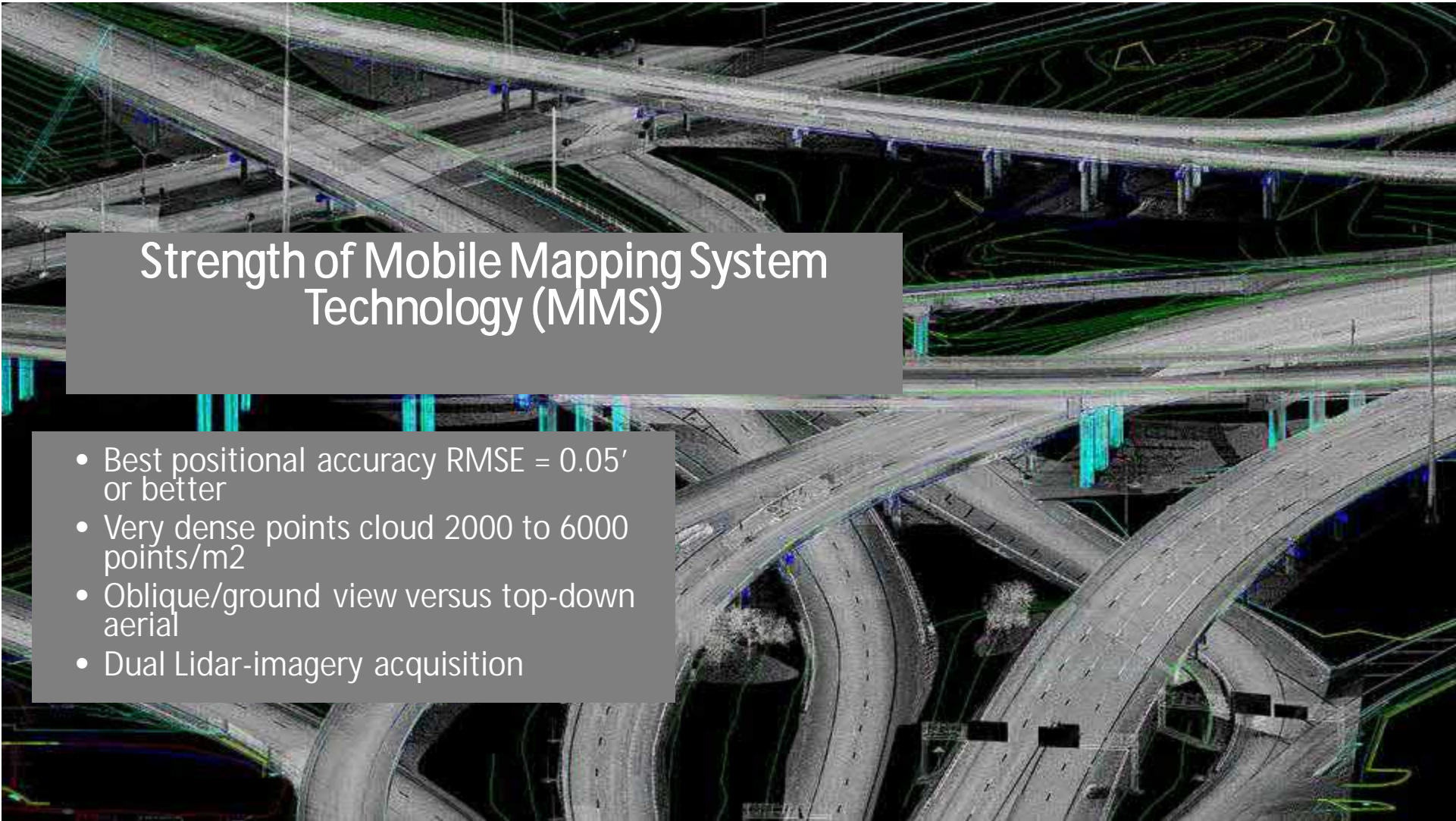
- Birds Eye View, i.e. beyond MMS coverage
- Affordable approach
- Easy to deploy
- Easy to process
- Excessive overlap



Limitations of Point Clouds from Imagery

- Less accurate than LiDAR
- No tree penetration
- FAA Regulations





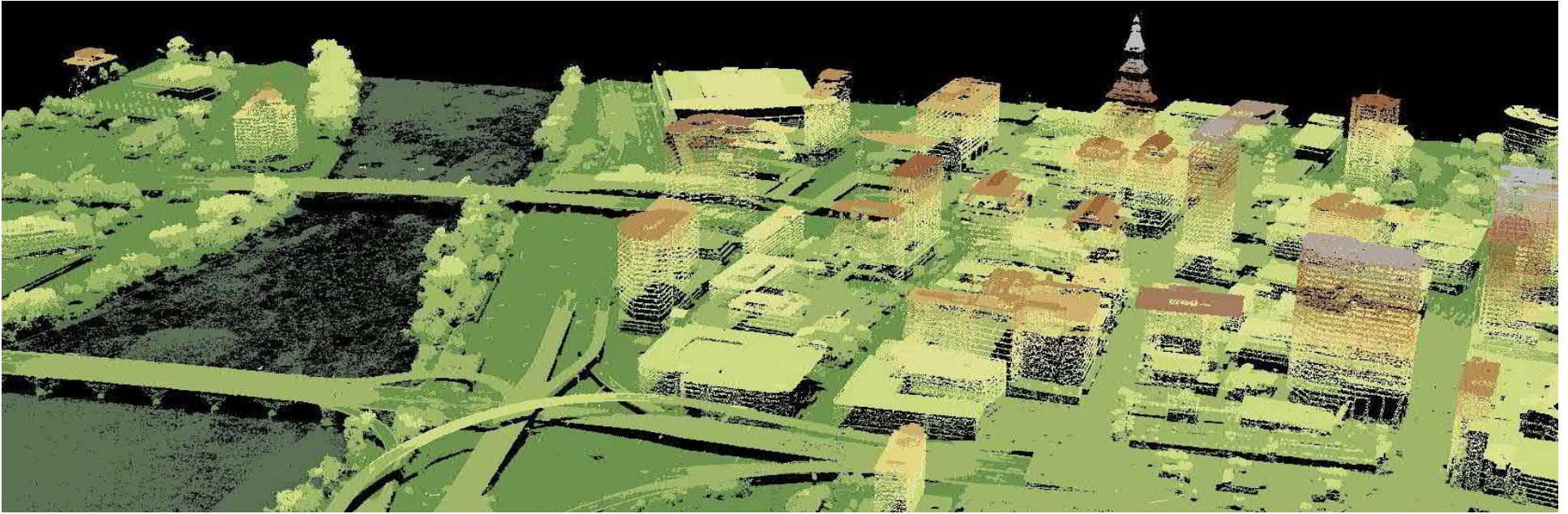
Strength of Mobile Mapping System Technology (MMS)

- Best positional accuracy RMSE = 0.05' or better
- Very dense points cloud 2000 to 6000 points/m²
- Oblique/ground view versus top-down aerial
- Dual Lidar-imagery acquisition

Limitations of Mobile Mapping Systems (MMS)

- Only on driven roads
- Limited range
- Not suitable for rural environments





Limitations of Aerial LiDAR

- Lower point cloud density as compared to MMS
- Limited positional accuracy for DOT's road design projects
- Not suitable for small projects
- Obscured areas

Data Fusion

The Petersburg/Overman Roads Intersection Improvement



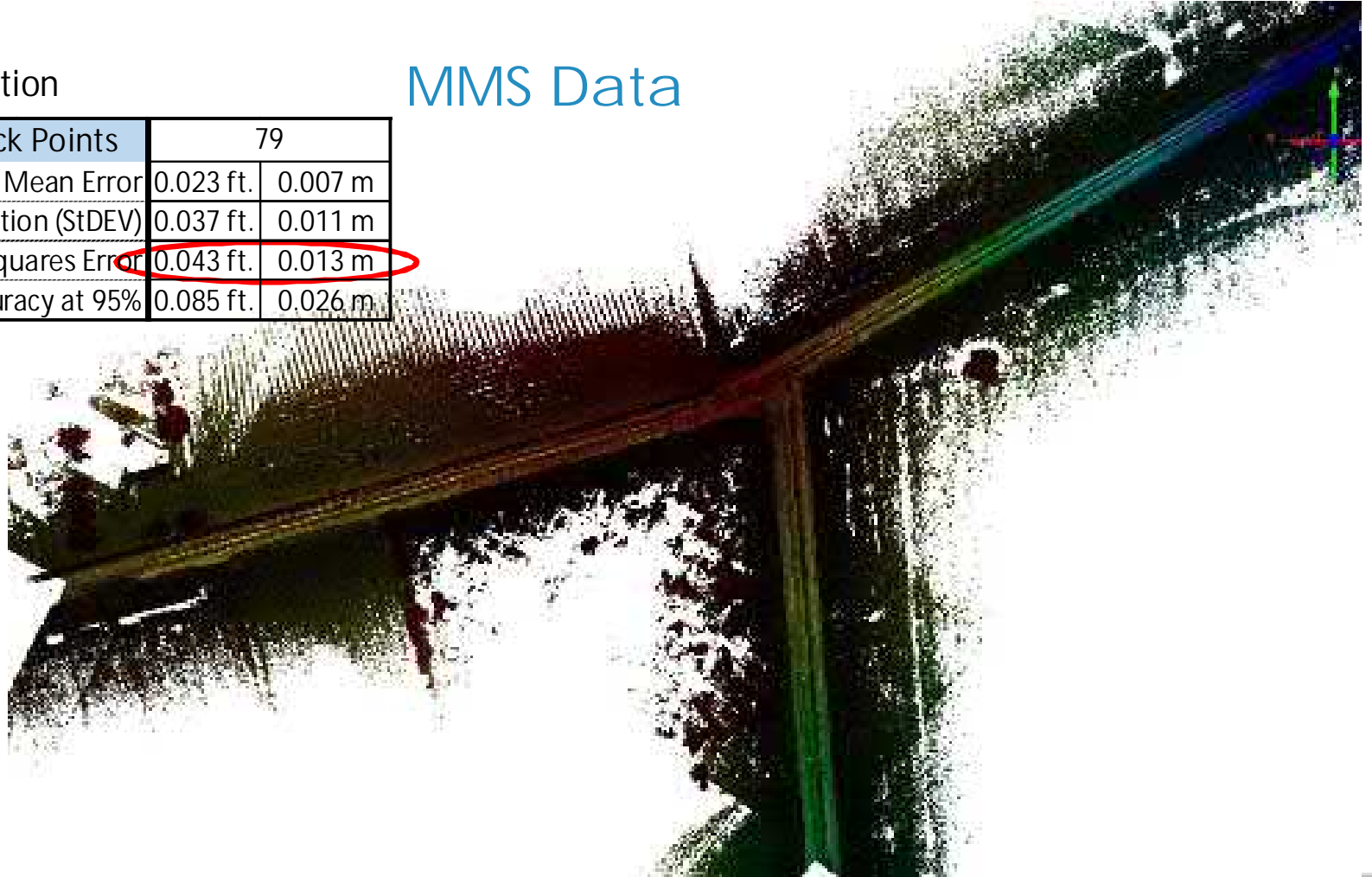
An aerial photograph of a multi-lane highway interchange, overlaid with a semi-transparent blue filter. The image shows several lanes of traffic, a central median, and a curved ramp structure. In the background, there are utility poles and a clear horizon line.

Hybrid Approach to Project Data
Accuracy Verification

Accuracy Validation

Number of Check Points	79	
Mean Error	0.023 ft.	0.007 m
Standard Deviation (StDEV)	0.037 ft.	0.011 m
Root Mean Squares Error	0.043 ft.	0.013 m
NSSDA Vert Accuracy at 95%	0.085 ft.	0.026 m

MMS Data



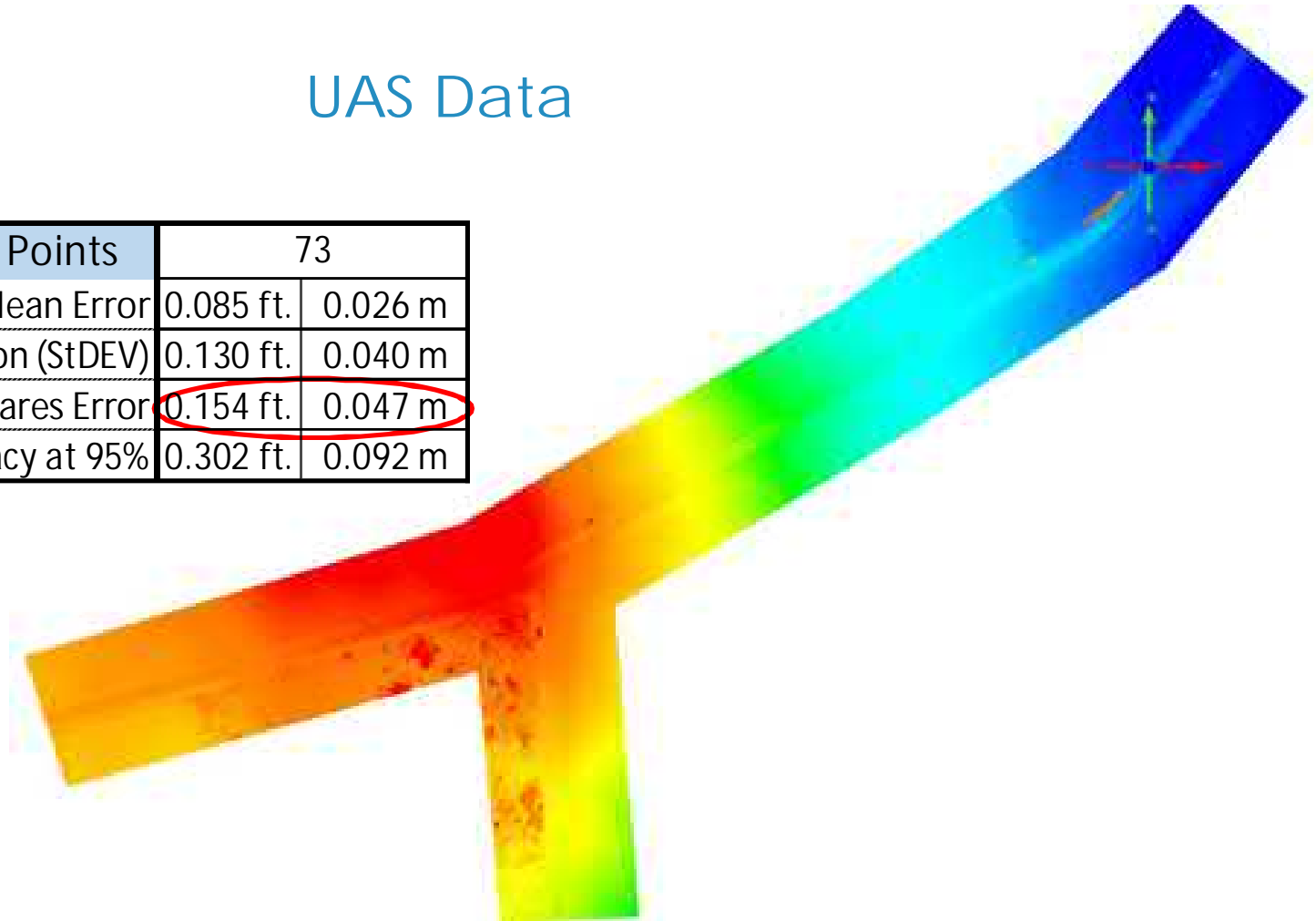
UAS Data



UAS Data

Accuracy Validation

Number of Check Points	73	
Mean Error	0.085 ft.	0.026 m
Standard Deviation (StDEV)	0.130 ft.	0.040 m
Root Mean Squares Error	0.154 ft.	0.047 m
NSSDA Vert Accuracy at 95%	0.302 ft.	0.092 m

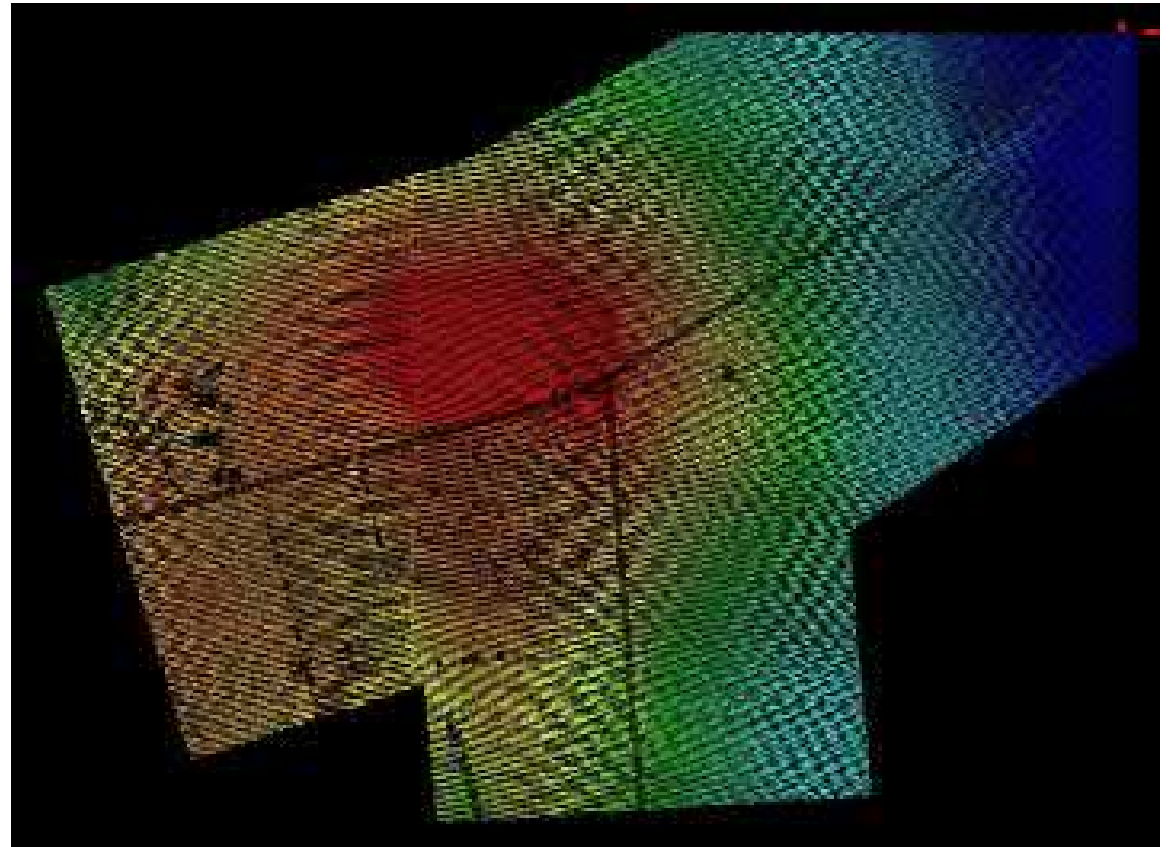


Aerial LiDAR: Existing Ohio Statewide Imagery Program (OSIP)

Accuracy Validation

Number of Check Points	197	
Mean Error	0.47 ft.	14.39 cm
Standard Deviation (StDEV)	0.16 ft.	4.90 cm
Root Mean Squares Error (RMSEz)	0.50 ft.	15.19 cm
NSSDA Vert Accuracy at 95% Confidence Level	0.98 ft.	29.79 cm

Aerial LiDAR Data



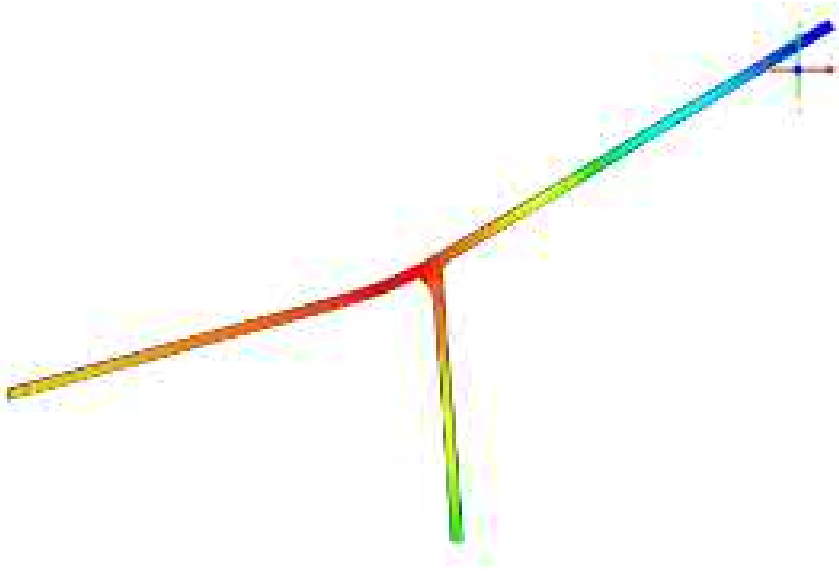
An aerial photograph of a multi-lane highway interchange, overlaid with a semi-transparent blue filter. The image shows several lanes of traffic, a central median, and a curved ramp structure. In the background, there are utility poles and a distant horizon line. The overall scene is presented in a monochromatic blue color scheme.

Hybrid Approach to Project Data

Data Preparation

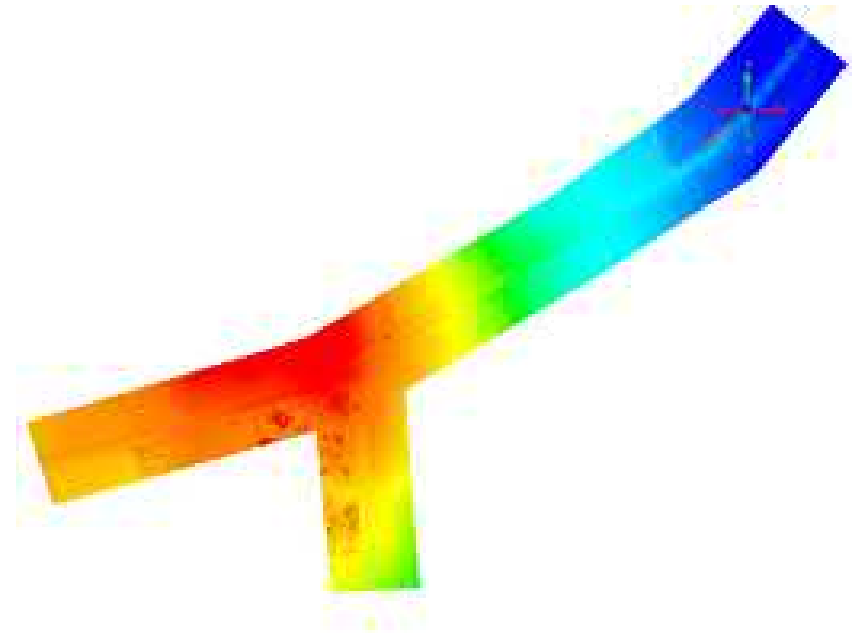
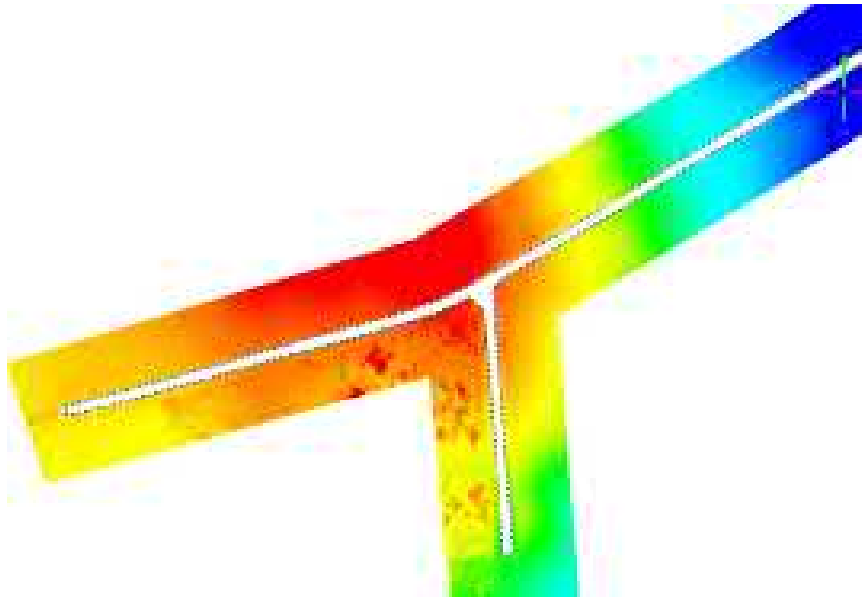
STEP 1: Preparing MMS Data

Only good around driven roads



MMS Data

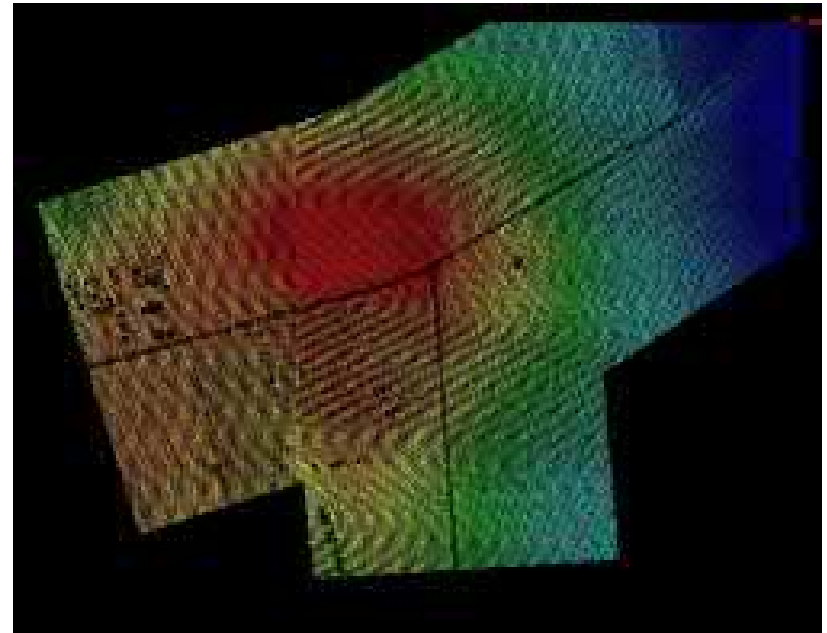
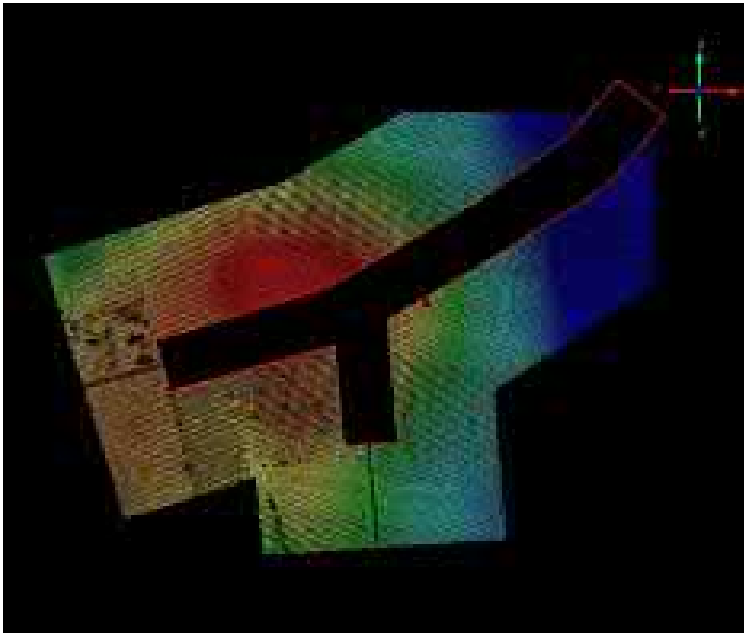
STEP 2: Preparing UAS Data



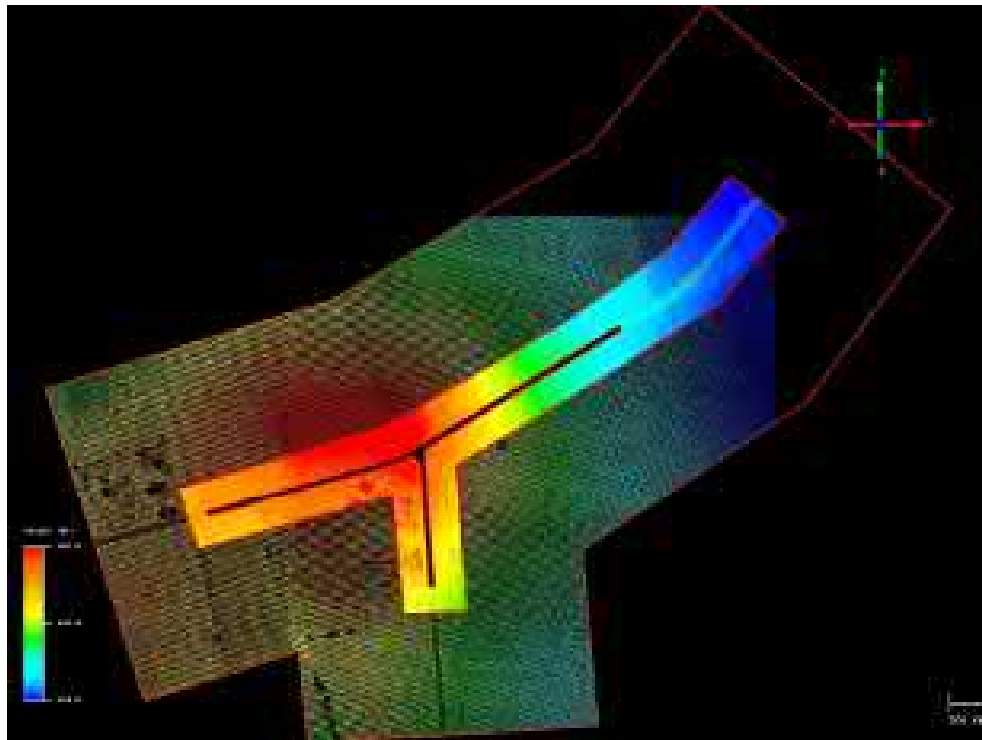
Drone-based DSM

STEP 3: Preparing Aerial Lidar Data

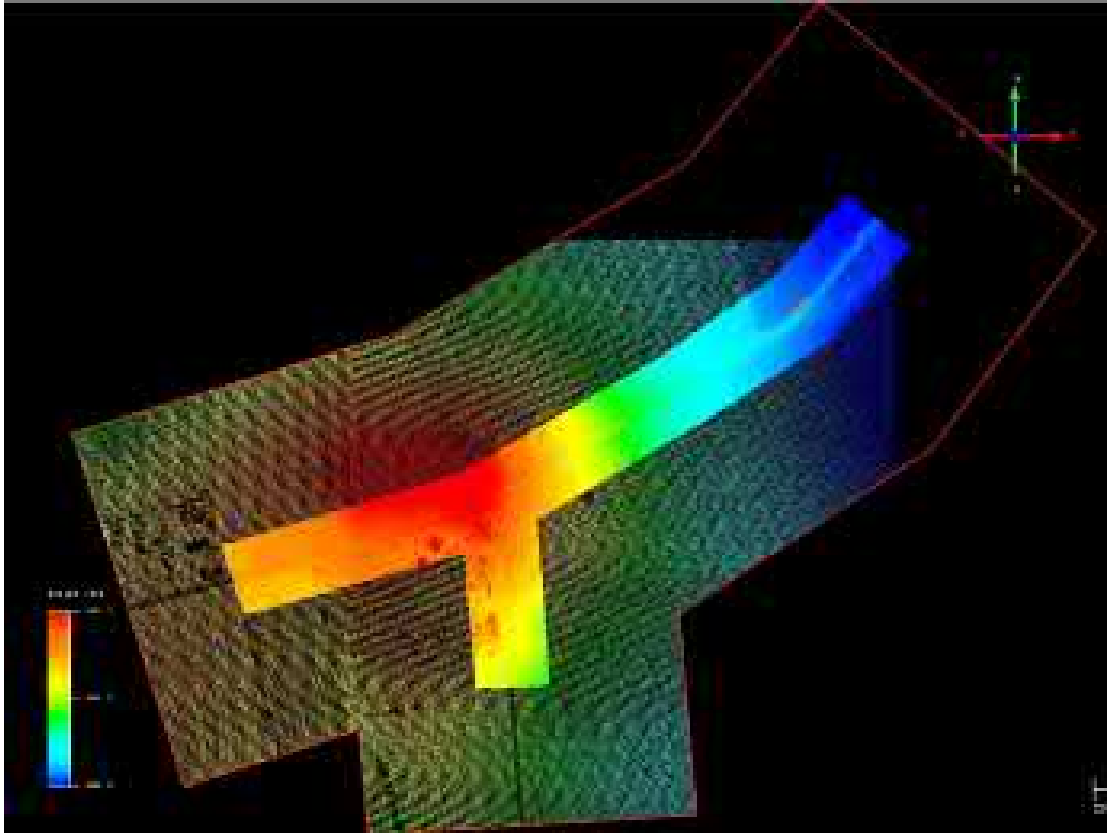
Aerial LiDAR from OSIP



STEP 4: Merging Aerial LiDAR + UAS DSM



STEP 5: Merging Aerial LiDAR + UAS DSM + MMS DSM (The Hybrid DSM)

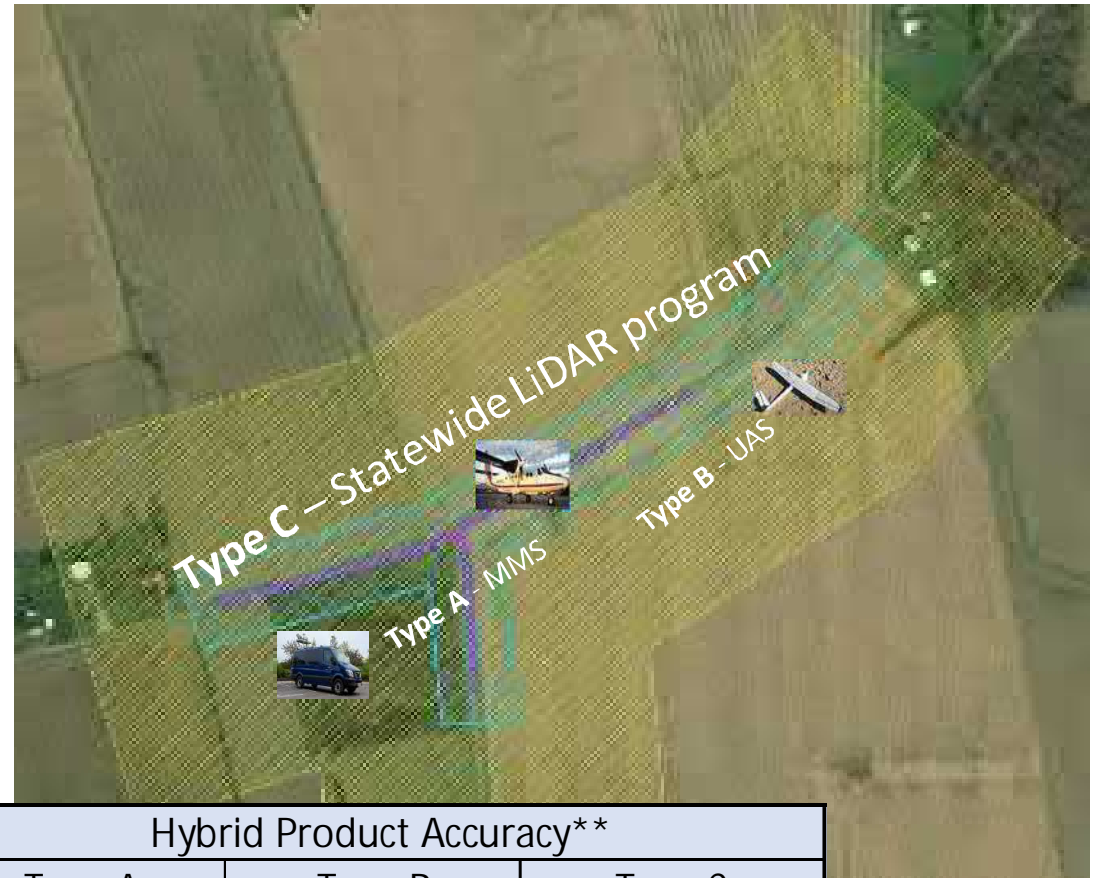


An aerial photograph of a complex highway interchange, featuring multiple lanes, overpasses, and ramps. The image is overlaid with a semi-transparent blue filter. The text is centered over the image.

Hybrid Approach to Project Data

Final Outcome: Accuracy on
Demand

Data Fusion provides accuracy where you need it most!



Product Specification	Hybrid Product Accuracy**		
	Type A	Type B	Type C
Terrain surface accuracy as verified using independent check points	$RMSE_v \leq 0.06$ ft.	$RMSE_v \leq 0.10$ ft.	$RMSE_v \leq 0.50$ ft.

** Type A = MMS lidar , Type B = UAS imagery-based points cloud, Type C = State wide lidar program

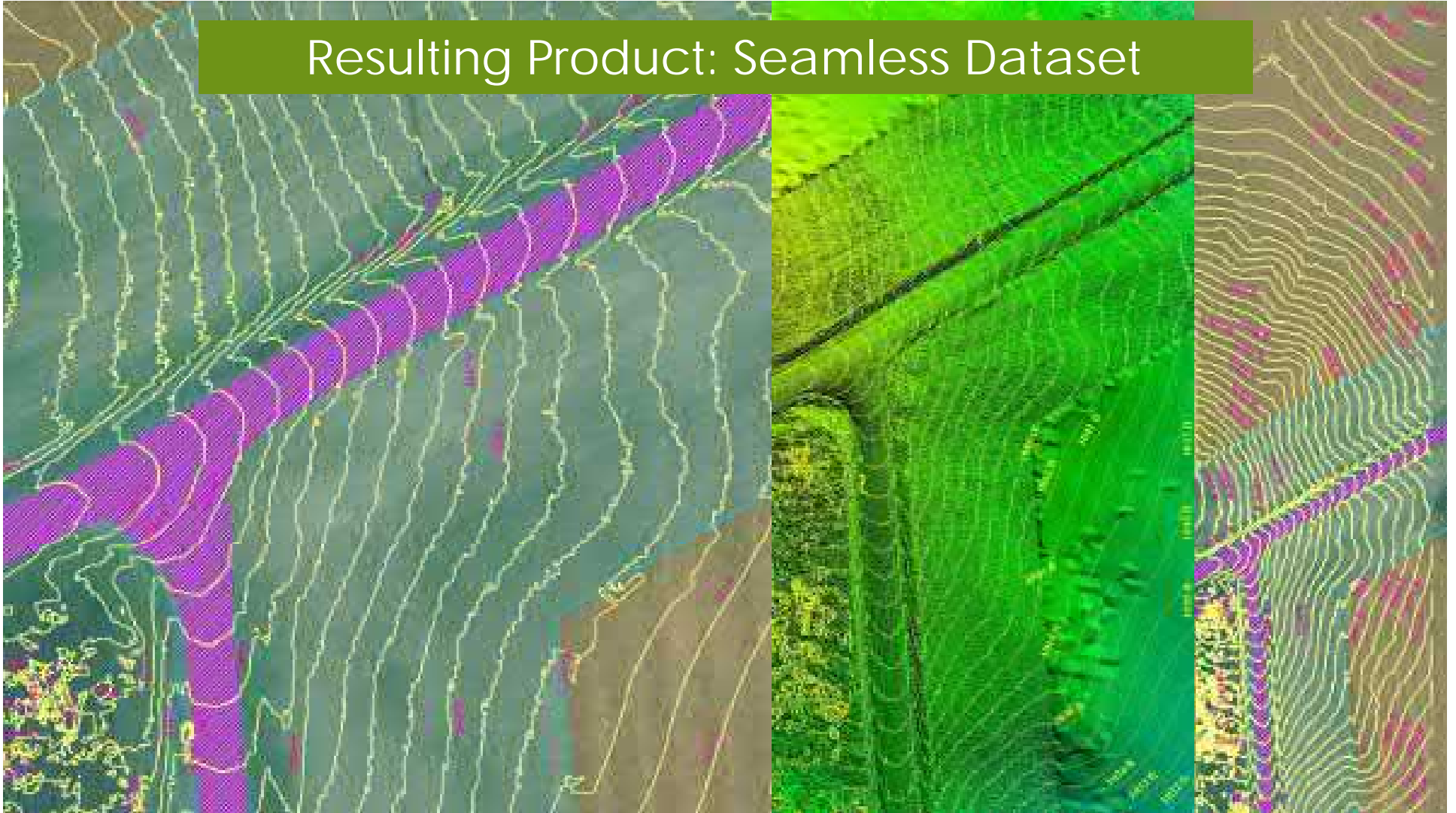


An aerial photograph of a complex highway interchange, featuring multiple lanes, overpasses, and ramps. The image is overlaid with a semi-transparent blue filter. In the background, several tall, thin structures, possibly towers or antennas, are visible against a clear sky.

Hybrid Approach to Project Data

Products Development and Final Deliverables

Resulting Product: Seamless Dataset



An aerial photograph of a multi-lane highway interchange, overlaid with a semi-transparent blue filter. The perspective is from an elevated position looking down the length of the highway, which curves to the right in the distance. Several tall utility poles are visible along the right side of the road.

Thank you!



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