Laserscanning
Scanning, scan geometries,
low-, intermediate- and high level tasks

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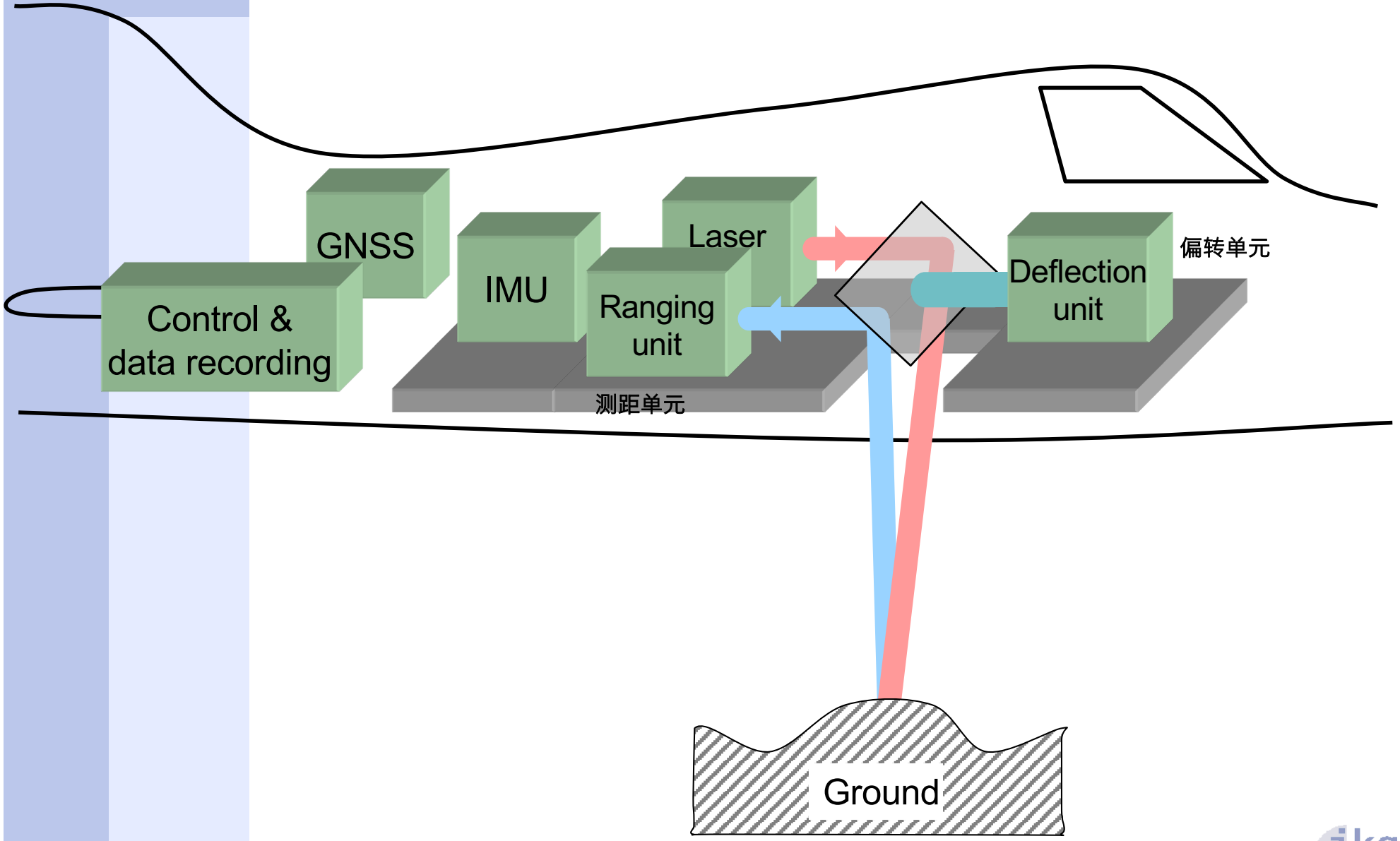
Basic components of an ALS system



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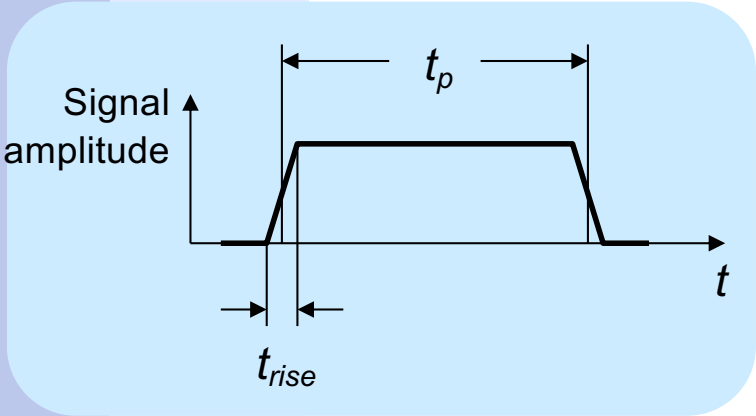
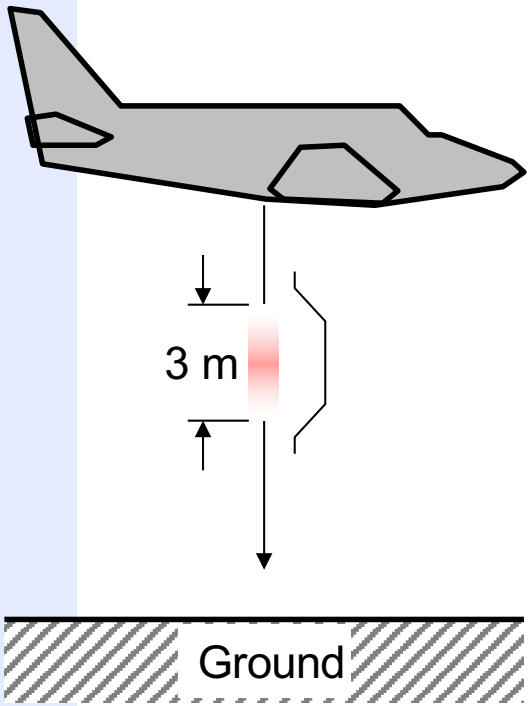
Pulsed laser operation 脉冲激光操作





Example characteristics:

- Pulse width
  t_p = 10 ns (→ 3 m @ speed of light)
- Pulse rise time
  t_{rise} = 1 ns (→ 30 cm @ speed of light)
- Peak power
  P_{peak} = 2,000 W
- Energy per pulse
  $E = P_{peak} \cdot t_p$ = 20 μJ
- Average power (@ pulse repetition rate F = 10 kHz)
  $P_{av} = E \cdot F$ = 0.2 W

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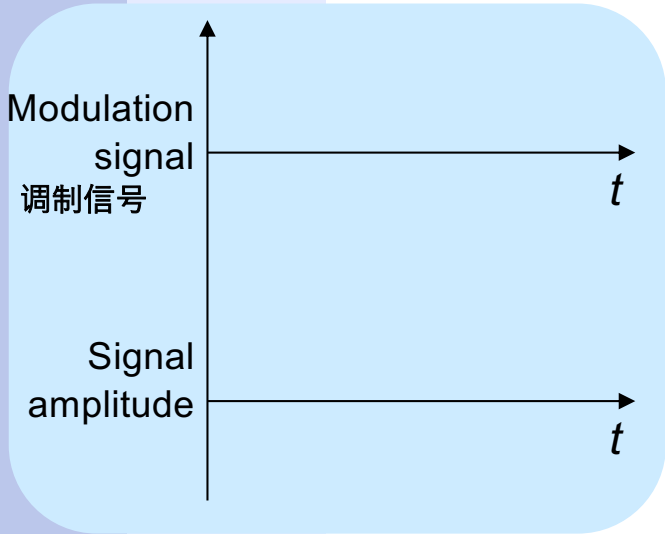
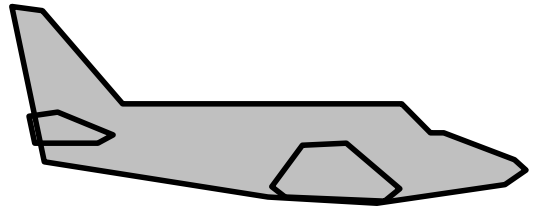
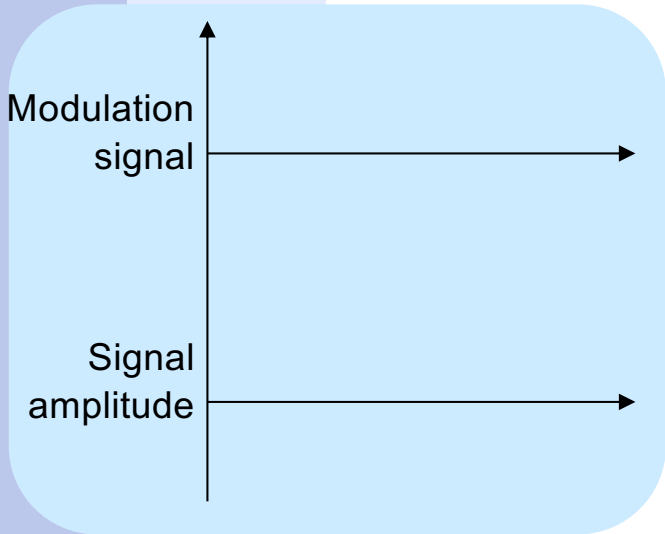
Continuous laser operation 连续的激光操作







Characteristics (ScaLARS):

- Two modulation frequencies
  f_{high} = 10 MHz, f_{low} = 1 MHz
  → λ_{short} = 30 m, λ_{long} = 300 m
- Average power (continuous operation)
  P_{av} = 0.26 W

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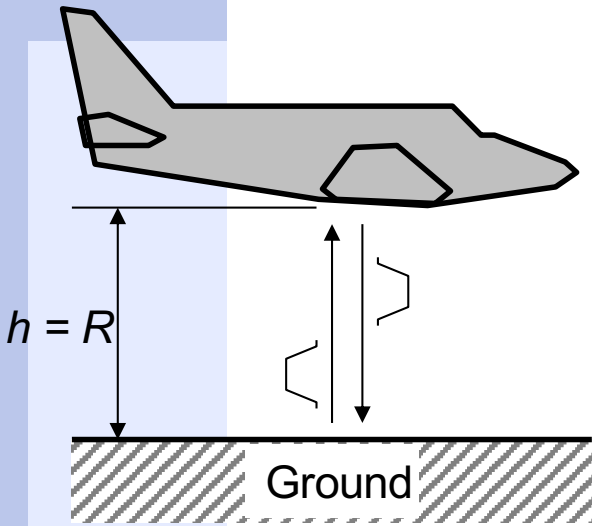
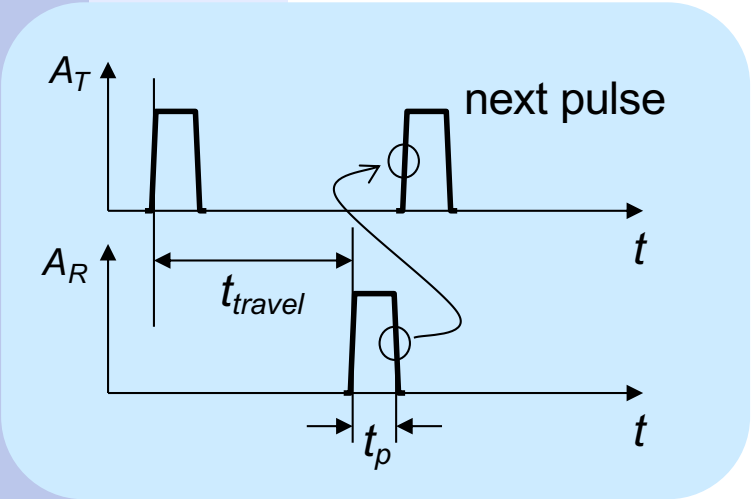
Ambiguities (pulse) 歧义/模糊问题（脉冲）





- Travelling time:

$$t_{travel} = \frac{2R}{c}$$

- Example:
  $h = R = 1000$ m → $t_{travel} = 6.7$ µs
- $t_p = 10$ ns can be neglected 可以忽略不计
- Maximum pulse frequency (assuming no transmit / receive overlap):

$$f_{\max} = 1/t_{travel} = \frac{c}{2R}$$

- Example:
  $h = R = 1000$ m → $f_{max} = 150$ kHz
- Nowadays:
  - Multiple pulses are “in the air” at a time
  - Ambiguities are resolved by software
  - Riegl: “MTA”, Leica “MPiA”, Optech “PulseTRAK”…

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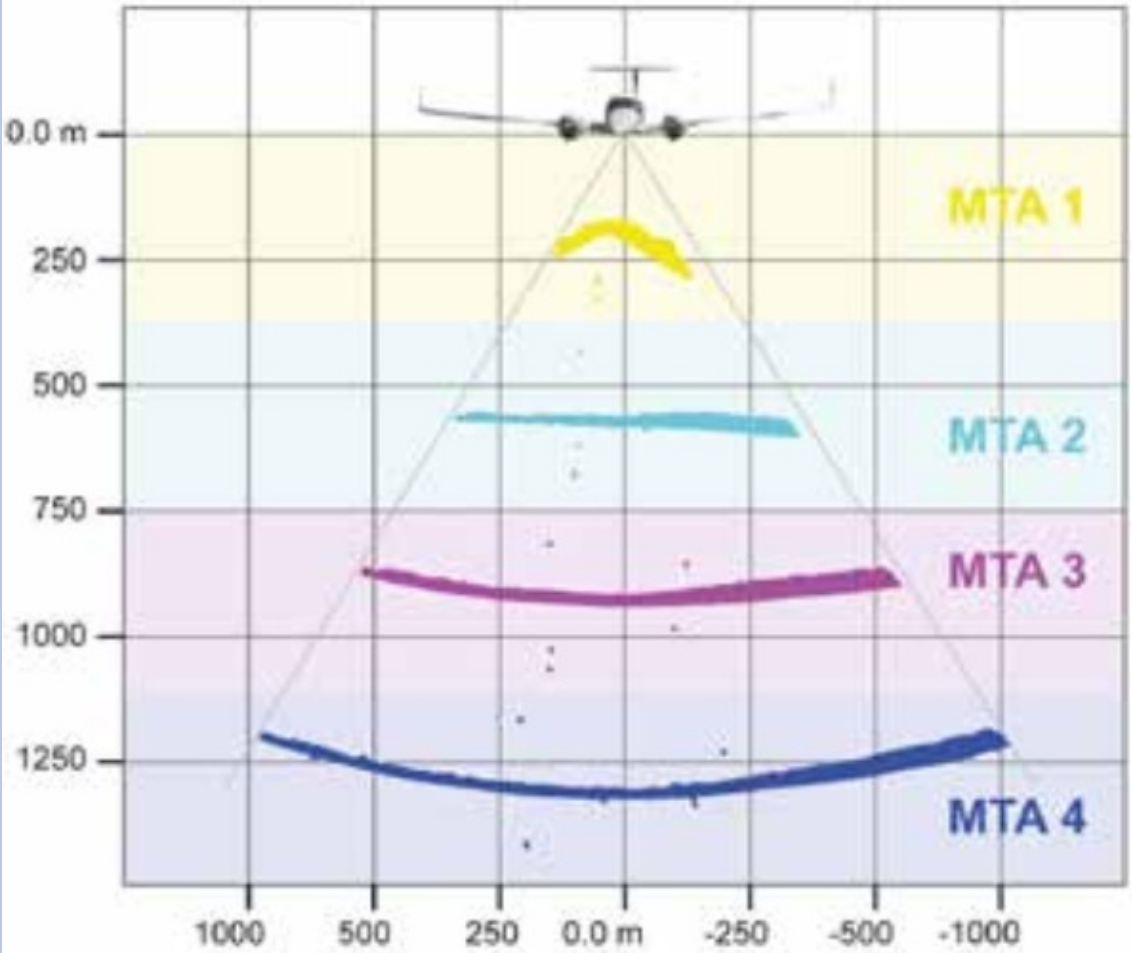
Illustration (from Riegl) 插图（来自Riegl）。



- Correct “MTA zone” is MTA2
- Correct zone is obtained using a “novel modulation scheme” and software

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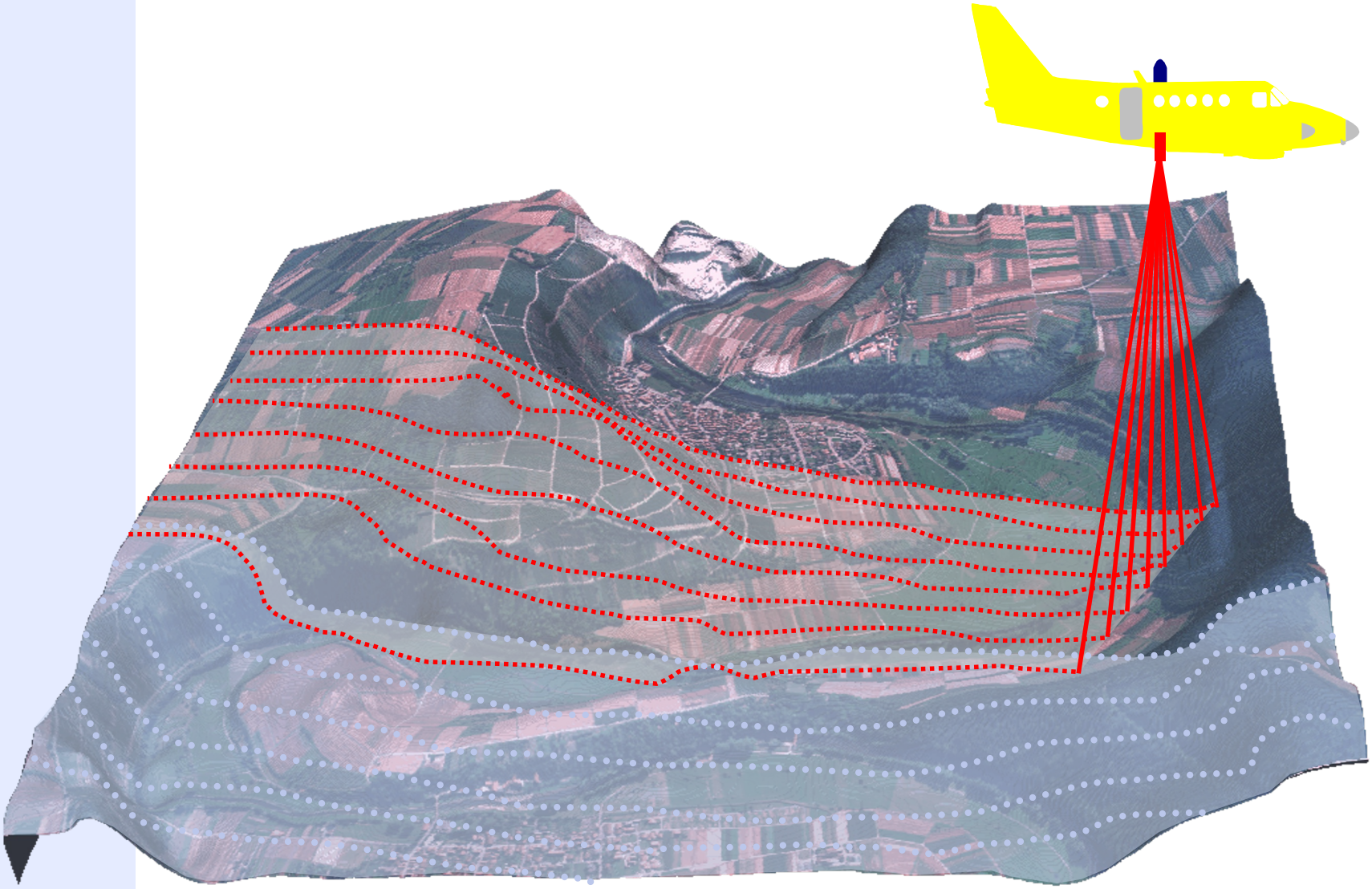
Image source: http://www.riegl.com/uploads/tx_pxpriegldownloads/RiMTA_DataSheet_2019-09-03.pdf

Acquisition in strips 在条状物中收购



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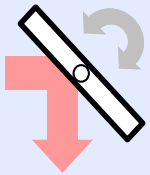
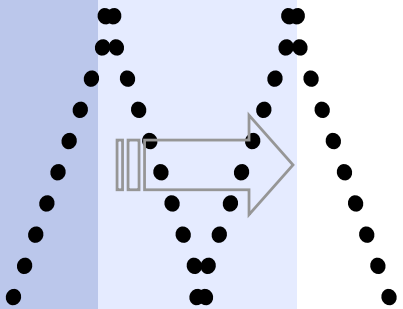
Scanning mechanisms & ground patterns

摆动的镜子

Oscillating mirror

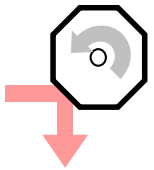


Z-shaped, sinusodial

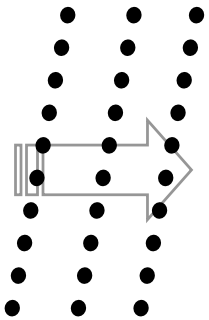


旋转的多边形

Rotating polygon

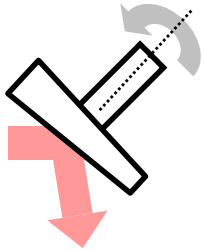


Parallel lines



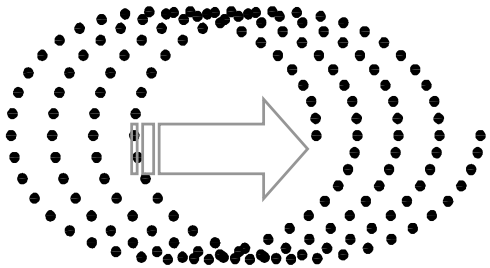
营养镜

Nutating mirror (Palmer scan)



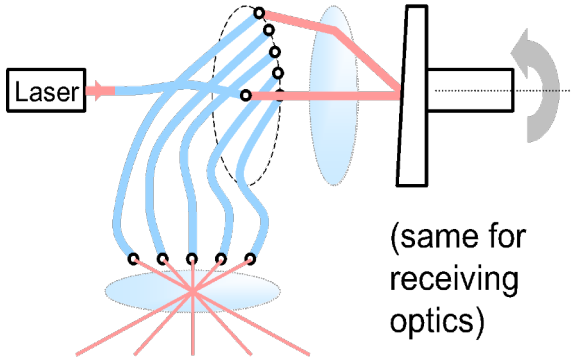
椭圆仪

“Elliptical” (not really)

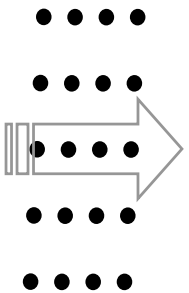


光纤交换器

Fiber switch



Parallel lines



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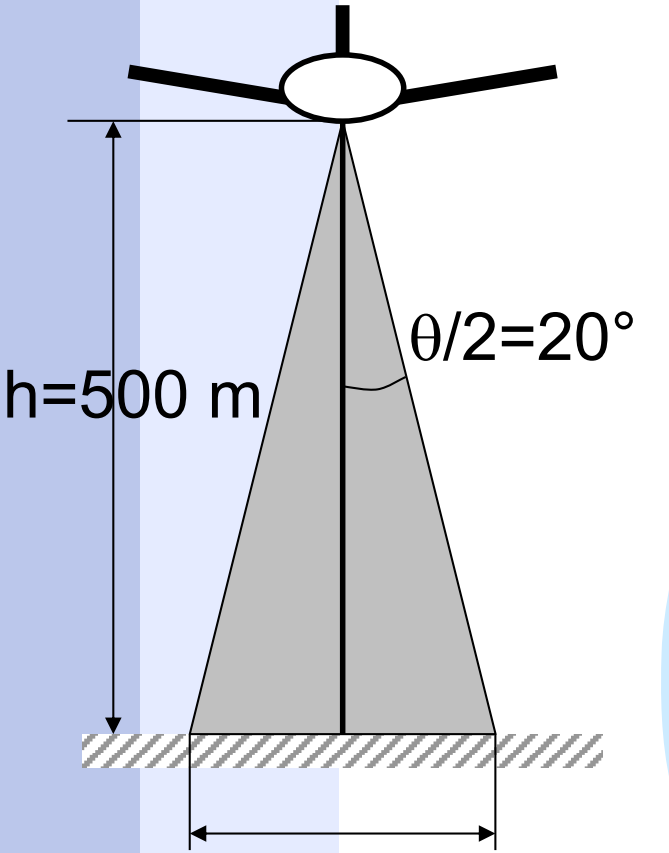
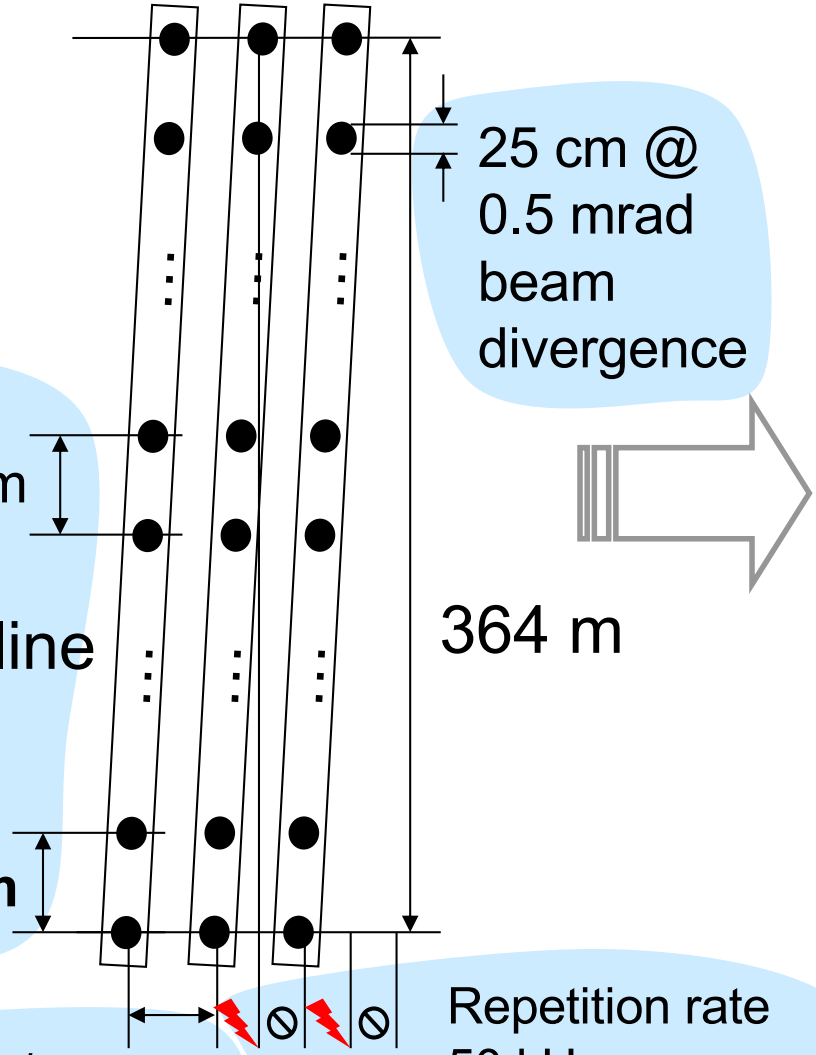
Polygon mirror example



$$2h\tan\left(\frac{\theta}{2}\right) = 0.7h = 364m$$



50 lines / s
v = 150 km/h

Repetition rate
50 kHz, average
pulse rate 25 kHz

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Example for a contemporary system: Riegl VQ-580 II

当代系统

Item	Specification
Scanning mechanism	Rotating polygon mirror
Scan pattern	Parallel scan lines
Laser pulse repetition rate (PRR)	Up to 2,000 kHz
Max. effective measurement rate	1,250 kHz (@ 2,000 kHz PRR and 75° scan angle)
Laser beam divergence	0.25 mrad
Scan angle range	+/- 37.5° = 75°
Total scan rate	30 – 300 lines/s (min. depends on laser PRR)
Angular step width	0.002° - 0.24° (depends on PRR, scan rate)
Accuracy, precision	(Both) 20 mm, one sigma, @ 150 m, under RIEGL test conditions

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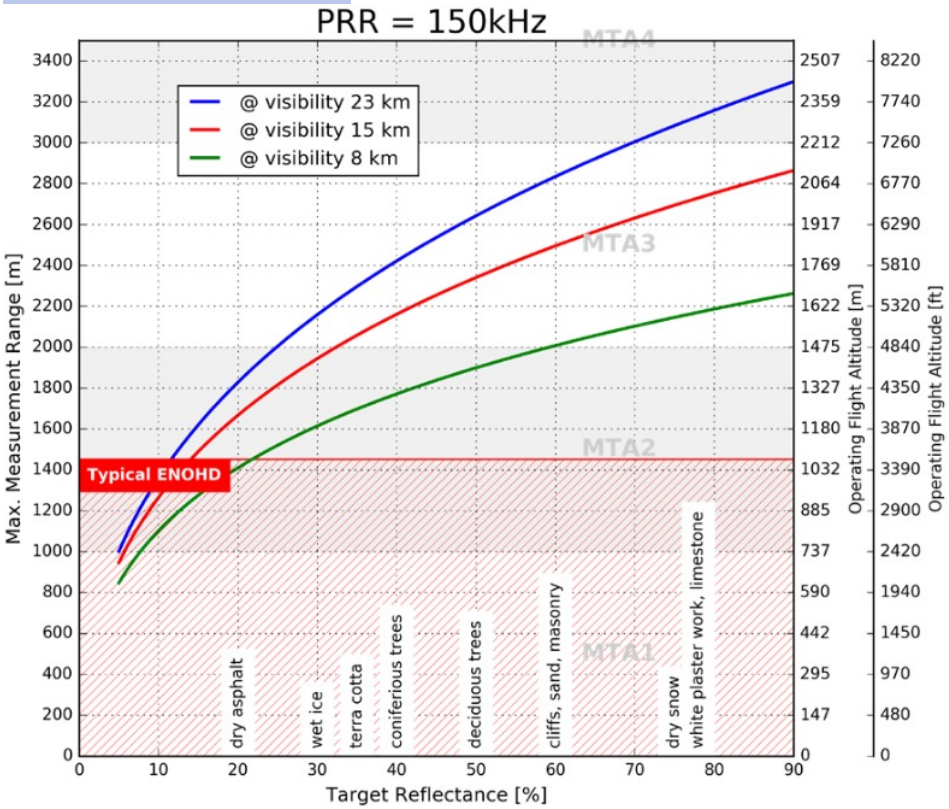
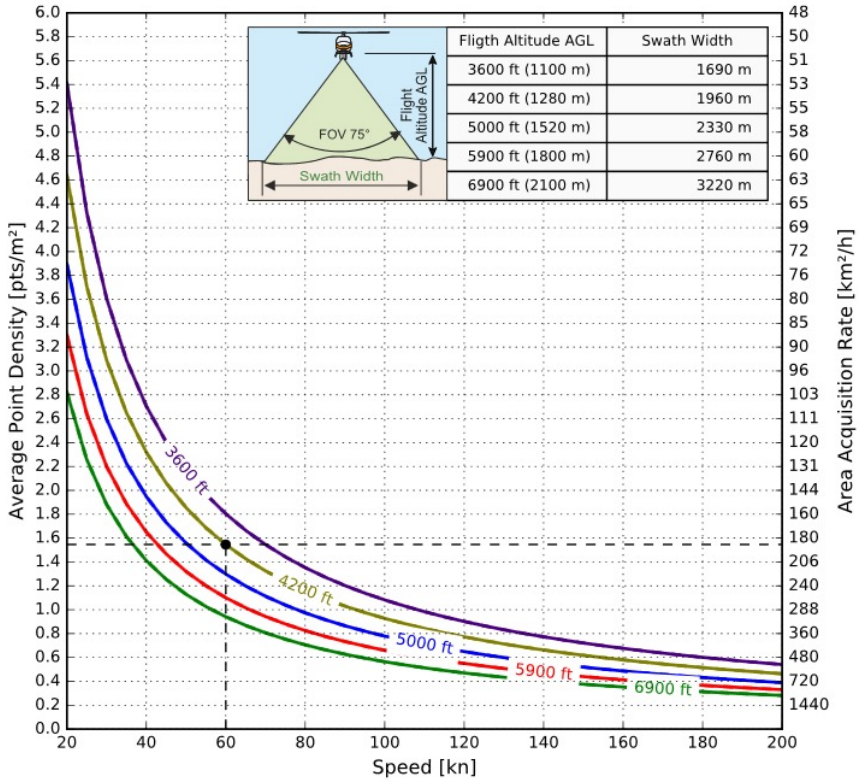
(Source: Riegl VQ-580 II data sheet)

Example for a contemporary system: Riegl VQ-580 II





Fligth Altitude AGL	Swath Width
3600 ft (1100 m)	1690 m
4200 ft (1280 m)	1960 m
5000 ft (1520 m)	2330 m
5900 ft (1800 m)	2760 m
6900 ft (2100 m)	3220 m

Example: VQ-580 II at 150,000 pulses/sec, laser power level 100%
Altitude = 4,200 ft AGL, Speed 60 kn

Results: Point Density ~ 1.55 pts/m²

(ambiguity resolved by multiple-time-around (MTA) processing; target size > laser footprint; average ambient brightness; operating flight altitude given at a FOV of +/- 37.5°; ENOHD = Extended Nominal Ocular Hazard Distance)

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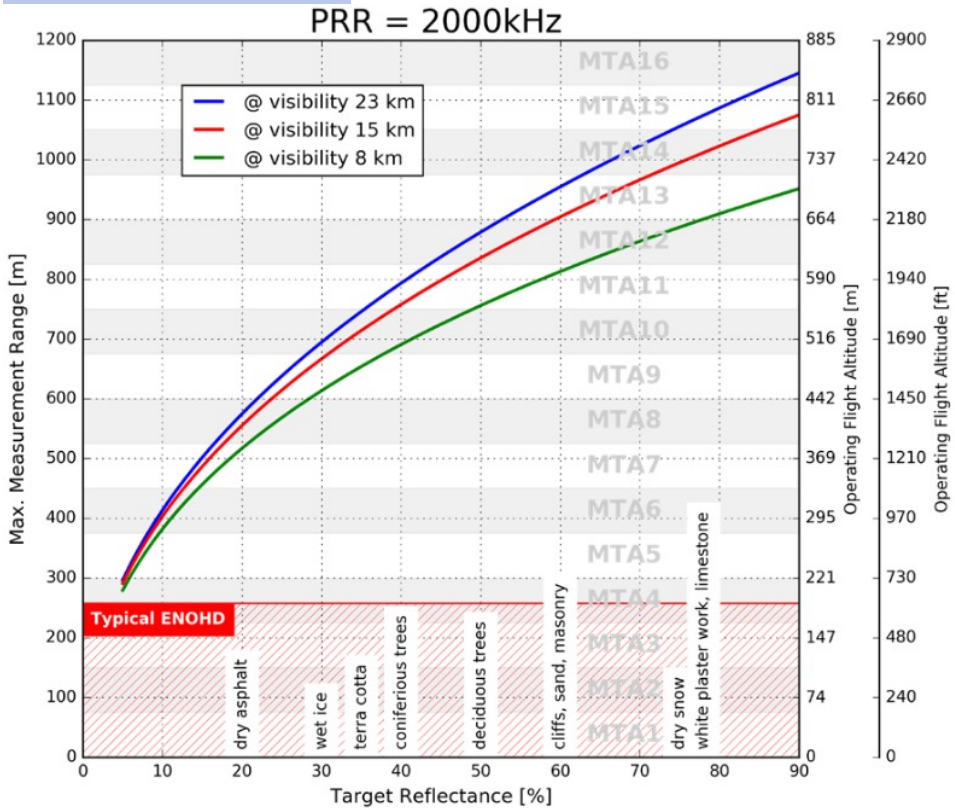
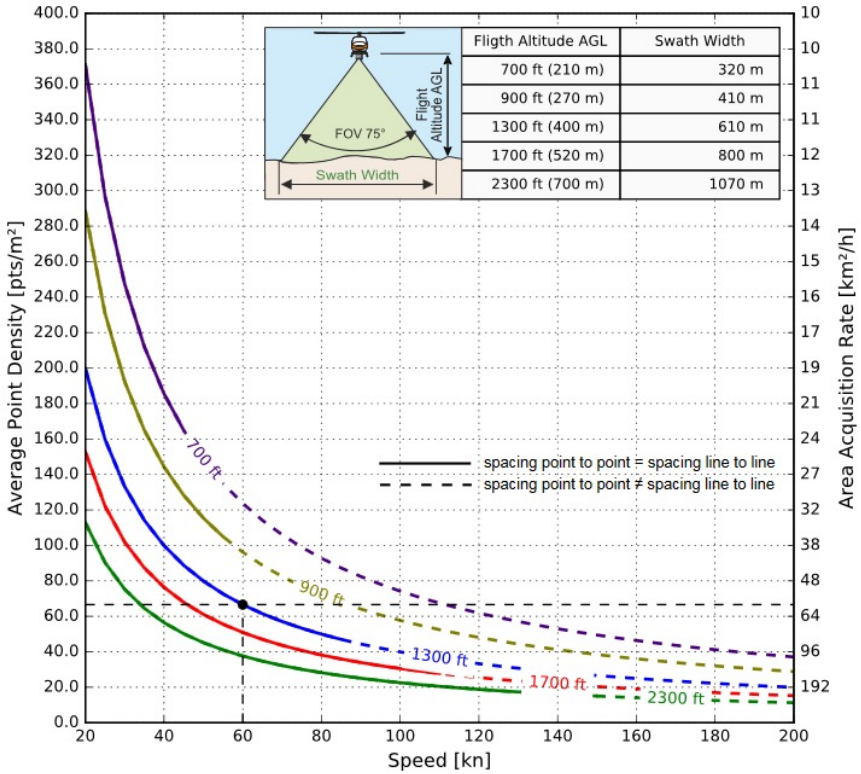
(Source: Riegl VQ-580 II data sheet)

Example for a contemporary system: Riegl VQ-580 II





Example: VQ-580 II at 2,000,000 pulses/sec, laser power level 100%
Altitude = 1,300 ft AGL, Speed 60 kn

Results: Point Density ~ 66.60 pts/m²

(ambiguity resolved by multiple-time-around (MTA) processing; target size > laser footprint; average ambient brightness; operating flight altitude given at a FOV of +/- 37.5°; ENOHD = Extended Nominal Ocular Hazard Distance)

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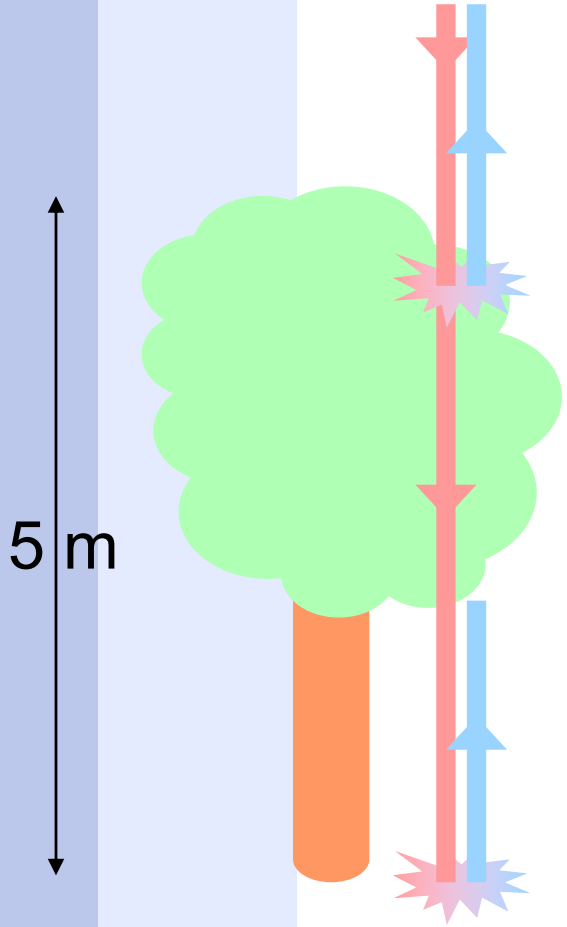
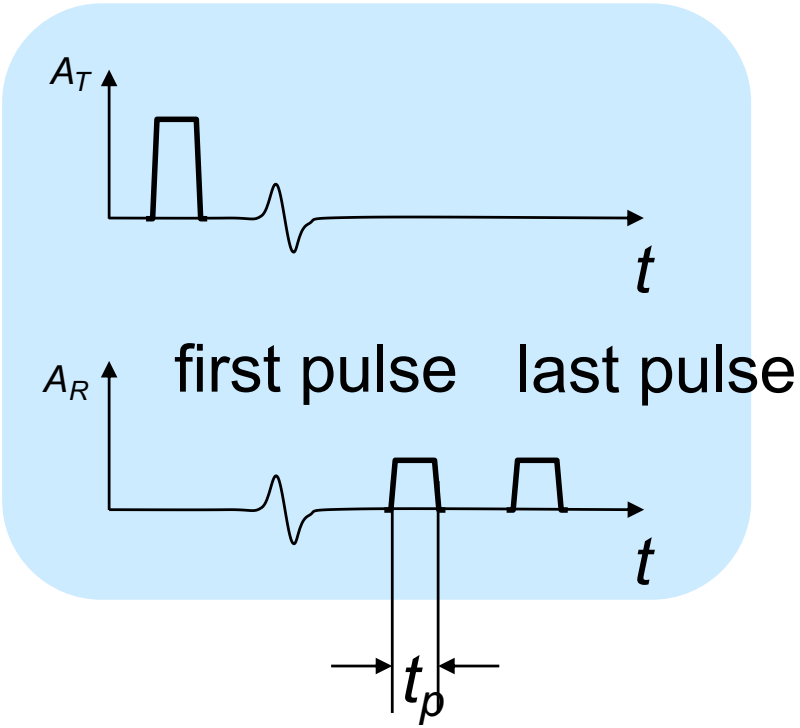
(Source: Riegl VQ-580 II data sheet)

Interaction with target 与目标的相互作用





Pulse width

10 ns → 3 m @ speed of light

→ Δh = 1.5 m

→ pulses separable 脉冲可分离

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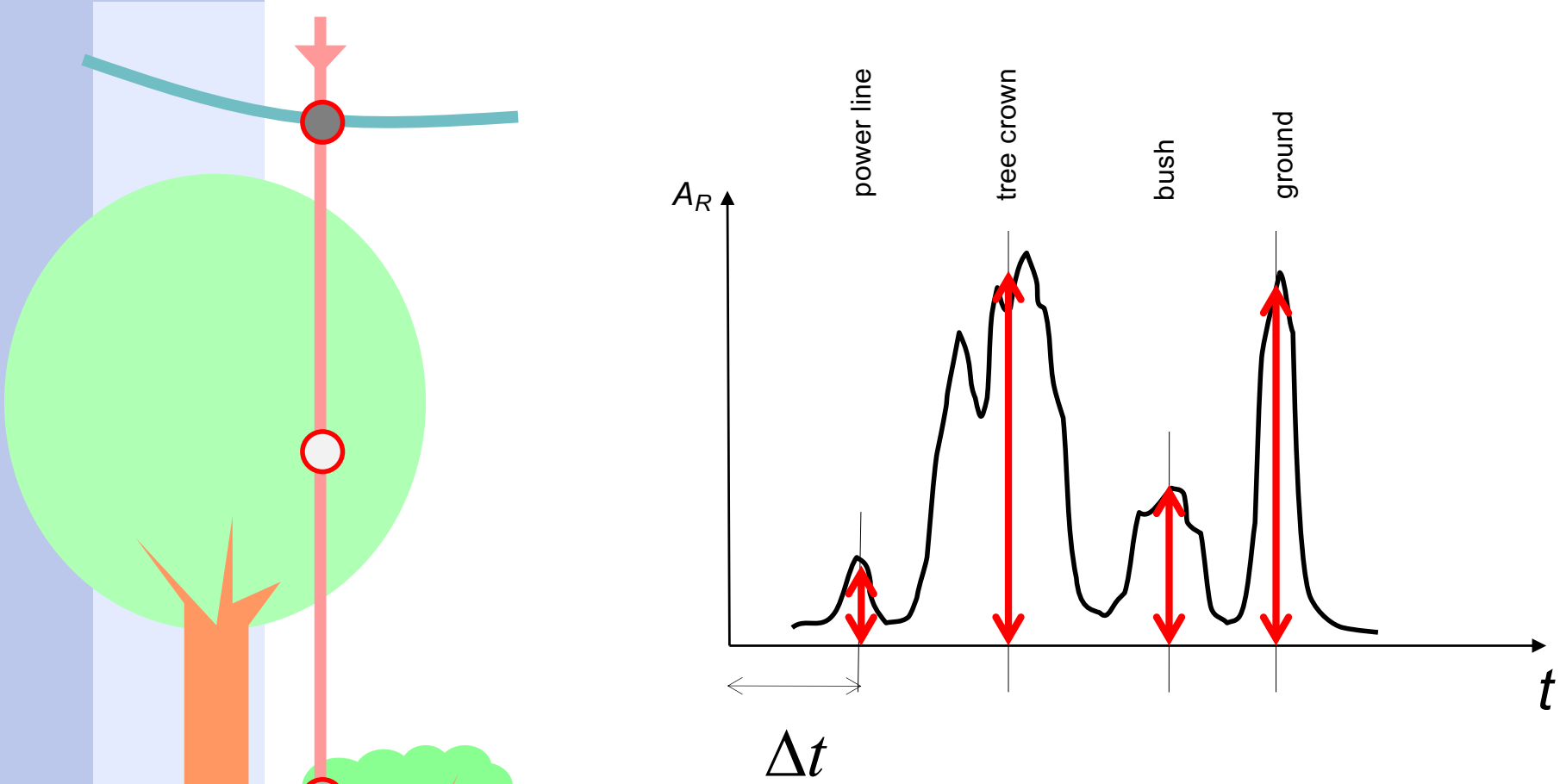
Reflected waveform and 3D points



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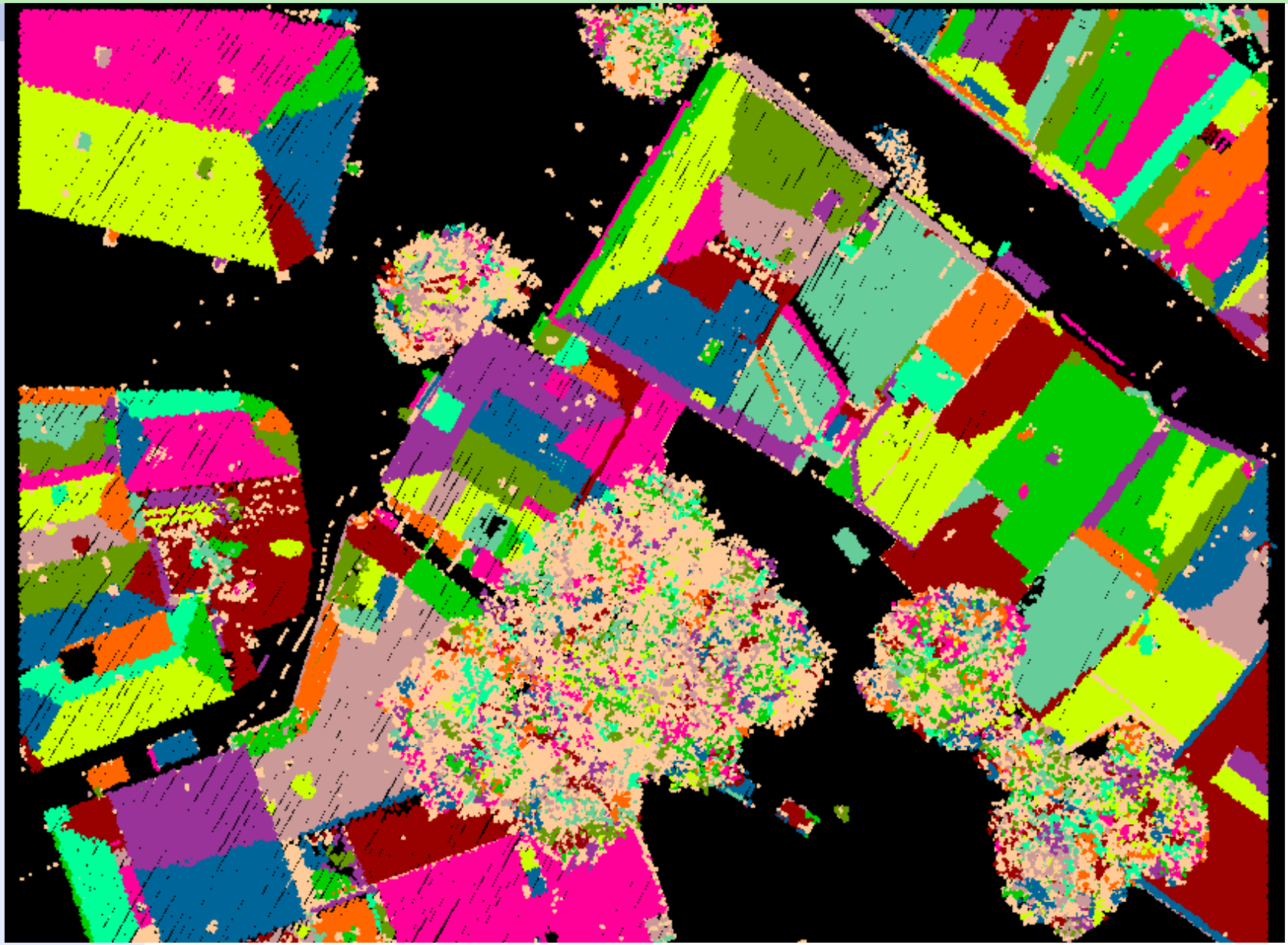
Helicopter scan, without ground (and segmented)



[Arik Darmawati, Masters Thesis, ITC Enschede]

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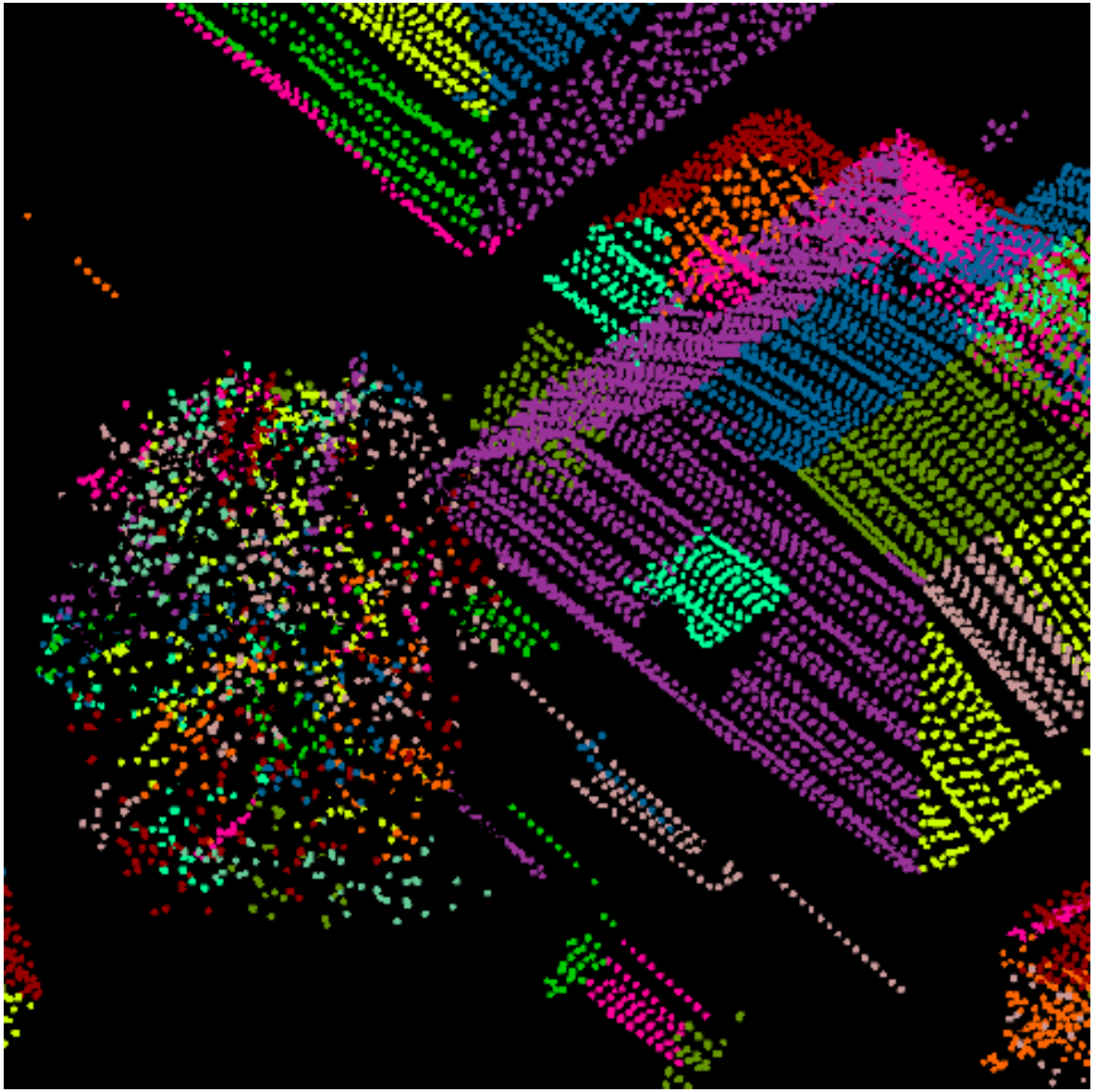
All echoes (without echoes on ground)



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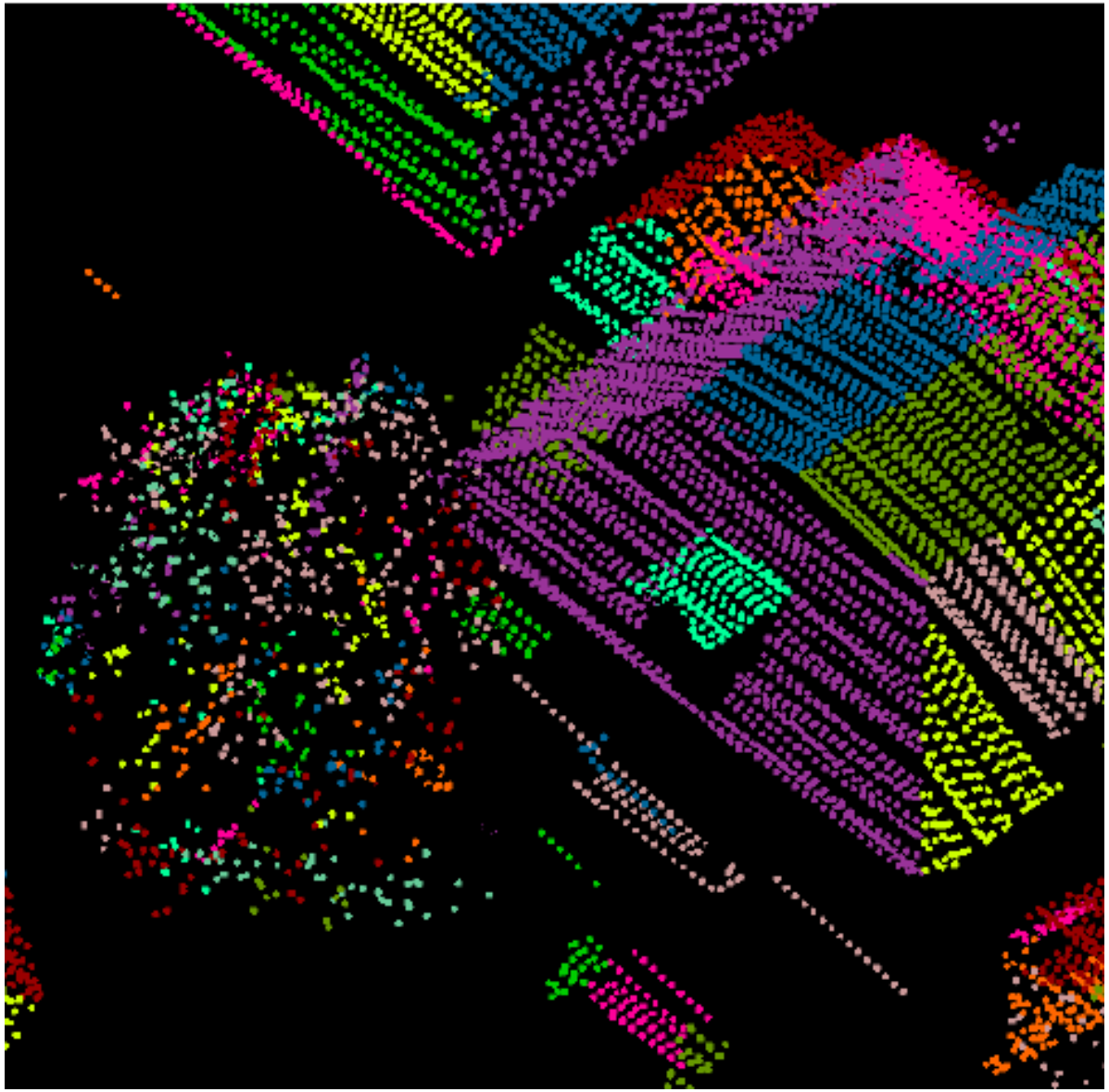
First echo



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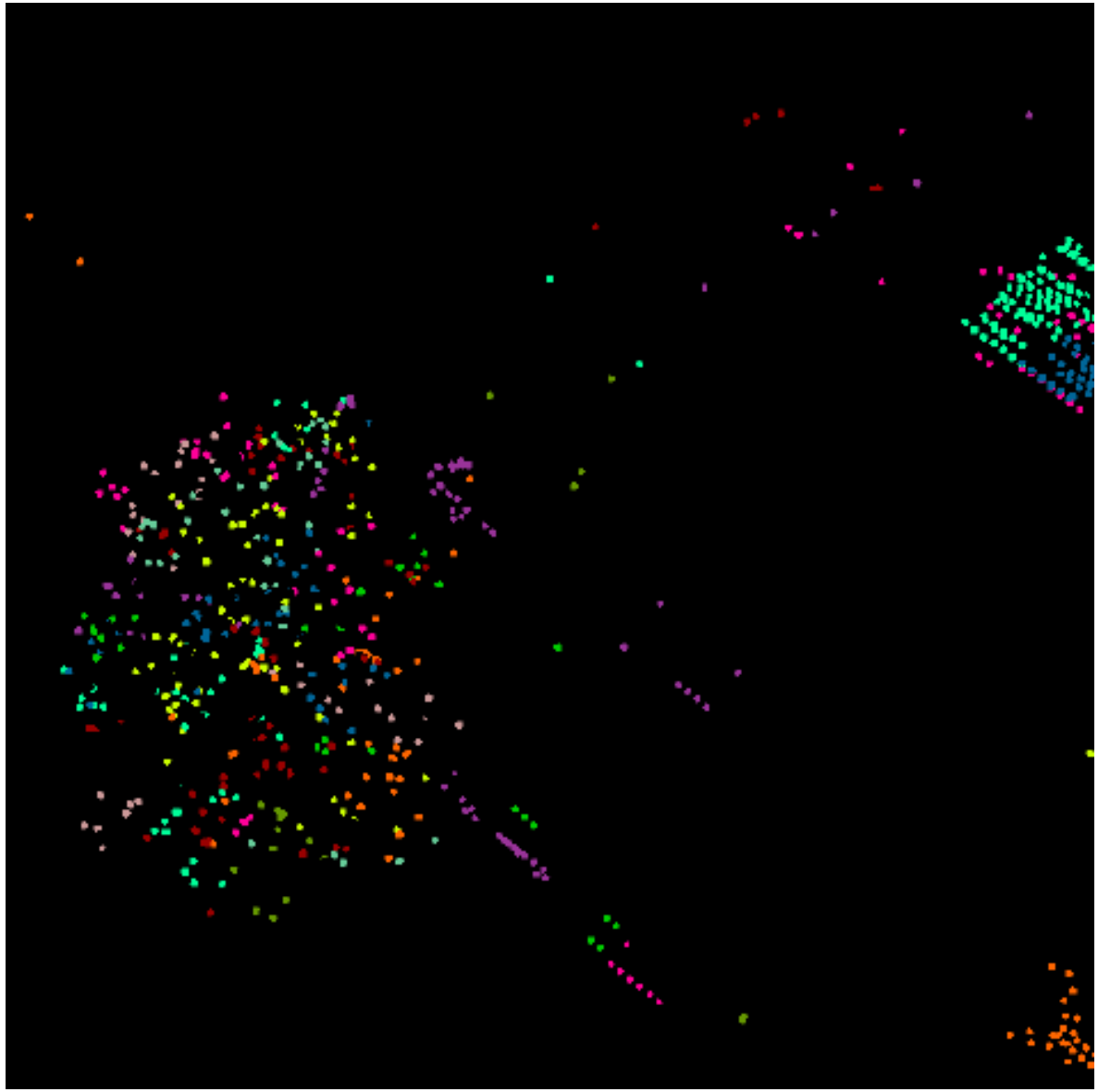
Second echo



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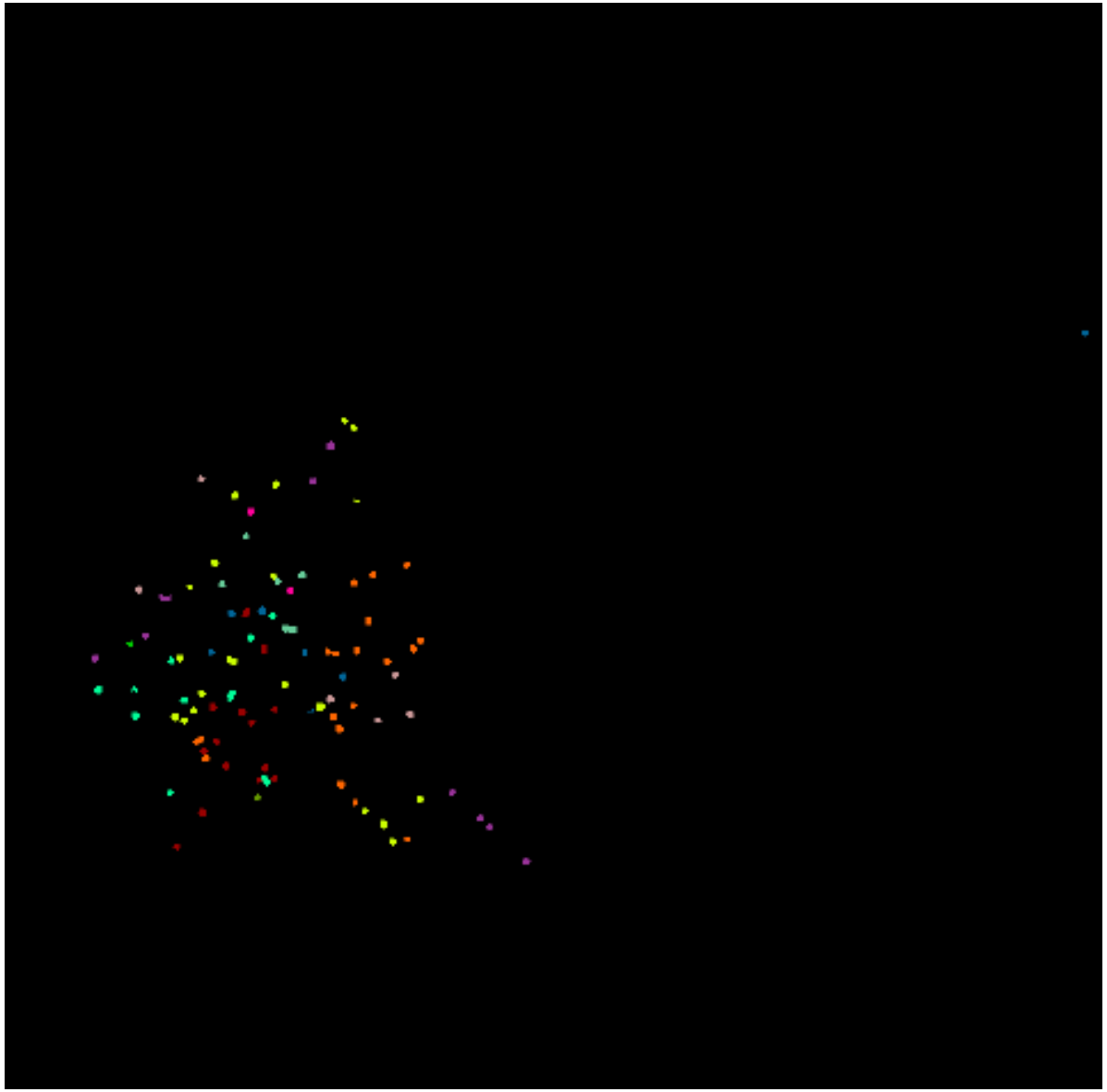
Third echo



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Fourth echo

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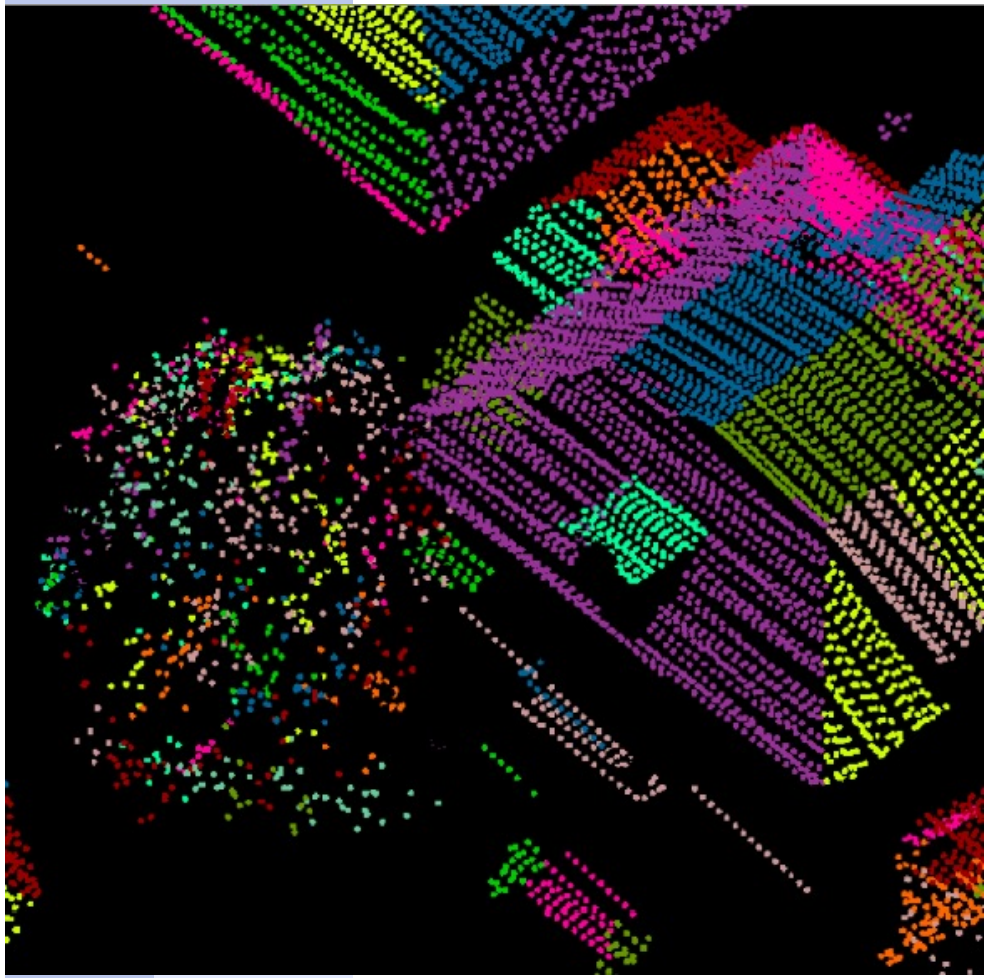
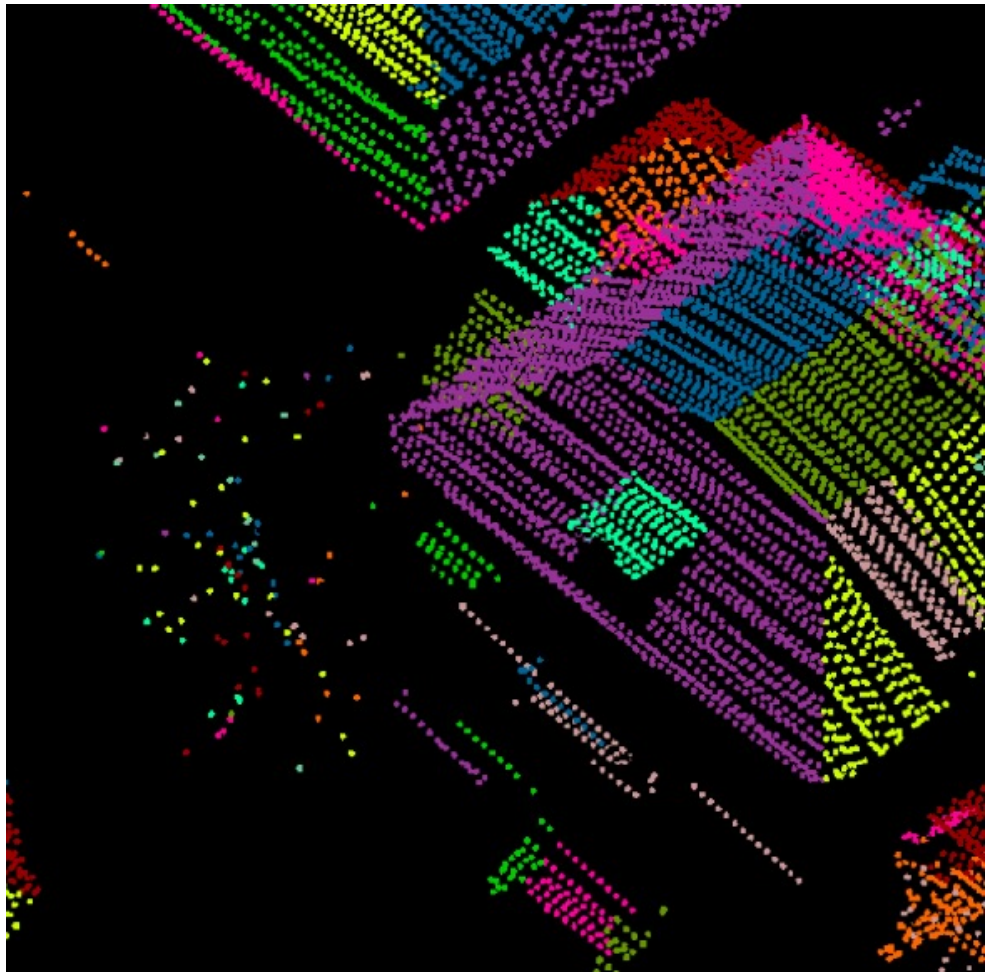
Differences between first & last pulse



First pulse



Last pulse

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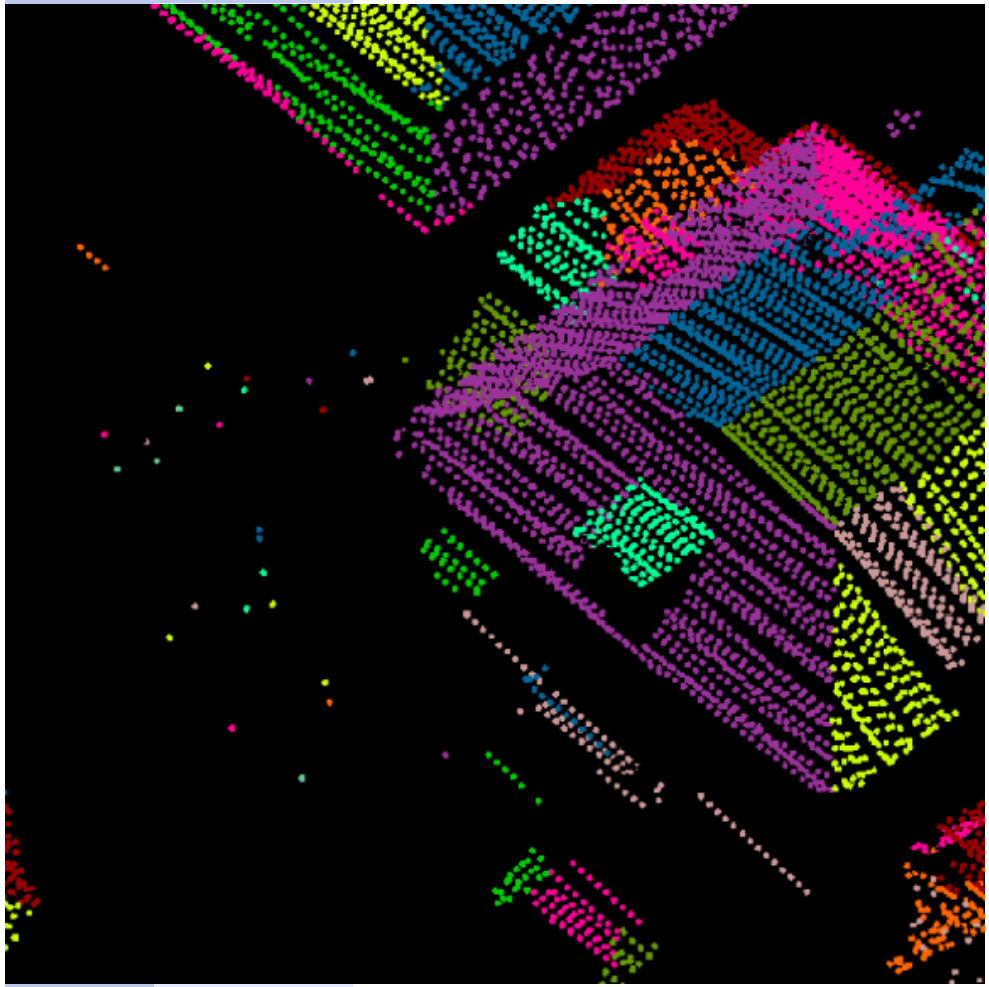
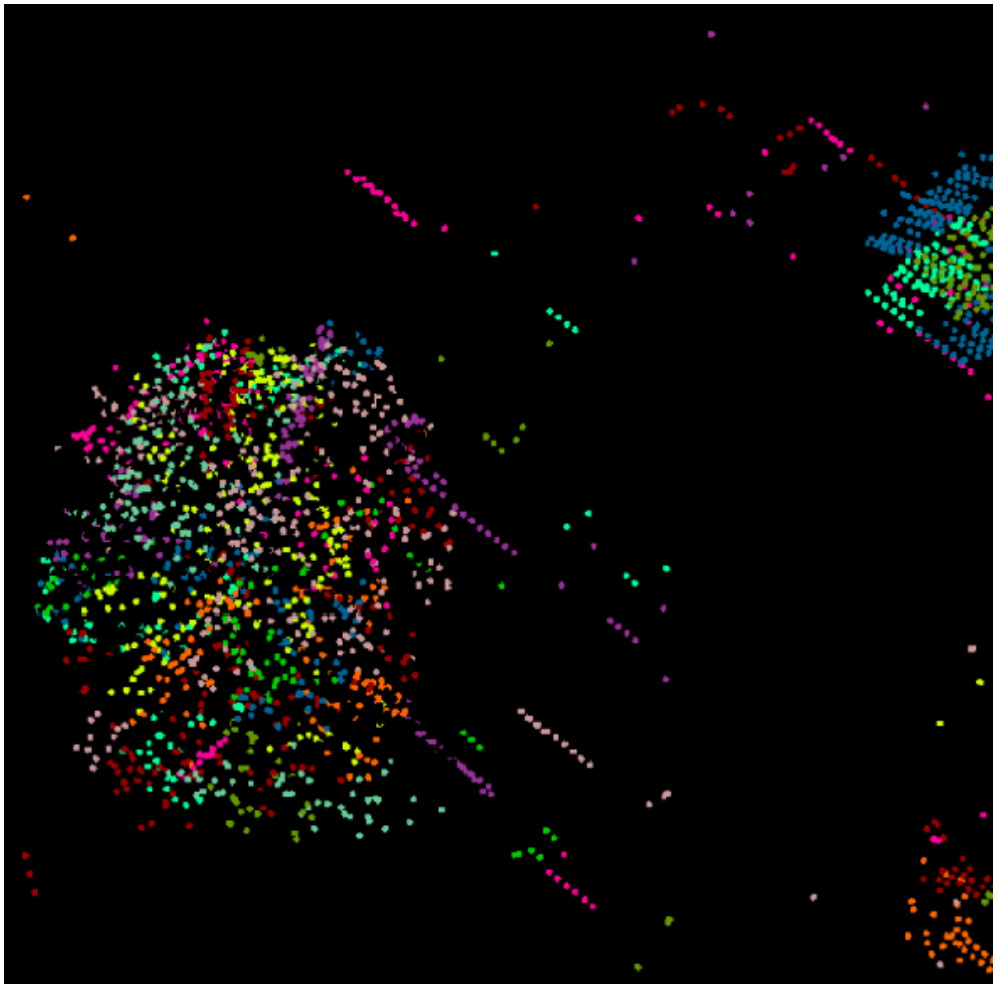
Differences between single & multiple pulse



Single pulse



Multiple pulse

[Arik Darmawati, Masters Thesis, ITC Enschede]

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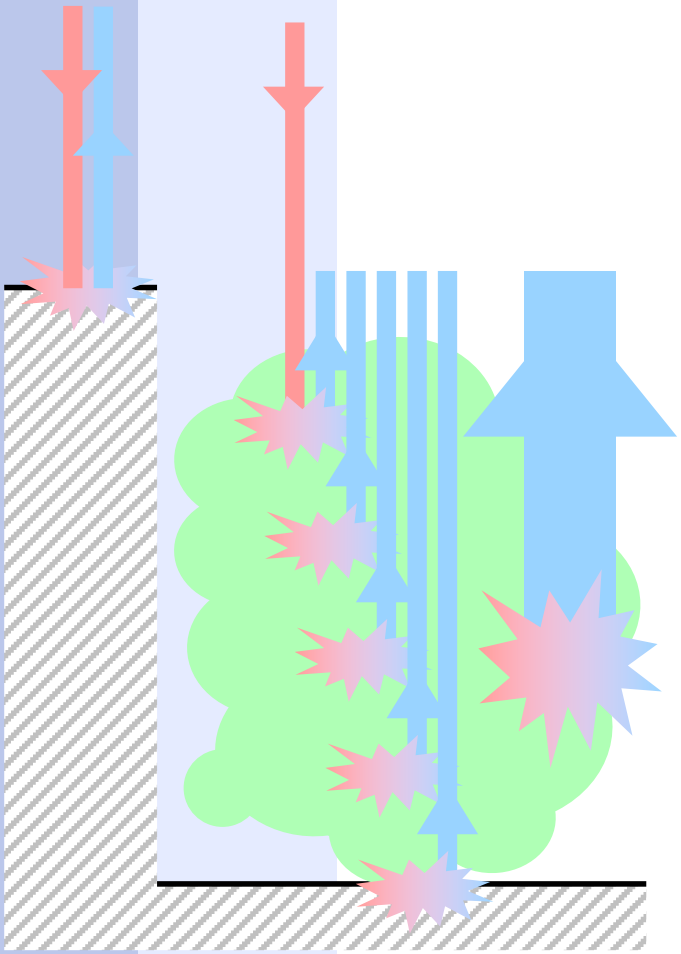
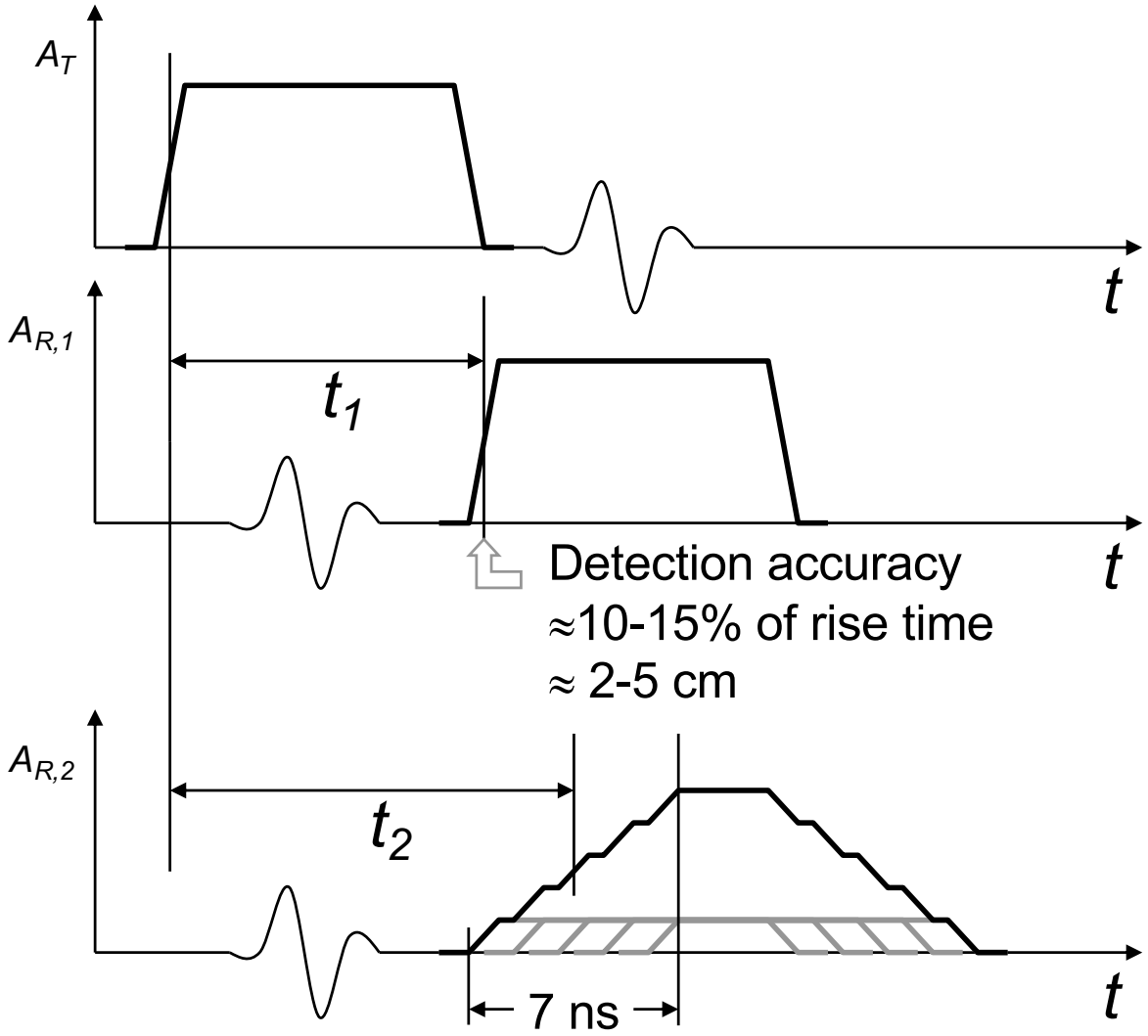
Interaction with target





Measured range will be an intermediate value (mixed echo)

中间值

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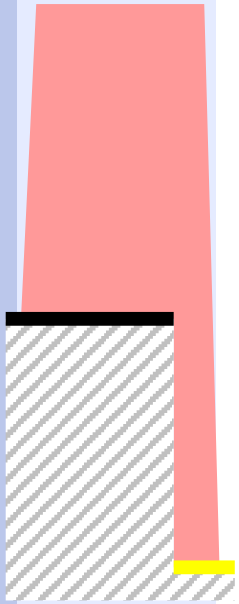
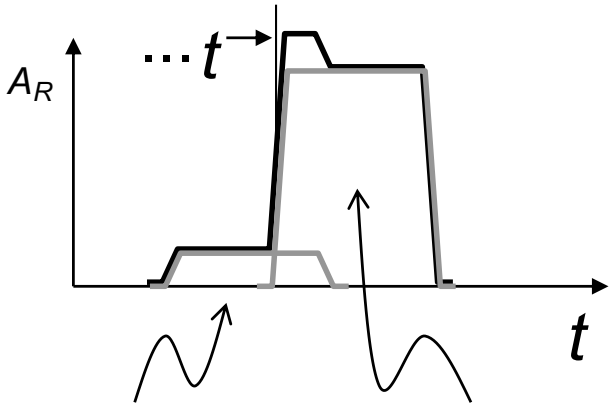
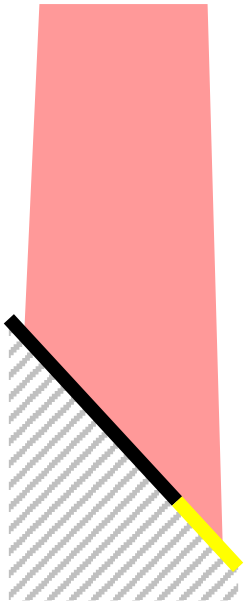
Interaction with target





Large area,
small reflectivity

Small area,
large reflectivity



(same for
sloped terrain)
倾斜的地形

- Minimum detectable object size depends on reflectivity
- Measured range depends on distribution of reflectivity inside laser ground spot area

范围取决于激光激光接地点区域内的反射率分布

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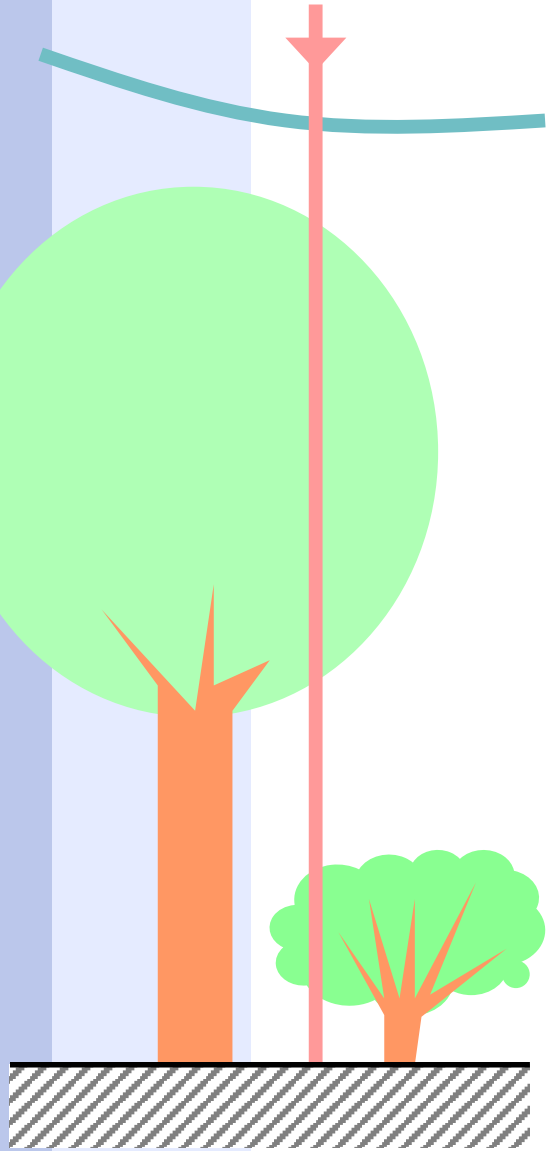
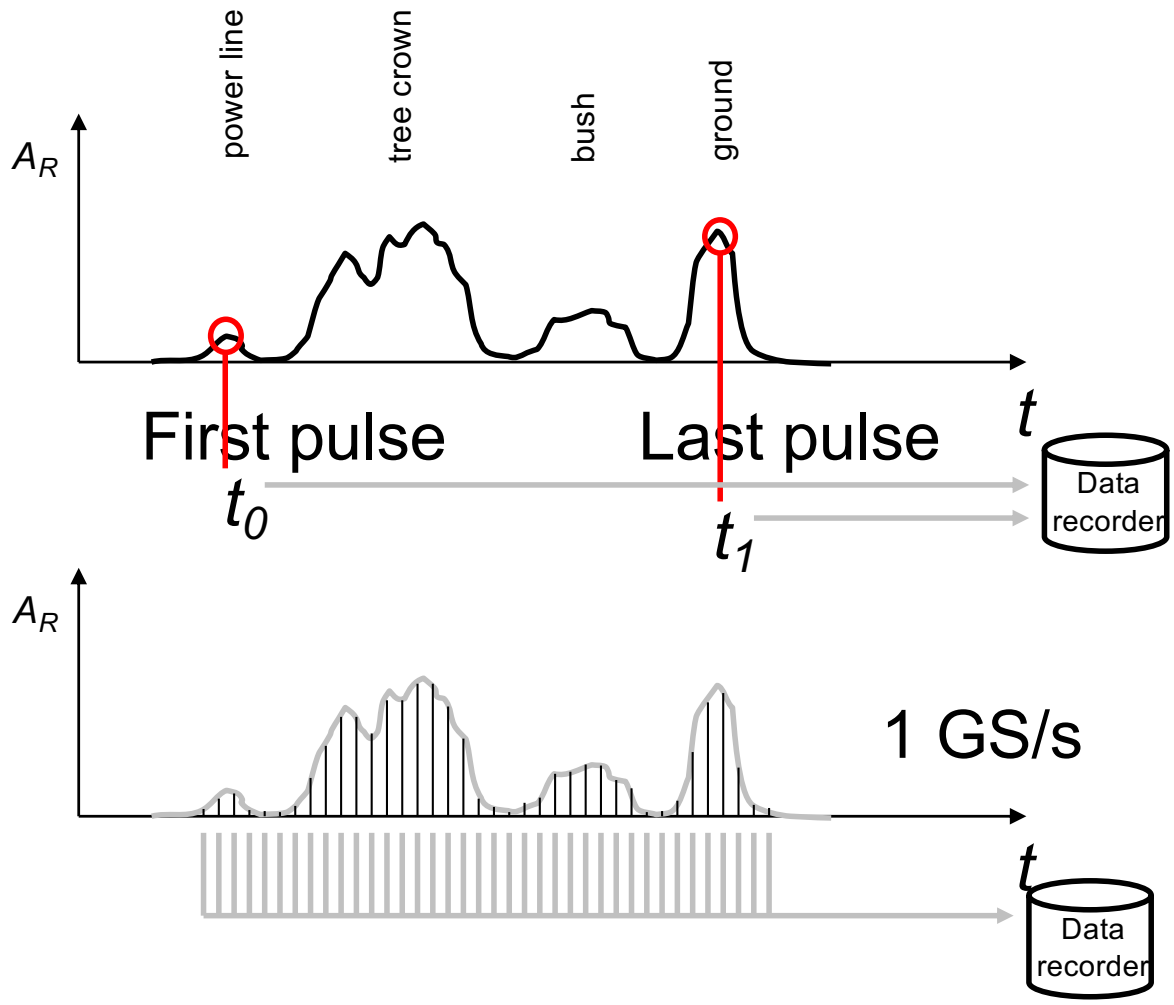
Ranging: full waveform analysis 测距：全波形分析





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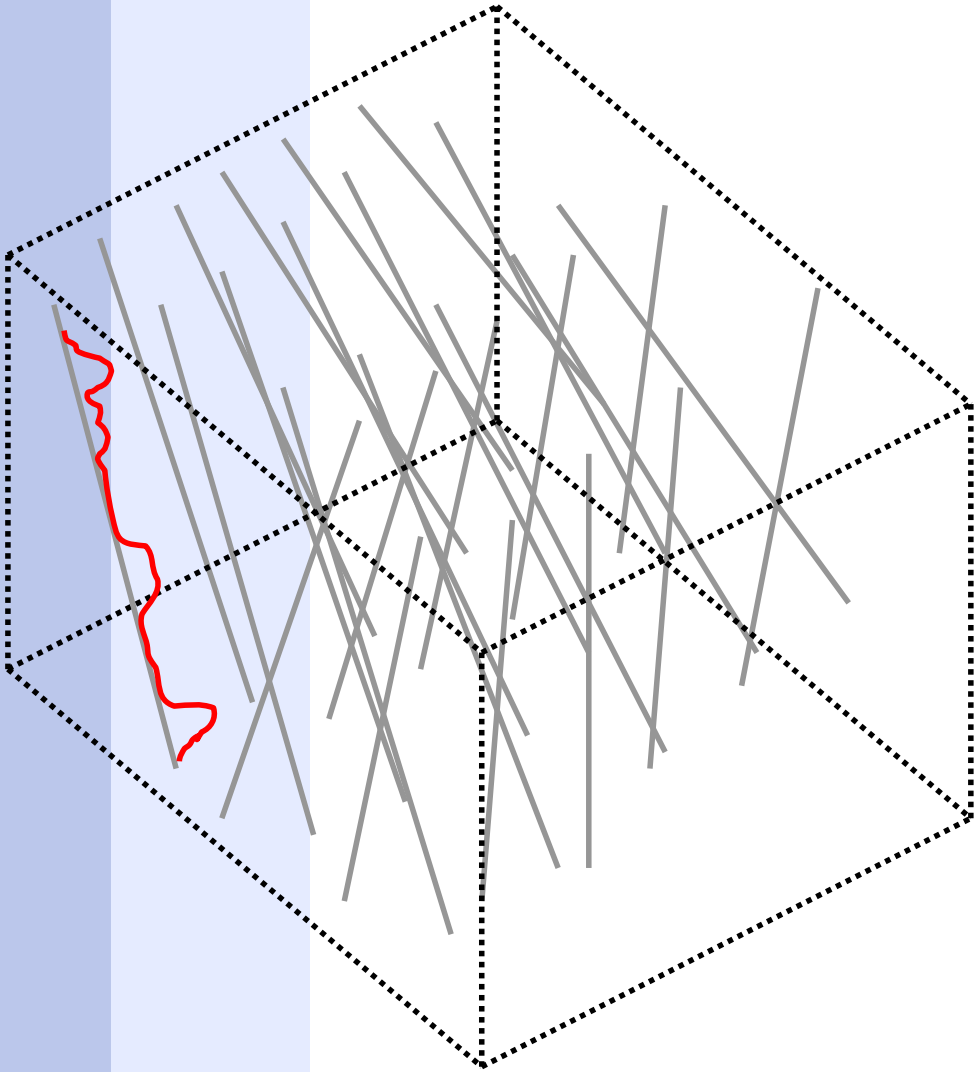
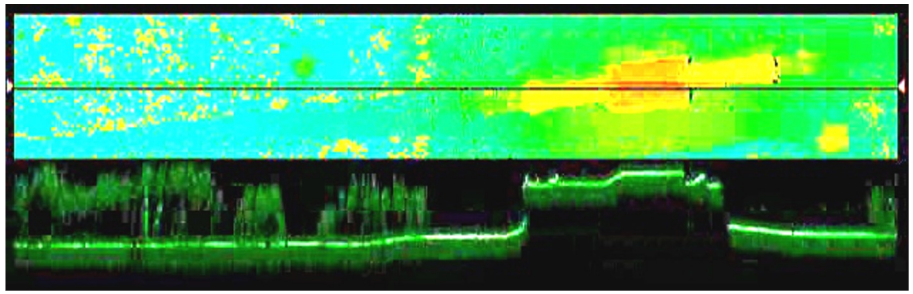
Ranging: full waveform analysis





Source: Riegl, 2006

© Claus Brenner

Terrestrial LiDAR

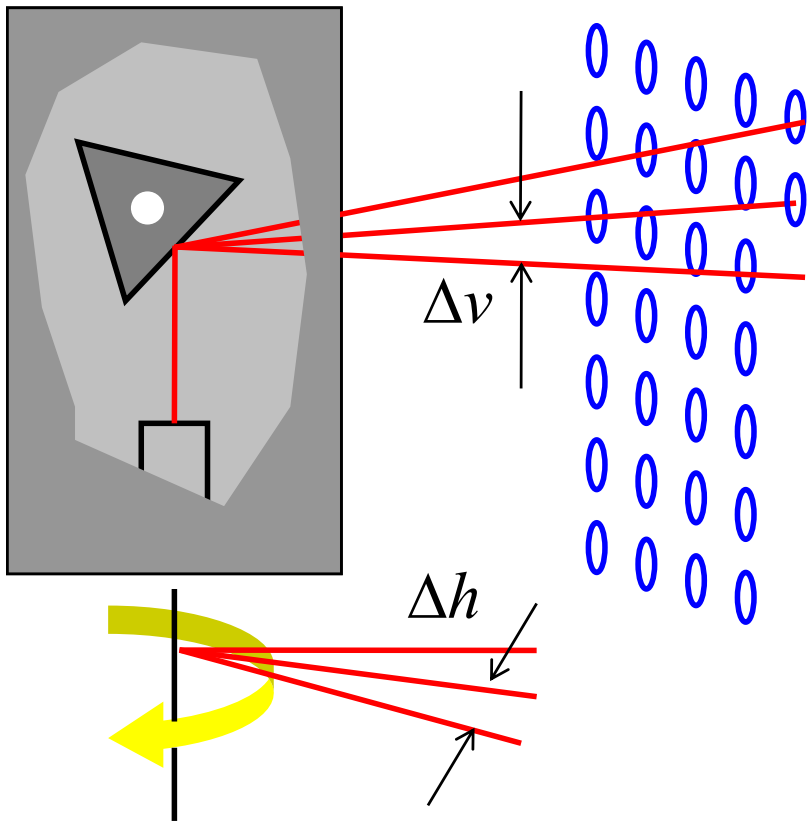
陆地

Regular scanning pattern of a terrestrial laser scanner

采样是以定期的角度增量进行的

- Sampling takes place in regular angular increments
- E.g. horizontal and vertical increments of 0.12°

水平和垂直增量



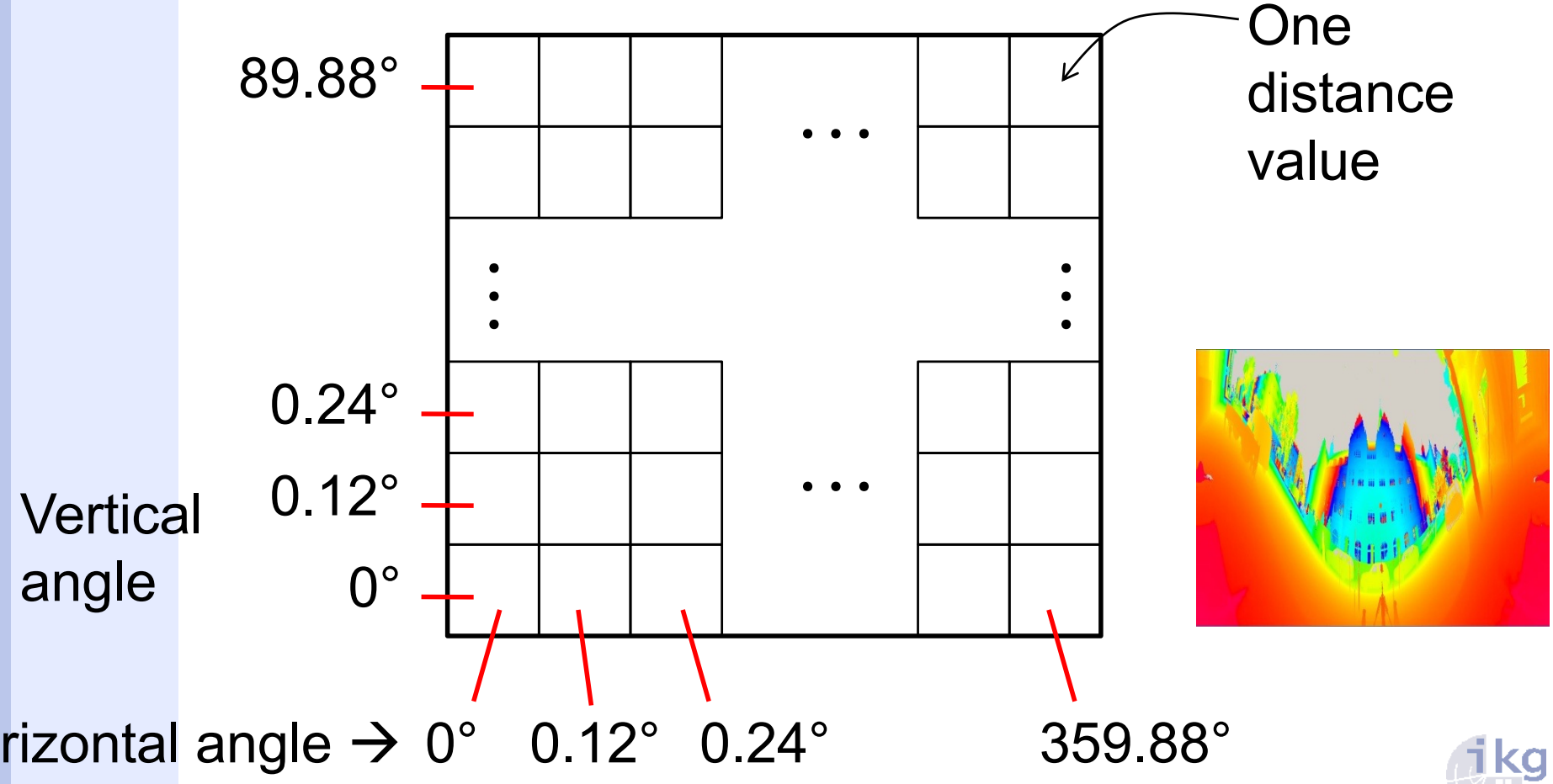
© Claus Brenner

One scan: Riegl LMS 360i

© Claus Brenner

Regular scanning pattern of a terrestrial laser scanner

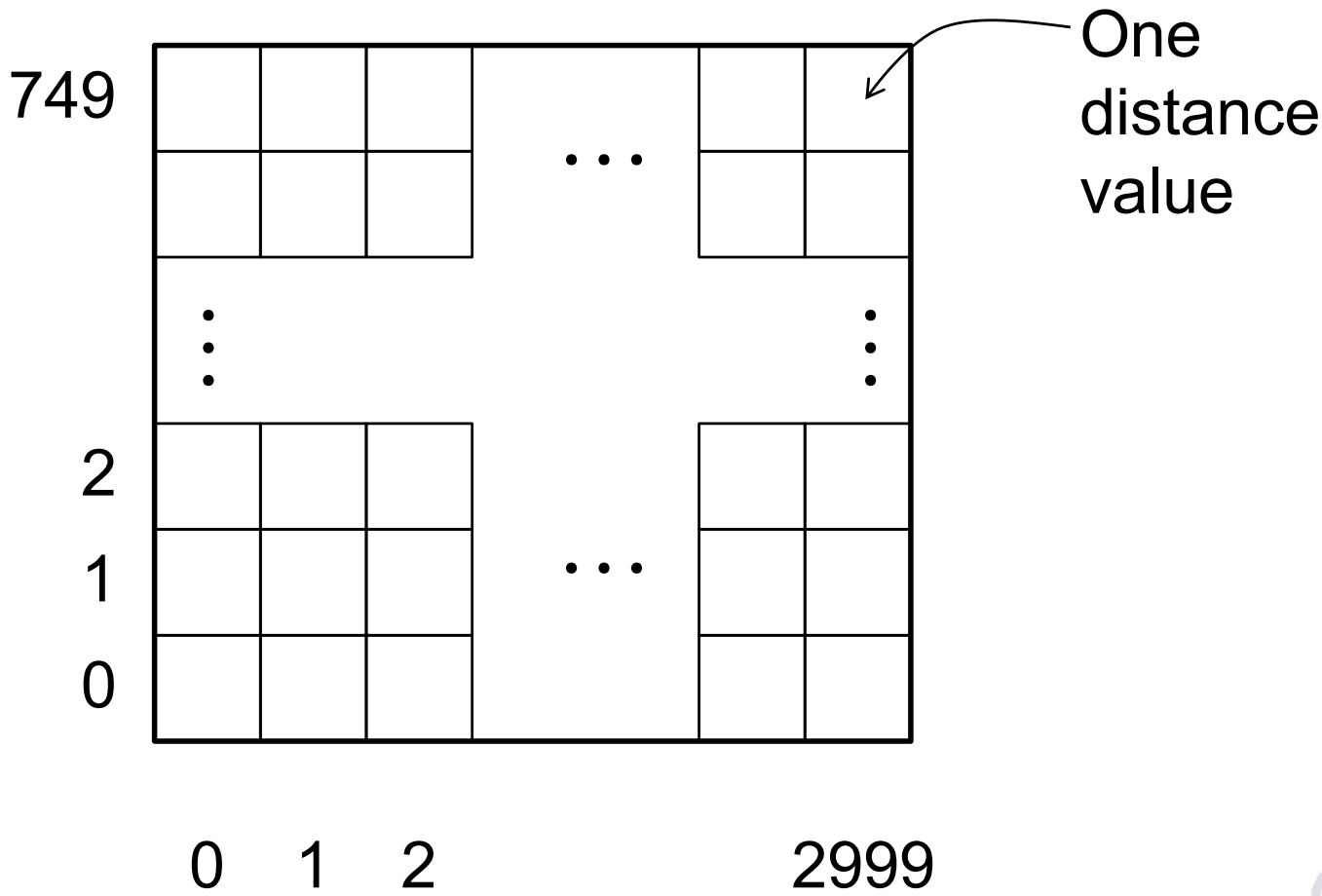
- Consequence: distance values are given in a regular raster
- Raster is given in regular angular spacing, e.g. 0.12°



© Claus Brenner

Regular scanning pattern of a terrestrial laser scanner

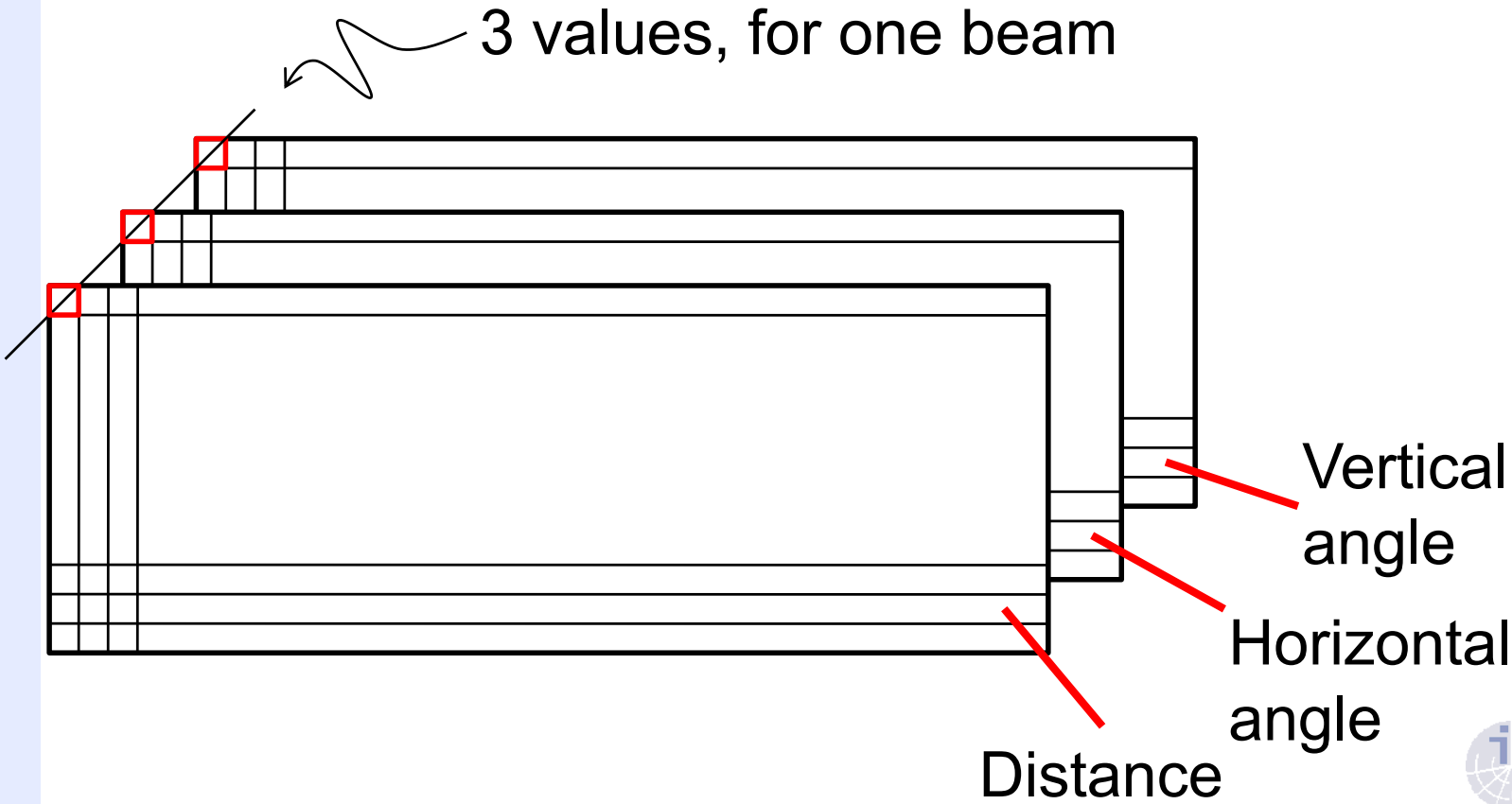
- The matrix of distance values may be seen as an image
- This is termed „distance image“, or „depth image“



© Claus Brenner

Real data delivered by the scanner 扫描仪提供的真实数据

- In addition to the distance image, the scanner also provides a horizontal and vertical angle image
- Reason: due to mechanical limitations, the scanner does not „hit“ the correct angles. It measures the angles instead.



© Claus Brenner

Conversion from polar to Cartesian coordinates

- Conversion of horizontal (h), vertical (v) angle and distance (d) to Cartesian coordinates

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = d \cdot \begin{pmatrix} \cos h \cdot \cos v \\ \sin h \cdot \cos v \\ \sin v \end{pmatrix}$$

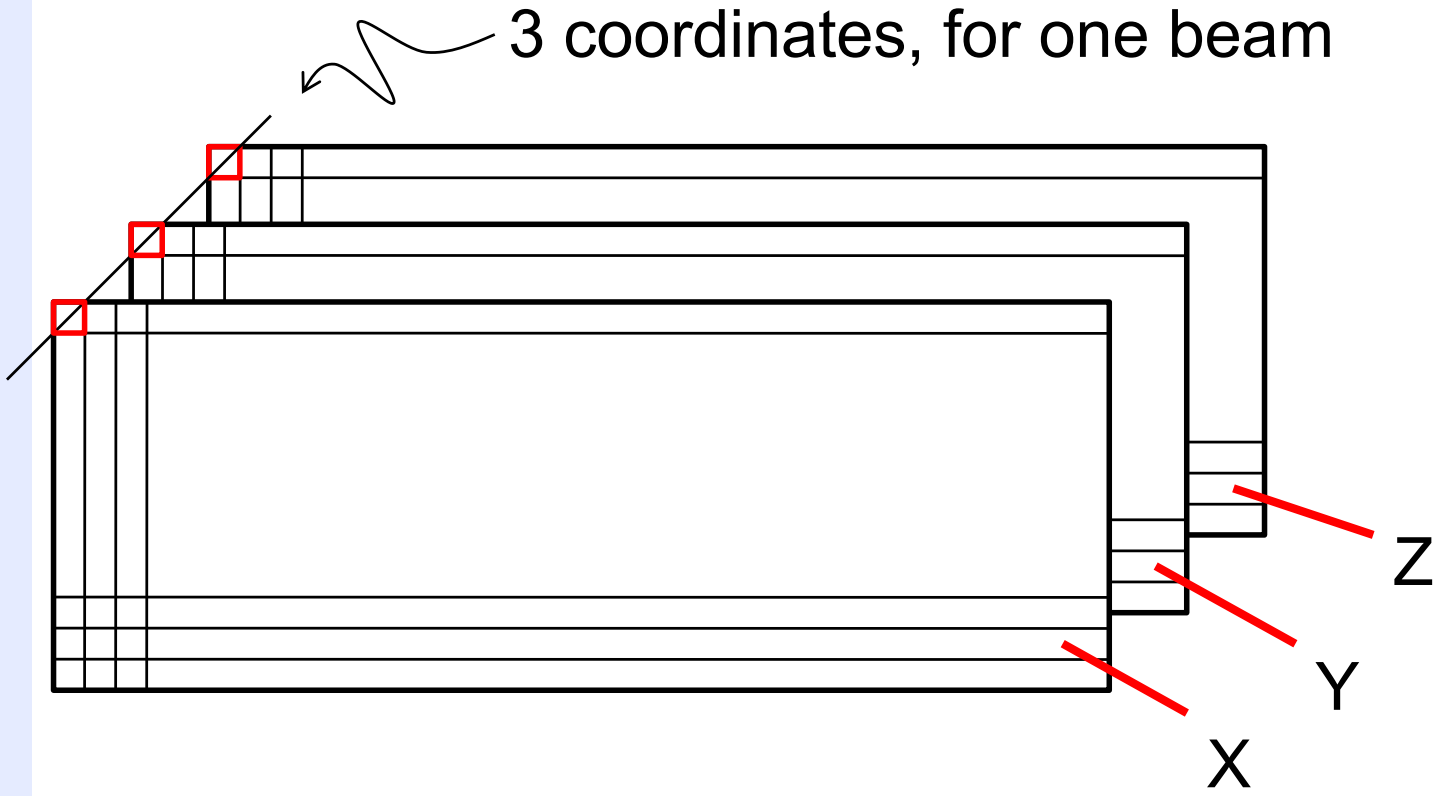
- In reality, corrections have to be applied, for example, since the axes of the scanner are not exactly perpendicular. Those 垂直 calibration parameters are determined by a factory calibration.

© Claus Brenner

Raster of values, as output by the software

- Therefore, the software usually outputs X Y Z images instead of polar measurements
- Any corrections are applied before by the software
- The corrections are typically not accessible by the user

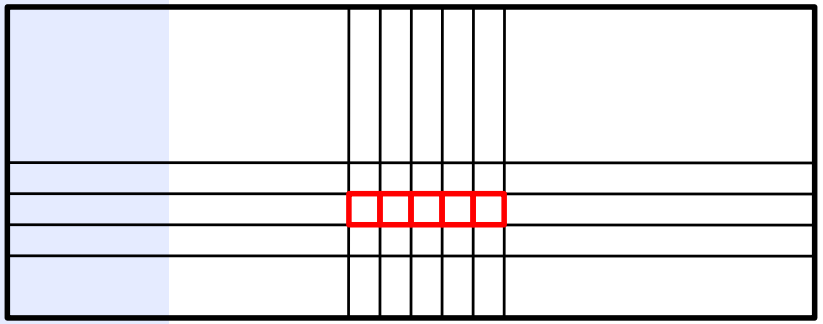
用户通常无法访问这些更正。

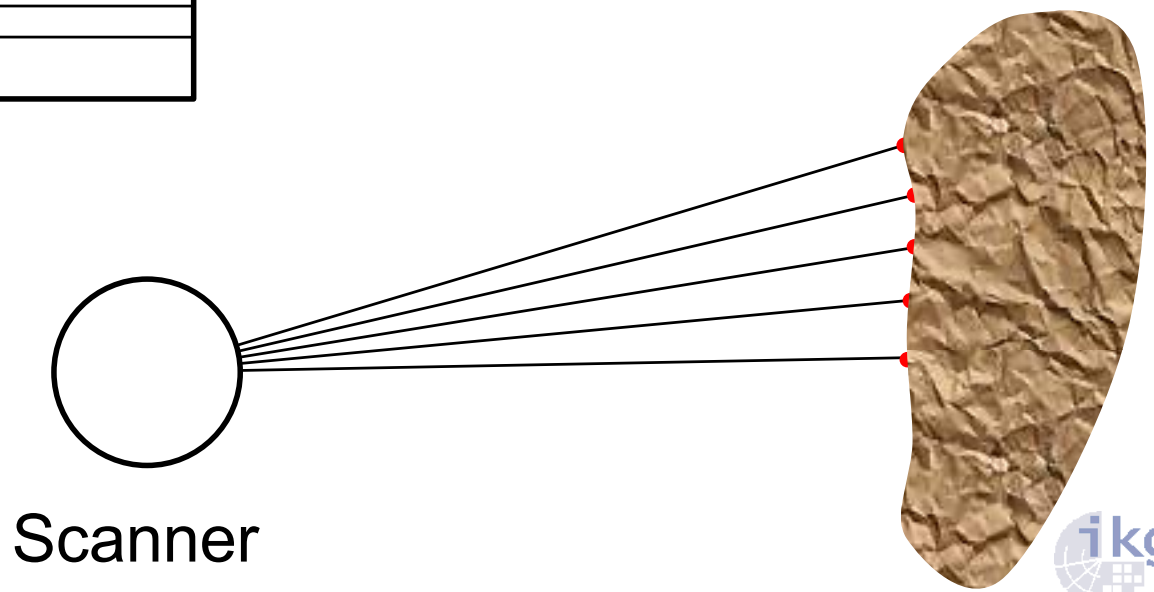


© Claus Brenner

Neighborhood defined by the raster

- „Pixels“ which are neighbors in the scan raster are neighbors in the sense of similar horizontal and vertical angles
- Often, the corresponding points in space are also „neighbors“ (close to each other)



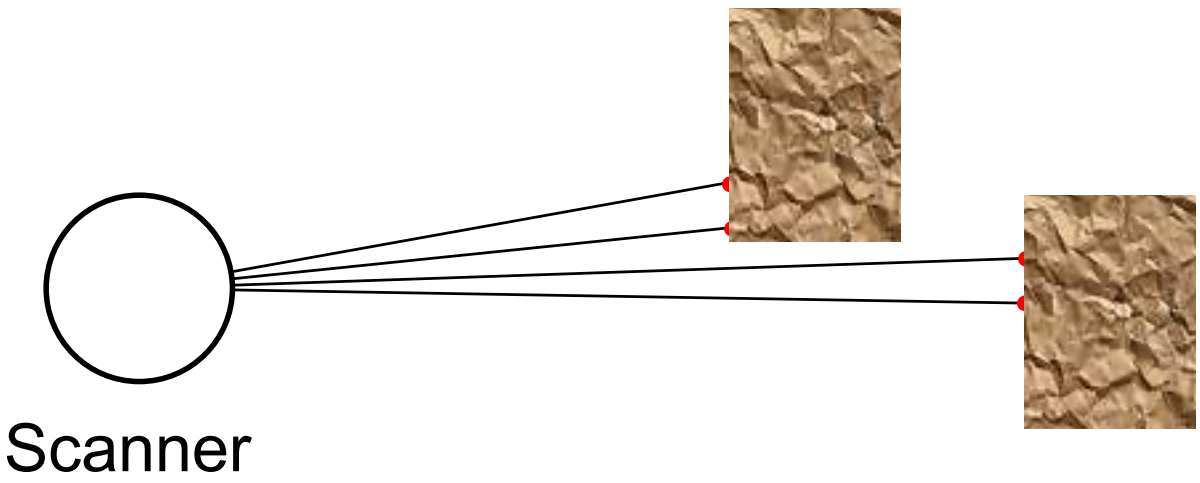


© Claus Brenner

Neighborhood defined by the raster

- However, subsequent beams may also hit different objects
- Nevertheless, this insight allows to devise processing algorithms, e.g. for segmentation, which work on the distance image instead of using the unstructured 3D point cloud

然而，这种洞察力允许设计处理算法，例如用于分割的算法，这些
算法在距离图像上工作，而不是使用非结构化的三维点云。
图像，而不是使用非结构化的三维点云。



© Claus Brenner

Coloring of point clouds

- In most cases, an external camera (attached to, but independent of the laser scanner) is used to acquire color 获得颜色
- This is called a „hybrid scanner system“
- Reason: if the color were to be measured synchronously with the beam, then the exposure time would be too short. E.g. for a scanner with 1.000.000 points per second, it would be only one microsecond

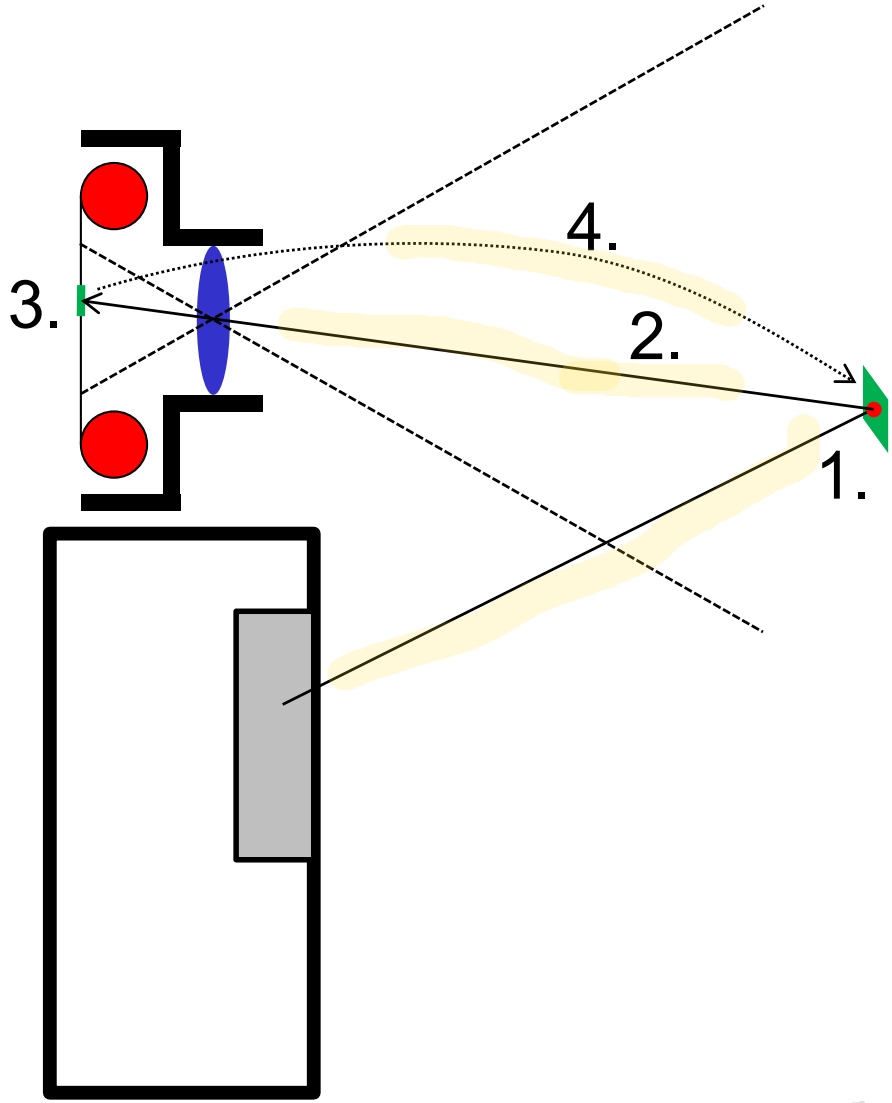
曝光时间

- The assignment of colors to the 3D points uses the known relative orientation between scanner and camera

© Claus Brenner

Coloring of point clouds

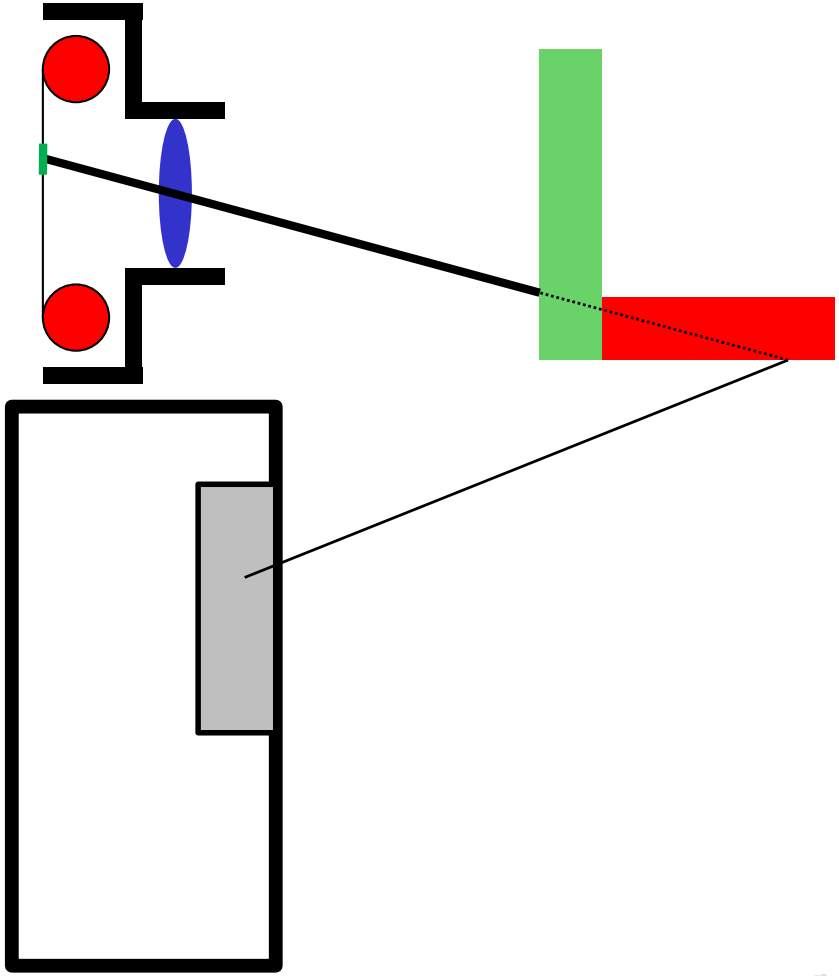
- 1. 3D coordinates of the scan point are known
- 2. Known orientation is used to project the point to the camera image
- 3. The color of the pixel is interpolated in the image
- 4. The determined color is assigned to the 3D point



© Claus Brenner

Coloring of point clouds

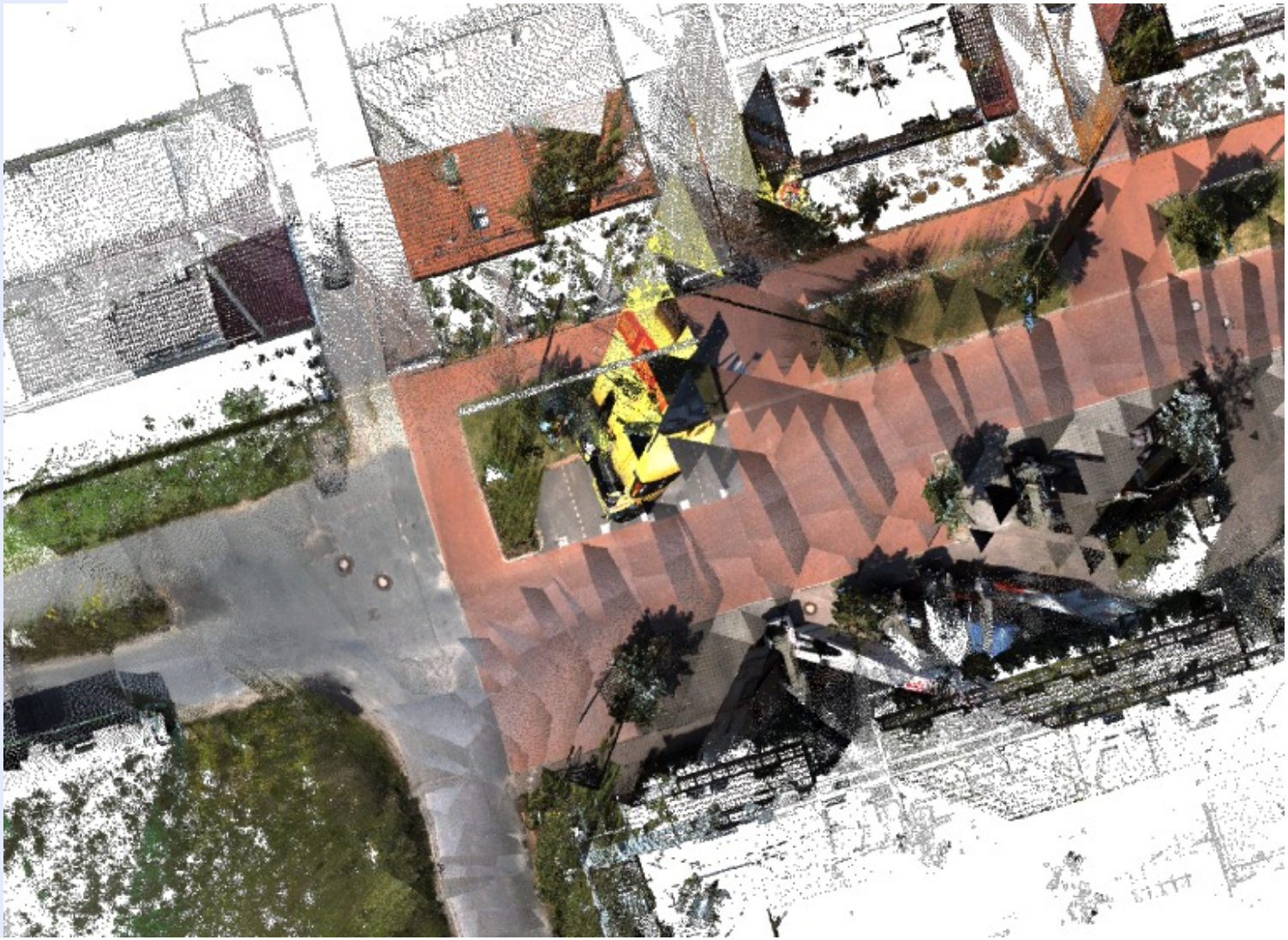
- Since the optical centers of scanner and camera don‘t coincide, errors occur regularly
- Especially for objects that are close
- In this example:
  - The scanner measures the red surface, which is not visible to the camera
  - The procedure from the previous slide assigns erroneously a green color to the red point.



© Claus Brenner

Coloring of point clouds

- Even worse with mobile mapping scans (since optical centers are far apart)



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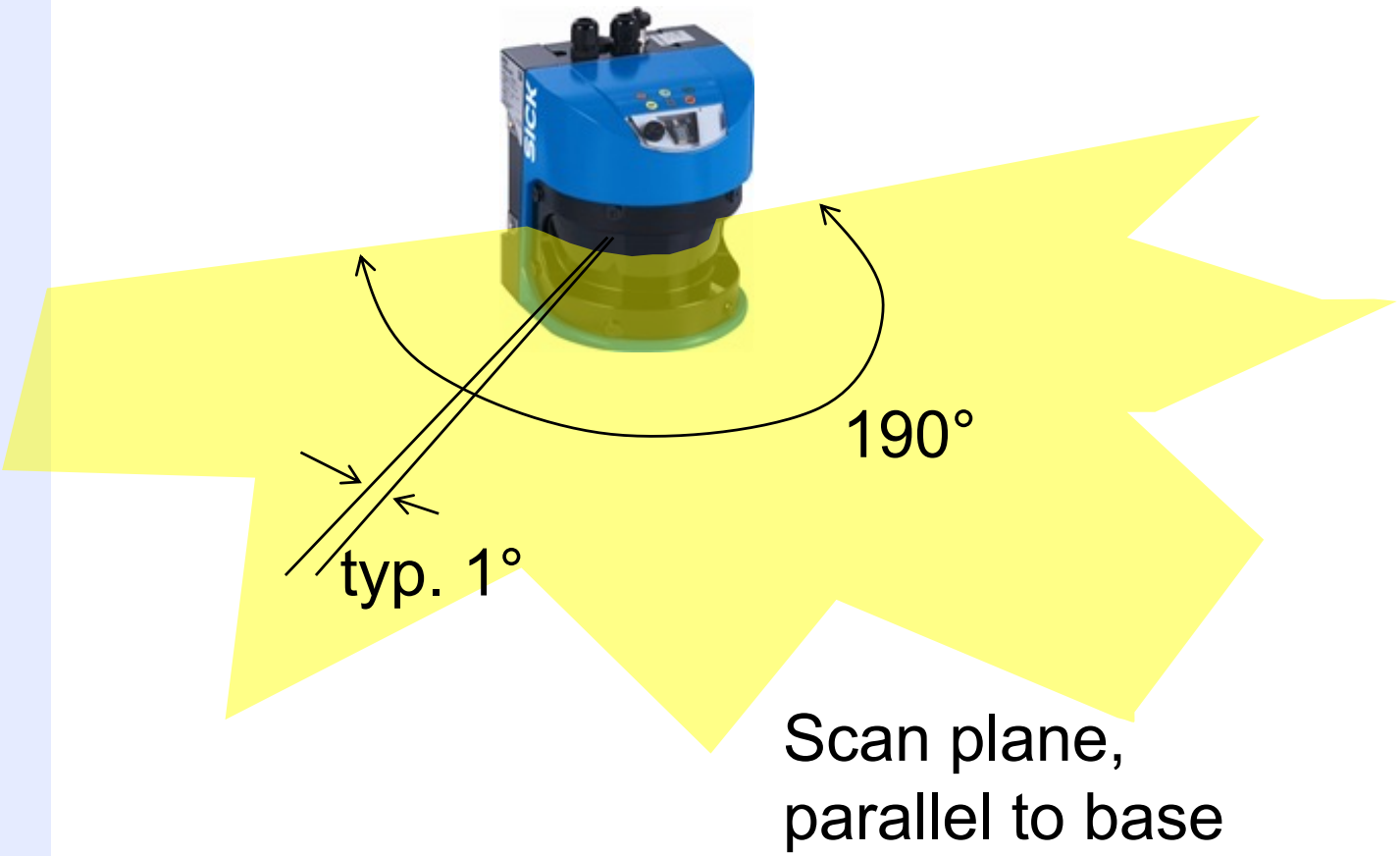
Other laser scanners

Sick Scanner (Sick AG, Waldkirch (Black Forest))

病态扫描器

Example: LMS500

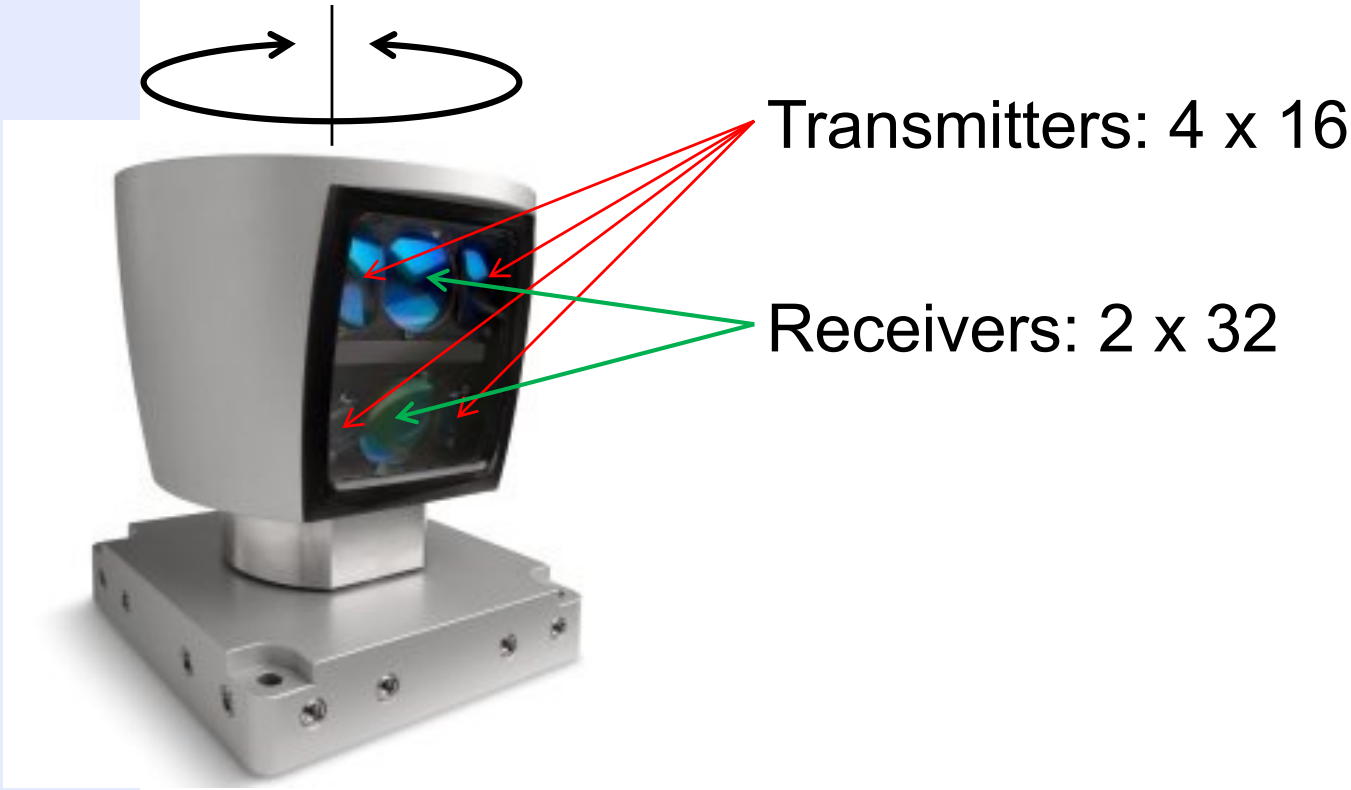


Sick Scanner (Sick AG, Waldkirch (Black Forest))

- Example: LMS500 (Pro)
- Range up to 80 m
- 190°, angle increments 1°, 0.667°, 0.5°, 0.333°, 0.25°, 0.167°
- 25, 35, 50, 75, 100 scans / second
- Measurement accuracy:
  - Systematic error 25 mm (1-10m), 35 mm (10-20m)
  - “Statistical error” (data sheet) 7 mm (1-10m), 9 mm (10-20m)
- Beam divergence: 4.7 mrad (~ 40 cm diameter at 80 m distance)

Velodyne HDL-64E (64 beams in parallel)

Entire head rotates, 5-20 revolutions/ second



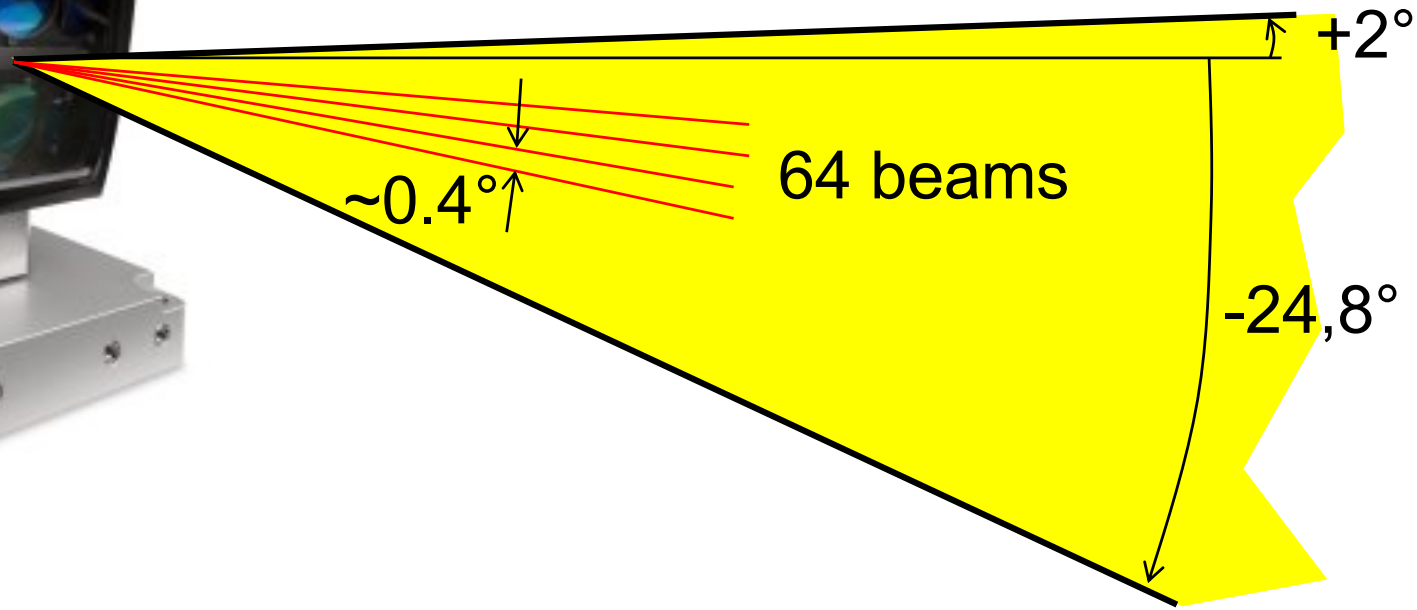
© Claus Brenner

(image source: velodynelidar.com)

Velodyne HDL-64E (64 beams in parallel)

64束扫描平面平行于旋转轴64束扫描平面平行于旋转轴

64 beam scan plane parallel to rotation axis



© Claus Brenner

(image source: velodynelidar.com)

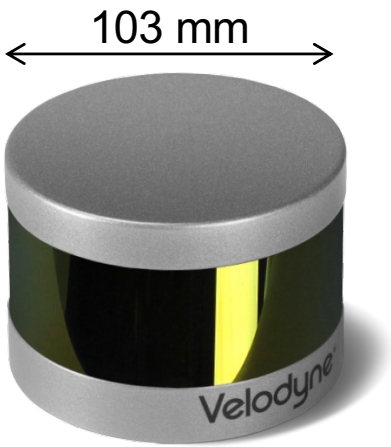
Velodyne HDL-64E S3 (64 beams in parallel)

- 360° horizontal, 26,8° vertical
- 0.08° horizontal, 0.4° vertical resolution
- Entire head rotates, 5-20 revolutions/s
- 5 cm accuracy (manufacturer specification)
- ~50 m range for road surface
- ~120 m range for cars and foliage
- **2.2 million scanned points per second**

- **Other models:**

HDL-32E

Puck (VLP-16),
Puck LITE,
Puck Hi-Res



VLS-128

(image source: velodynelidar.com)

(up to ~9.6 M points per second)

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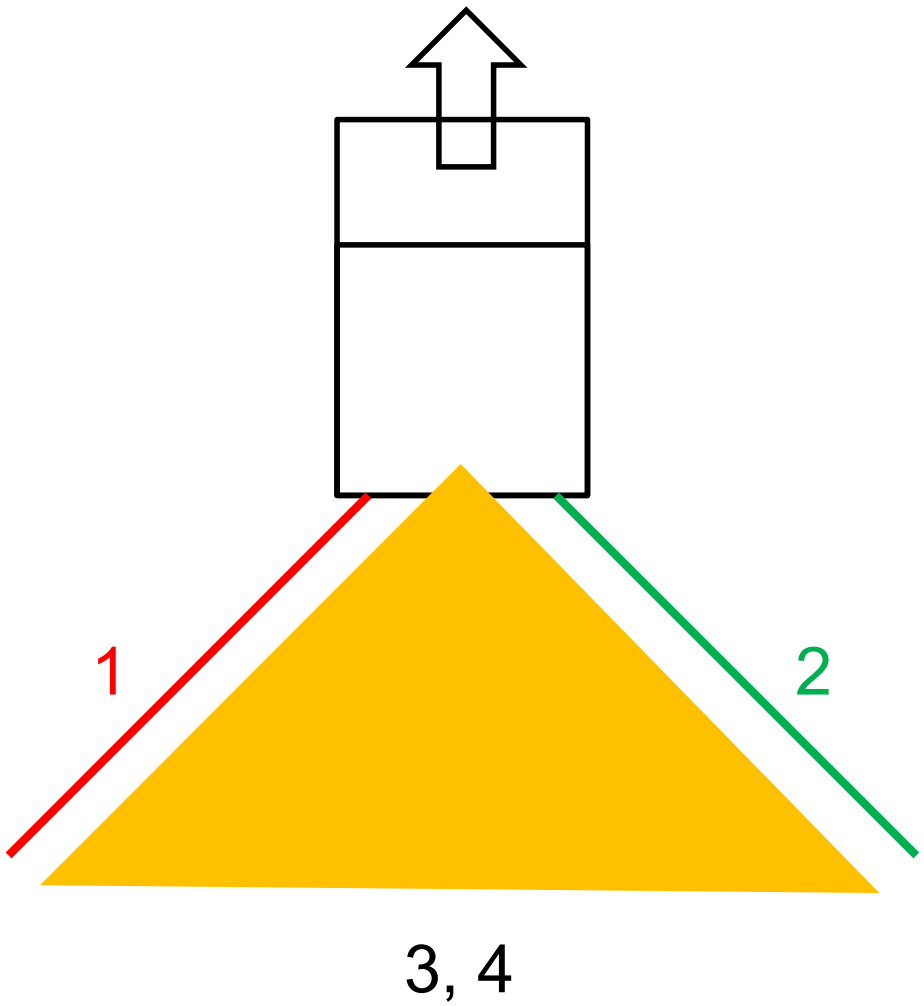
Mobile mapping geometries

Mobile Mapping: Streetmapper @ ikg, Hannover (2008)

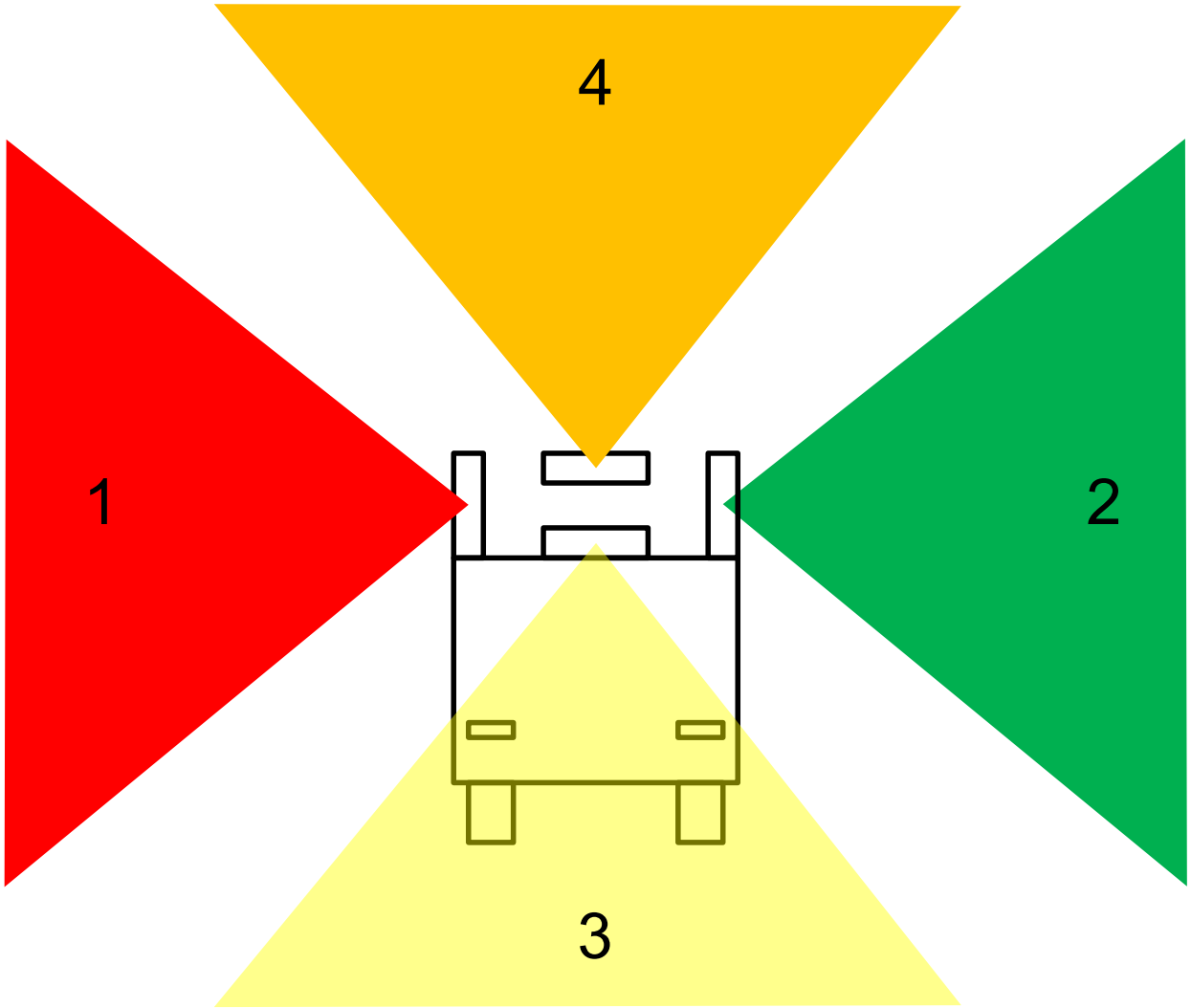
© Claus Brenner

Streetmapper: Scan geometry (seen from above)



© Claus Brenner

Streetmapper: Scan geometry (seen from behind)

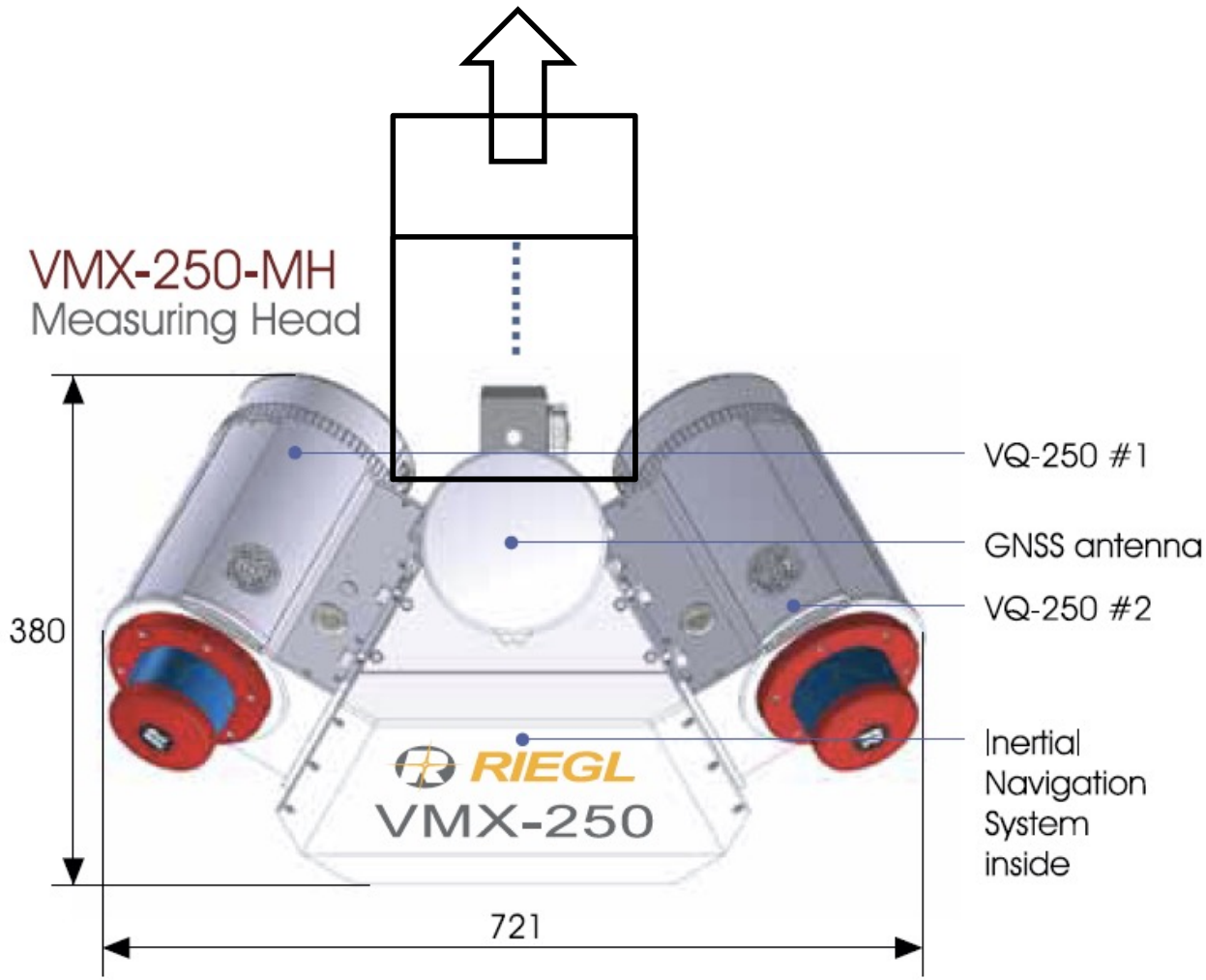


© Claus Brenner

Riegl VMX-250: Scan geometry

© Claus Brenner

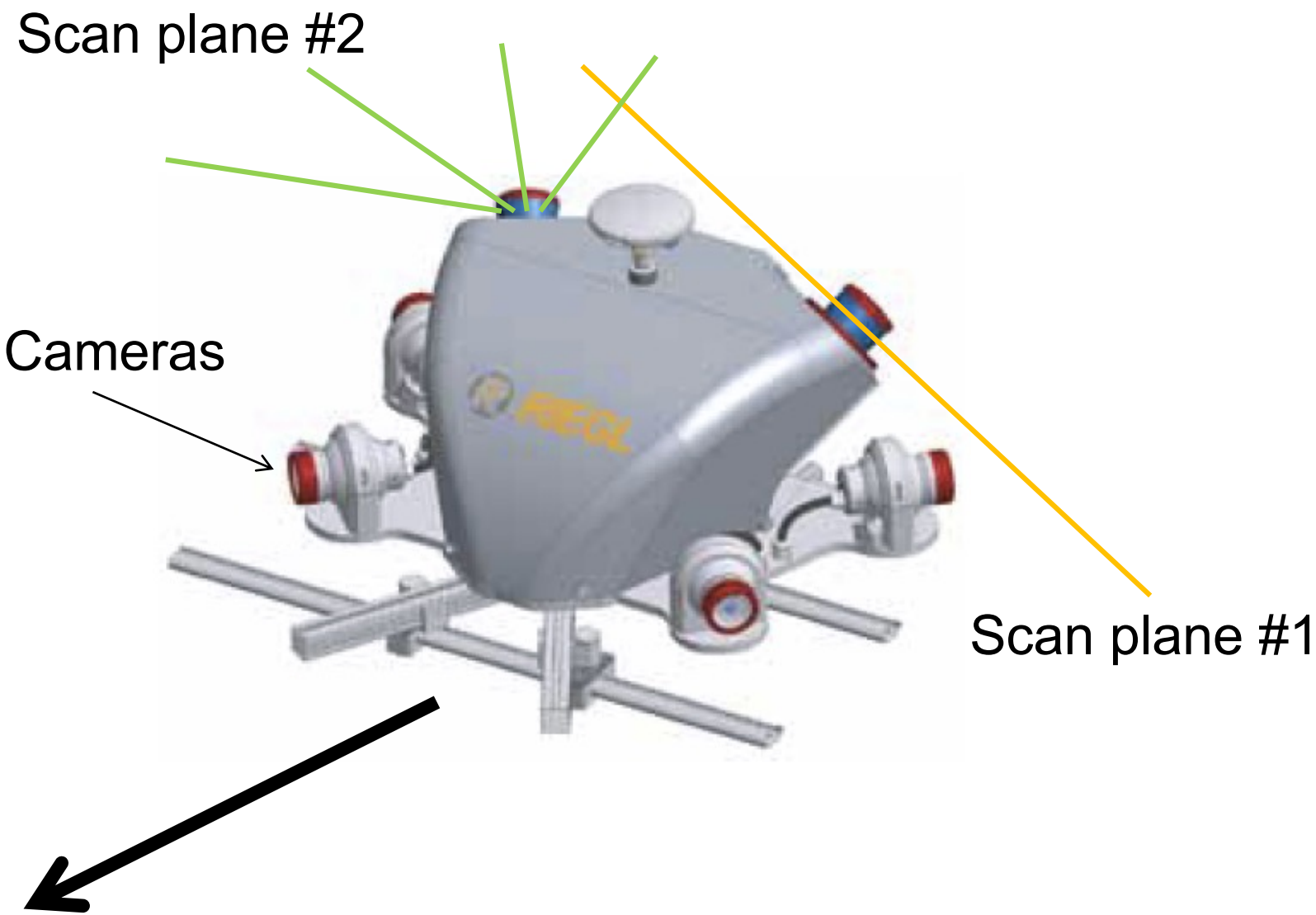
Riegl VMX-250: Scan geometry



Source: Riegl

© Claus Brenner

Riegl VMX-250: Scan geometry



© Claus Brenner

Source: Riegl

VMX-250 specifications

Technical Data Mobile Laser Scanning System *RIEGL* VMX®-250

Laser Product Classification	Class 1 Laser Product according to IEC60825-1:2007 The following clause applies for instruments delivered into the United States: Complies with 21 CFR 1040.10 and 1040.11 except for deviations pursuant to Laser Notice No. 50, dated June 24, 2007.

CLASS 1 LASER PRODUCT

2 x VQ-250 Measurement Performance

Effective Measurement Rate[1]	100 kHz	200 kHz	300 kHz	400 kHz	**600 kHz**
Max. Unambiguous Measuring Range [2]					
natural targets $\rho \geq 10\%$	180 m	130 m	110 m	100 m	**75 m**
natural targets $\rho \geq 80\%$	500 m	380 m	340 m	300 m	**200 m**
Max. Number of Targets per Pulse	practically unlimited (details on request)				

Minimum Range	1.5 m
Accuracy [3)5)]	10 mm
Precision [4)5)]	5 mm
Max. Effective Measurement Rate [1)]	600 000 meas./sec (2 x 300 000 meas./sec)
Line Scan Speed (selectable)	up to 200 lines/sec (2 x 100 lines/sec)

1) Rounded values, based on 2 *RIEGL* VQ-250 laser scanners.
2) The following conditions are assumed: target larger than the footprint of the laser beam, perpendicular angle of incidence, visibility 23 km, average ambient brightness.
3) Accuracy is the degree of conformity of a measured quantity to its actual (true) value.
4) Precision, also called reproducibility or repeatability, is the degree to which further measurements show the same result.
5) One sigma @ 150 m range under *RIEGL* test conditions.

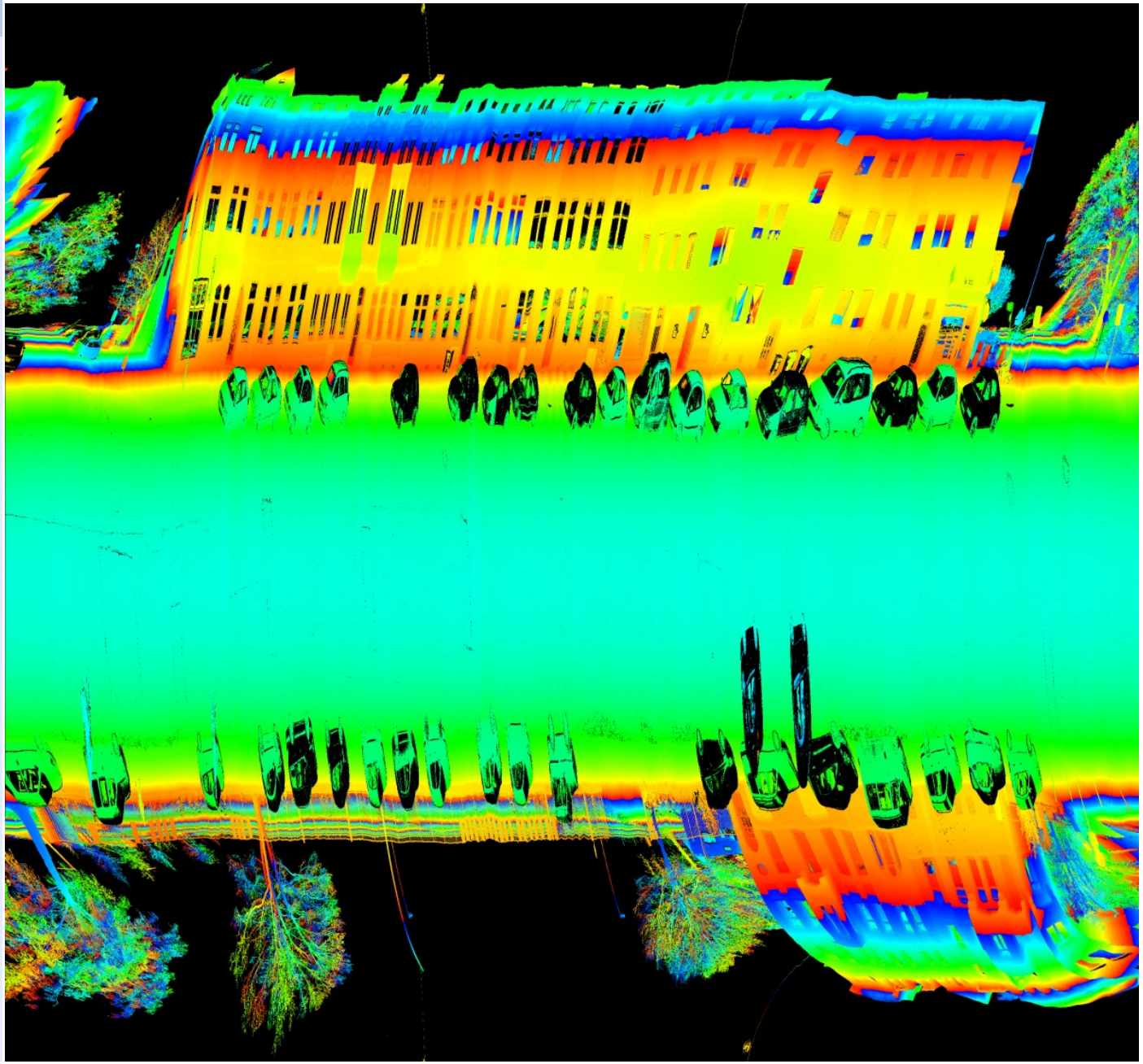
INS/GNSS Performance[6)]

Position (absolute)	typ. 20 - 50 mm
Position (relative)[7)]	typ. 10 mm
Roll & Pitch	0.005°
Heading	0.015°

6) One sigma values, no GNSS outages, with DMI option, post-processed.
7) With a control point spacing < 300 m.

(Quelle: www.riegl.co.at)

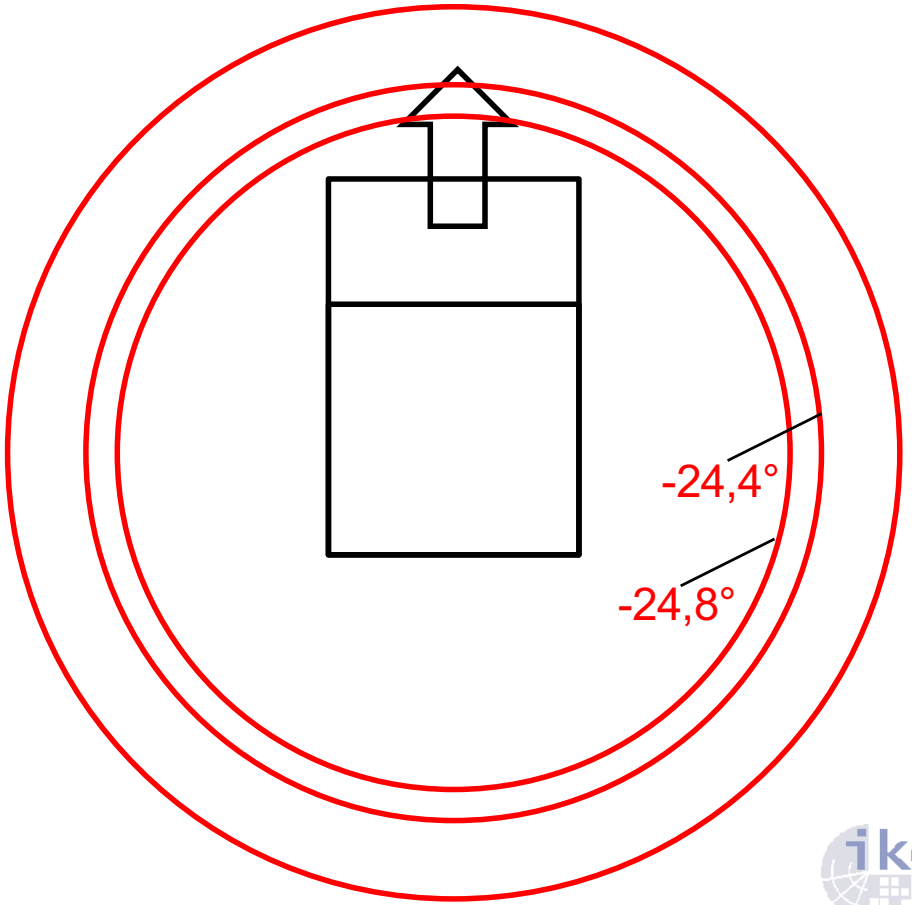
Scan strip (Hannover: Schneiderberg)



(c) Claus Brenner

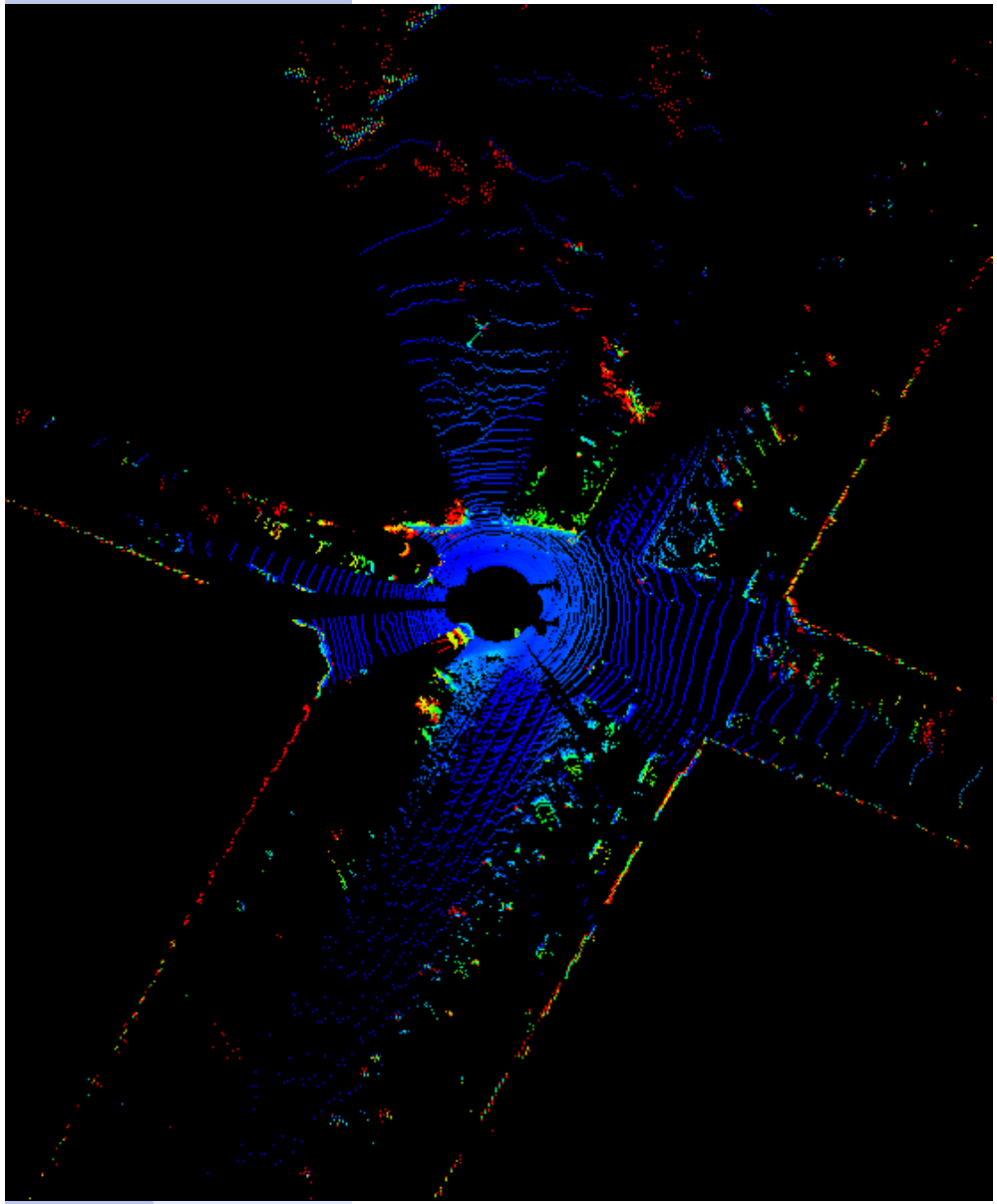
Typical mount of a Velodyne scanner

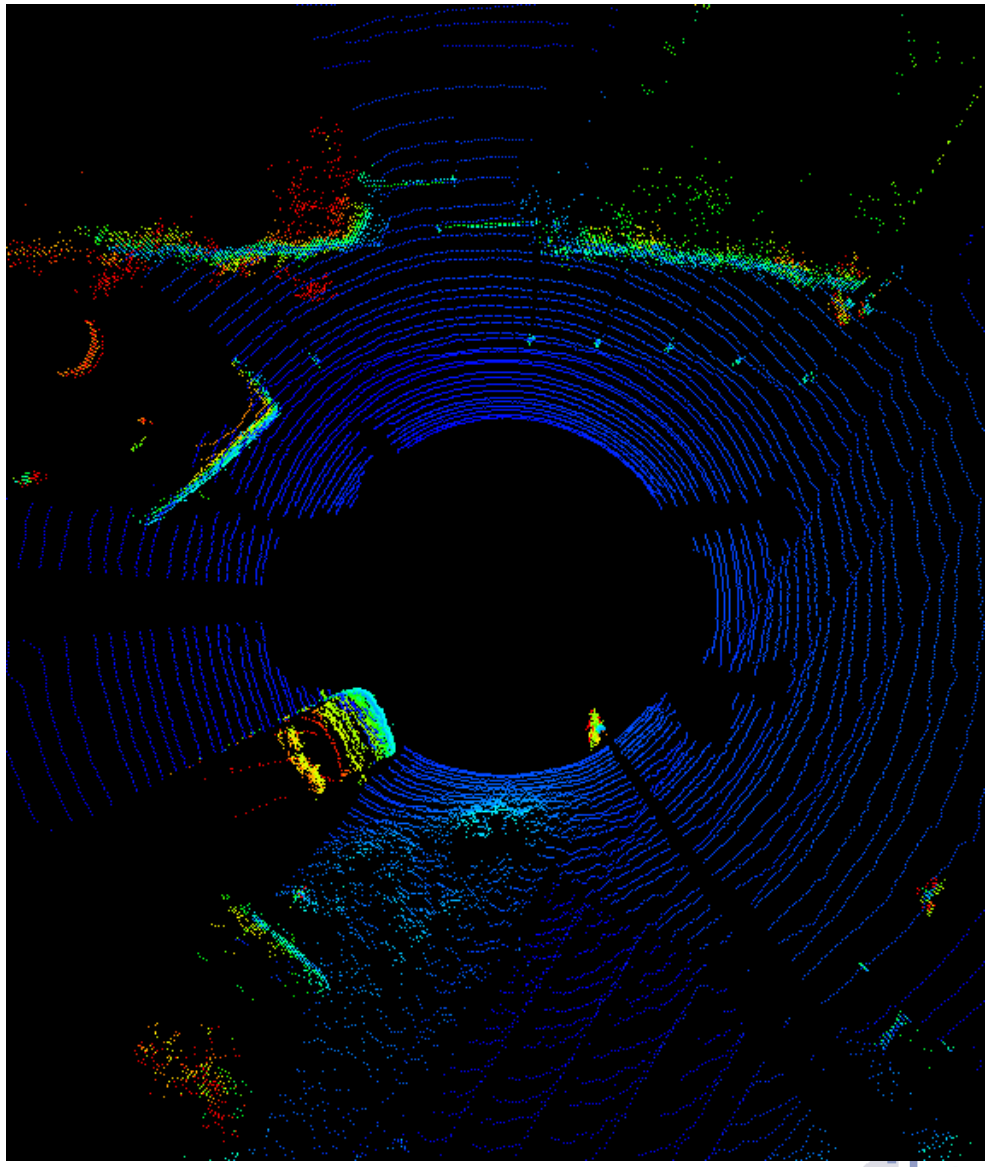
Source: KIT MRT



© Claus Brenner

Example scan Velodyne HDL-64E

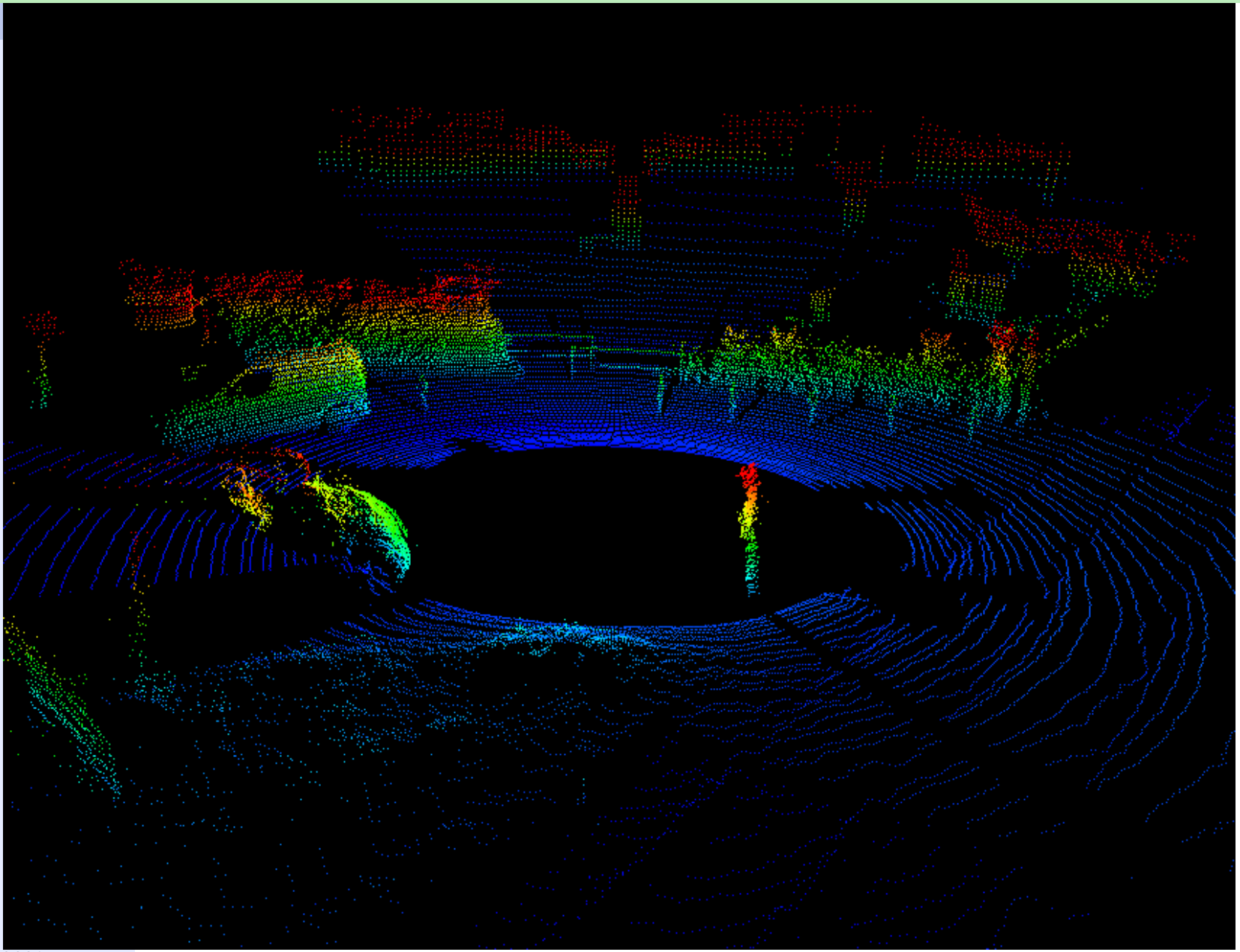




© Claus Brenner

Data courtesy Karlsruher Institut für Technologie (KIT), Institut für Mess- und Regelungstechnik

Example scan Velodyne HDL-64E

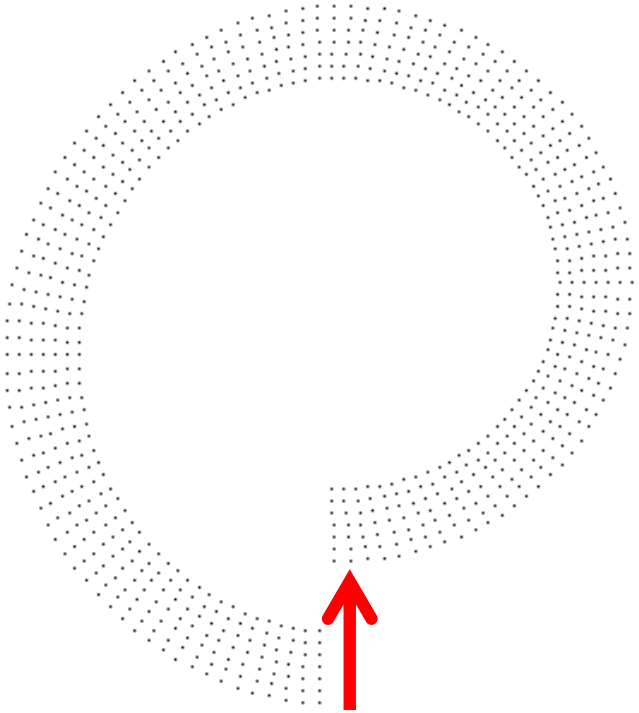


© Claus Brenner

Data courtesy Karlsruher Institut für Technologie (KIT), Institut für Mess- und Regelungstechnik

Typical mount of a Velodyne scanner

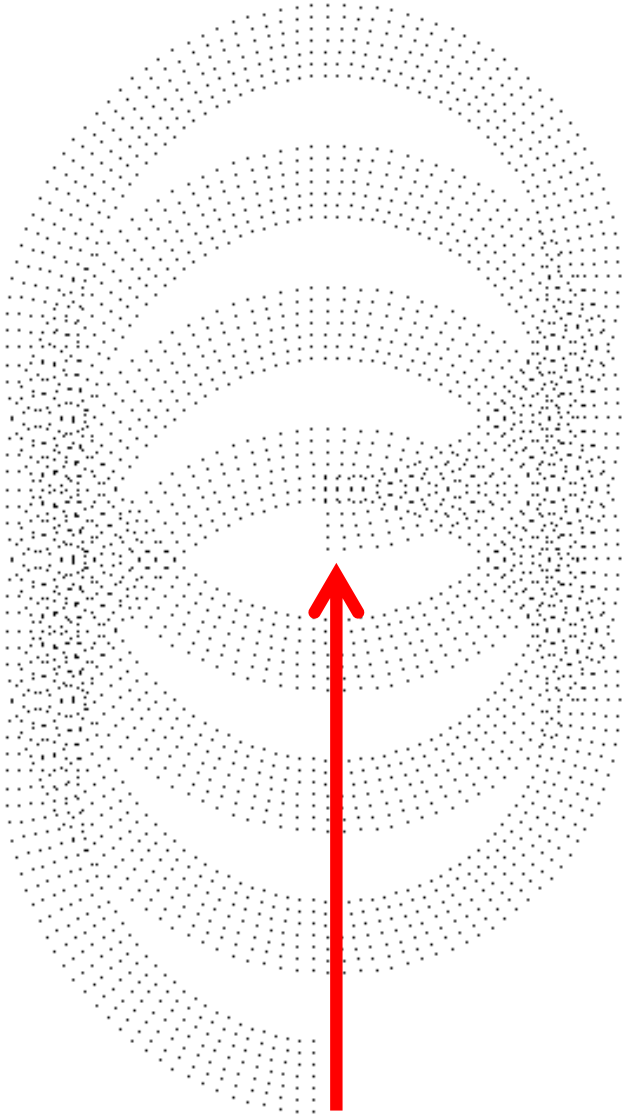
Source: KIT MRT



© Claus Brenner

Typical mount of a Velodyne scanner

Source: KIT MRT



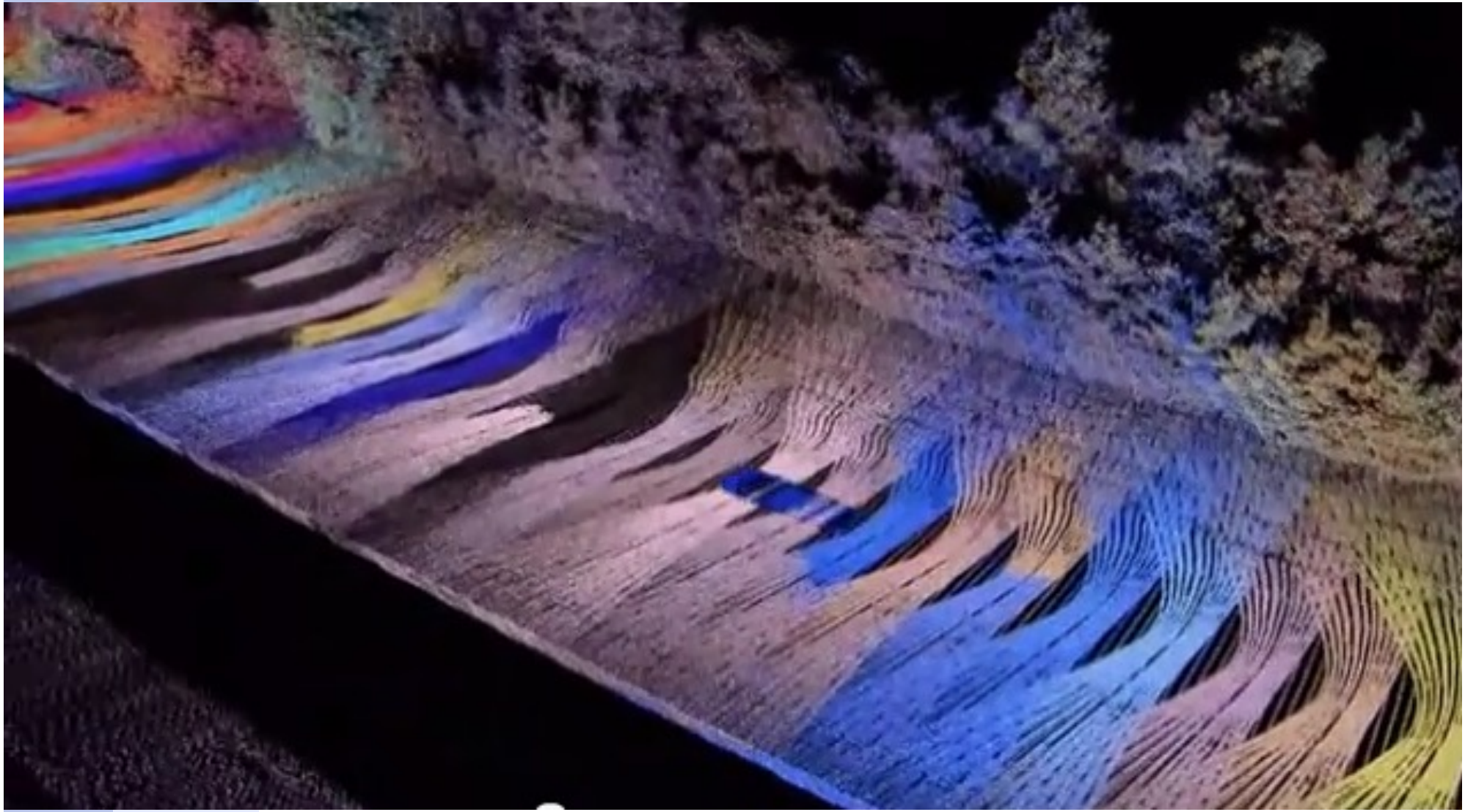
© Claus Brenner

Navteq „true“: tilted mount of a Velodyne scanner

© Claus Brenner

Source: Navteq

Scanpattern „Navteq true“

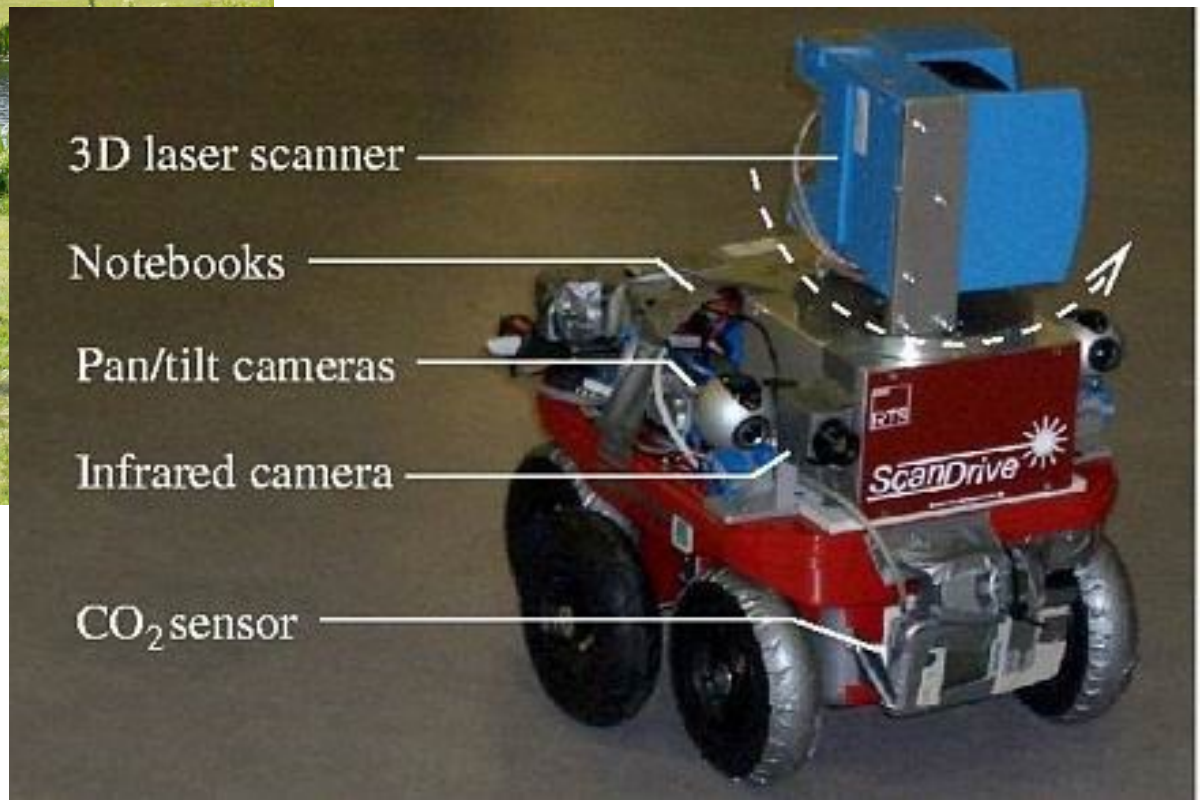


© Claus Brenner

Source: „**NAVTEQ True, Understanding the Collection Process**“

Nokia Here 3D Mapping

Sick scanners on turn tables, ISE RTS



Source: ISE RTS, Leibniz Universität Hannover

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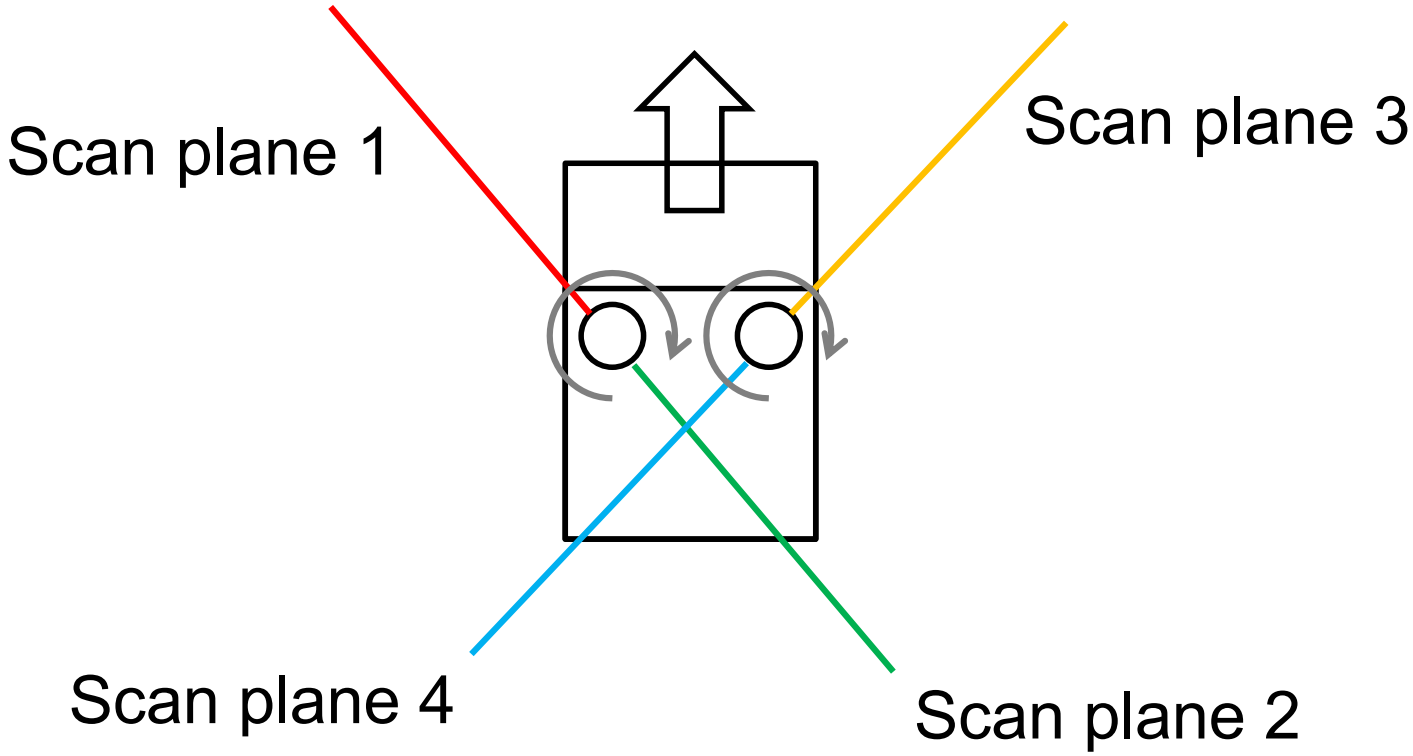
Sick scanners on turn tables, ISE RTS



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Robotics: often just one plane, parallel to ground

© Claus Brenner

http://www.faculty.jacobs-university.de/anuechter/robots.html

Google Street View: 3 scanners

© Claus Brenner

Street View Trike

Street View Trike

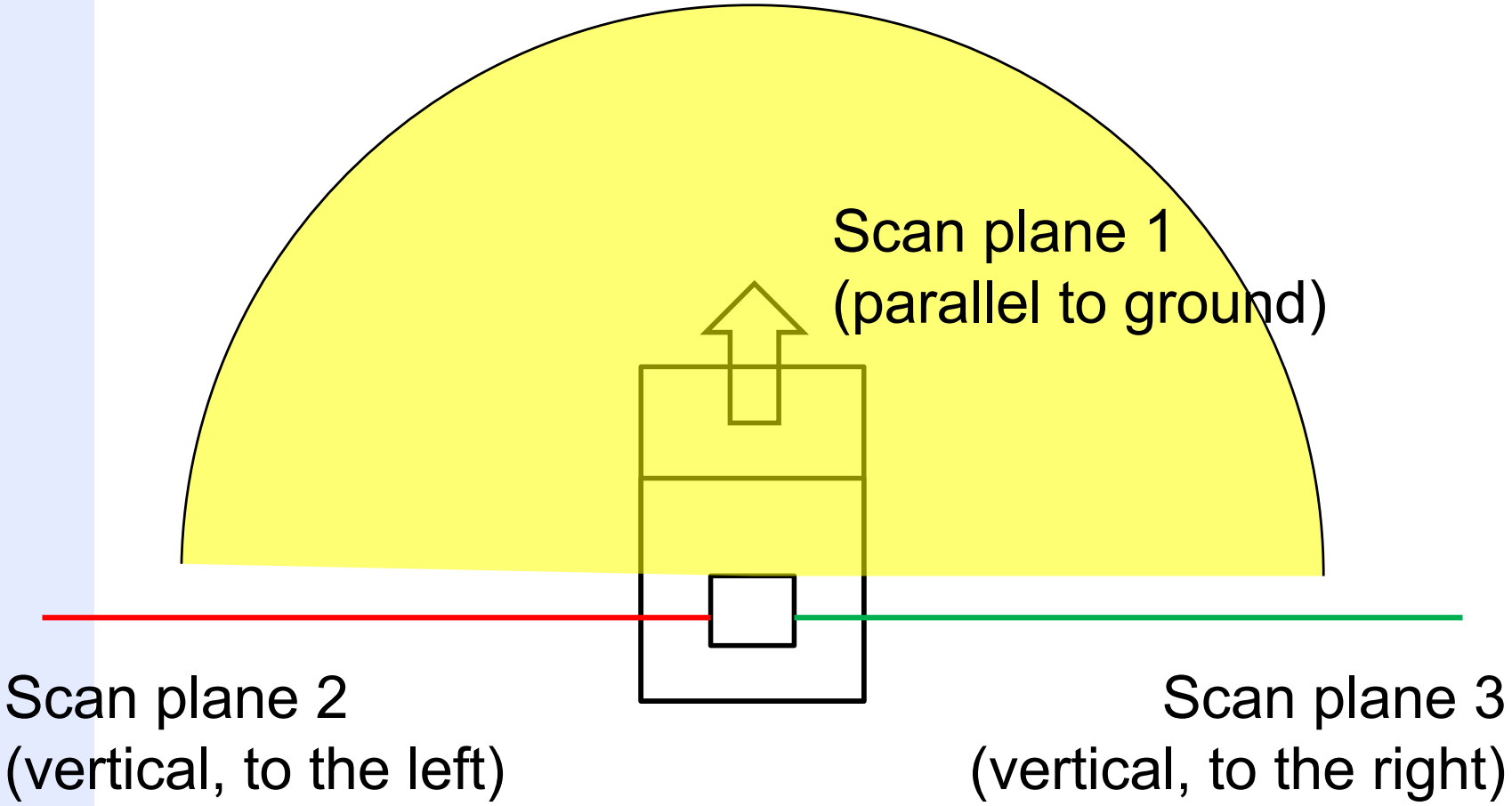
Street View Car, R7 camera (and 3 scanners)

Still in use 22.10.2018: „Hannover Refresh“

Shortened mast!

© Claus Brenner

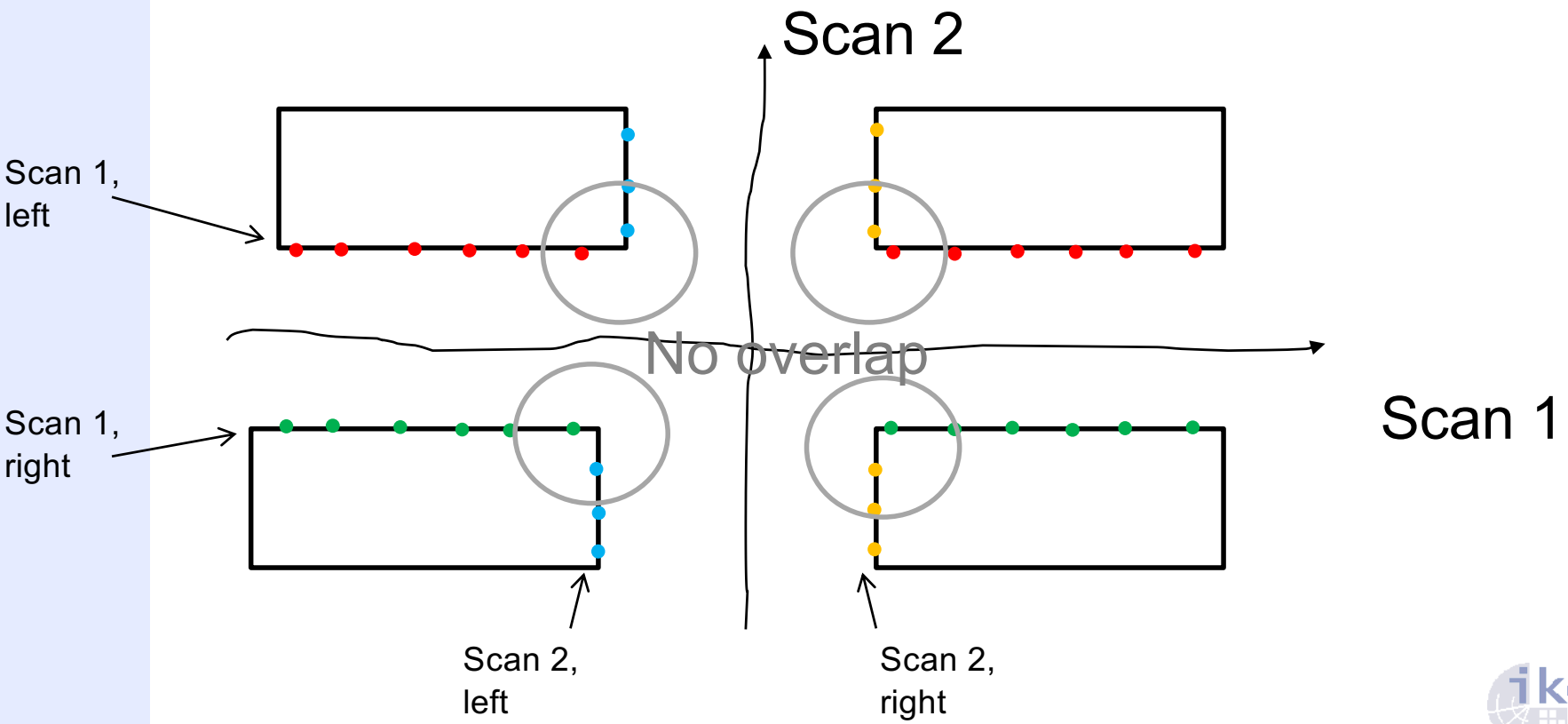
Google Street View (seen from above)



© Claus Brenner

Google Street View

- Horizontal scanner is useful for alignment of subsequent 后续扫描 scans (to determine the car's relative position)
- Upright vertical scans are useful for scanning the facades 外墙, but do not provide much overlay useful for alignment



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Typical tasks for laser data processing

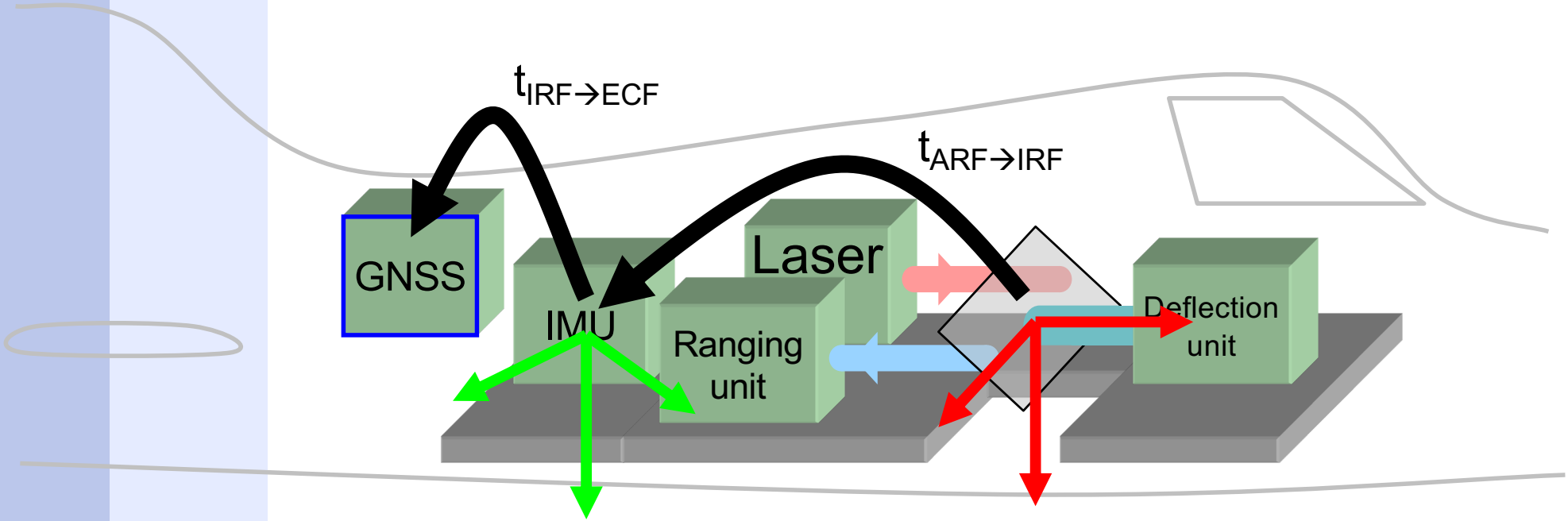
Typical tasks: Laserscanning

- „Low level“
  - Calibration (instrument), relative orientation (e.g. scanner, camera)
  - Analysis of „full waveform“ scan data
  - Orientation/ localization: determine transformation to a local or global coordinate system
- „Intermediate level“
  - Filtering, classification of points
  - Derivation of height models or triangulated surfaces
  - 提取特征 Extraction of features (planes, cylinders and other simple shapes)
- „High level“
  - Find complex (meaningful) objects
  - Understand object structures (buildings, facades)
  - Understand scenes

© Claus Brenner

„Low level“

Calibration / relative orientation



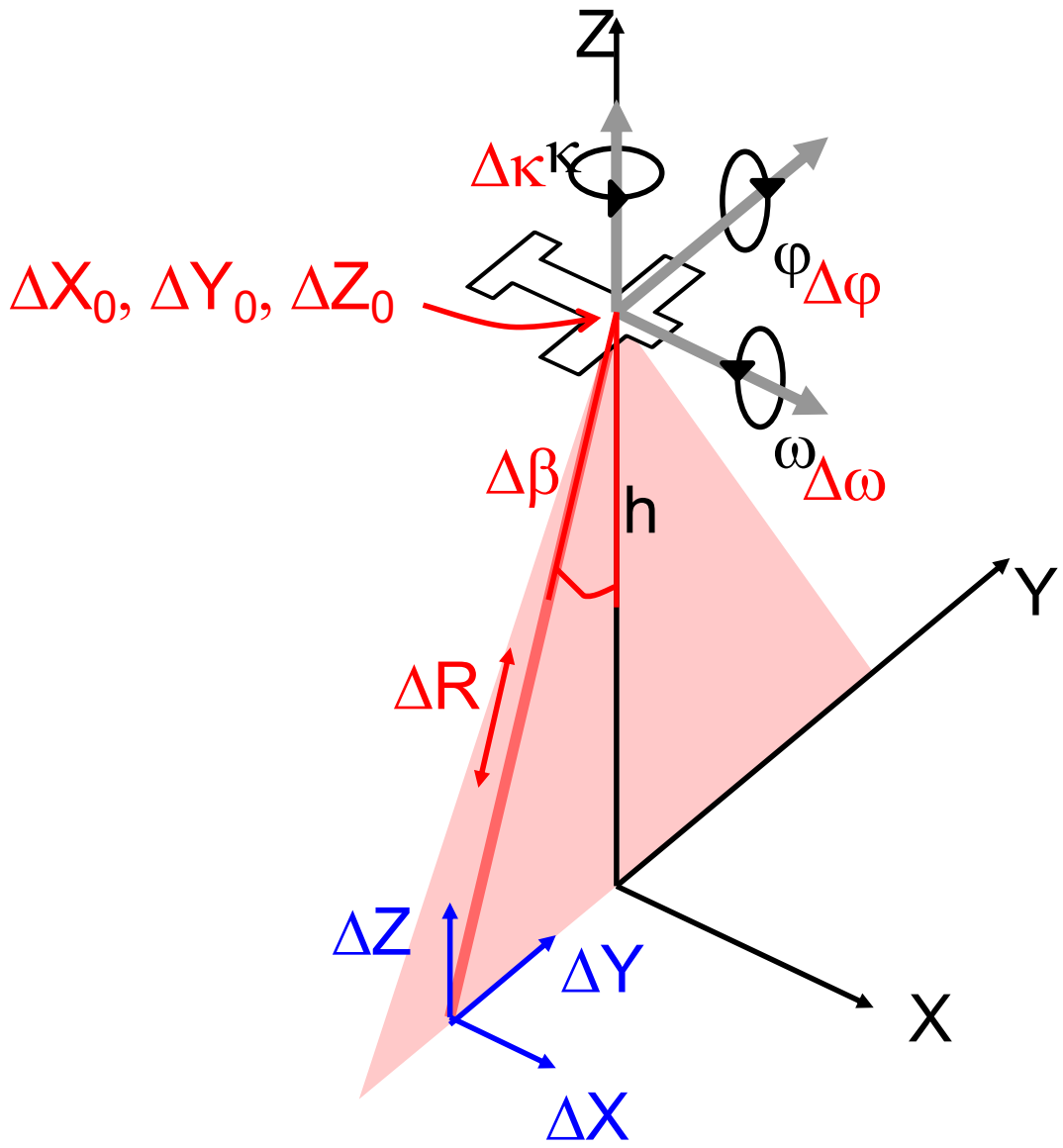
Inertial reference frame
Moving with aircraft

Aircraft/ scanner reference frame
Moving with aircraft

Earth centered reference frame
ECEF, WGS84

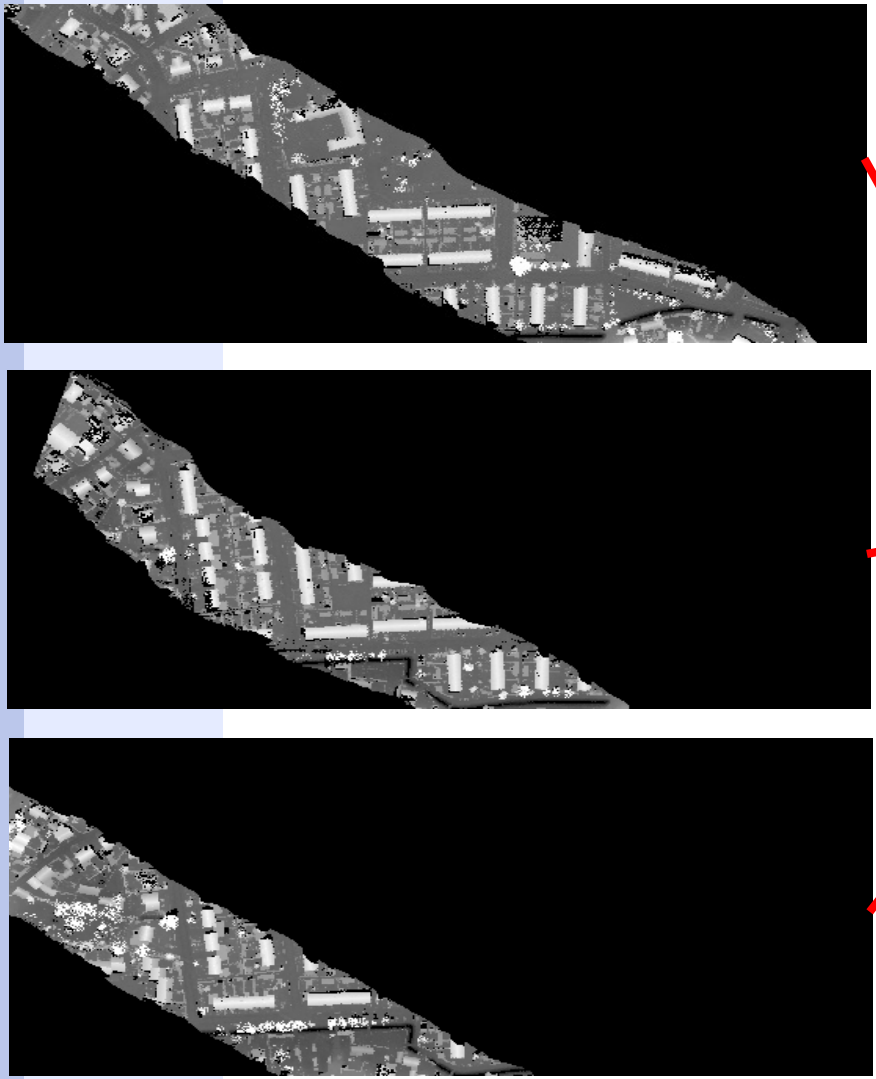
© Claus Brenner

Calibration, error sources

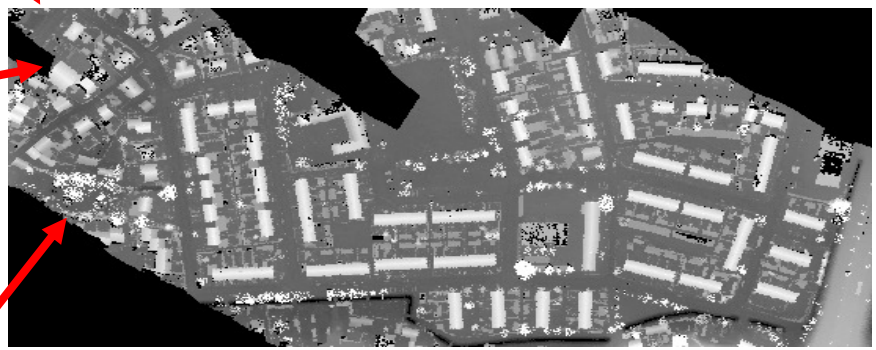


© Claus Brenner

Strip adjustment 带状调整带状调整



Create a seamless data set by correcting for the systematic errors.



(Slide provided by George Vosselman)

© Claus Brenner

Strip adjustment

Original data

After fitting

Original data

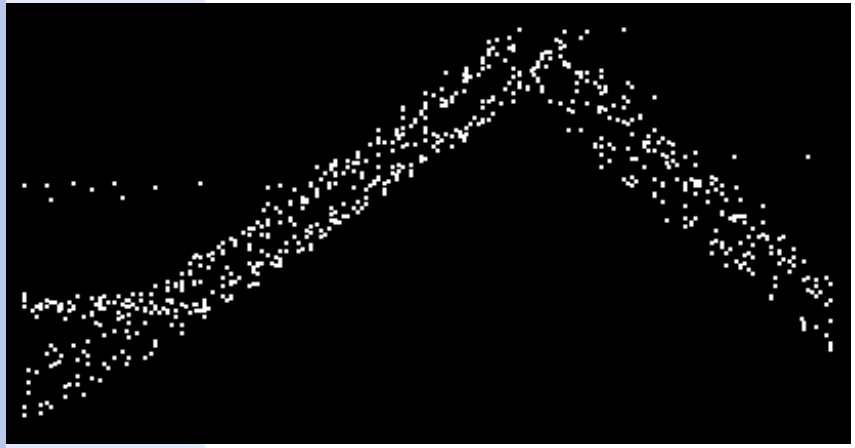
After fitting

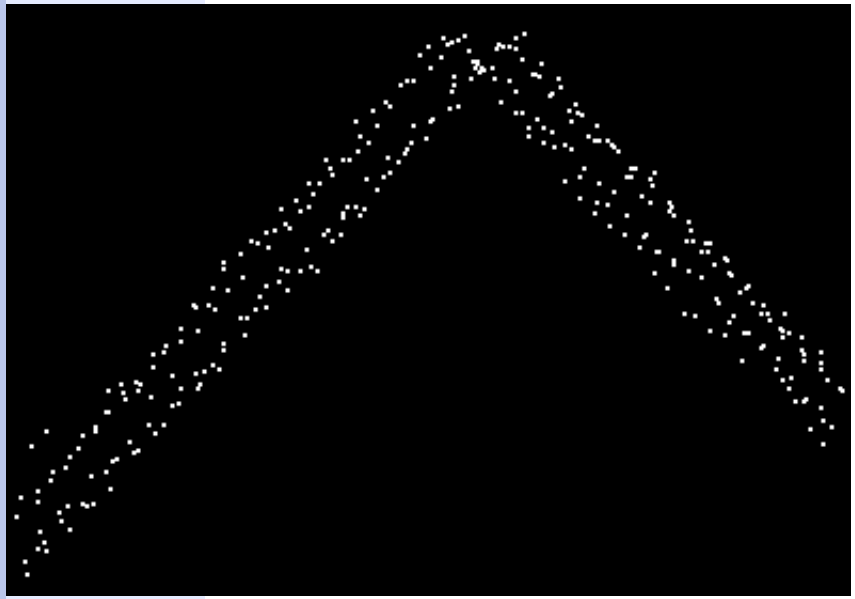
(Slide provided by George Vosselman)

© Claus Brenner

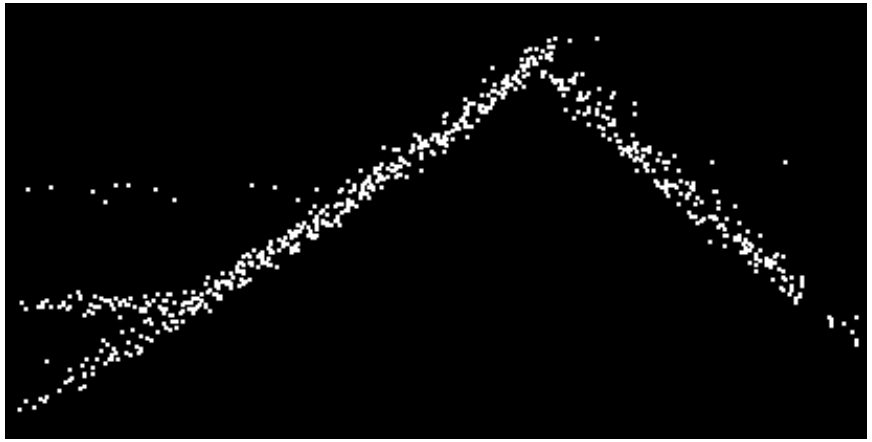
Strip adjustment

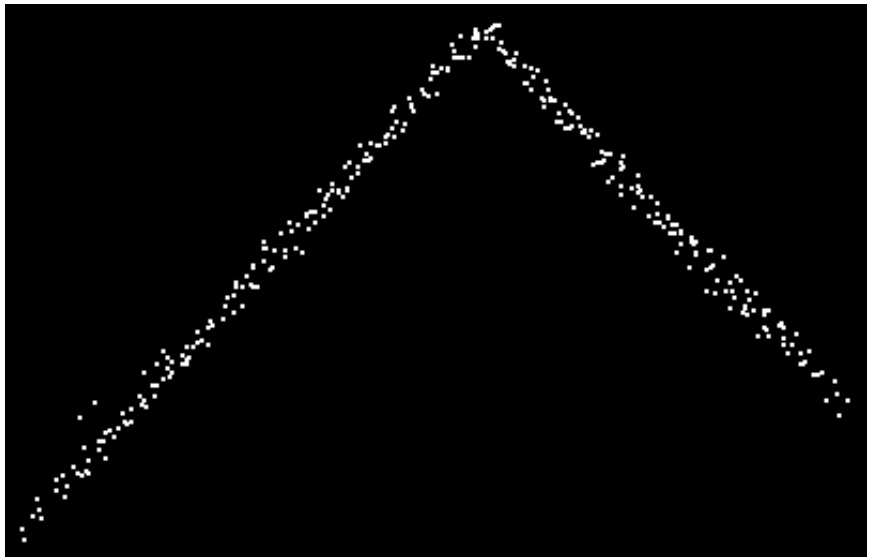
Original data





After fitting





(Slide provided by George Vosselman)

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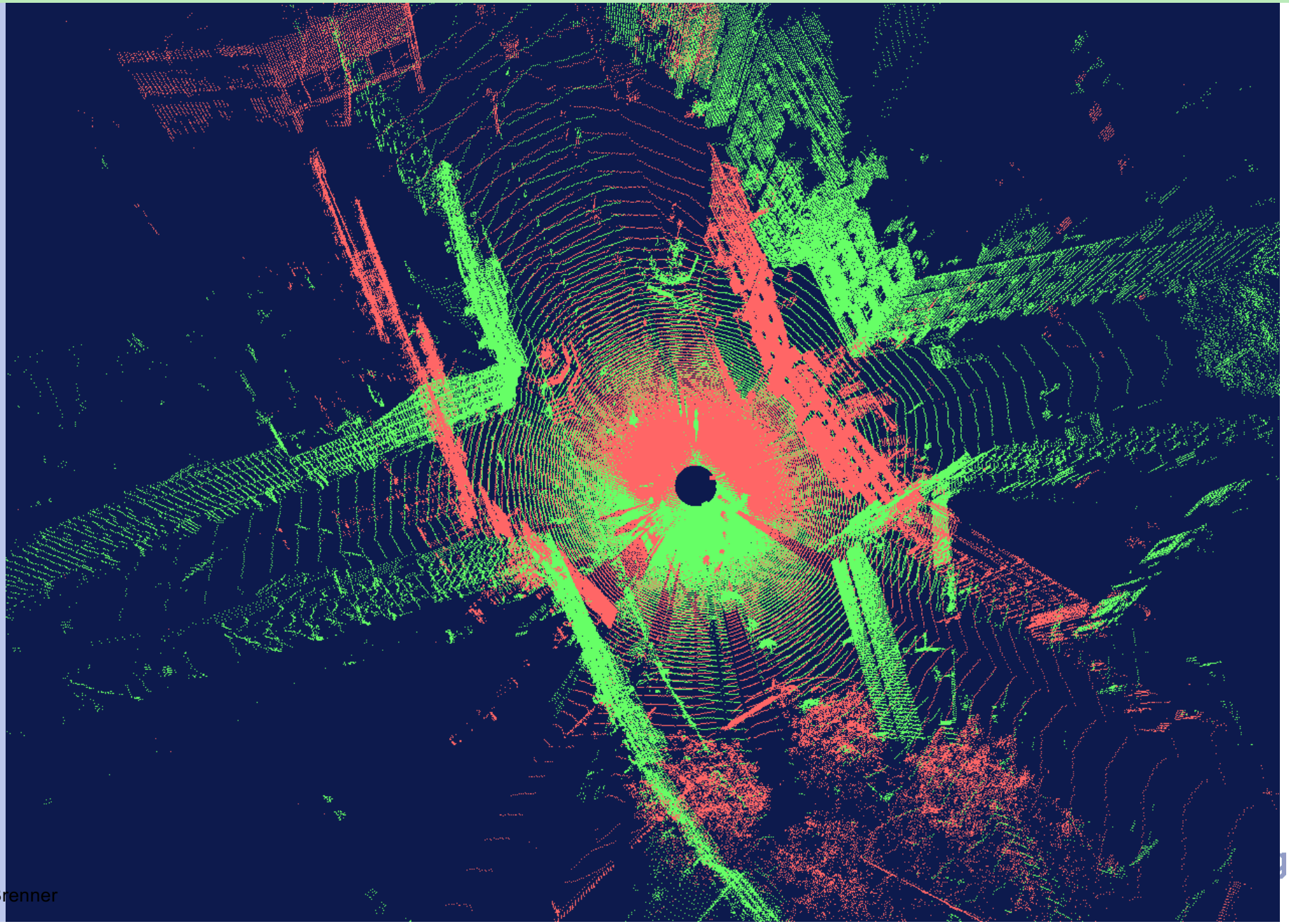
Relative orientation of terrestrial laser scans



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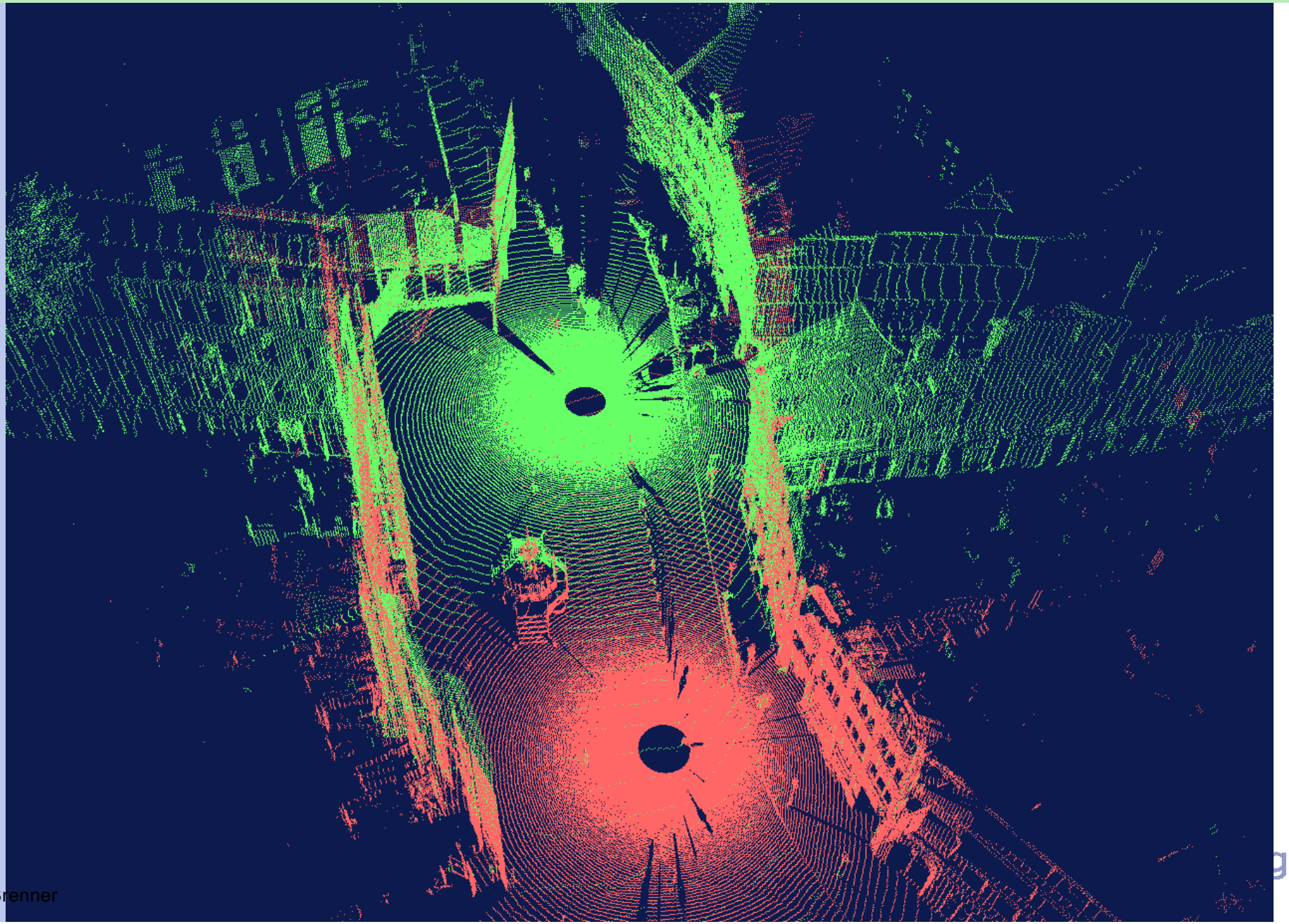
Relative orientation of terrestrial laser scans



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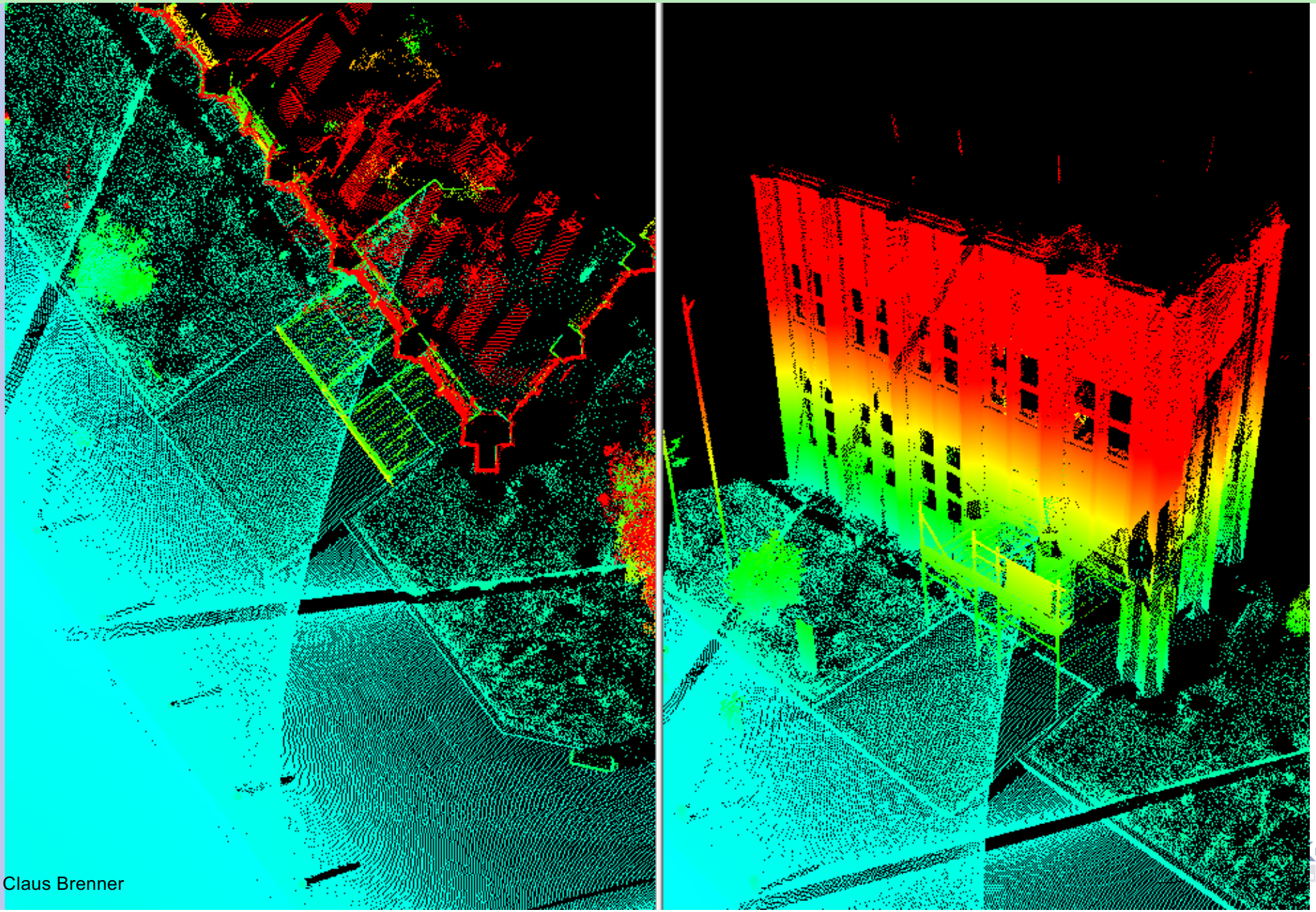
错误的外部方向

Example: wrong exterior orientation (ISE RTS)

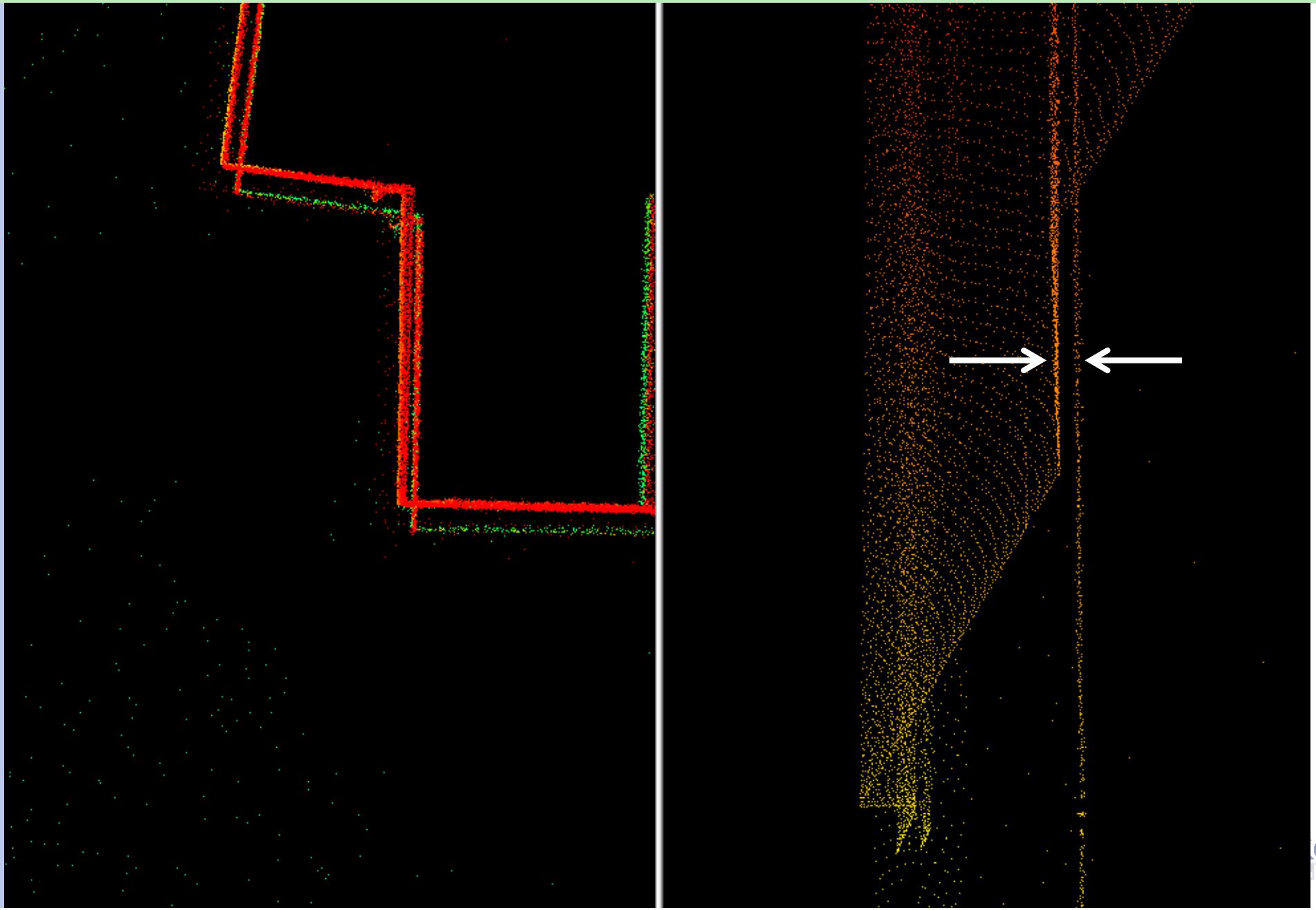
© Claus Brenner

Example: wrong exterior orientation (Riegl VMX)



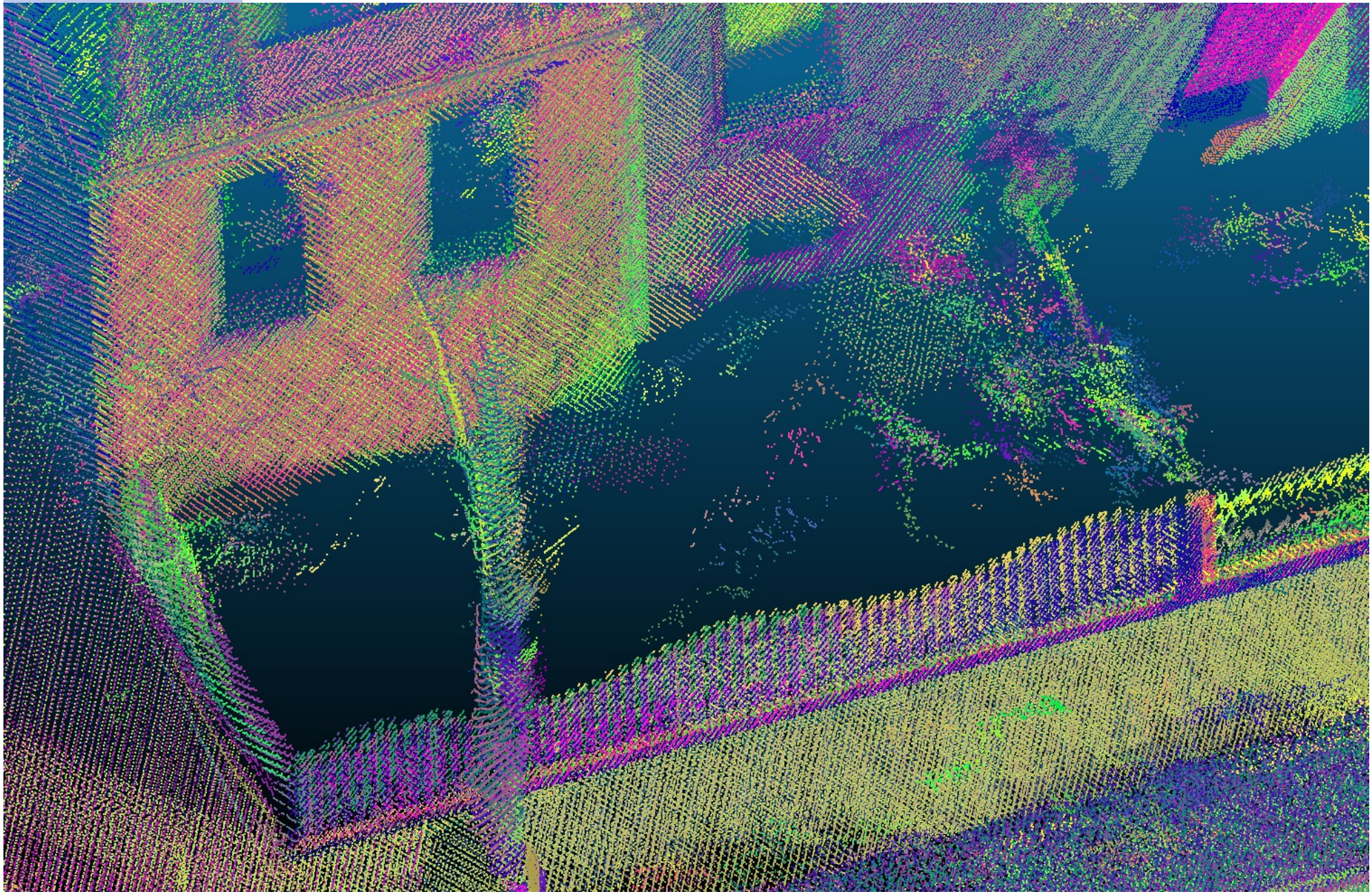
© Claus Brenner

Example: wrong exterior orientation (Riegl VMX)

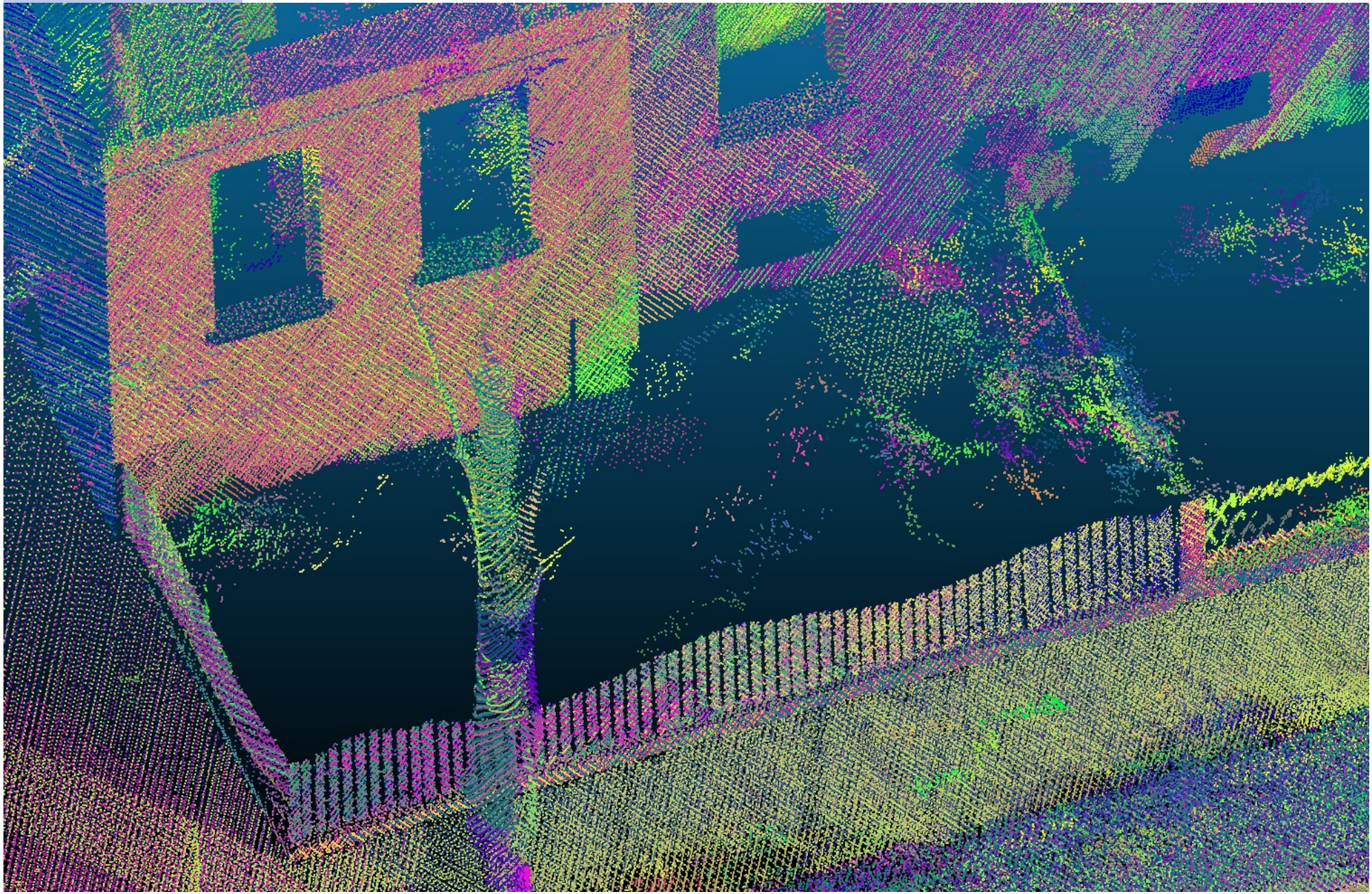


©

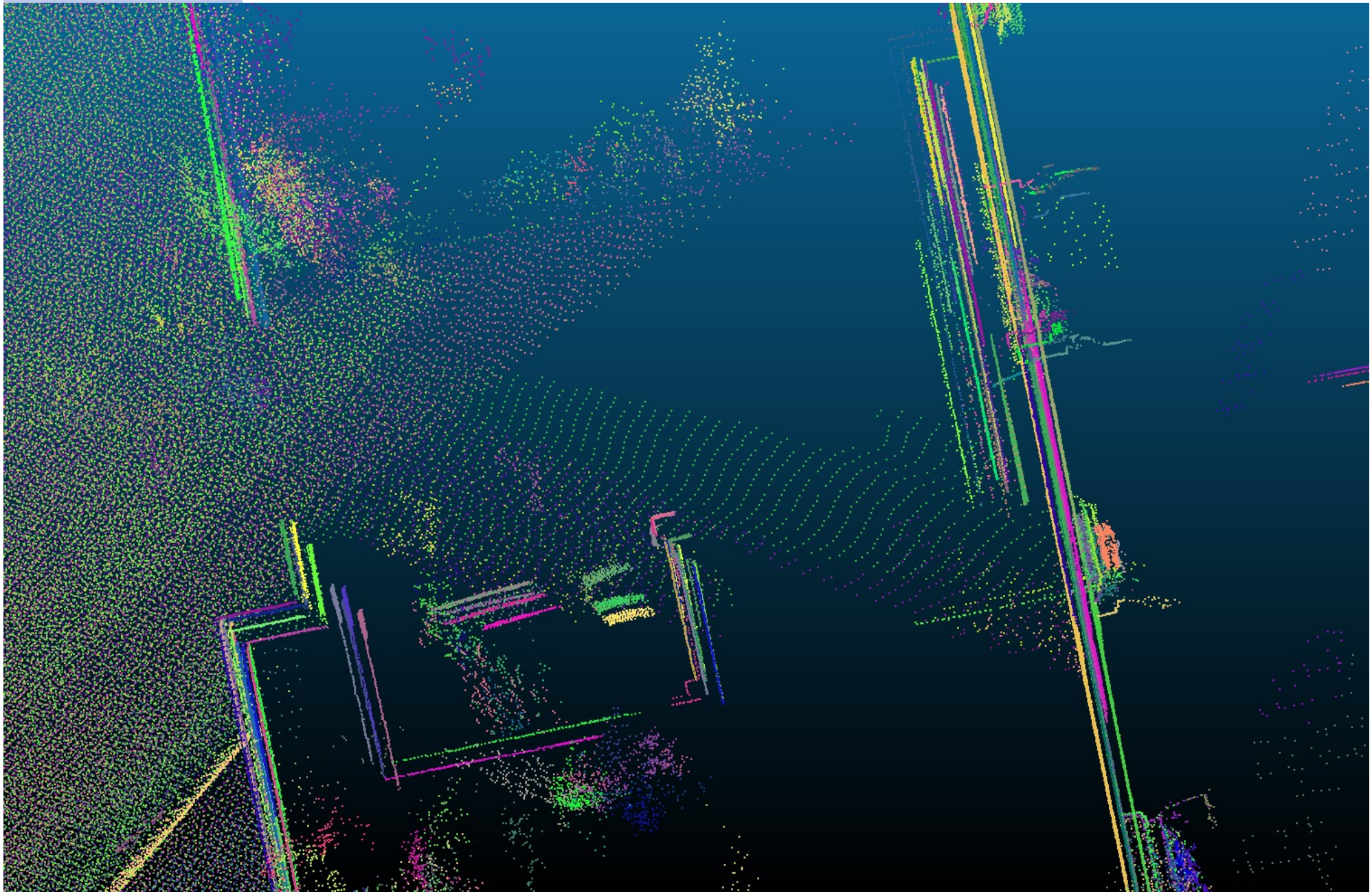
Before adjustment (8 strips)



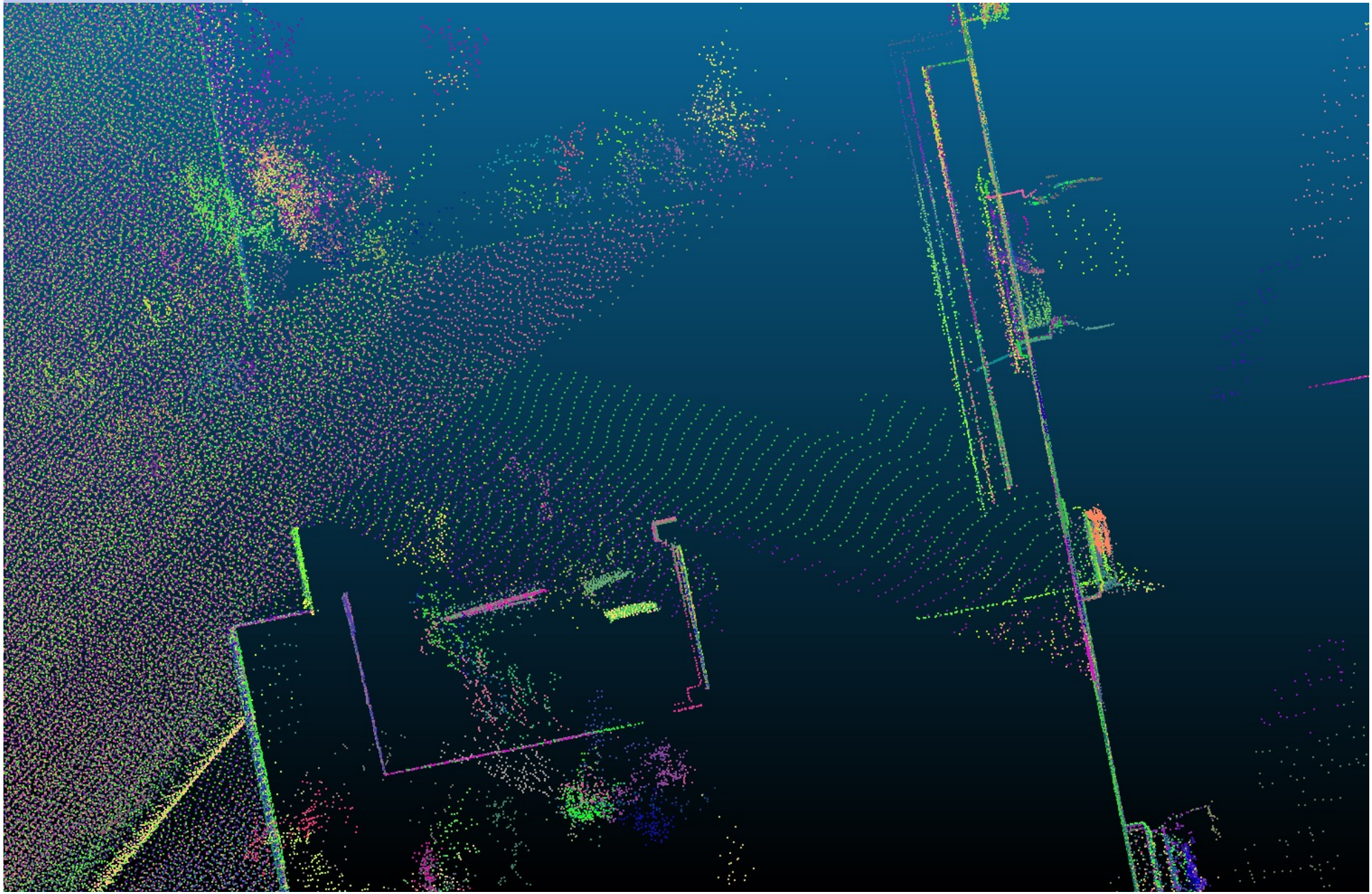
After adjustment (8 strips)

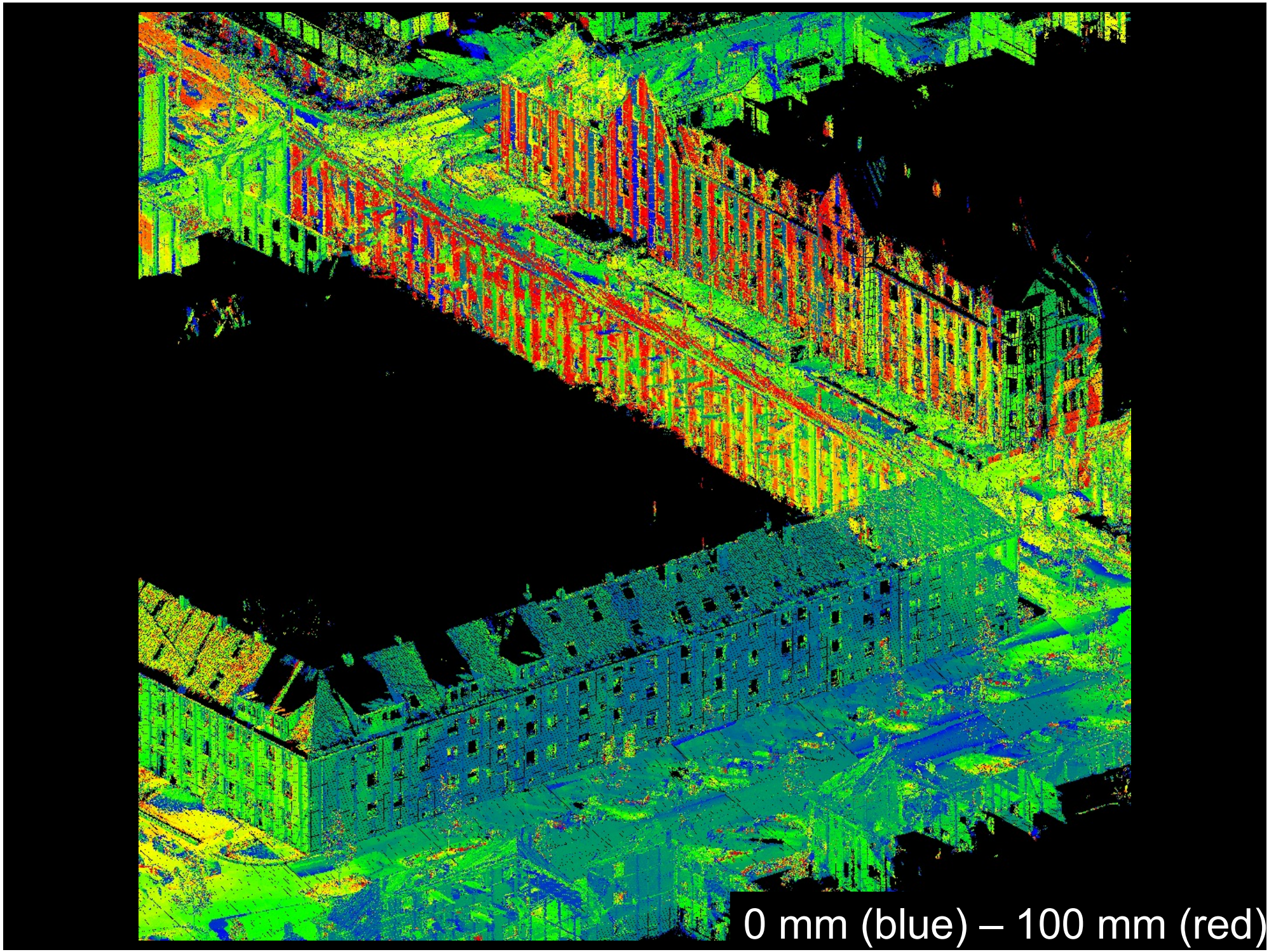


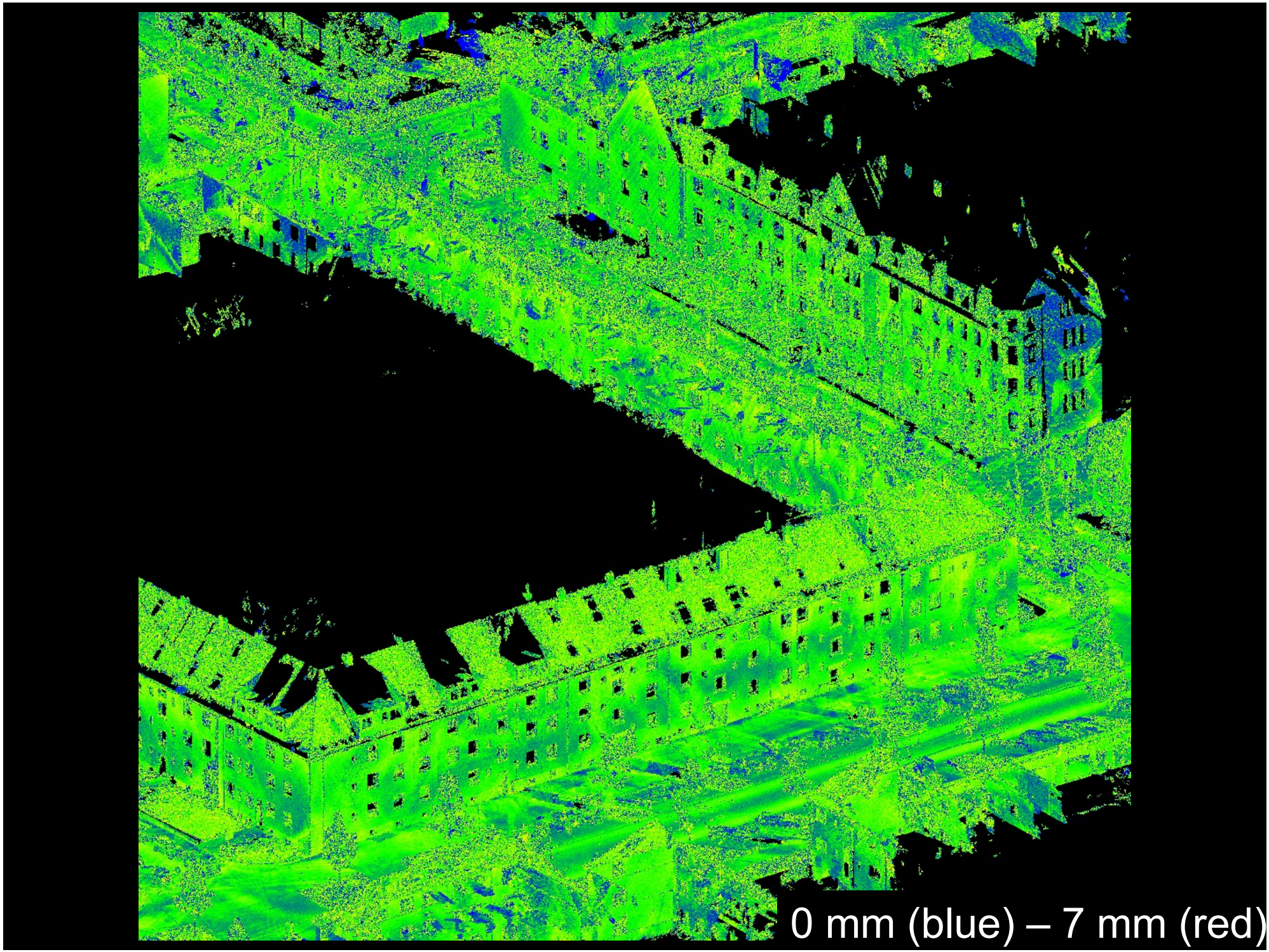
Before adjustment (8 strips)



After adjustment (8 strips)



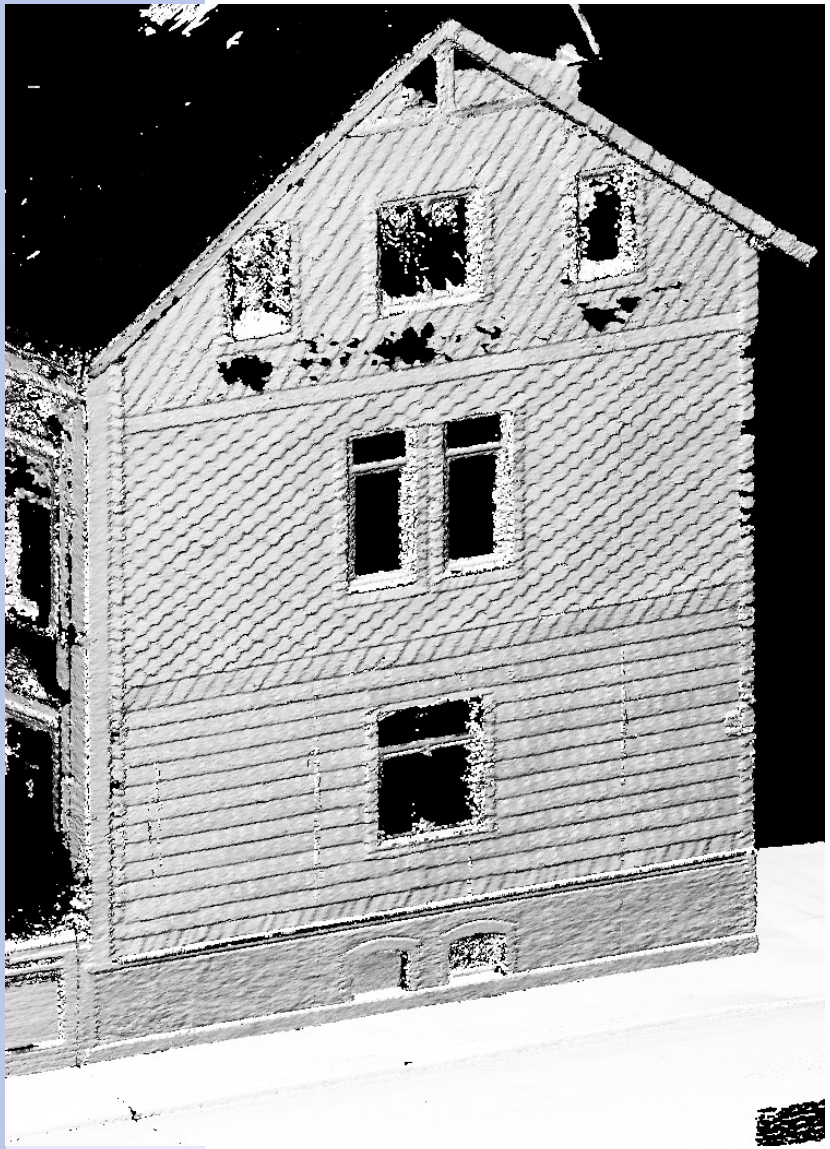

0 mm (blue) – 100 mm (red)


0 mm (blue) – 7 mm (red)

B

Example of a “latent map”

Badenstedt: 150 strips, ~1 bn. points

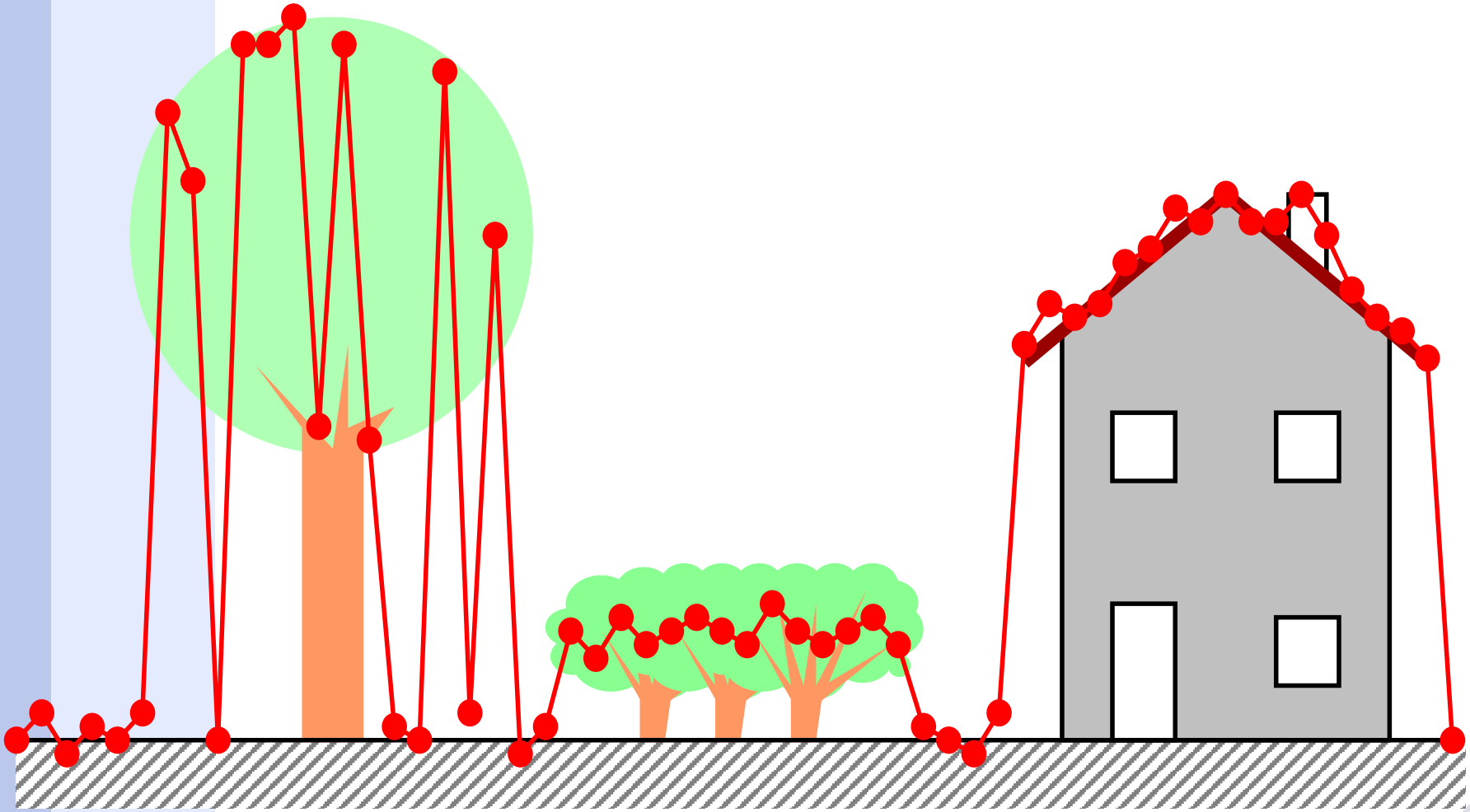


(Quelle: Google StreetView)

Example “latent map”

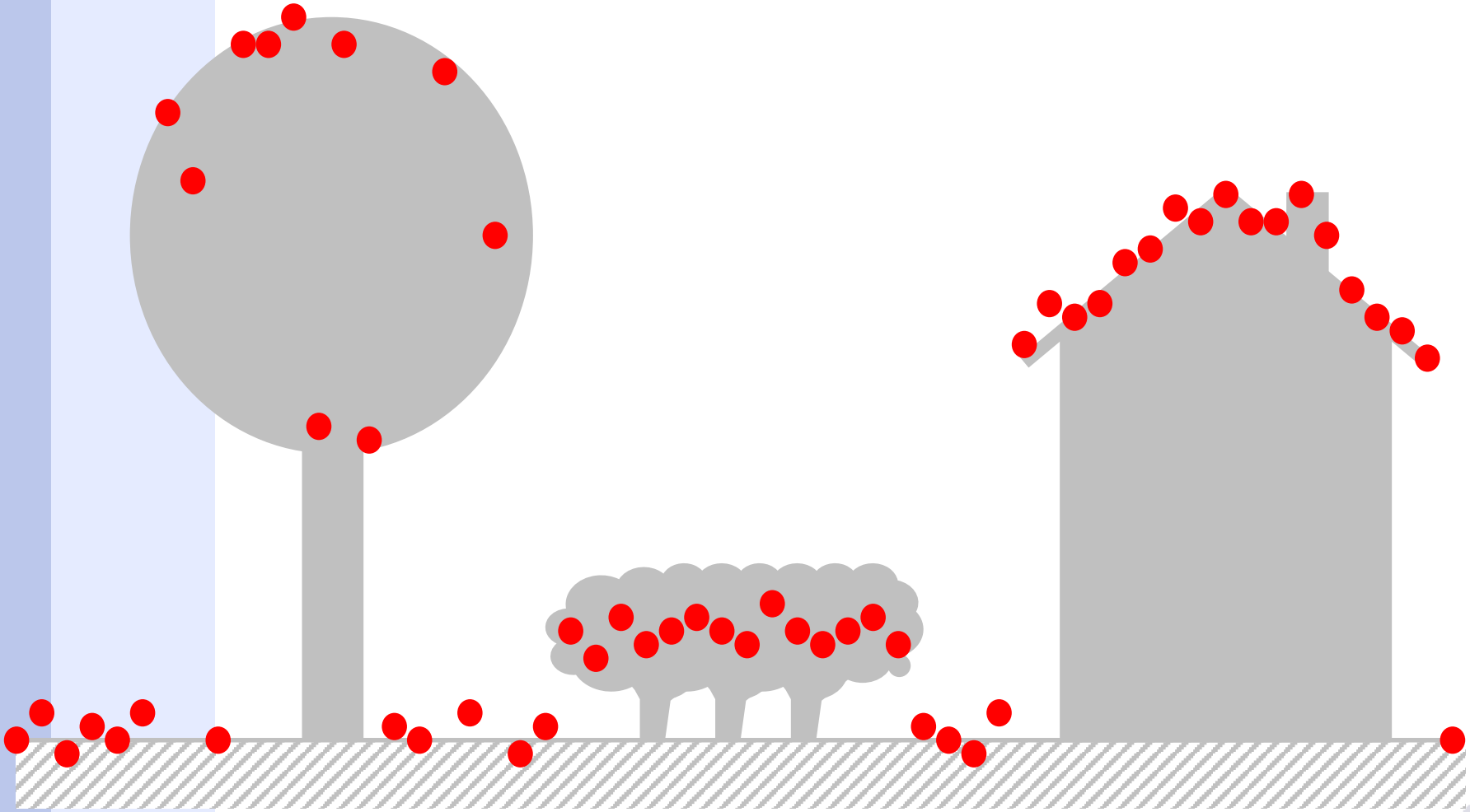
„Intermediate level“

Filtering



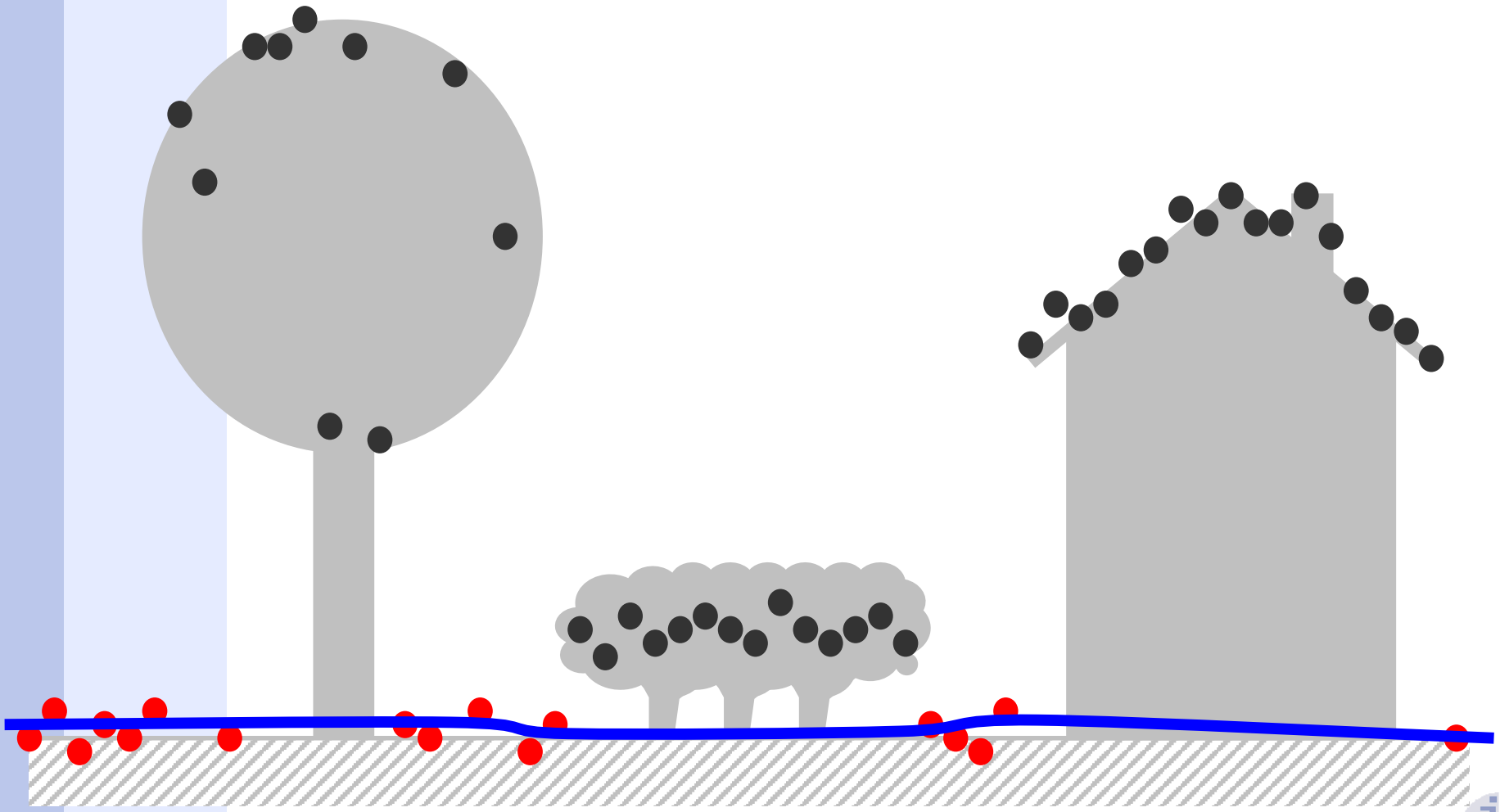
© Claus Brenner

Filtering



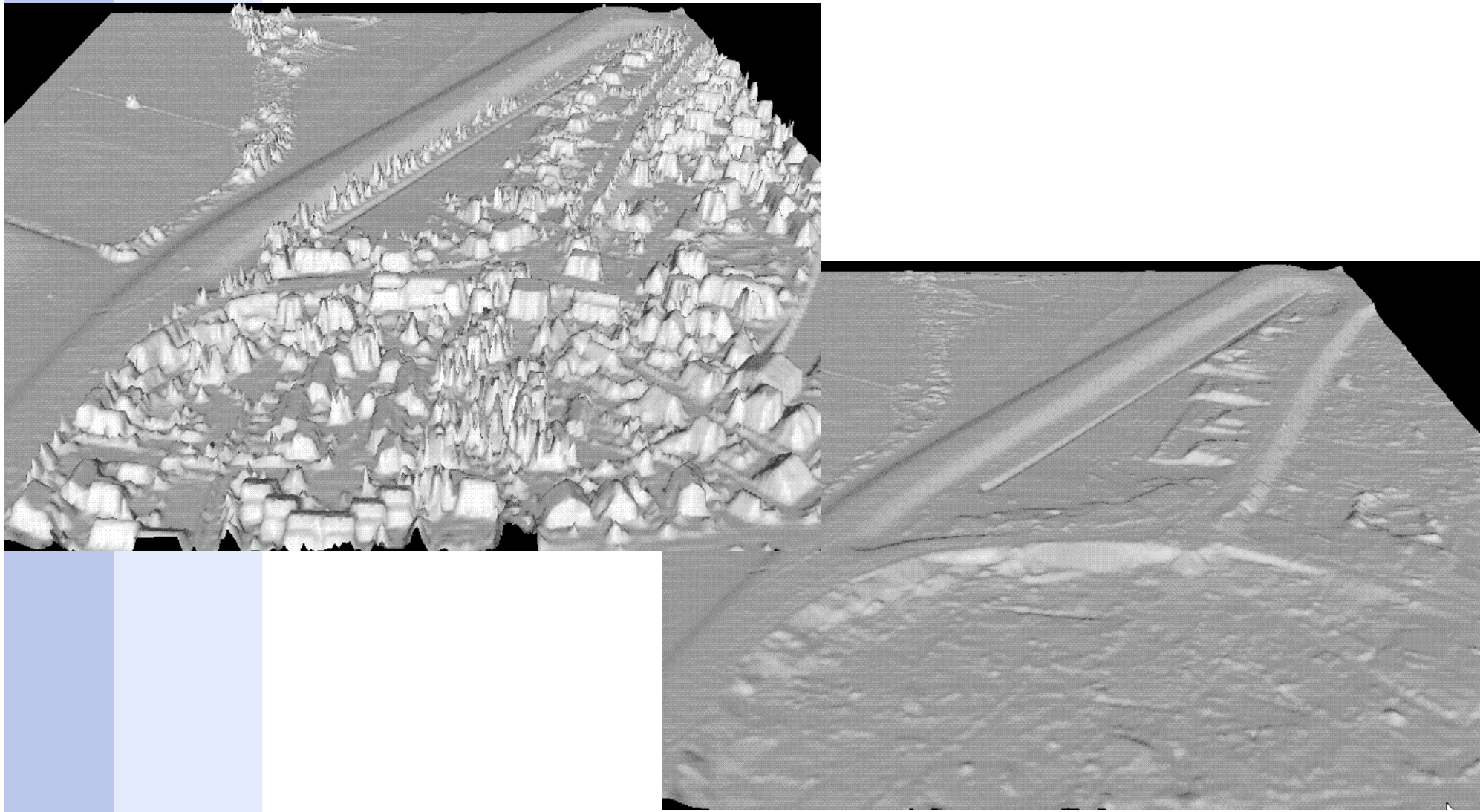
© Claus Brenner

Filtering



© Claus Brenner

Filtering

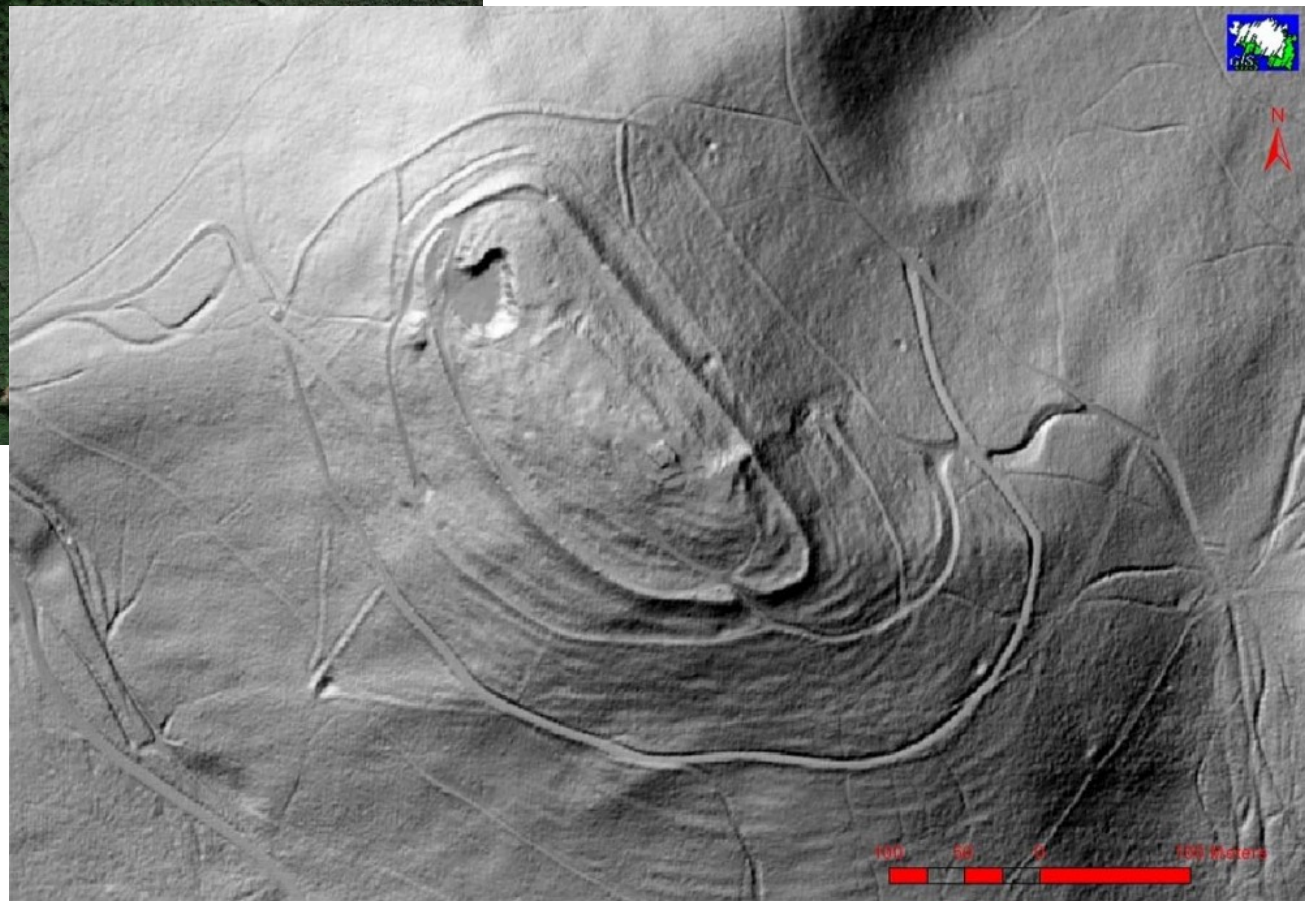


(Source: George Vosselman)

© Claus Brenner

Filtering in Archeology: Ringkogel, Hartberg

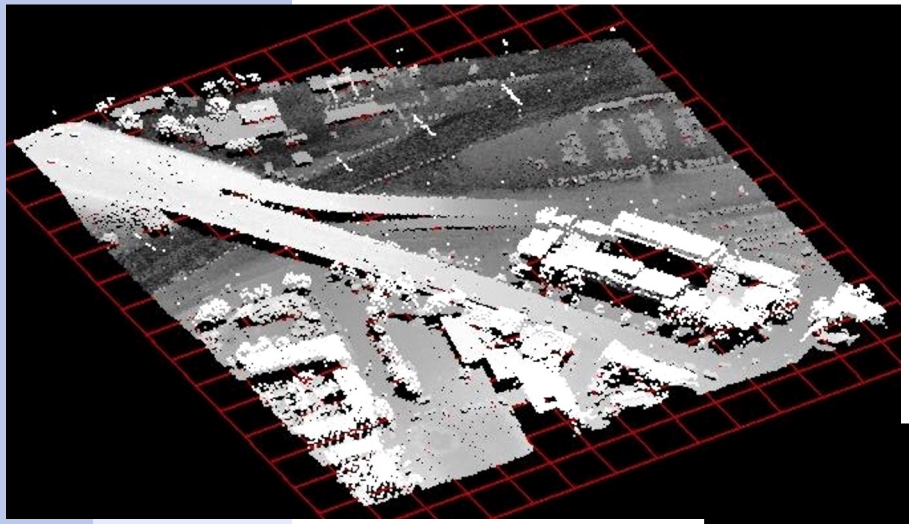
(Source: Google Maps)

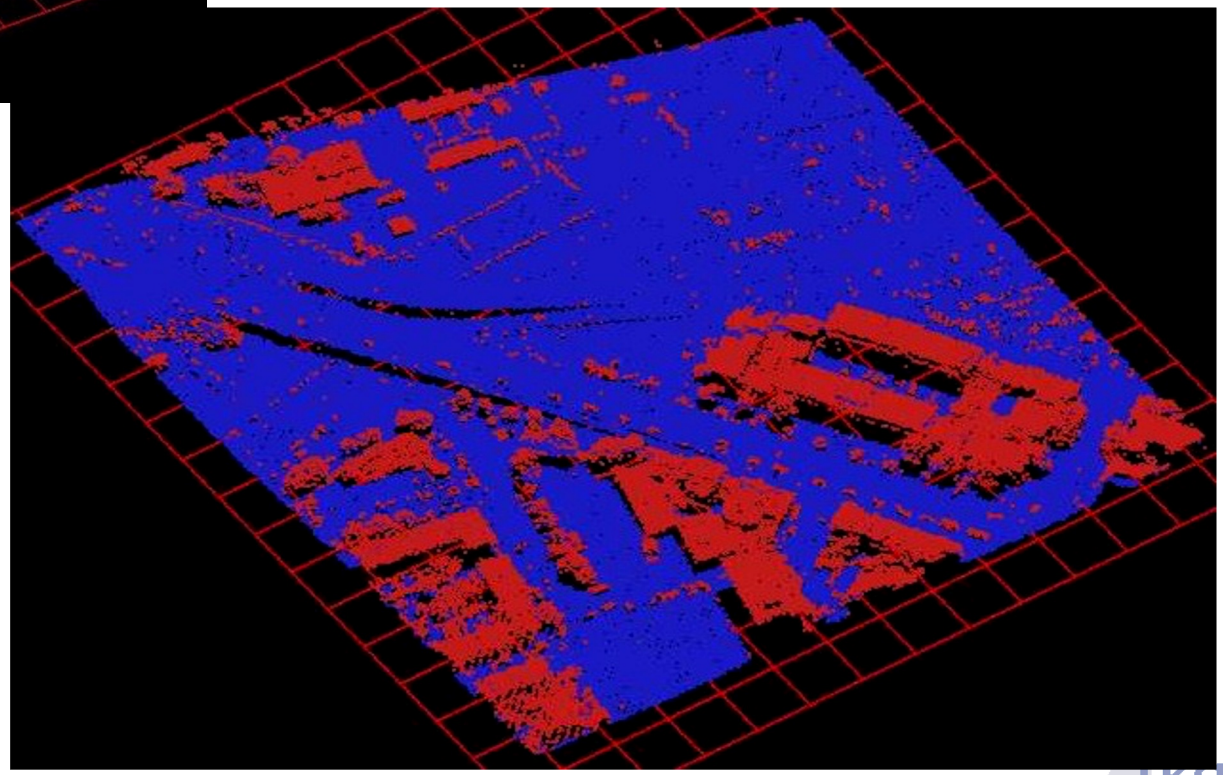


© Claus Brenner

(Source:www.isbe-archaeologie.at)

Filtering





Slide provided by George Sithole, George Vosselman

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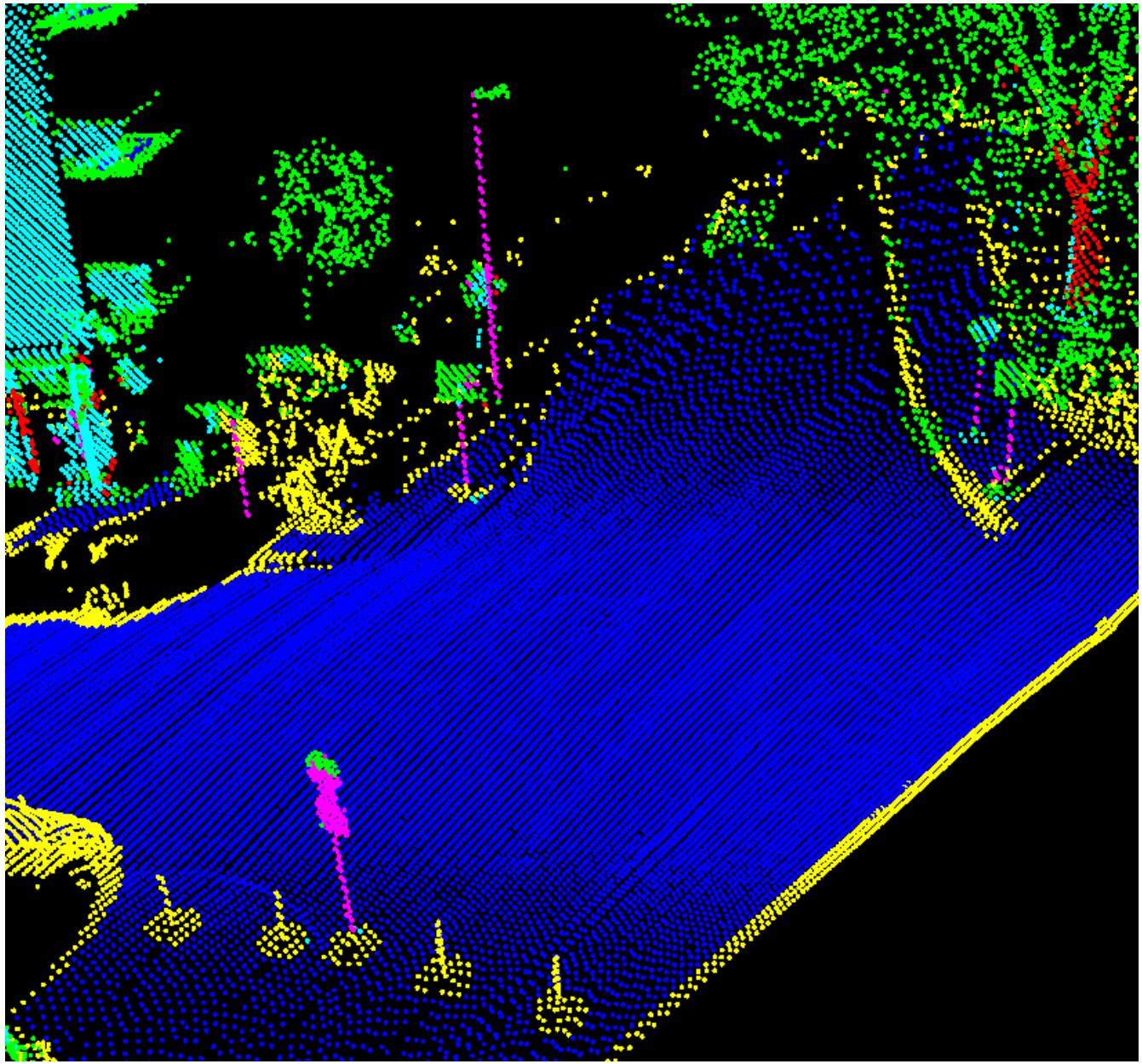
Classification of points in Mobile Mapping



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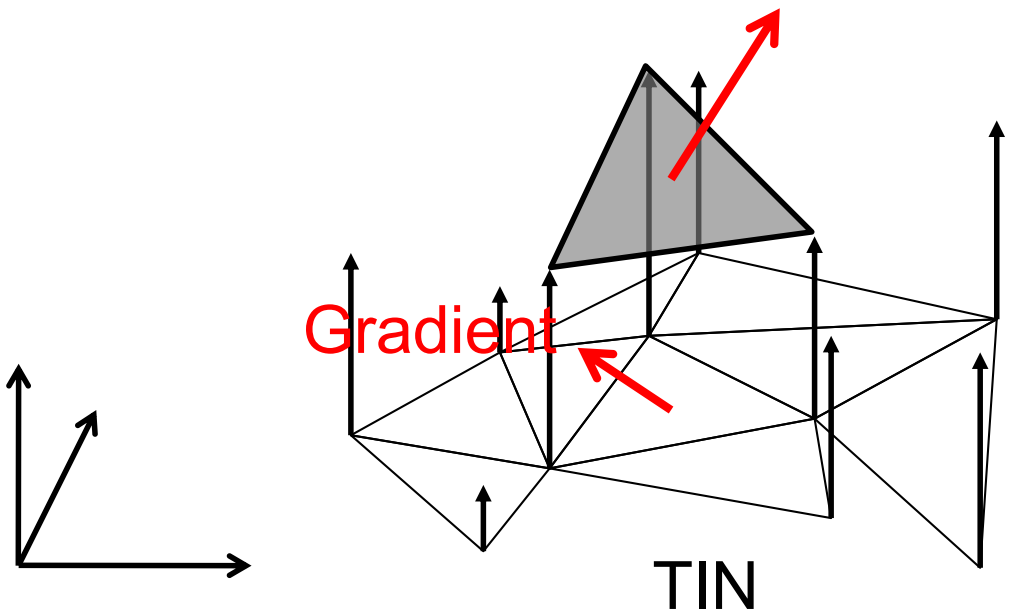
Point clouds vs. raster data

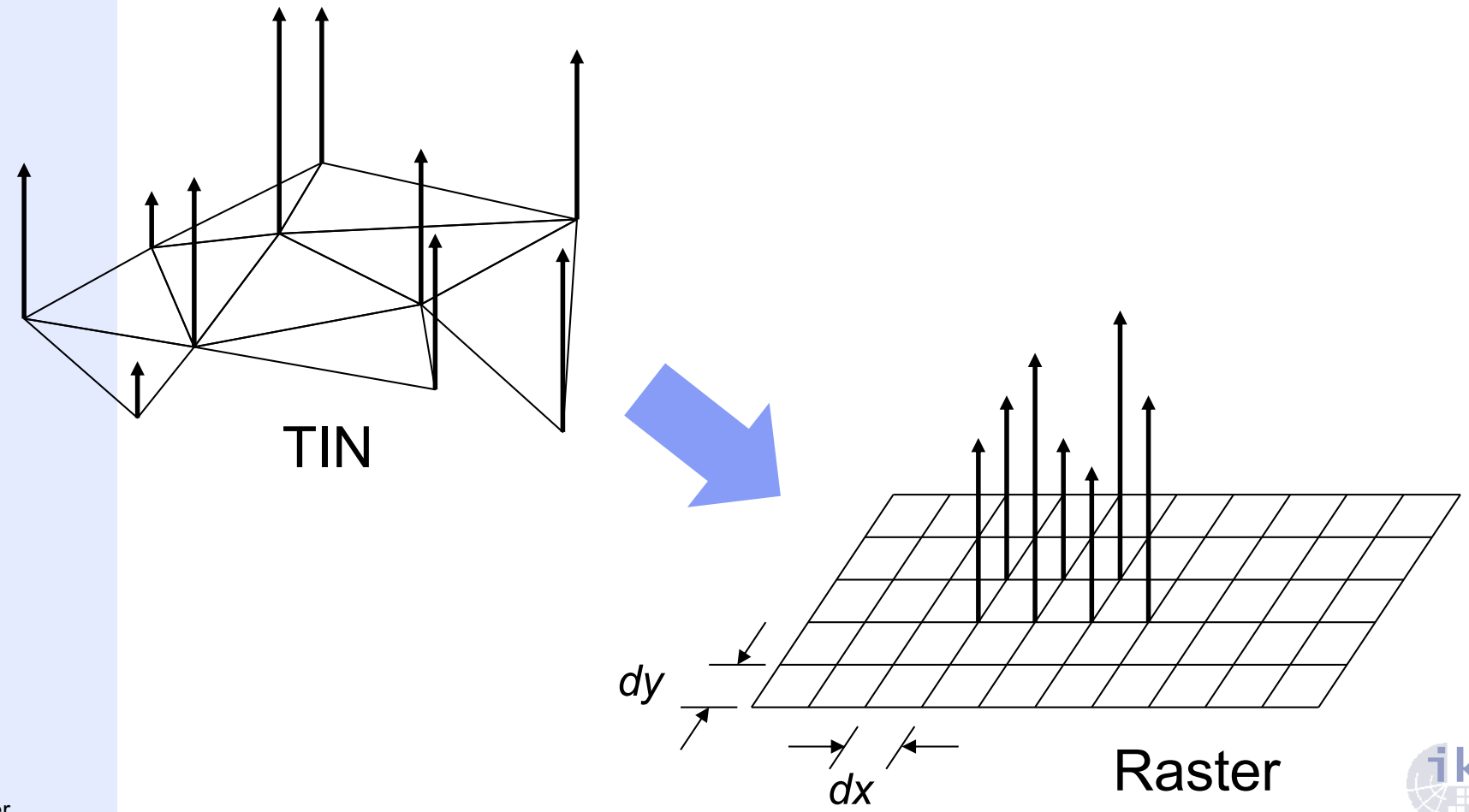
- Processing of point clouds is expensive (time, space)
- Example:
  - Compute the gradient in a 地势 "terrain" point cloud, for a given point
  - Can be solved as follows: a) compute a 三角测量法 triangulation (TIN) in the plane, b) pick correct triangle, c) compute gradient vector from triangle face normal vector
  - Requires triangulation and efficient search for enclosing triangle



© Claus Brenner

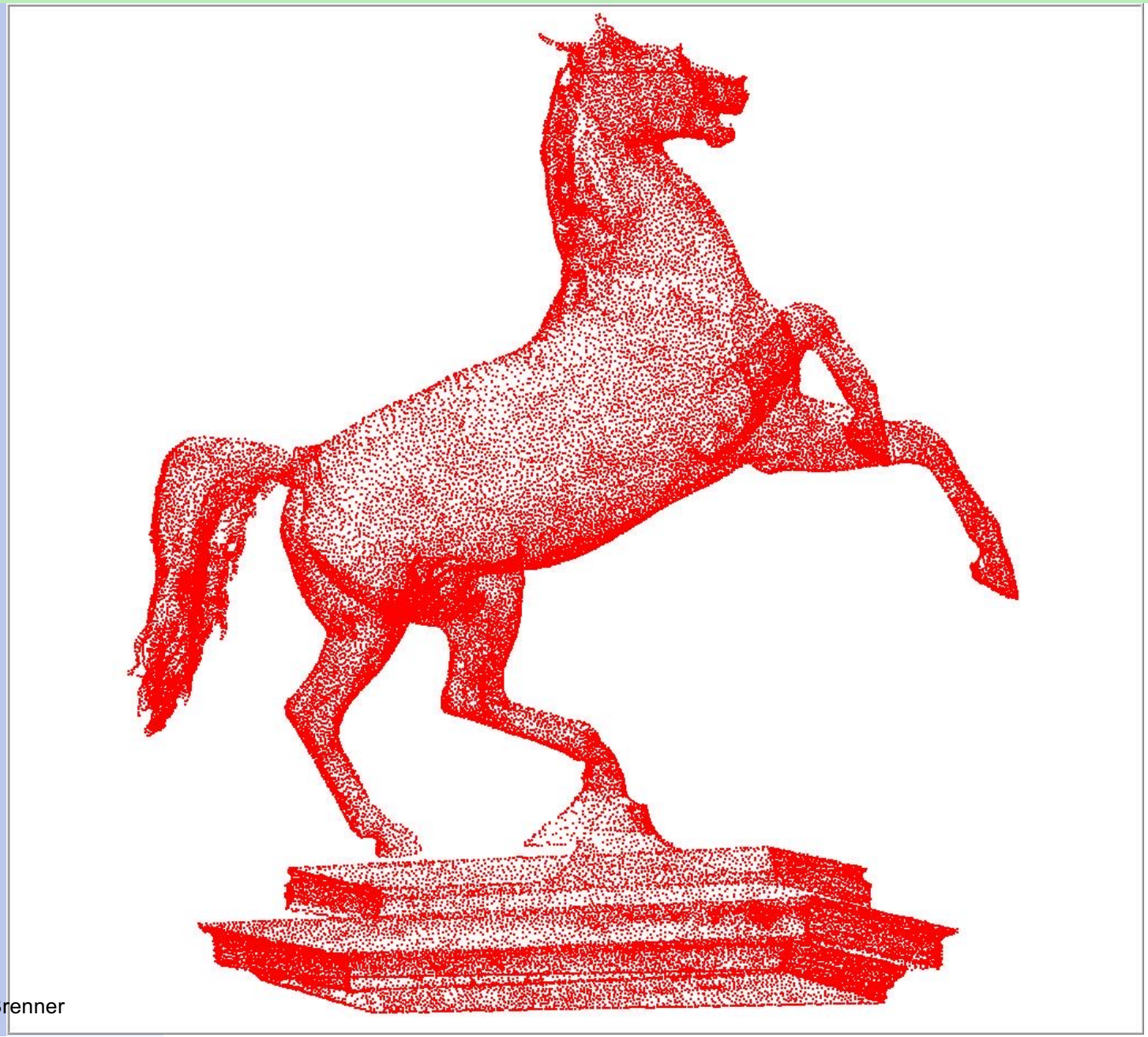
Regular rasters

- Computed from the point cloud by interpolation 插值
- Raster width is typically chosen according to the original point cloud density 光栅宽度通常根据原始点云密度来选择



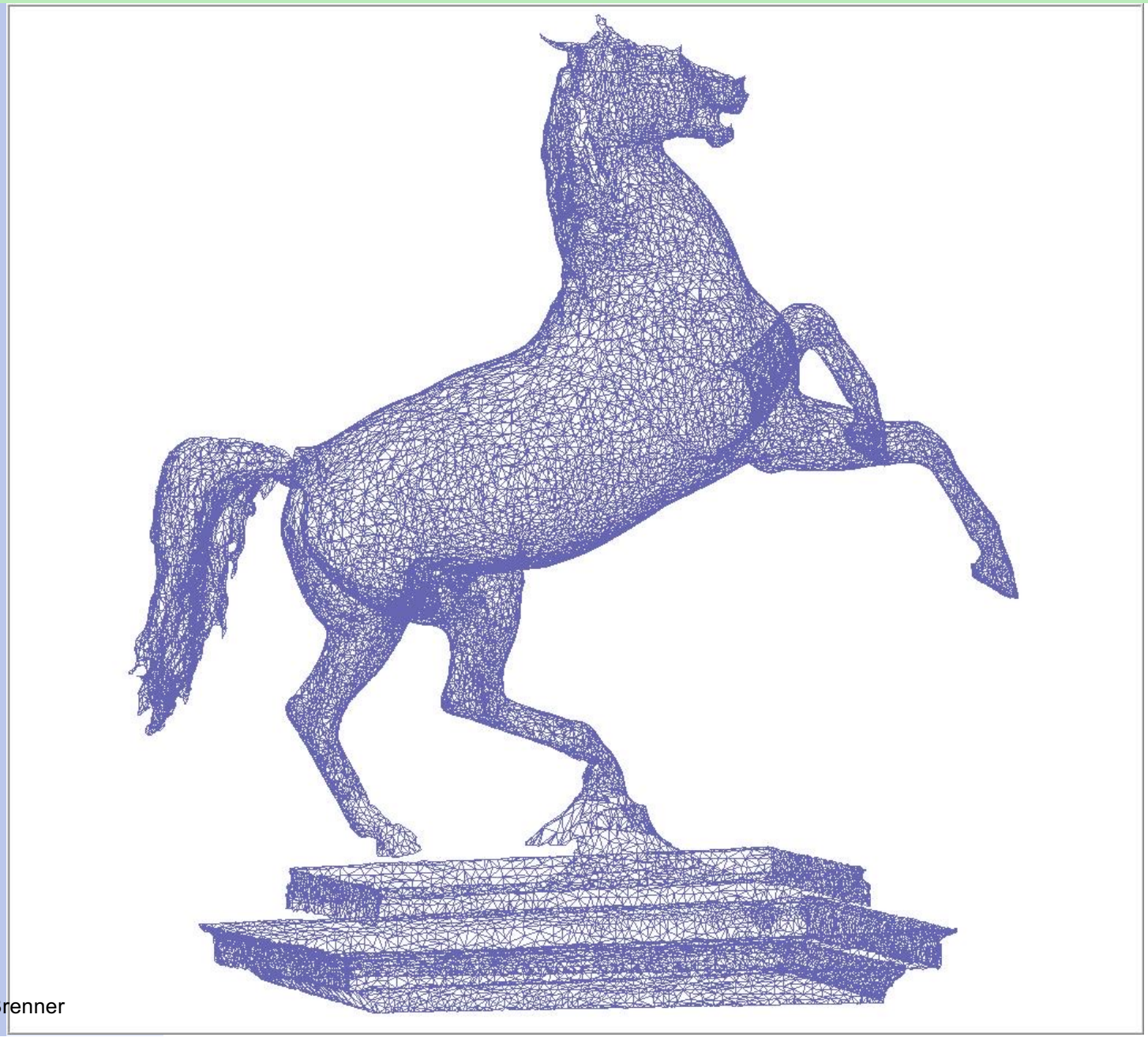
© Claus Brenner

Point cloud (terrestrial scan)



© Claus Brenner

Triangulation (edges)



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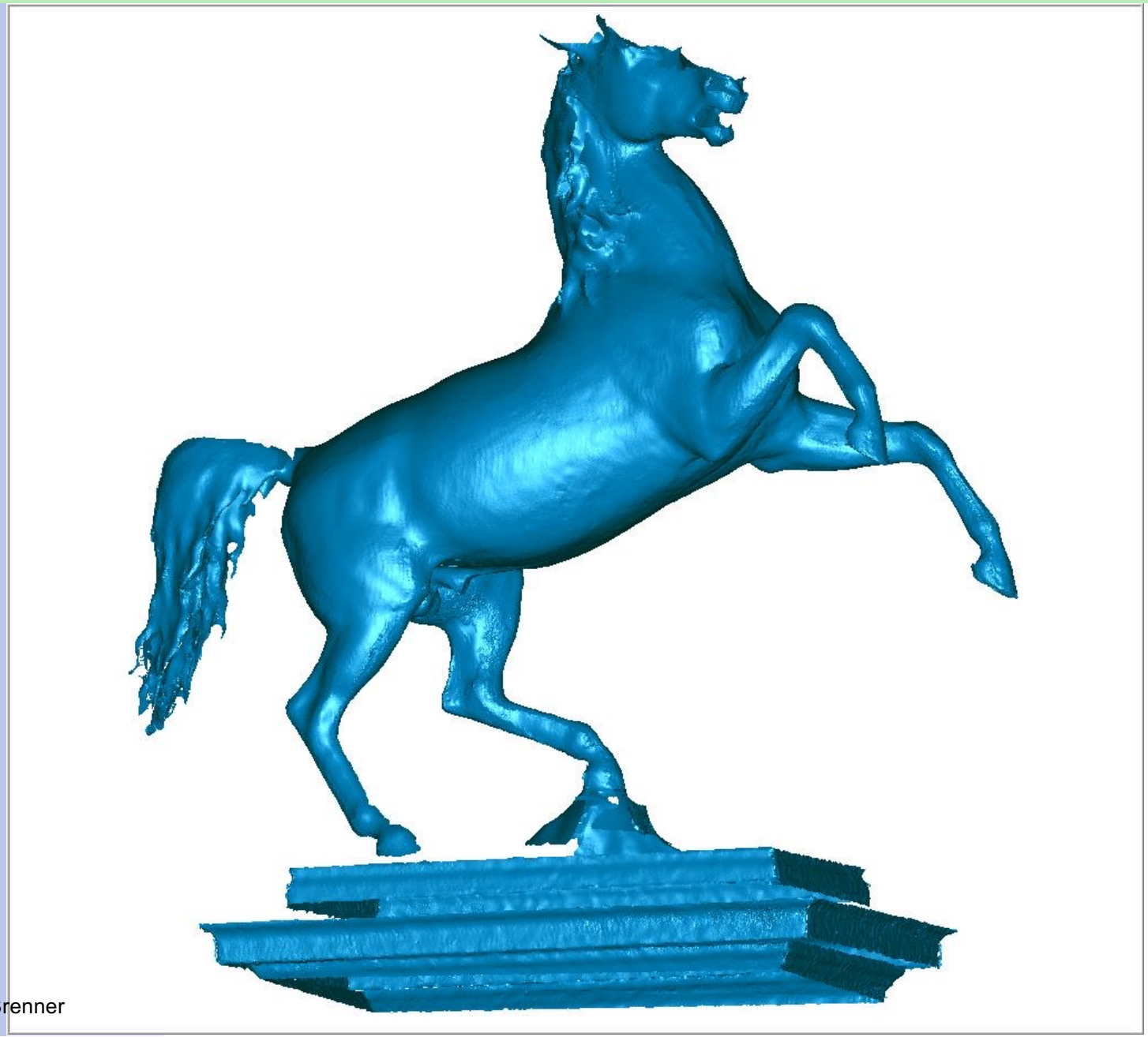
Triangulation (surfaces)



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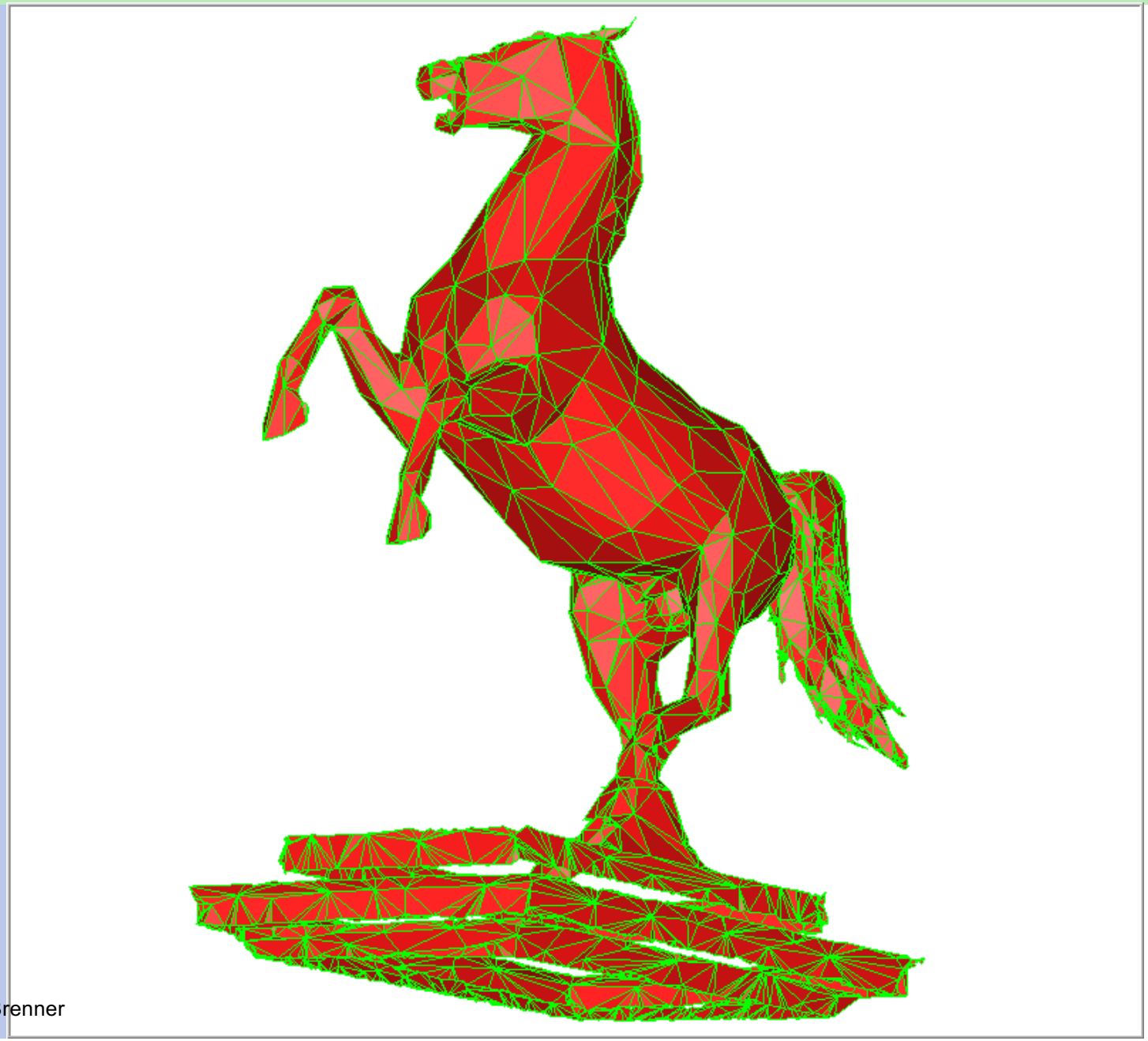
Triangulation, reduction of triangles

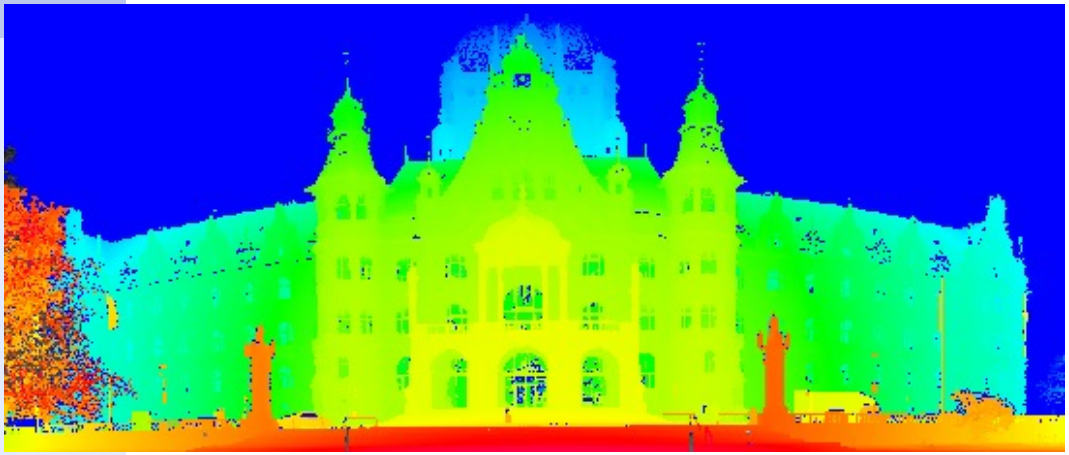


< 5%
possible

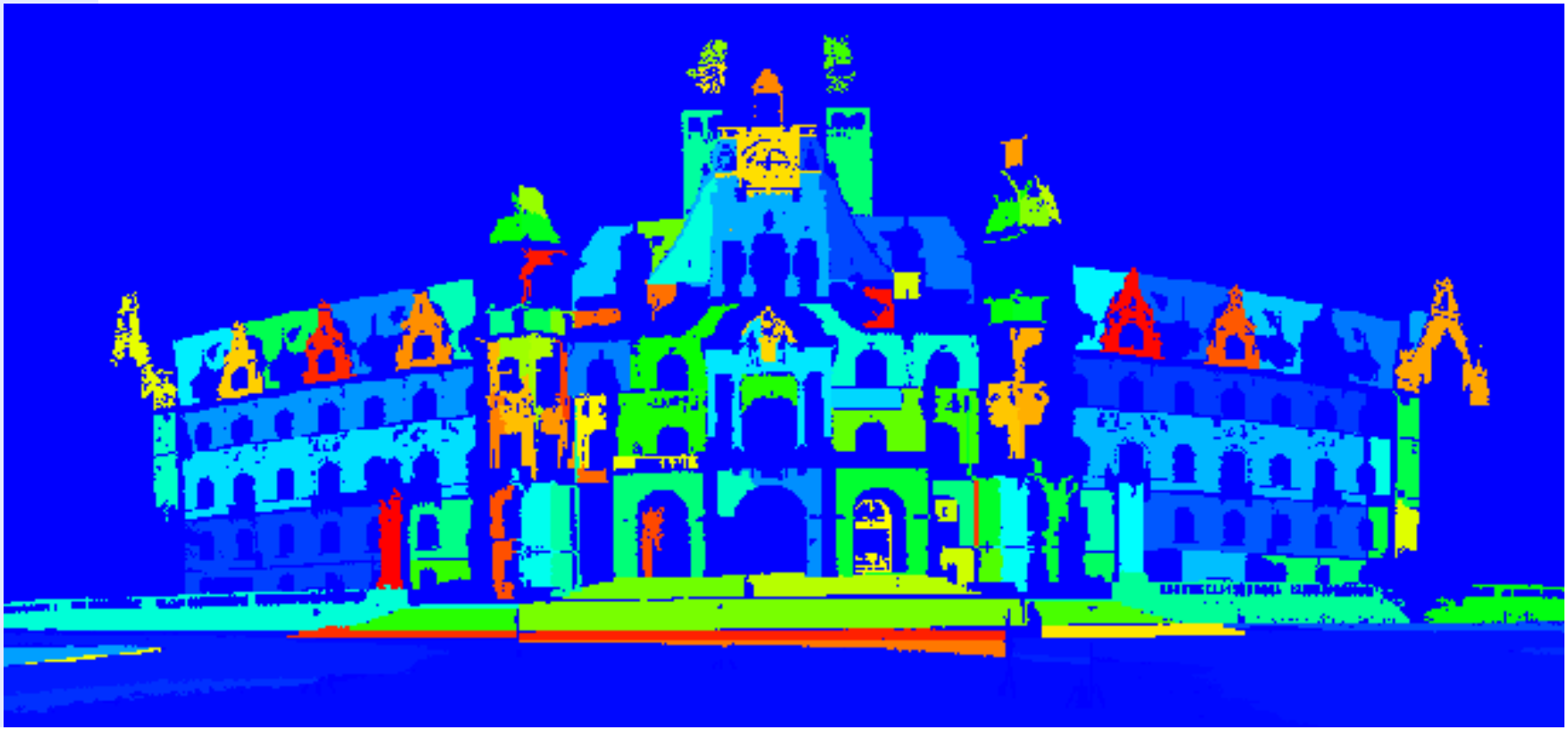
© Claus Brenner

Extraction of planes 提取平面

Scan data

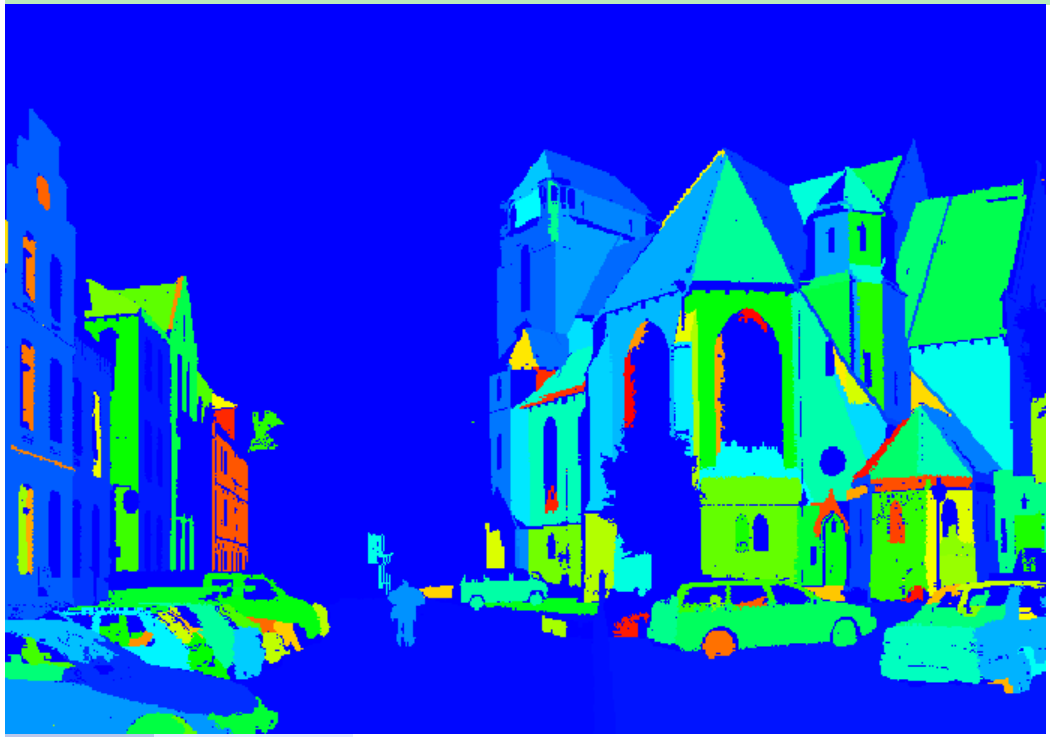


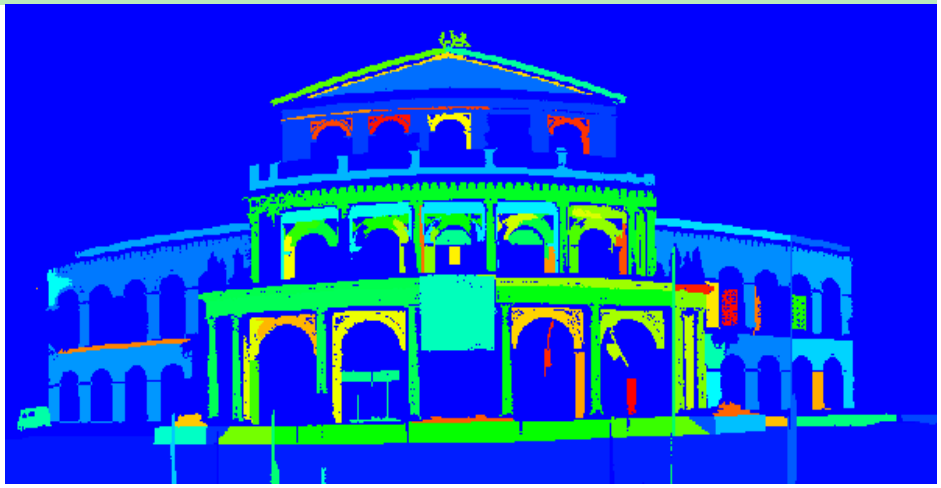
Segmentation

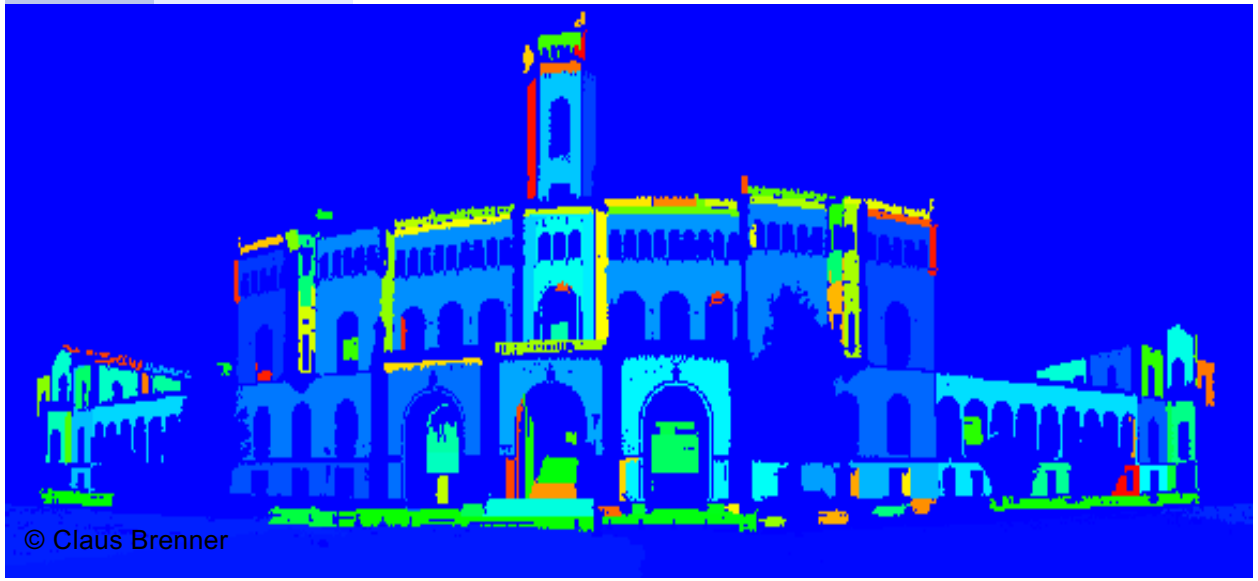


© Claus Brenner

Extraction of planes







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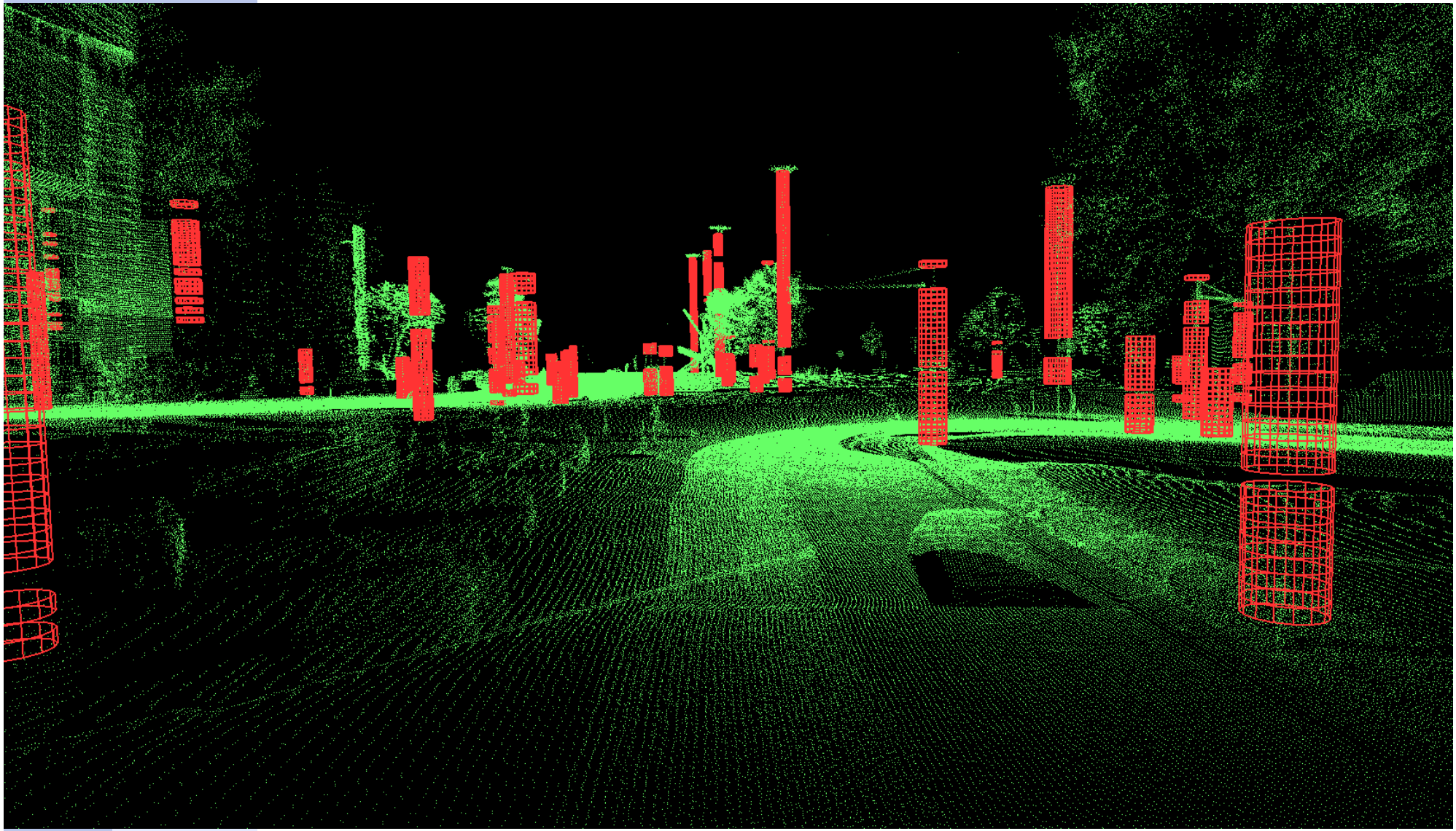
Extraction of poles (street lighting, traffic lights, trees)



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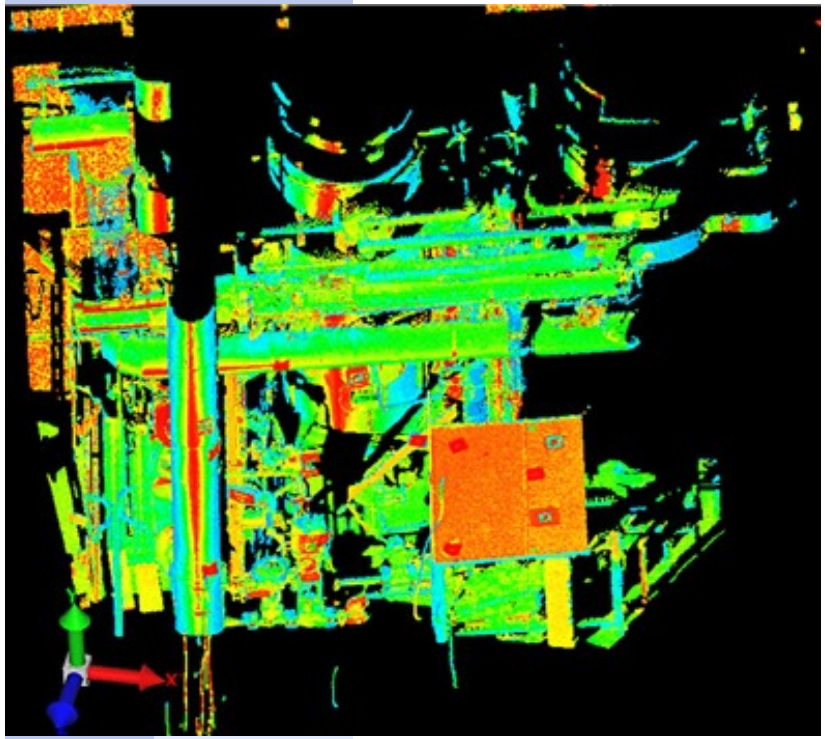
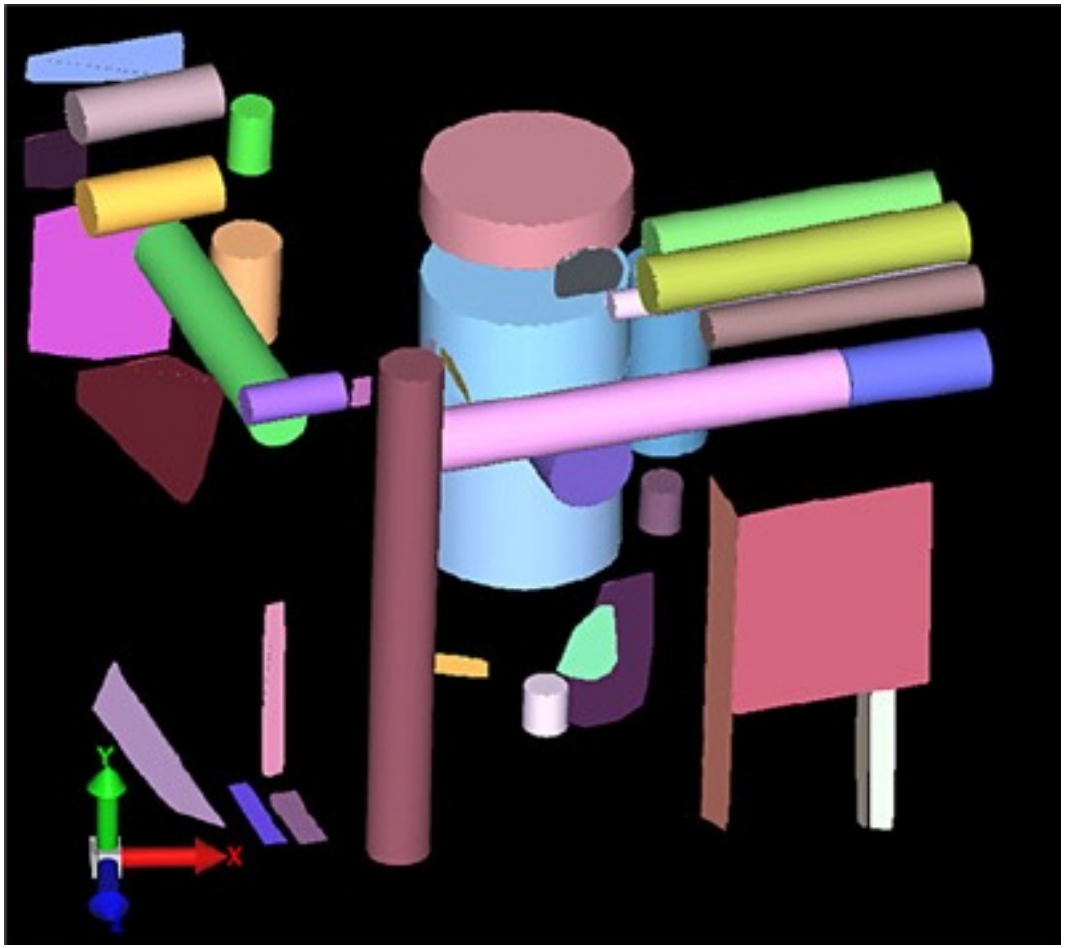
Extraction of simple shapes in industrial settings





[Rabbani, Dijkman, van den Heuvel, Vosselman, ISPRSJ 61 (2007) 355–370]

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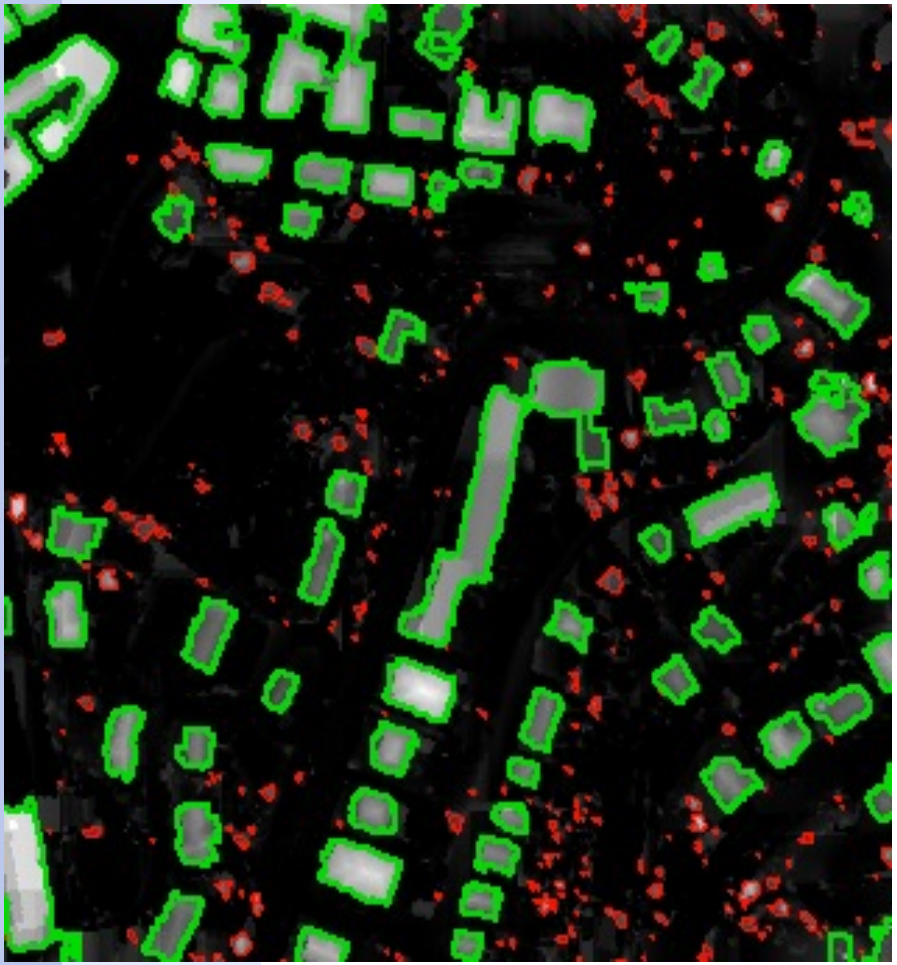
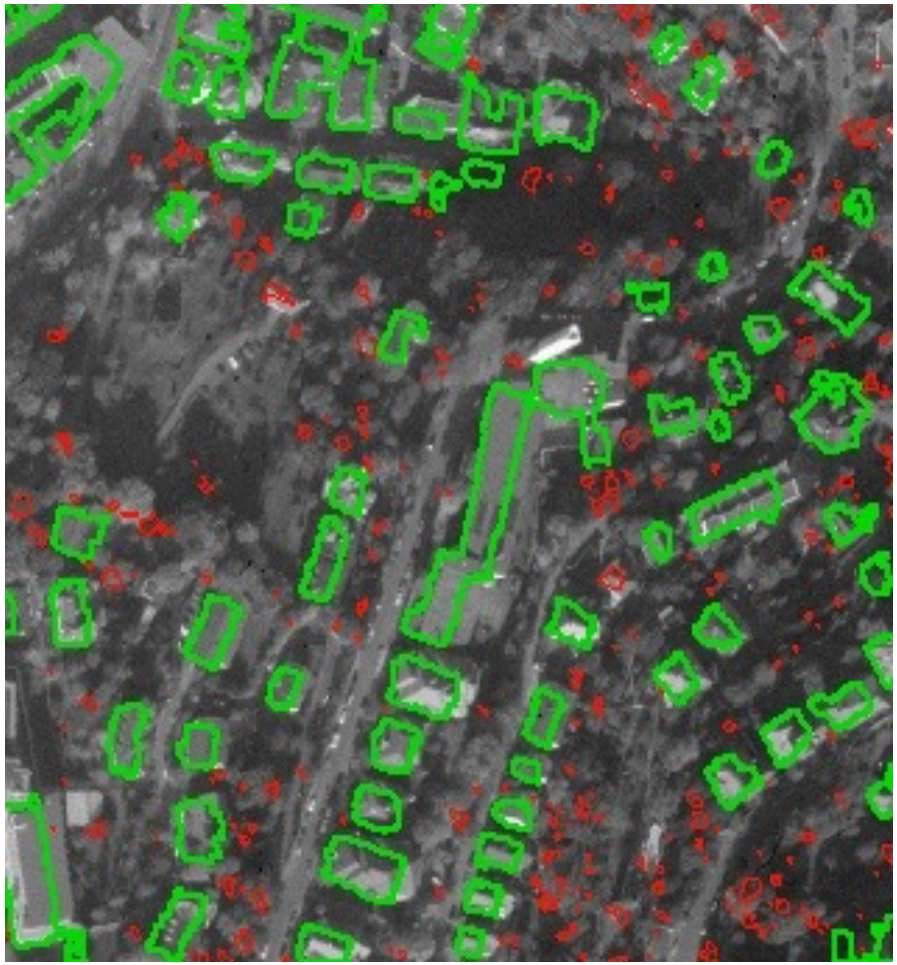
„High level“

Detection of buildings



DSM – DTM



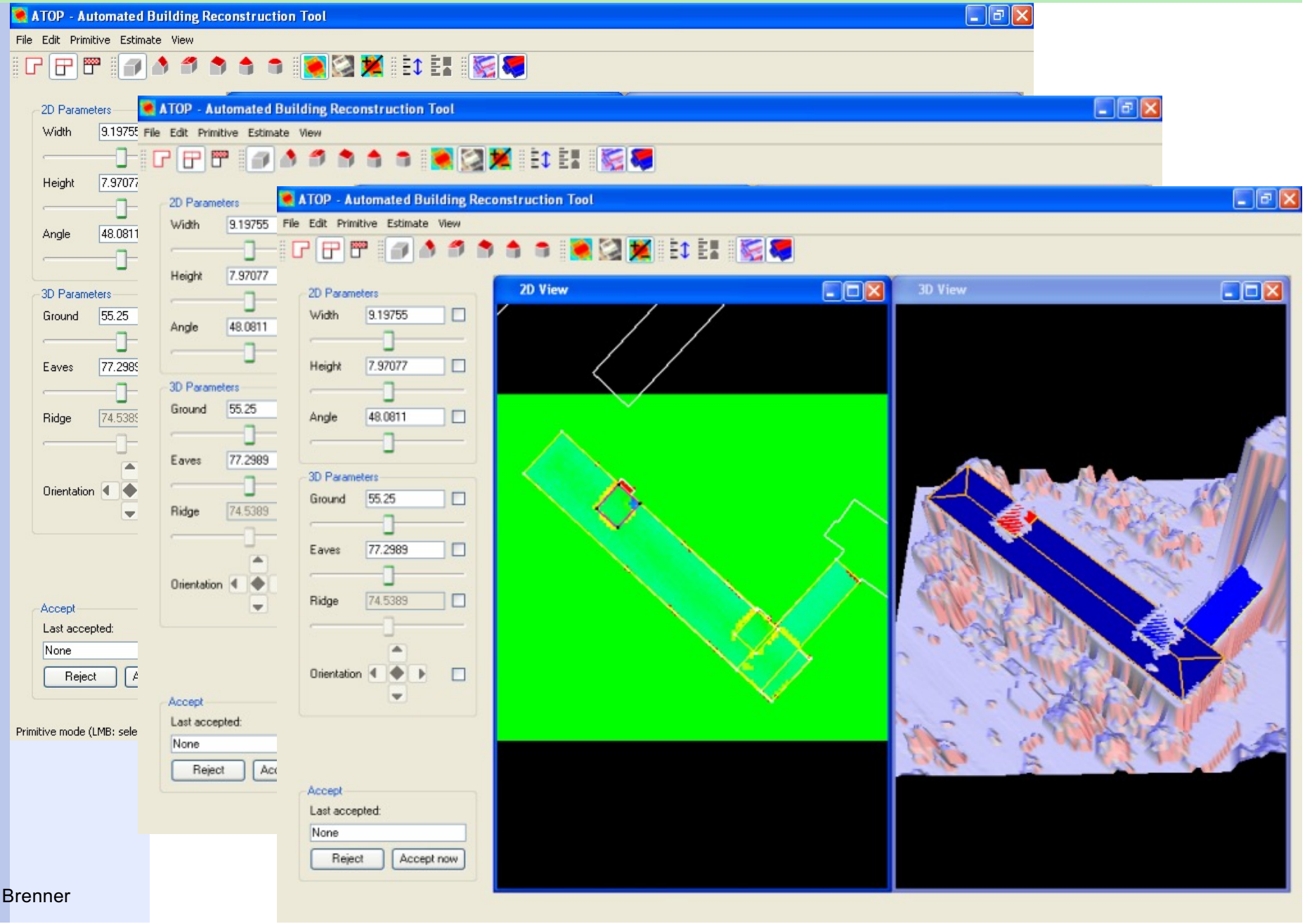
Orthophoto

Height > 5 m <u>and</u> footprint > 50 m^2

Height > 5 m

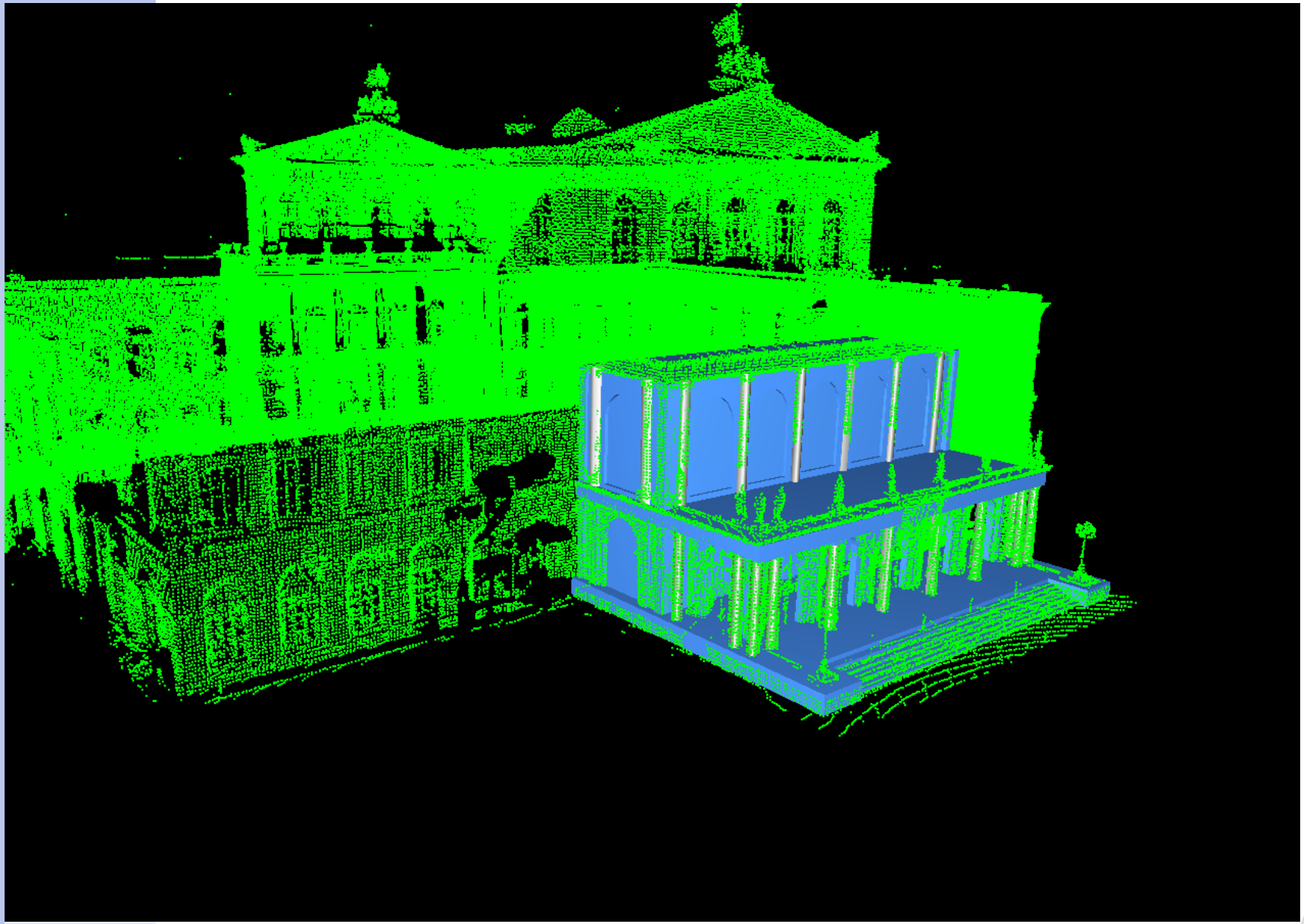
© Claus Brenner

Extraction and reconstruction of buildings



(c) Claus Brenner

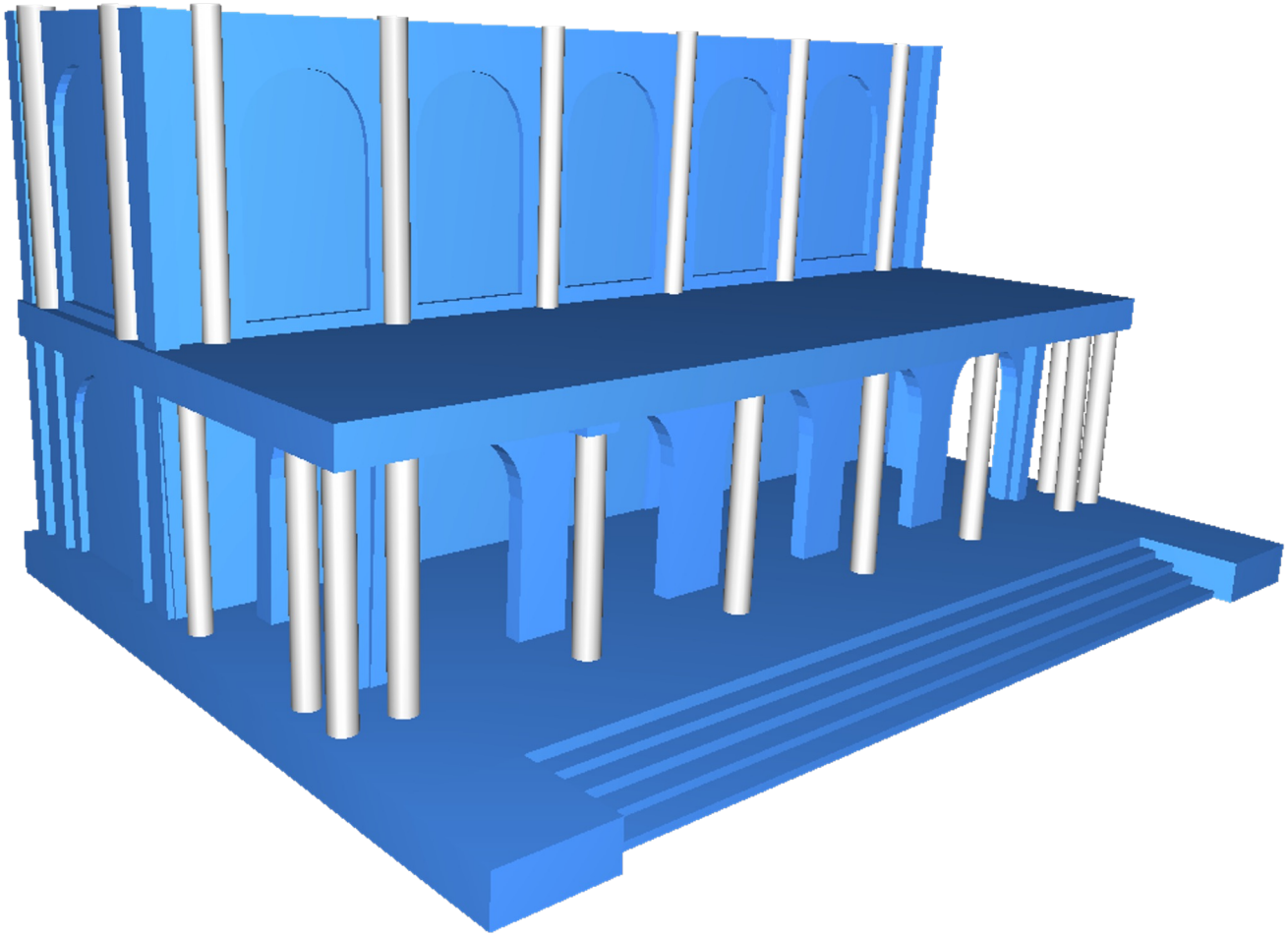
Derivation of CAD models (mainly manual)



(Modelled using Cyclone)

© Claus Brenner

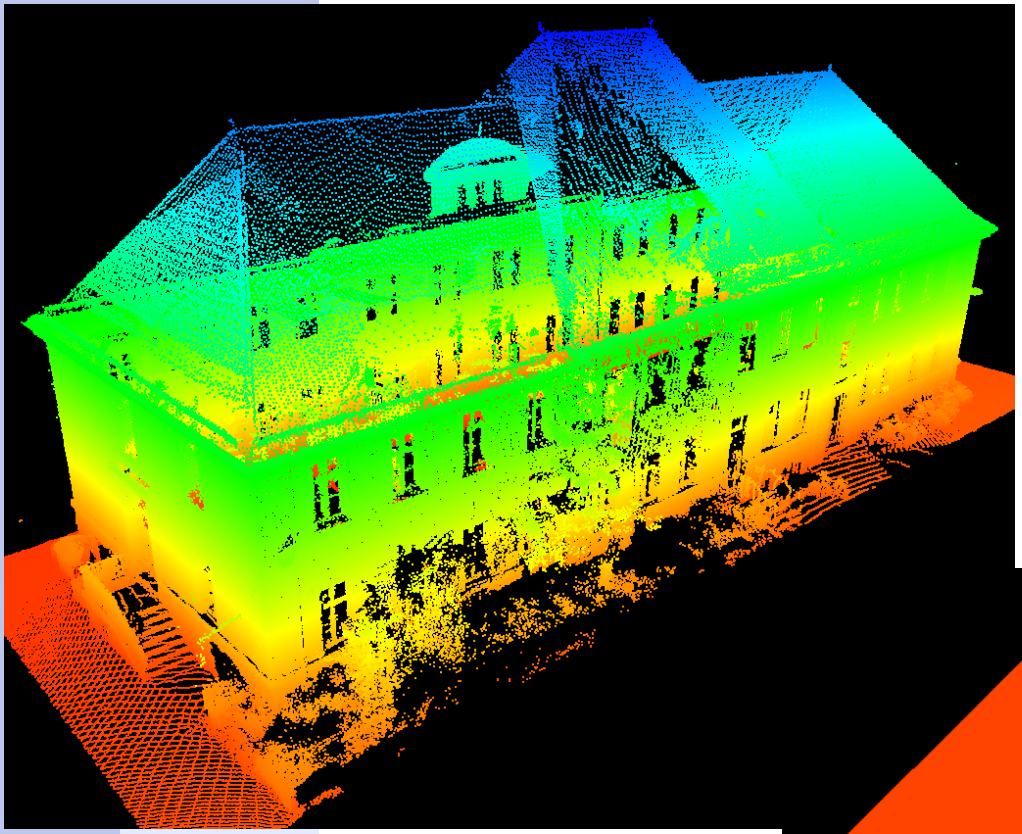
Derivation of CAD models (mainly manual)

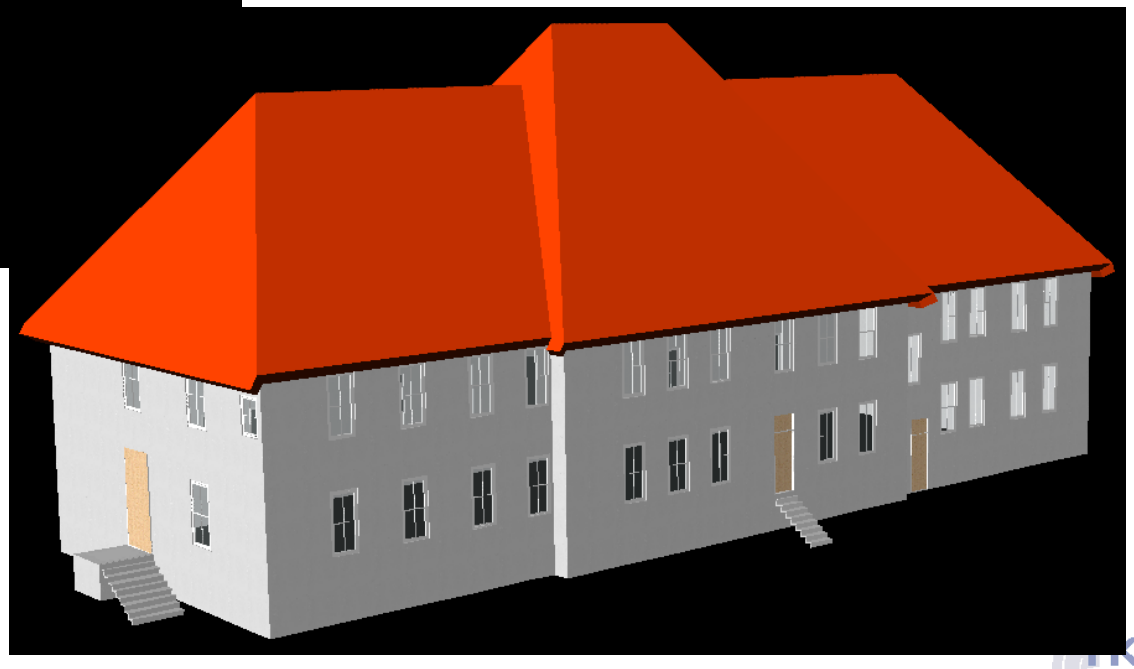


(Modelled using Cyclone)

© Claus Brenner

Derivation of CAD models (mainly manual)





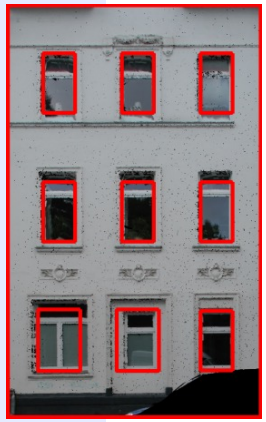
(Modelled using AutoCAD / CloudWorx)

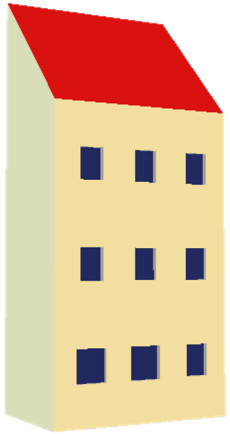
© Claus Brenner

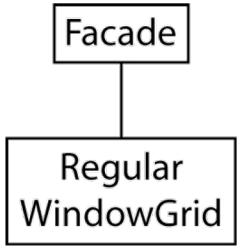
Automatic extraction of facade structures

自动提取外墙结构

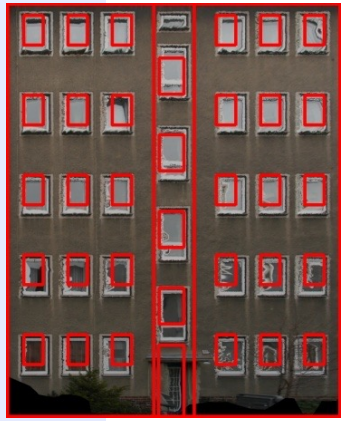
- Regular array of windows (with exceptions)

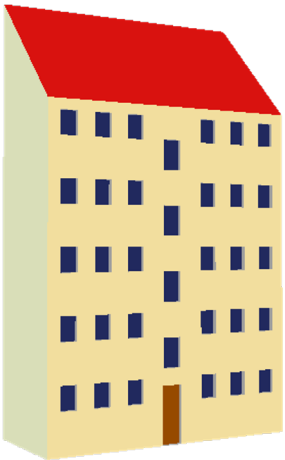


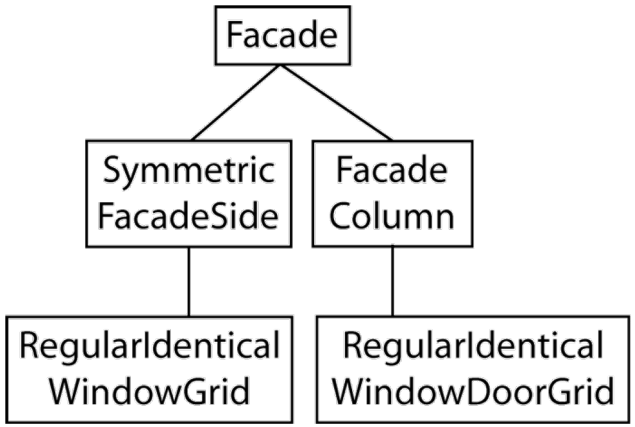




- Symmetric structure around staircase 楼梯周围的对称结构







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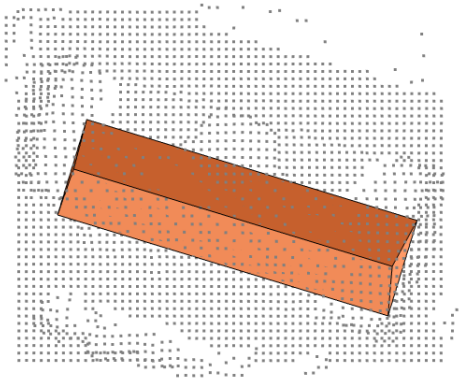
(Ph.D thesis Nora Ripperda)

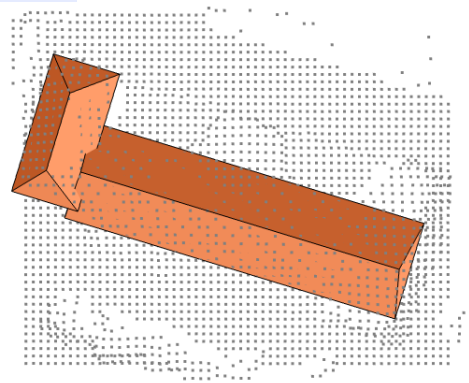
Extraction of roof structures 屋顶结构

Reference image

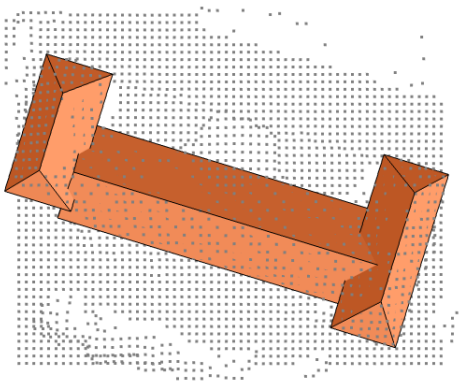
Point cloud



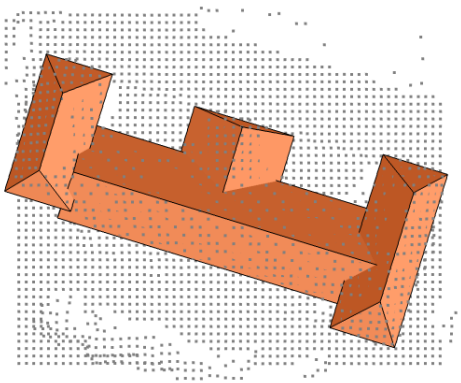
First primitive



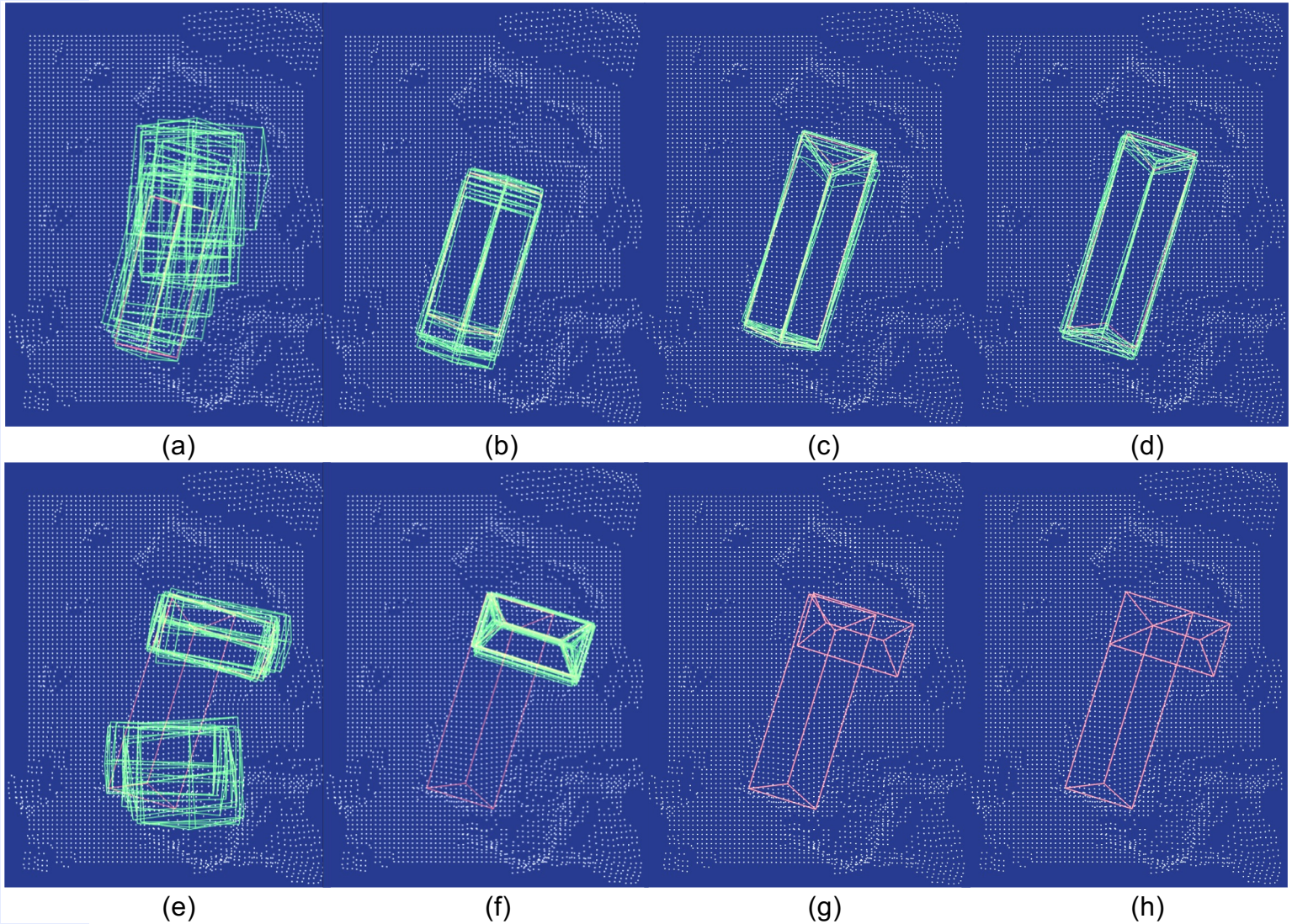
+Second primitive



+Third primitive



Reconstruction

Hai Huang

Extraction of roof structures