MGE-MSR-05 – Application and Evaluation of Mobile Sensor Systems

Final Presentation

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Location: MNL Library

Good GNSS conditions

Good traffic situation

Panel-based geometry useful for evaluation

TLS Measurement Tools

4 Terrestrial Laser Station locations

8 target locations

of these: 4 GNSS measurements

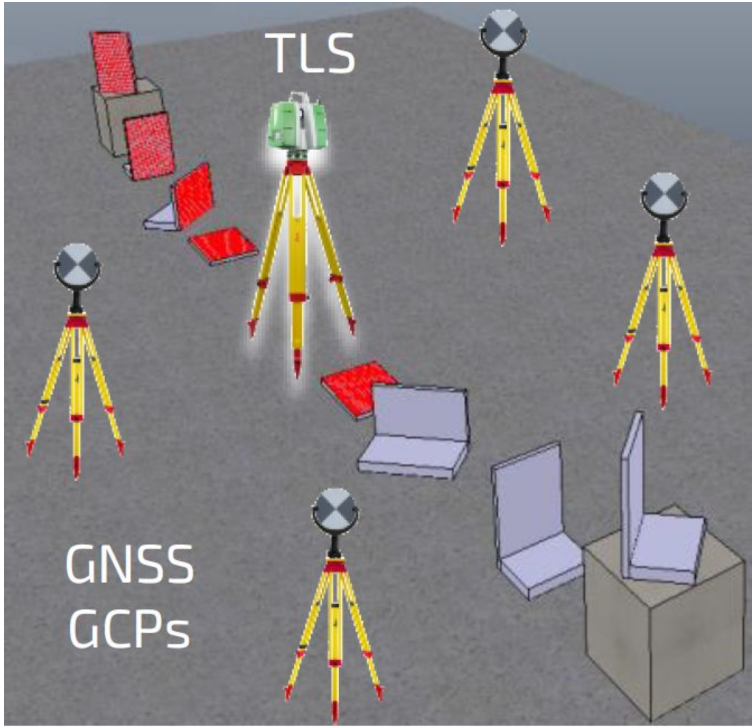
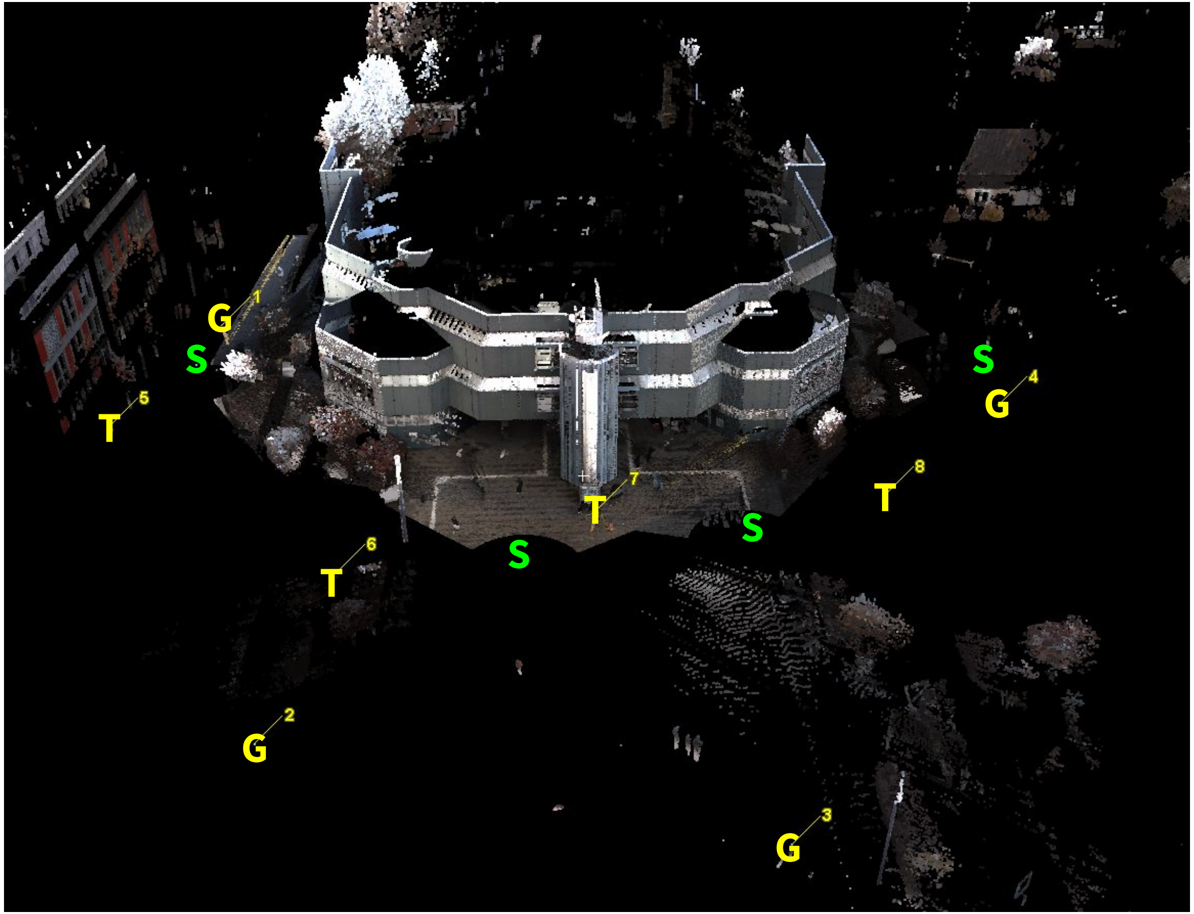


Image source: WS 2020/21 - Lasse Klingbeil & Tomislav Medic: MSR-07 - Introduction - Slide 2

TLS Measurement Setup



S - TLS
T - Target
G - Target + GNSS

Kinematic Measurement Tools

Mobile setup with known relation between sensors

Side-facing profile laser scanner

GNSS antenna

IMU

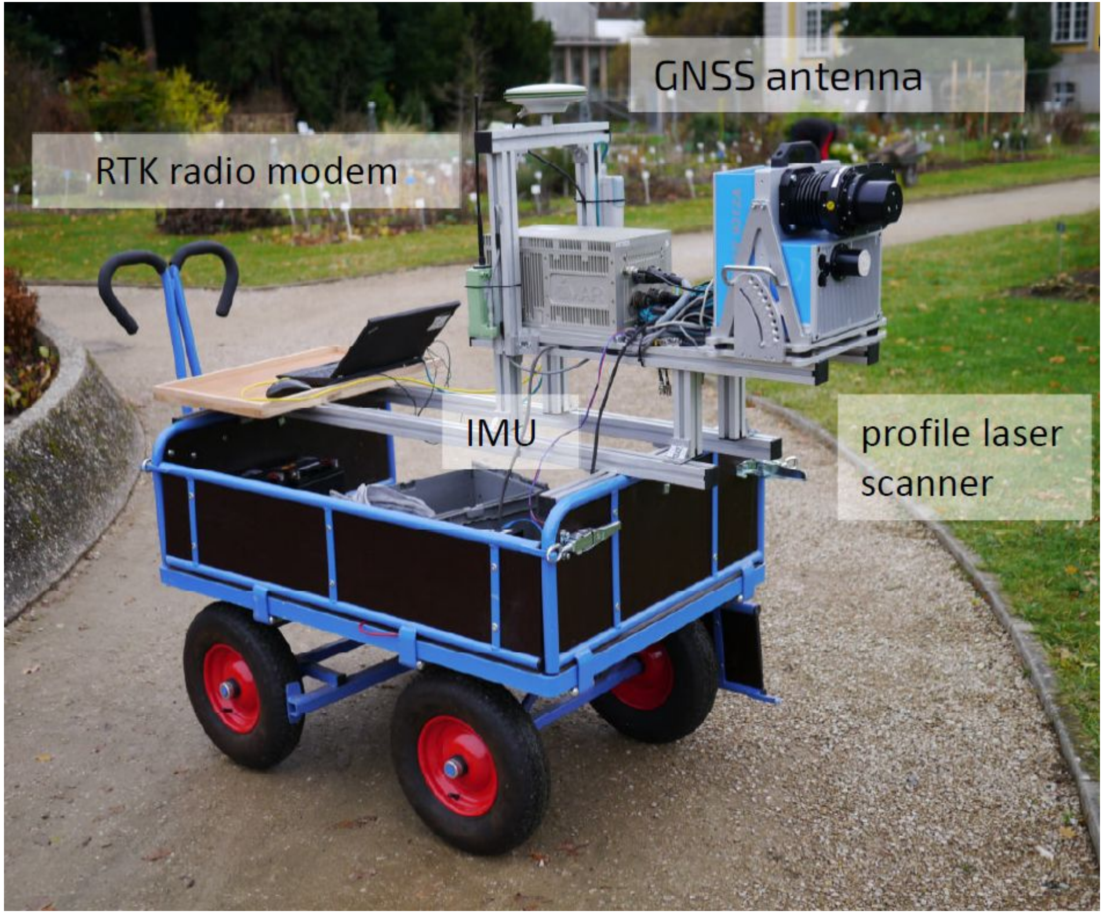
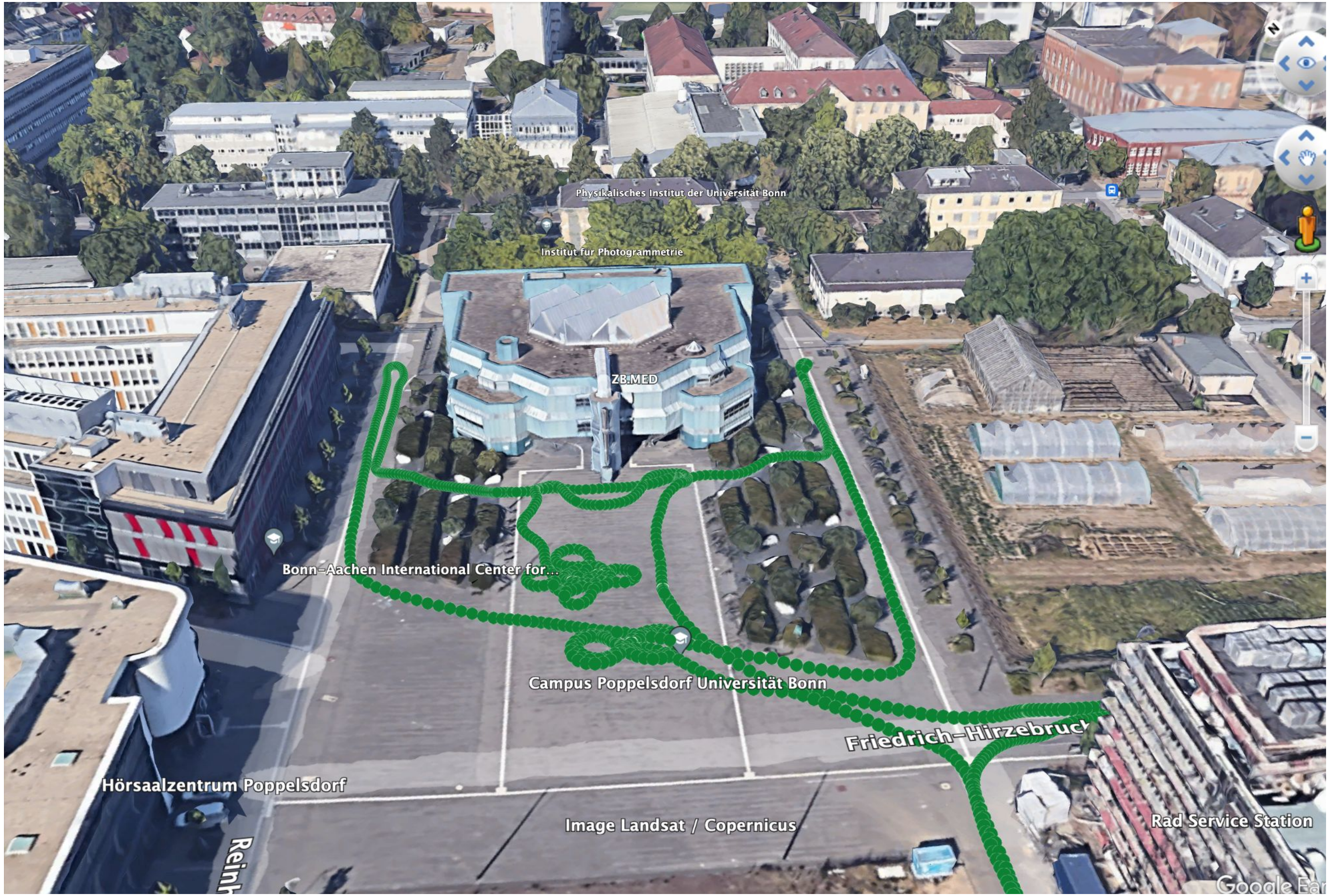


Image source: WS 2022/23 - Klingbeil - MSR-01 Sensor and State Estimation - Geodesy Part - 01: Introduction - Slide 43

Kinematic Measurement Path



2. TLS: Overview

2.1 Principle & Accuracy

2.2 Measurement

2.3 Processing & Results

- GNSS processing
- Point cloud processing

2.1 TLS: Principle and Accuracy

Image source: WS 2022/23 - Klingbeil - MSR-01 Sensor and State Estimation - Geodesy Part - 08 3D Sensors - Slide 45

Leica P50	
Type	Panorama Scanner
Distance measurement system	TOF with Waveform Digitising (WFD) technology
Range accuracy	1.2 mm + 10ppm over full range (120 m / 270 m mode)
Scan rate	Up to 1,000,000 pts/s
FOV	Horizontal: 360° Vertical: 290°

2.1 TLS: Principle and Accuracy

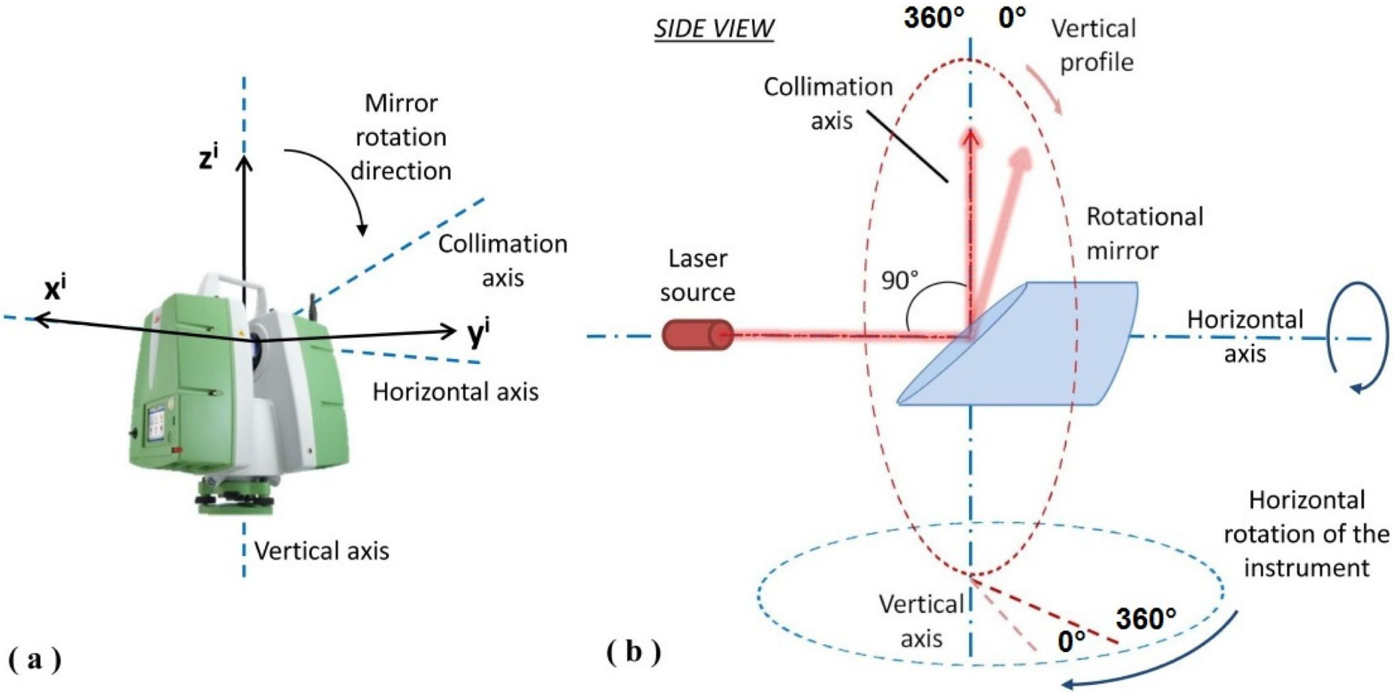


Image source: Medić T et al "Sensitivity Analysis and Minimal Measurement Geometry for the Target-Based Calibration of High-End Panoramic Terrestrial Laser Scanners." RS. 2019;

2.1 GNSS: Principle and Accuracy

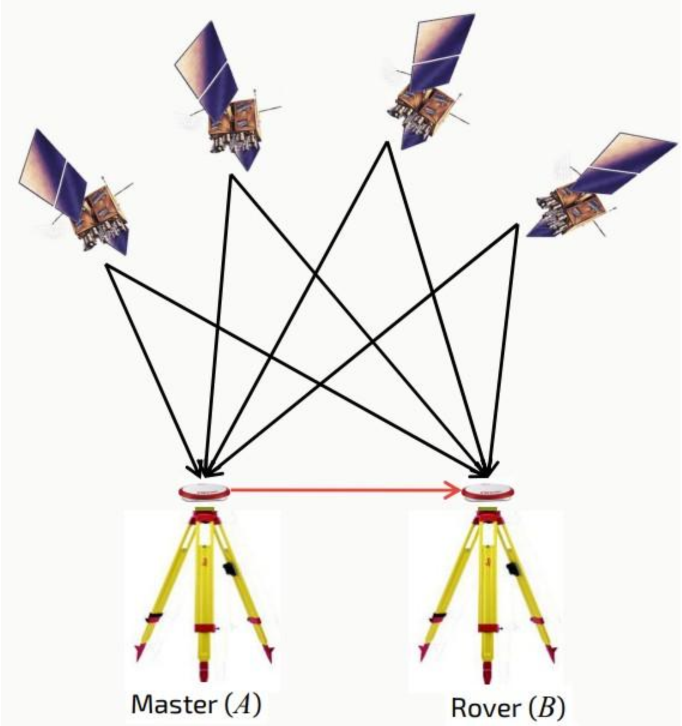
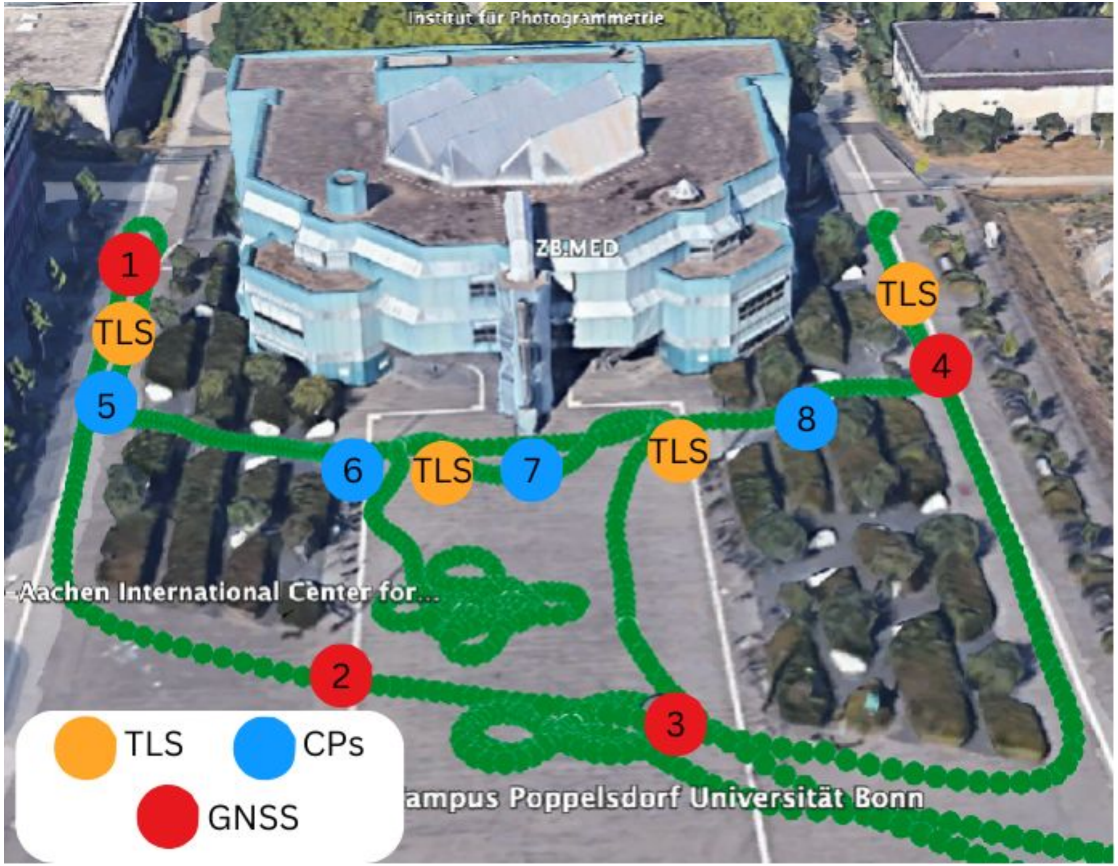


Image source: WS 2022/23 - Dr. Lasse Klingbeil: GNSS - 06 - Differential GNSS using carrier phases - slide 14

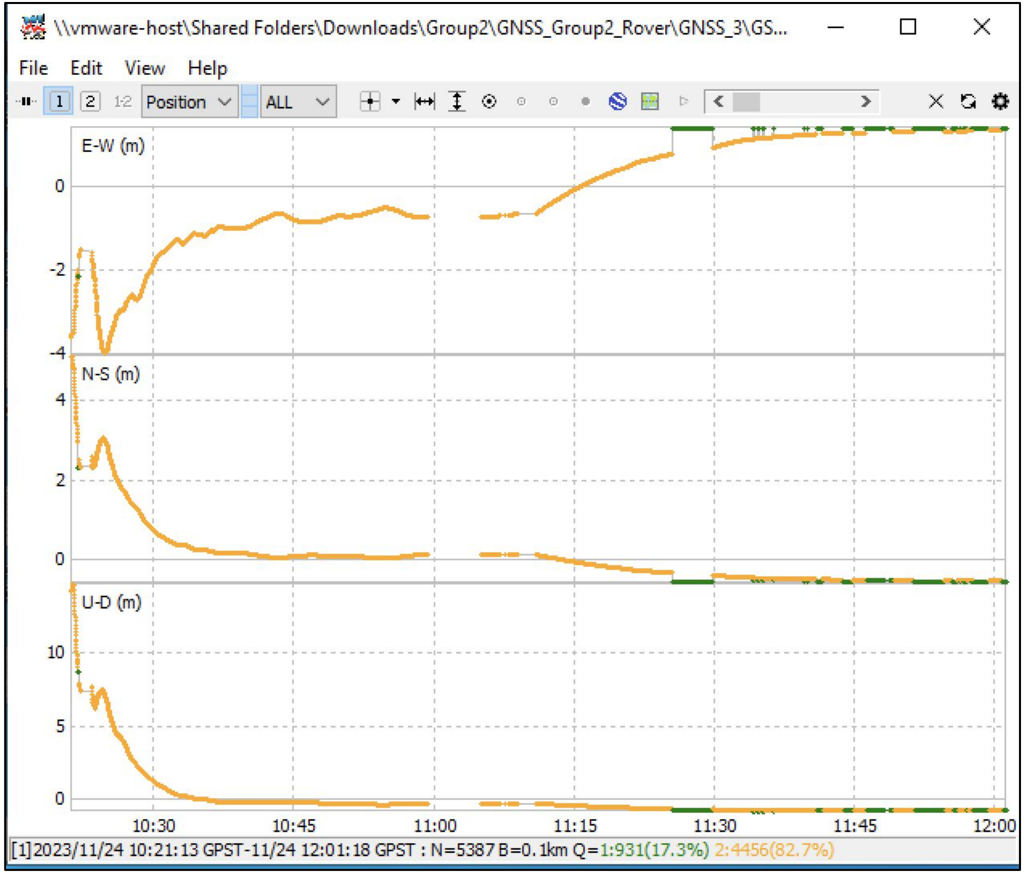
Relative GNSS measurement with VRS	
Baseline	< 100 meters
Duration	Around 1 hour
Real time	Post Processing
Position accuracy	(~1-2 cm)
Environment -related errors	Multi path Non-line-of-sight

2.2 TLS: Measurement



1. Planning about the location of measurement points, date, and time
2. Setting tripods for 4 control points, 4 TLS points, and 4 GNSS points(also used as CPs)
3. Perform TLS, each point takes around 10 minutes
4. Perform GNSS measurements, each point takes around 1 hour

2.3 GNSS processing Point 1



Parameters:

- GPS and Galileo Satellites
- Elevation angle 15°
- Frequencies L1 and L2

Output:

- Solution for Static Mode: ALL
- Float solution > Fixed solution

2.3 GNSS processing Point 1

Parameters:

- GPS and Galileo Satellites
- Elevation angle 30°
- Frequencies L1 and L2

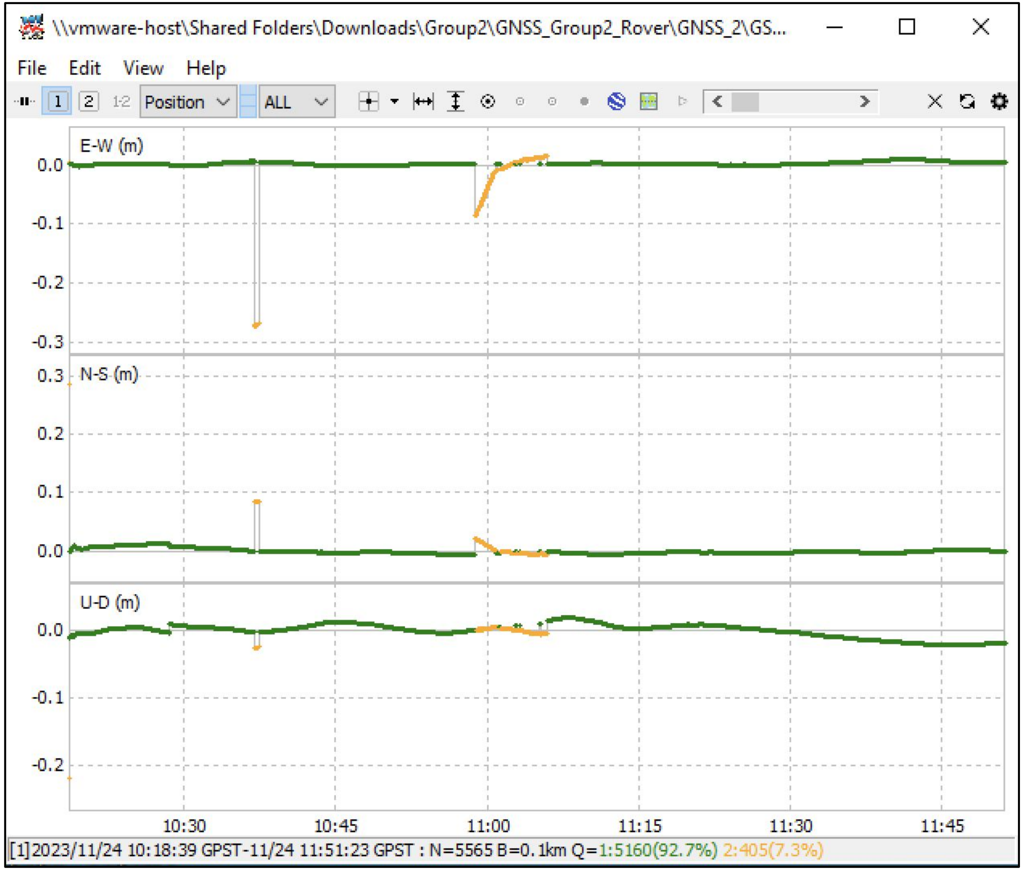
Output:

- Solution for Static Mode: ALL
- Fixed solution > Float solution

We get a fixed solution, leading to a better accuracy

*Error in height

2.3 GNSS processing Point 2



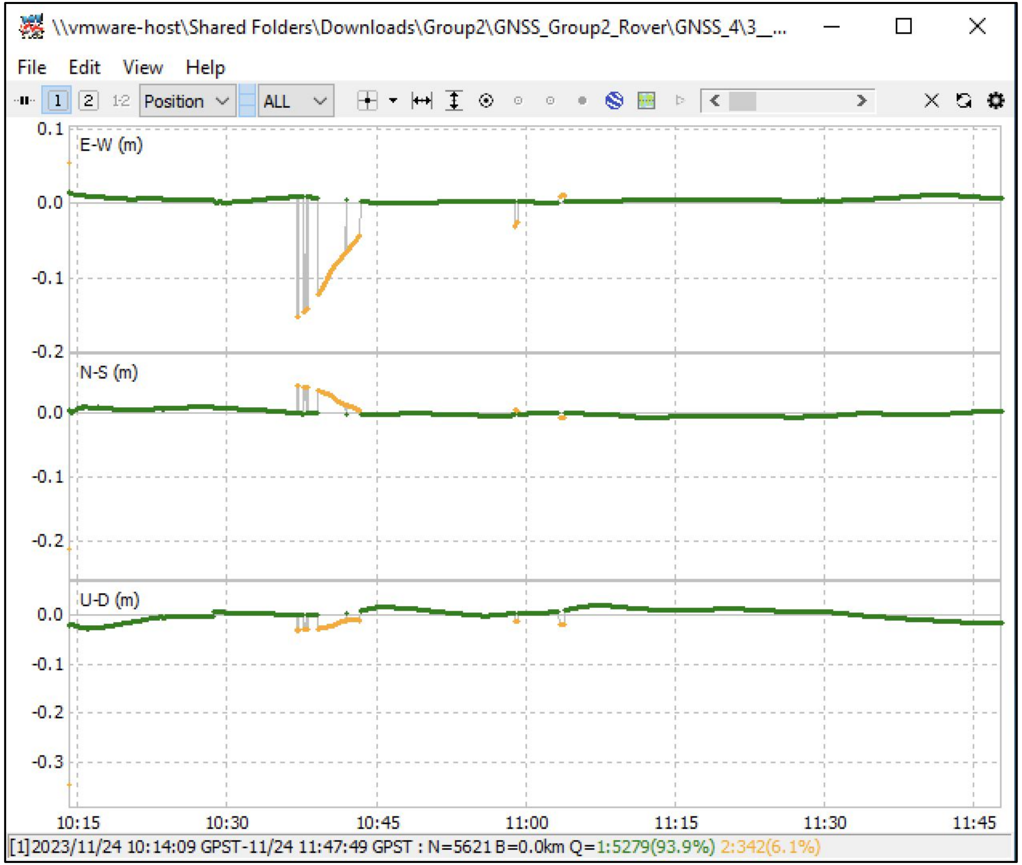
Parameters:

- GPS and Galileo Satellites
- Elevation angle 15°
- Frequencies L1 and L2

Output:

- Solution for Static Mode: ALL
- Fixed solution

2.3 GNSS processing Point 3



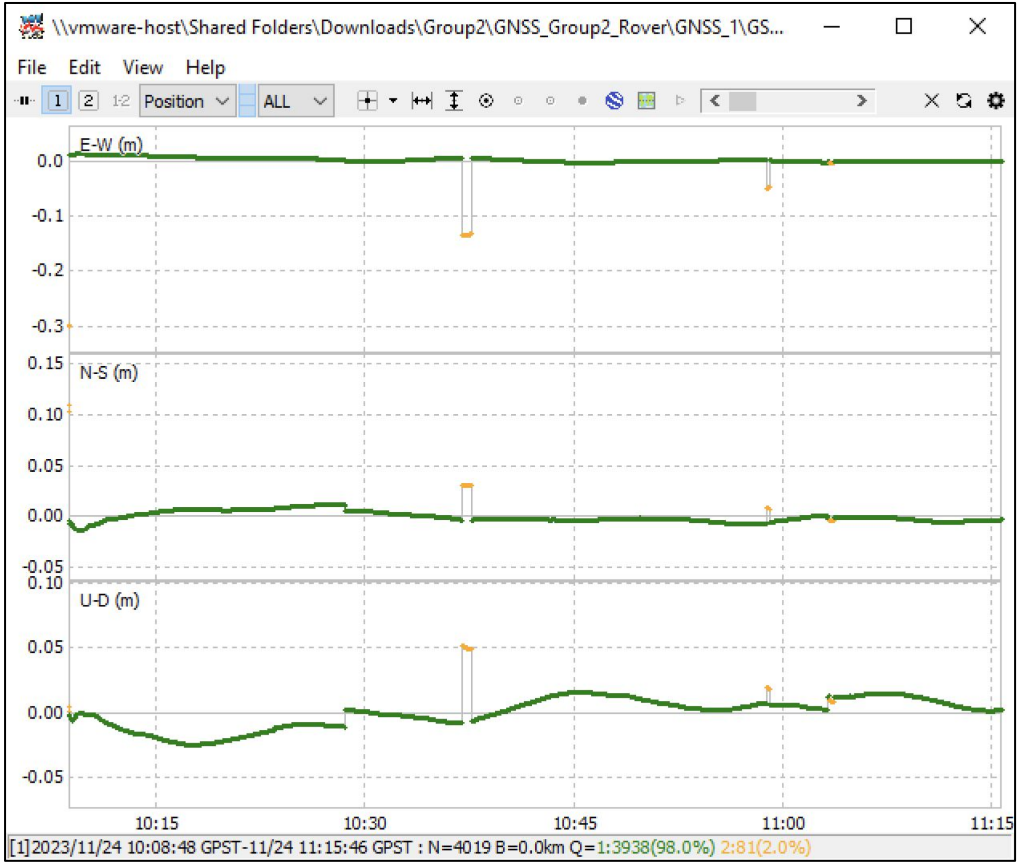
Parameters:

- GPS and Galileo Satellites
- Elevation angle 15°
- Frequencies L1 and L2

Output:

- Solution for Static Mode: ALL
- Fixed solution

2.3 GNSS processing Point 4



Parameters:

- GPS and Galileo Satellites
- Elevation angle 15°
- Frequencies L1 and L2

Output:

- Solution for Static Mode: ALL
- Fixed solution

2.3 TLS: GNSS positions

ID	E (m)	N (m)	H (m)	Fixed Solution (%)(↑)	Float Solution (%)(↓)	Elevation angle (degree)	Remarks
P1	364928.114	5621219.634	109.613	69.8	30.2	30	Measured between two planes of buildings.
P2	364905.078	5621172.278	109.286	92.7	7.3	15	Open-area
P3	364921.764	5621148.212	109.185	93.9	6.1	15	Open-area
P4	364967.620	5621164.584	109.590	98.0	2.0	15	Open-area

2.3 TLS: Registration process

1. Import data into Leica cyclone
2. Get TLS point cloud with targets
3. Click the Auto-Add Constraints command
4. Get the results

2.3 TLS: Registration result

ScanWorlds' Constraints | Constraint List | ModelSpaces

Constraint ID	ScanWorld	ScanWorld	Type	Status	Weight	Overlap Points	Error	Error Vector	Group Error	Group Error Vector	Group
7	scan3: SW-00...	scan10: SW-0...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, 0.001, 0.000) m	n/a	n/a	Ungrouped
4	scan3: SW-00...	scan5: SW-00...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, 0.000, 0.001) m	n/a	n/a	Ungrouped
8	scan3: SW-00...	scan5: SW-00...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.000 m	0.000, 0.000, 0.000) m	n/a	n/a	Ungrouped
8	scan3: SW-00...	scan7: SW-00...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, 0.000, 0.001) m	n/a	n/a	Ungrouped
7	scan3: SW-00...	scan5: SW-00...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, 0.000, -0.001) m	n/a	n/a	Ungrouped
7	scan3: SW-00...	scan7: SW-00...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, -0.001, -0.001) m	n/a	n/a	Ungrouped
7	scan5: SW-00...	scan7: SW-00...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, -0.001, 0.000) m	n/a	n/a	Ungrouped
7	scan5: SW-00...	scan10: SW-0...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, 0.001, 0.001) m	n/a	n/a	Ungrouped
6	scan5: SW-00...	scan7: SW-00...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, 0.000, -0.001) m	n/a	n/a	Ungrouped
6	scan5: SW-00...	scan10: SW-0...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, 0.000, -0.001) m	n/a	n/a	Ungrouped
2	scan5: SW-00...	scan7: SW-00...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.000 m	0.000, 0.000, 0.000) m	n/a	n/a	Ungrouped
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8	scan5: SW-00...	scan7: SW-00...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.000 m	0.000, 0.000, 0.000) m	n/a	n/a	Ungrouped
7	scan7: SW-00...	scan10: SW-0...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.002 m	0.000, 0.002, 0.001) m	n/a	n/a	Ungrouped
5	scan7: SW-00...	scan10: SW-0...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, 0.000, -0.001) m	n/a	n/a	Ungrouped
1	scan7: SW-00...	scan10: SW-0...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.001, 0.000, -0.001) m	n/a	n/a	Ungrouped
6	scan7: SW-00...	scan10: SW-0...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, -0.001, 0.000) m	n/a	n/a	Ungrouped
2	scan7: SW-00...	scan10: SW-0...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.001 m	0.000, -0.001, 0.000) m	n/a	n/a	Ungrouped

The results are good because most of the error vectors (X, Y)are approximately zero, which are roughly equivalent to the accuracy of P50 (1.2 mm)

2.3 TLS: Georeference

ScanWorlds' Constraints | Constraint List | ModelSpaces

Constraint ID	ScanWorld	ScanWorld	Type	Status	Weight	Overlap Points	Error	Error Vector	Group Error	Group Error Vector	Group
2	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.024 m	(0.006, 0.002, -0.023) m	n/a	n/a	Ungrouped
1	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.034 m	(-0.002, -0.010, 0.032) m	n/a	n/a	Ungrouped
4	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.008 m	(-0.007, 0.000, 0.004) m	n/a	n/a	Ungrouped
3	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.016 m	(0.003, 0.008, -0.013) m	n/a	n/a	Ungrouped

ID	Weight	Error (m)	Error vector (m)
1	1	0.034	(-0.002, -0.010, 0.032)
2	1	0.024	(0.006, 0.002, -0.023)
3	1	0.016	(0.003, 0.008, -0.013)
4	1	0.008	(-0.007, 0.000, 0.004)

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3	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	0.9000	n/a	0.010 m	(0.003, 0.005, -0.008) m	n/a	n/a	Ungrouped
2	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	0.9000	n/a	0.018 m	(0.006, -0.001, -0.017) m	n/a	n/a	Ungrouped
4	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.012 m	(-0.007, -0.001, 0.009) m	n/a	n/a	Ungrouped

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4	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.008 m	(-0.007, 0.000, 0.004) m	n/a	n/a	Ungrouped
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4	1	0.008	(-0.007, 0.000, 0.004)

Change the weights → acc. Fixed solution pct.

ID	W	Fixed solution(%)	Error (m)	Error vector (m)
1	0.5	69.8	0.046	(-0.002, -0.010, 0.045)
2	0.9	92.7	0.018	(0.006, -0.001, -0.017)
3	0.9	93.9	0.010	(0.003, 0.005, -0.008)
4	1	98.0	0.012	(-0.007, -0.001, 0.009)

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3	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	0.9000	n/a	0.010 m	(0.003, 0.005, -0.008) m	n/a	n/a	Ungrouped
2	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	0.9000	n/a	0.018 m	(0.006, -0.001, -0.017) m	n/a	n/a	Ungrouped
4	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.012 m	(-0.007, -0.001, 0.009) m	n/a	n/a	Ungrouped

2.3 TLS: Georeference

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1	1	0.034	(-0.002, -0.010, 0.032)
2	1	0.024	(0.006, 0.002, -0.023)
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Change the weights → acc. Fixed solution pct.

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2	0.9	92.7	0.018	(0.006, -0.001, -0.017)
3	0.9	93.9	0.010	(0.003, 0.005, -0.008)
4	1	98.0	0.012	(-0.007, -0.001, 0.009)

- Point 1 suffers from multi-path and NLOS, leading to high uncertainty in the up-direction. Therefore, we do not place much emphasis on the error vector of the up-direction.
- By using a reweighting strategy, we can ensure that the accuracies of points 2, 3, and 4 are close to the accuracy of the GNSS measurements (~ 1 - 2 cm). Especially for height, the error vectors of the heights of these three points are lower than 2 centimeters

2.3 TLS: Georeference

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1	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.034 m	(-0.002, -0.010, 0.032) m	n/a	n/a	Ungrouped
4	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.008 m	(-0.007, 0.000, 0.004) m	n/a	n/a	Ungrouped
3	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.016 m	(0.003, 0.008, -0.013) m	n/a	n/a	Ungrouped

ID	Weight	Error (m)	sum error, sum error^2
~~1~~	~~1~~	~~0.034~~	~~(-0.002, -0.010, 0.032)~~
2	1	0.024	0.048 ,0.0299
3	1	0.016	
4	1	0.008	

Change the weights acc. Fixed solution pct. →

ID	W	Fixed solution(%)	Error (m)	sum error, sum error^2
~~1~~	~~0.5~~	~~69.8~~	~~0.046~~	~~(-0.002, -0.010, 0.045)~~
2	0.9	92.7	0.018	0.040, 0.0238
3	0.9	93.9	0.010	
4	1	98.0	0.012	

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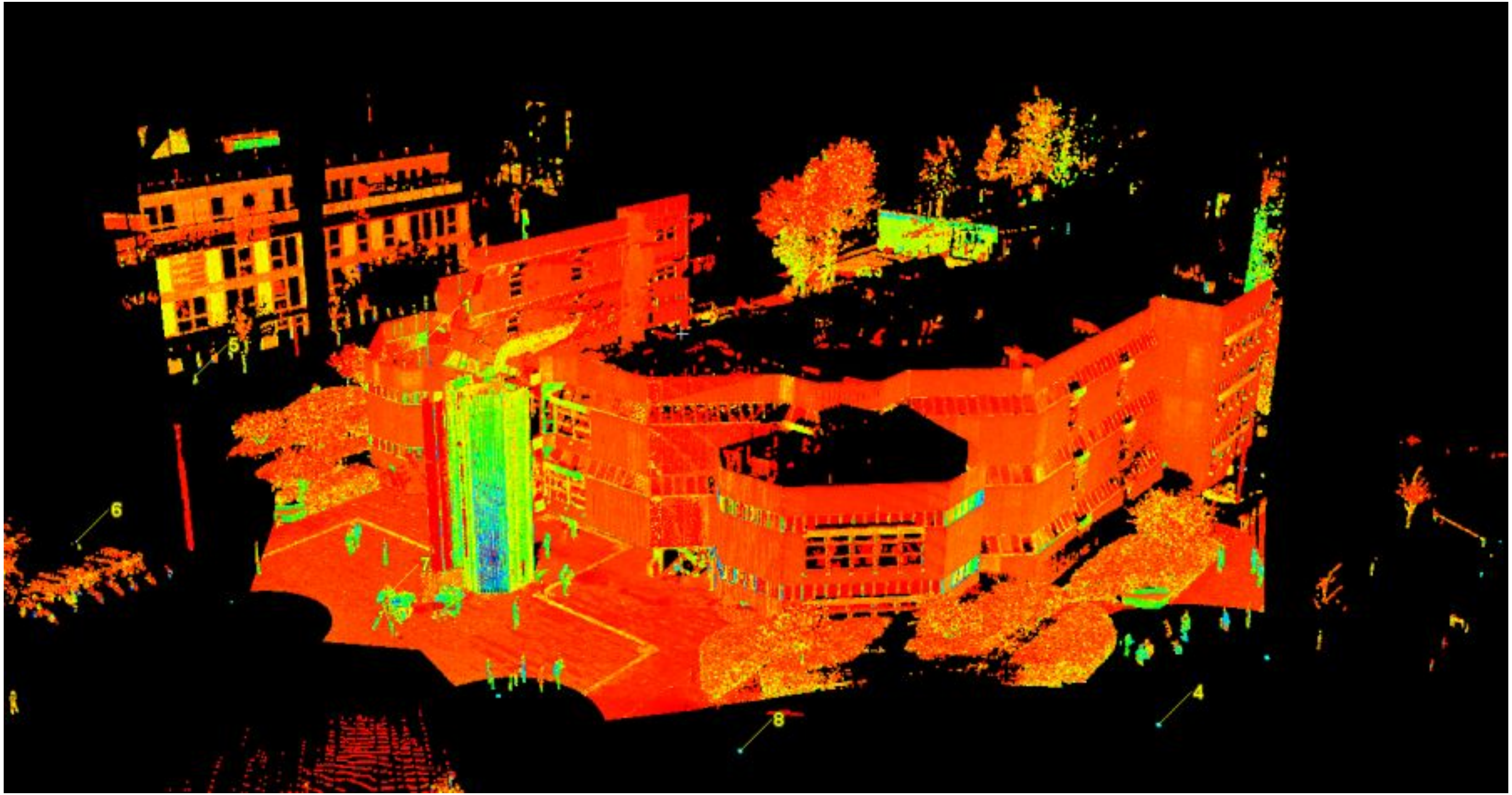
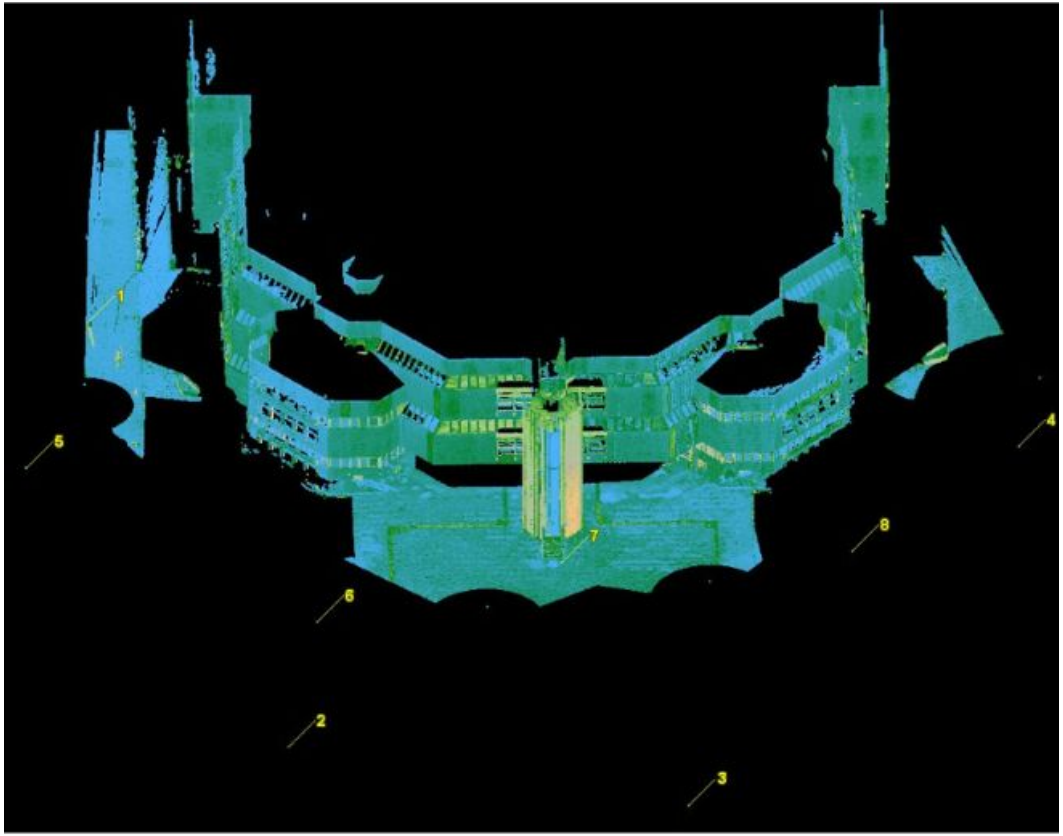
2	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	0.9000	n/a	0.018 m	(0.006, -0.001, -0.017) m	n/a	n/a	Ungrouped
4	ScanWorld [R...	coor.txt (Level...	Coincident: Vertex - Vertex	On	1.0000	n/a	0.012 m	(-0.007, -0.001, 0.009) m	n/a	n/a	Ungrouped

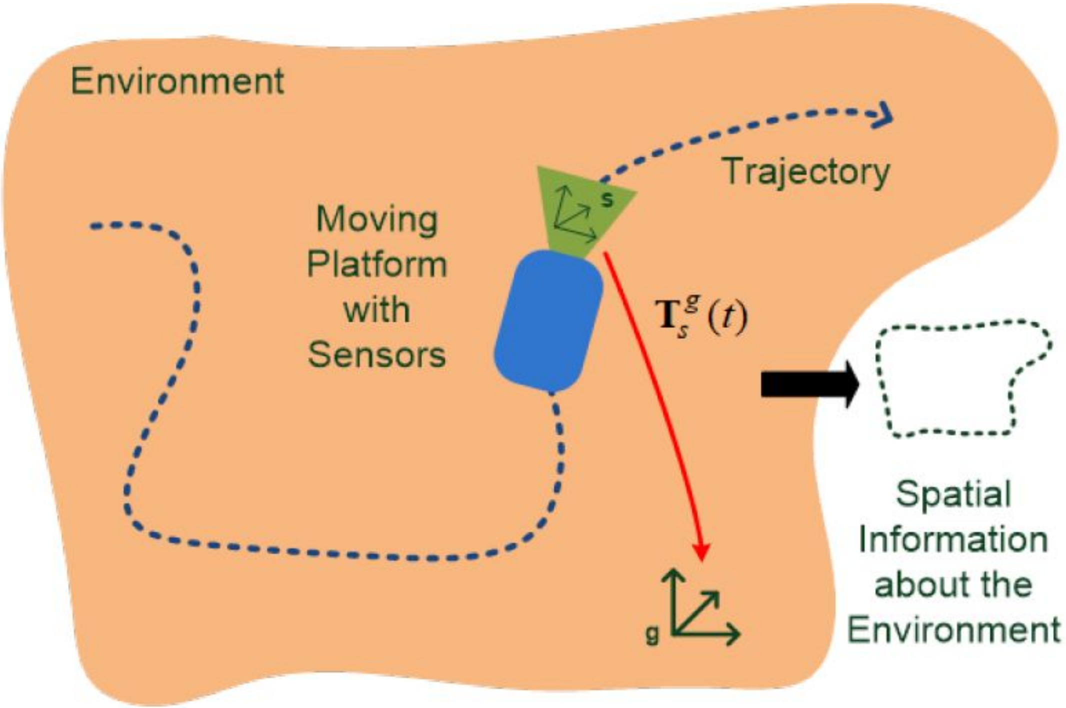
2.3 TLS: Result



2. TLS: Cleaned PCD Result



Mobile Mapping and Georeferencing



Source: Dr. Lasse Klingbeil, Georeferencing of Mobile Mapping Data

Mobile Mapping and Georeferencing

$$\boxed{\mathbf{x}_o^g} = \boxed{\mathbf{T}_b^g(t_k)}\boxed{\mathbf{T}_s^b(t_k)}\boxed{\mathbf{x}_o^s(t_k)}$$

Global Frame

Trajectory Estimation

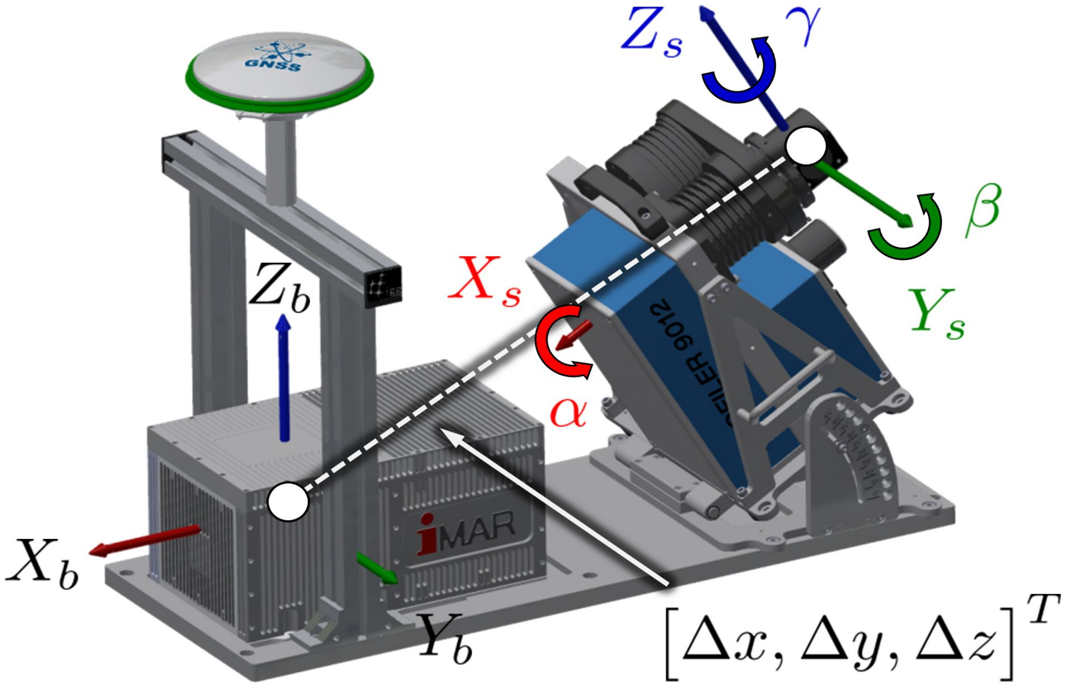
System Calibration

Sensor Frame

Mobile Mapping System

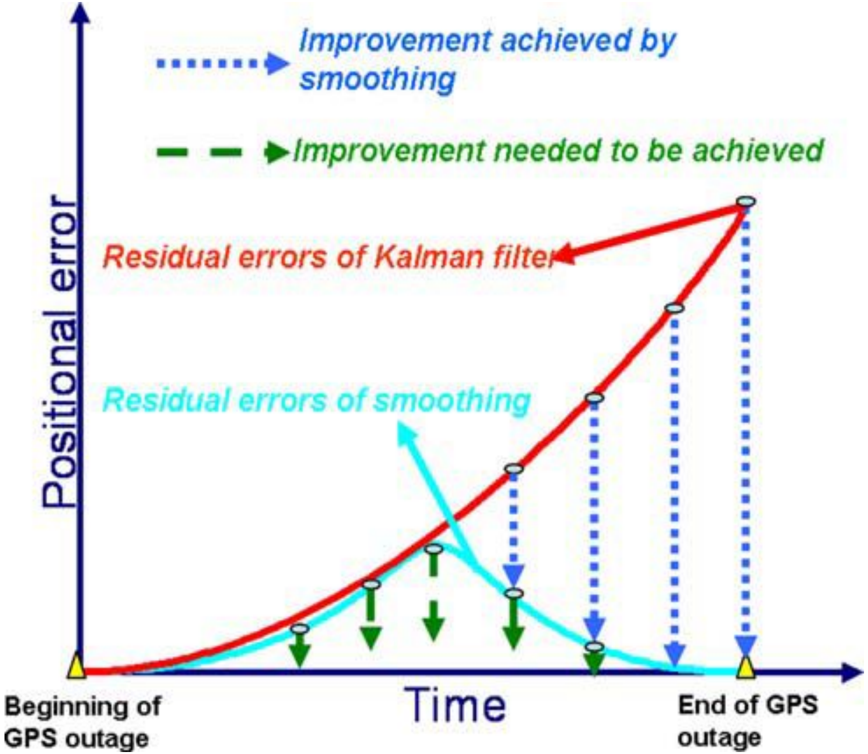
IGG MMS:

- GNSS
- IMU
- 2D Laser Scanner



Source: Dr. Lasse Klingbeil, Georeferencing of Mobile Mapping Data

Trajectory Estimation



Source: Dr. Lasse Klingbeil, MSR-02 Lecture Slides

Rauch-Tung-Striebel Smoother

Backward recursion equations for the smoothed means $\mathbf{m}_k^s$ and covariances $\mathbf{P}_k^s$:

$$\begin{aligned}
\mathbf{m}_{k+1}^- &= \mathbf{A}_k\,\mathbf{m}_k \\
\mathbf{P}_{k+1}^- &= \mathbf{A}_k\,\mathbf{P}_k\,\mathbf{A}_k^T + \mathbf{Q}_k \\
\mathbf{G}_k &= \mathbf{P}_k\,\mathbf{A}_k^T\,[\mathbf{P}_{k+1}^-]^{-1} \\
\mathbf{m}_k^s &= \mathbf{m}_k + \mathbf{G}_k\,[\mathbf{m}_{k+1}^s - \mathbf{m}_{k+1}^-] \\
\mathbf{P}_k^s &= \mathbf{P}_k + \mathbf{G}_k\,[\mathbf{P}_{k+1}^s - \mathbf{P}_{k+1}^-]\,\mathbf{G}_k^T,
\end{aligned}$$

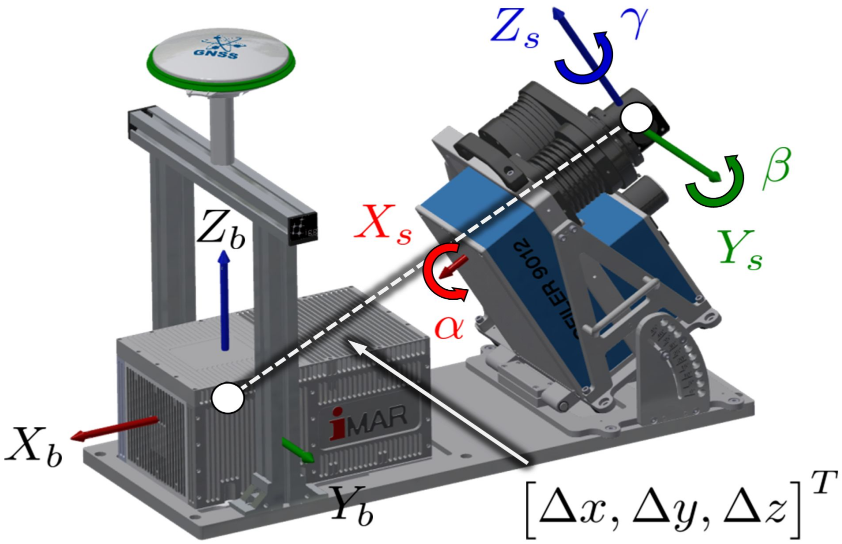
- $\mathbf{m}_k$ and $\mathbf{P}_k$ are the mean and covariance computed by the Kalman filter.
- The recursion is started from the last time step T, with $\mathbf{m}_T^s = \mathbf{m}_T$ and $\mathbf{P}_T^s = \mathbf{P}_T$.

Source: Simo Särkkä, Lecture Slides

System Calibration

- Estimation of:
  - Translation (**Δx, Δy, Δz**)
  - Rotation (α, β, γ)

- Body frame coincides with IMU frame
- Static transformation



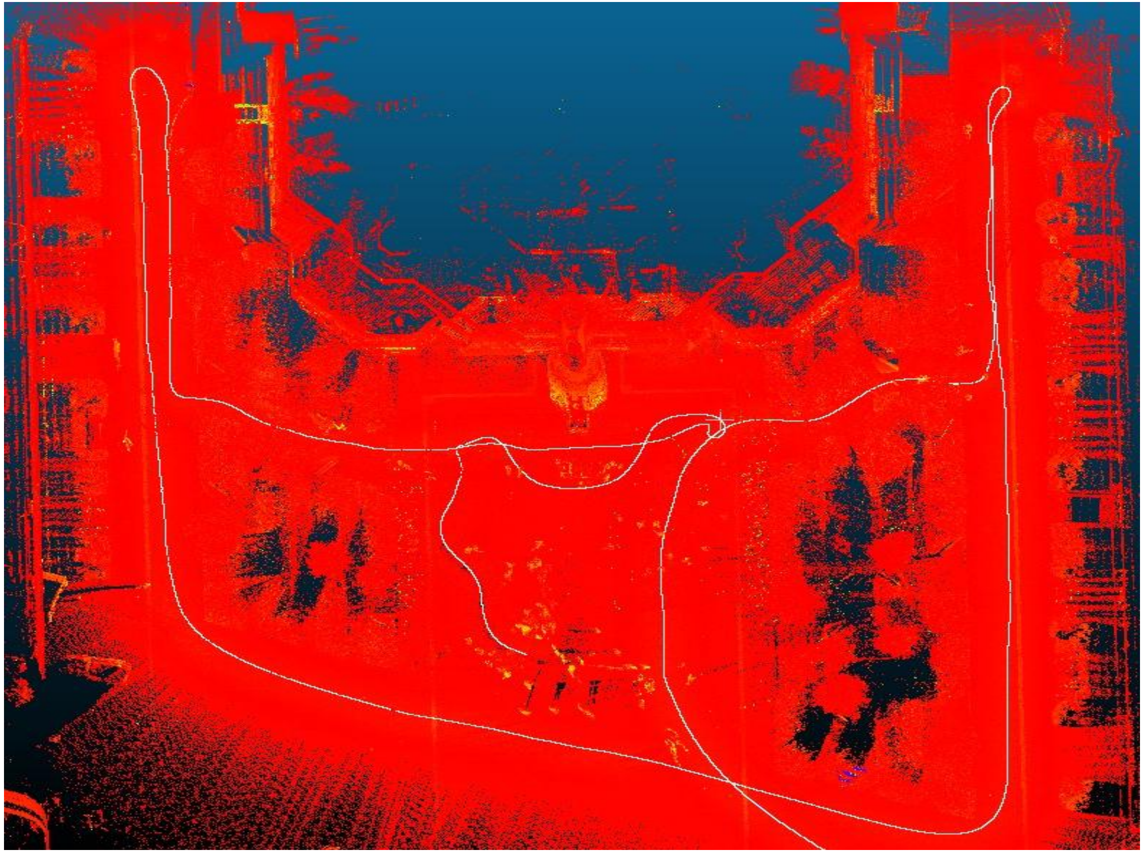
$$\mathbf{x}_o^g = \mathbf{T}_b^g(t_k)\boxed{\mathbf{T}_s^b(t_k)}\mathbf{x}_o^s(t_k)$$

Sensor Synchronization

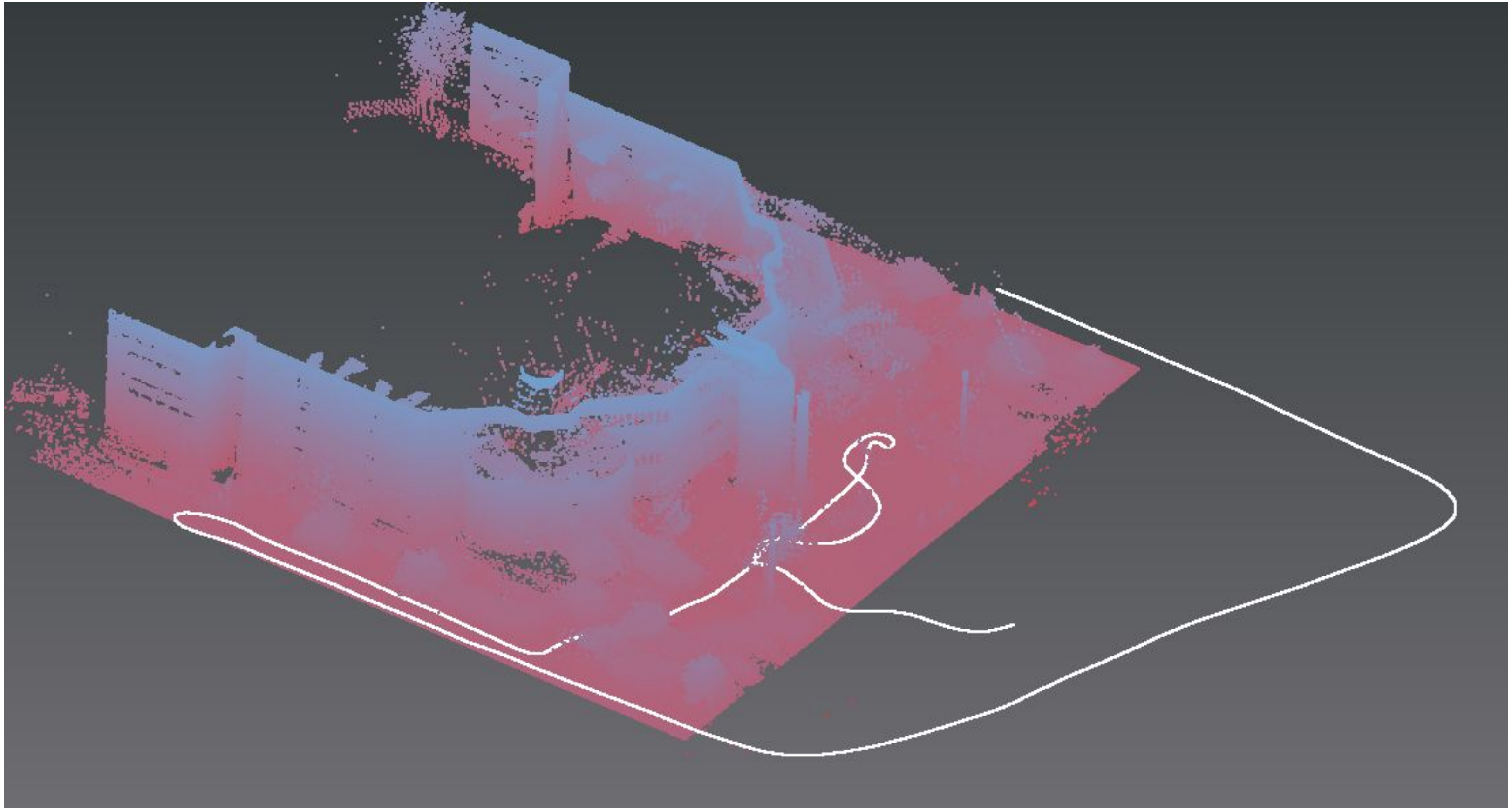
- **Sensors (GNSS, IMU, LS) have:**
  - **Different clocks** $\Rightarrow$ **Use one common (Master) clock**
  - **Different measurement rates** $\Rightarrow$ **Interpolation**

$$\mathbf{x}_o^g = \mathbf{T}_b^g(\boxed{t_k})\mathbf{T}_s^b(\boxed{t_k})\mathbf{x}_o^s(\boxed{t_k})$$

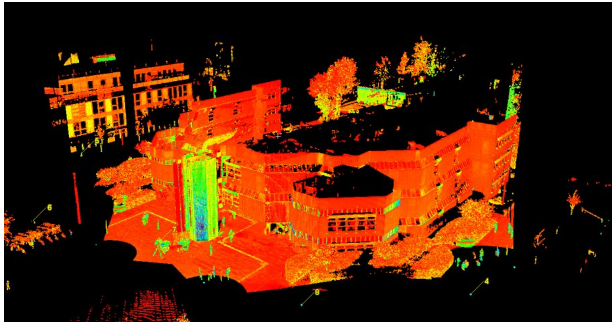
MMS Trajectory



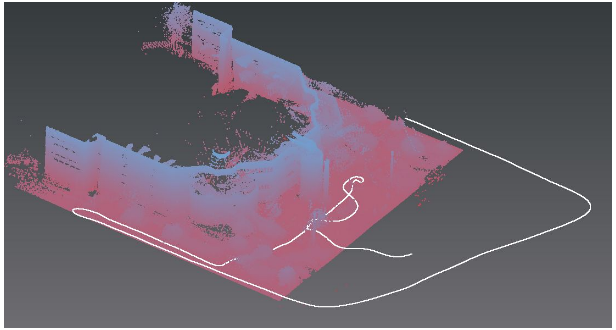
MMS Trajectory



Analysis



Georeferenced TLS pointcloud



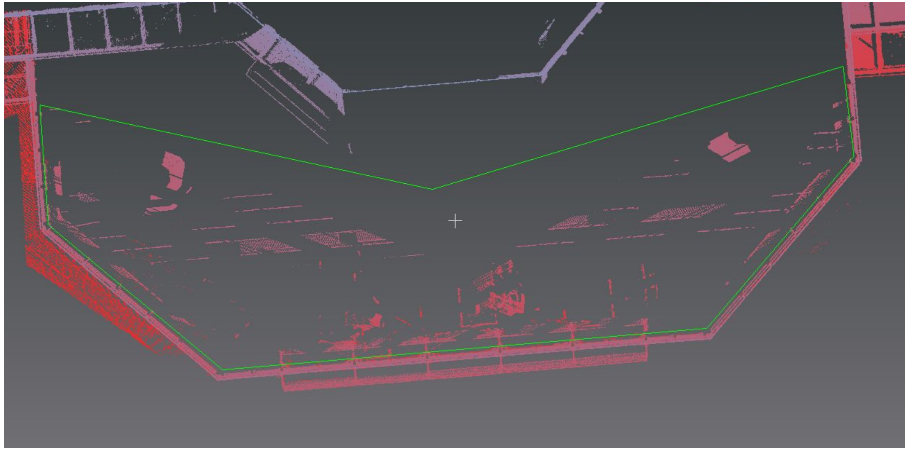
Georeferenced Mobile Systems Point Cloud

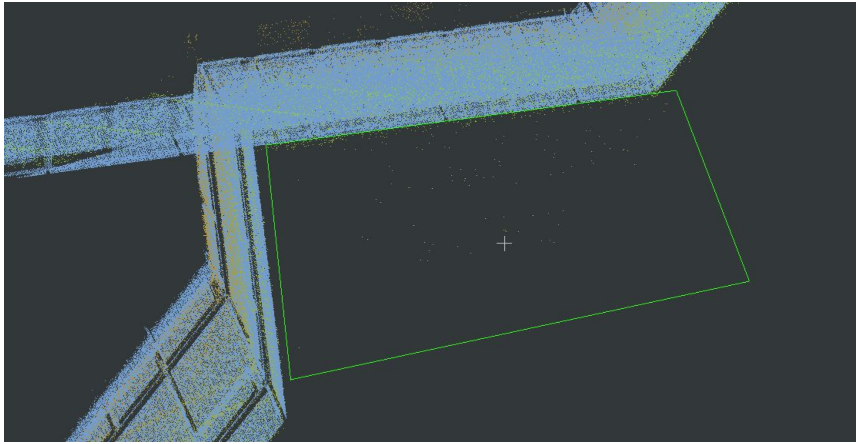
Cleaning →

Analysis

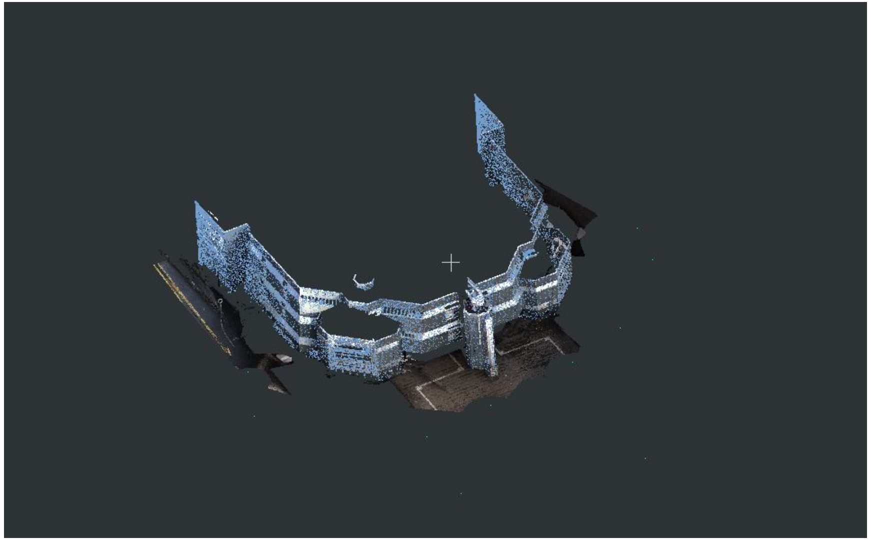
Cleaning Point Clouds

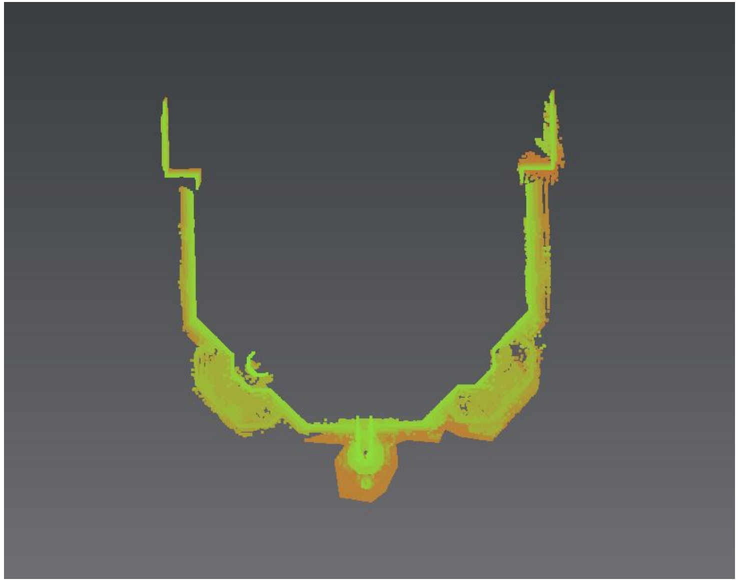
Why do we clean? Unwanted interiors, clear outliers





Degrees of cleaning

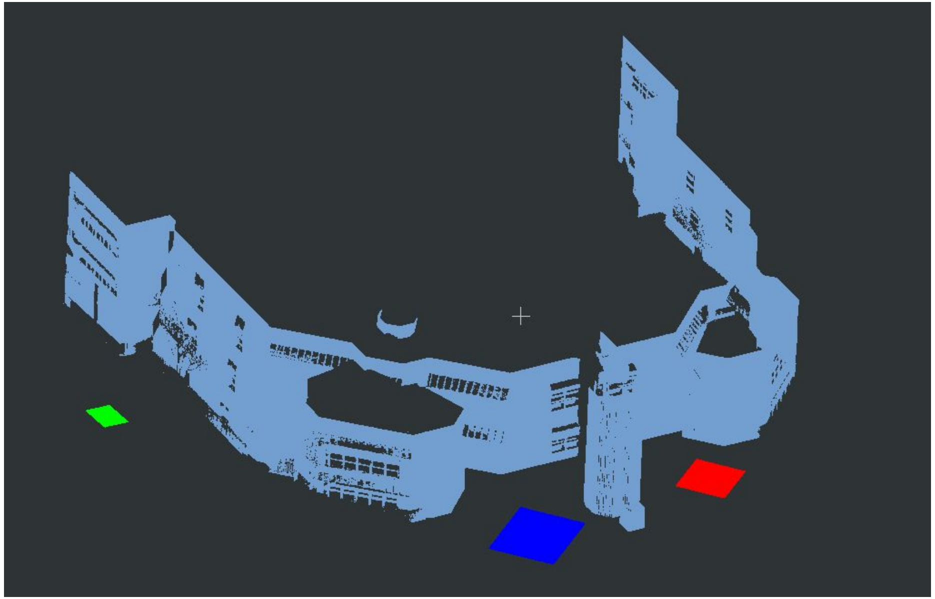




Point Clouds for Analysis

TLS Cloud for comparison

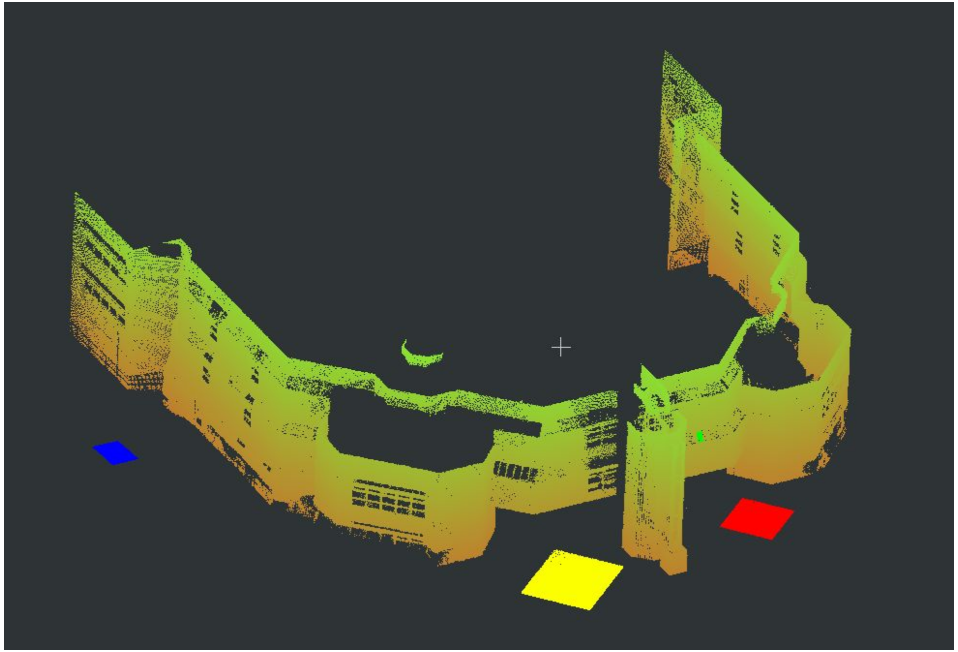
Cleaned Point Cloud + 4 Planes (1 Slant Face)



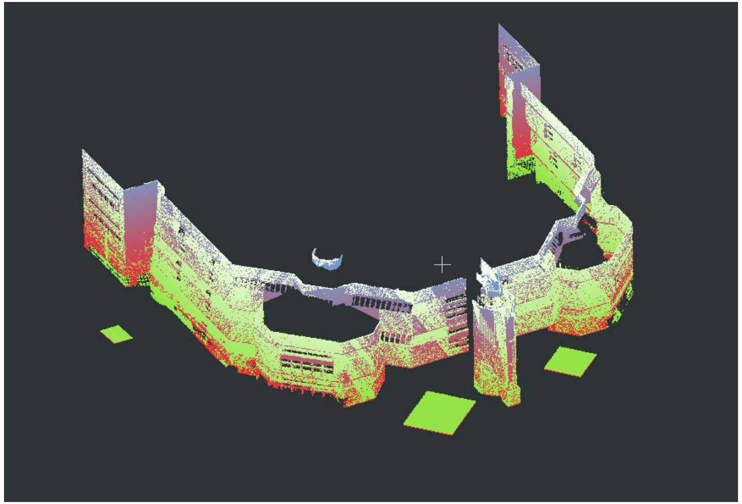
Point Clouds for Analysis

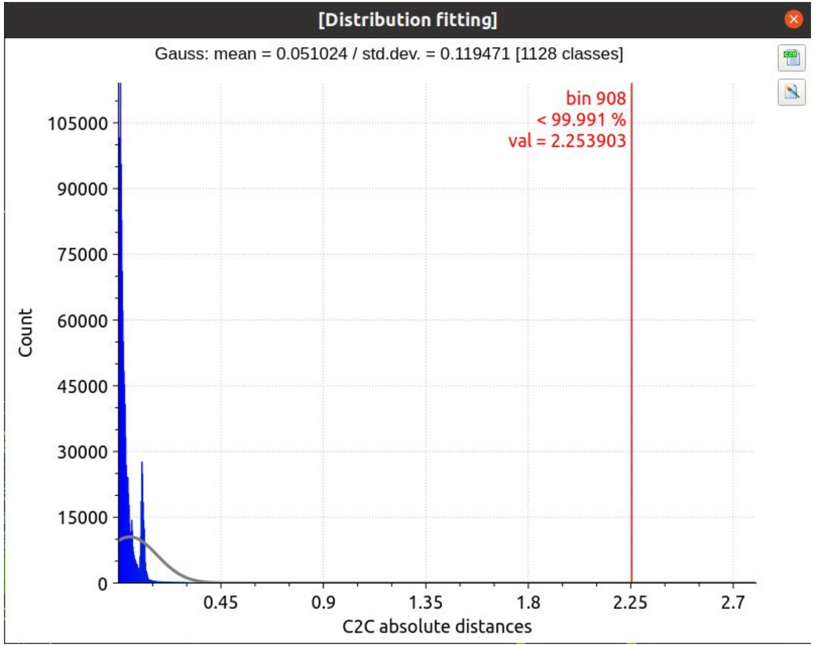
Mobile Platform Cloud for comparison

Cleaned Point Cloud + 4 Planes (1 Slant)



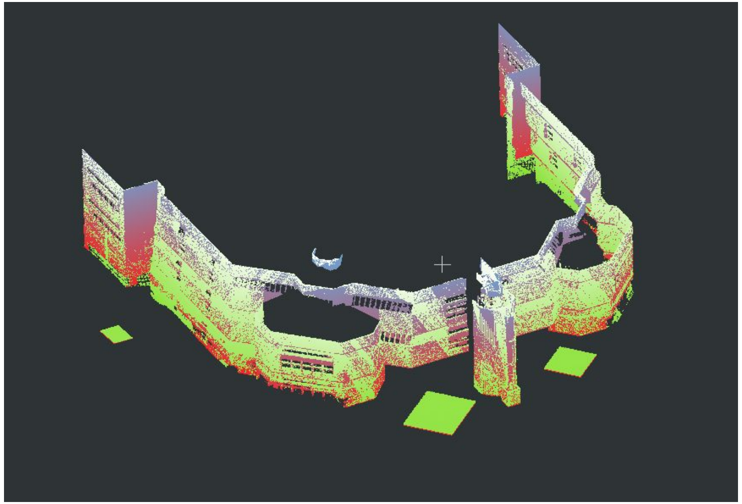
Point to Point Comparison

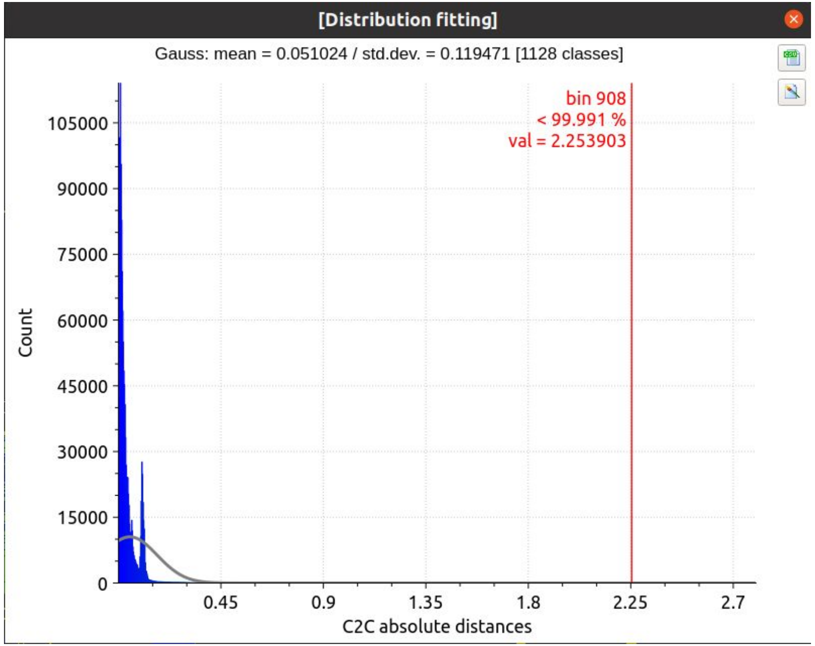




- Mean: 5.1024 cm
- Std: 11.9471 cm

Point to Point Comparison





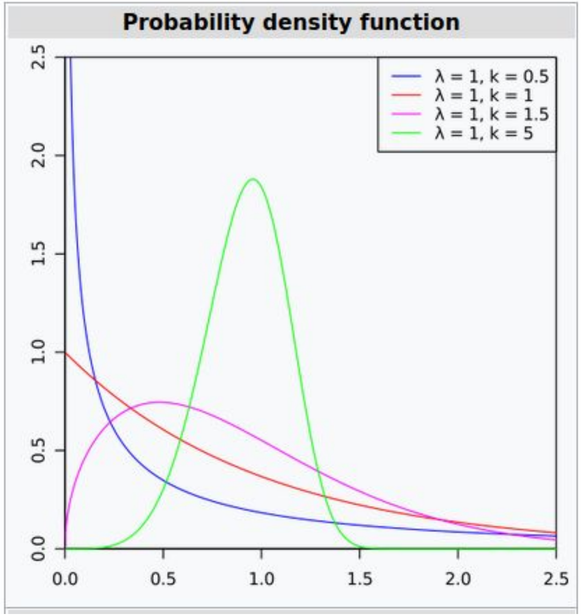
- Mean: 5.1024 cm
- Std: 11.9471 cm

Weibull Distribution

Weibull distribution fits our data

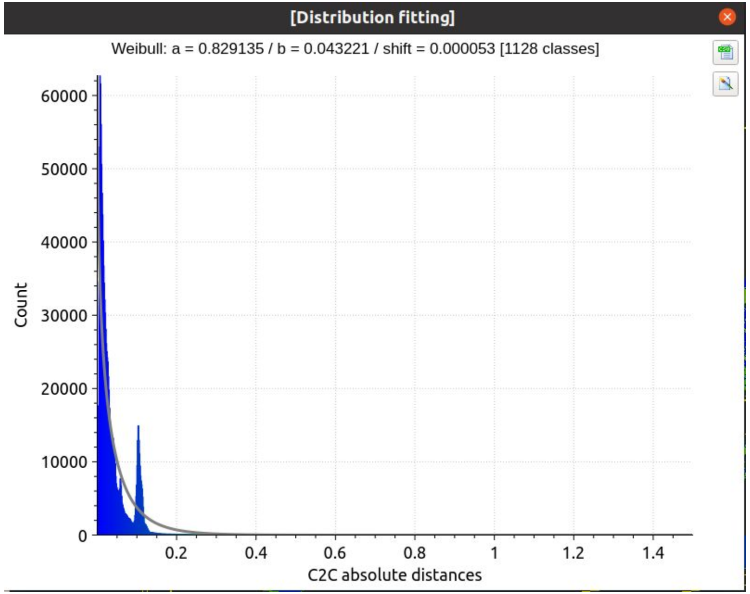
- The probability density function of a Weibull random variable is, where $k > 0$ is the *shape parameter* and $\lambda > 0$ is the *scale parameter* of the distribution.
- Notion of exponential decay towards one side.

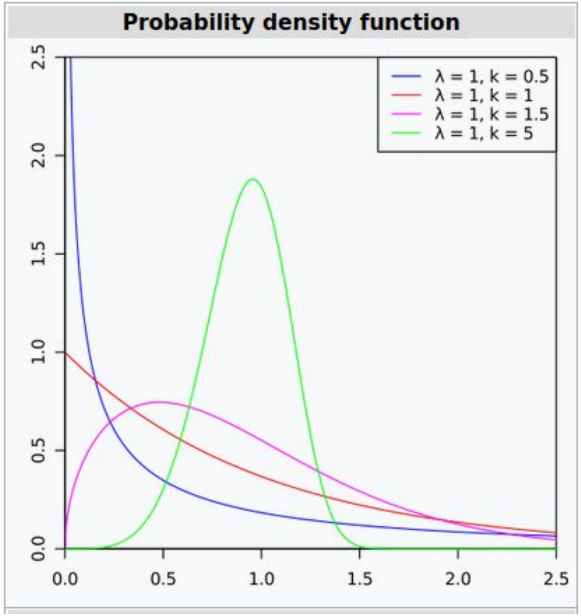
$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k}, & x \geq 0, \\ 0, & x < 0, \end{cases}$$



[Courtesy: Wikipedia]

Weibull distribution fits our data

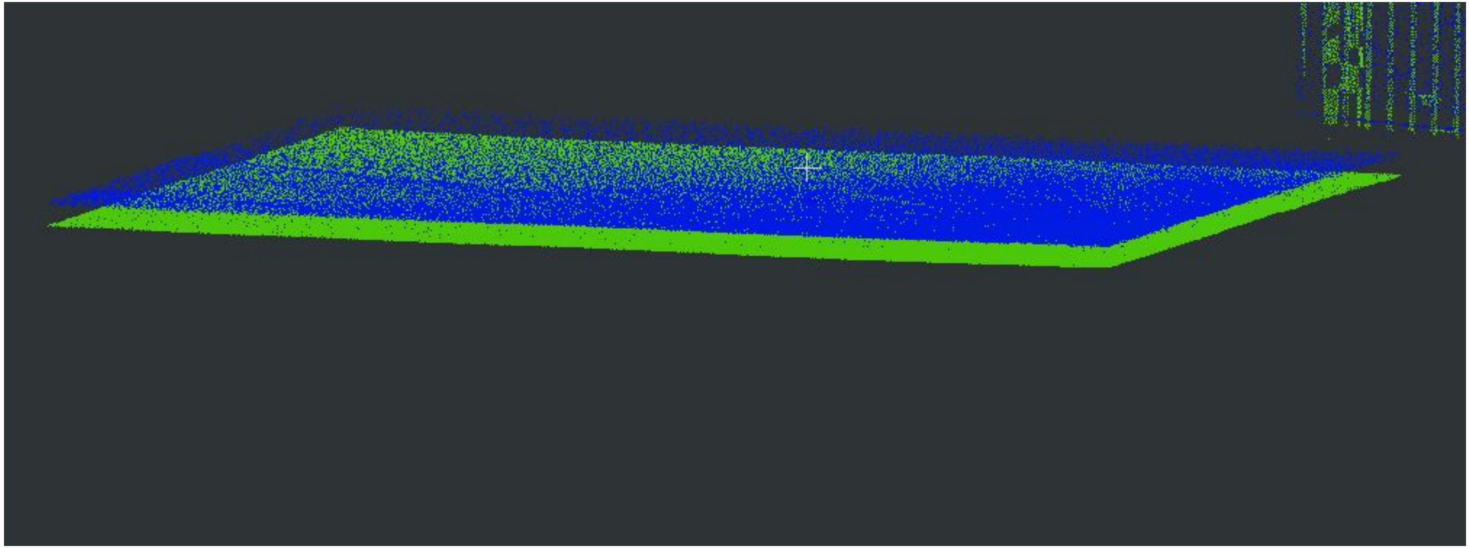




b or k < 0.5

Reasons for long-tail distribution

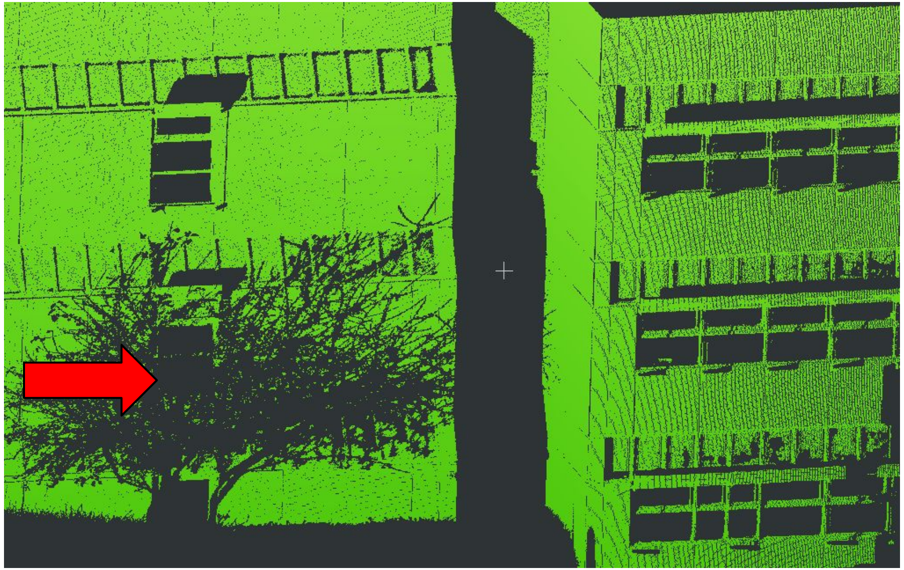
Clear off-set in Z direction



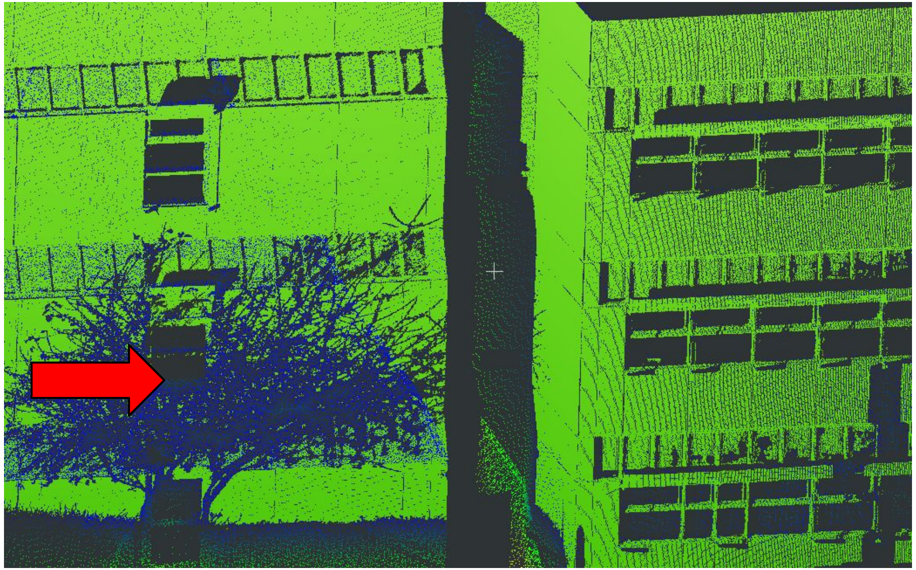
Can be linked to system calibration
(for example 4.3cm variation between the GNSS and target ?)

Reasons for long-tail distribution

Avoidable and Unavailable one-to-one map



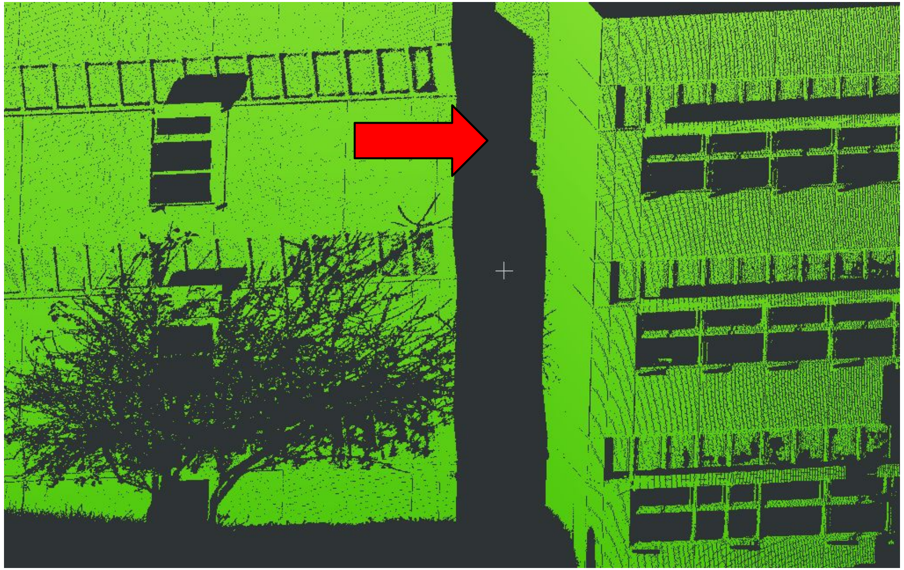
TLS Map



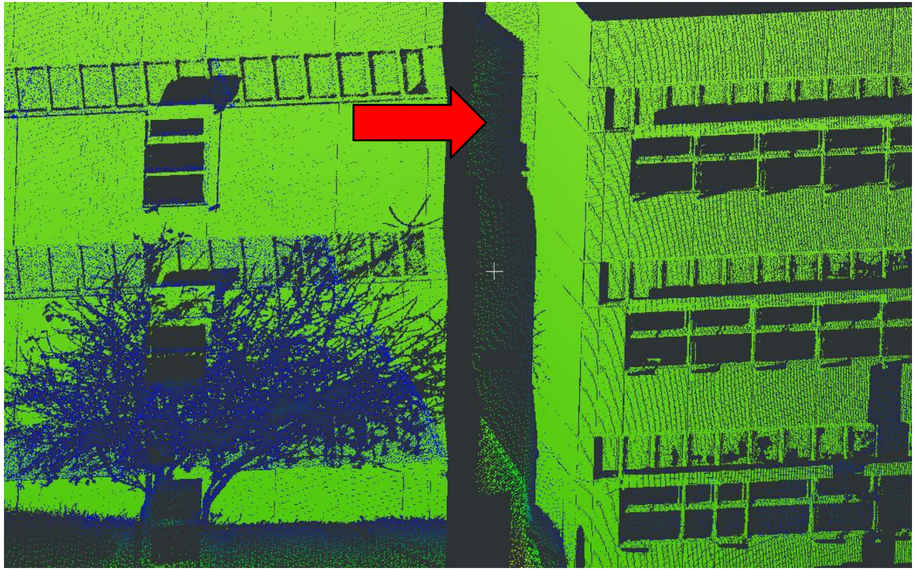
Mobile System Map

Reasons for long-tail distribution

Avoidable and Unavailable one-to-one map



TLS Map

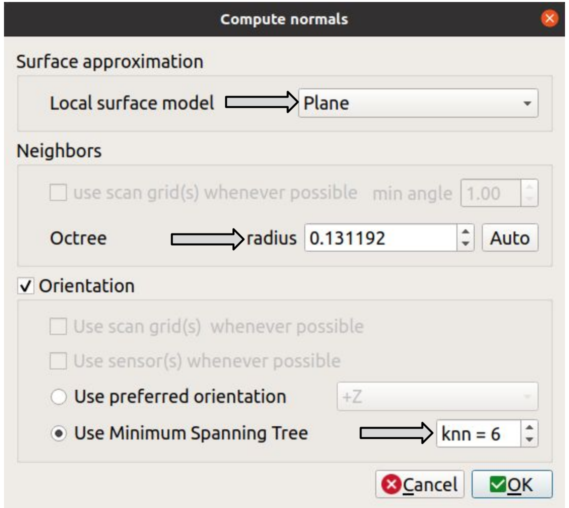


Mobile System Map

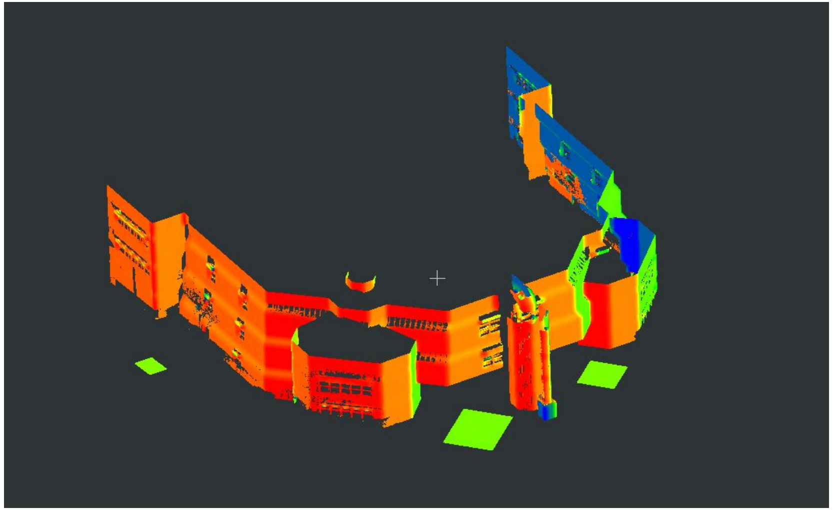
Point to Mesh

Compute Normals before meshing

Visualize to verify if the normals are computed correctly



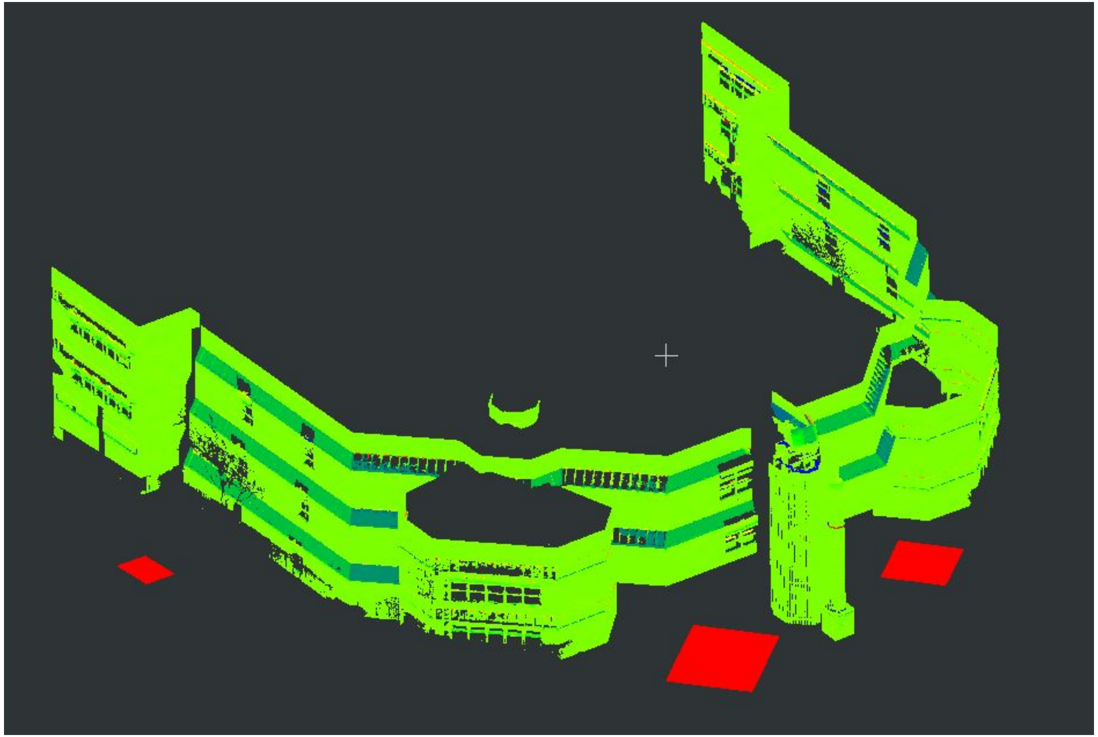
Local plane normal



Color Map = f(Nx) or f(Ny)

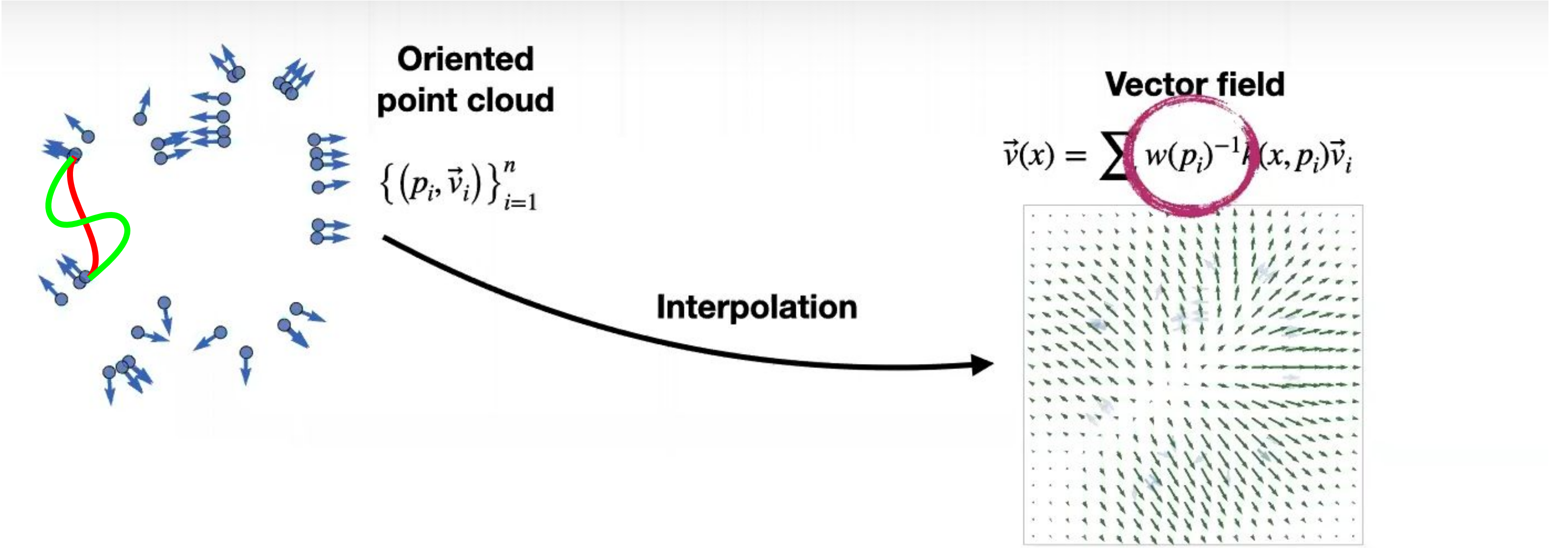
Point to Mesh

Compute Normals before meshing



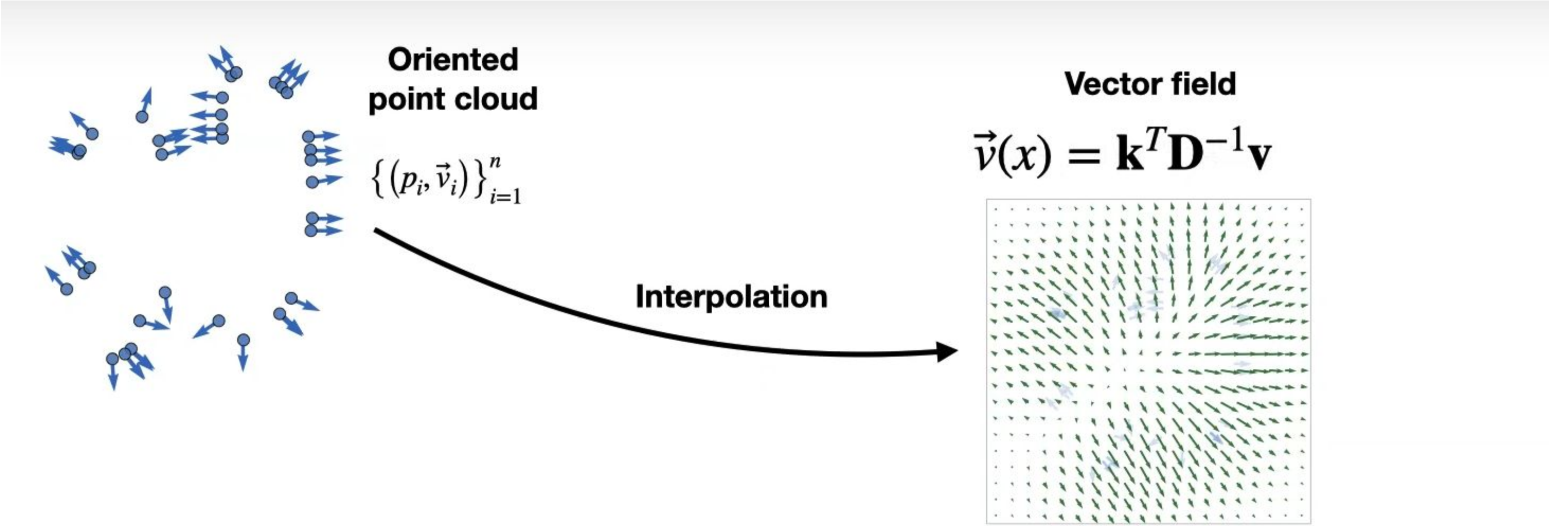
Color Map = f(Nz)

Poisson Reconstruction



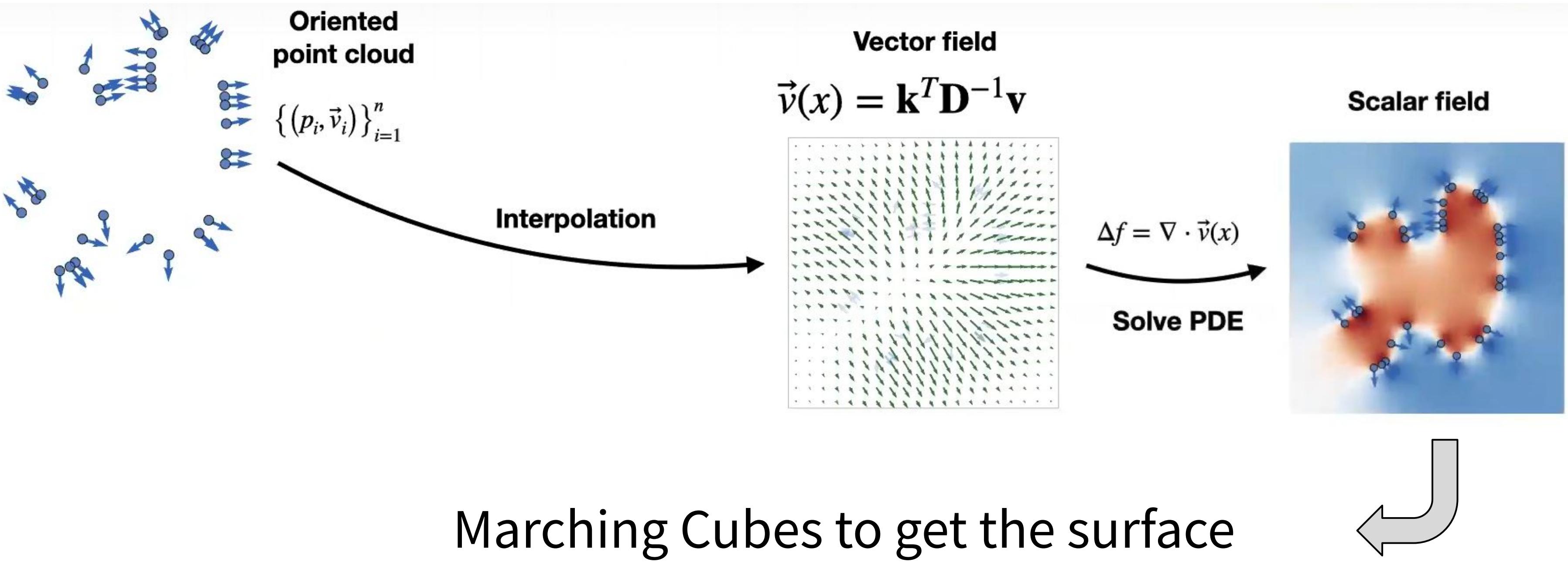
[Courtesy: Silvia Sellán - Uncertain Surface Reconstruction]

Poisson Reconstruction



[Courtesy: Silvia Sellán - Uncertain Surface Reconstruction]

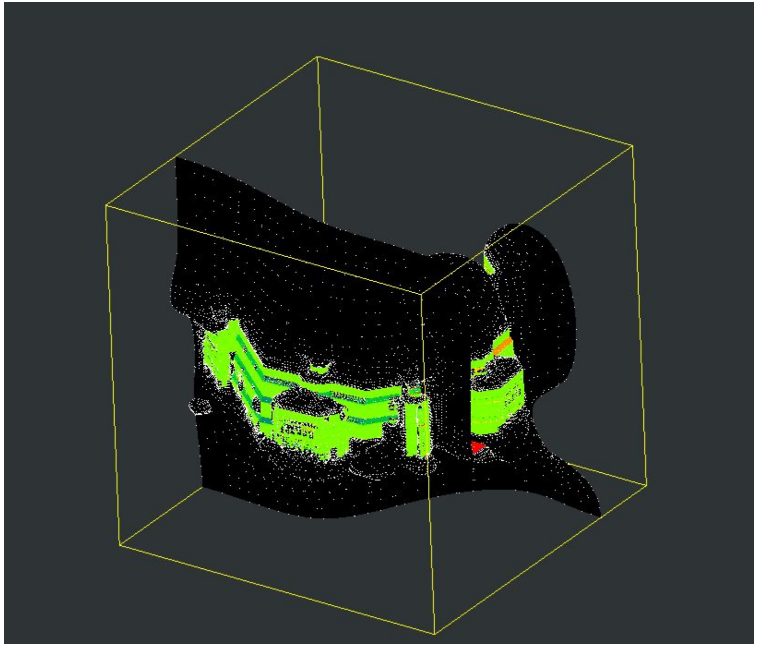
Poisson Reconstruction



Marching Cubes to get the surface

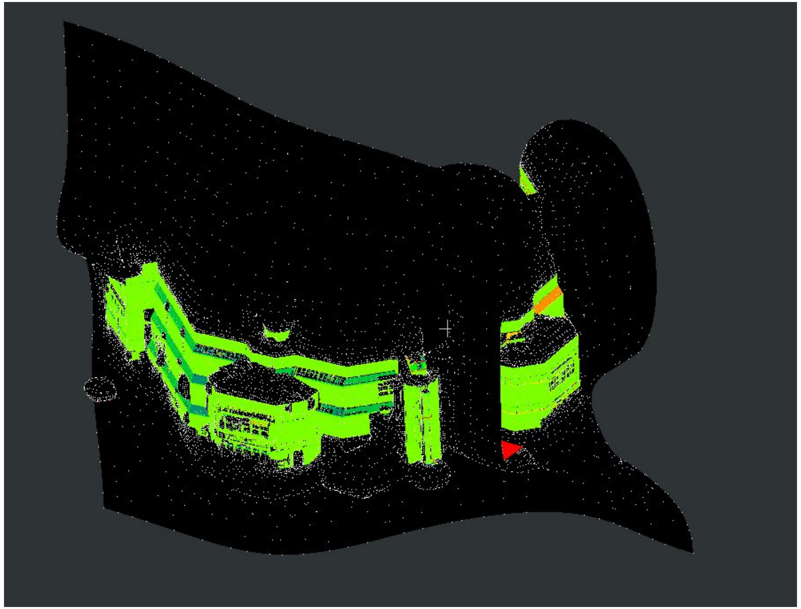
[Courtesy: Silvia Sellán - Uncertain Surface Reconstruction]

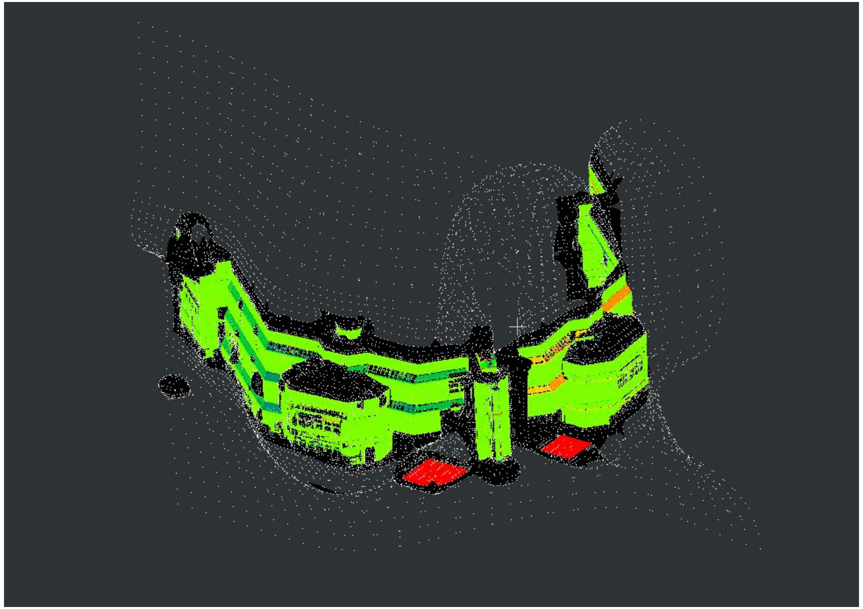
Poisson Reconstruction Results



Mesh is extracted for a volume and not just for the regions where points exist

Poisson Reconstruction Results

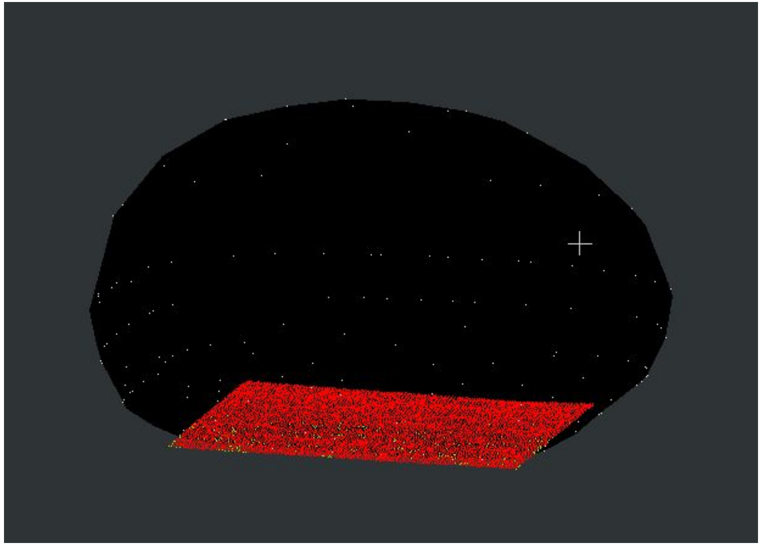




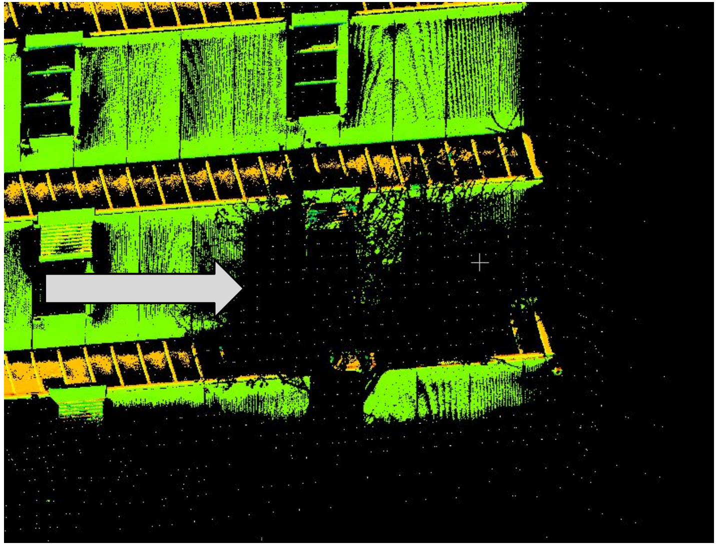
Option to toggle mesh spread (Just for visualization)

Poisson Reconstruction Results

Some observation in Poisson Reconstruction

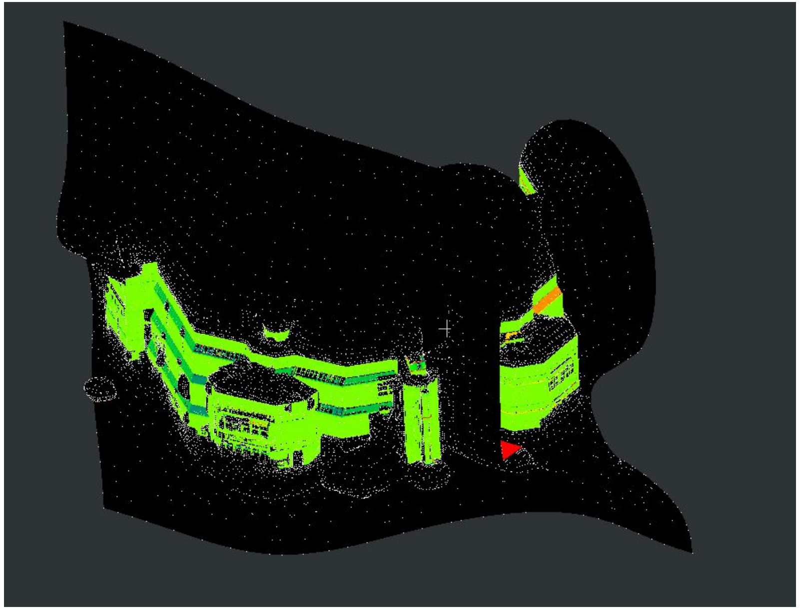


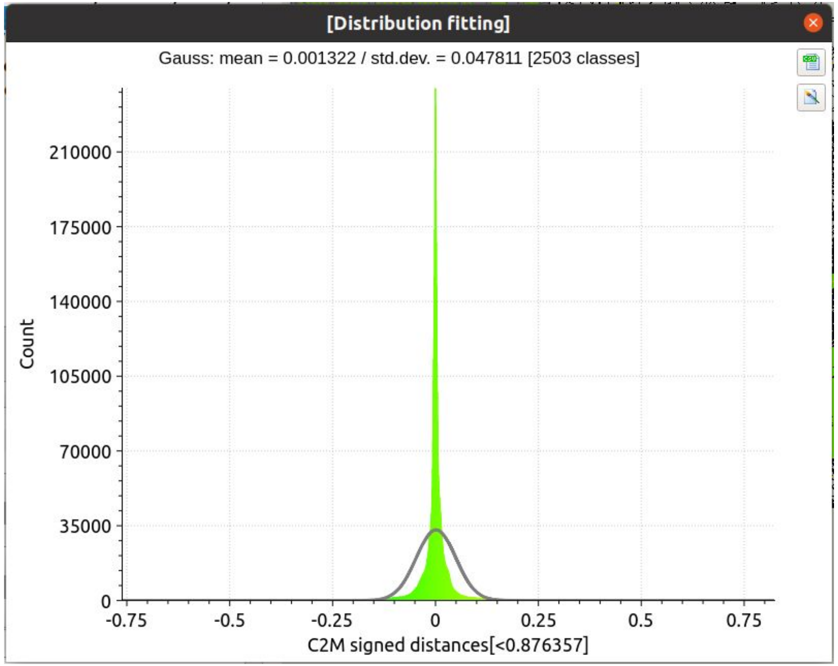
Outputs a closed shape



Because its generated from a continuous field, will have no gaps.

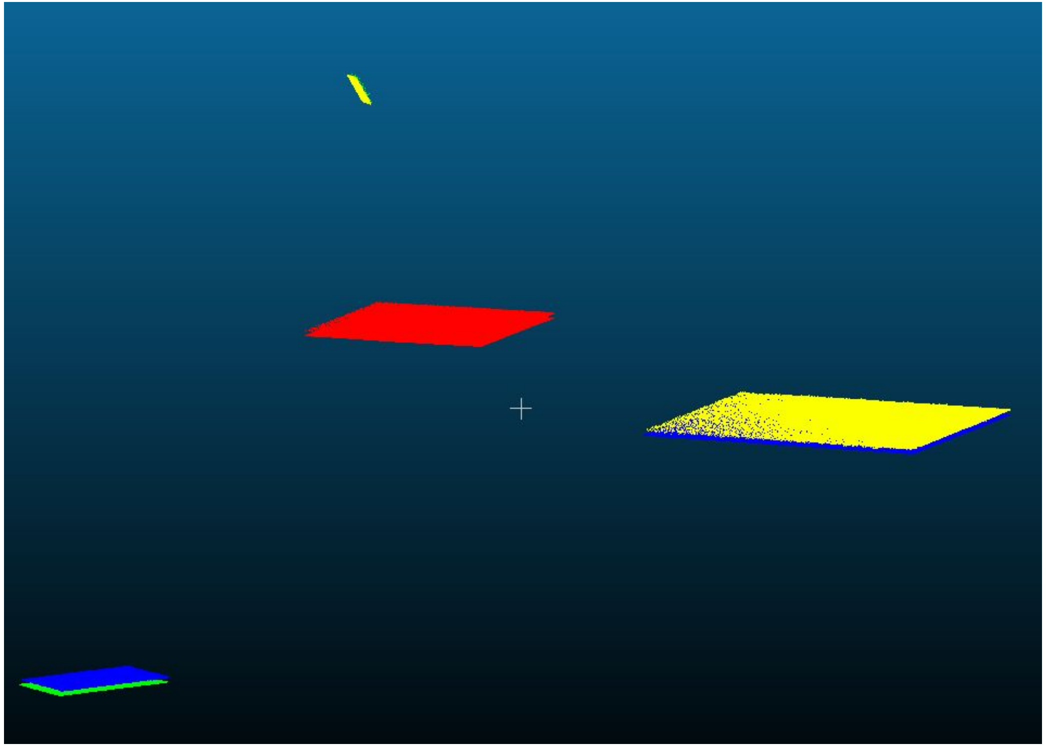
Point to Mesh

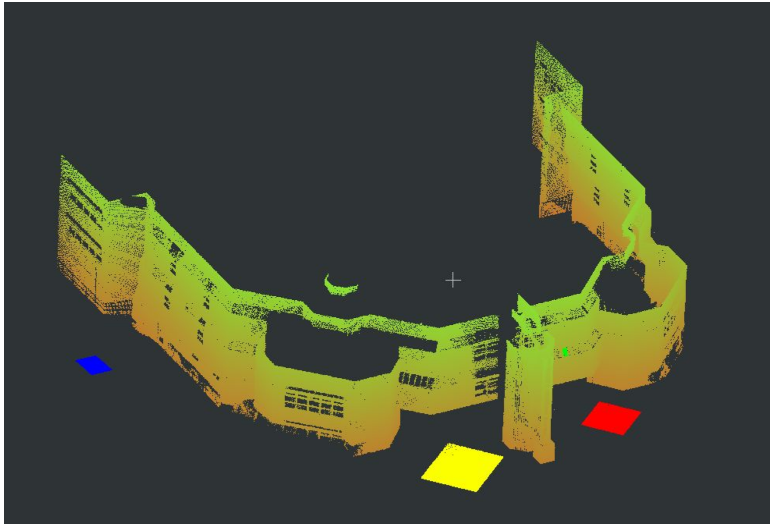




- Mean: 1.322 cm
- Std: 4.7811 cm

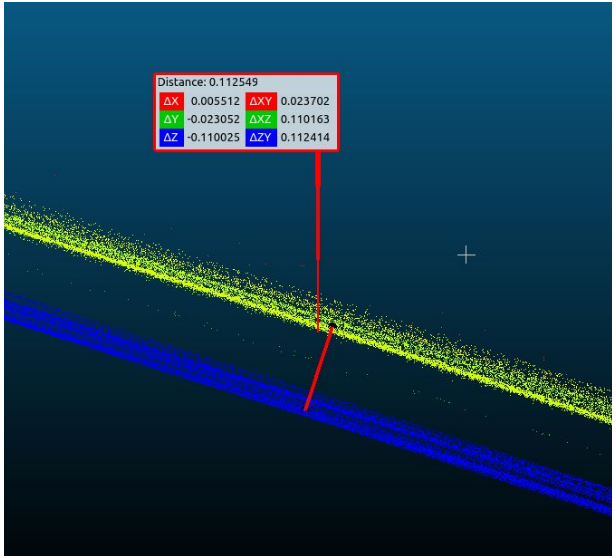
Comparison with Planes



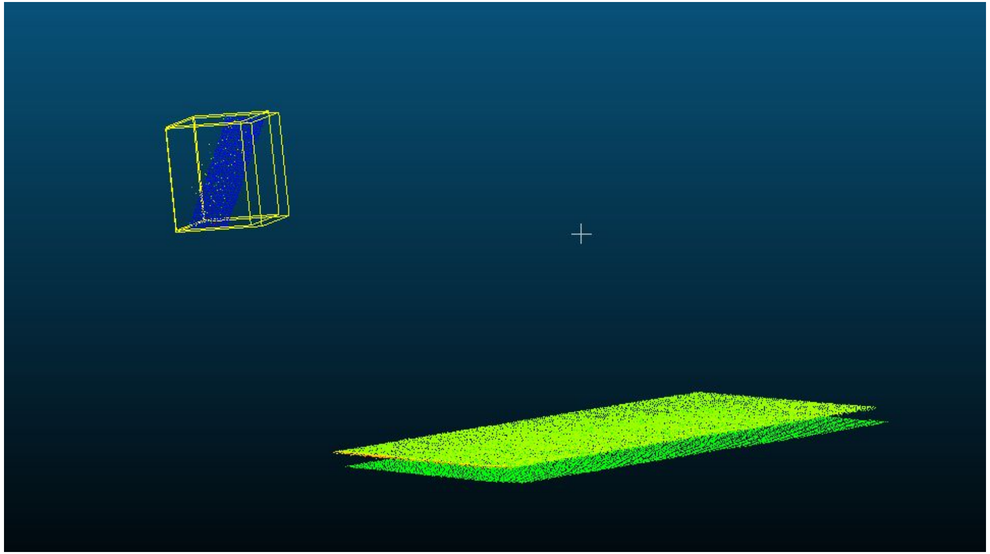


Comparison with Planes

Point2Point for all planes

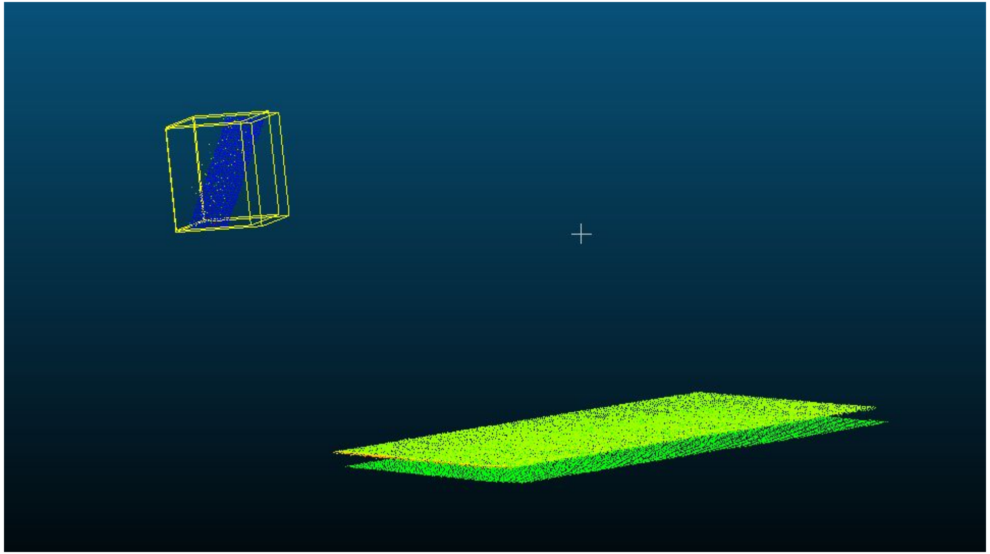


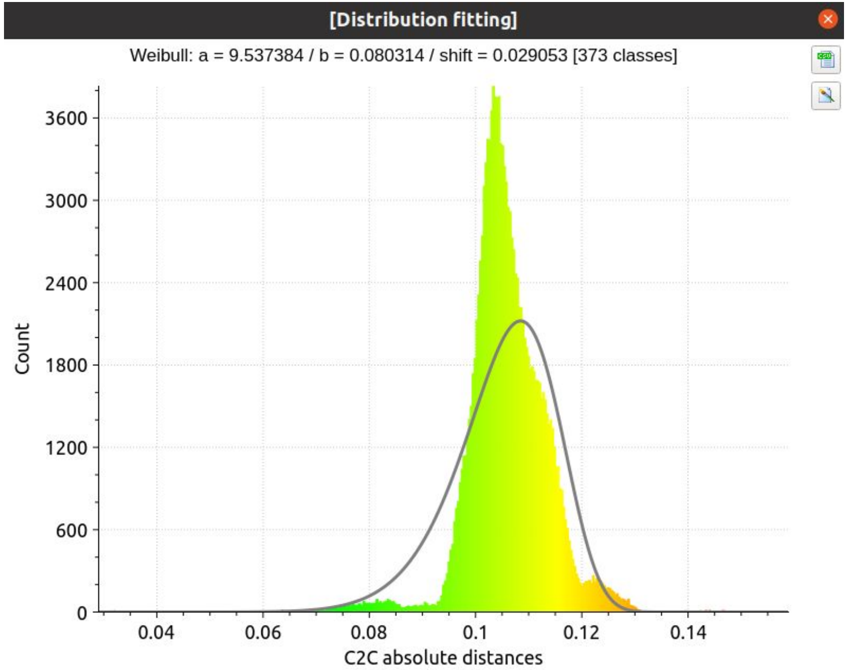
- Mean: 10.5997 cm
- Std: 0.7923 cm



- Mean: 4.5879 cm
- Std: 1.5749 cm

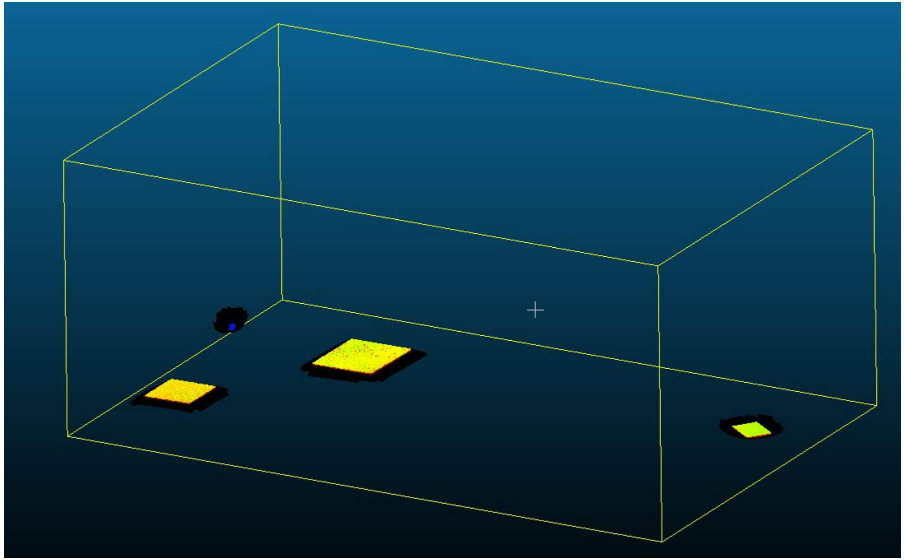
Comparison with Planes

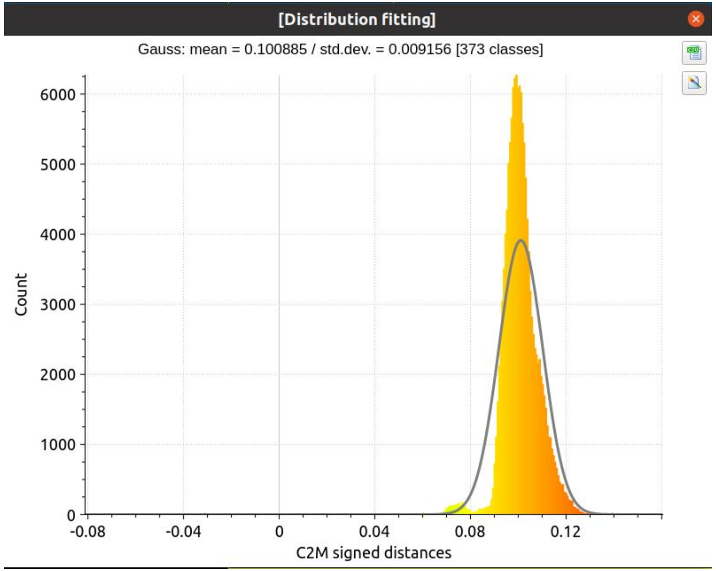




There are no long tail outliers because the geometry is simple and covered by both systems equally.

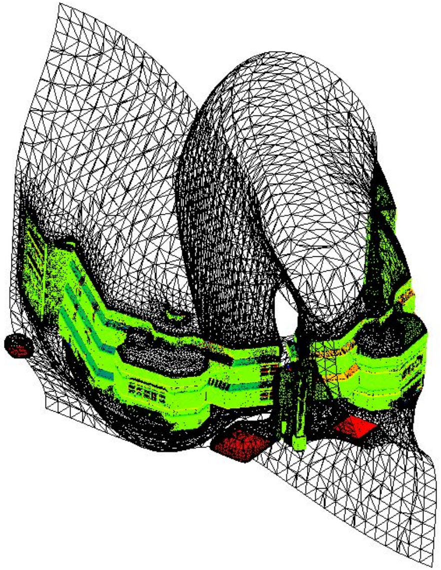
Comparison with Planes (Point to Mesh)

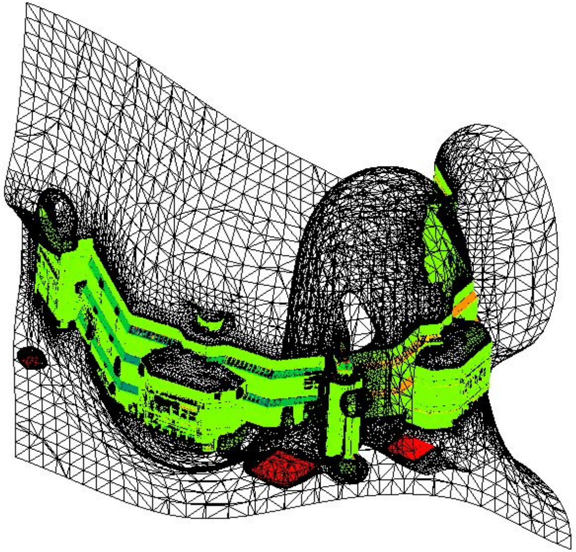




- Mean: 10.0885 cm
- Std: 0.9156 cm

Mesh to Mesh





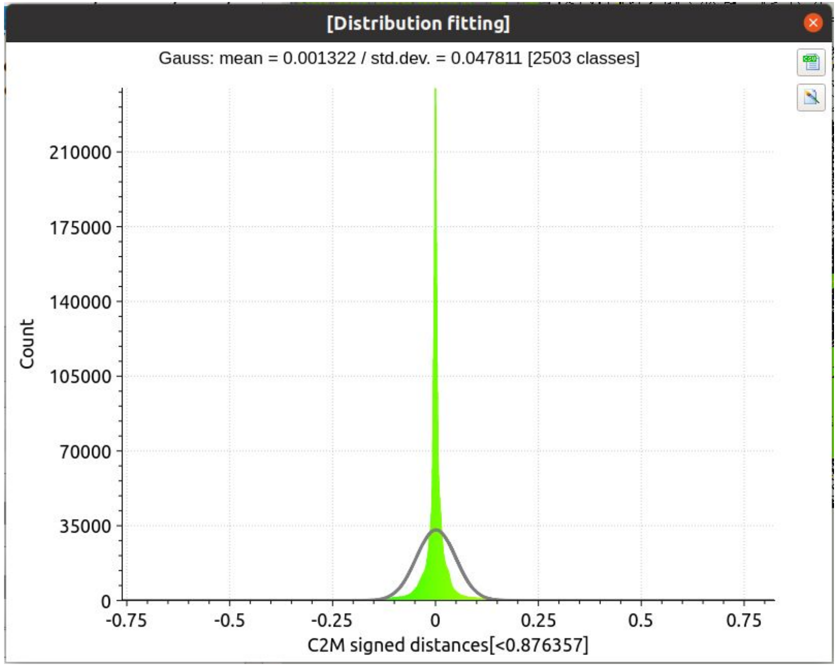
On the left, poisson reconstruction of mobile system data, on the right, poisson reconstruction of TLS

Conclusions

- Full point clouds:
  - Point to mesh has close 1cm mean error.
  - Ground planes have 10cm mean error.
- Comparisons based solely on full point cloud data may be misleading:
  - Height error of approximately 10cm is evident.
- Conclusion:
  - To address cost and georeferencing issues, implementing only three control points along with the mobile platform is necessary.

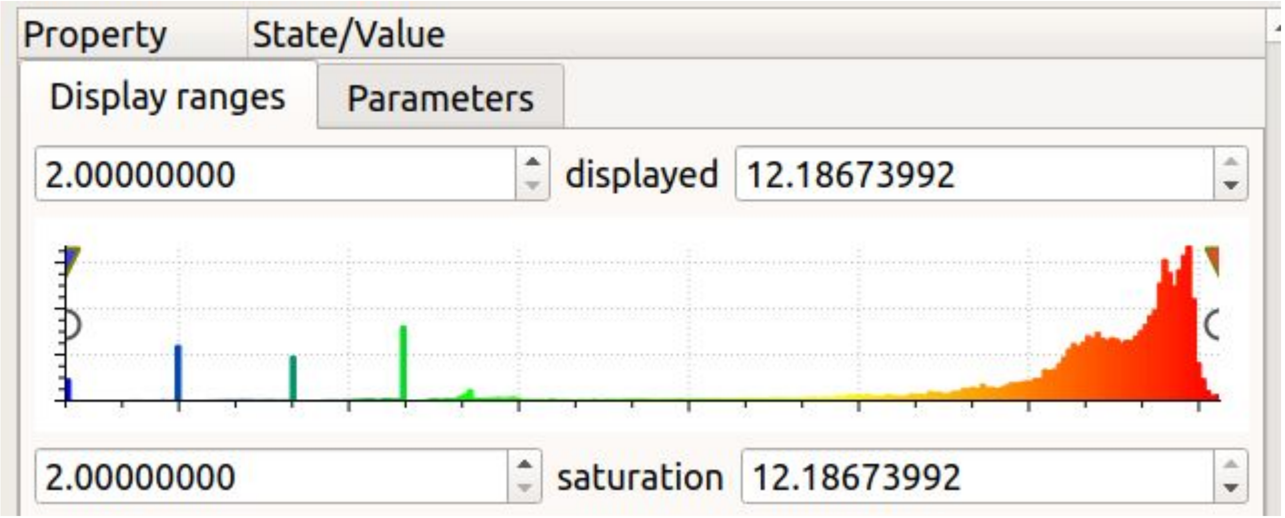
Thank you for your attention

Point to Mesh



Console

[10:40:34] Scalar field RMS = 0.0478297
[10:41:52] [Distribution fitting] Gauss: mean = 0.001322 / std.dev. = 0.047811
[10:41:52] [Distribution fitting] Gauss: Chi2 Distance = 10000000.000000
[10:41:52] Scalar field RMS = 0.0478297


Property
State/Value
Display ranges
Parameters
2.00000000
displayed
12.18673992
2.00000000
saturation
12.18673992