
Error budget of laser scanners: Applications in geomorphic surface change quantification

Lukas Winiwarter, Bernhard Höfle

lukas.winiwarter@uni-heidelberg.de

3DGeo Research Group, Institute of Geography, Heidelberg University

2019-12-05 | euroSDR PCP Workshop 2019, Stuttgart



Motivation

Point cloud data acquisition

- Influences applicability (Fitness-for-use)



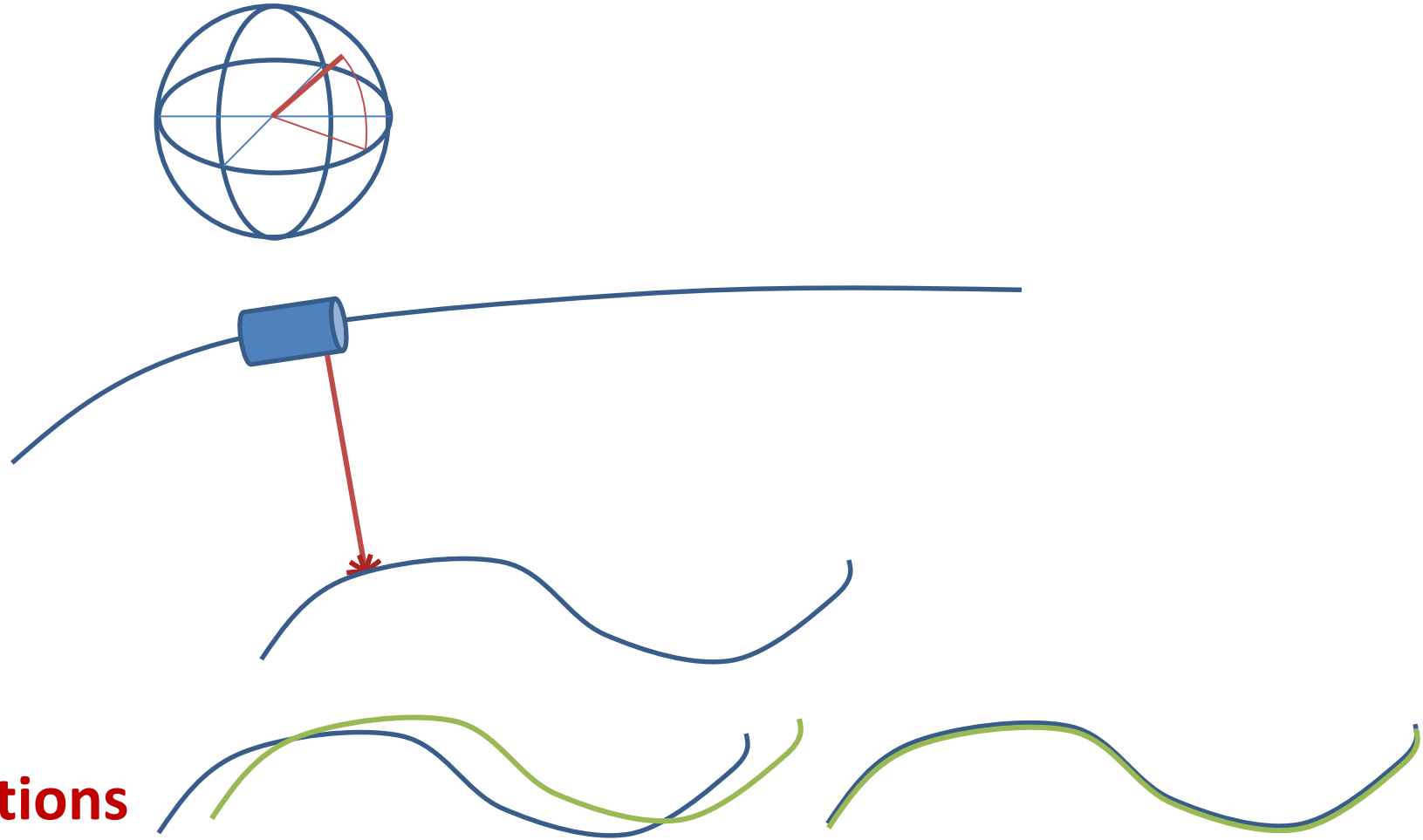
Geomorphic surface change

- Identification and Quantification of
 - Slope instabilities
 - Pre-Failure rockfalls
 - Volume movements
 - Forest growth



Point cloud observation

- Polar measurements
 - 2D/3D Scanners
 - φ, r / φ, θ, r
- Trajectory/Position
 - Measured or **Estimated**
- Coregistration
 - Introducing **correlations**



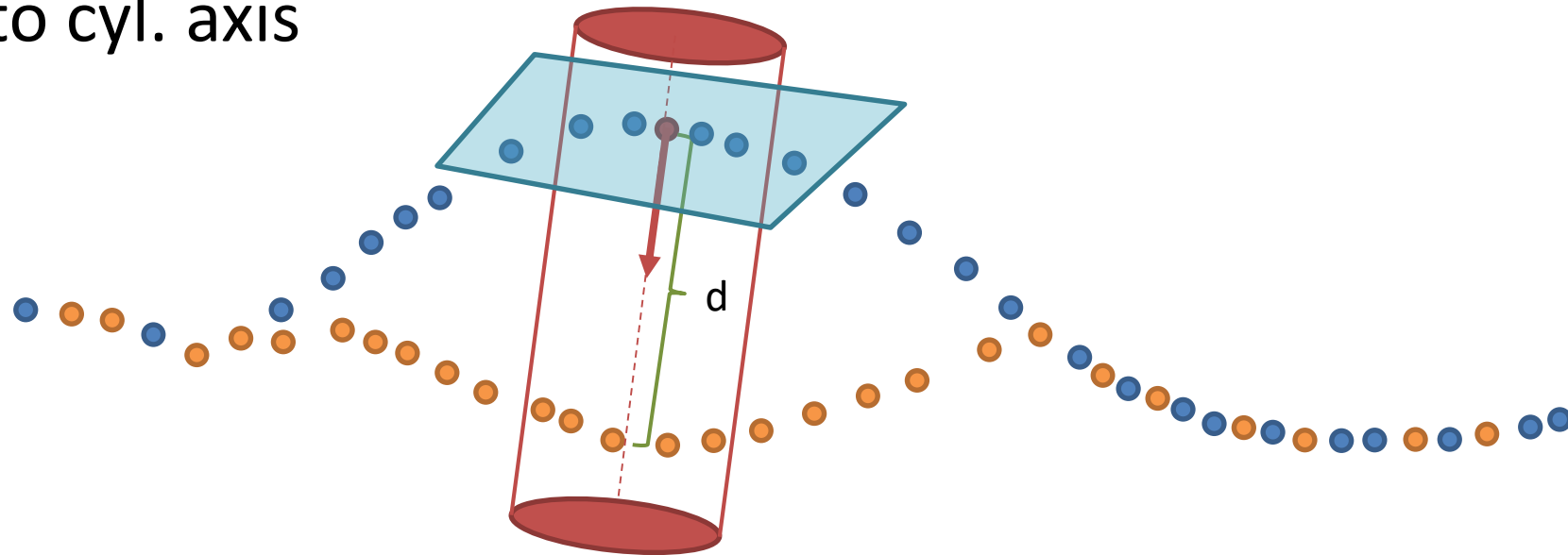
Multiscale Model-To-Model Cloud Comparison (M3C2)

- Lague et al. (2013):
Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z)
- Method to **compare two point clouds** to each other
 - e.g. bitemporal analysis
- Result: Metric distances (divergence)
- Additionally: „Level of Detection“ based on t-Test

M3C2 - Method

cf. Lague et al. (2013)

- „3D“ Change quantification
- Local **search cylinder** based on normal vector
- Aggregate points from two epochs
- Project onto cyl. axis



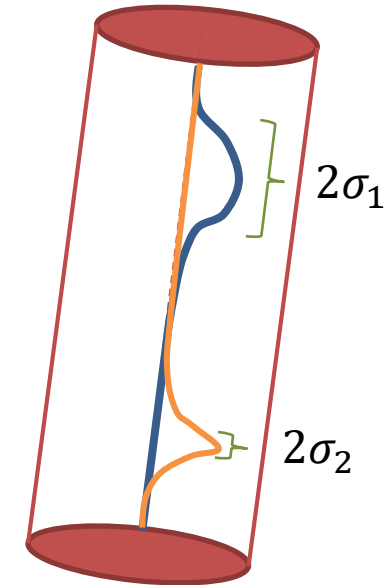
M3C2 - Significance

cf. Lague et al. (2013)

- Estimate „point cloud accuracy“ by **local plane fit**
- Std. dev. of projected points = σ_0 of plane fit
- „Coregistration err“ as fixed term
- Welch's t-Test

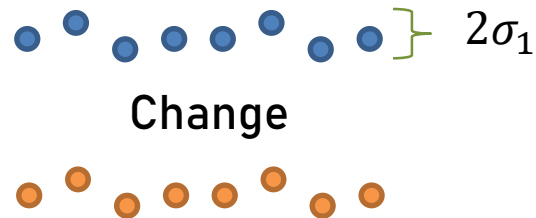
$$T = \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}} + reg \sim F(n_1 + n_2)$$

- Level of detection at 95 % significance:
- $LoD_{95} = 1.96 \cdot T$



Planarity assumption

- Implicit assumptions
 - Planar objects
 - Perpendicular to laser beam
- Reality (natural surfaces)



- Leading to **false negatives!** (Type-II-error)

Coordinate Systems and Error propagation

cf. Glira et al. (2015)

- Bitemporal data: Alignment accuracy
- **Transformation model** from opalsICP (with reduction point P_0):

$$\begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} r_i \cos(\varphi_i) \sin(\theta_i) - x_0 \\ r_i \cos(\varphi_i) \cos(\theta_i) - y_0 \\ r_i \sin(\varphi_i) - z_0 \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix}$$

- Derivatives with respect to:
 - $a_{kl}, t_x, t_y, t_z, r_i, \varphi_i, \theta_i$
- Derivatives of equations for Point i with respect to Point j

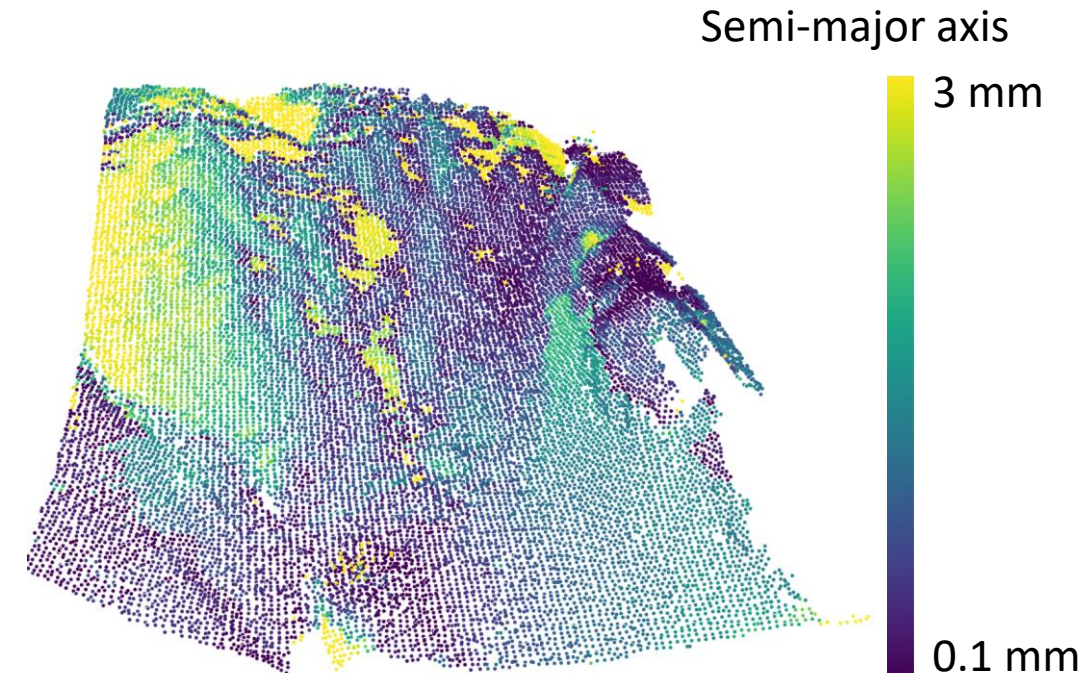
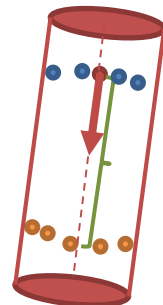
Propagating errors to change values

- For transformed dataset: use full covariance information
 - Not feasible to calculate a priori – on demand calculation
- Result: 3x3 covariance matrix for local CoGs

$$Q_{xx} = \begin{pmatrix} q_1(a_{1,1}, a_{1,1}) & q_2(a_{1,1}, a_{1,2}) & q_3(a_{1,1}, a_{1,3}) & q_4(a_{1,1}, t_1) & q_5(a_{1,1}, a_{2,1}) & \dots & q_{12}(a_{1,1}, t_3) \\ q_{13}(a_{1,2}, a_{1,1}) & q_{14}(a_{1,2}, a_{1,2}) & q_{15}(a_{1,2}, a_{1,3}) & q_{16}(a_{1,2}, t_1) & q_{17}(a_{1,2}, a_{2,1}) & \dots & q_{24}(a_{1,2}, t_3) \\ q_{25}(a_{1,3}, a_{1,1}) & q_{26}(a_{1,3}, a_{1,2}) & q_{27}(a_{1,3}, a_{1,3}) & q_{28}(a_{1,3}, t_1) & q_{29}(a_{1,3}, a_{2,1}) & \dots & q_{36}(a_{1,3}, t_3) \\ q_{37}(t_1, a_{1,1}) & q_{38}(t_1, a_{1,2}) & q_{39}(t_1, a_{1,3}) & q_{40}(t_1, t_1) & q_{41}(t_1, a_{2,1}) & \dots & q_{48}(t_1, t_3) \\ q_{49}(a_{2,1}, a_{1,1}) & q_{50}(a_{2,1}, a_{1,2}) & q_{51}(a_{2,1}, a_{1,3}) & q_{52}(a_{2,1}, t_1) & q_{53}(a_{2,1}, a_{2,1}) & \dots & q_{60}(a_{2,1}, t_3) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ q_{133}(t_3, a_{1,1}) & q_{134}(t_3, a_{1,2}) & q_{135}(t_3, a_{1,3}) & q_{136}(t_3, t_1) & q_{137}(t_3, a_{2,1}) & \dots & q_{144}(t_3, t_3) \end{pmatrix}$$

$\sigma_r, \sigma_\varphi, \sigma_\theta$

Scan Positions



Multidimensional mean testing

- Use full covariance information: 3D test
 - H0: **Two means (CoGs) are the same**, i.e. the distance between them is not significantly different from zero.

- Test statistic follows Hotelling's t-squared distribution:

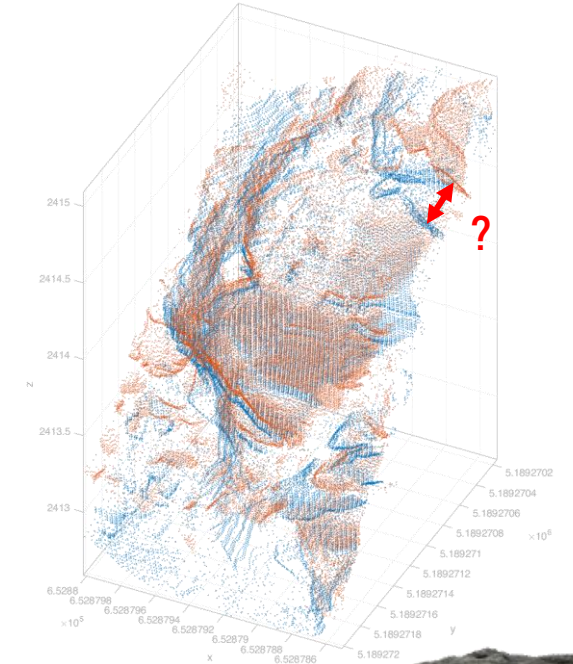
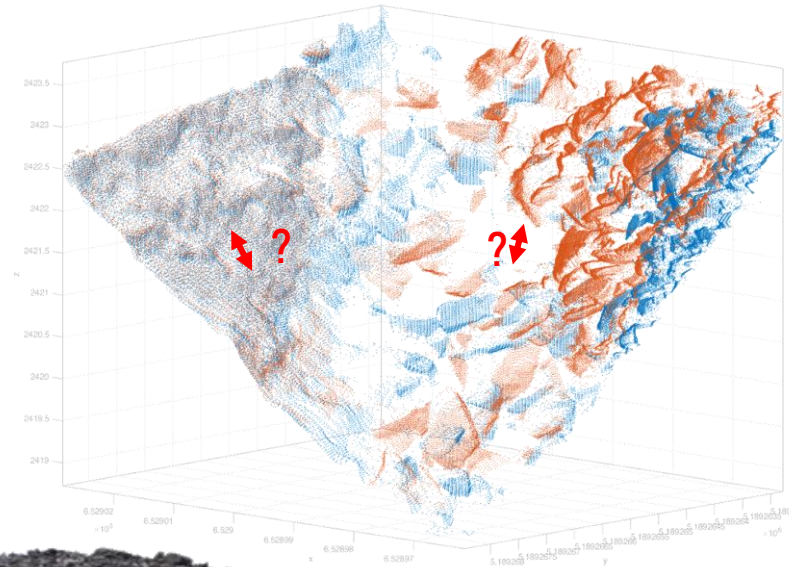
$$t^2 = \frac{n_1 n_2}{n_1 + n_2} (\bar{x}_1 - \bar{x}_2)^T \hat{\Sigma}^{-1} (\bar{x}_1 - \bar{x}_2) \sim T^2(p, n_1 + n_2 - 2)$$

- Reformulate for Level of Detection at 95 %:

$$LoD_{95} = \sqrt{\frac{T^2(0.95, p, n_1 + n_2)}{t^2}}$$

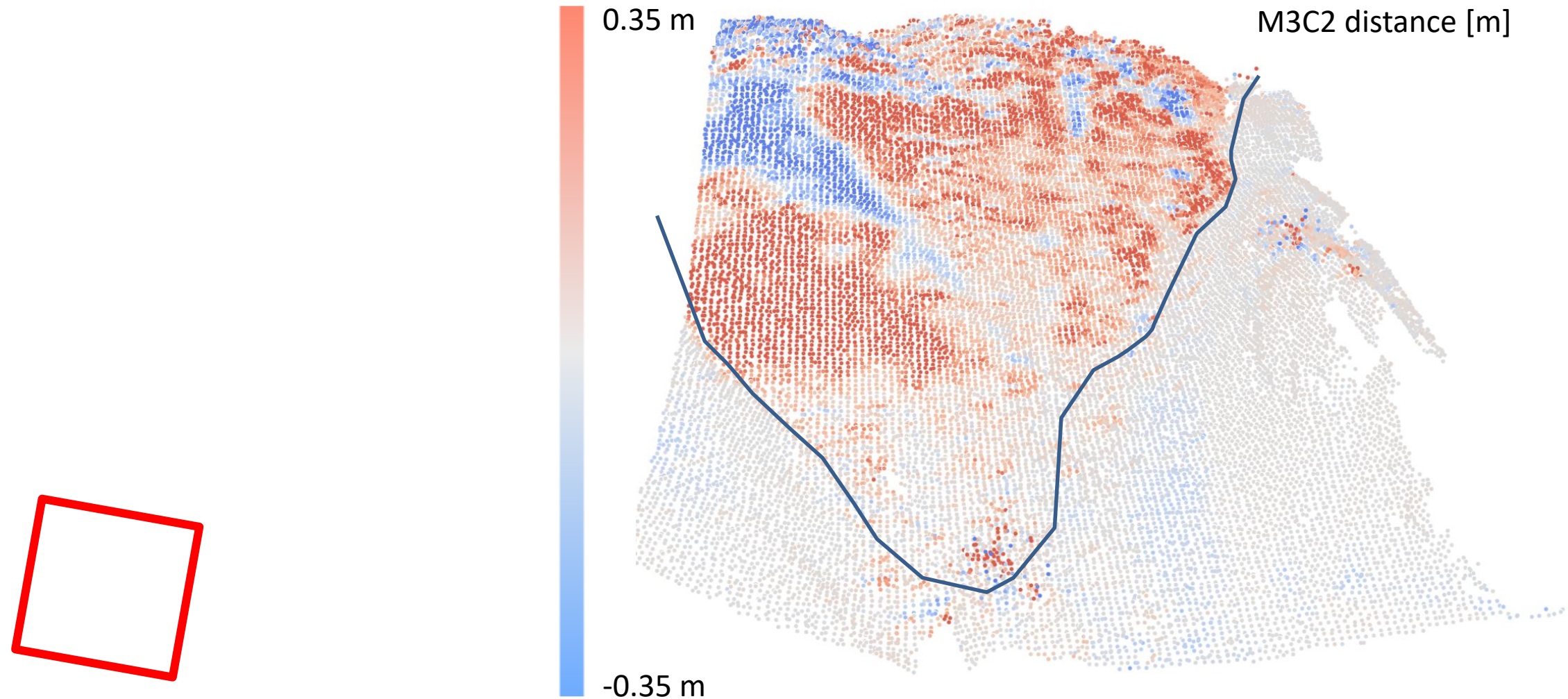
Application: Geomorphic surface change

- Process geomorphology
- Äußeres Hochebenkar
Rock Glacier
- Ötztal valley, Tyrol

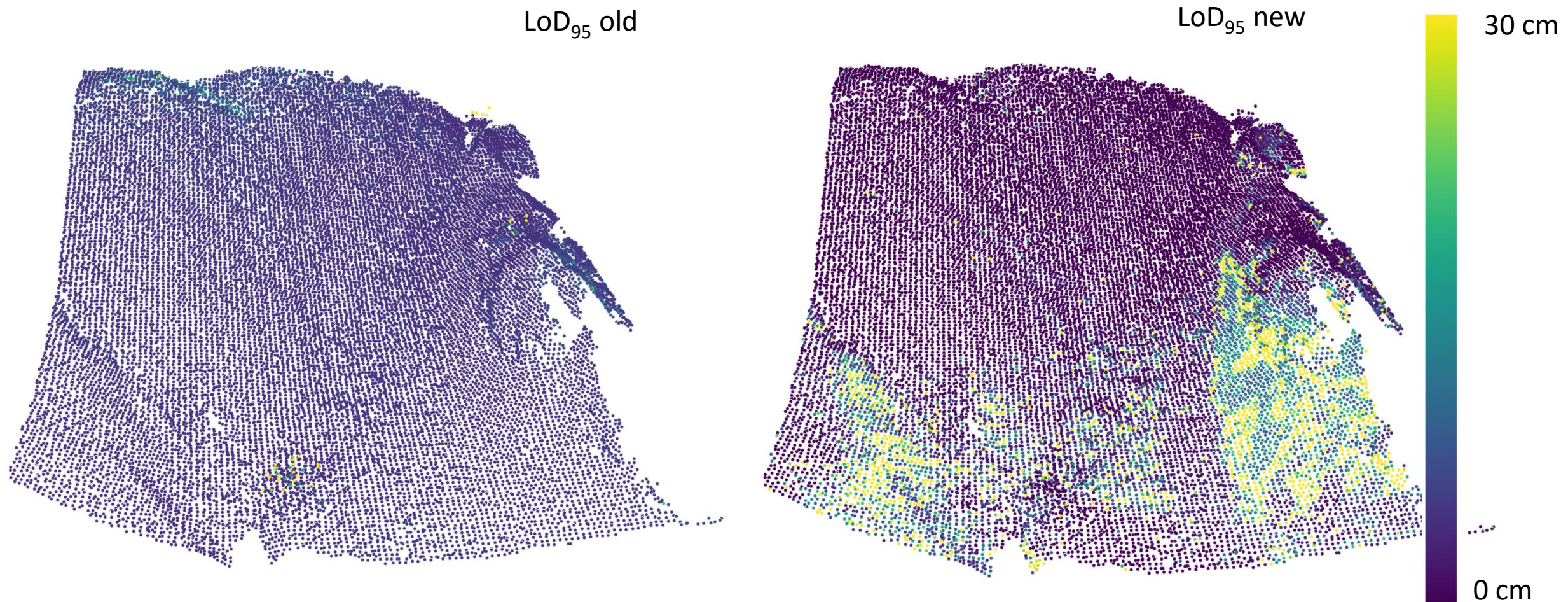


Results

Parameters:
 $r=0.2$ m
 $z_{\text{Max}} = 2$ m
 $\text{Ref_err} = 0.02$ m
 $n_{\text{Scanpos}} = 7$

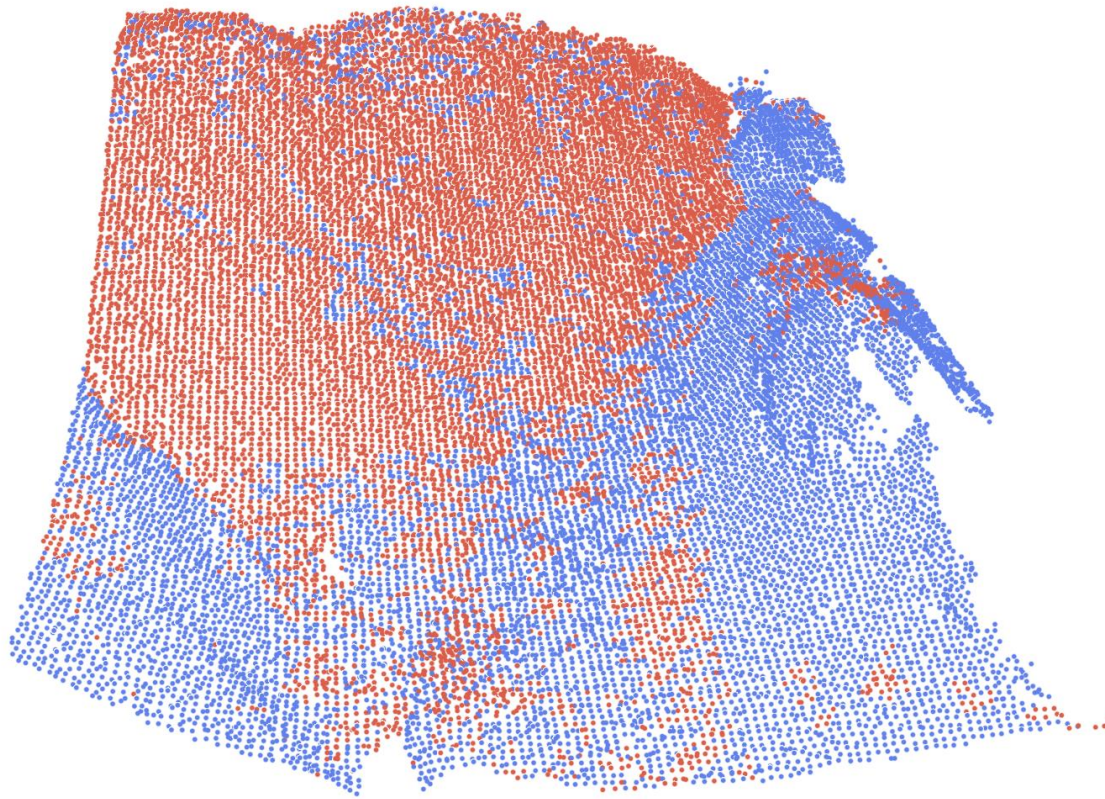


Results – Comparison to Lague et al. (2013)

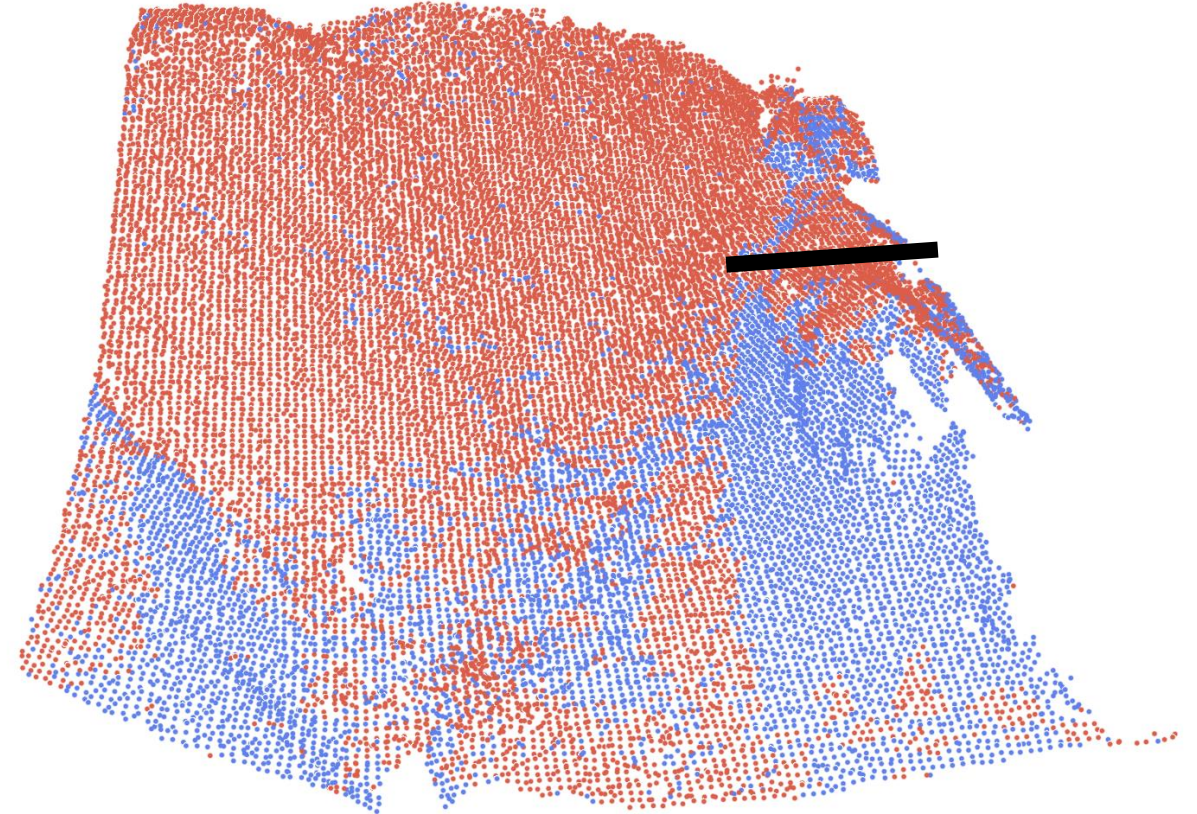


Results – Comparison to Lague et al. (2013) II

Significant change old (Y/N)

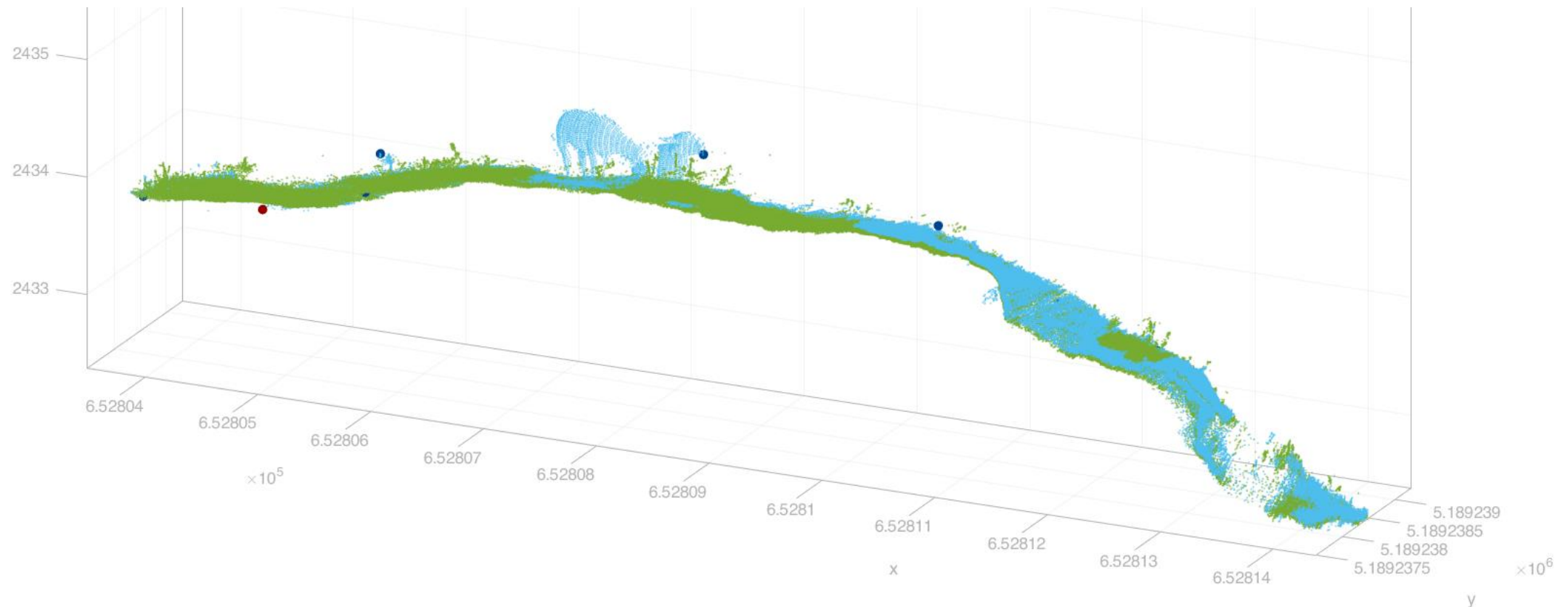


Significant change new (Y/N)



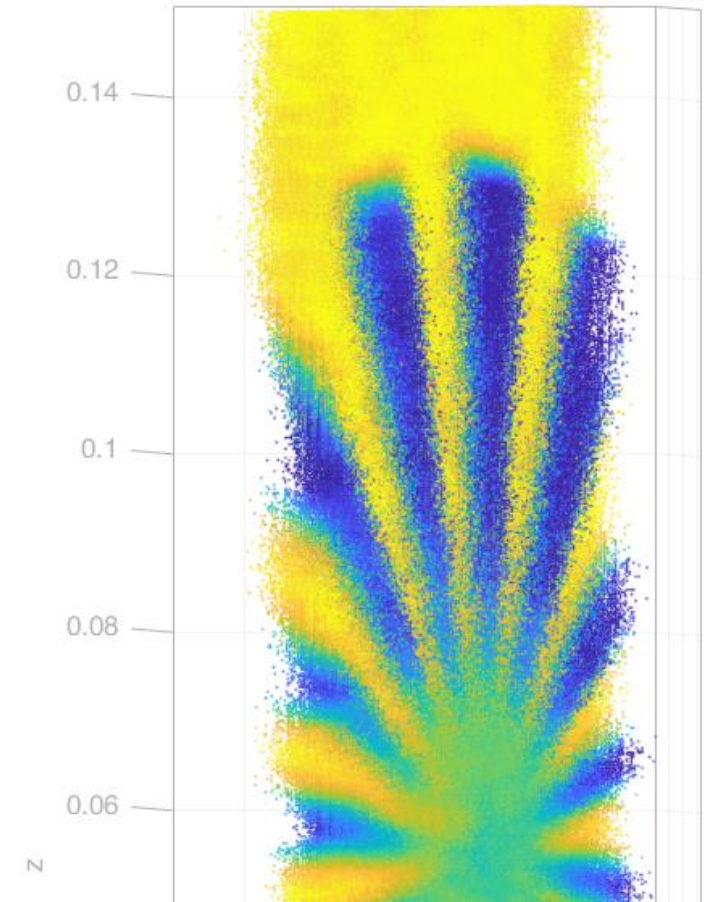
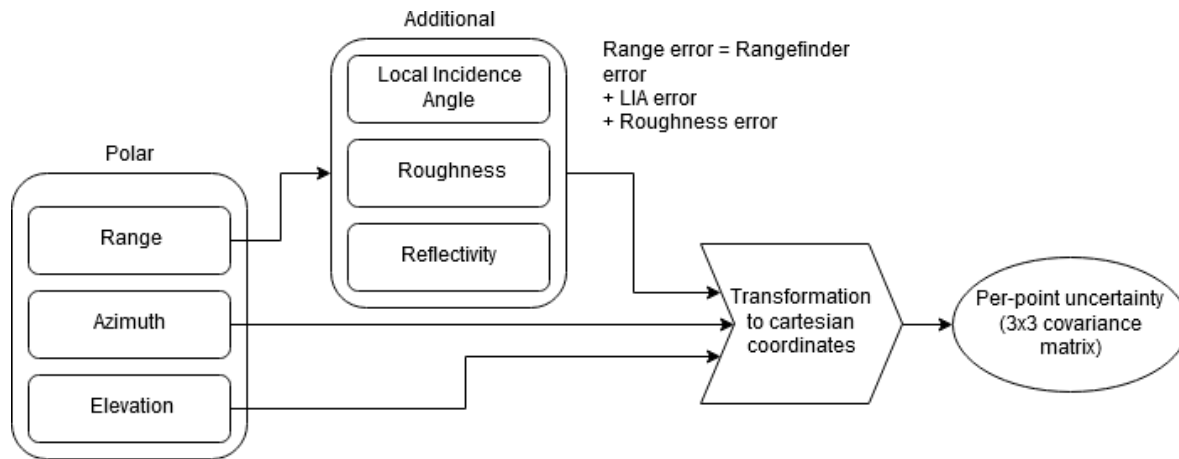
Results – Comparison to Lague et al. (2013) III

- Significant change?



Extendability

- Including object properties



- Using multiple sensor models → Multitemporal, historical data

Discussion

- Rigorous **propagation of error** enables confidence band estimation
- Additional **Metadata** required
 - Sensor accuracy
 - Coregistration procedure or trajectory
- Merging of multiple data sources possible
 - **Historic applications**
- More than bitemporal: 4D analyses

Summary

- Using trajectory- or coregistration errors allows more analyses
- Point clouds are not the only „original data“
- When pushing limits in uncertainty, know where data comes from
 - And what you are actually observing
- Sensors are able to deliver more information than what standard analyses allow to extract

References

Lague, D., Brodu, N., & Leroux, J. (2013). Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (NZ). *ISPRS Journal of Photogrammetry and Remote Sensing*, 82, 10-26.

Glira, P., Pfeifer, N., Briese, C., & Ressel, C. (2015). A Correspondence Framework for ALS Strip Adjustments based on Variants of the ICP Algorithm. *Photogrammetrie-Fernerkundung-Geoinformation*, 2015(4), 275-289.