Open-source Scientific Software py4dgeo for Change Analysis in 3D/4D Point Clouds

Tutorial held at ISPRS Congress 2026

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Era of Point Cloud Abundance and Ubiquity

Rapid development of technologies on hardware and software side at lower costs

The **new challenge** is how to handle thousands of point clouds

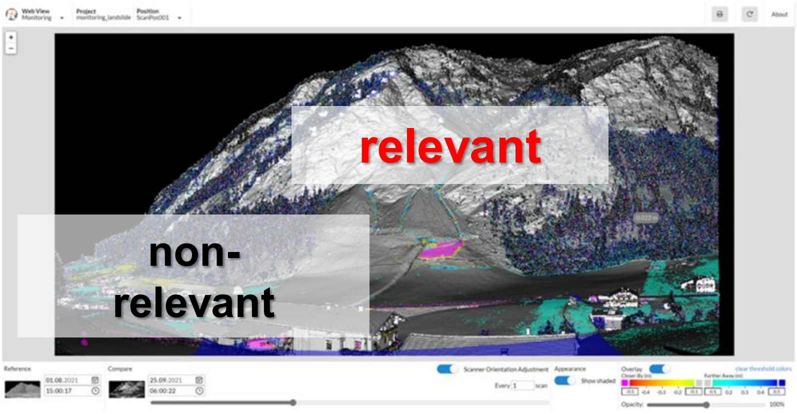
180418_070012.laz
180418_080012.laz
180418_090027.laz
180418_102550.laz
180418_110027.laz
180418_120027.laz
180418_130027.laz
180418_140027.laz
650.1 GB / 1.0 TB

?

We want more and **better information** - not more data

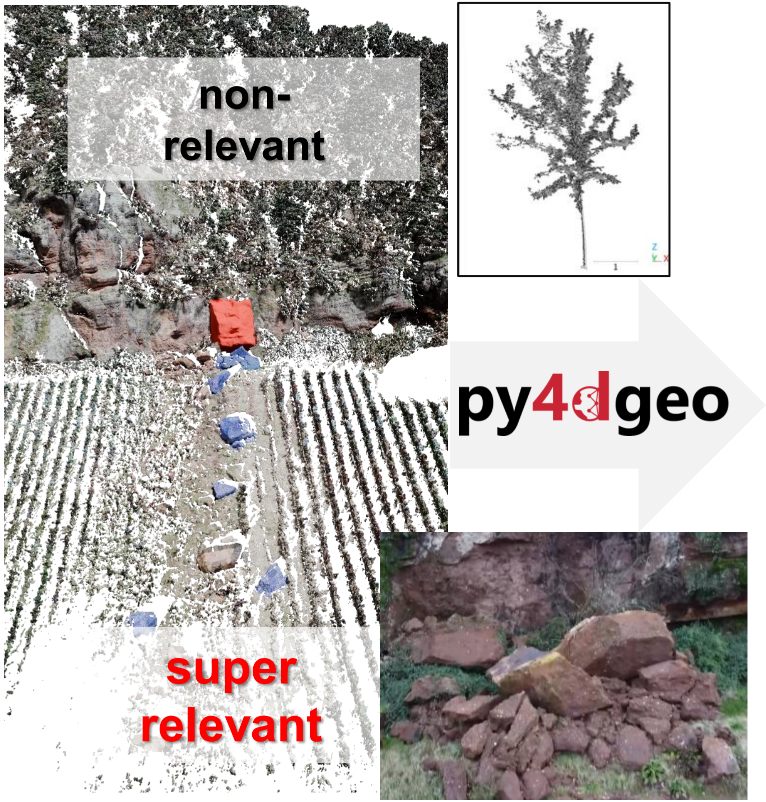
Achieve **better decisions and knowledge increase**

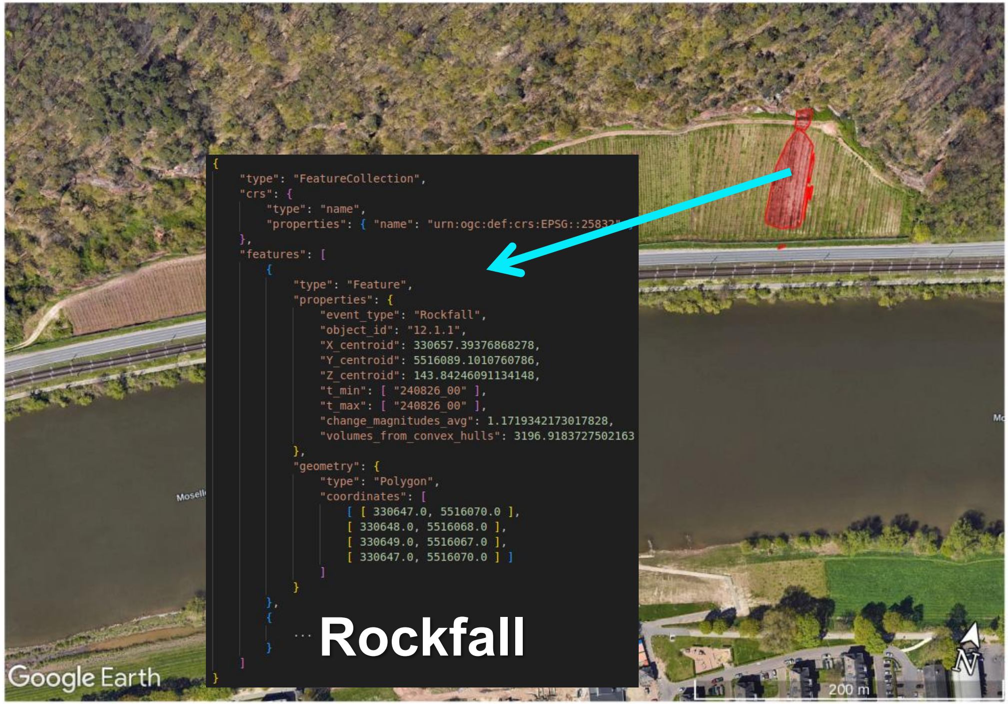
py4dgeo



Modified from: http://www.riegl.com/uploads/tx_pxpriegldownloads/Whitepaper_RIEGL_DMT.pdf

Example:
Operational Rockfall Monitoring ([AIMon5.0]())





Main Sources of 3D / 4D Point Clouds

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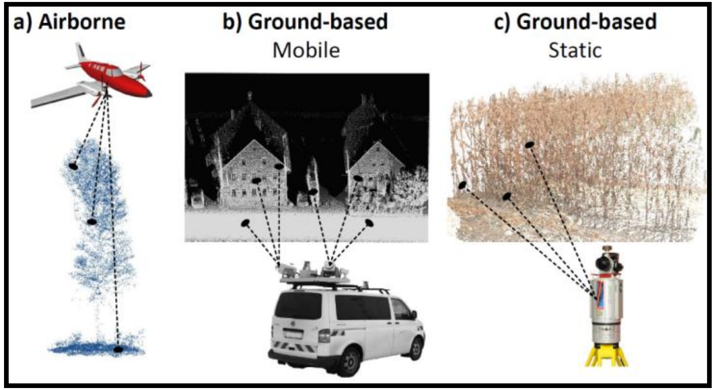
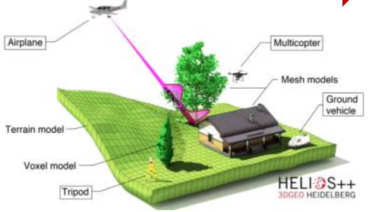
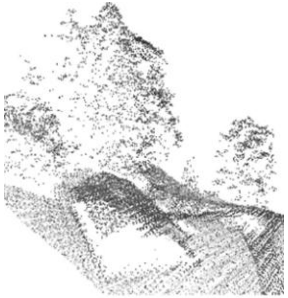
Laser Scanning / LiDAR



Photogrammetry: SfM / GS

LiDAR Simulation



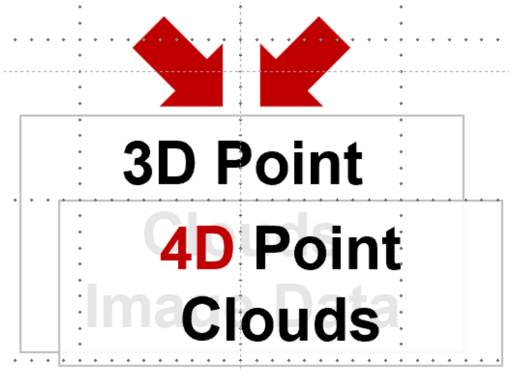


3D Point Clouds

4D Point Clouds

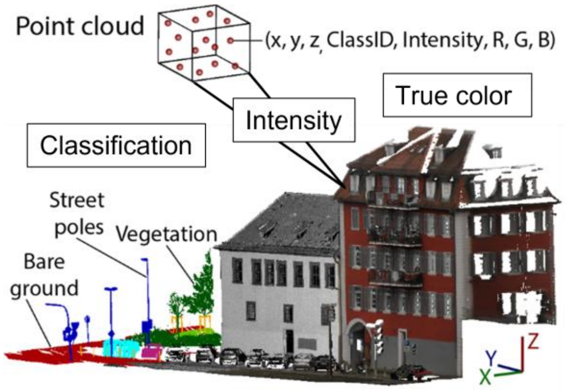
Image Data

Our Material: Point Cloud Data Model



*"A point cloud is **a set of points** P_i, $i = 1, \ldots, n$, embedded in three-dimensional Cartesian space and time."* [Otepka et al. (2013)]

Each point P_i has **3 coordinates** and a global/individual **timestamp**: **XYZT** and may have additional **attributes**



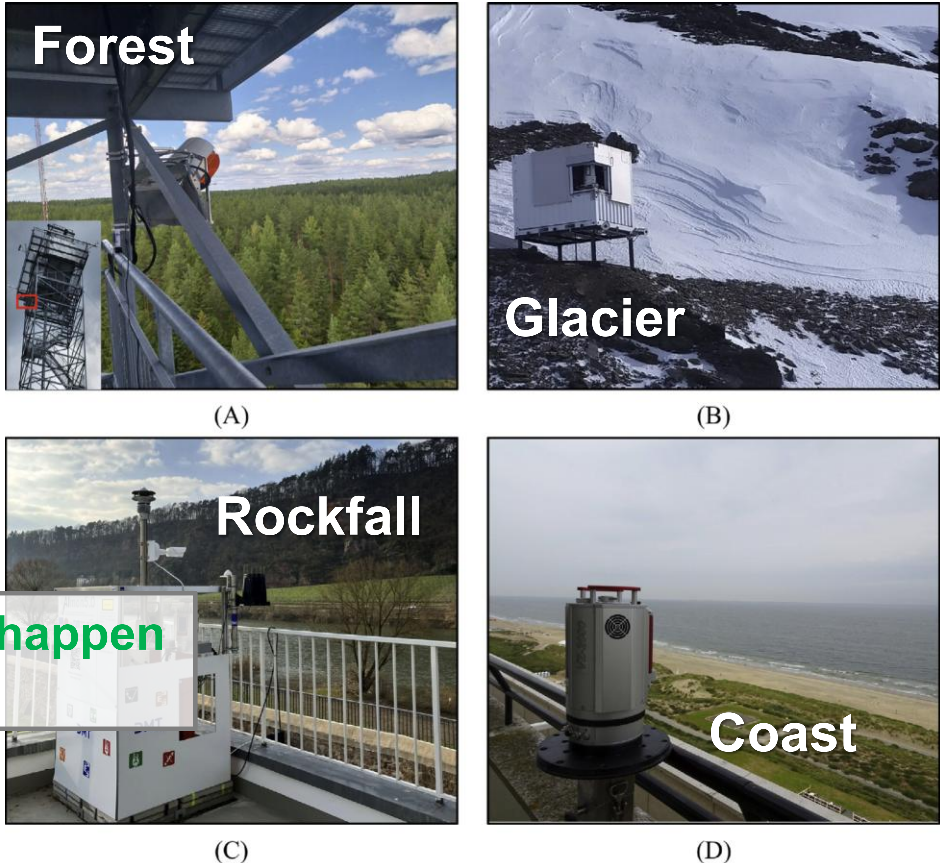
modified after Ghamisi et al. (2019)

PLS – Permanent Laser Scanning

→ **Autonomous (near-)continuous 3D laser scanning** from one or multiple fixed positions

→ Significant **temporal dimension** and rel. high frequency (min,h,d): 4D = 3D + time

→ Huge **time series** of point clouds
→ Even: **Continuous data stream** of 4D points



+ We can observe the changes as they happen
- No chance for manual analysis

Lindenbergh et al. (2025): Fig. 6,

AImon5.0

Echtzeitüberwachung gravitativer Massenbewegungen zum Risikomanagement kritischer Infrastrukturen mit KI-unterstützter 3D-Metrologie

DMT

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SEIT 1386

TUM

DB NETZE

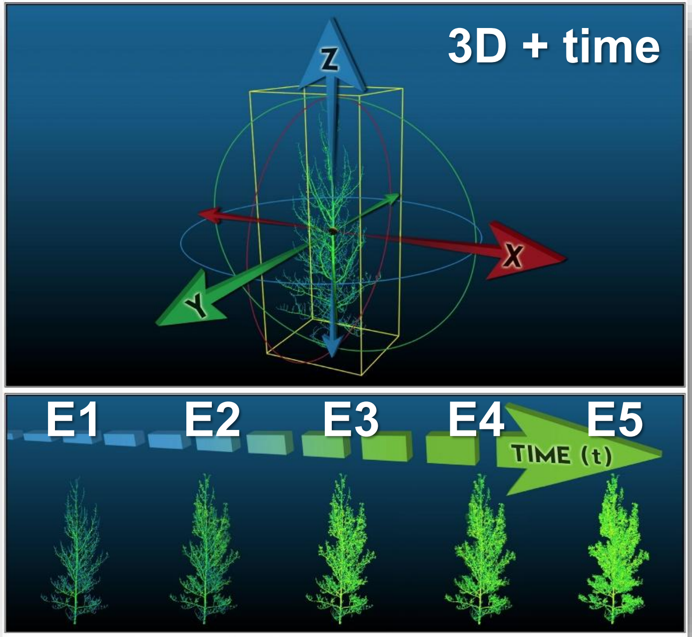
RheinlandPfalz
LANDESAMT FÜR GEOLOGIE UND BERGBAU

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

https://youtu.be/bOp4XN9FM48?feature=shared

What changes in 3D point clouds?

- **Temporal dimension** through repeat acquisition
  - **Epoch (E): Point cloud has 1 temporal anchor**
  - **Time series: Series of epochs**
- **Change** can regard any properties – what does it tell us?
  - Change in biophysical and chemical properties
  - **Change in geometric / morphologic properties**



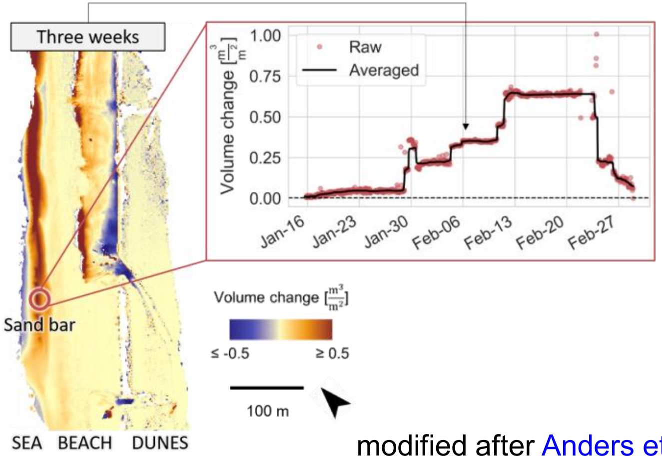
modified after Eitel et al. (2016)

Change Analysis in 3D/4D Point Clouds

Quantification along different dimensions

- **1D:** One direction in Z, vertical increase or lowering
- **2D:** Location in XY, horizontal displacement
- **3D:** 3D displacement, change in size and/or shape
- **>3D:** The above + changes in feature space

py4dgeo



modified after [Anders et al. (2019)]

Change Analysis in 3D/4D Point Clouds – Types of Results

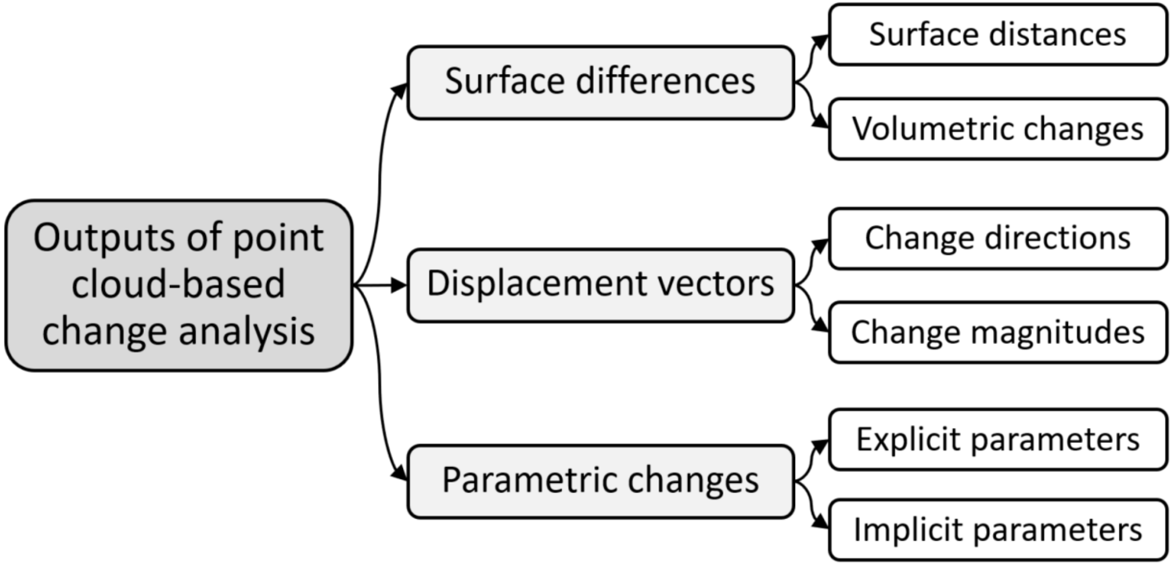
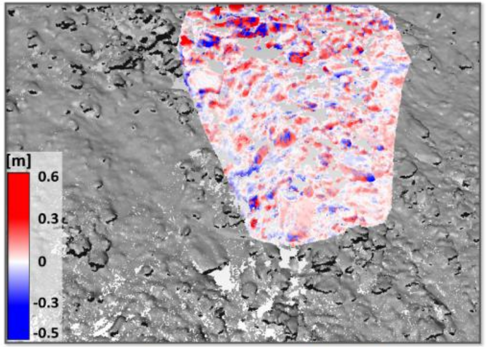
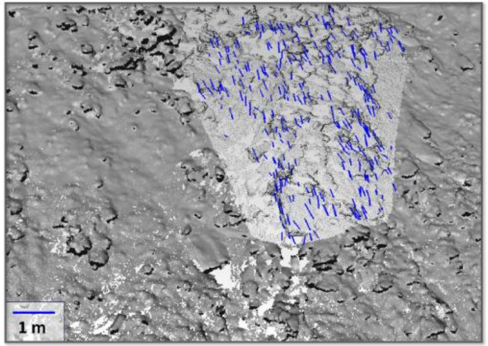


Figure 3. Types of results of point cloud-based change analysis.

Yang & Holst (2025): CC BY 4.0



(a) Surface differences by C2M



(b) Displacement vectors by feature point matching

Yang & Holst (2025): CC BY 4.0

3D Methods – Categories of Methods

Methods	General principles	Advantages	Limitations	Representative algorithms
Nearest neighbor-based	Calculating EDs of the points in one point cloud to their nearest neighbors in another point cloud.	Simple, fast and easy to implement.	Change values are sometimes underestimated.	C2C, C2M (Cignoni et al., 1998), M2M (Aspert et al., 2002) py4dgeo
Feature-based	Calculating EDs of feature elements (e.g., points and planes) extracted and matched from two scans or their converted 2D images.	Real displacement vectors can be derived.	Low spatial resolution and incorrect correspondences in repetitive structures.	F2S3 (Gojcic et al., 2020), CD-PB M3C2 (Zahs et al., 2022), Image-based feature points (Hosseini et al., 2023) py4dgeo
Parameter-based	Calculating changes of parametric elements (e.g., normals of planes or centers of spheres) estimated by the parameterization of point cloud surfaces.	Parameters of interest and their uncertainties can be estimated.	Required prior knowledge for parameterized objects; Challenging for highly irregular surfaces.	Geometric primitives (Yang et al., 2021), B-spline surface (Harmening et al., 2021)
Defined direction-based	Calculating EDs of constructed corresponding points from two scans along defined directions (e.g., gravity direction or surface normal).	Introducing defined directions to calculate changes with high resolution.	Change values are under- or over-estimated if defined directions are unrealistic.	DoD (Lane et al., 2003), M3C2 (Lague et al., 2013), Patch-based M3C2 (Yang and Schwieger, 2023a) py4dgeo
Local (rigid) registration-based	Performing a rigid registration procedure locally on selected subsets of two scans to derive the transformation matrix and displacement vectors.	Dense displacement fields can be derived without feature detection procedure.	Extracting corresponding rigid areas without prior knowledge is challenging.	Local ICP (Teza et al., 2007), Patch matching (Raffl and Holst, 2024)

Table 1. Five categories of point cloud-based change analysis methods by the correspondence definition (Yang, 2023).

Yang & Holst (2025):

3D Methods – How to Define Correspondences?

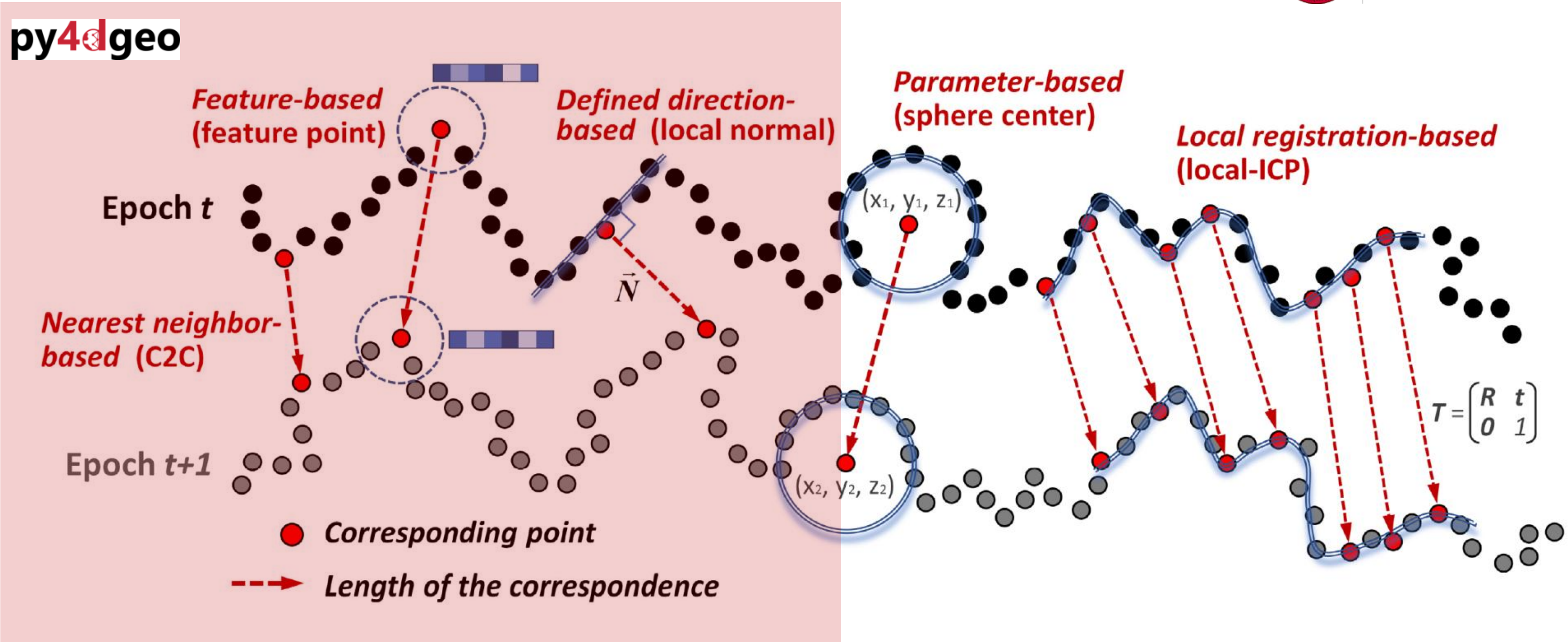


Figure 4. A schematic illustration of five types of correspondence definitions in point cloud-based change analysis.

Selection of Point Cloud-Based Method

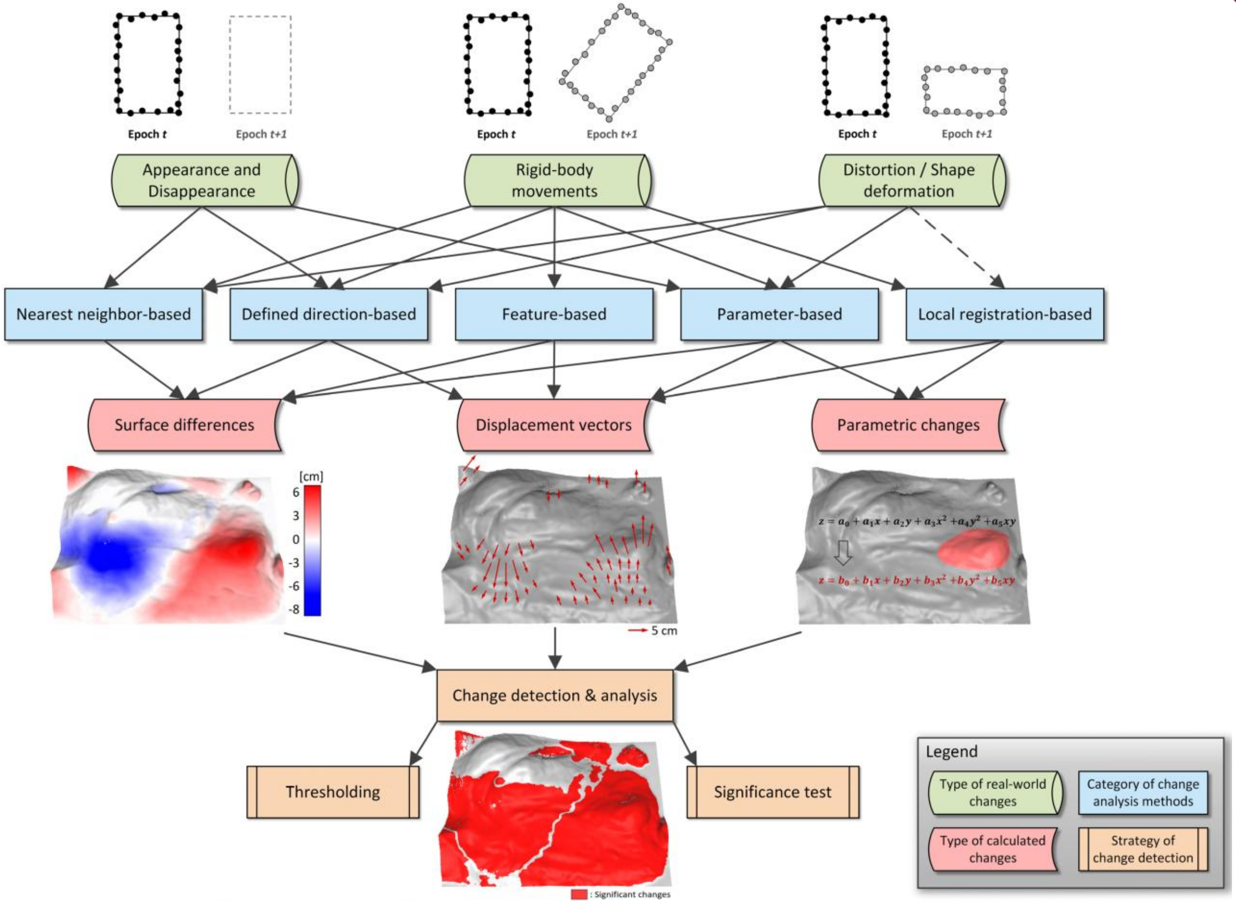
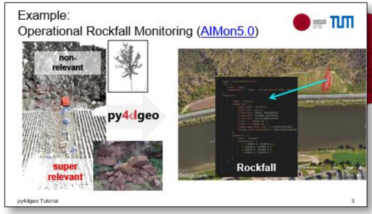


Figure 8. A workflow of method selection for point cloud-based change analysis.

Yang & Holst (2025):

Short Recap

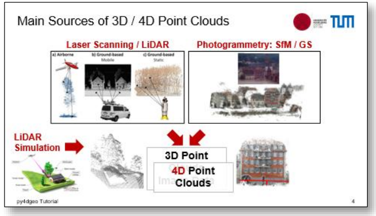


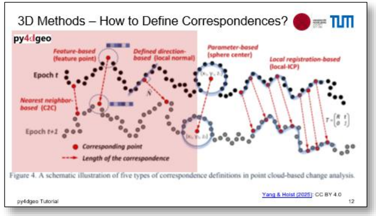
OPERATION
Automation & Quality

DEVELOPMENT
Open Tools

TECHNOLOGY
3D/4D Point Clouds

RESEARCH
Methods for Analysis





Open Online Course

E-learning course on Time Series Analysis in Remote Sensing for Understanding Human-Environment Interactions (E-TRAINEE)

E-TRAINEE

E-TRAINEE Module 3

Structure

The module is structured into the following themes:

- Principles of 3D/4D geographic point clouds
- Programming for point cloud analysis with Python
- Principles and basic algorithms of 3D change detection and analysis
- Time series analysis of 3D point clouds
- Machine learning-based 3D/4D point cloud analysis
- Case study: Multitemporal 3D change analysis at an active rock glacier
- Case study: Time series-based change analysis of sandy beach dynamics

Our Upcoming Talks at the ISPRS Congress 26

1. **Detection of hygroscopic dead tree branch movement using permanent laser scanning**
2. **Time-Adaptive Change Analysis through Extension of the M3C2 Algorithm using Multi-Modal Laser Scanning Data in a Salt Marsh Environment**
3. **Low-cost Terrestrial Laser Scanners for Permanent Monitoring of Beach-Dune Systems**
4. **Out-of-Distribution Detection for Real-World Honey Bee Monitoring Using Simulated Permanent Laser Scanning**
5. **Scan Outlier Ratio (ScOR): LiDAR Scanning and Survey-Aware Filtering of Detached Points in Terrestrial and Permanent Laser Scanning Point Clouds**
6. **Spatiotemporal reconstruction of 4D point clouds at different time scales through implicit neural representations for topographic monitoring applications**
7. **Topo4d: Topographic 4D STAC Extension for Curating and Cataloging Multi-Source Geospatial Time Series Datasets**

https://www.isprs2026toronto.com/full-program

References and Sources

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Ghamisi et al. (2019): https://doi.org/10.1109/MGRS.2018.2890023
Kuschnerus et al. (2021): https://doi.org/10.5194/esurf-9-89-2021
Lague et al. (2013): https://doi.org/10.1016/j.isprsjprs.2013.04.009
Lindenbergh et al. (2025): https://doi.org/10.1016/j.ophoto.2025.100094
Otepka et al. (2013): https://doi.org/10.3390/ijgi2041038
Yang & Holst (2025): https://doi.org/10.5194/isprs-annals-X-G-2025-1003-2025

ETRAINEE Online Course: https://3dgeo-heidelberg.github.io/etrainee/
py4dgeo: https://github.com/3dgeo-heidelberg/py4dgeo
HELIOS++LiDAR Simulation: https://github.com/3dgeo-heidelberg/helios
VAPC: https://github.com/3dgeo-heidelberg/vapc

AIMon5.0 Research Project: https://www.uni-heidelberg.de/aimon
AIMon5.0 Toolbox GitHub: https://github.com/3dgeo-heidelberg/aimon