# HARMONISATION OF HETEROGENEOUS POINT CLOUD USING ROAD MARKING AS BENCHMARK

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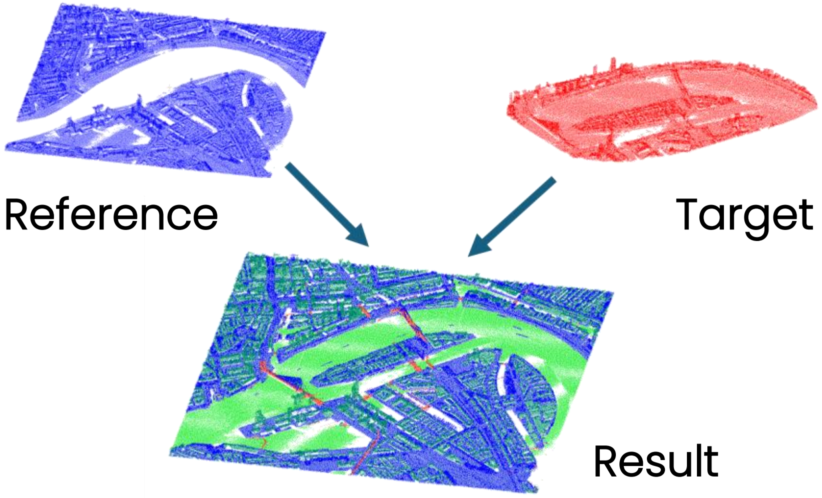
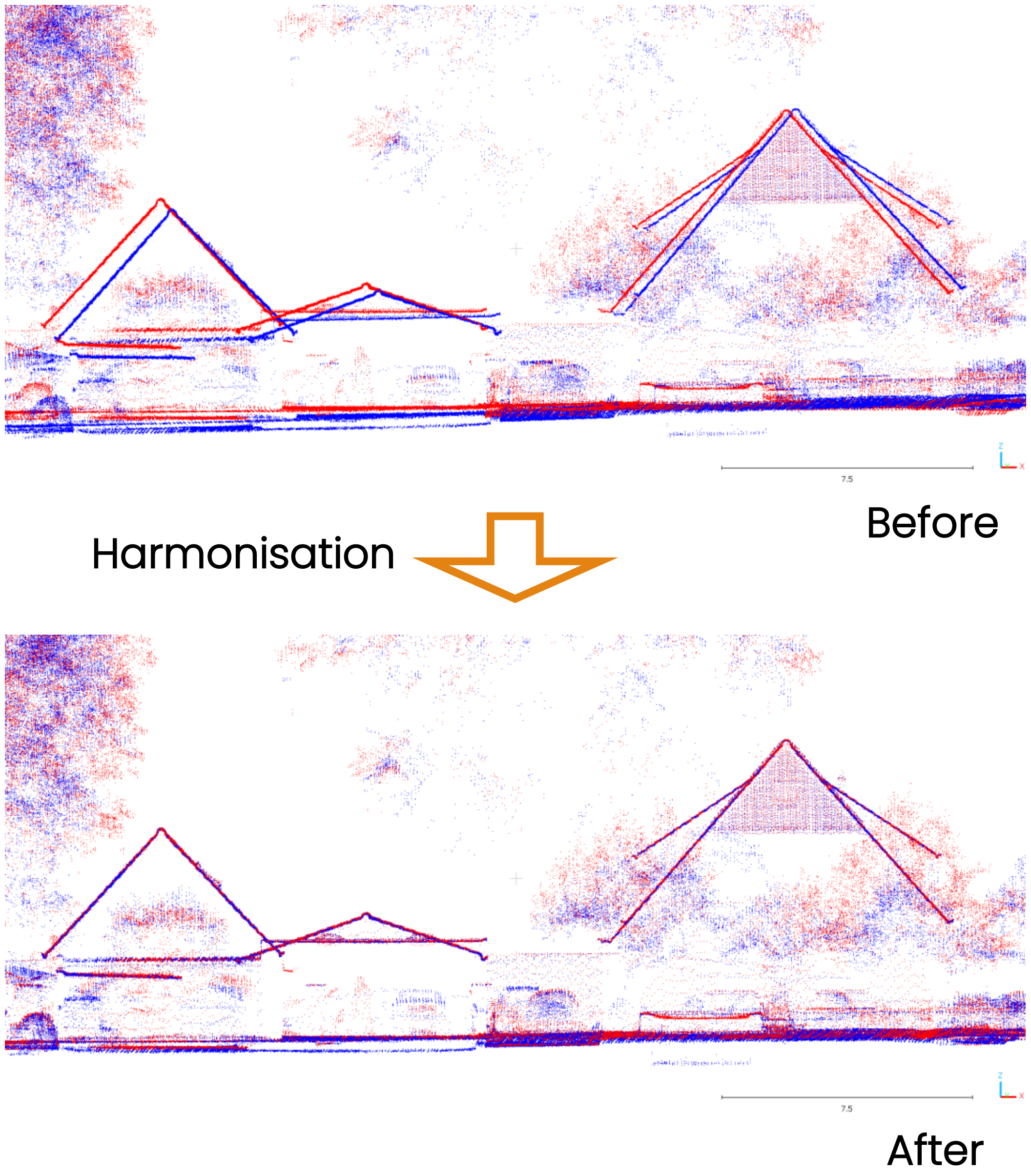
# BACKGROUND

**Harmonisation** is process to correct spatial discrepancies



# BACKGROUND

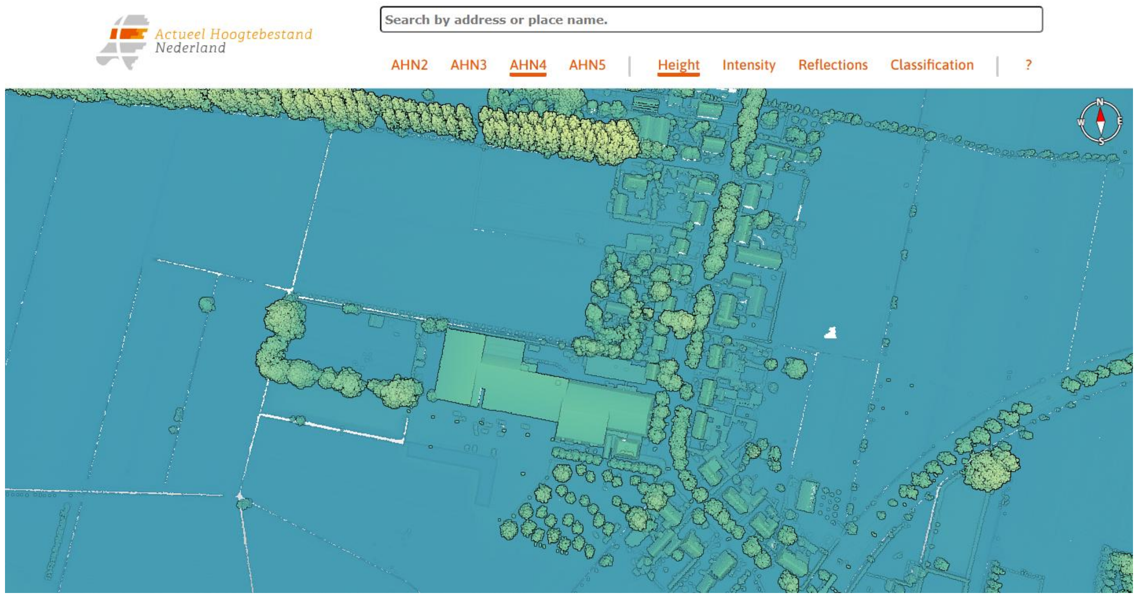
Integrale Hoogtevoorziening Nederland (IHN)

Objective:

Harmonise national point cloud datasets

Example of national point cloud datasets:

1. Actueel Hoogtebestand Nederland (AHN)
   Nationwide point cloud
2. ProRail's SpoorInBeeld
   Railways point cloud
3. Rijkswaterstaat Projects
   Roadways and tunnels



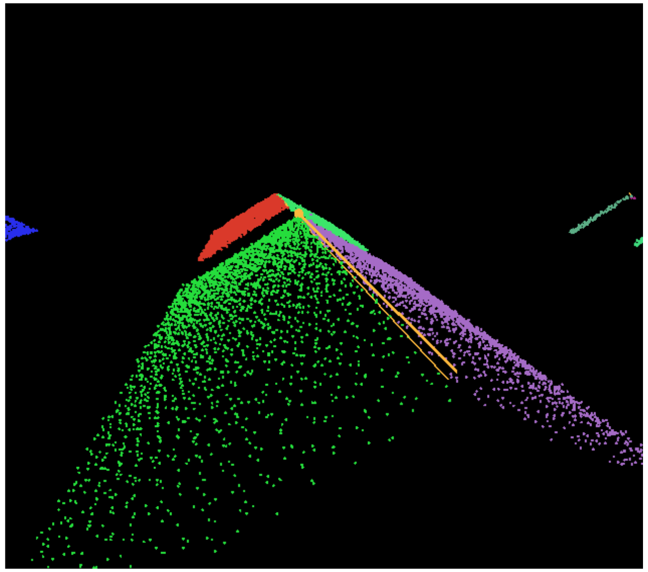

# BACKGROUND

Harmonisation requires **benchmarks** for alignment

Mainly extracted from buildings feature

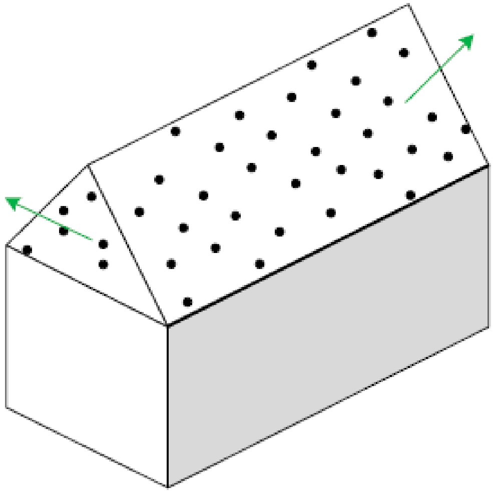
Artificial target need pre planned survey

- Datasets need to be acquired at the same time



Building Ridge Lines
(Elberink and Vosselman, 2024)

Artificial Target
(Csanyi and Toth, 2005)

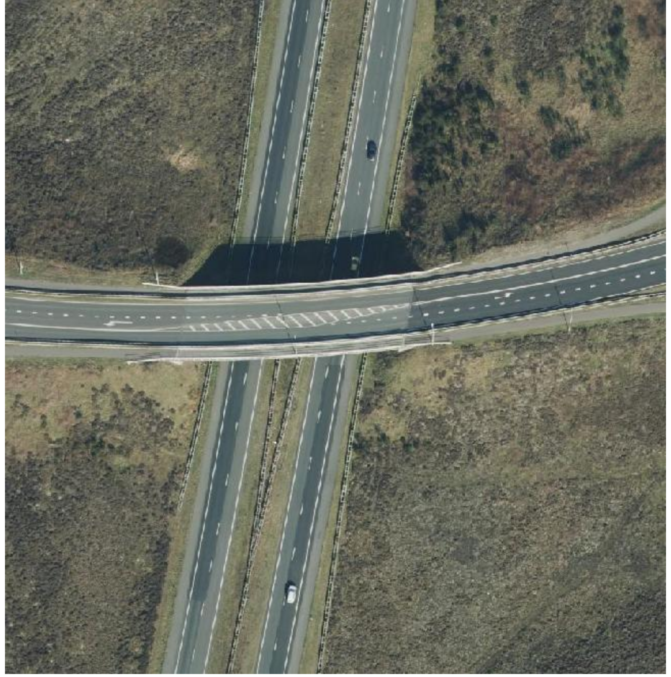


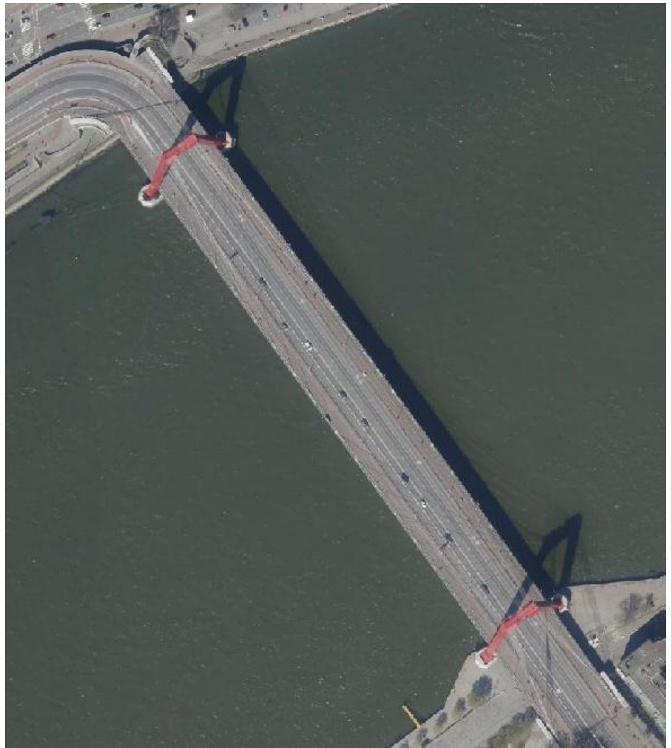
Normal Vector of Building Linear Surface
(Wu and Fan, 2016)

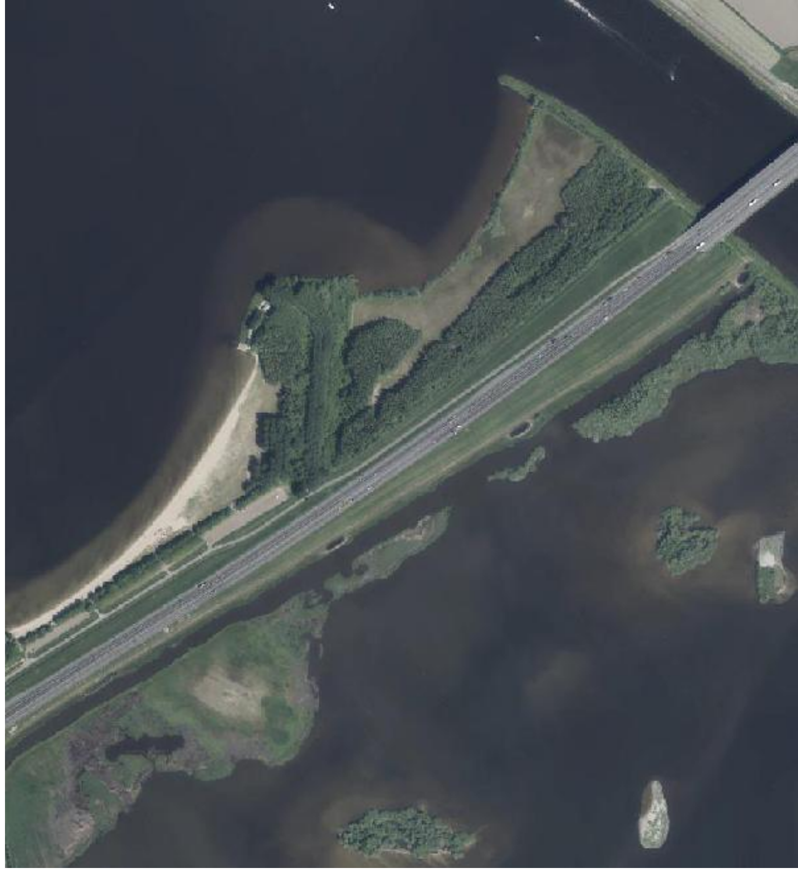
# BACKGROUND

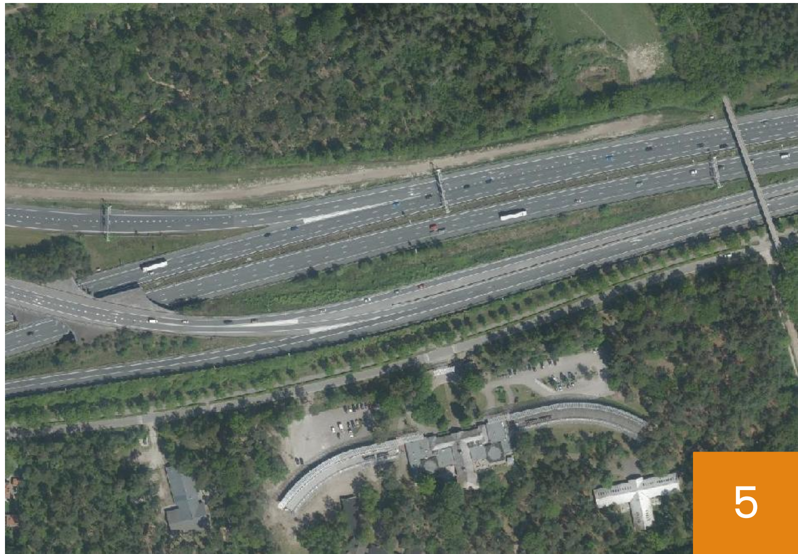
But what if there are no buildings?

And the datasets acquired in years apart?







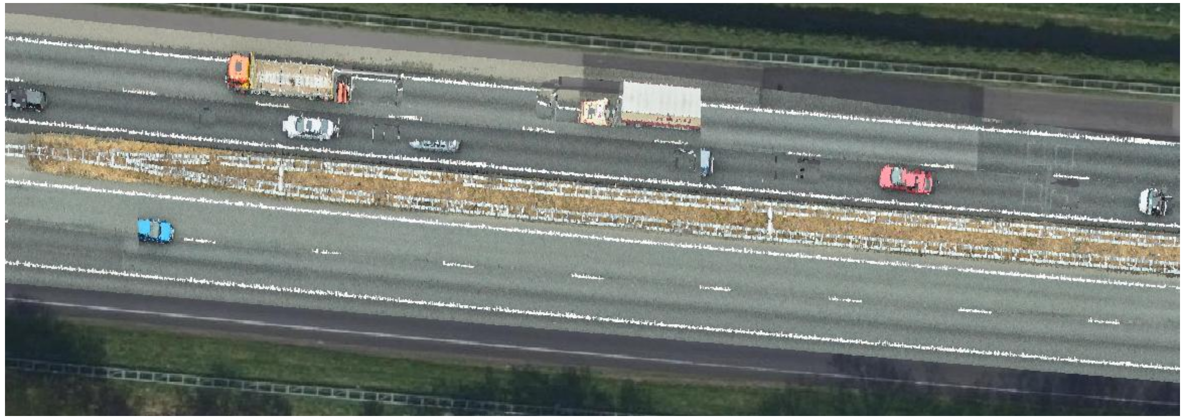


# BACKGROUND

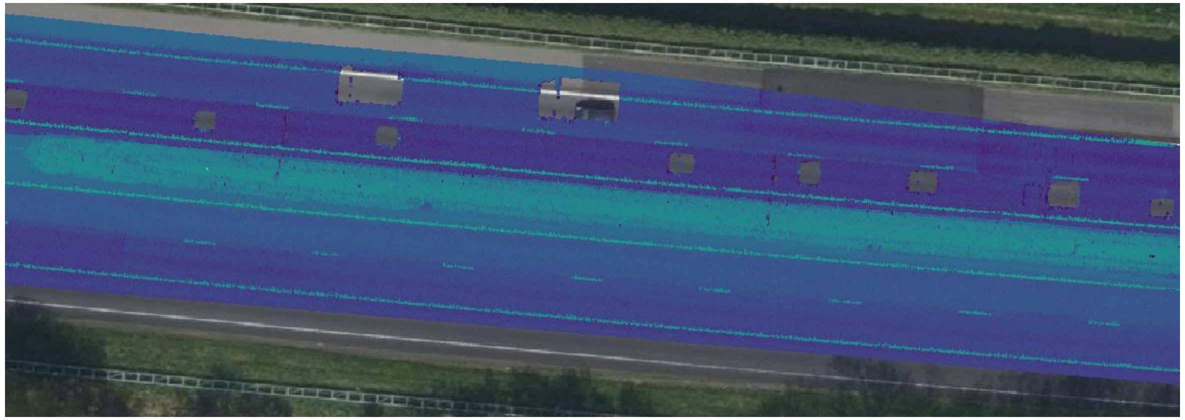
In Heide (2024), a method for road marking extraction was proposed

Introduces adaptive intensity range thresholding

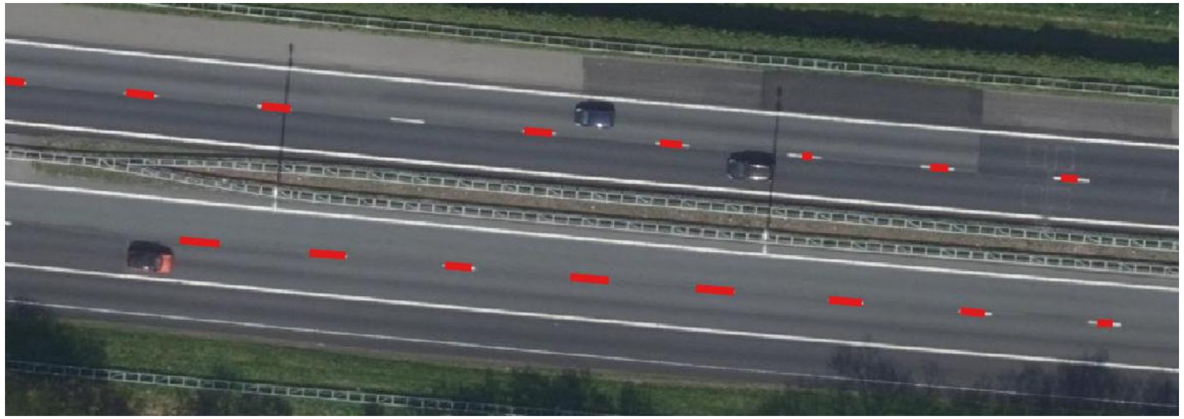
However, its performance in harmonisation has not yet been tested



RGB view



Intensity view

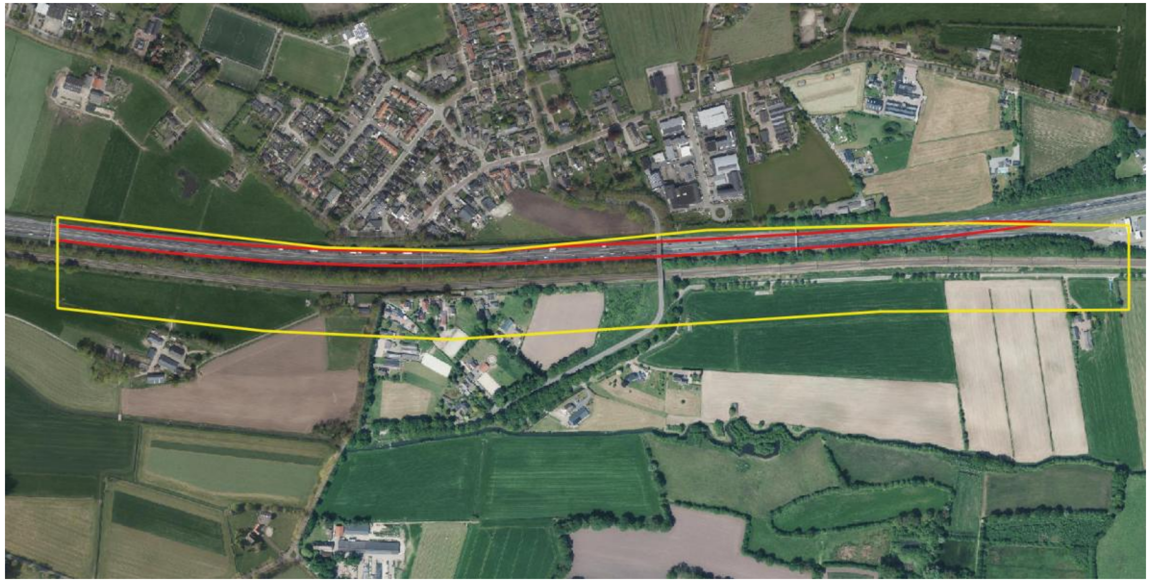


Extracted Road Marking

# RESEARCH QUESTION:

"How suitable are road markings extracted using the method proposed in Heide (2024) as a benchmark for heterogeneous LiDAR point cloud harmonisation?"

# STUDY CASE: Harmonisation of ProRail's SpoorInBeld and AHN Datasets



Area Of Interest (AOI)

Location: Southern Terschuur, municipality of Barneveld, province of Gelderland

| Dataset | Year | Mean Density (points/m$^2$) | | Intensity Range on Road Markings |
|---|---|---|---|---|
| | | Inside AOI | Road Only | |
| ProRail SpoorInBeeld | 2019 | 66 | 70 | 24,000 ~ 50,000 |
| ProRail SpoorInBeeld | 2021 | 134 | 144 | 1 ~ 35,000 |
| ProRail SpoorInBeeld | 2023 | 155 | 170 | 21 ~ 35,000 |
| AHN3 | 2018 | 10 | 10 | 1 ~ 850 |
| AHN4 | 2020-2022 | 23 | 24 | 12 ~ 1,500 |
| AHN5 | 2023 | 17 | 17 | 254 ~ 4,000 |

Datasets Specification

*Values shown in the table are calculated specifically for the AOI.

# HARMONISATION WORKFLOW

**Acquire point cloud data**

- AHN and ProRail point cloud
- Multiple Acquisition time

**Road marking extraction**

- Automatic Extraction (conducted in Rijkswaterstaat)
- Manual Digitisation

**Correspondence establishment**

- RANSAC-based inlier voting

**Transformation calculation**

- RANSAC-weighted centroid alignment

**Validation**

- DTM Differencing

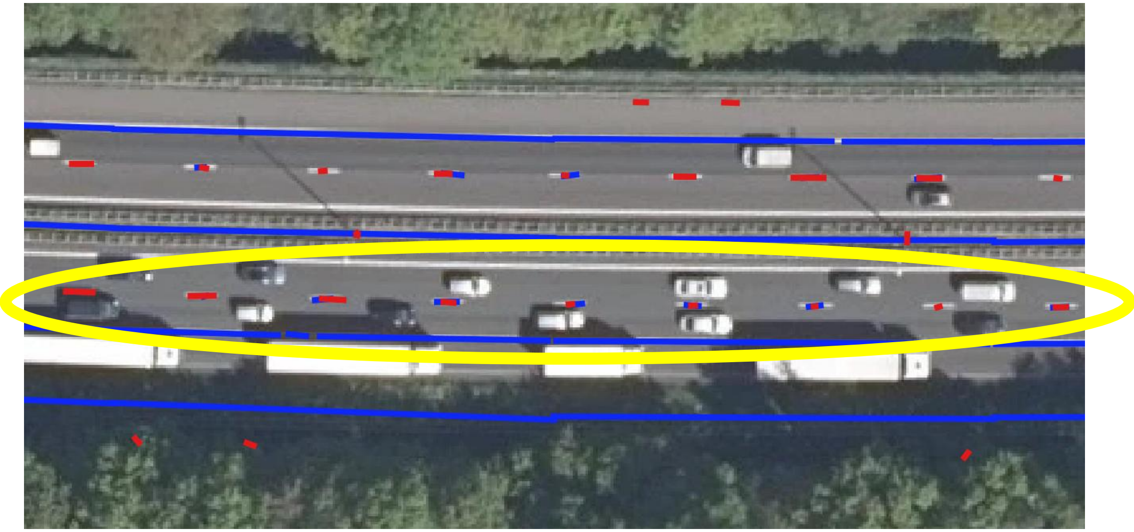
# VARIATION IN BENCHMARK POSITION AND SHAPE

Time gaps between datasets cause environmental changes

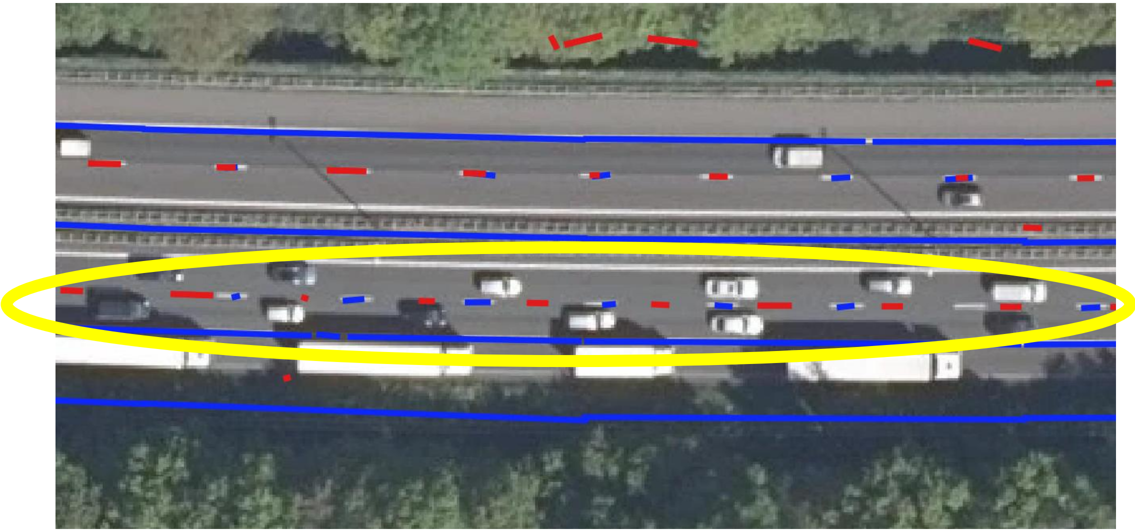
Different LiDAR sources affect road marking shape

**Sub-research Question 1:**

"How can reliable **correspondences** between road markings be **established** across LiDAR datasets with different acquisition times?"



Alignment of ProRail 2019 to AHN3 (2018)



Alignment of ProRail 2023 to AHN3 (2018)

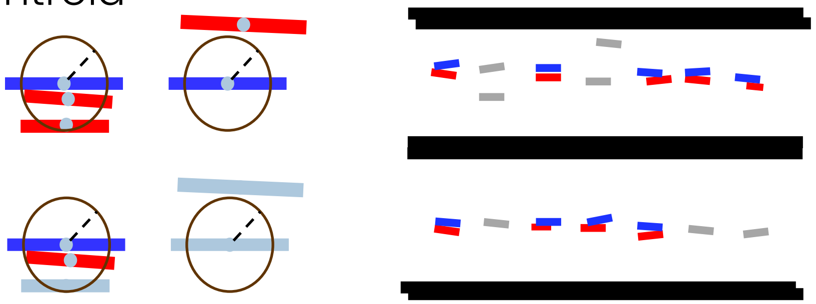
# CORRESPONDENCE ESTABLISHMENT

## RANSAC-based inlier voting:

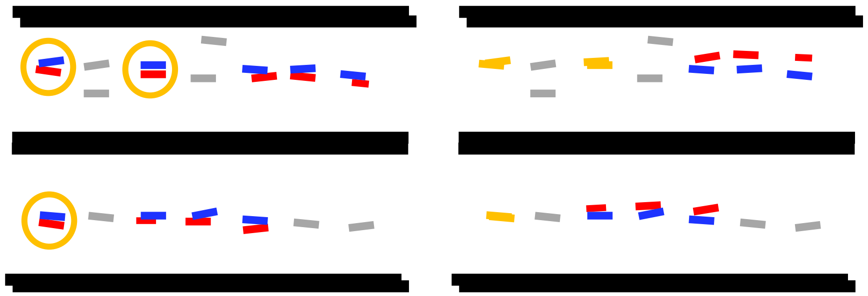
<u>Goal:</u>

Identify road marking pairs that consistently support a valid transformation

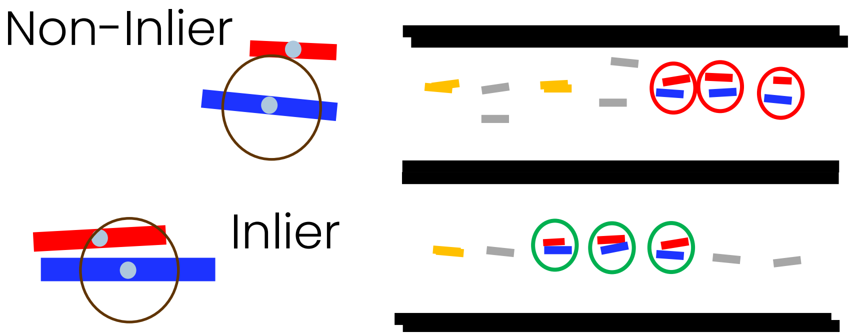
1. **Initial filter**: nearest neighbour match from centroid



2. **RANSAC alignment**: Estimate transformation using 3 random pairs



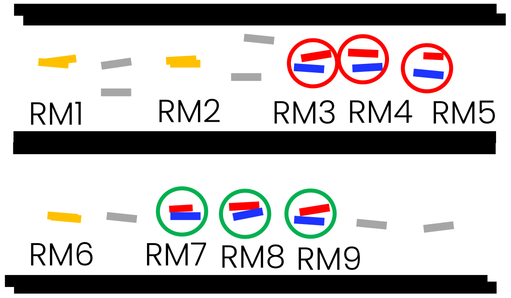
3. **Inlier Detection**: detect match that fall within tolerance



# CORRESPONDENCE ESTABLISHMENT

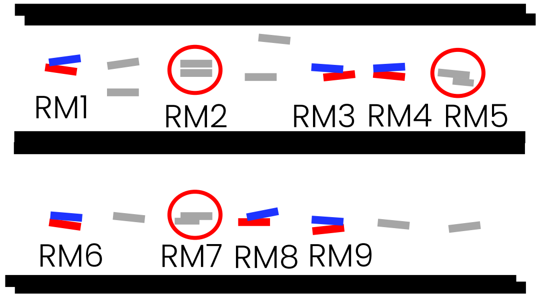
4. **Inlier Counting**: count the number of inliers per iteration to assess the

| Iteration-n | | |
|---|---|---|
| ID | Inlier count | Total iteration |
| RM 1 | +0 | 1000 |
| RM 2 | +0 | 1000 |
| RM 3 | +0 | 1000 |
| RM 4 | +0 | 1000 |
| RM 5 | +0 | 1000 |
| RM 6 | +0 | 1000 |
| RM 7 | +1 | 1000 |
| RM 8 | +1 | 1000 |
| RM 9 | +1 | 1000 |




5. **Final Assessment**: Identify geometrically unstable road marking pairs based on inlier votes

| Iteration-1000 | | |
|---|---|---|
| ID | Inlier count | Total iteration |
| RM 1 | 998 | 1000 |
| RM 2 | 122 | 1000 |
| RM 3 | 835 | 1000 |
| RM 4 | 923 | 1000 |
| RM 5 | 32 | 1000 |
| RM 6 | 890 | 1000 |
| RM 7 | 14 | 1000 |
| RM 8 | 841 | 1000 |
| RM 9 | 915 | 1000 |



# CORRESPONDENCE ESTABLISHMENT RESULT

| Manually Digitized | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reference | | AHN3 (2018) | | | AHN4 (2020-2022) | | | AHN5 (2023) | | |
| Target | | Prorail2019 | Prorail2021 | Prorail2023 | Prorail2019 | Prorail2021 | Prorail2023 | Prorail2019 | Prorail2021 | Prorail2023 |
| Total target RM | | 292 | 316 | 320 | 292 | 316 | 320 | 292 | 316 | 320 |
| Rejected | | 3 | 200 | 209 | 66 | 130 | 172 | 228 | 136 | 117 |
| Total processed RM | | 289 | 116 | 111 | 226 | 186 | 148 | 64 | 180 | 203 |
| RANSAC inlier count | 0-200 | 133 | 84 | 84 | 86 | 60 | 94 | 49 | 51 | 34 |
| | 201-400 | 5 | 0 | 1 | 4 | 3 | 1 | 0 | 9 | 3 |
| | 401-600 | 9 | 2 | 3 | 3 | 6 | 2 | 0 | 8 | 1 |
| | 601-800 | 11 | 1 | 1 | 11 | 11 | 3 | 1 | 13 | 2 |
| | 801-1000 | 131 | 29 | 22 | 122 | 106 | 48 | 14 | 99 | 163 |

| Automatically Extracted | | | | | | | |
|---|---|---|---|---|---|---|---|
| Reference | | AHN3 (2018) | | | AHN5 (2023) | | |
| Target | | Prorail2019 | Prorail2021 | Prorail2023 | Prorail2019 | Prorail2021 | Prorail2023 |
| Total target RM | | 559 | 369 | 696 | 559 | 369 | 696 |
| Rejected | | 240 | 306 | 588 | 470 | 275 | 503 |
| Total processed RM | | 319 | 63 | 108 | 89 | 94 | 193 |
| RANSAC inlier count | 0-200 | 155 | 43 | 81 | 62 | 67 | 116 |
| | 201-400 | 82 | 0 | 2 | 0 | 1 | 2 |
| | 401-600 | 2 | 1 | 1 | 2 | 1 | 1 |
| | 601-800 | 80 | 1 | 0 | 2 | 1 | 2 |
| | 801-1000 | 0 | 18 | 24 | 23 | 24 | 72 |

## Interpretation of Result:

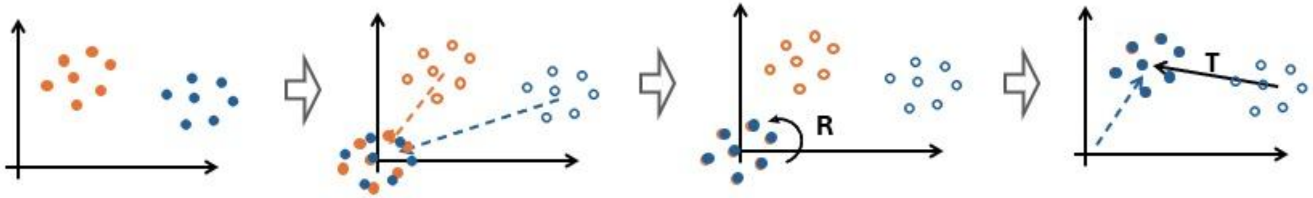
- Larger time gaps, lower number of RM passing the initial filter
  - Indicate more environmental changes in higher time gaps alignment
- The number of the most stable correspondences (bin 801-1000) of automatic RM is lower than the manual one
  - Indicates that the extraction quality influences the number of stable correspondences

# TRANSFORMATION MATRIX CALCULATION

RANSAC-Weighted Centroid Alignment

Estimate transformation matrix (Rotation R and Translation T),

Based on least-squares method in Arun et al. (1987),




Utilise the number of RANSAC inlier as weights ($w_i$).

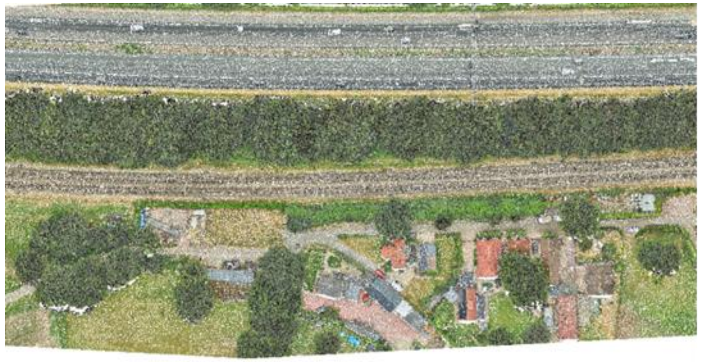
$$w_i = \frac{c_i}{T}$$

$c_i$ : inlier count for $i$-th
$T$ : total RANSAC iteration

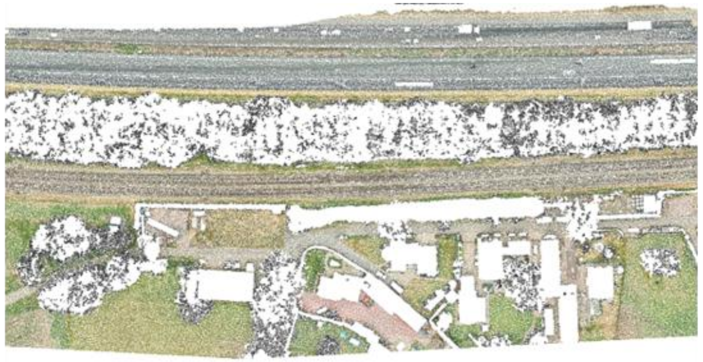
| Iteration-1000 | | |
|---|---|---|
| ID | Inlier count | Total iteration |
| RM 1 | 998 | 1000 |
| RM 2 | 122 | 1000 |
| RM 3 | 835 | 1000 |
| RM 4 | 923 | 1000 |
| RM 5 | 32 | 1000 |
| RM 6 | 890 | 1000 |
| RM 7 | 14 | 1000 |
| RM 8 | 841 | 1000 |
| RM 9 | 915 | 1000 |

# VALIDATION

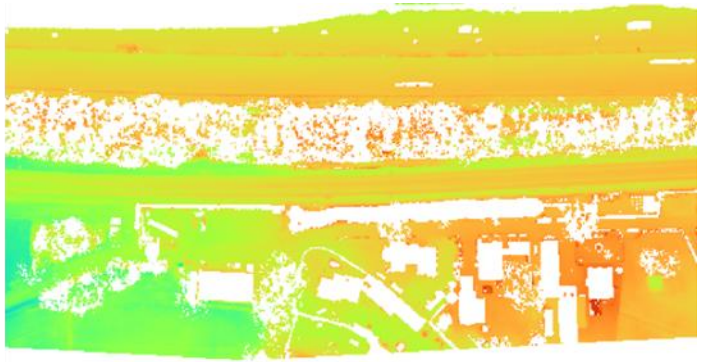
1. `Digital Terrain Model (DTM) Generation



Unfiltered point cloud



Ground points only



Rasterised ground points

2. DTM Differencing

$$DTM_{difference} = DTM_{reference} - DTM_{target}$$

# HARMONISATION RESULTS

| Mean DTM Pixel Difference (m) of Alignment Using Established Correspondence | | | | |
|---|---|---|---|---|
| Reference | Target | Untranformed | Manually Digitised | Automatic Extracted |
| AHN3 (2018) | Prorail2019 | 0.060 | 0.012 | 0.014 |
| | Prorail2021 | 0.002 | -0.035 | -0.001 |
| | Prorail2023 | 0.012 | 0.007 | 0.010 |
| AHN4 (2020-2022) | Prorail2019 | 0.105 | 0.000 | Not available |
| | Prorail2021 | 0.047 | 0.004 | Not available |
| | Prorail2023 | 0.054 | 0.024 | Not available |
| AHN5 (2023 | Prorail2019 | 0.096 | -0.006 | -0.043 |
| | Prorail2021 | 0.037 | -0.011 | -0.020 |
| | Prorail2023 | 0.051 | 0.020 | 0.004 |

Interpretation of Result:

- In general, both method successful to reduce misalignment gap
- In case alignment of Prorail2021–AHN3 manual RM, the result getting worse

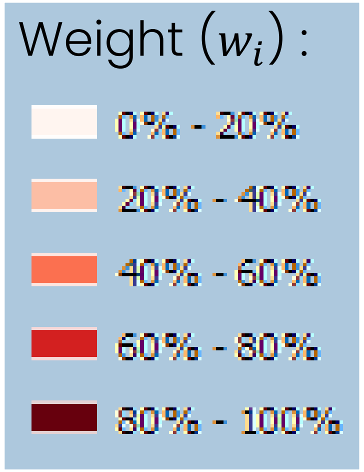
Sub-research Question 2:

“How does **weighting** the road markings based on their **geometric stability** influence the **accuracy** of multi-temporal LiDAR co-registration?”

# EVALUATING THE IMPACT OF STABILITY-BASED WEIGHTING

RANSAC-Weighted Centroid Alignment Method

Equal Weighting (Nearest Neighbour Method)




Higher-weighted benchmarks (darker red) have greater influence on the transformation matrix calculation

# EVALUATING THE IMPACT OF STABILITY-BASED WEIGHTING

| Mean DTM Difference (m) Using Manual Digitised RM | | | | |
|---|---|---|---|---|
| Reference | Target | Untransformed | RANSAC-Weighted | NN Search |
| AHN3 (2018) | Prorail2019 | 0.060 | 0.012 | 0.011 |
| | Prorail2021 | 0.002 | -0.035 | -0.004 |
| | Prorail2023 | 0.012 | 0.007 | 0.021 |
| AHN4 (2020-2022) | Prorail2019 | 0.105 | 0.000 | 0.001 |
| | Prorail2021 | 0.047 | 0.004 | -0.005 |
| | Prorail2023 | 0.054 | 0.024 | 0.015 |
| AHN5 (2023) | Prorail2019 | 0.096 | -0.006 | -0.017 |
| | Prorail2021 | 0.037 | -0.011 | -0.012 |
| | Prorail2023 | 0.051 | 0.020 | 0.021 |

| Mean DTM Difference (m) Using Automatic Extracted RM | | | | |
|---|---|---|---|---|
| Reference | Target | Untransformed | RANSAC-Weighted | NN Search |
| AHN3 (2018) | Prorail2019 | 0.060 | 0.014 | 0.011 |
| | Prorail2021 | 0.002 | -0.001 | -0.010 |
| | Prorail2023 | 0.012 | 0.010 | 0.014 |
| AHN5 (2023) | Prorail2019 | 0.096 | -0.043 | -0.024 |
| | Prorail2021 | 0.037 | -0.020 | -0.005 |
| | Prorail2023 | 0.051 | 0.004 | 0.008 |

Interpretation of Result:

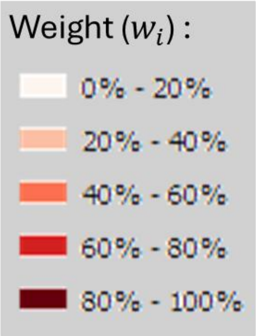
- The proposed method not always give a better result
- In some cases, it give worse alignment result

# CASE WHERE NN SEARCH PERFORM BETTER

Alignment of **Prorail2021** to **AHN3**, using **manual** digitised road markings

RANSAC-Weighted Centroid Alignment Method
Mean DTM Difference (m): -0.035

Equal Weighting (Nearest Neighbour Method)
Mean DTM Difference (m): -0.004



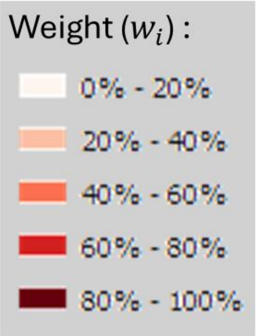

Concentrated higher-weight on northern lane of highway, make the distribution uneven

# CASE WHERE RANSAC-WEIGHTED PERFORM BETTER

Alignment of **Prorail2023** to **AHN5**, using **automatic** extracted road markings

RANSAC-Weighted Centroid Alignment Method
Mean DTM Difference (m): 0.004

Equal Weighting (Nearest Neighbour Method)
Mean DTM Difference (m): 0.008




The proposed correspondence establishment method works to reduce misalignment

However, in some cases it filter out spatially important benchmark that maintain even distribution

Despite weight variation, the higher-weighted benchmarks are evenly distributed

# HARMONISATION RESULTS

| Mean DTM Pixel Difference (m) of Alignment Using Established Correspondence | | | | |
|---|---|---|---|---|
| Reference | Target | Untranformed | Manually Digitised | Automatic Extracted |
| AHN3 (2018) | Prorail2019 | 0.060 | 0.012 | 0.014 |
| | Prorail2021 | 0.002 | -0.035 | -0.001 |
| | Prorail2023 | 0.012 | 0.007 | 0.010 |
| AHN4 (2020-2022) | Prorail2019 | 0.105 | 0.000 | Not available |
| | Prorail2021 | 0.047 | 0.004 | Not available |
| | Prorail2023 | 0.054 | 0.024 | Not available |
| AHN5 (2023 | Prorail2019 | 0.096 | -0.006 | -0.043 |
| | Prorail2021 | 0.037 | -0.011 | -0.020 |
| | Prorail2023 | 0.051 | 0.020 | 0.004 |

Interpretation of Result:

- In general, both method successful to reduce misalignment gap
- In case alignment of Prorail2021–AHN3 manual RM, the result getting worse
- In most case, manually digitised RM perform slightly better

Sub-research Question 3:

"How does the accuracy of automatically extracted road markings influence the accuracy of LiDAR co-regsitration?"

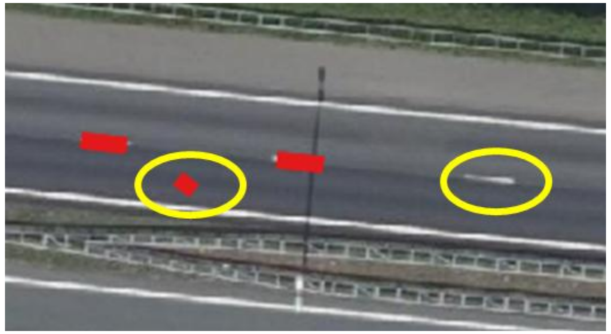
# EVALUATE THE IMPACT OF EXTRACTION ACCURACY TO ALIGNMENT ACCURACY

**Evaluate**
- Detection Accuracy Measurement (based on Heipke et al., 1997 approach)
- Line Centroid Accuracy Measurement

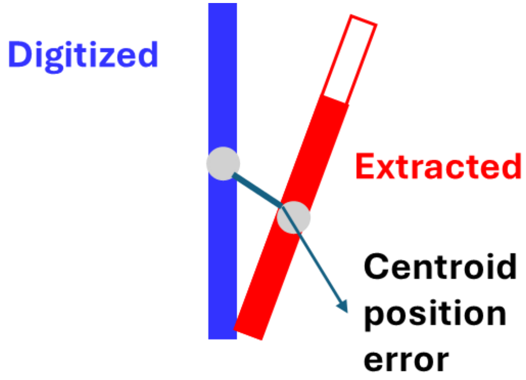
**Align**
- Automatic Extracted Alignment
- Manually Digitised Alignment

**Compare**
- Accuracy Metrics Comparison
- DTM Difference Residual Comparison

Detection Errors:



Line Centroid Errors



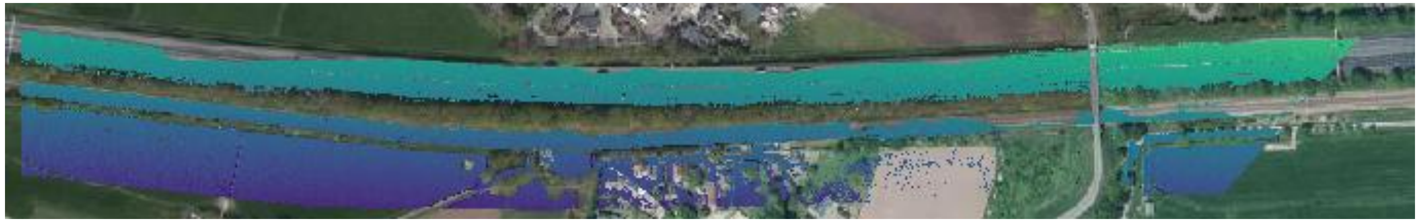
# EVALUATING THE IMPACT OF EXTRACTION ACCURACY TO ALIGNMENT ACCURACY

| | | Test 1 | | Test 2 | | Test 3 | | Test 4 | | Test 5 | | Test 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Reference | Target | Reference | Target | Reference | Target | Reference | Target | Reference | Target | Reference | Target |
| | | AHN3 | Prorail2019 | AHN5 | Prorail2019 | AHN3 | Prorail2021 | AHN5 | Prorail2021 | AHN3 | Prorail2023 | AHN5 | Prorail2023 |
| Mean Δ3D of Centroid | | 0.207 | 0.138 | 0.202 | 0.138 | 0.207 | 0.129 | 0.202 | 0.129 | 0.207 | 0.151 | 0.202 | 0.151 |
| Completeness (%) | | 0.802 | 0.887 | 1 | 0.887 | 0.802 | 0.807 | 1 | 0.807 | 0.802 | 0.959 | 1 | 0.959 |
| Correctness (%) | | 0.412 | 0.463 | 0.552 | 0.463 | 0.412 | 0.689 | 0.552 | 0.689 | 0.412 | 0.44 | 0.552 | 0.44 |
| Quality (%) | | 0.374 | 0.438 | 0.405 | 0.438 | 0.374 | 0.592 | 0.405 | 0.592 | 0.374 | 0.432 | 0.405 | 0.432 |
| Weight | 0% - 20% | 155 | | 62 | | 43 | | 67 | | 81 | | 116 | |
| | 20% - 40% | 82 | | 0 | | 0 | | 1 | | 2 | | 2 | |
| | 40% - 60% | 2 | | 2 | | 1 | | 1 | | 1 | | 1 | |
| | 60% - 80% | 80 | | 2 | | 1 | | 1 | | 0 | | 2 | |
| | 80% - 100% | 0 | | 23 | | 18 | | 24 | | 24 | | 72 | |
| Mean Residual Map (m) | | 0.0022 | | -0.0485 | | 0.0395 | | -0.0116 | | 0.0031 | | -0.0156 | |

Interpretation of Result:

- No direct correlation between extraction accuracy and alignment accuracy can be found.

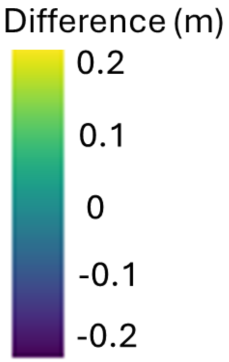
# TEST 2: PRORAIL 2019 TO AHN 5

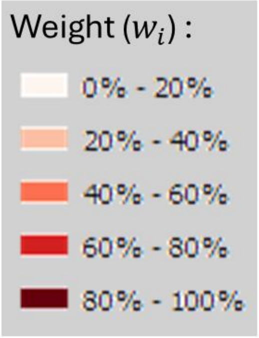


DTM Accuracy Difference (Mean value: -0.0485 m)

Benchmark Distribution of Alignment Using **Automatic** Extracted RM

Benchmark Distribution of Alignment Using **Manual** Digitised RM

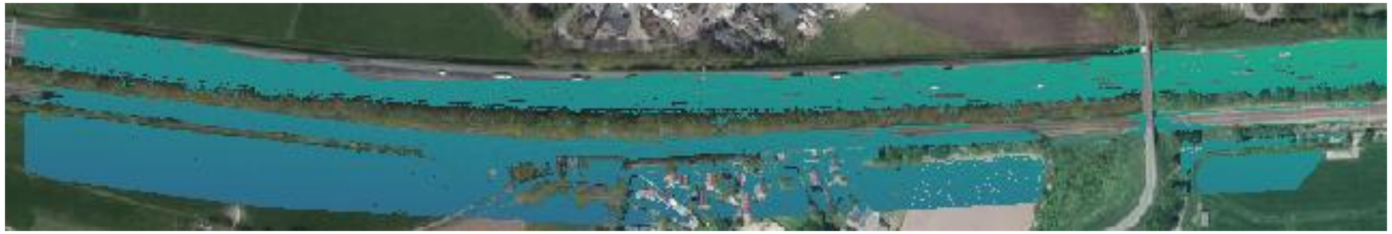



Extraction accuracy directly influence the distribution of benchmark.

Distribution of benchmark affect the alignment accuracy

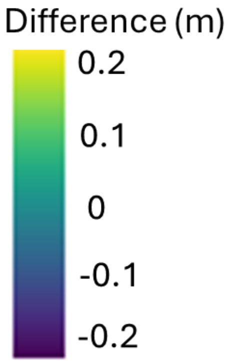
# TEST 6: PRORAIL 2023 TO AHN 5

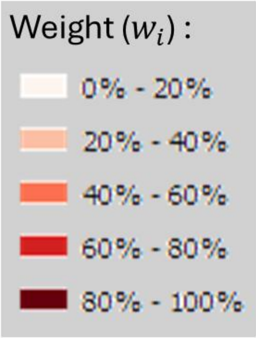


DTM Accuracy Difference (Mean value: -0.0156 m)

Benchmark Distribution of Alignment Using **Automatic** Extracted RM

Benchmark Distribution of Alignment Using **Manual** Digitised RM

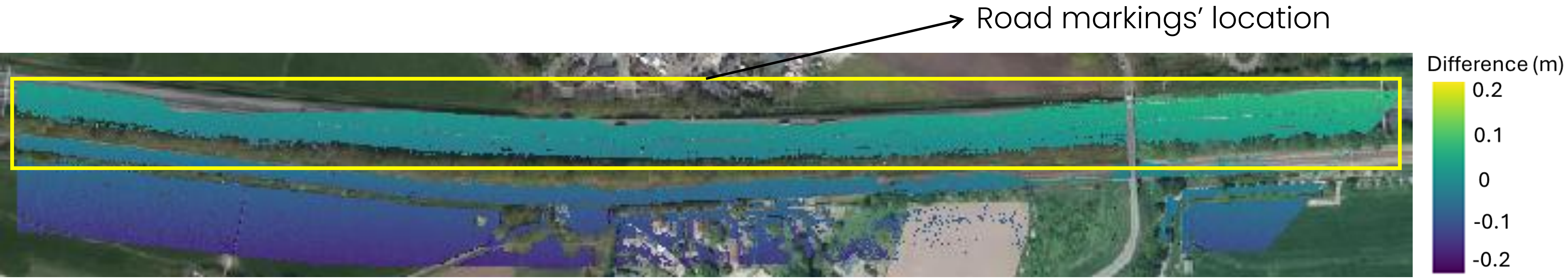



Extraction errors reduce the number of high-stability benchmarks

If high-stability benchmarks are evenly distributed, alignment accuracy difference remains small

# DTM DIFFERENCE VALUE DISTRIBUTION




Sub-research Question 4:

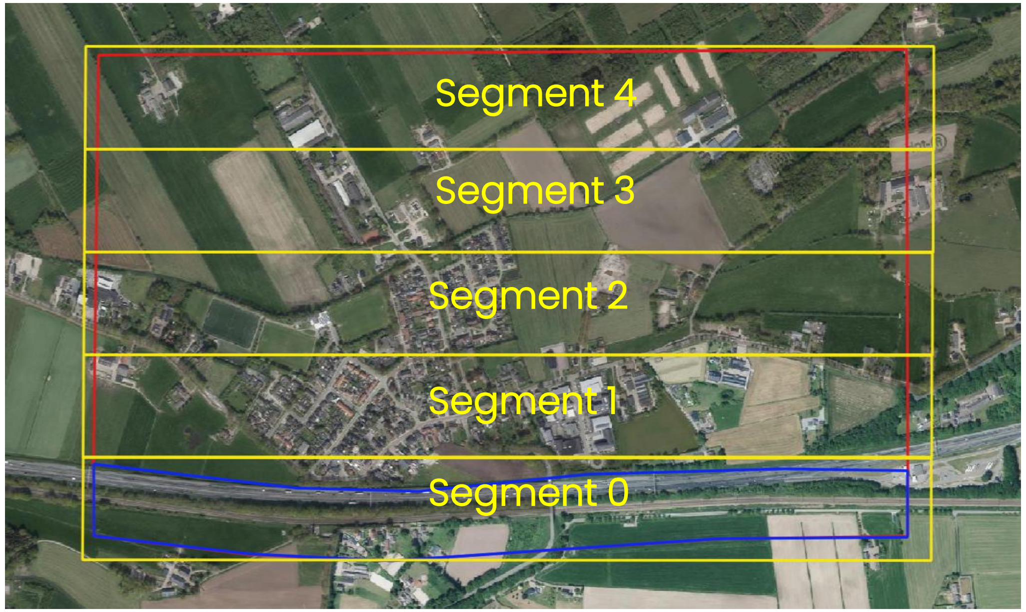
"How does the **alignment error** change with **increasing distance** from the area where road markings are used as a benchmark?"

# EVALUATE THE EFFECT OF BENCHMARK DISTANCE ON ALIGNMENT ACCURACY

**Align**
- Automatic Extracted Alignment
- Manually Digitised Alignment

**Segment**
- Divide AOI to several segment

**Compare**
- Compare alignment accuracy with adjacent segment




Red line: Extent of the AOI

Blue line: Benchmark area

Yellow line: DTM segments

# EVALUATE THE EFFECT OF BENCHMARK DISTANCE ON ALIGNMENT ACCURACY

1.

| Mean DTM Difference per Segment (m) | | | | | |
|---|---|---|---|---|---|
| Segment | Segmen 0 | Segmen 1 | Segmen 2 | Segmen 3 | Segmen 4 |
| Untransformed | -0.033 | -0.030 | -0.020 | -0.020 | -0.027 |
| Manual | 0.001 | -0.006 | -0.017 | -0.015 | -0.022 |
| Automatic | -0.019 | 0.147 | 0.318 | 0.486 | 0.645 |

2.

| Difference Between Adjacent Segments (m) | | |
|---|---|---|
| Extraction Method | Manual | Automatic |
| Δ between Segment 0 and 1 | -0.007 | 0.166 |
| Δ between Segment 1 and 2 | -0.011 | 0.170 |
| Δ between Segment 2 and 3 | 0.002 | 0.169 |
| Δ between Segment 3 and 4 | -0.007 | 0.159 |
| Mean Δ | -0.006 | 0.166 |

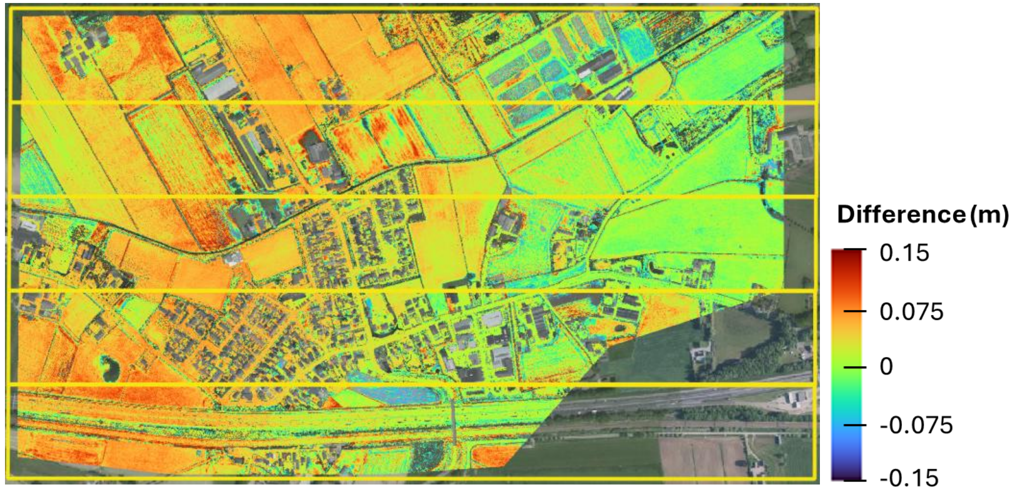
3.

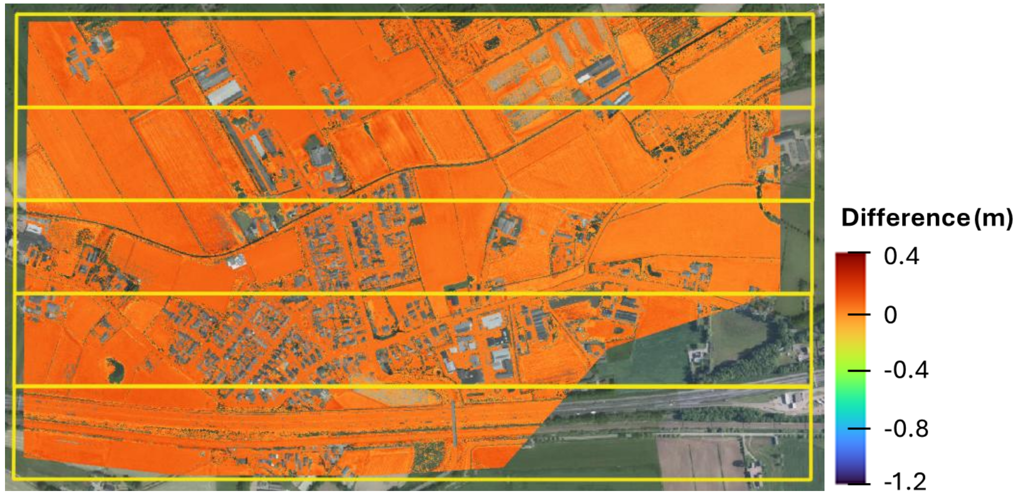
| Comparison of Rotation Angles | | | |
|---|---|---|---|
| Rotation Axis | Manual RM | Automatic RM | Difference |
| Omega (°) | 0.0007 | -0.0462 | -0.0469 |
| Phi (°) | -0.0042 | -0.0010 | 0.0032 |
| Kappa (°) | 0.0059 | 0.0041 | -0.0018 |

Interpretation of Result:

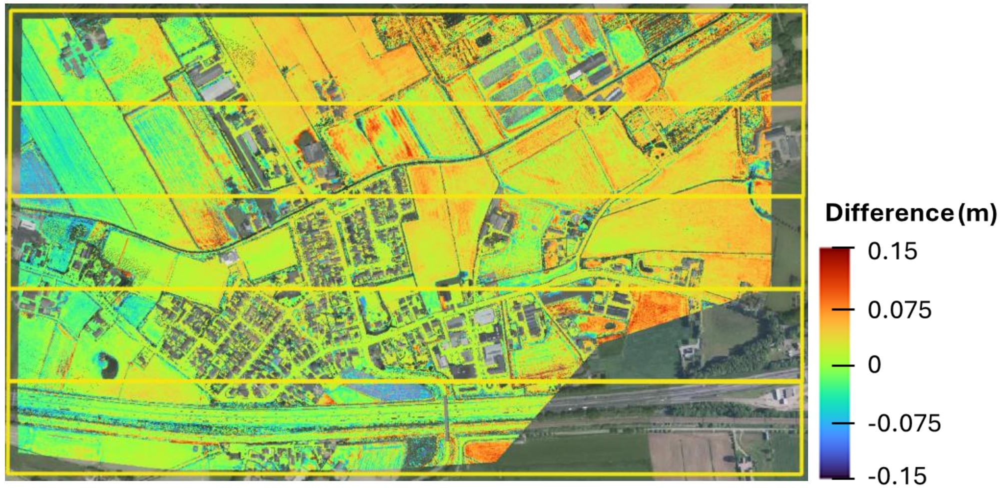
- Alignment error tends to increase as the distance increase
- Automatic extraction RM leads to a faster decline in accuracy
- Alignment error increases due to rotation error, mainly in omega (x-axis)

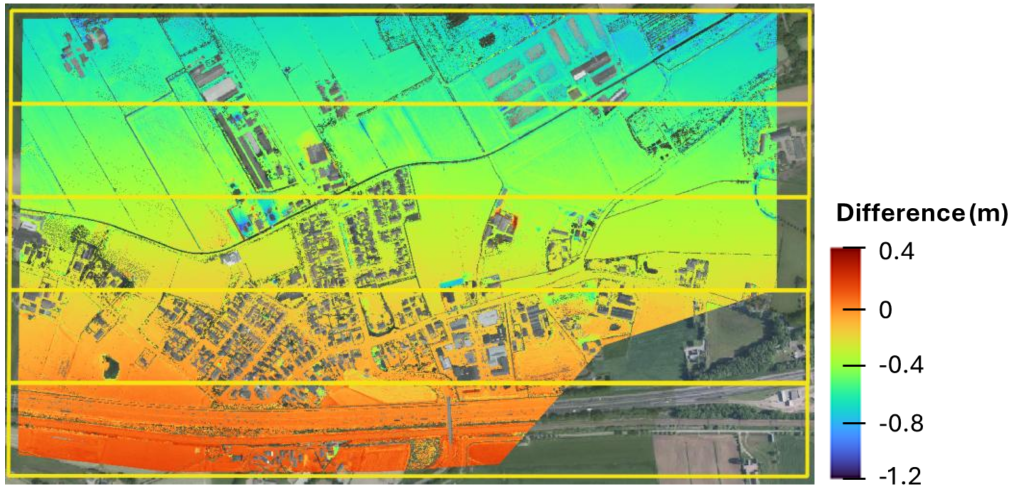
Untransformed



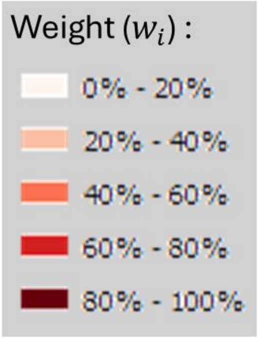

Transformed




Manually Digitized Road Markings

Automatically Extracted Road Markings




Automatically Extracted Road Markings

Manually Digitized Road Markings

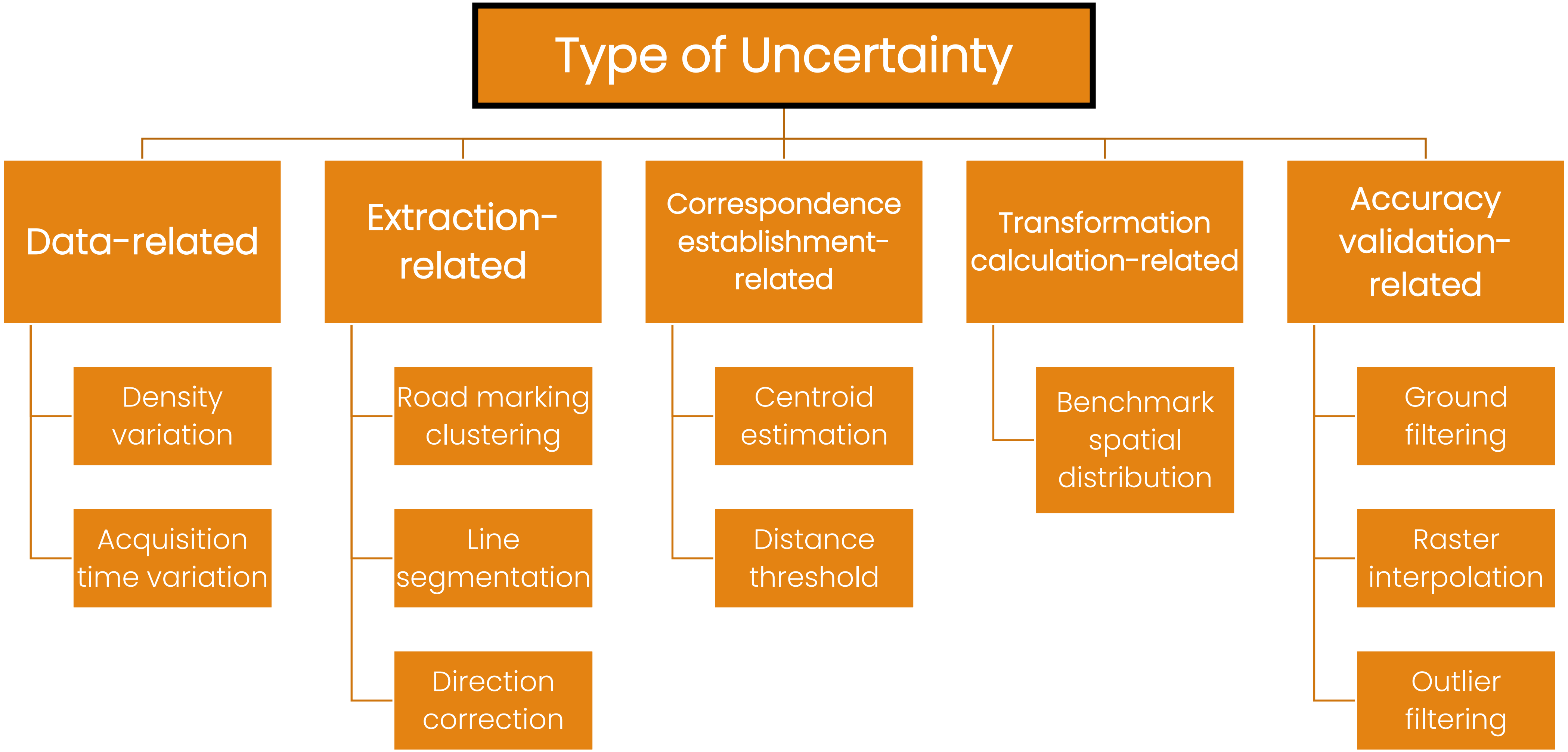
Some noises that extracted as road markings (road edge lines are still assigned high stability weights, which might impact the alignment quality.

# HARMONISATION WORKFLOW

Input point cloud data → Road marking extraction → Correspondence establishment → Transformation calculation → Validation

Sub-research Question 5:

“What are the types of **uncertainty** that affect the **accuracy** of road marking extraction for position harmonisation?”


Type of Uncertainty
Data-related
Extraction-related
Correspondence establishment-related
Transformation calculation-related
Accuracy validation-related
Density variation
Acquisition time variation
Road marking clustering
Line segmentation
Direction correction
Centroid estimation
Distance threshold
Benchmark spatial distribution
Ground filtering
Raster interpolation
Outlier filtering

Main Research Question:

"How suitable are road markings extracted using the method proposed in Heide (2024) as a benchmark for heterogeneous LiDAR point cloud harmonisation?"

Extraction errors influence the number of high stability benchmark:

**Automatic** Extracted RM

**Manually** Digitised RM

Alignment time gap influence the number of usable benchmark:

ProRail2019 to AHN5 (2023), **4 years time gap**

ProRail2023 to AHN5 (2023), **0 years time gap**

- With the current extraction quality, many low-stability road markings are still detected.
- In larger alignment time gaps, where the number of usable benchmarks is lower, the likelihood of an uneven distribution of high-stability benchmarks is higher.
- The uneven distribution of high-stability benchmarks directly affects alignment accuracy.

## Main Research Question:

"How suitable are road markings extracted using the method proposed in Heide (2024) as a benchmark for heterogeneous LiDAR point cloud harmonisation?"

## Main Limitations of the Proposed Approach in Addressing the Research Question

The quality of benchmark distribution is not quantified:

**Uneven** Distribution: not support the alignment

**Even** Distribution: support the alignment

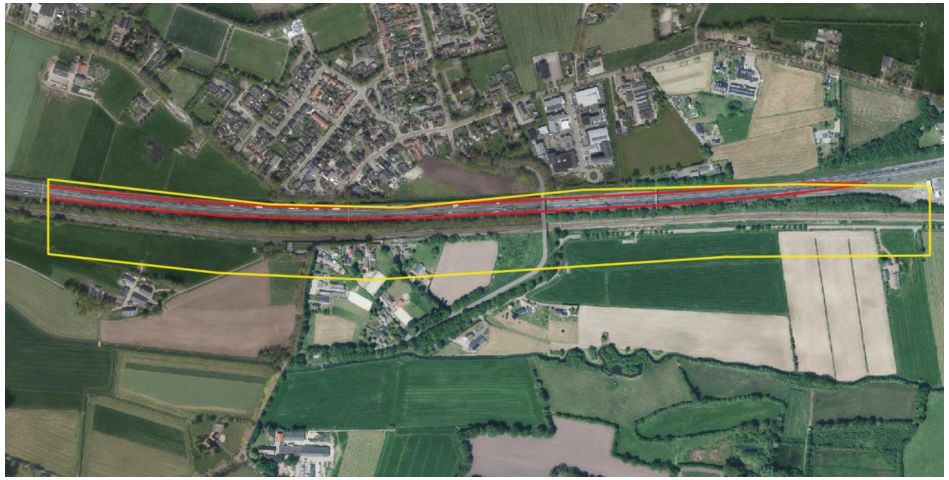
- The quality of benchmark distribution links extraction accuracy to alignment accuracy
- Without quantifying the benchmark distribution, the error propagation from extraction error to alignment error remain unexplored
- As a result, the extent to which benchmark extraction errors can be tolerated while still supporting accurate alignment remains unknown

## Main Research Question:

"How suitable are road markings extracted using the method proposed in Heide (2024) as a benchmark for heterogeneous LiDAR point cloud harmonisation?"

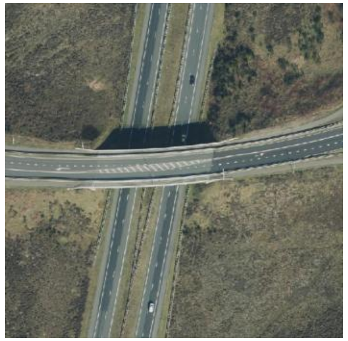
## Main Limitations of the Proposed Approach in Addressing the Research Question

<u>The study is limited to a single case:</u>



Road markings only distributed around x-axis

- Limits the analysis of different benchmark distributions.



More complex road markings distributions

# THANK YOU FOR THE ATTENTION