Reproducibility of Automated Bullet Matching Scores Using High-Resolution 3D LEA Scans

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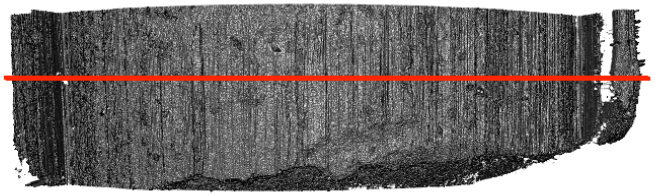
Outline

Automated Matching Algorithms

Multiple algorithms have been proposed based on 3D imaging of bullet LEAs:

- Chu et al. (2010): cross-correlation function
- Chu et al. (2013): consecutively matching striae
- Hare, Hofmann, Carriquiry (2017): random forest using multiple features

Automated Matching Algorithm



Step 1: 3D scan

Automated Matching Algorithm

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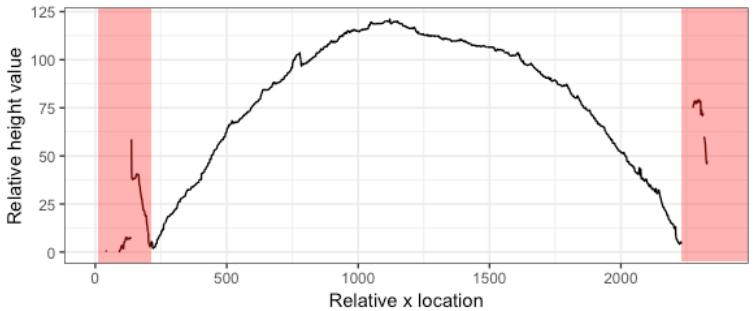

Step 2: Horizontal crosscut

Automated Matching Algorithm

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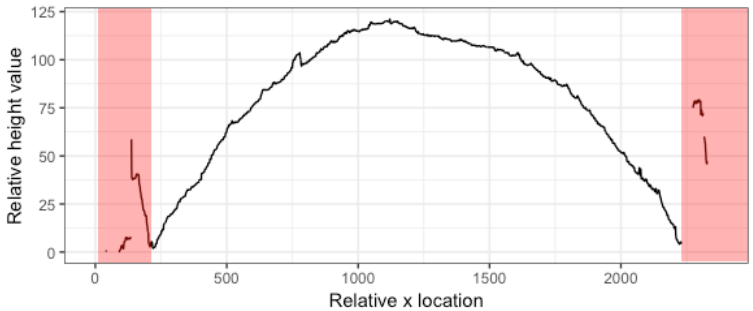

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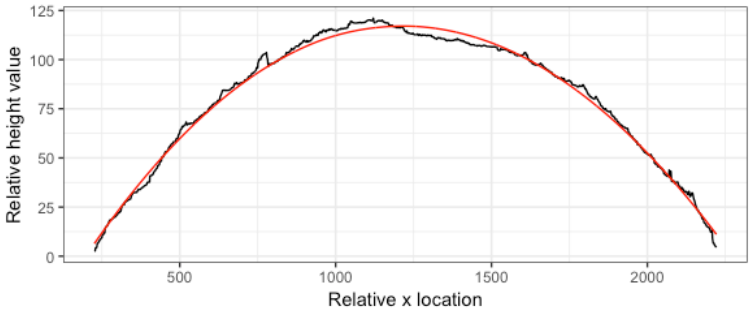

Step 3: Curvature removal

Automated Matching Algorithm

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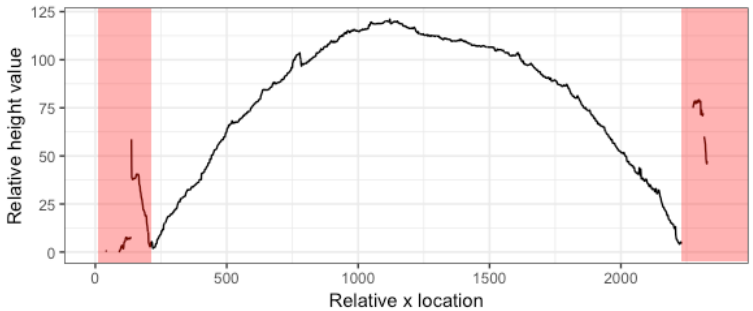

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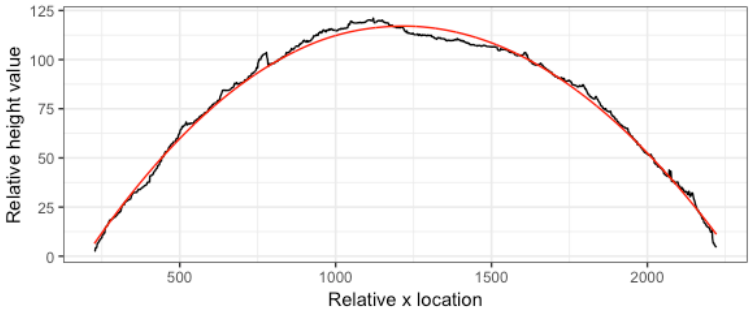

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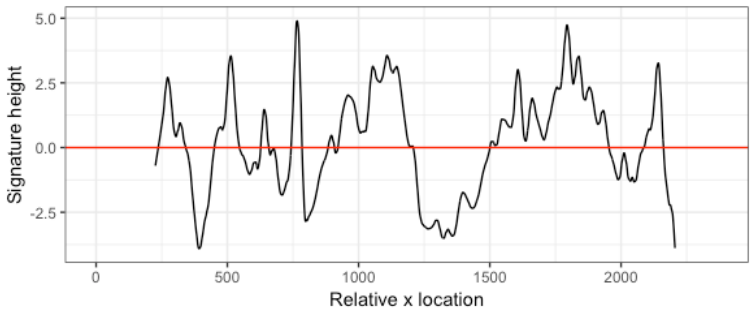
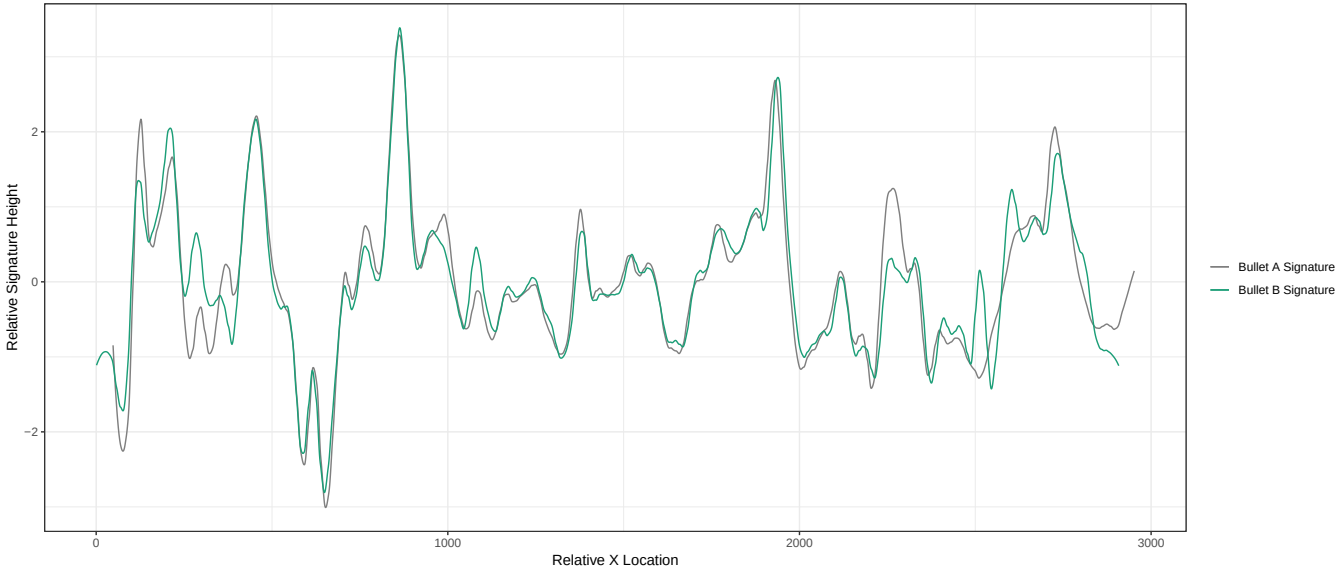


Step 4: Extracted signature

Automated Matching Algorithm

Signatures are compared to one another, and pairwise features are extracted from aligned pairs of signatures.

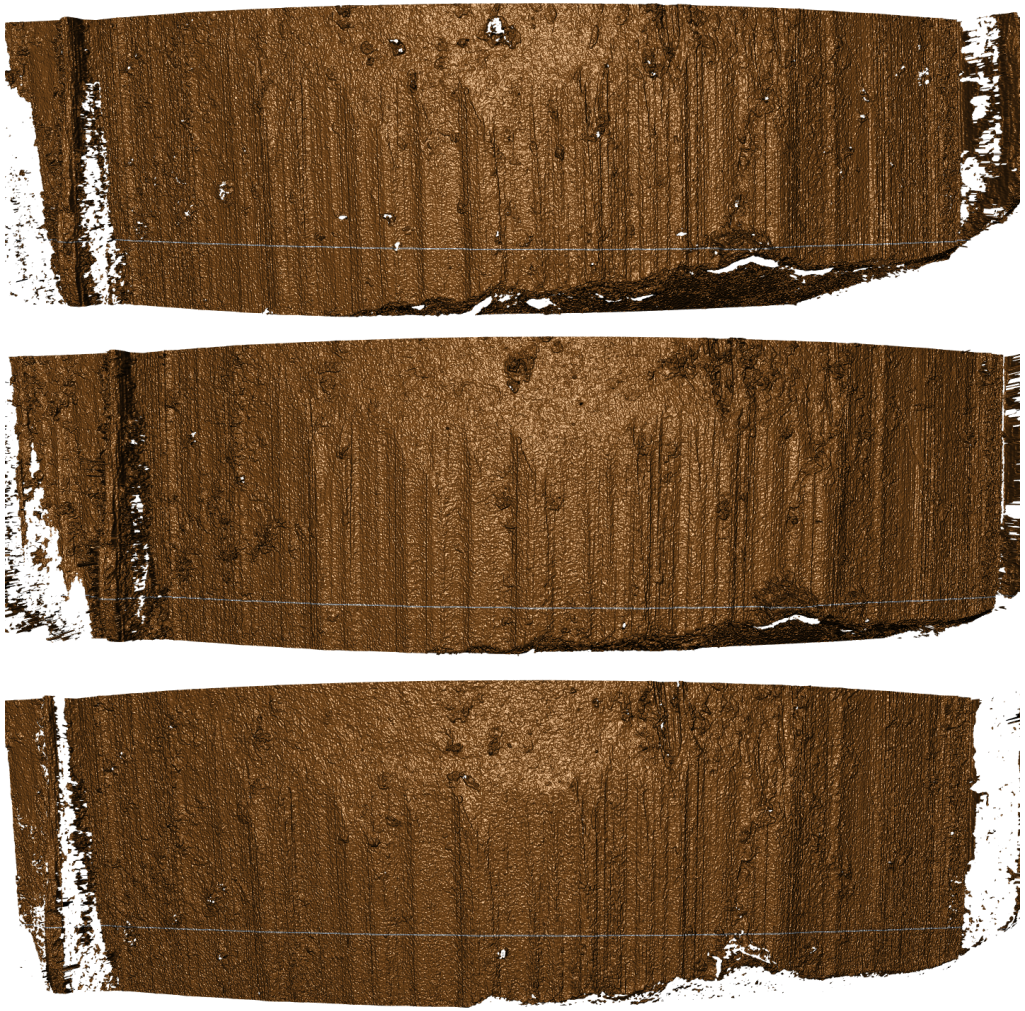


Automated Matching Algorithm

This entire process is dependent on the scan data that is captured:

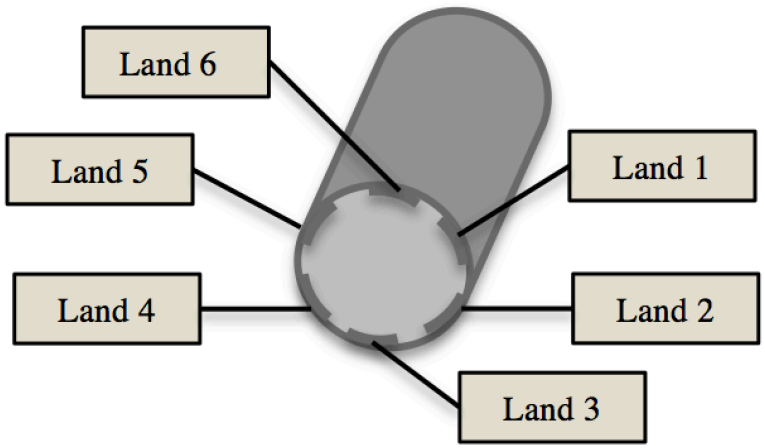
- Which operator scanned the LEA
- Which microscope was used

Variability in Scan Data



Outline

Introduced Variability in Scanning



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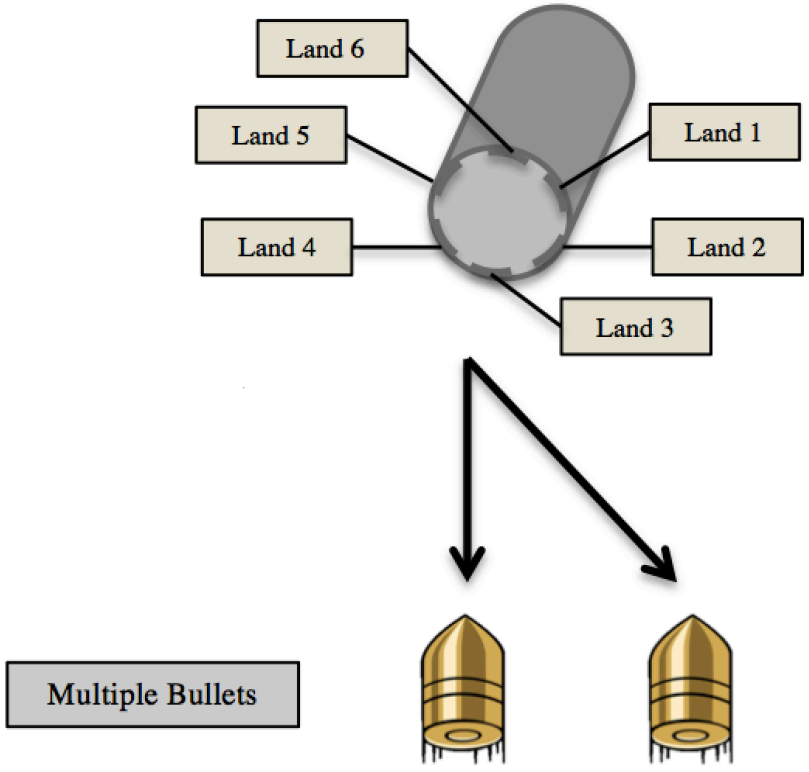

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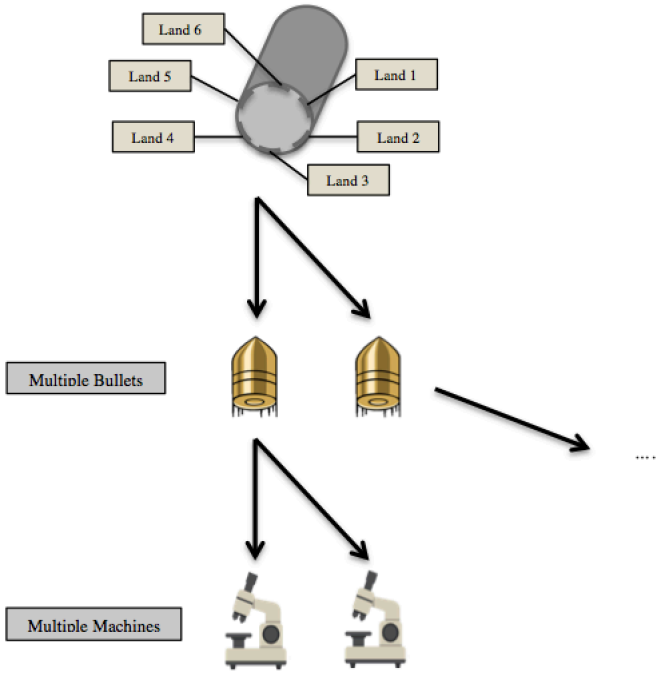

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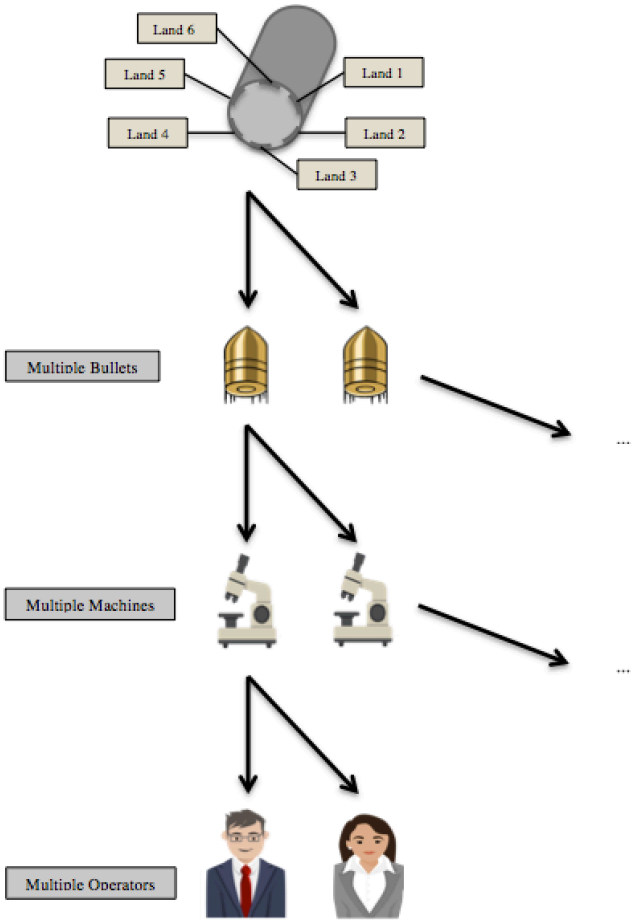
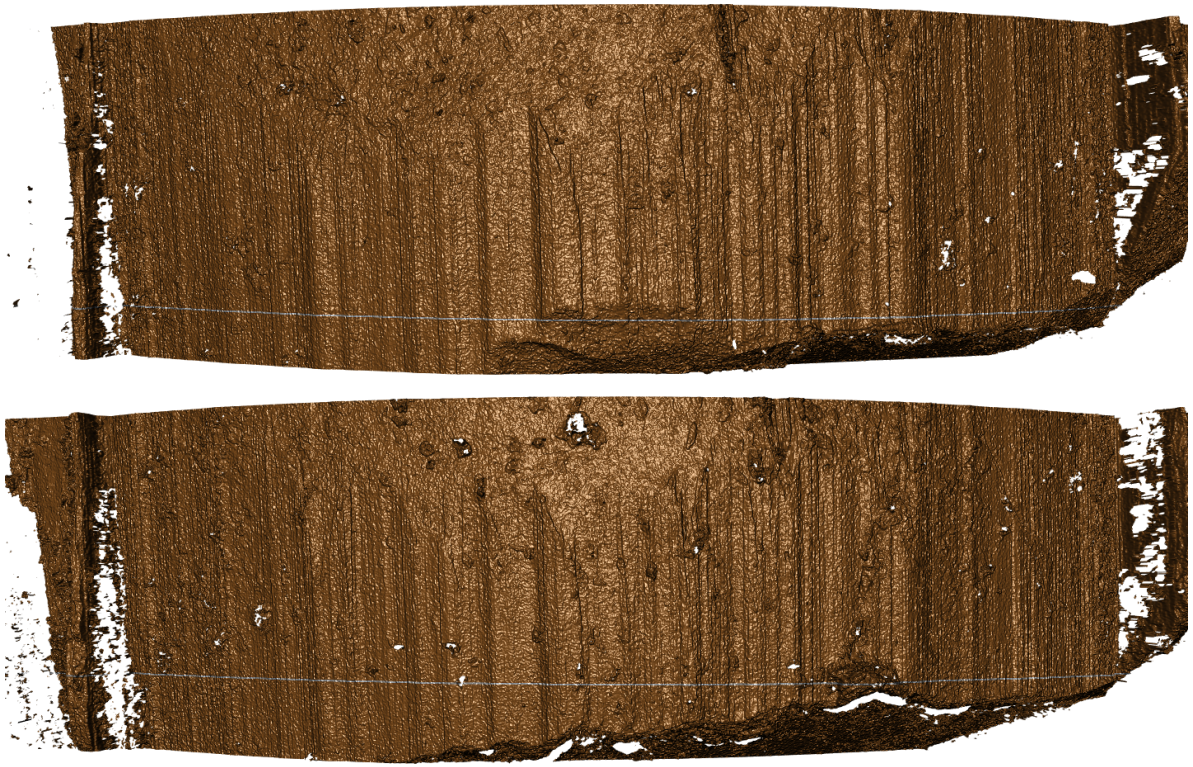


Introduced Variability in Scanning

Same bullet, same operator, different machines:

Introduced Variability in Scanning

Different bullets, same operator, same machine:



Stages of Impact

We want to consider variability introduced in:

- The extracted 2D signature
- Random forest scores (or other pairwise similarity metrics).

Outline

Introduced Variability in Scanning

- How similar are striation patterns for two different bullets?
- Are there differences in scans due to **operator**?
- Are there differences in scans due to **machine**?
- For the same operator and machine:
  - How similar will repetitions of the same bullet be?

Scanning Repetitions

There are multiple ways we can think about **repetitions**:

- Immediate recapture
- Restaging on different days

We focus on restaging for our repetitions.

Scanning Repetitions

Restaging helps us answer the forensic question of interest.

- A firearms examiner should be able to come back to the same evidence at a later date and reach the same conclusion
  - Data collected under the same conditions (operator, machine) should be consistent regardless of timing
- Multiple firearms examiners should be able to independently look at evidence and reach the same conclusion
  - Data collected under different conditions should be consistent

Gauge Repeatability and Reproducibility

Also known as **Gauge R&R studies**, these are studies typically used in industrial engineering to evaluate a measurement method or measurement tool.

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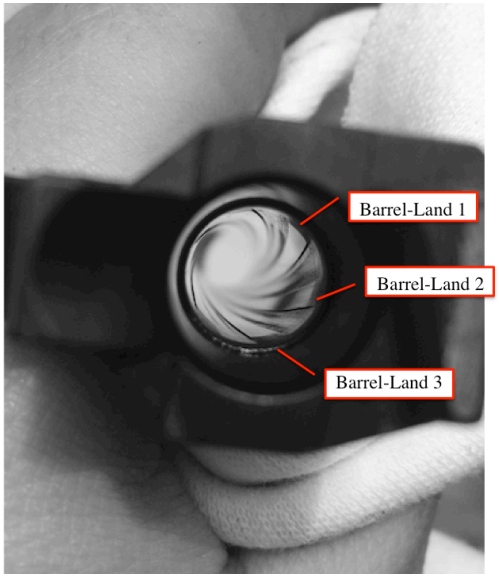
Also known as **Gauge R&R studies**, these are studies typically used in industrial engineering to evaluate a measurement method or measurement tool.

- How **repeatable** are measurements of the same object taken under the same environmental conditions?
  - Repeat measurements using the same tool, same operator
- How **reproducible** are measurements of the same object taken under different environmental conditions?
  - Repeat measurements using different tools, different operators

Gauge R&R: *Parts* in bullet context

Traditionally, parts would be similar objects (e.g. steel punches). Here, we consider *parts* to be repetitions of specific *barrel-lands*.



- The **pattern** is the barrel-land.
- The **impression** is the corresponding bullet.

Gauge R&R Data Collection

Repeated scans were captured for three barrels.

- Bullets: *three* bullets fired through each barrel
- Operators: *five* operators
- Machines: *two* confocal light microscopes (same brand)
- Restaging repetitions: at least *three* for each operator-bullet-machine combination

This results in **90** repetitions of each barrel-land, **30** scans originating from each of the 3 bullets.

Gauge R&R: Signatures

Co-aligned signatures give us an initial visual of variability (Hamby set barrel):

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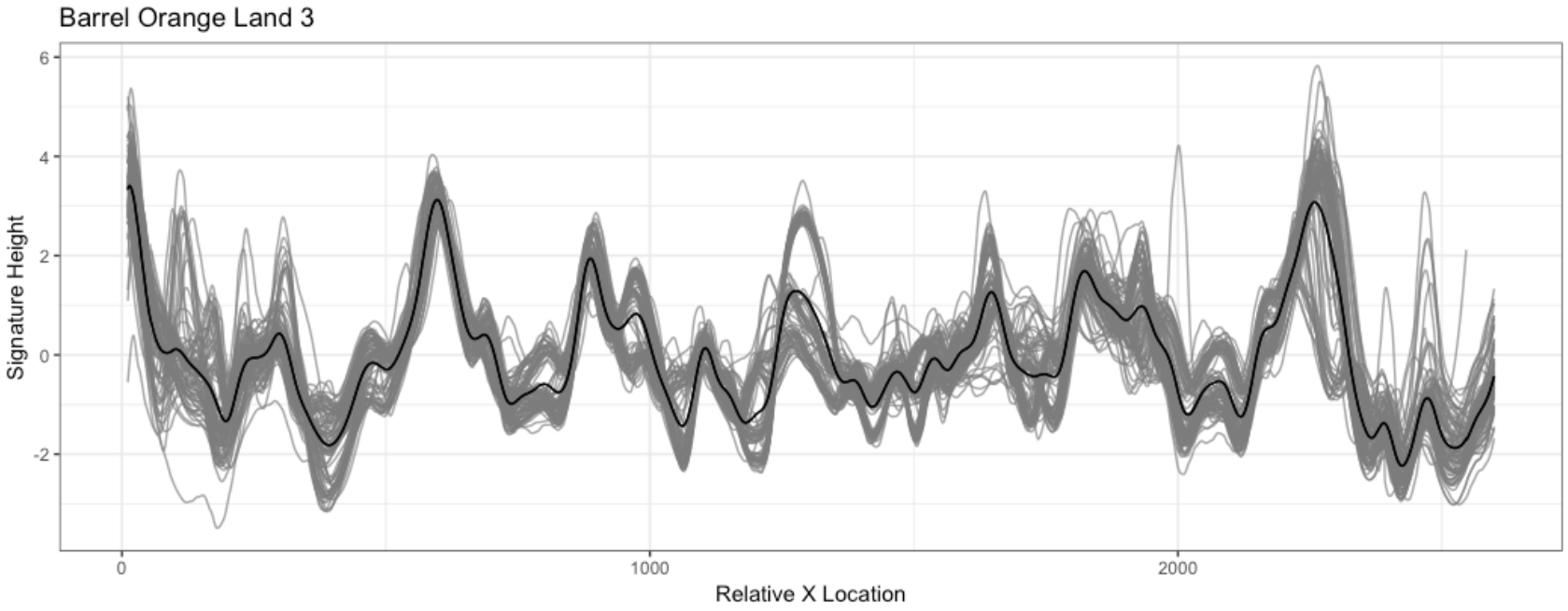

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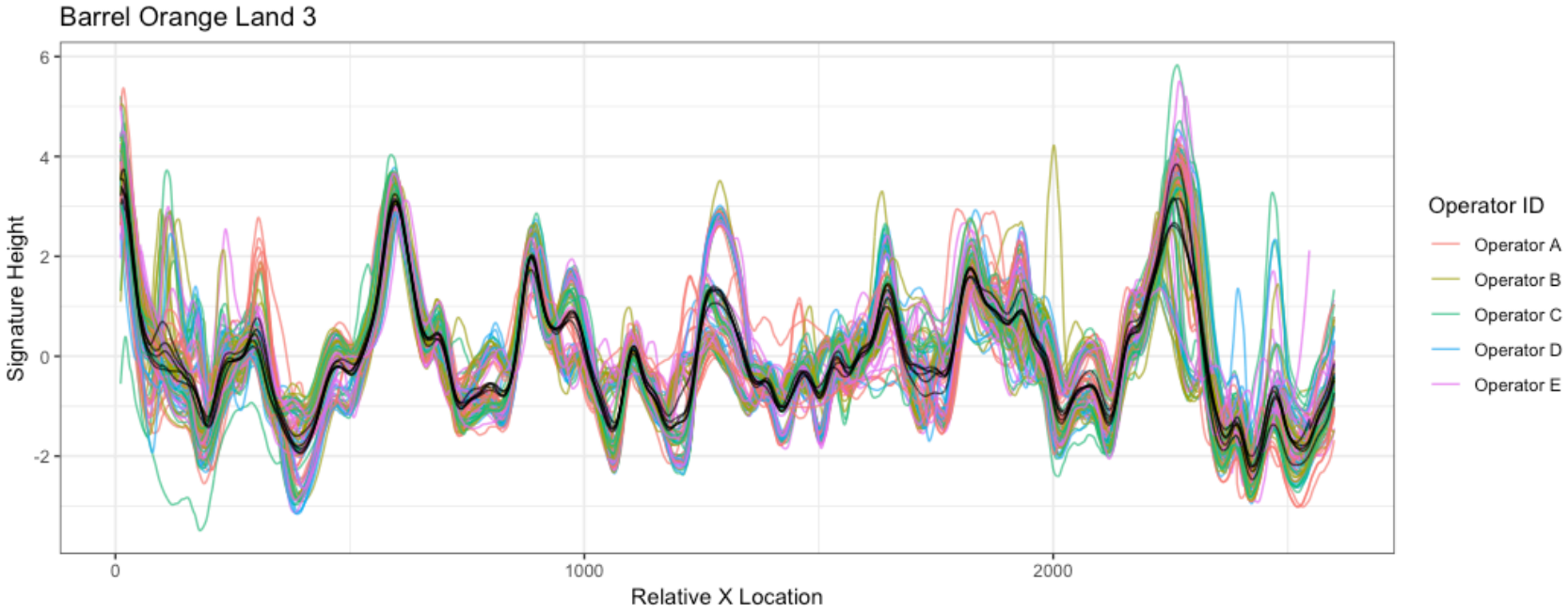

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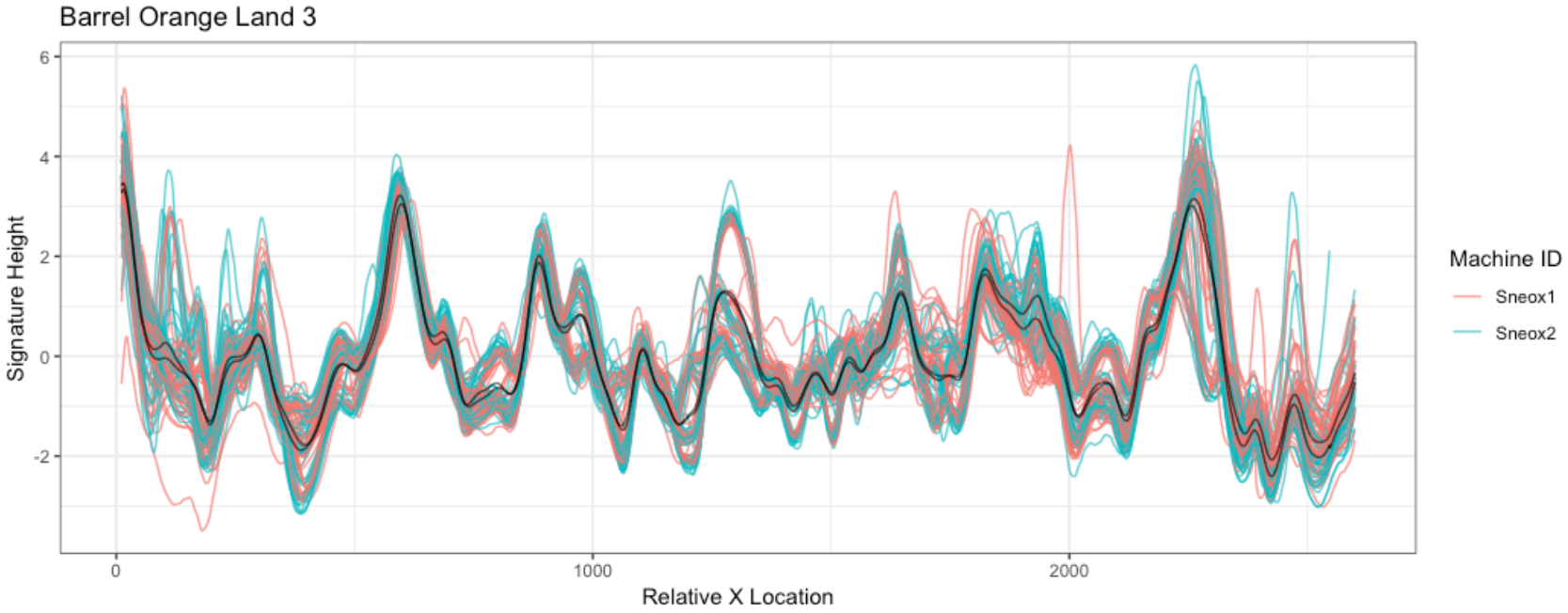
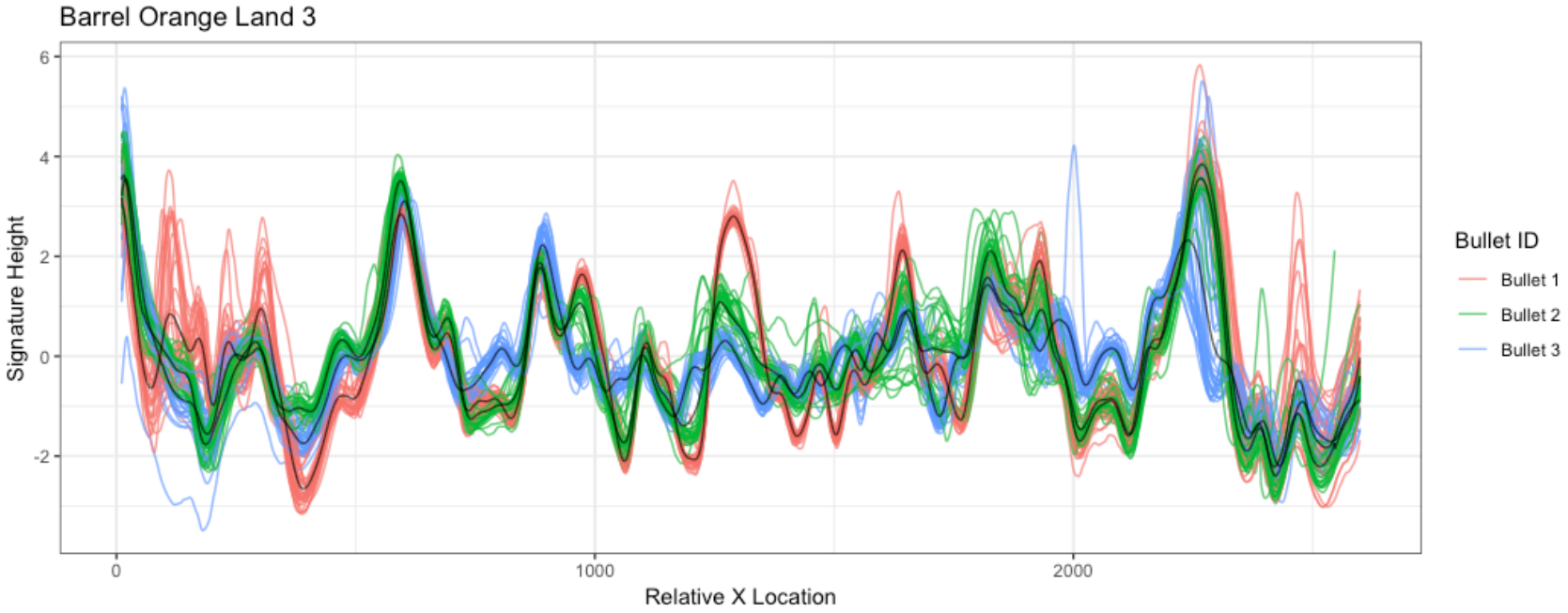


Gauge R&R: Signatures

Much of the variability structure appears to be from bullet:



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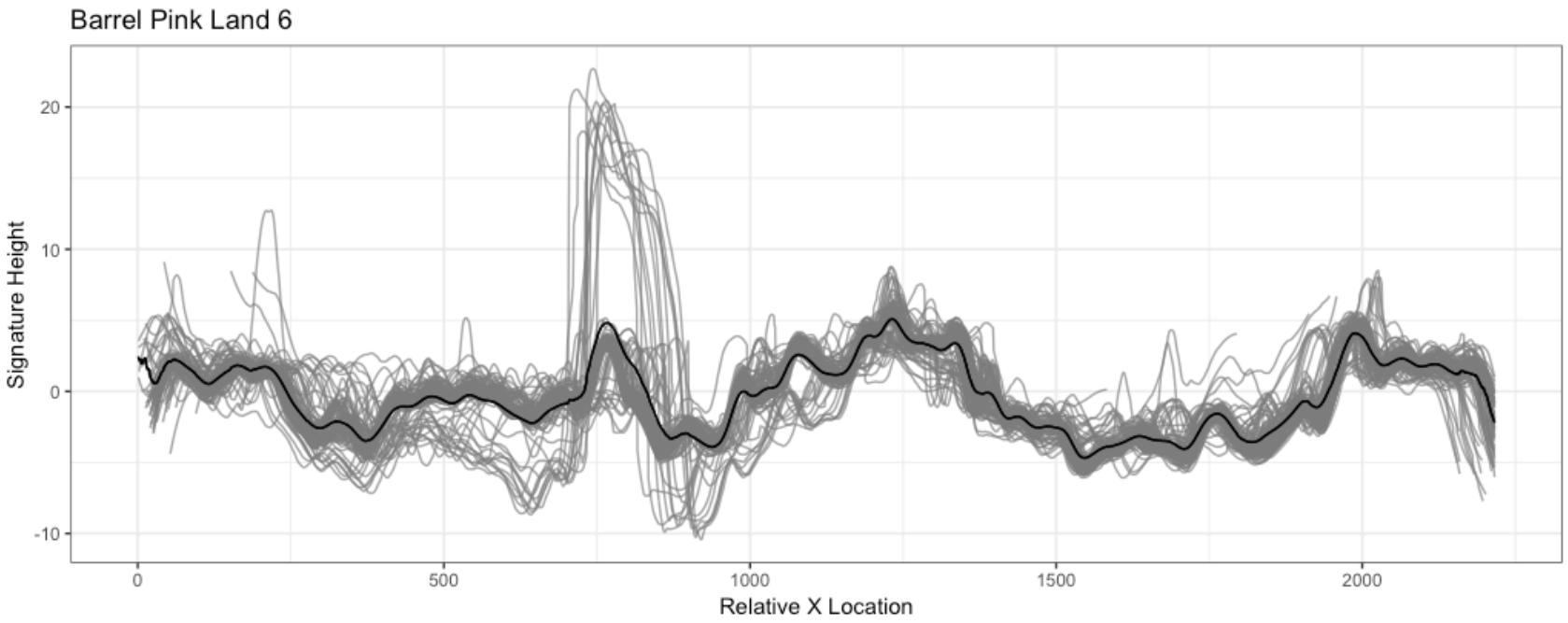

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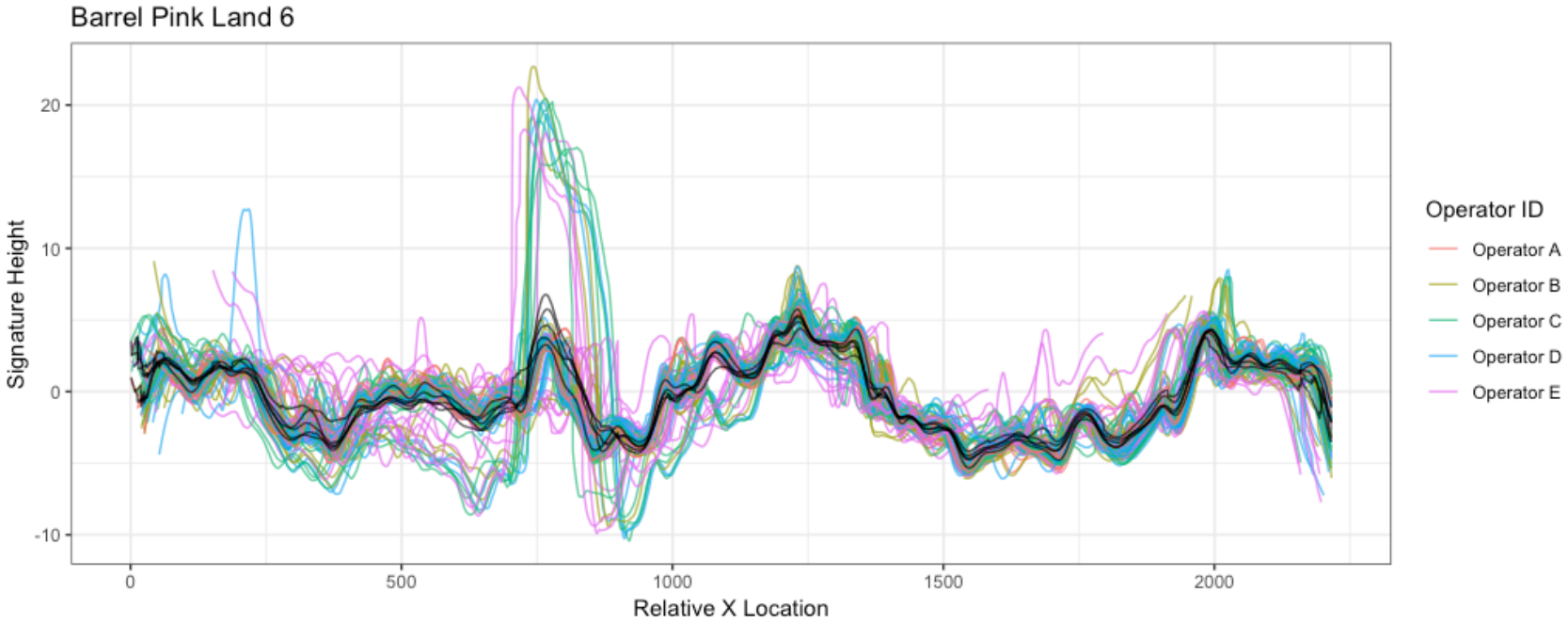

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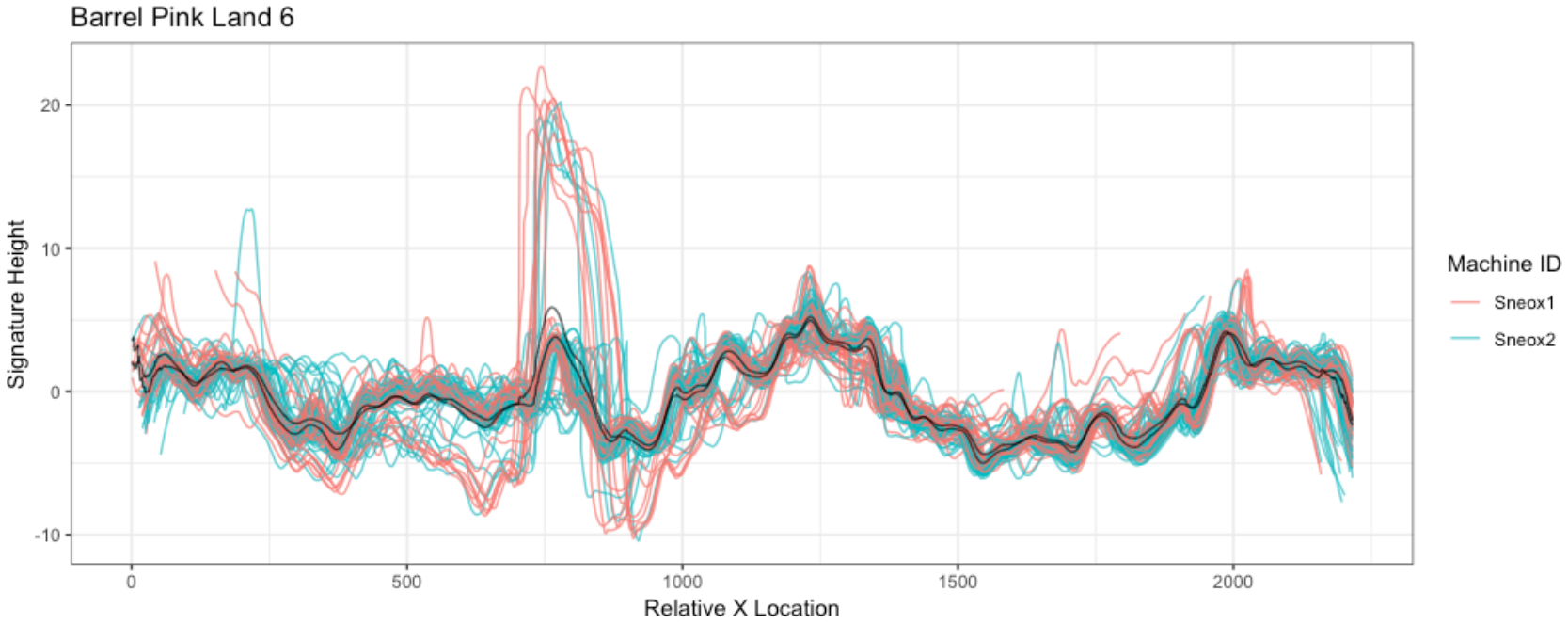

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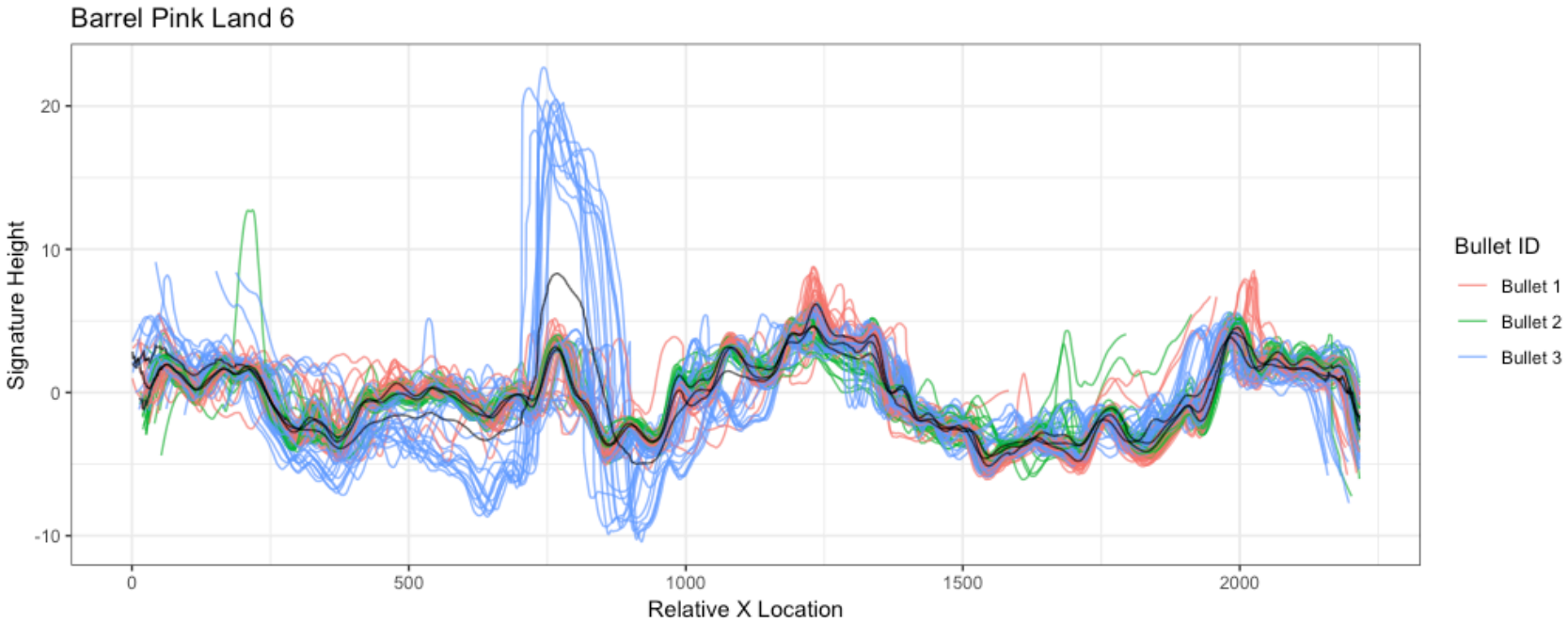
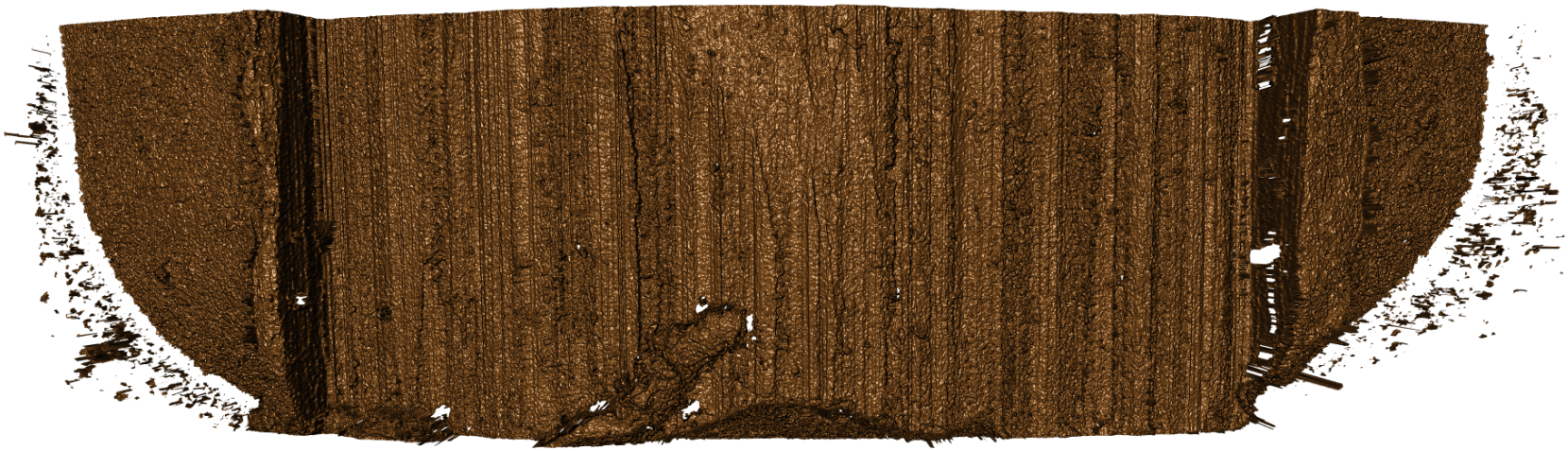


Gauge R&R: Signatures

Distinct structure on the bullet:



Pairwise comparisons model

We want to quantify the impact these differences could have on automated pairwise comparisons.
We compare each signature originating from the same barrel-land to each other and investigate variability in pairwise matching scores.

Pairwise comparisons model

With our pilot study data, we can fit a mixed-effects model for all same-source comparisons:
That is, scores which compare two signatures that originate from the same barrel-land.

$$
\begin{aligned}
s_{p,p'} = & \text{ Random Forest score comparing Signature p, Signature p'} \\
= & \mu_{BL} + \beta I[\text{Same Bullet (within source)}] + \omega I[\text{Same Operator}] \\
& + \eta I[\text{Same Machine}] + \beta\omega I[\text{Same Bullet and Operator}] \\
& + \beta\eta I[\text{Same Bullet and Machine}] \\
& + \eta\omega I[\text{Same Machine and Operator}] \\
& + \epsilon
\end{aligned}
$$

Pairwise comparisons results

- Individual bullet characteristics are the most significant contribution to variability in pairwise matching scores.
- After accounting for individual land differences, the remaining *random effects* for Barrel Orange (Hamby set) are:

Description	Parameter	Estimate
Same bullet	σ_β	0.097
Same operator	σ_ω	0.004
Same machine	σ_η	0.001
Bullet-operator interaction	$\sigma_{\beta\omega}$	0.013
Bullet-machine interaction	$\sigma_{\beta\eta}$	0.001
Machine-operator interaction	$\sigma_{\eta\omega}$	0.002
Residual error	σ	0.163

Pairwise comparisons results

- Individual bullet characteristics are the most significant contribution to variability in pairwise matching scores.
- After accounting for individual land differences, the remaining *random effects* for Barrel Pink (Houston set) are:

Description	Parameter	Estimate
Same bullet	σ_β	0.019
Same operator	σ_ω	0.006
Same machine	σ_η	0.010
Bullet-operator interaction	$\sigma_{\beta\omega}$	0.004
Bullet-machine interaction	$\sigma_{\beta\eta}$	0.003
Machine-operator interaction	$\sigma_{\eta\omega}$	0.006
Residual error	σ	0.151

Outline

Conclusions

- After accounting for variability due to bullet characteristics, operator-related differences account for minimal variability
- Inherent relationship between operators and breakoff and other bullet characteristics
- Machine effect is larger for Houston barrel than Hamby set barrel
- Bullet effect is larger for Hamby barrel - tank rash
- Detailed protocols are crucial to reducing variability in extracted signatures

Acknowledgments

- We would like to thank the efforts of the Iowa State University Roy J. Carver High Resolution Microscopy Lab in scanning the variability pilot study data and providing the scans to us.
- We would like to thank Jim Hamby and Melissa Nally for providing us the bullets used in this study.