Computerized Image Analysis Applied to Fingerprinting Stamp Perforations

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Outline

- Fingerprinting extra perforations in 19th c. revenue stamps
  - Published in The American Revenuer Q1 (2014): 2-19.
- New research
  - A history of perforation quality of U.S. stamps
  - Measurement of potential re-perforations
  - Other perforation fingerprinting applications
  - Extension of method to other types of stamp separation

Extra Perforations on 19th Century Revenue Stamps

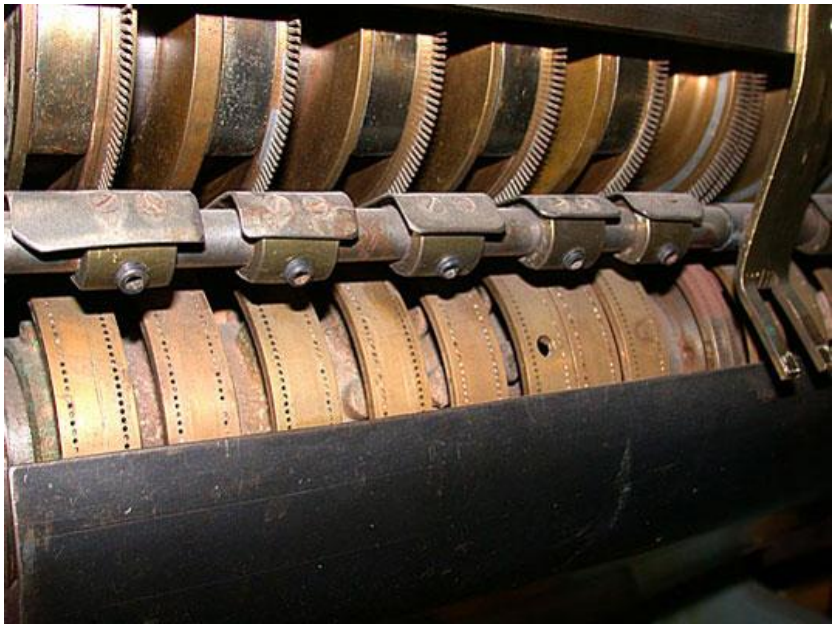
Collectors have argued over these stamps for more than 120 years. Stamp production was rushed with a shortage of equipment. Genuine, original perforation errors were common. Premiums later put on these stamps by dealers led to forgery.

Nine of these stamps actually have genuine extra perforations, and the rest are forgeries with added extra perforations.

Best Source of Perforation Fingerprints

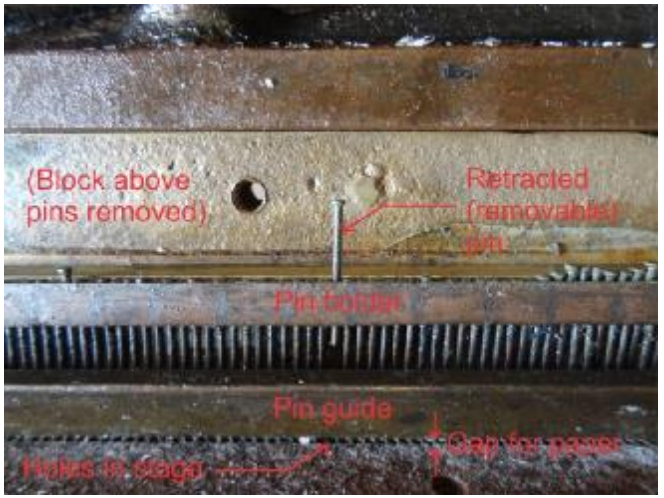
Very difficult to machine hole spacings → patterns of variable hole spacings

Rotary perforator



Thousands of pins → little repetition of patterns

Manual stroke perforator



Repeating pattern from a few pins

↓

Good potential for fingerprinting

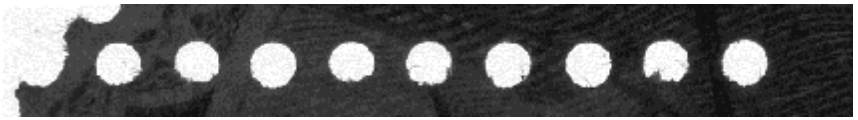
Fitting Circles to Digital Image Data

- An active research area in astronomy
- 2D methods gain resolution over 1D methods

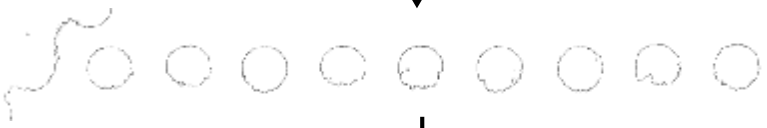
  +/- 1 pixel at 2400 dpi → linear resolution of +/- 11 um

  → 2D resolution < 1 um
- Fast methods using matrix algebra
- Best approaches to partial arcs a frequent challenge
  - Different methods have peculiar responses to outlier data points
  - Important to the fitting of circles to the edges of separated stamps
  - Coope method performed best (linear least squares adapted to circles)

Example of Approach



2400 dpi scan,
Film transmission mode,
Horizontal scanning
(0.01% accuracy)

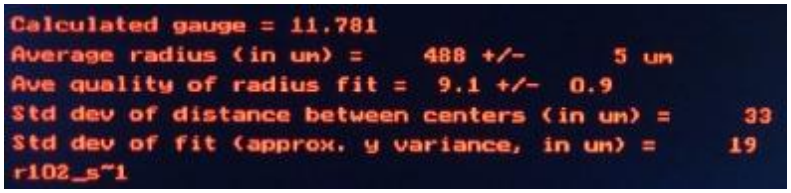


Trace contour routine

Brush and crop

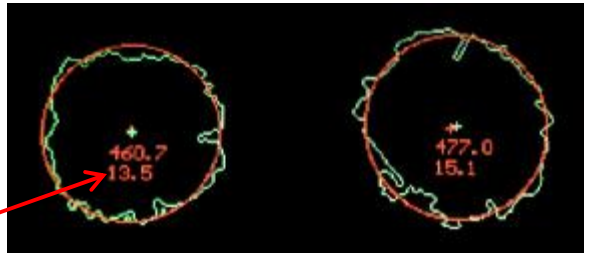
Radius (um)

Quality of Fit



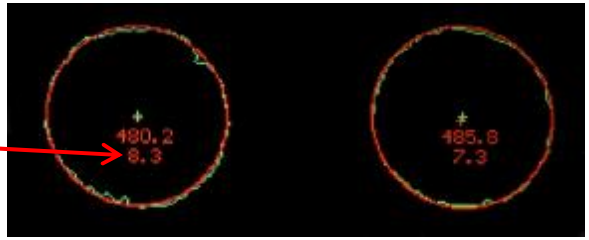
Left-to-right scanning with a mask to approx. locate holes, then Coope analysis routine to each, then gather statistics for entire row

Extra perfs



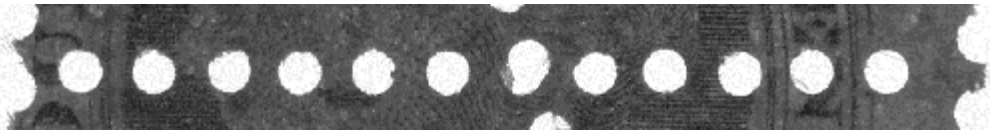
Large error

Quality of Radius Fit Examples



Small error

Manual Example of Fingerprint Matching



1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698

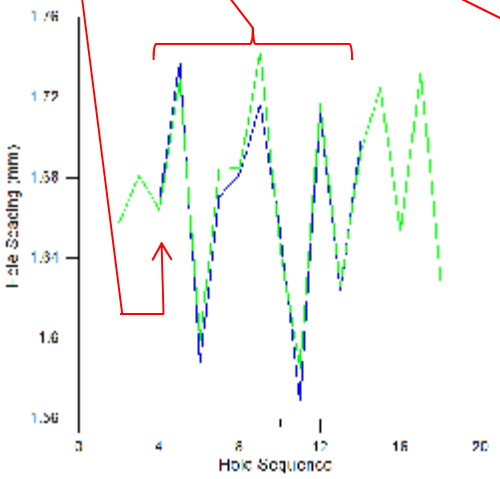
1.658	1.681	1.664	1.729	1.599	1.684	1.685	1.742	1.644	1.585	1.717	1.626	1.693	1.725	1.654	1.732	1.629

R20

Offset	Overlap	Score																								
						1.658	1.681	1.664	1.729	1.599	1.684	1.685	1.742	1.644	1.585	1.717	1.626	1.693	1.725	1.654	1.732	1.629				
9	8	0.3													1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698
8	9	0.1												1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698		
7	10	0.3											1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698			
6	11	0.2										1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698				
5	11	0.2									1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698					
4	11	0.2								1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698						
3	11	0.1							1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698							
2	11	7.5						1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698								
1	11	0.1					1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698									
0	11	0.2				1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698										
-1	10	0.2			1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698											
-2	9	0.2		1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698												
-3	8	0.5	1.668	1.737	1.587	1.671	1.682	1.716	1.653	1.569	1.712	1.624	1.698													

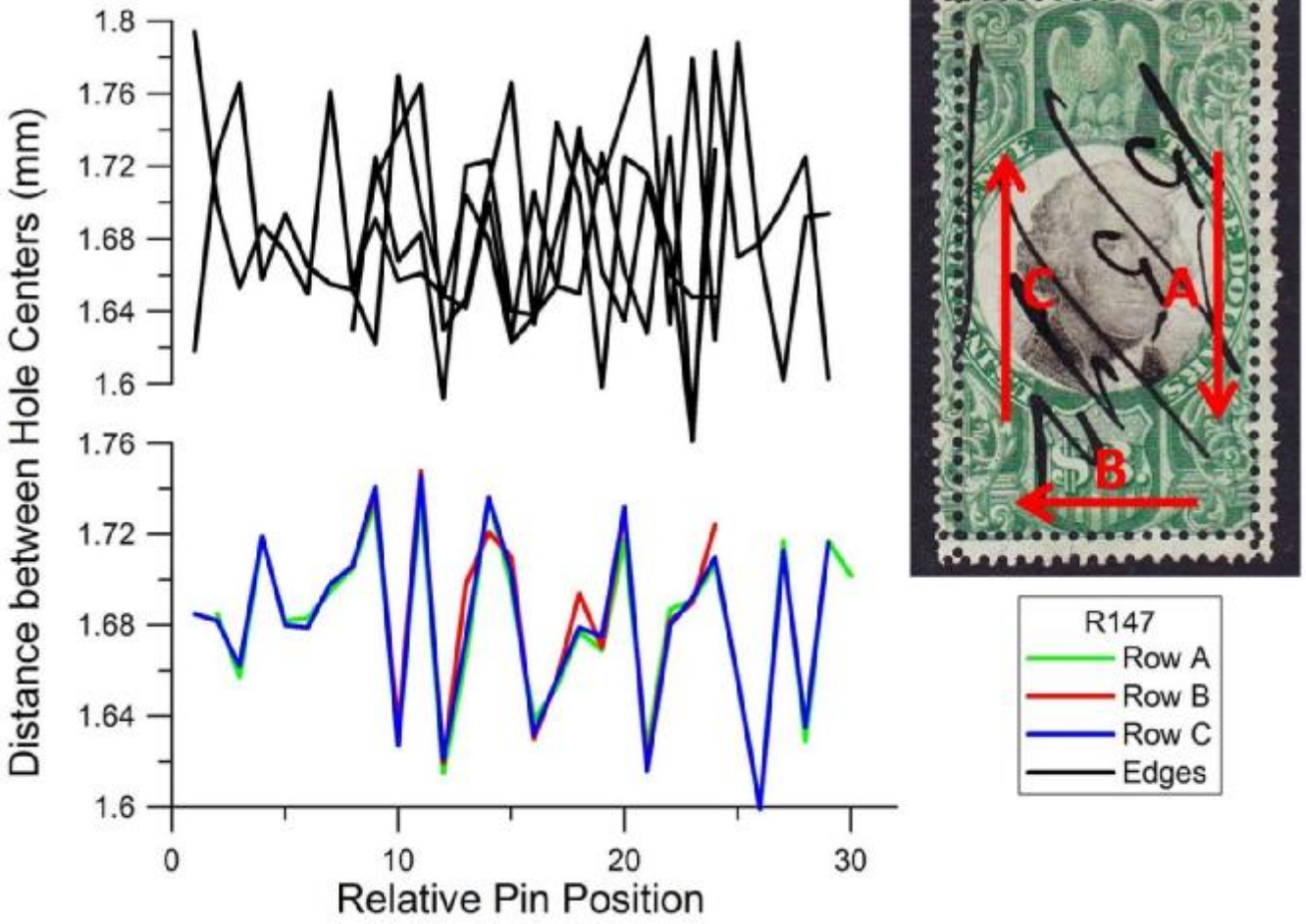
Long row

Short row tested in all possible alignments with the long row with a minimum overlap of 8



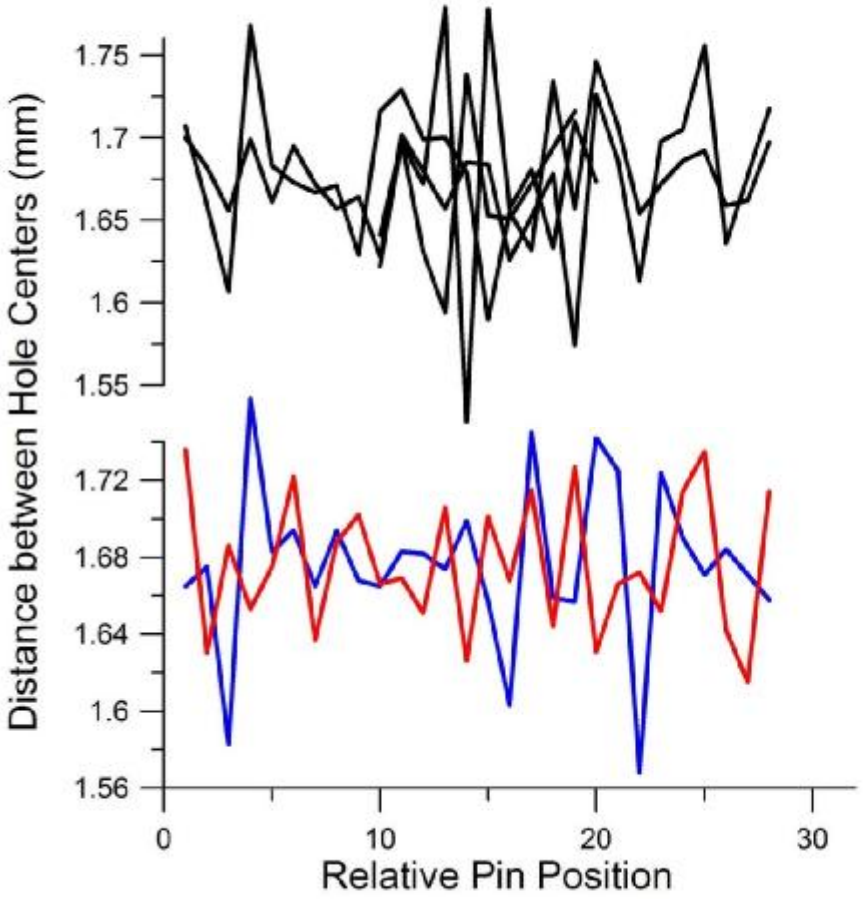
The computer discovers a very high correlation score when the start of the short row is offset 2 holes from the start of the long row. The overlap is 11 holes (the length of the short row). The graph shows the closeness of the match.

Matching Added Extra Perforations



- Four edge perforation rows (upper plot) -- no matching
- The three extra lines of perforation (lower plot) are nearly identical
  -- a very strong indication of forgery using a stroke perforator
- The rotating fingerprint directions suggest that the stamp was rotated in the perforator

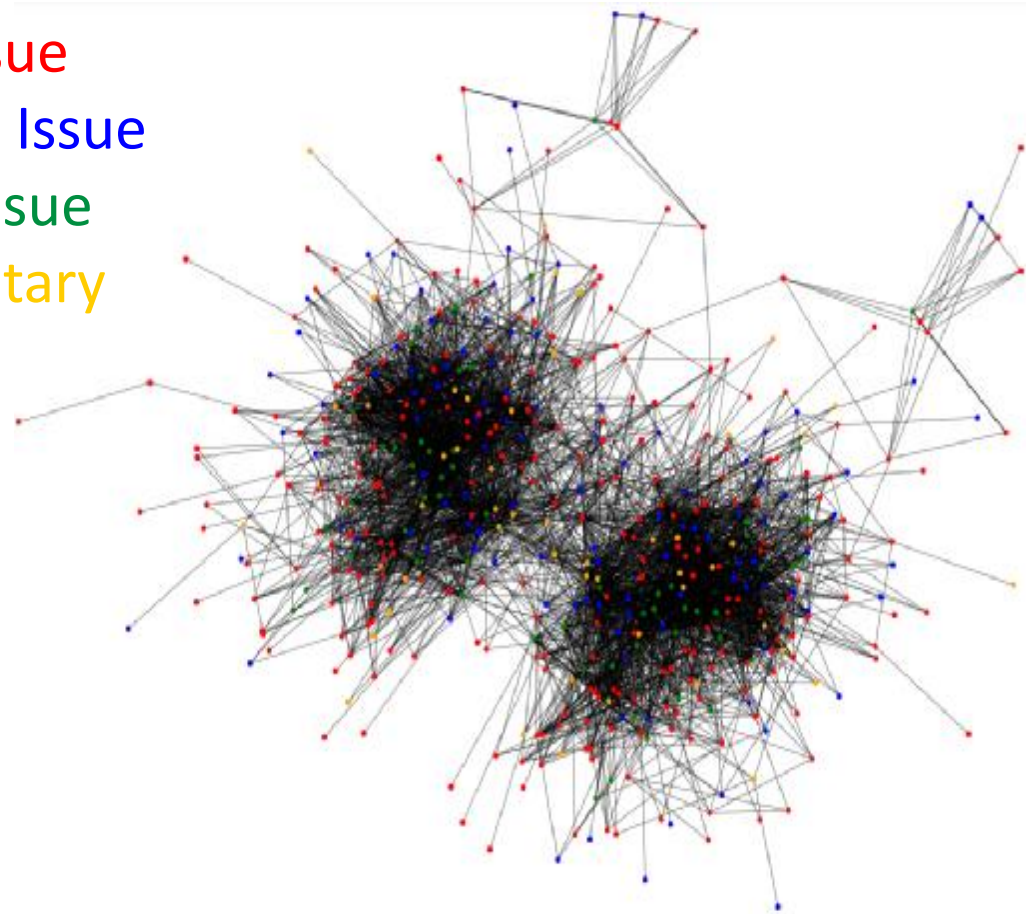
Non-Matching Original Extra Perforations



- No matching of the perforation fingerprints

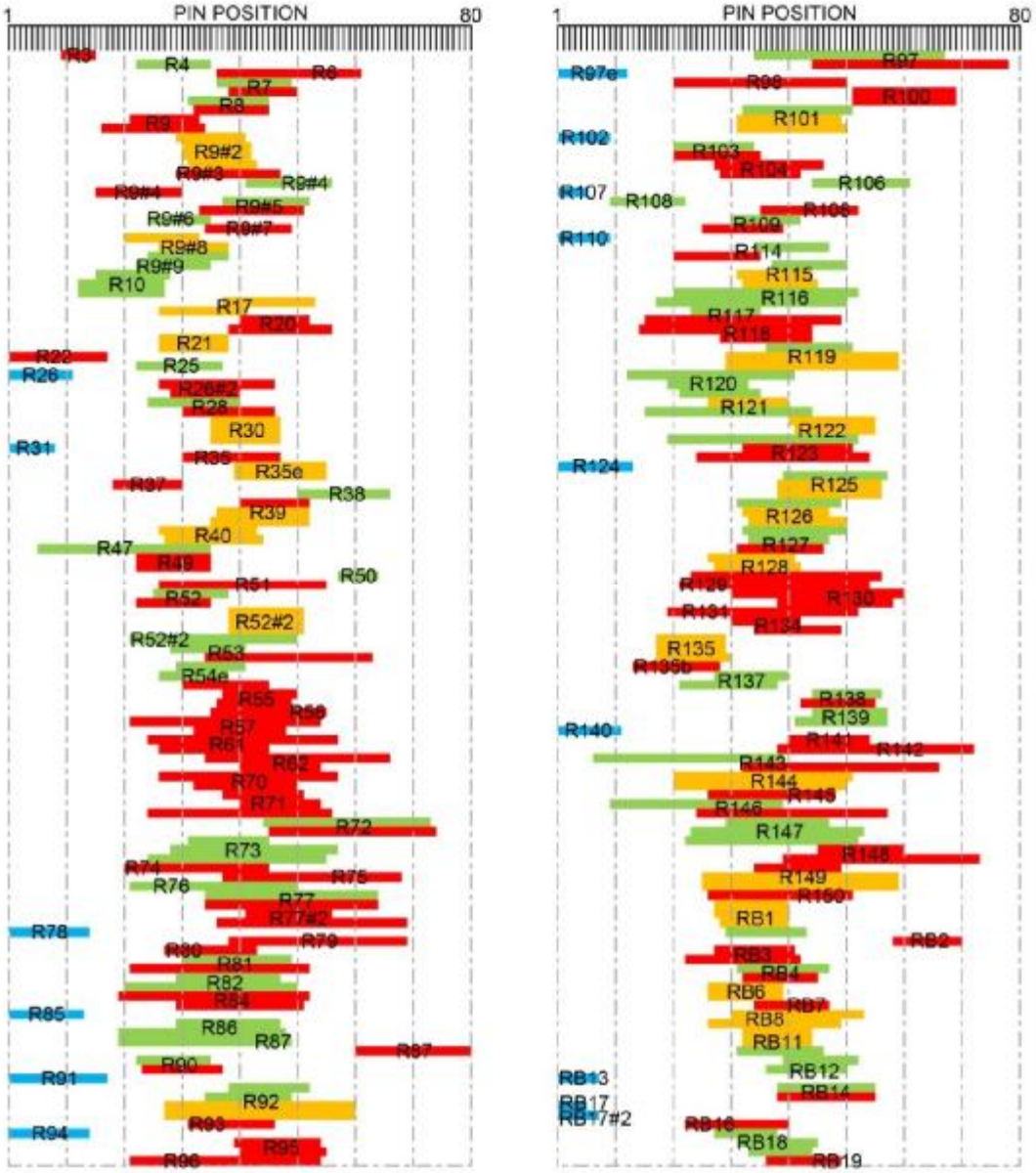
Exploring the Entire Network of Added Perforations

First Issue
Second Issue
Third Issue
Proprietary



- Analysis of all of the correlated perforation patterns (including all sequences both forwards and backwards) from the first three issues and the proprietaries separate into a single group (forwards) and its mirror image (backwards) using Harel-Koren analysis.
- ***The added perforations appear to consist only of a single interconnected group.***

Computer-Generated Hypothetical Stroke Perforator of Minimum Size Showing the Pin Positions for the Production of Each Forgery



Pin #	Center-to-center Distance (mm)									
1-10		1.715	1.679	1.743	1.698	1.678	1.697	1.650	1.702	1.713
11-20	1.670	1.649	1.725	1.628	1.687	1.656	1.755	1.559	1.717	1.677
21-30	1.731	1.631	1.633	1.690	1.675	1.662	1.715	1.669	1.692	1.695
31-40	1.700	1.745	1.625	1.746	1.622	1.674	1.739	1.696	1.629	1.653
41-50	1.685	1.678	1.714	1.620	1.690	1.686	1.706	1.649	1.600	1.715
51-60	1.629	1.706	1.710	1.671	1.728	1.606	1.713	1.700	1.747	1.640
61-70	1.712	1.702	1.689	1.686	1.671	1.591	1.709	1.606	1.730	1.661
71-80	1.696	1.689	1.664	1.679	1.682	1.690	1.661	1.701	1.710	1.701

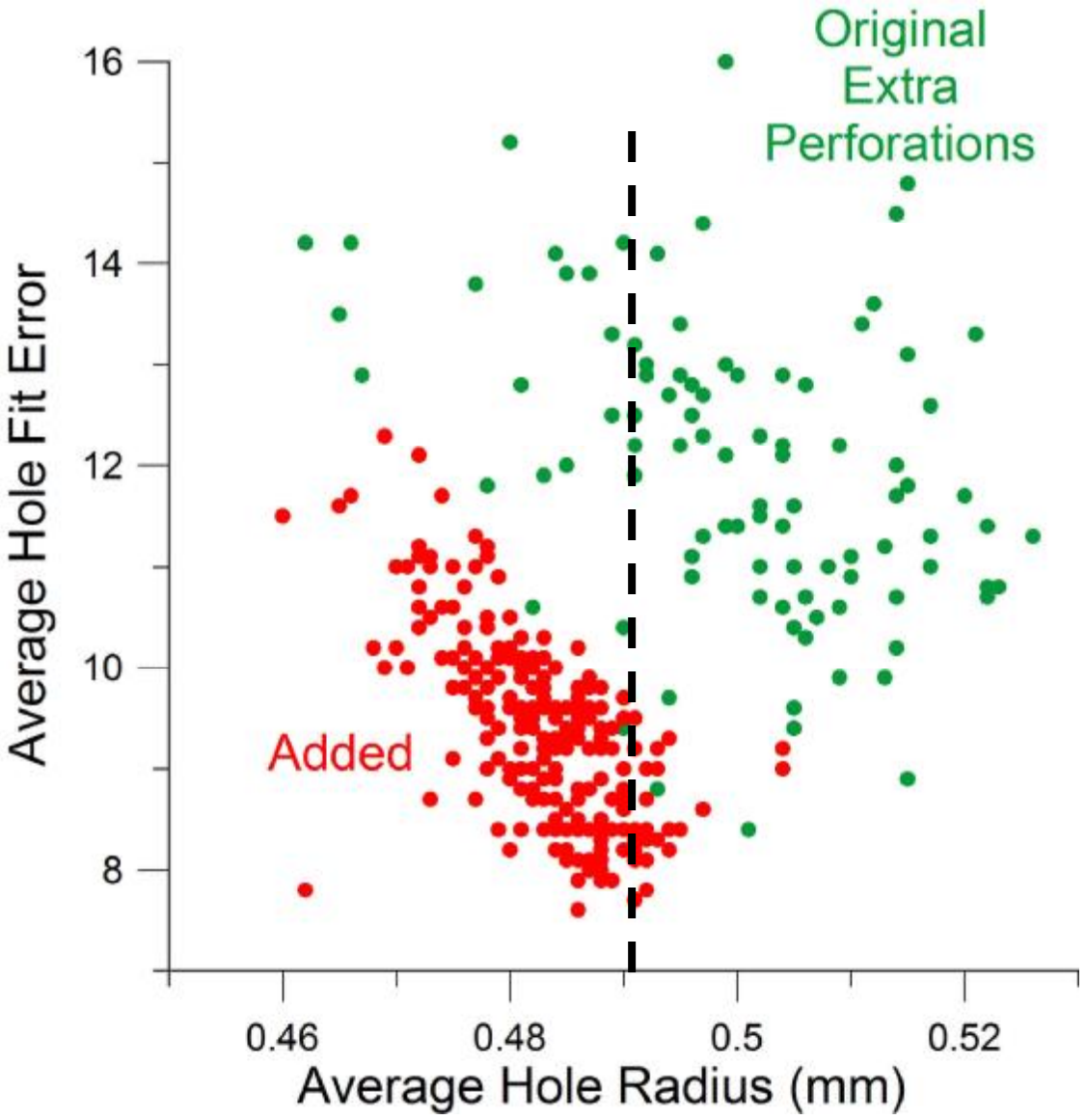
An 80-pin sequence can hypothetically produce all of the known 19th c. revenue forgeries.

Example Surprise Findings

Partial Row Perforations that are Original Perforation Errors

Original and Added Extra Perforations on the Same Stamp

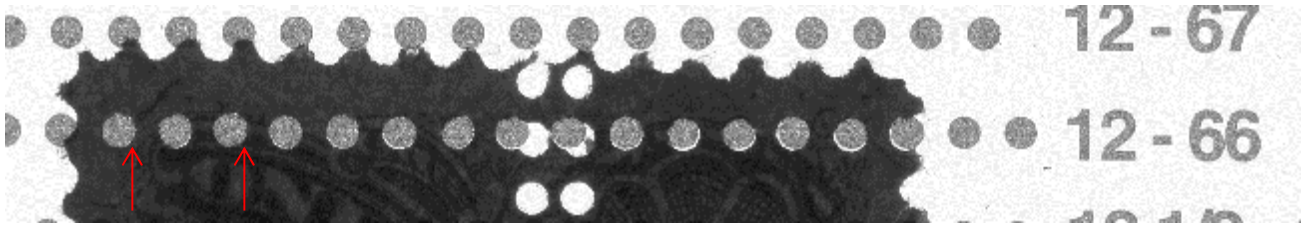
Differentiating Original and Added Perfs



- The added (fake) holes are smaller and more sharply cut than the genuine extras
- The basis for a simple test using a specialist perforation gauge.

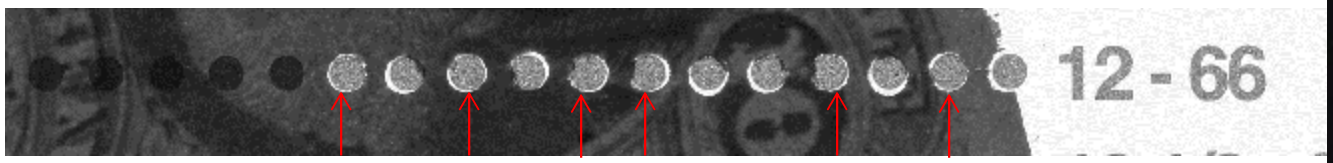
Use of a Transparent Specialist Gauge

- The 12-66 dots on the Sonic Imagery Labs Specialist Gauge are 0.49 mm radius
- Use a magnifier with the gauge and strong light
- Good for most, but not all, extra perforation rows



Scott R119 holes can be individually aligned closely to the 12-66 dots → Likely Fake

R119



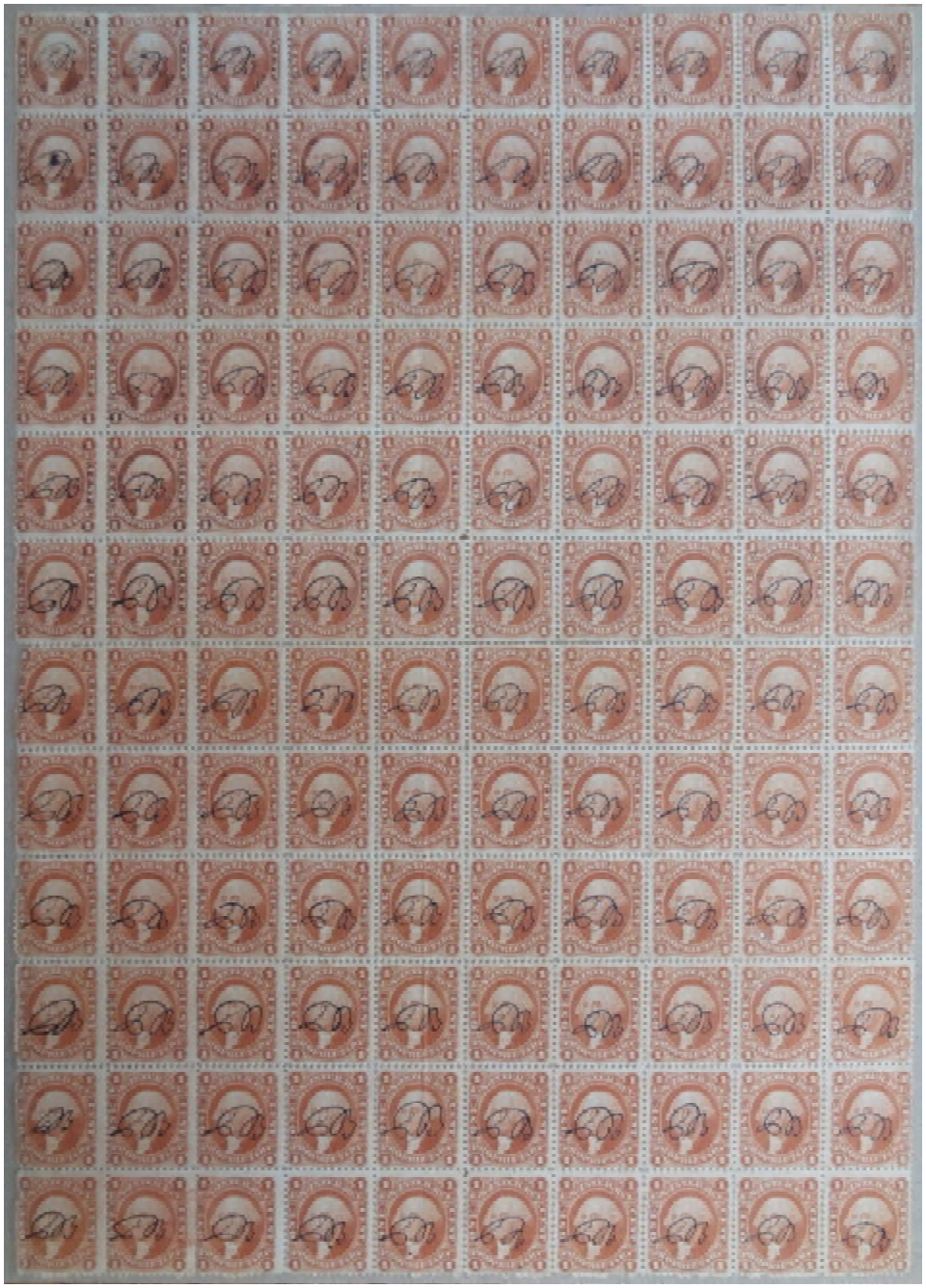
R33b partial row holes much larger than 12-66 dots → Genuine

R33b

What Can Be Learned About the Quality of Perforation over Its History?

- U.S. went with rotary perforation from the beginning
- Rotary perforators VERY difficult to fabricate
  - BEP was having problems getting bids for production contracts in the 1970s
  - National Bureau of Standards came to the rescue, and BEP funded an initiative to develop advances in numerical controlled machining to improve the manufacturability of perforators
    - Advanced designs, sensors, software control of 23 sources of error
    - Automated sensing of drill bit fatigue and drill bit exchange
- BEP started contracting out perforating in the later 20th century

Examined the perforations from 27 sheets of stamps representing the 1860s to 2007

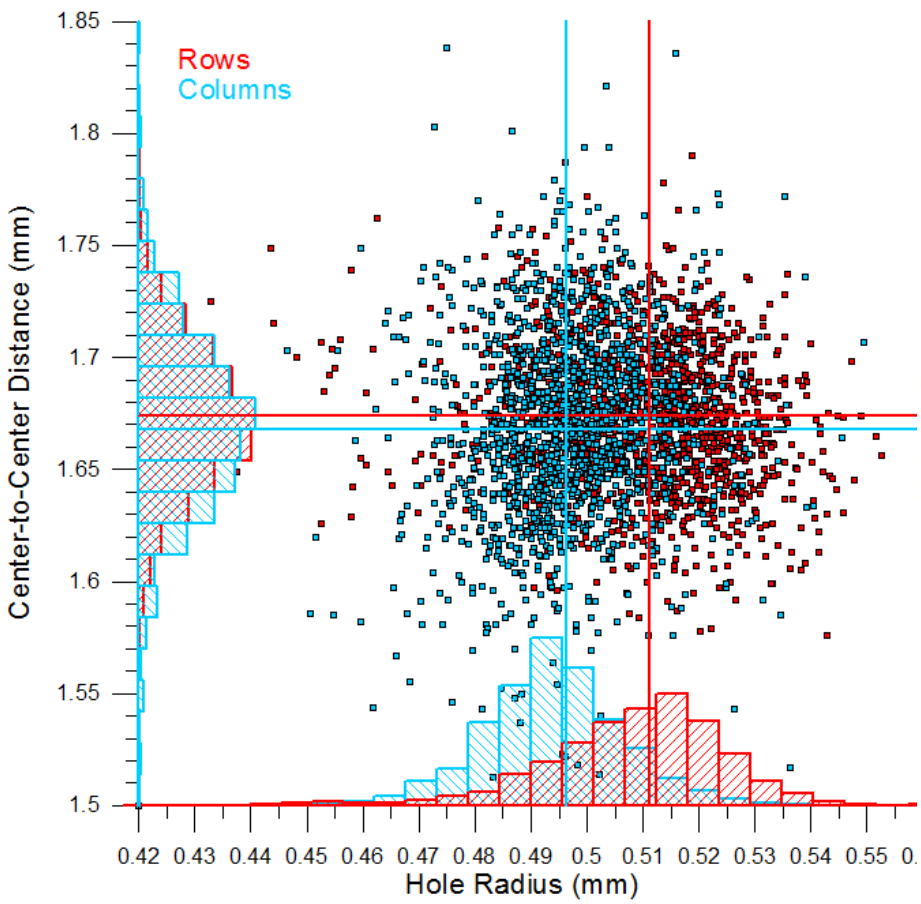


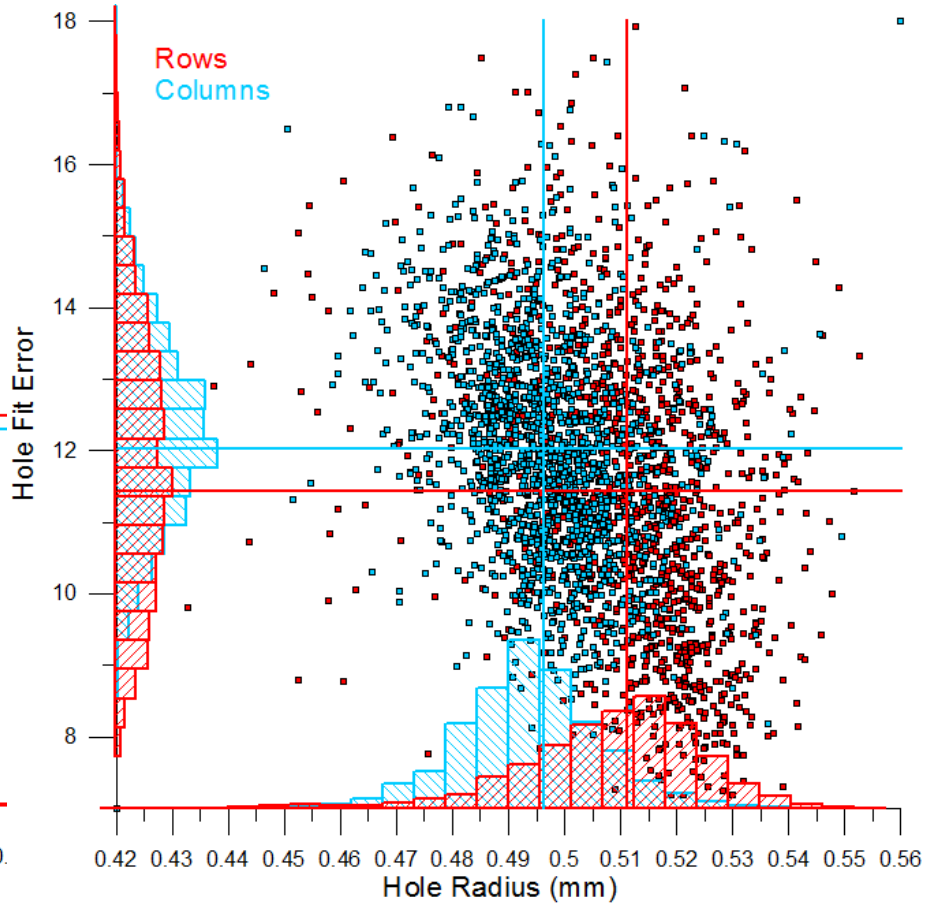
R3 Block of 120

c. 1862-1871
Treadle-operated rotary perforator

Analyze all of the interior perforations

R3 Block of 120 (1-way)

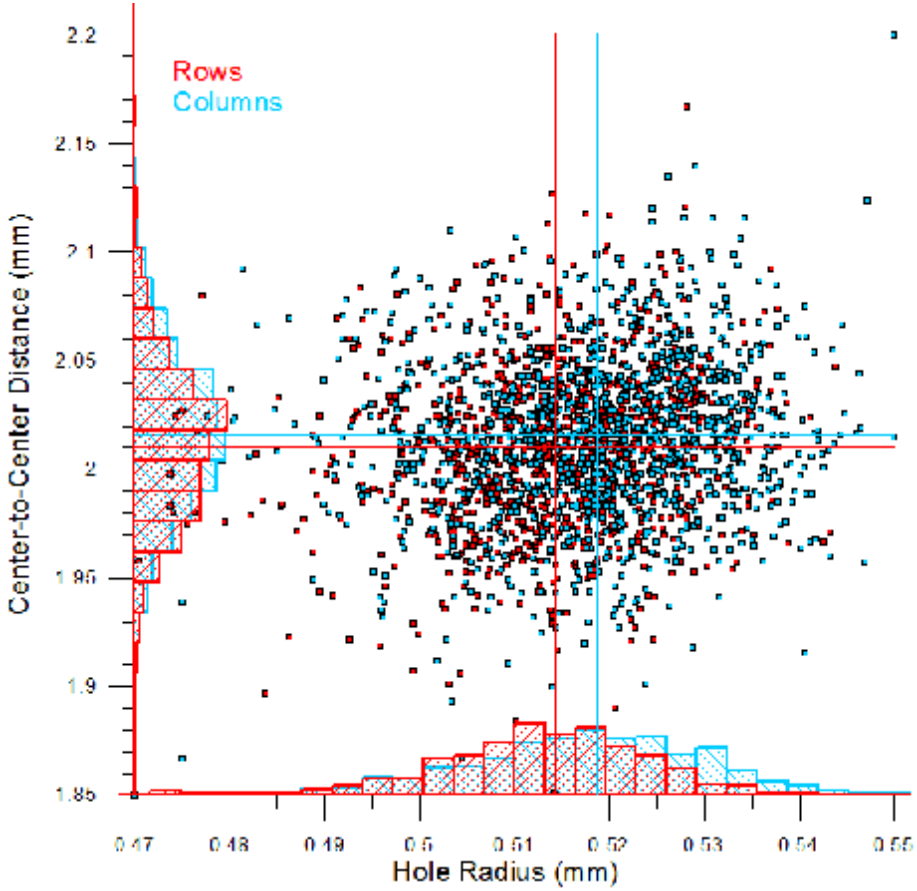


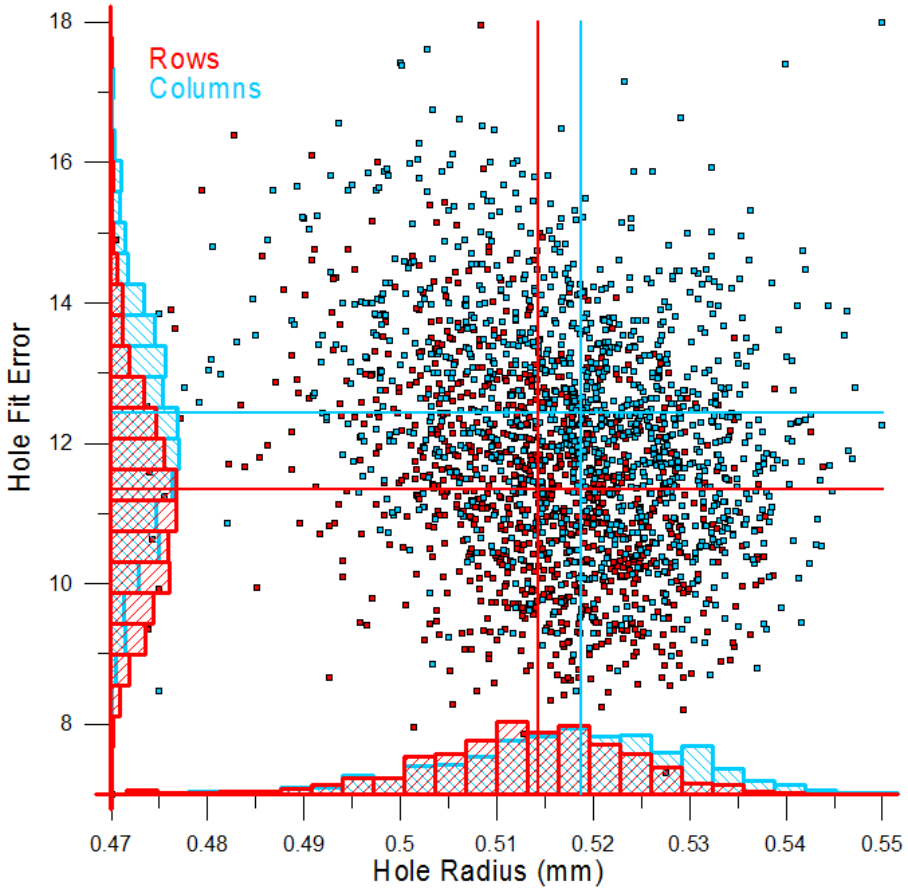


Can see the difference between the two perforators used
Slight skew in HFE plot from roughness

Gauge 12

Sheet of #RE25 (1-way), c. 1914

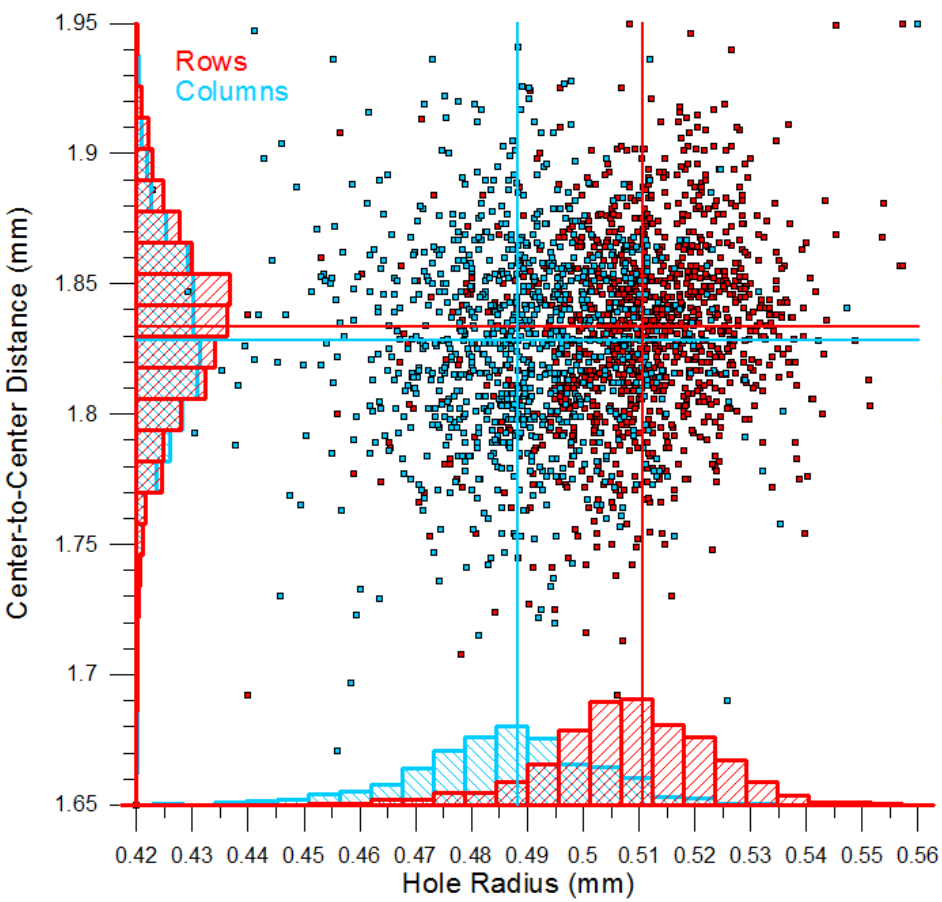


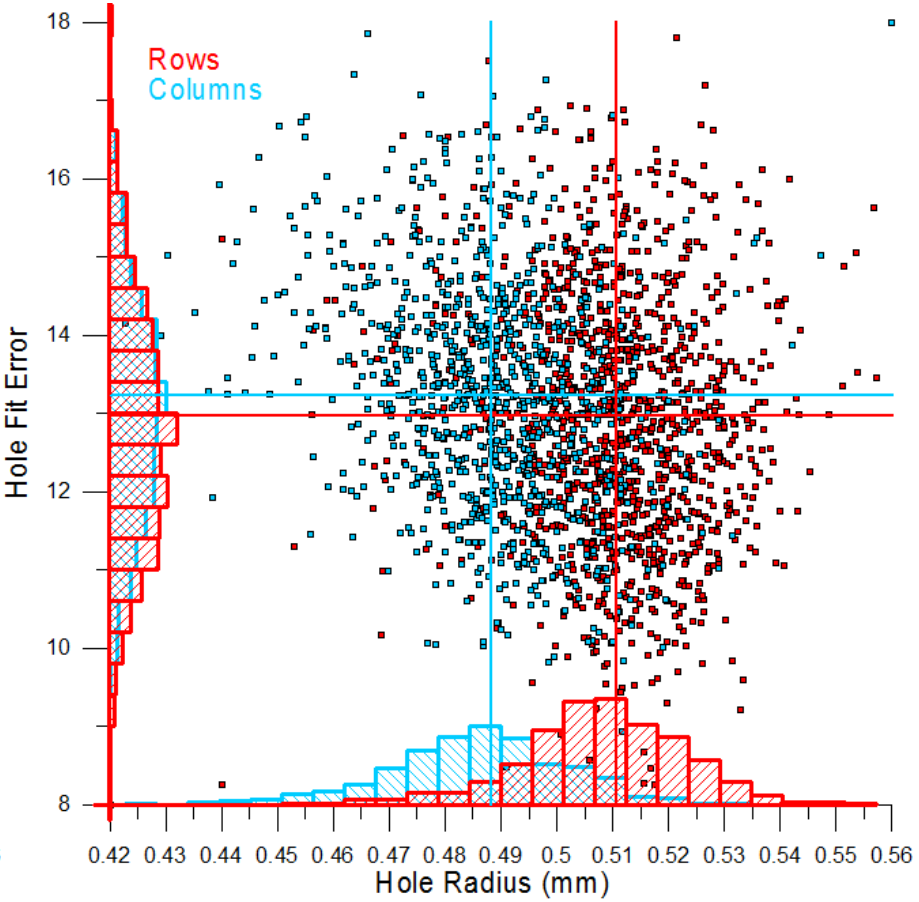


More closely matched perforators

Gauge 9.9 x 10.0

Sheet of #RB66 (1-way), c. 1919

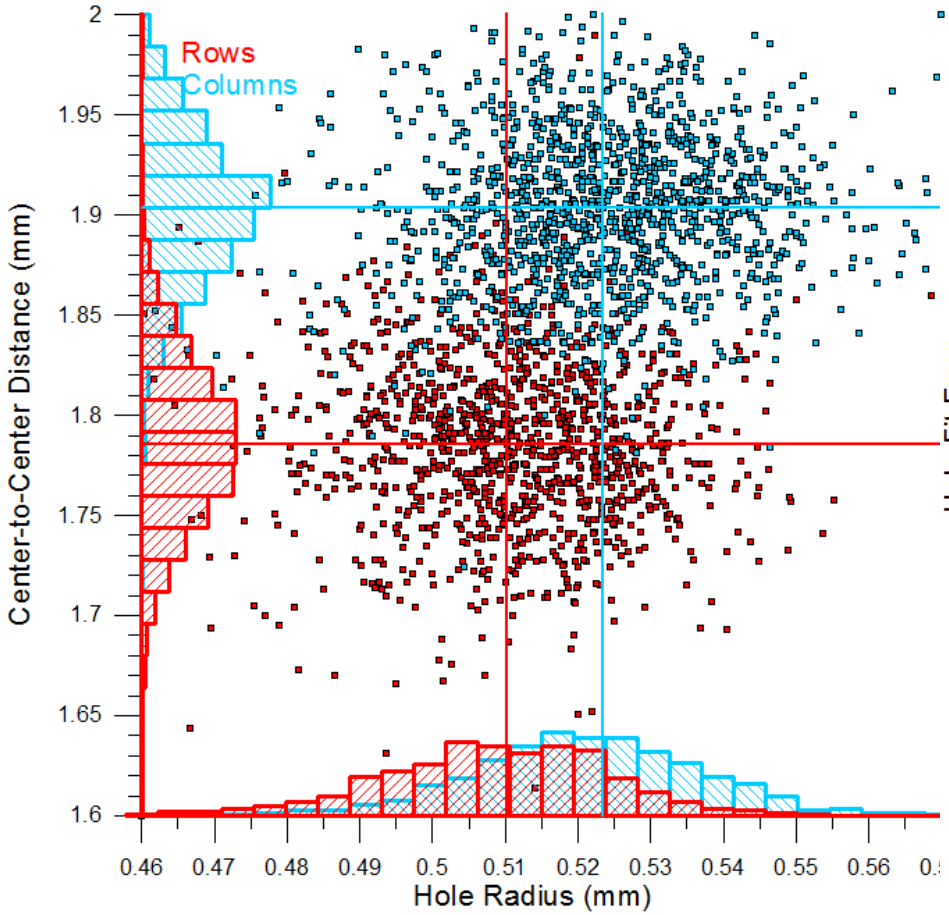


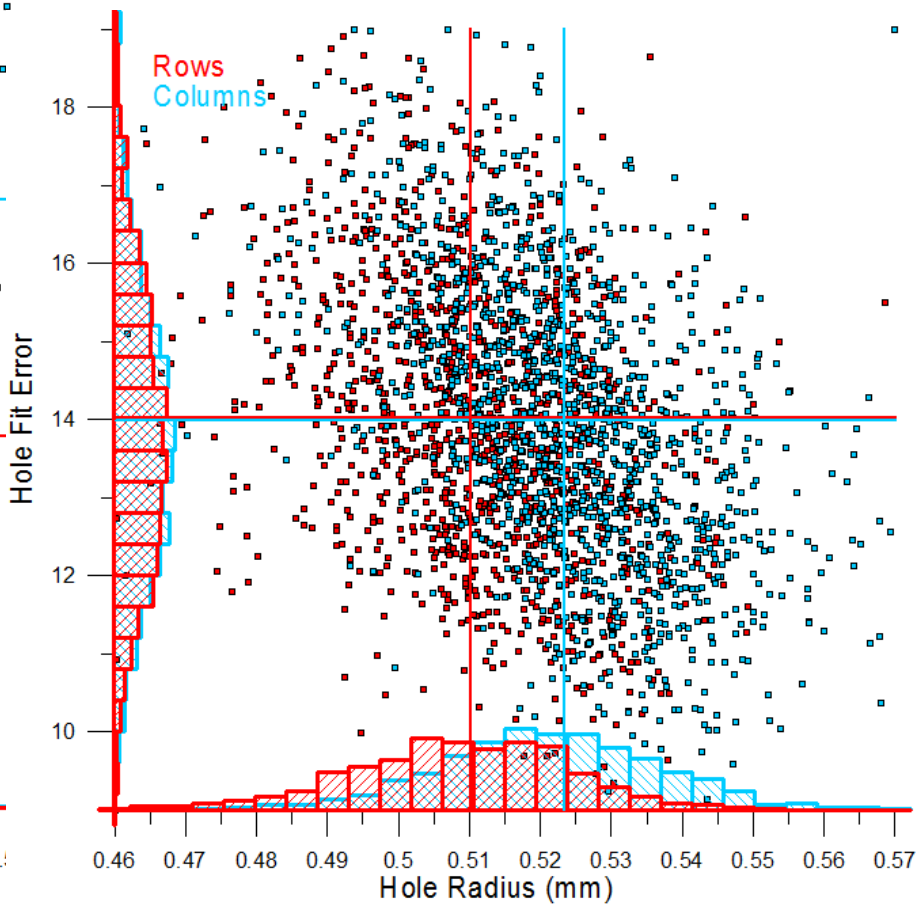


Radii very different between the two perforators

Gauge 10.9

Sheet of US#634 (Experimental Electric Eye, “2-way”), c. 1935



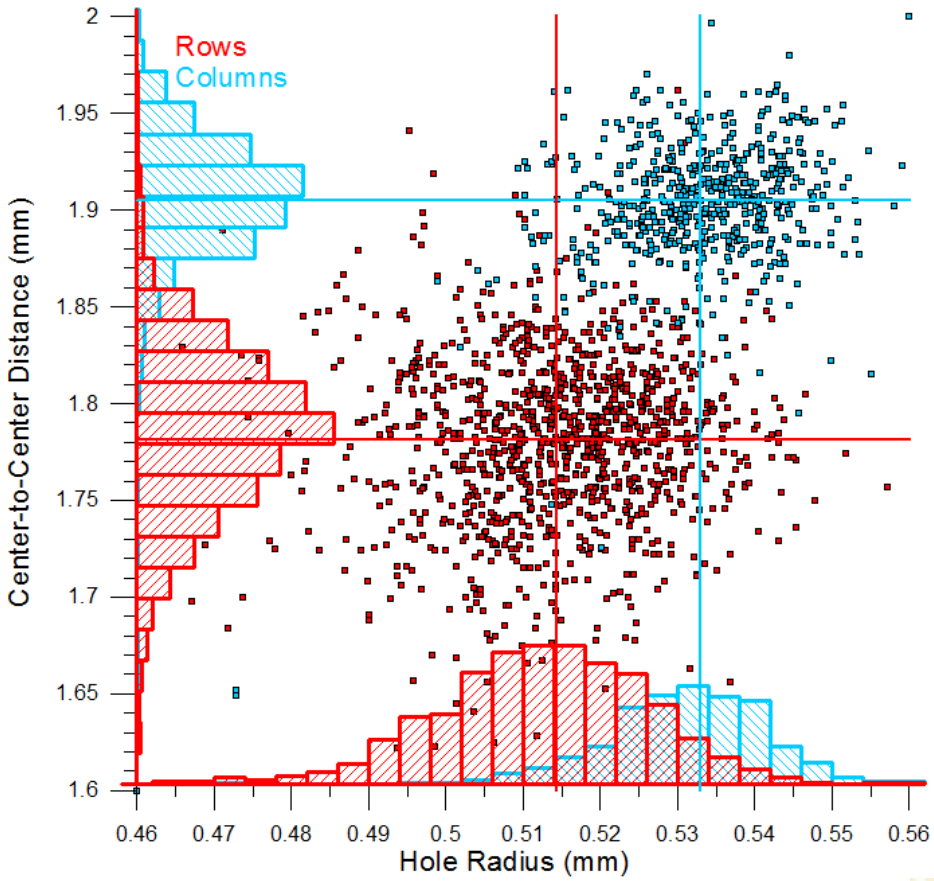


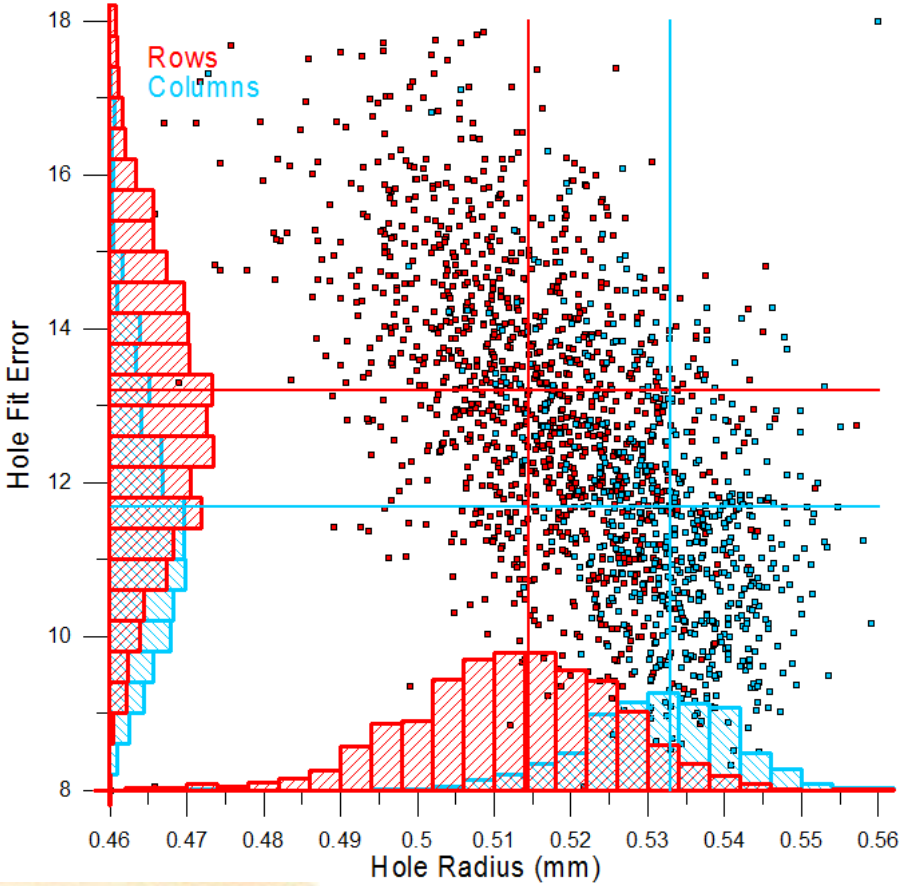
Different perforator characteristics for horizontal and vertical

Gauge 10.5 x 11.2

Skew from roughness

Sheet of US#894 (2-way), c. 1940

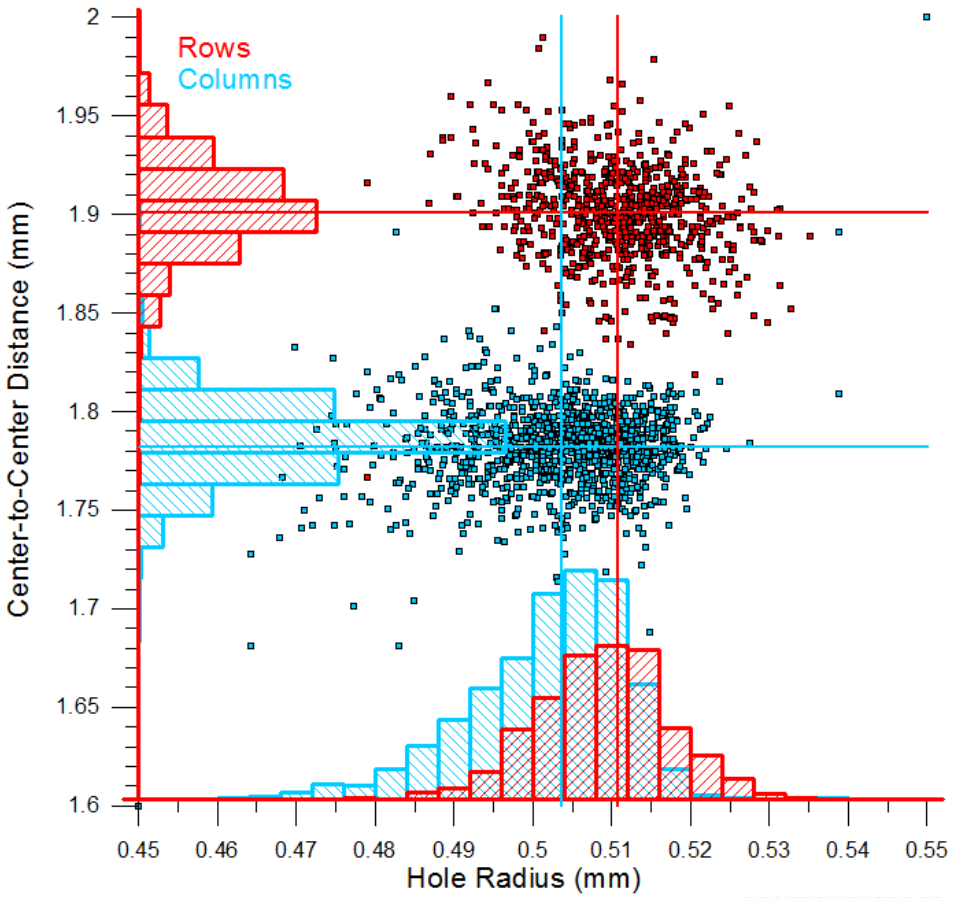


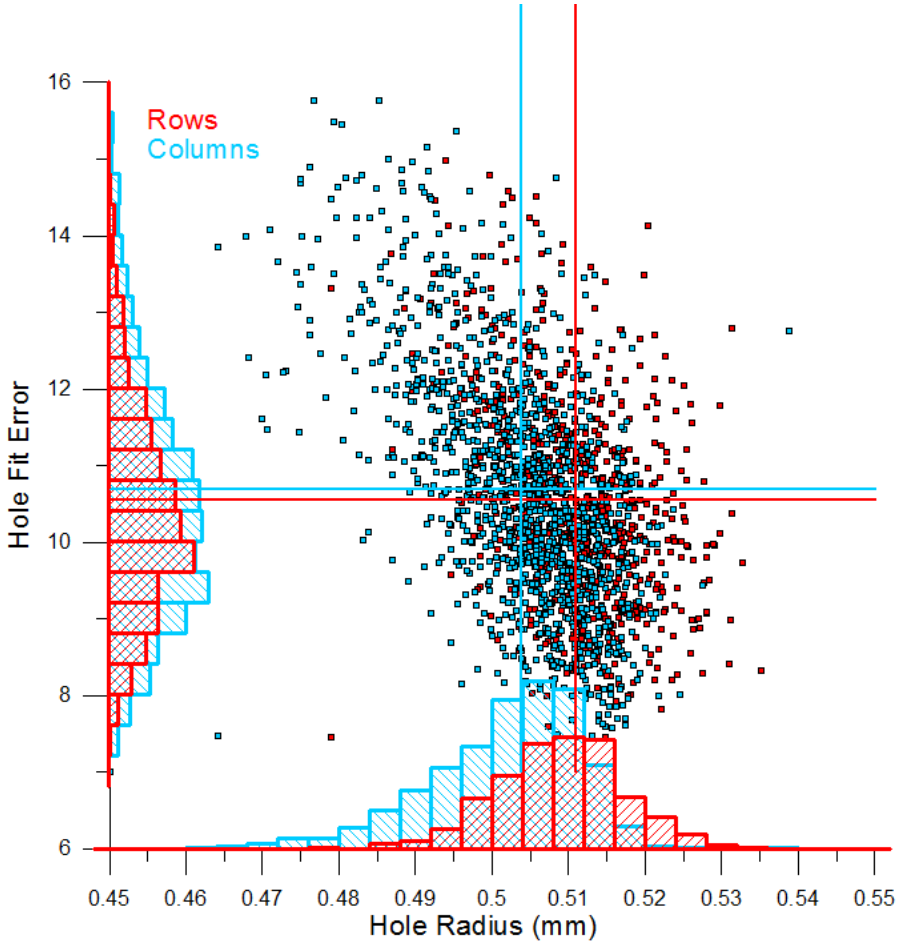


Less variation in the vertical hole spacing

Gauge 10.5 x 11.2

Sheet of US#989 (2-way), c. 1950



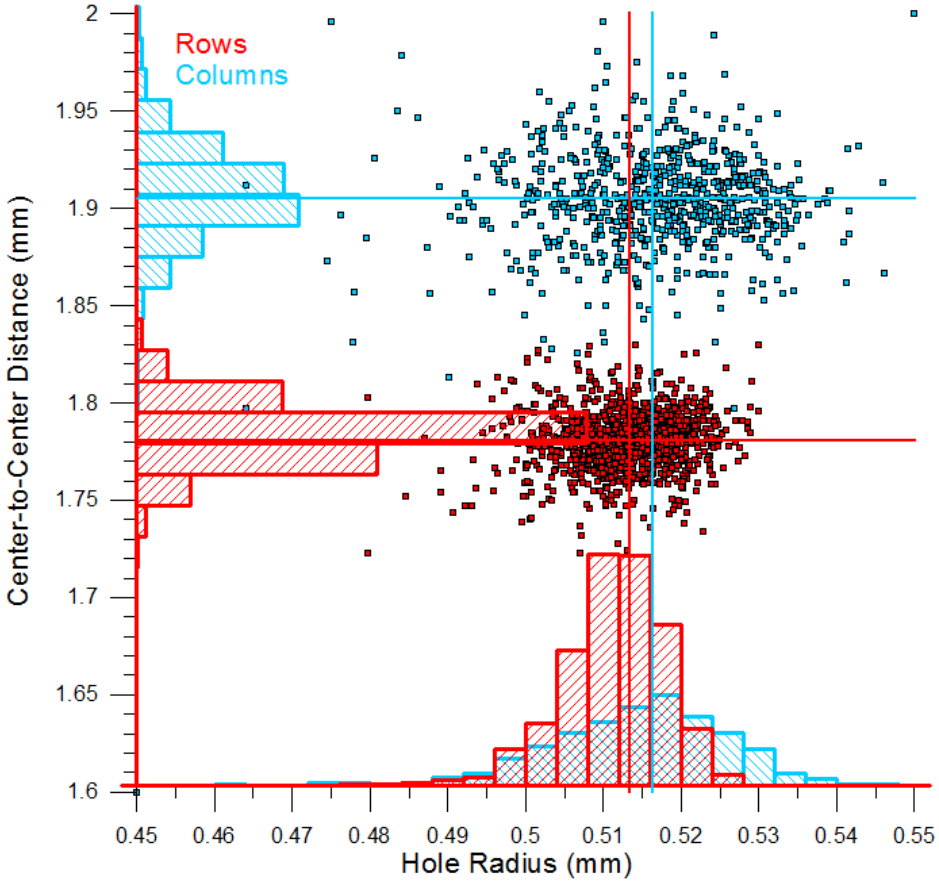


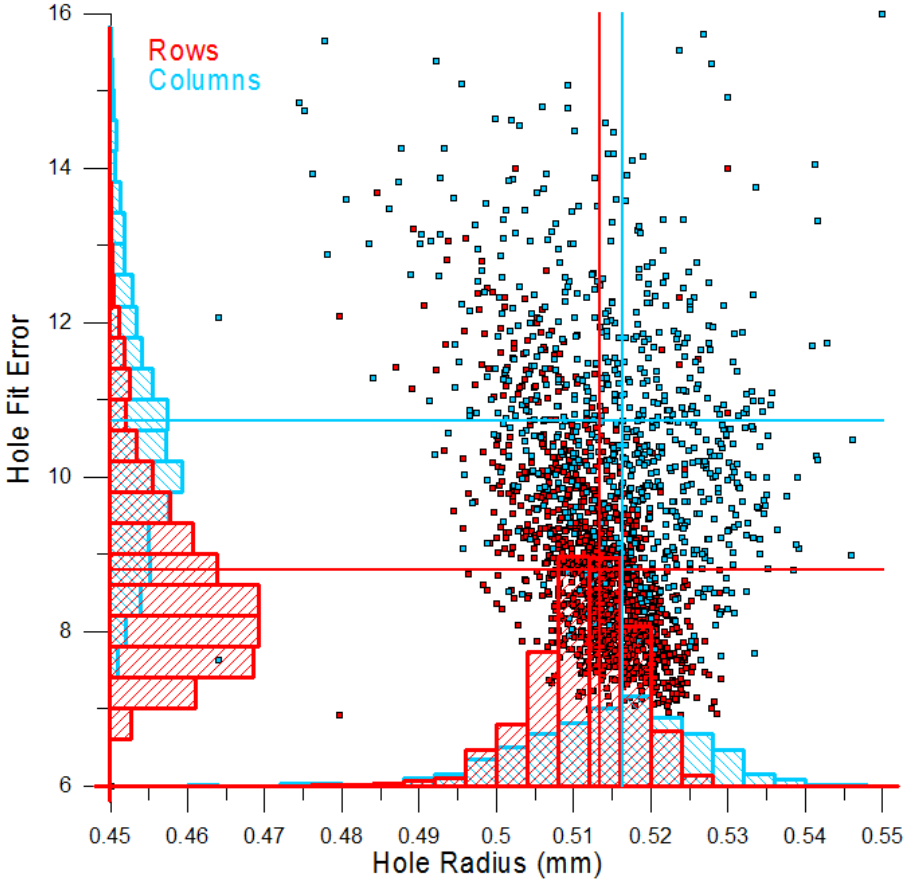
Narrower distributions
Sharper hole cuts

Gauge 10.5 x 11.2

Higher precision perforators built by Harris Seybold in the early 1940s

Sheet of US#1173 (2-way), c. 1960

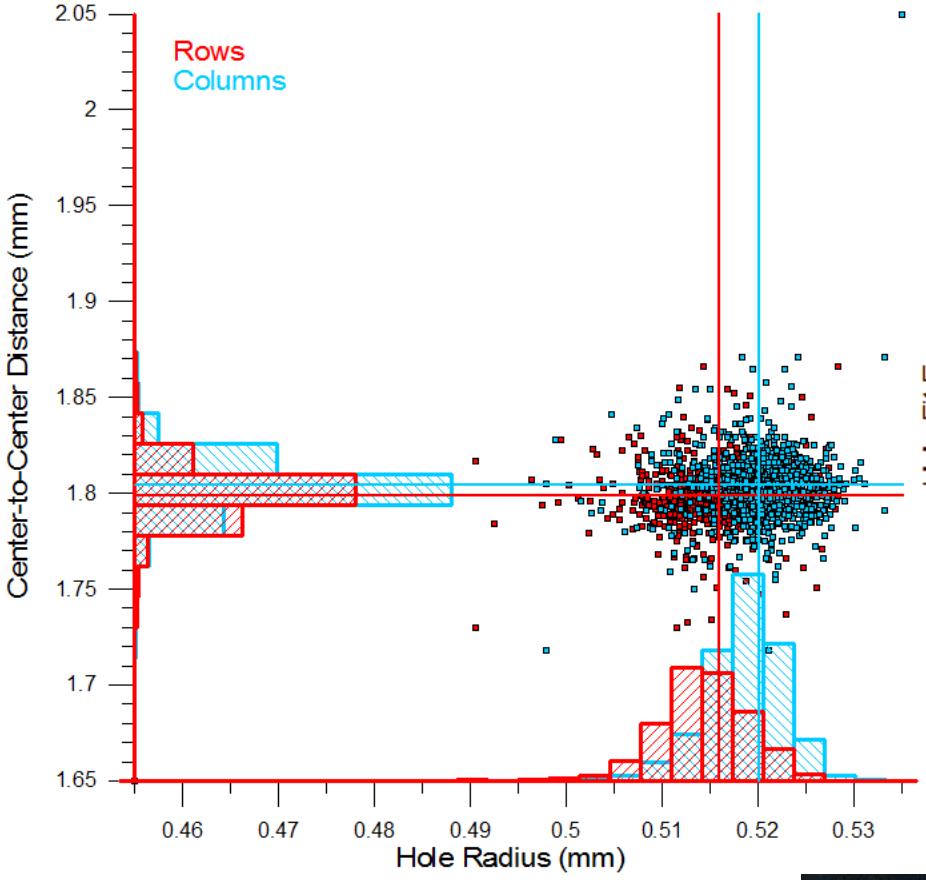


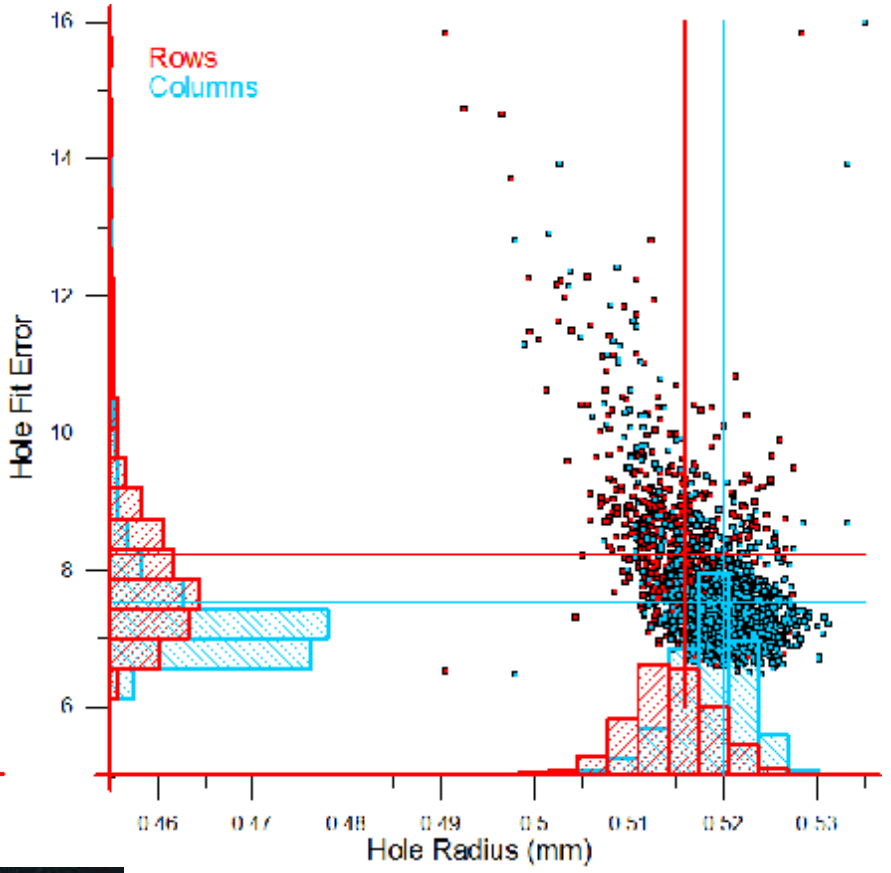


Even better, though some roughness in the perfs

Gauge 10.5 x 11.2

Sheet of US#1580 (In-line Rotary Harrow), 1975



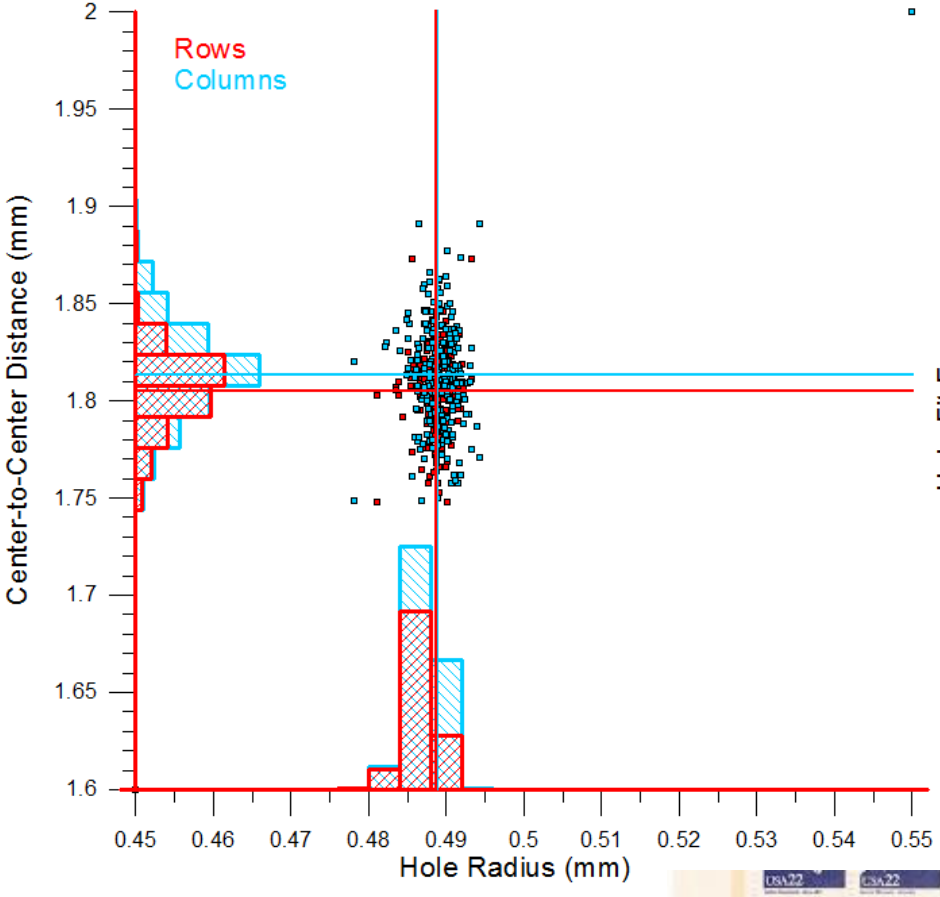


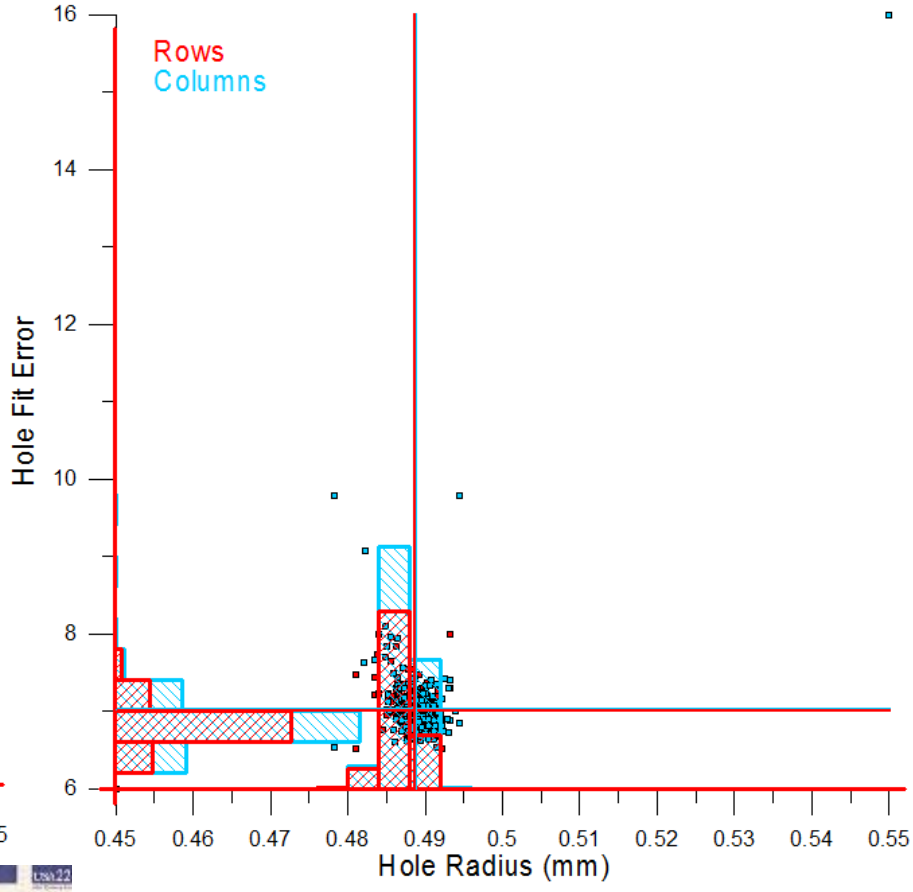
Narrower and similar distributions
Sharper hole cuts

Gauge 11.1

Skew from roughness for a small portion of the data

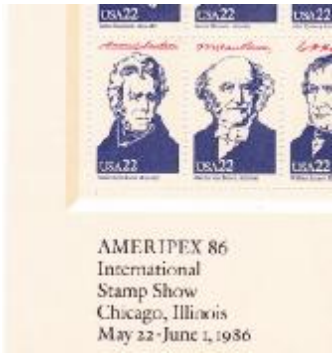
Sheet of US#2216 (Off-line Eureka Stroke Perforator), 1986





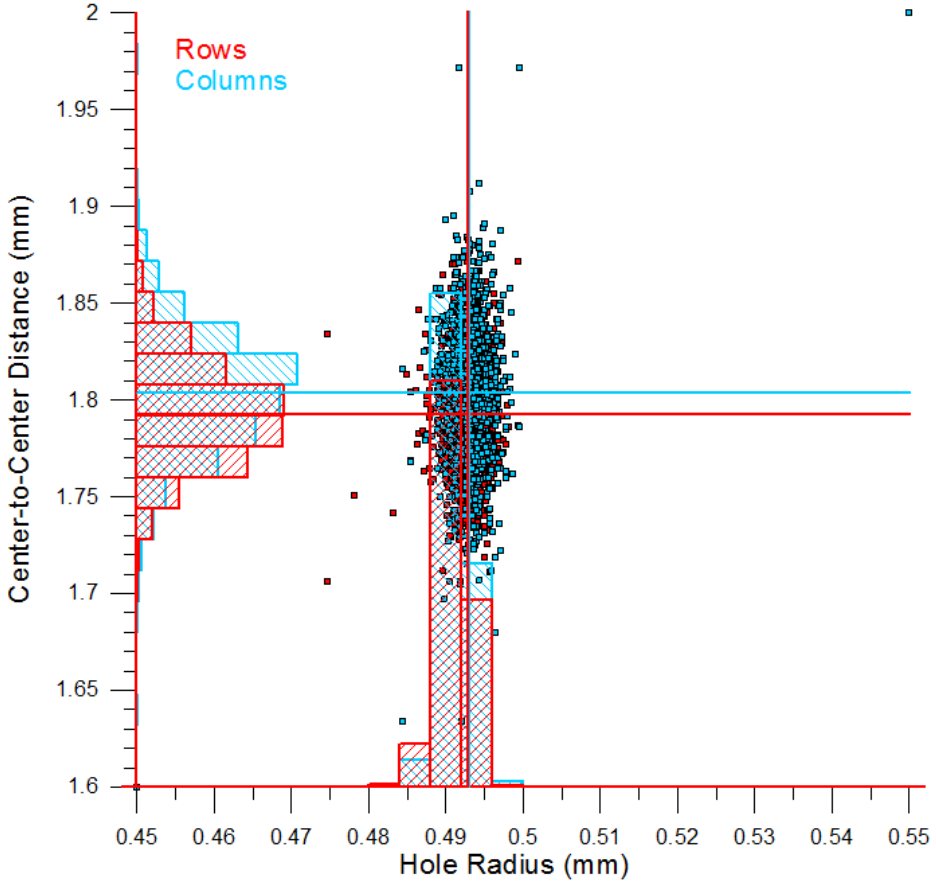
Narrow distributions
Sharp hole cuts

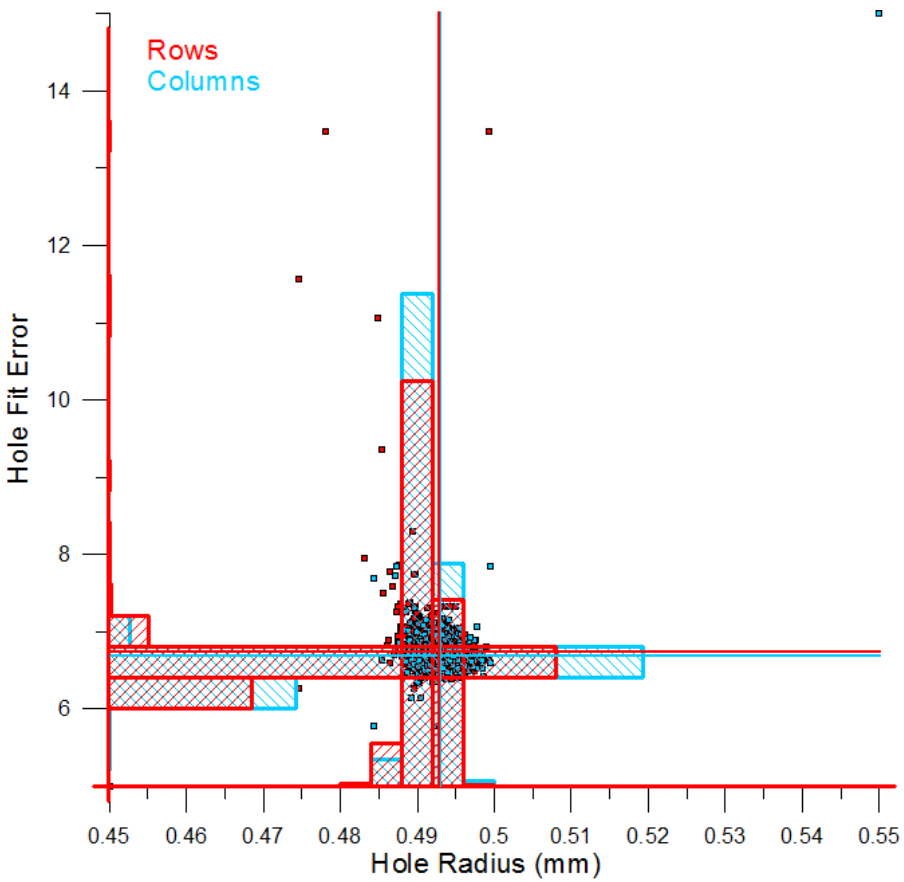
Gauge 11



Bobst-Champlain perforator with
Eureka bullseye die

Sheet of US#2477 (Eureka Stroke Perforator), 1991

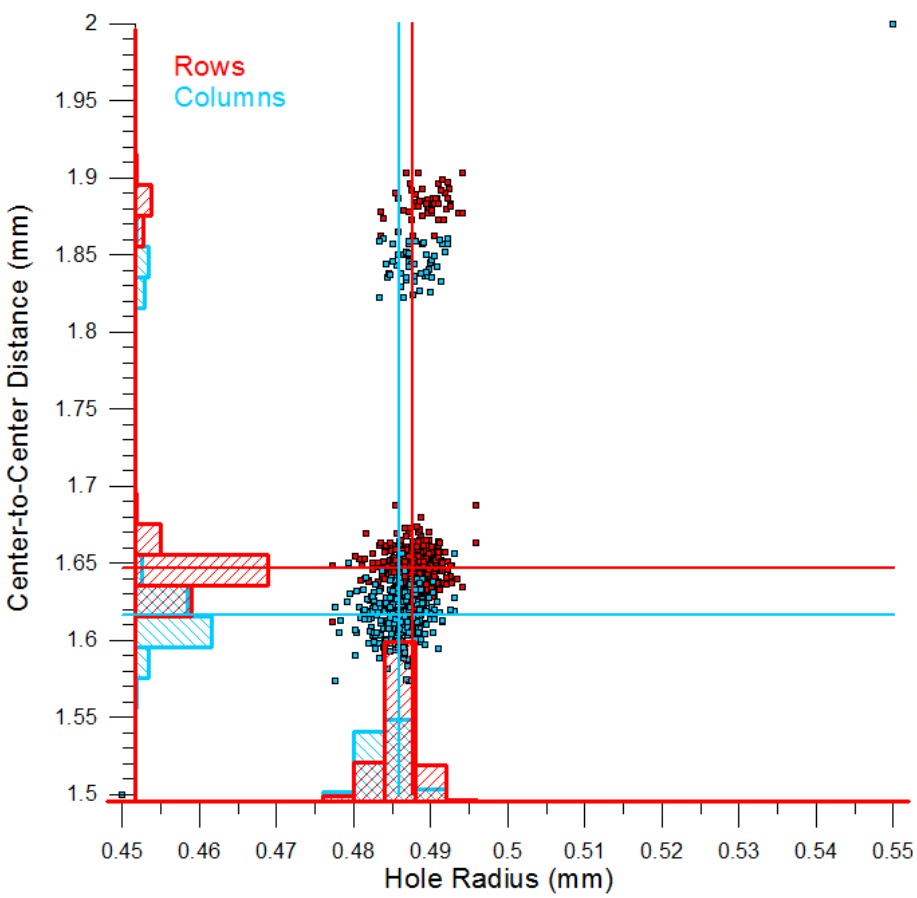


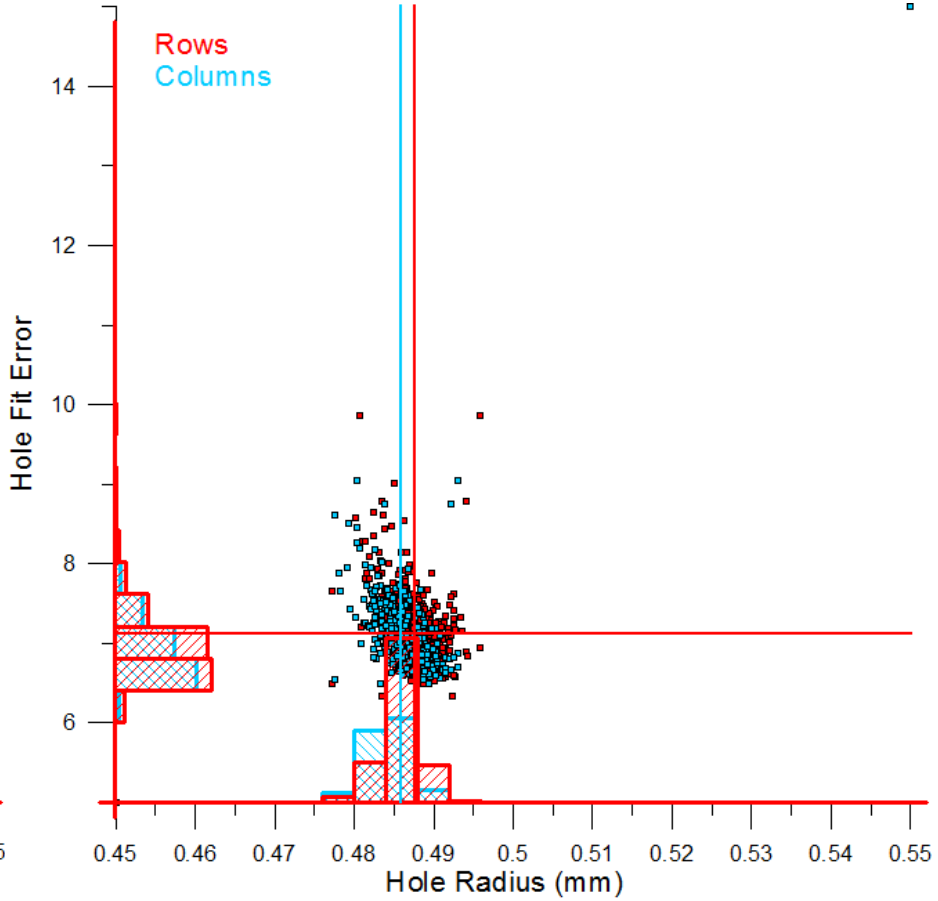


Similar, but more spread in hole spacing distribution

Gauge 11.1 x 11.2

Sheet of US#3209 (Wista BPA 9070 Stroke Perforator), 1998

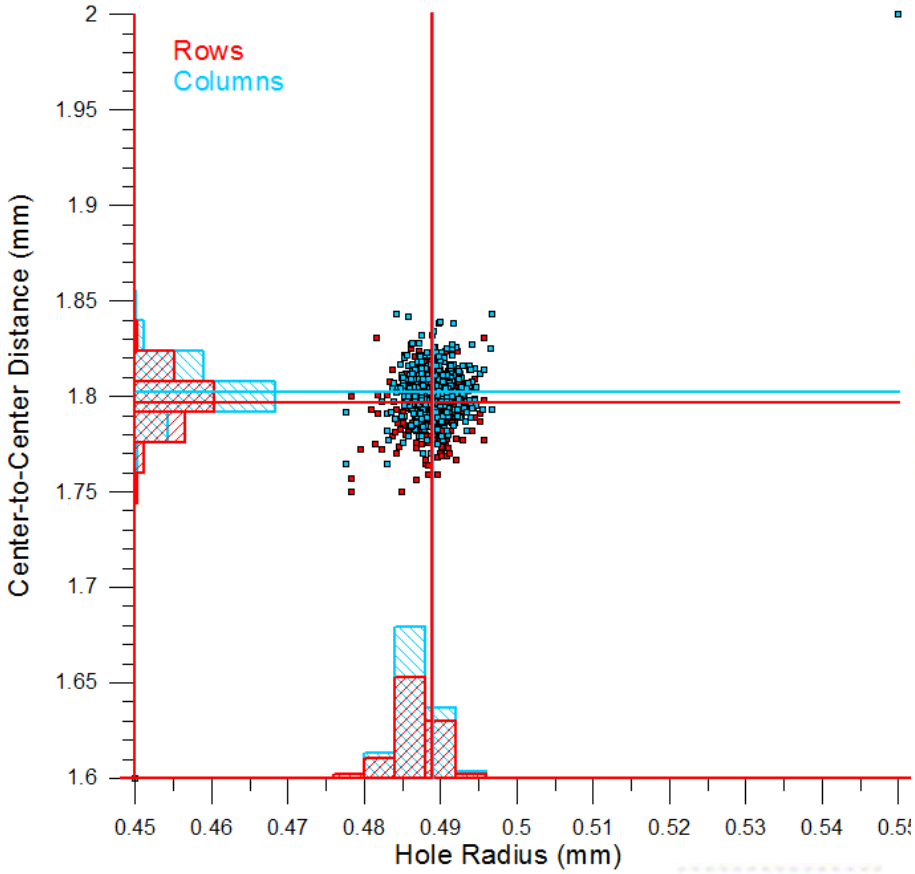


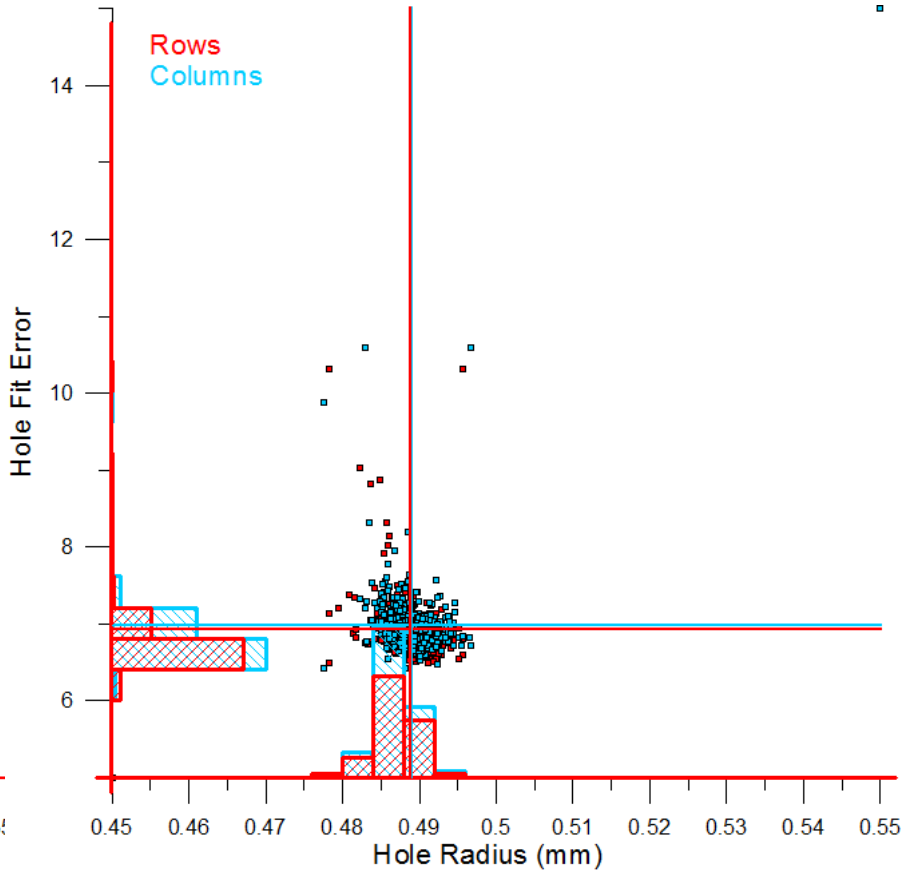


Very narrow distributions

Gauge 12.2 x 12.4

Sheet of US#3533 (Wista Stroke Perforator), 2001

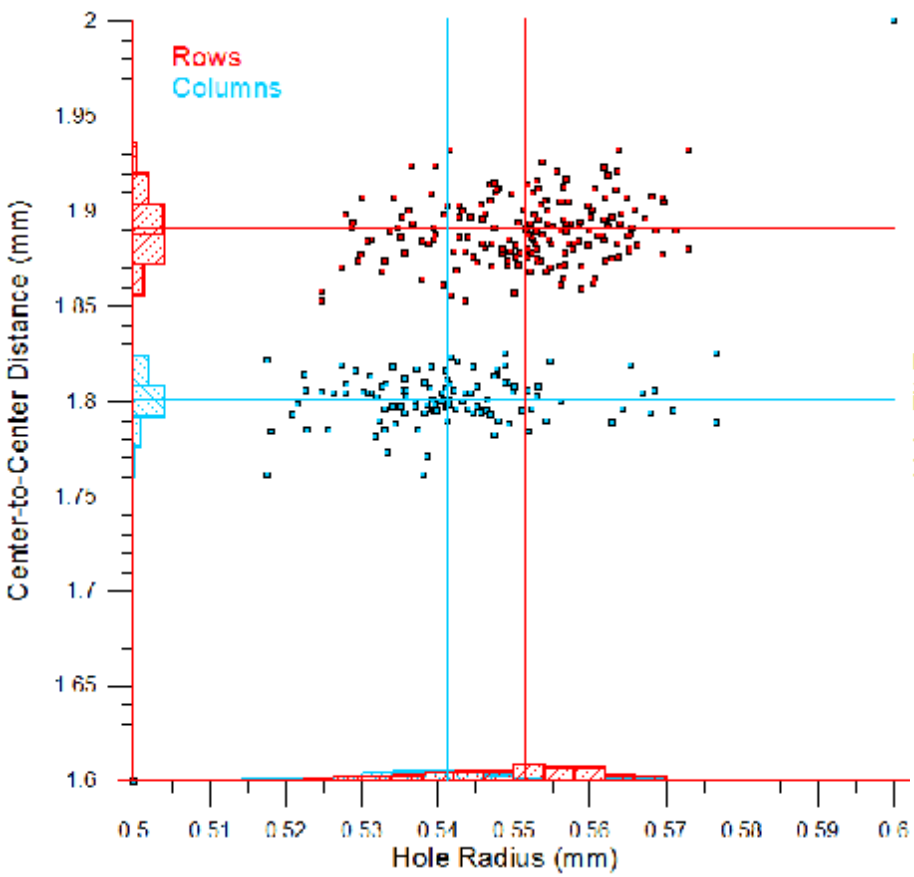


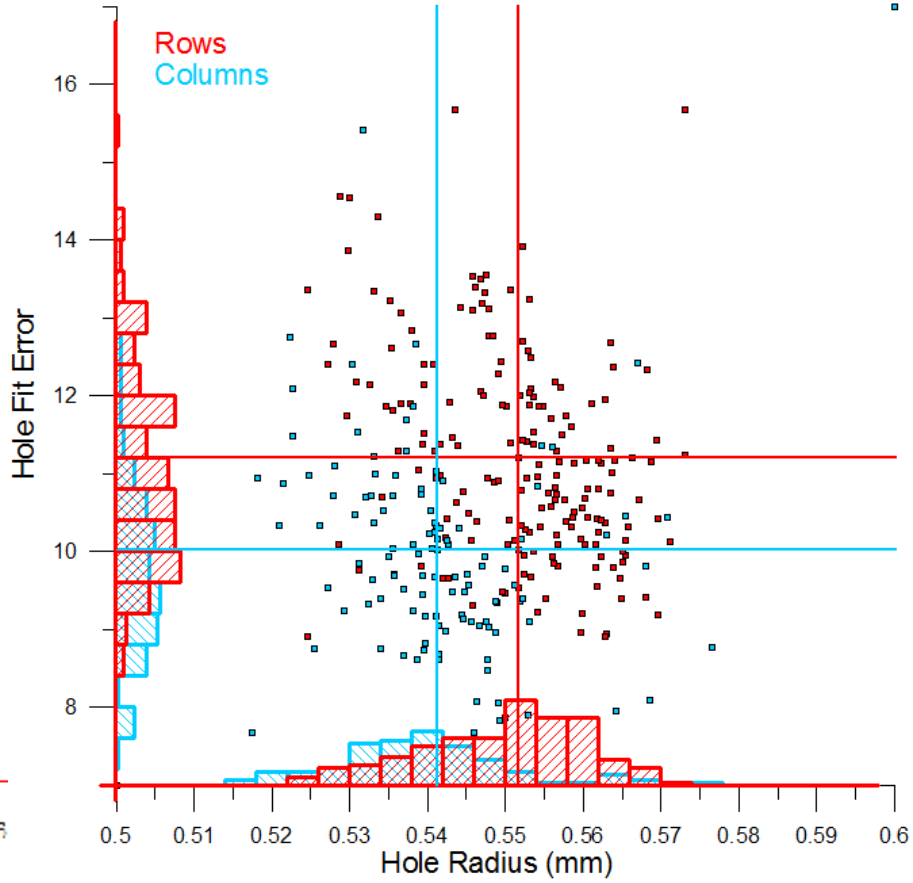


Similar results

Gauge 11.1

Sheet of US#3409 (Ab Produktion Svenka Rotary Perforator), 2000



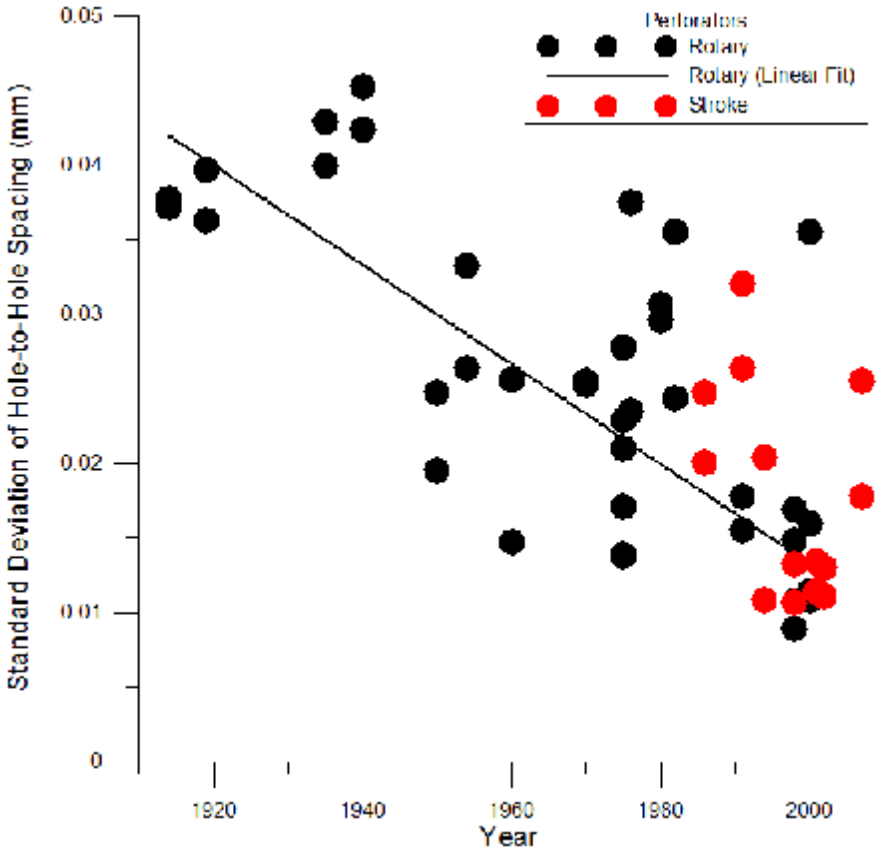


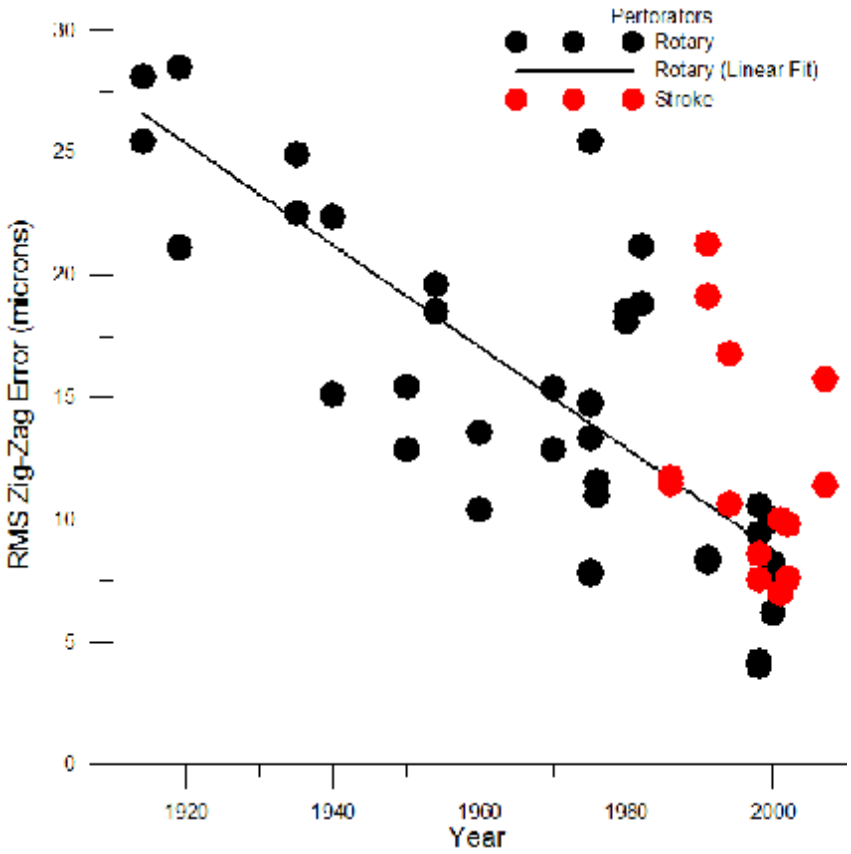
Large holes sizes
Wider distributions of radii and HFE

Gauge 11.1 x 10.6

Swedish “lawnmower” method

Hole Placement Precision

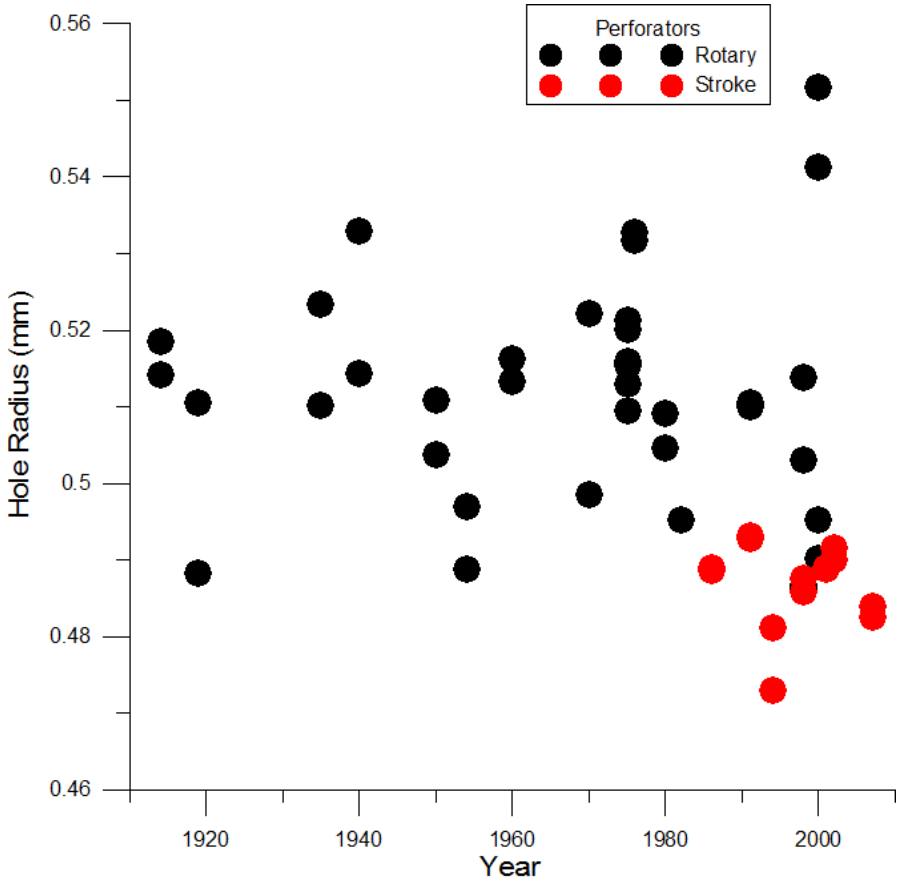




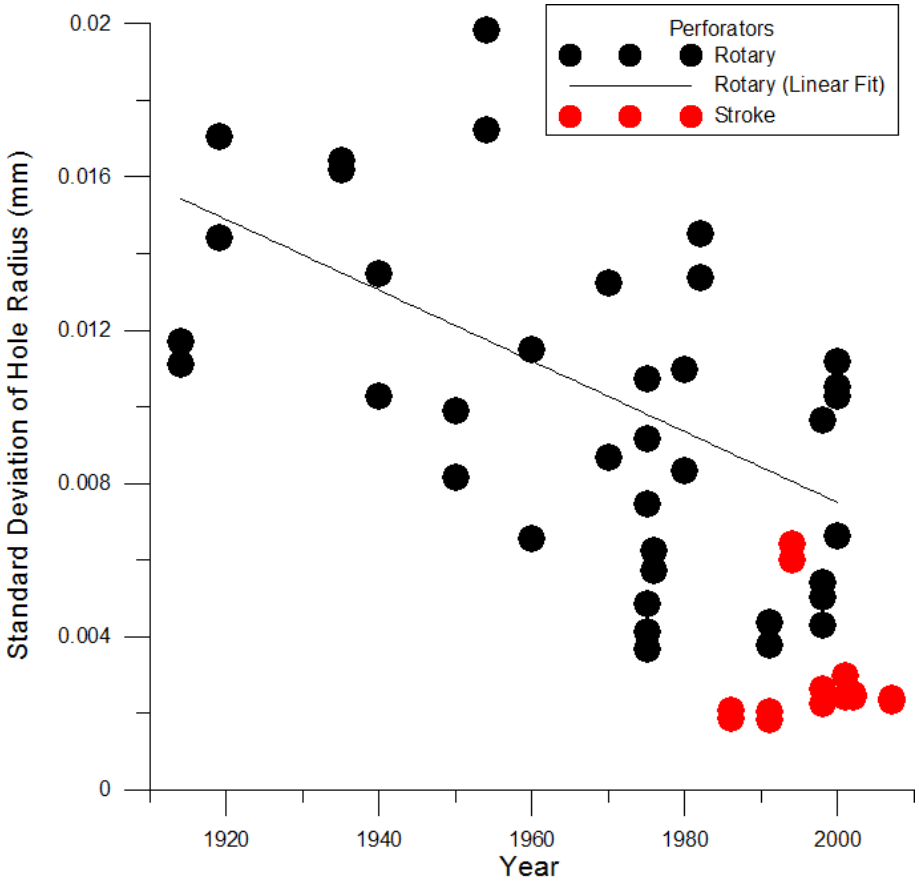
For rotary perforation:

- Improvement following new Harris Seybold manufacturing practice c. 1941
- No improvement during 1950s-1970s
- There is a substantial improvement after BEP-NBS initiative c. 1980

Radius Precision

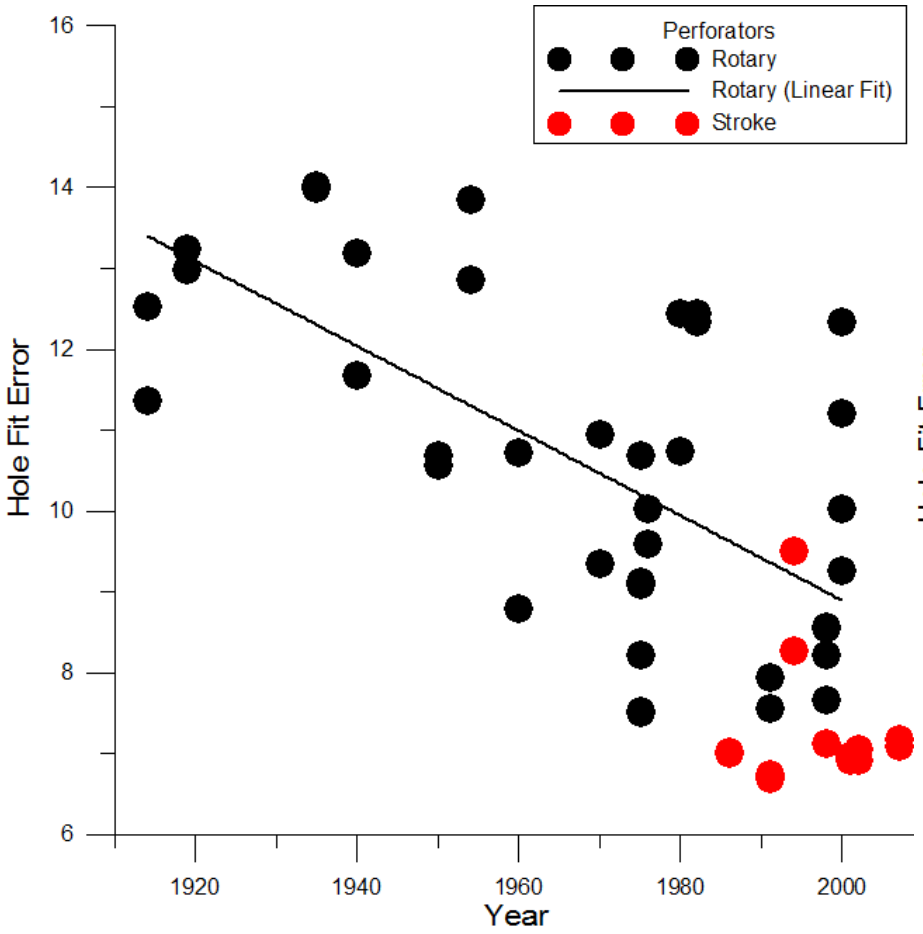


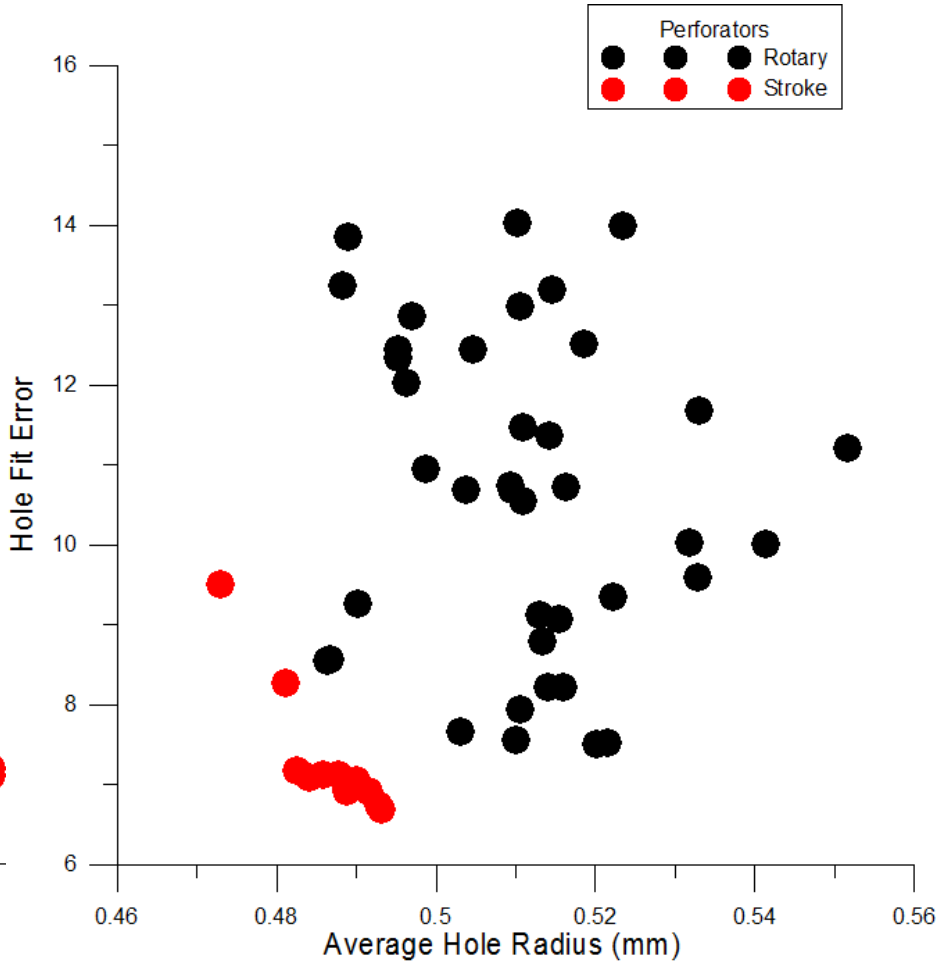
- Rotary hole radii approx. constant
- Stroke hole radius smaller
- Holes typically smaller than pins by 1-4%



- Gradual decline in rotary hole variation
- Stroke hole size variation small

Hole Cut Characteristics

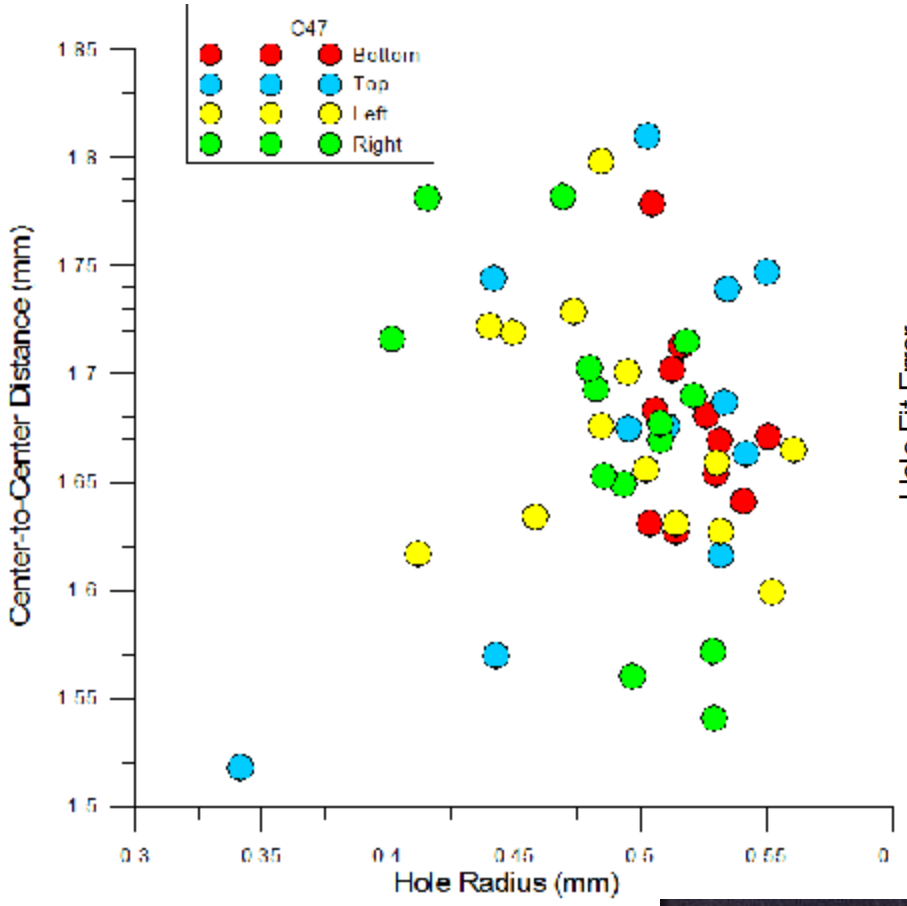


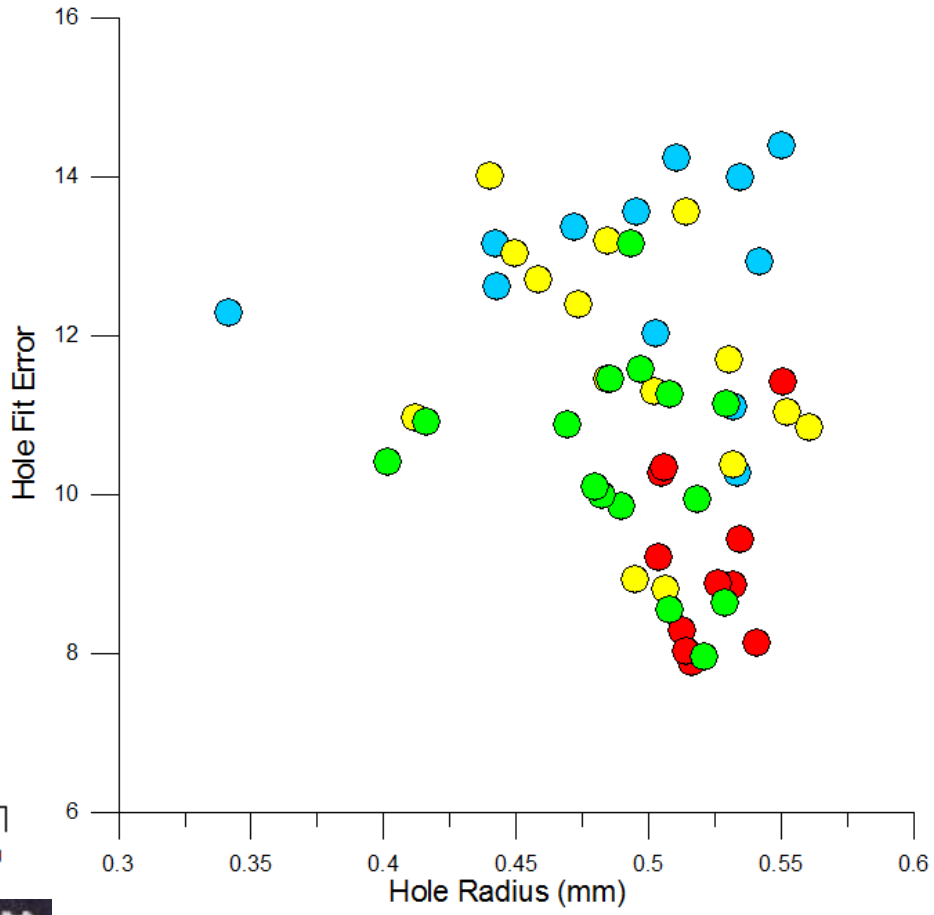


- Gradual improvement in sharpness of rotary hole cutting
- More perfect hole cutting with stroke perforators

- Stroke perforation characteristics cluster apart from rotary perforation characteristics

Example Analysis Suggesting Re-perforation





Bottom edge:
Narrower distribution of radii
Narrower distribution of spacings
Narrower distribution of Hole Fit Error
Small average value for Hole Fit Error

Fingerprinting of Comb Perforation (Wista-perforated US #4129)

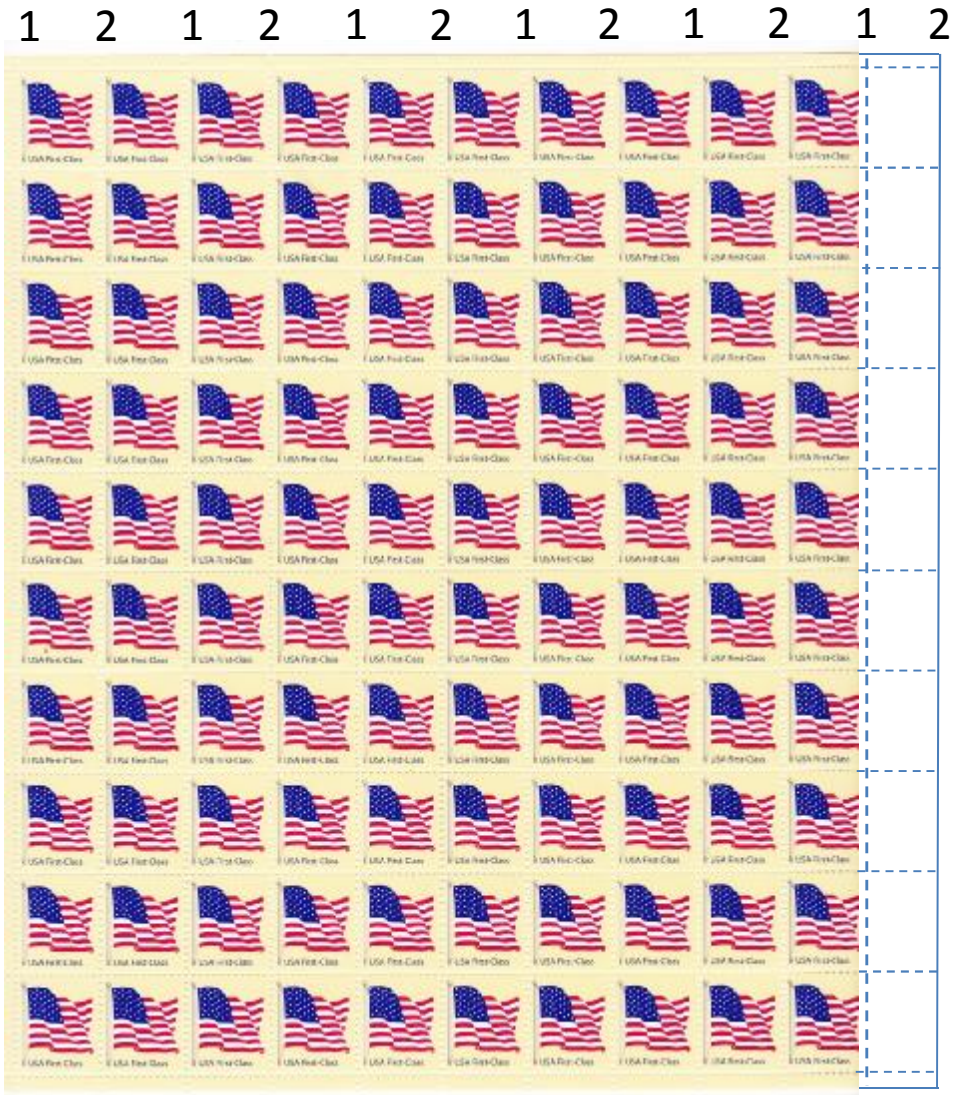
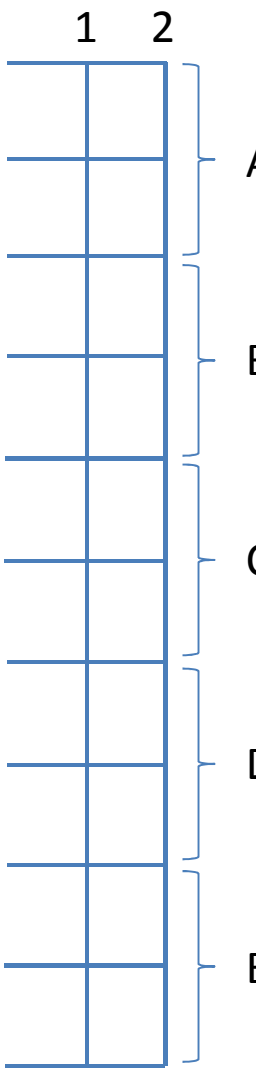


Image clipped at right edge



Perforation columns analyzed in 5 segments

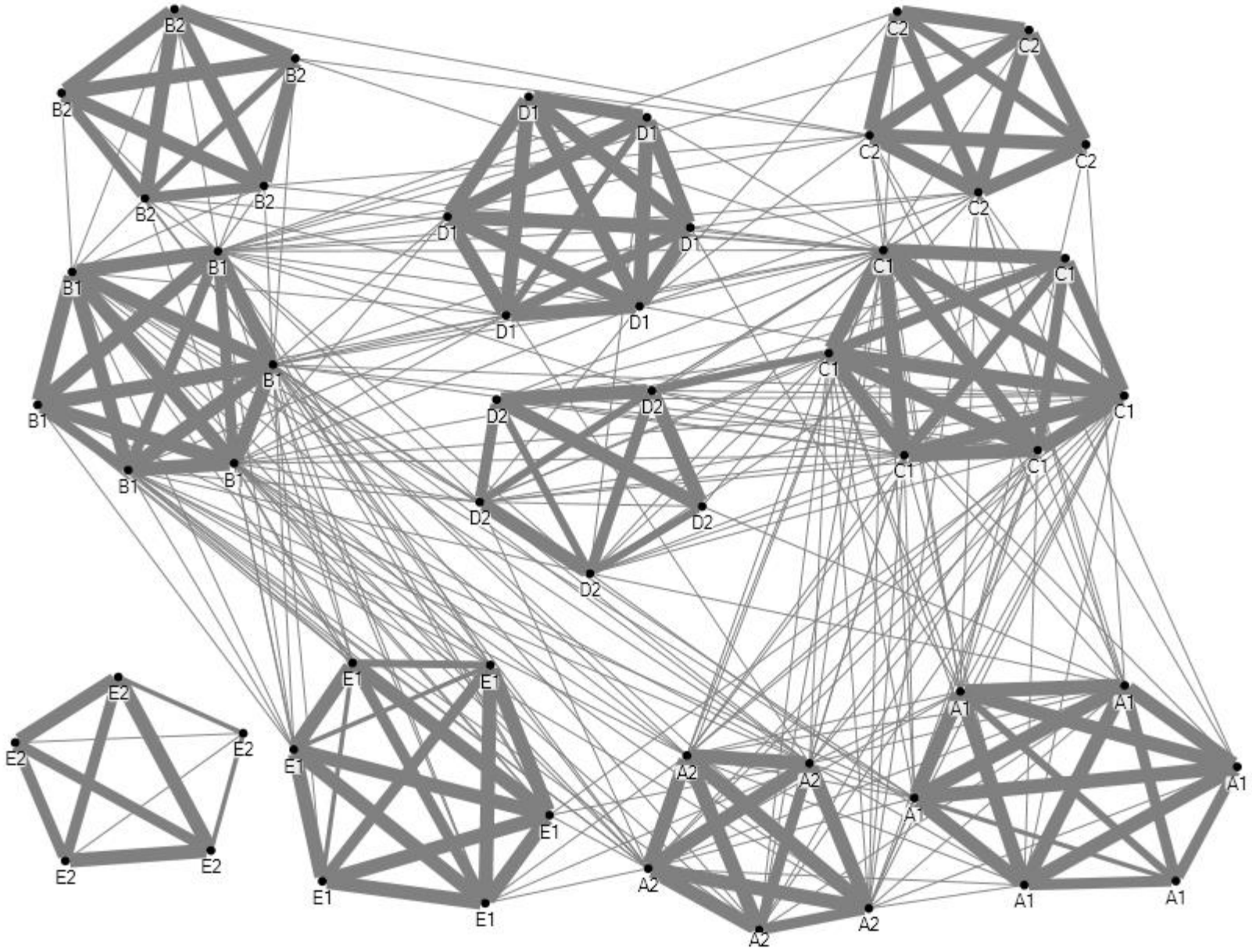
"2 hop comb"

For each segment:
6 column "1" fingerprints should match
5 column "2" fingerprints should match

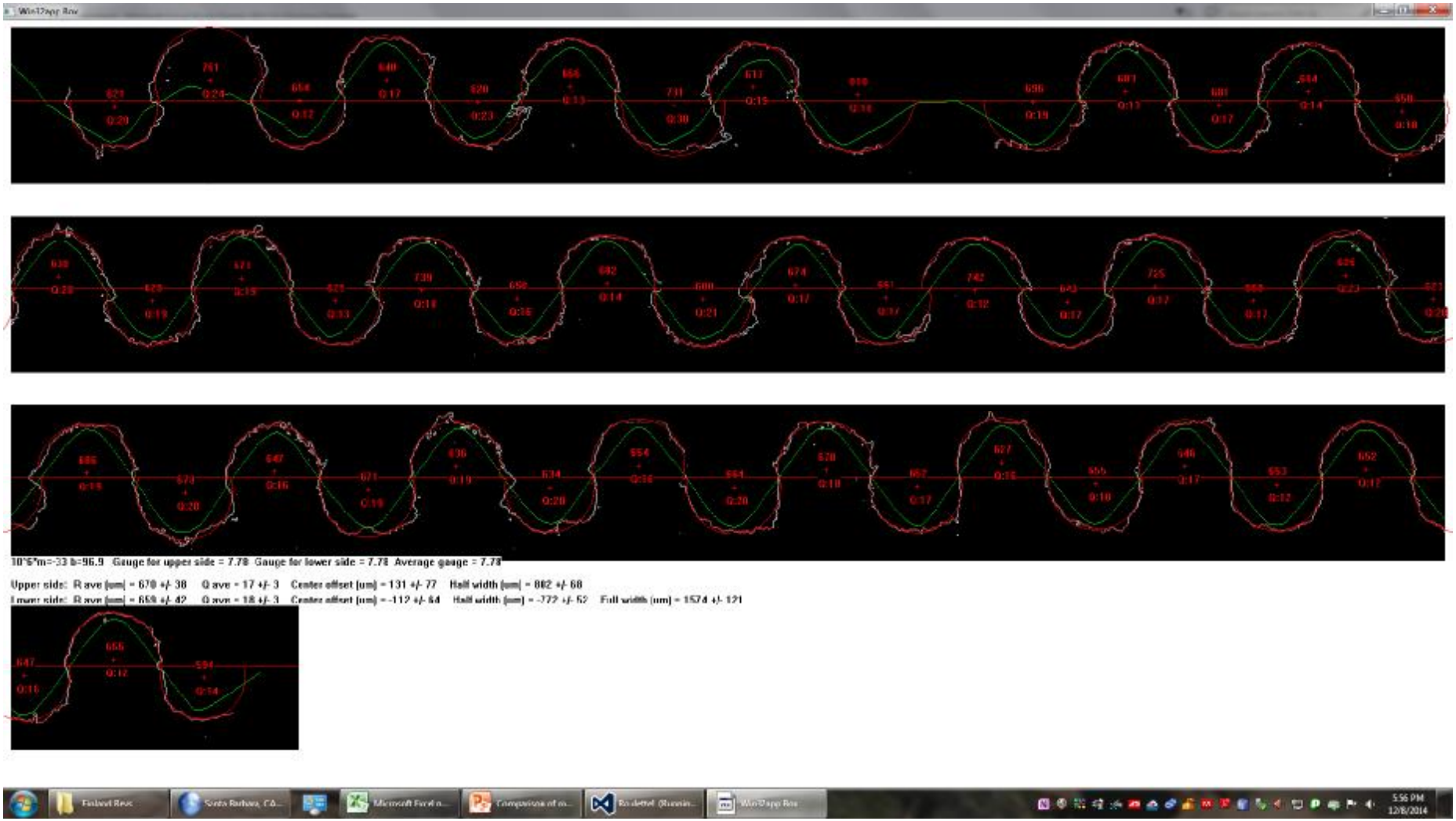
Network of Fingerprint Matches for Comb-Perforated US #4129

Wider lines are stronger fingerprint matches

148/149 strong correlations (>=6) are with own groups!



Other Separation: Roulettes



Hand rouletted – use a parabolic fit to first remove edge curvature

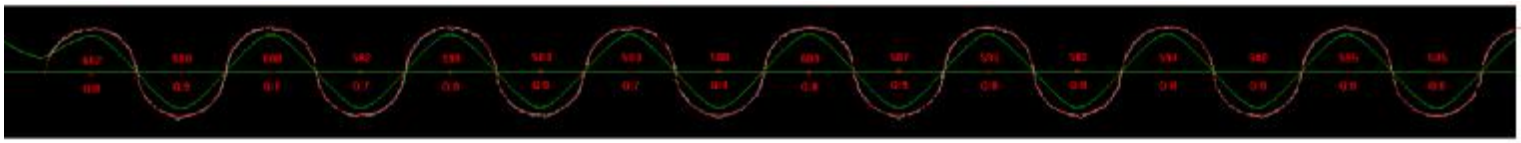
Use a smoothed approximation (green) to locate peaks, troughs, and missing teeth

Fit partial arcs to peaks and troughs avoiding bridges

Results cluster in to types described in the literature; fingerprint next

Other Separation: Die Cuts

Printed by American Packaging Corp. for Sennett Security Products?
"Serpentine Die Cut 8 ½"



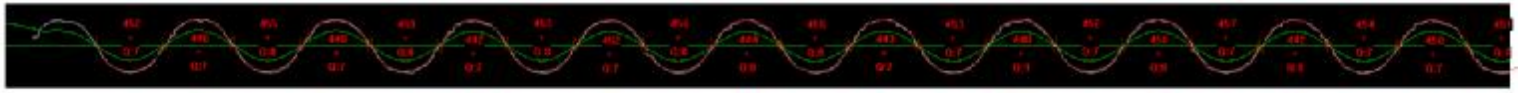
Gauge for upper side = 8.39 Gauge for lower side = 8.39 Average gauge = 8.39

Upper side: R ave (um) = 596 +/- 3 Q ave = 8.1 +/- 0.2 Center offset (um) = -2 +/- 6 Half width (um) = 593 +/- 5

Lower side: R ave (um) = 585 +/- 3 Q ave = 8.7 +/- 0.6 Center offset (um) = 7 +/- 5 Half width (um) = -577 +/- 4 Full width (um) = 1171 +/- 9

#4208

Printed by Banknote Corp. of America for Sennett Security Products,
"Serpentine Die Cut 10 ¾"



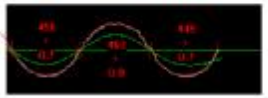
Gauge for upper side = 10.90 Gauge for lower side = 10.90 Average gauge = 10.90

Upper side: R ave (um) = 445 +/- 5 Q ave = 8.1 +/- 0.5 Center offset (um) = -99 +/- 8 Half width (um) = 345 +/- 4

Lower side: R ave (um) = 455 +/- 3 Q ave = 8.0 +/- 0.4 Center offset (um) = 107 +/- 3 Half width (um) = -347 +/- 2 Full width (um) = 693 +/- 6

#4227

Printed by Avery Dennison,
"Serpentine Die Cut 11"



Gauge for upper side = 10.81 Gauge for lower side = 10.81 Average gauge = 10.81

Upper side: R ave (um) = 459 +/- 8 Q ave = 8.7 +/- 1.0 Center offset (um) = -111 +/- 13 Half width (um) = 347 +/- 5

Lower side: R ave (um) = 443 +/- 8 Q ave = 8.3 +/- 0.5 Center offset (um) = 90 +/- 12 Half width (um) = -353 +/- 6 Full width (um) = 700 +/- 11

Summary

- An inexpensive scanner provides micron-level precision measurements of hole sizes, spacings, and hole cut
- Perforation statistics from sheets of stamps reveal the improvement in machining techniques during the 20th century
- Statistical comparisons can be made of stamp edges using these techniques to indicate possible re-perforation
- Inconsistencies in features such as hole spacing can be used to fingerprint perforation equipment
- Related methods can be developed to analyze other types of separation such as rouletting and die-cutting