Thread Count Automation Project

Co-directors
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ANNUAL REPORT :: 2009

The Thread Count Automation Project (TCAP), initiated in 2007,
is dedicated to creating and disseminating
computer-assisted, signal-processing-based tools
that support conservators and art historians
in their examination and analysis of fine art,
in particular paintings on canvas.

1 Background

Given over twenty years of technical advances in multispectral imaging of paintings, the accelerating digitization of these images in museum archives, and a growing emphasis on an archaeology of the object in art historical studies, the time is ripe for the development of digital signal processing tools in support of painting analysis from digitized images. In attempting to enter a nascent, cross-disciplinary field, our strategy was to seek problems the fundamental technical solutions for which are rather ordinary from a traditional basic research perspective. Such problems are typically bypassed by researchers seeking funding from the usual sources focused more on advances to technology and science than to the application. Thus, to help close this gap, we seek to develop compelling applications of basic signal processing to painting analysis as a method of accelerating the development of cross-disciplinary scholarly activity that will ultimately expose more fundamentally challenging tasks of high utility and bring major improvements to the practice of painting analysis and conservation.

For this plan, a target application should

(a) use data now at museums [thereby not requiring a new imaging device or a disruptive imaging campaign];

(b) be a widely performed, tedious task [where just stuffing the task onto the computer offers significant labor savings and documentation capabilities]; and

(c) have a basic solution apparent to an undergraduate engineer [so algorithm creation is a more likely-to-succeed development task than risky basic research] that can be explained to and operated by art historians.

The target application chosen by Professor Rick Johnson in 2007 was thread counting of canvas density from x-rays of paintings. At that time there were no automatic schemes or software tools for this application. Furthermore, among art historians, there was not a widely accepted, precise methodology regarding the procedure of data collection or the format of its archival recording. But, it is a skill for which (almost) all conservators of paintings have been trained.

Thread counting has a history of use for dating and attribution in studies of the paintings of the Dutch masters Rembrandt van Rijn (van de Wetering, *Rembrandt: The Painter at Work*, 1997) and Vincent van Gogh (Lister, Peres, and Fielding, "Tracing an Interaction: Supporting Evidence, Experimental Grounds" in *Van Gogh and Gaugin: The Studio of the South*, Druick and Zegers with Salvesen, 2001). In these studies, the average of counts of local density at various spots across the canvas of one painting is compared to the similar average for the canvas support of a separate painting as key evidence in claiming the two canvases are (or are not) from the same canvas roll. Such original proximity, when consistent with other evidence, can be used in conjunction with knowledge of the artist's studio practice to support precise claims regarding relative dating of the paintings.

These thread counts have traditionally been taken manually on (analog) x-rays with the aid of a magnifying eyepiece. X-rays are used because the original canvas can typically no longer be seen from the front or the back. The front is covered with paint. The back is usually covered with a newer supporting canvas glued to the back of the old one. Fortunately, from the 16th century on through the early twentieth century, canvas was typically prepared for painting by first applying a ground layer that commonly included radio-opaque material. This ground layer is thicker in the grooves between the individual threads. An x-ray will reveal these filled grooves as they pass less x-ray energy that exposes the x-ray film. The developed x-ray film is posted on a lightbox and a magnifying aid is used to enlarge a view where the variation in threads is illustrated with a periodic shift from dark to light and back. The variations are counted against a ruler inserted into the magnified view, and recorded in threads/centimeter. For a simple weave, the count (in threads/cm) of the (nearly) vertically oriented threads and the count of the (nearly) horizontal threads are recorded for each spot.

The tedium and time consumption of traditional "manual" thread counting are sufficiently substantial that most studies rely on averages from a relatively small number (less than a few dozen) of spot counts across the painting canvas. This makes this task ripe for the time-saving and documentation benefits of performing the "manual" count on the enlarged digital image on the computer screen. Then, once the image data is in the computer, the algorithmic tricks of signal processing can be applied to perform the thread counting automatically.

2 Exploiting Spectral Analysis

Indeed, extracting the frequency of a dominant periodic component in a signal measured in the presence of various other additive components is an applied mathematics task critical in a variety of engineering applications. The Fourier transform is a basic analytical tool for such frequency estimation tasks. In the summer of 2007, Professor Rick Johnson wrote a simple algorithm for computing thread density with a Fourier transform of intensity data from the scanned x-ray of a van Gogh painting.

This confirmation of concept was expanded into a competition among research teams at various universities for the best algorithms to count threads automatically in excerpts from scanned x-rays. Winners (from Rice University, University of Wisconsin-Madison, and Worcester Polytechnic Institute) were selected in summer 2008. The selection was made against a set of over 900 spot counts from scanned x-rays of over 20 Van Gogh paintings. These spot counts were performed by a student team at Cornell University supervised by Professor Rick Johnson using a crude graphical user interface developed (in Matlab, for easy connection to the candidate counting algorithms) at Cornell. The count at each spot in the test set was confirmed by two independent hand-counters. The best algorithms (with over 95% of counts within 1 th/cm of verified hand count) were then inserted in larger programs that can automatically count the average thread density and determine the average thread angle in 1 cm squares across the entire painting. As Professor Don Johnson's two-dimensional Fourier transform based scheme (described in Johnson, Johnson, Klein, Sethares, Lee, and Hendriks, "A Thread Counting Algorithm for Art Forensics," *Proc. 13th IEEE DSP Workshop*, Marco Island, FL, Janaury 2009) was the winner among fully automatic schemes, he was persuaded to join TCAP as co-director in 2009.

The data generated by such thorough coverage – with average thread counts determined within every small square across the entire surface of a painting – can be turned into color-coded maps of the thread density as it varies across the painting. The pattern of these variations can be used to identify neighbors on the original canvas roll (as described in Johnson, Hendriks, Noble, and Franken, "Advances in Computer-Assisted Canvas Examination: Thread counting algorithm", *37th Annual Meeting of American Institute for Conservation of Historic and Artistic Works*, Los Angeles, CA, May 2009).

The resulting first-generation software has been compiled for free distribution (along with a free training seminar) to conservators at museums and students and staff at graduate conservation programs (in the United States, the Netherlands, and England). This novel, pioneering effort to develop image analysis algorithms suited to the specific task of thread counting as part of an art historical examination of canvas supports of old masters paintings is representative of a nascent interdisciplinary effort between the engineering and applied mathematics of signal processing and art historical painting analysis described in Barni, Pelagotti, and Piva, "Image Processing for the Analysis and Conservation of Paintings: Opportunities and Challenges," *IEEE Signal Processing Magazine*, vol. 22, pp. 141-144, September 2005.

3 Major Projects

In coordination with a studio practice project underway at the Van Gogh Museum (`http://www3.vangoghmuseum.nl/vgm/index.jsp?page=13321&lang=en`), TCAP, in collaboration with Dr. Ella Hendriks (Head, Conservation Department, Van Gogh Museum), provided thread count reports during 2009 on all paintings by Vincent van Gogh in the collection of the Van Gogh Museum (a task beyond imagining with traditional manual count techniques). These reports include maps of thread density and angle for the horizontal and vertical threads and histograms of the thread densities in both directions in 1 cm squares on 0.5 cm centers across the painting surface. (A sample thread count report for "The Sheep Shearers" is attached as an appendix to this annual report.) This effort is being broadened to include similar thread count reports for other Van Gogh paintings from cooperative museums (including, so far, Kröller-Müller Museum, National Gallery - London, Cleveland Museum of Art, Phillips Collection, Art Institute of Chicago, Philadelphia Museum of Art, Museum of Modern Art, Harvard University (Fogg) Museum, Courtauld Institute Galleries, Stedelijk Museum, Detroit Institute of Arts, the Beyeler Institute, Musée d'Orsay, Museu de Arte de Sao Paulo, Princeton University Art Museum, Norton Simon Museum, Neue Pinakothek, E. G. Bührle Collection, and Wadsworth Atheneum). TCAP has counted over 200 van Gogh paintings in 2009, and has begun assembling a growing collection of sub-groups of rollmate candidates with "matching" patterns of varying local thread density. Identifying such sub-groups and interpreting their implications is expected to be a major activity for TCAP in 2010 and 2011.

All of this thread count data, and other data, such as ground materials assessment, critical to rollmate status evaluation, is to be archived by the end of 2010 in the studio practice project of the Van Gogh Museum. Beginning in 2011, the museum study staff will complete and examine this collection of data with specific attention to rollmate possibilities and dating issues. Preliminary results indicate that the automatically-generated expansive thread count data will advance the investigations in a variety of issues in van Gogh studies. Indeed, some parts of the general understanding of either Vincent's studio practice or the procedures followed by canvas manufacturers will require re-thinking to achieve consistency with the forensic data being generated.

In 2009, TCAP also initiated a similar effort for 17th century Dutch artists. In cooperation with Robert van Langh and Ige Verslype from the Rijksmuseum, Petria Noble at the Mauritshuis, and Michiel Franken of the Netherlands Institute for Art History (RKD), thread count reports were drafted for paintings by Rembrandt (connected to a pilot project funded by the Mellon Foundation `http://mac.mellon.org/issues-in-conservation-documentation`). The Metropolitan Museum of Art in New York City has since provided scans of x-rays of some of their Rembrandt paintings to this effort. The National Gallery of Art in Washington, DC is expected to join this effort in 2010. The Rembrandt paintings studied have quite substantial non-uniformity in the thread thickness (apparent in the x-rays). This challenged the robustness of our current algorithms. Two alternatives were pursued (and will be followed into 2010): (i) adding a pre-calculation triage component to our current scheme that removes examination squares with unreliable data from being counted and (ii) upgrading our algorithms to accommodate more weave non-uniformity.

Asked for a thread count report for "The Art of Painting" by Vermeer in the collection of the Kunsthisrisches Museum in Vienna, we discovered that this 17th century canvas showed weave and thread regularity similar to that observed in the 19th century canvases used by van Gogh. Thus, at the close of 2009, TCAP established a project with the goal of counting threads for all Vermeer paintings on canvas. Initially, scans of the x-rays of paintings by Vermeer in the collections of the Kunsthistorisches Museum, the Rijksmuseum, the Mauritshuis, the Metropolitan Museum of Art, and the National Gallery of Art in DC (which covers over a third of Vermeer's known oeuvre) are being sought before approaching further museums in 2010. The ultimate goal is to extend the study to Vermeer's 17th century contemporaries that used the same regularly woven canvas supports as did Vermeer.

During 2009, TCAP prepared thread count reports for paintings on canvas by Henri Matisse to be included in a forthcoming exhibition jointly created by the Art Institute of Chicago and the Museum of Modern Art in New York City. TCAP continues to provide thread count reports on a regular basis for Renoir and Monet paintings, for which an on-line catalog is being created by the Art Institute of Chicago.

4 Limited Investigations

Museums and galleries that contacted TCAP with requests on specific paintings to which TCAP responded with thread count reports in 2009 include:

- J. Paul Getty Museum (Los Angeles, CA): a painting by Guido Cagnacci
- Leiden Galleries (New York City): 2 paintings by Jan Lievens
- National Gallery of Art (Washington, DC): 4 paintings by Luis Meléndez
- Germanisches Nationalmuseum (Nürnberg, Germany): a painting by(?) Jan van Thielen
- Munch Museet (Oslo, Norway): a painting by Edvard Munch

5 Publications

Available at `http://people.ece.cornell.edu/johnson/` and/or
`http://www.ece.rice.edu/~dhj`.

- D. H. Johnson, C. R. Johnson, Jr., A. G. Klein, W. A. Sethares, H. Lee, and E. Hendriks, "A Thread Counting Algorithm for Art Forensics," *Proc. 13th IEEE DSP Workshop*, Marco Island, FL, January 2009.
- C. R. Johnson, Jr., E. Hendriks, P. Noble, and M. Franken, "Advances in Computer-Assisted Canvas examination: Thread counting algorithms," *37th Annual Meeting of American Institute for Conservation of Historic and Artistic Works*, Los Angeles, CA, May 2009.

6 Presentations

In September 2009, the TCAP co-directors along with their primary conservation collaborator Dr. Ella Hendriks (Van Gogh Museum) presented the first training workshop (at the Courtauld institute in London) for their current package of semi-automatic and fully automatic thread counting software (compiled from Matlab for Windows) to an audience of over 30. A forerunner was presented to University of Amsterdam conservation students and Rijksmuseum staff in March 2009 by Ella Hendriks, Petria Noble (Mauritshuis), Michiel Franken (RKD), and Rick Johnson that concluded with training in use of TCAP's semi-automatic thread counting software tool.

The TCAP co-directors gave a number of (unpublished) talks about TCAP efforts in 2009, including:

- **R. Johnson**, "Computer-assisted Thread Counting from Scanned X-rays," Museum of Modern Art, New York City, January 23, 2009.
- **D. Johnson**, R. Johnson, and E. Hendriks, "Computer Analysis of the Canvas Weaves of Vincent van Gogh's Paintings," EU-Artech Symposium: Van Gogh and Contemporaries, Amsterdam, the Netherlands, May 15, 2009.
- **R. Johnson**, "Engineering Painting Image Analysis: Automated Thread Counting," Art Conservation Department, Buffalo State SUNY, Buffalo, NY, April 10, 2009; Center for Interdisciplinary Science for Art, Architecture, and Archaeology, University of California, San Diego, CA May 18, 2009.
- **R. Johnson**, "Threads, Strokes and Other Numbers: Engineering Painting Analysis," Department of Electrical and Computer Engineering, University of California, Santa Barbara, May 19, 2009.
- **R. Johnson**, E. Hendriks, and D. Johnson, "Automated Thread Counting, Matching Weave Maps, and Rollmate Candidates in the Paintings of Vincent van Gogh," National Gallery of Art, Washington, DC, September 3, 2009; Center for Applied Mathematics, Cornell University, Ithaca, NY, Septemeber 25, 2009; Conservation Center, Institute for Fine Arts, New York University, New York City, NY, October 16, 2009.

- E. Hendriks, **R. Johnson**, and D. Johnson, "Automated Thread Counting from X-Rays of Canvas Supports," ICOM-CC Working Group Paintings, London, England, September 19, 2009.
- **R. Johnson**, E. Hendriks, and D. Johnson, "Counting Van Gogh," Workshop on Image Analysis Tools for Cultural Heritage, Tilburg University, Tilburg, the Netherlands, December 7, 2009.
- **D. Johnson**, "Signal Processing and Analyzing Works of Art," School of Engineering and Electronics, University of Edinburgh, December 17, 2009.

7 Personnel

Cornell University:

- Rick Johnson
- Selina Lok (spring '09)
- Peter Kung (spring '09)
- Ling-wei Lee (spring '09)
- Linda Zhang (spring '09)
- Michell Cho (spring '09)
- Naoto Hamashima (fall '09)
- Vikram Rao (fall '09)
- Harold Yang (fall '09)

Rice University:

- Don Johnson
- Lucia Sun

8 Principal Collaborators

- Ella Hendriks (Van Gogh Museum)
- Chris Stolwijk (Van Gogh Museum)
- Sjraar van Heugten (Van Gogh Museum)
- Louis van Tilborgh (Van Gogh Museum)
- Frans Stive (Van Gogh Museum)

- Muriel Geldof (Instituut Collectie Nederland)
- Petria Noble (Koninklijk Kabinet van Schilderijen Mauritshuis)
- Michiel Franken (Rijksbureau voor Kunsthistorische Documentatie)
- Ige Verslype (Rijksmuseum)
- Robert van Langh (Rijksmuseum)
- Elke Oberthaler (Kunsthistorisches Museum)
- Charlotte Hale (Metropolitan Museum of Art)
- Sarah Fisher (National Gallery of Art - DC)
- Ann Hoenigswald (National Gallery of Art - DC)
- Jim Coddington (Museum of Modern Art)
- Kristin Lister (Art Institute of Chicago)
- Frank Zuccari (Art Institute of Chicago)
- Inge Fielder (Art Institute of Chicago)
- Kelly Keegan (Art Institute of Chicago)
- Johanna Salvant (Centre de recherche et de restauration des musées de France)
- Michel Menu (Centre de recherche et de restauration des musées de France)
- Meta Chavannes (Kröller-Müller Museum)
- Luuk van der Loeff (Kröller-Müller Museum)

9 Appendix

A sample thread count report (for "The Sheep Shearers" by Vincent van Gogh) is appended to this document.

THREAD COUNT REPORT

The Sheep-Shearers (after Millet)

(F634 / JH1787 / S42)

from the van Gogh Museum

Presented by
VAN GOGH MUSEUM, AMSTERDAM
in collaboration with the
Thread Count Automation Project of
CORNELL UNIVERSITY and **RICE UNIVERSITY**

Prepared by: R. Johnson, E. Hendriks, and D. Johnson
June 2009

Summary

This report provides the canvas weave densities and local thread angle variations of "The Sheep-Shearers (after Millet)" (F634 / JH1787 / S42) by Vincent van Gogh held in the collection of the van Gogh Museum. Automatic counts were made from high resolution digital scans of x-rays (600 dpi, 1:1 with painting surface; 8-bit greyscale). These x-rays, at sufficient enlargement, expose the canvas weave to be in the "plain" category. Software automates the process of determining, across the entire scanned x-ray, the thread count of the canvas weave pattern in two directions (nearly vertical and nearly horizontal in the x-ray) and the angles of these threads referenced to true vertical and horizontal respectively. The thread-count processing software revealed the minimum (min), maximum (max), average (avg) and standard deviation (σ) of the thread counts and angles for the horizontal and vertical threads for the entire painting to be

F634	min	max	avg	σ
horizontal thread density (th/cm)	13.8	22.0	**18.0**	1.2
vertical thread density (th/cm)	10.8	12.0	**11.4**	0.2
horizontal thread angle (degrees)	-19.9	12.8	**-1.5**	1.2
vertical thread angle (degrees)	-12.7	1.8	**-1.4**	0.8

Using the criterion that the thread count having the smallest standard deviation corresponds to warp threads, calculations revealed that canvas warp corresponded to the vertical threads.

For each x-ray film covering the painting, this report provides a horizontal thread count map, a horizontal thread count deviation map, a vertical thread count map, a vertical thread count deviation map, a horizontal thread angle map, a vertical thread angle map, a histogram of horizontal and vertical thread counts and a table of minimum, maximum, average, and standard deviation of horizontal and vertical thread densities and angles. A table of contents occurs on page 3.

Acknowledgments: The thread counting software arose from a collaboration between the van Gogh Museum (Amsterdam) and the Thread Count Automation Project initiated by Professor Rick Johnson in the School of Electrical and Computer Engineering at Cornell University. The calculations were performed by Professor Don Johnson (Rice University) using the technique described in Johnson et al., "A Thread Counting Algorithm for Art Forensics," *Proc. 13th IEEE DSP Workshop*, January 2009. The software used here has been in development since 2007 in a collaboration among researchers B. Sethares, R. Arora, and H. Lee at the University of Wisconsin, A. Klein at Worcester Polytechnic Institute, D. Johnson at Rice University, and R. Johnson and J. Ng at Cornell University. A student team at Cornell (J. Ng, C. Cheung, M. Cho, P. Kung, S. Lok, B. Stubler, M. Wu, L. Zhang) plus a "corresponding" student at WPI (I. Ozil) are responsible for testing numerous early versions of the software suite and performing the manual counts used to assess the candidate thread counting algorithms. For more information on the software used, contact Professor Rick Johnson at `johnson@ece.cornell.edu` or Professor Don Johnson at `dhj@rice.edu`. The x-rays provided for algorithm development were selected by Dr. Ella Hendriks of the Van Gogh Museum and digitized by Frans Stive of the Van Gogh Museum by scanning them into 16-bit greyscale tiff files at high resolution (greater than 300 dpi, typically 600 dpi).

Introduction

This report provides a series of figures representing visualizations of various thread count and angle data for F634. The VISIBLE LIGHT color image was downloaded in jpeg format from the publicly accessible website `http://www.vggallery.com/`. All x-ray scans used in this report were provided at 600 dpi. The scans were then cropped in Photoshop by Professor Don Johnson (Rice University) to exclude portions of the x-ray outside the canvas. When scans included a portion of the canvas's front edge, it was used to align the corresponding edge of the cropped image, thereby enabling a consistent orientation of the cropped images with respect to the painting. The software processed the x-rays individually according to the following protocol.

- The DENSITY MAPS record the average thread densities (in threads/cm) computed in overlapping 1 cm squares on $1/2$ cm centers for each x-ray. The density at each location is indicated by a color. The axes on the density maps indicate the distance (in centimeters) from the origin in the upper left corner of the image. Two sets of illustrations for each scanned x-ray film are provided: one with a color bar of thread density values and the other with a color bar indicating deviation from the average density. Separate maps are provided for (near) horizontal and (near) vertical threads. A RANGE TABLE records the minimum, maximum, mean, and standard deviation over the set of averages computed for each 1 cm square. X-rays of canvas taken from the same roll should have a very close (within tenths of a thread/cm) match of average densities of threads in the warp direction and a close match (within ± 1 thread/cm) in the weft direction.

- The THREAD ANGLE MAPS indicate with color the values of the average thread angle (relative to horizontal and vertical alignment of the x-ray) in the 1 cm squares examined to compose the weave maps. The axes on the angle maps are marked with values in centimeters indicating the distance from the origin in the upper left corner of the image. Separate maps are provided for the (near) horizontal and (near) vertical threads. These angle maps vividly display cusping when present.

- The HISTOGRAM plots the number of evaluation squares having average densities within each range increment (of 0.1 th/cm) along the x-axis. This plot is useful for visualizing the distribution of the thread densities. Canvases from the same roll should have quite similar histograms in both directions. Often, the threads in the warp direction show less variability, i.e. a narrower distribution, in their count than the weft threads.

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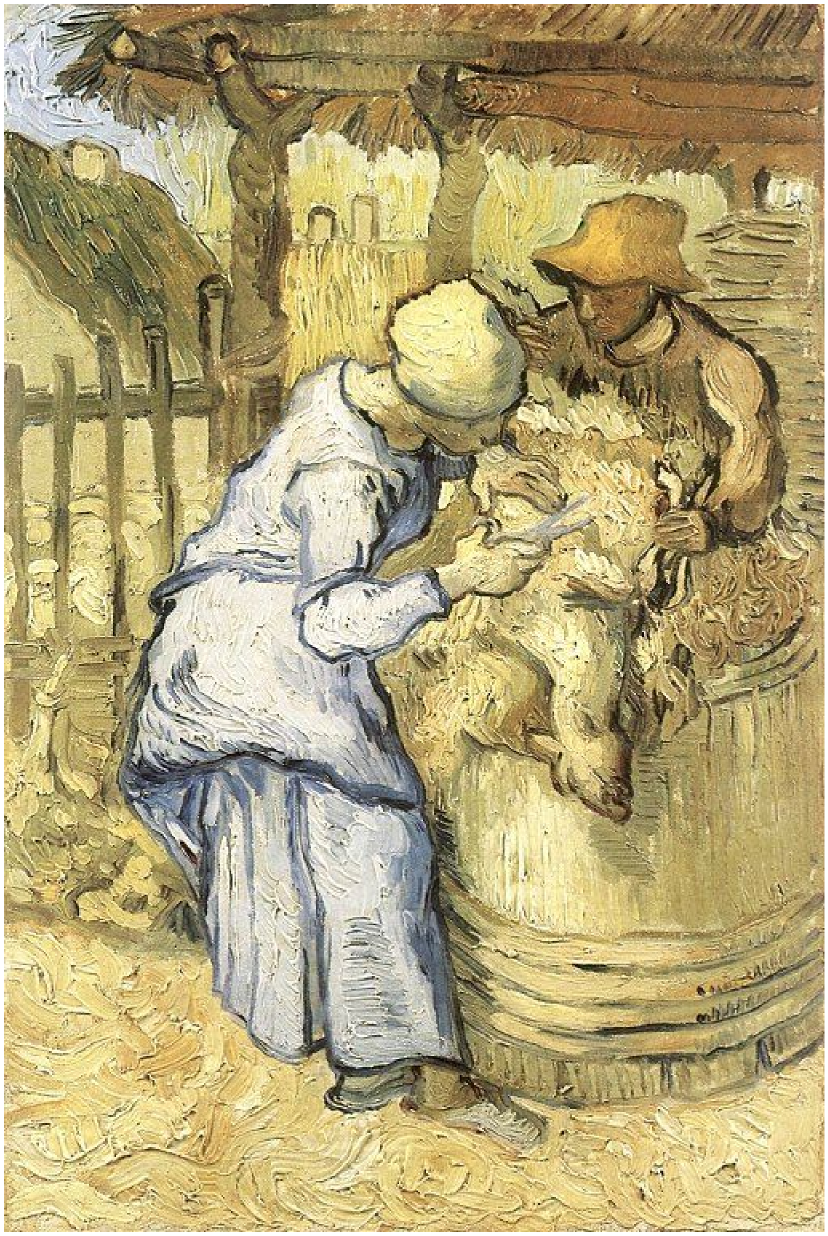
"The Sheep-Shearers (after Millet)" (F634 / JH1787 / S42)

[43.5 × 29.5 cm, 15.09.1889, van Gogh Museum]



X-Ray Layout

The following diagram depicts where the x-rays are with respect to the painting. X-ray size is to scale, as is the outline of the painting. However, the overlap of each x-ray with its neighbors is only approximate.

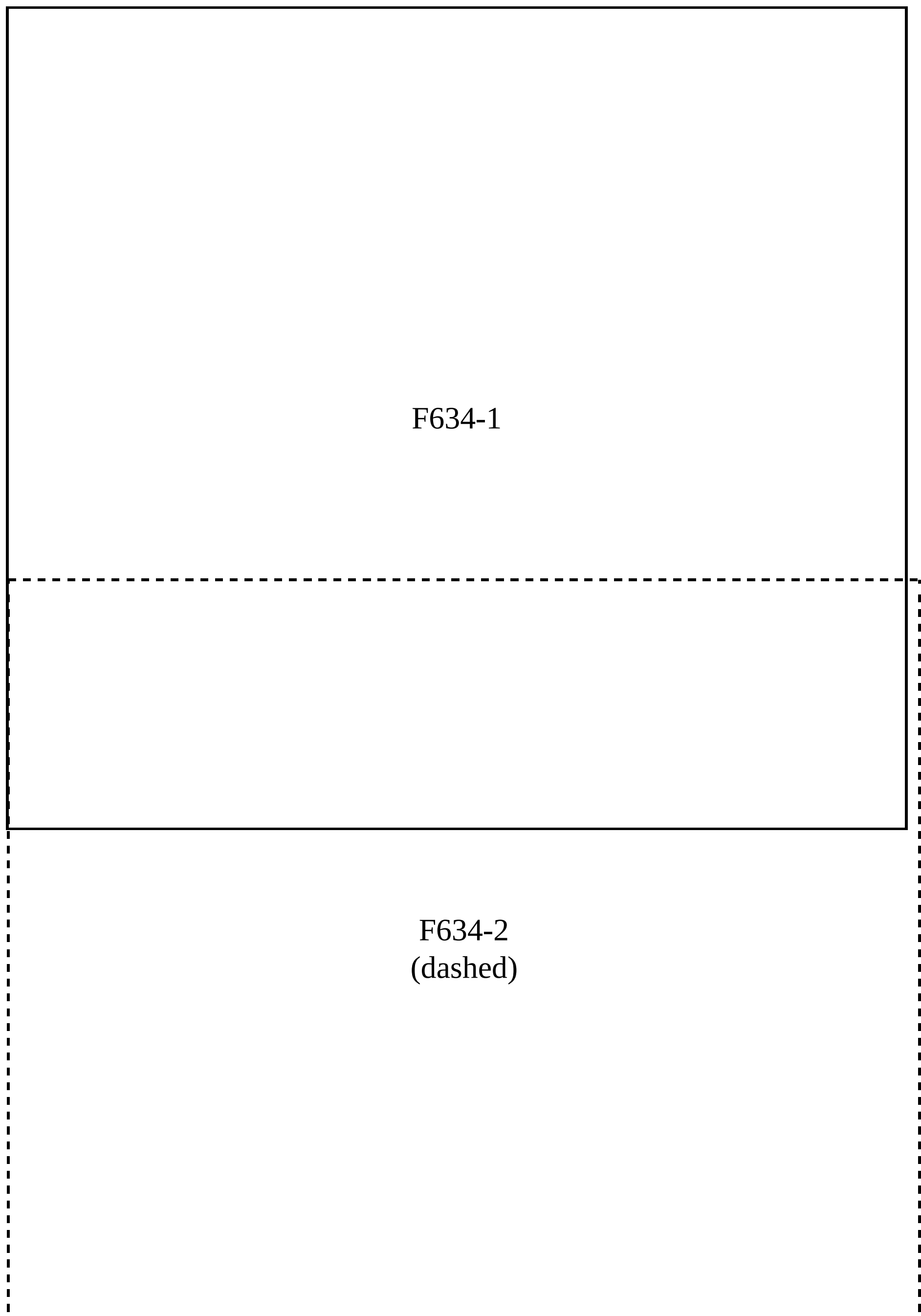


Figure 1: X-ray image: Film F634-1

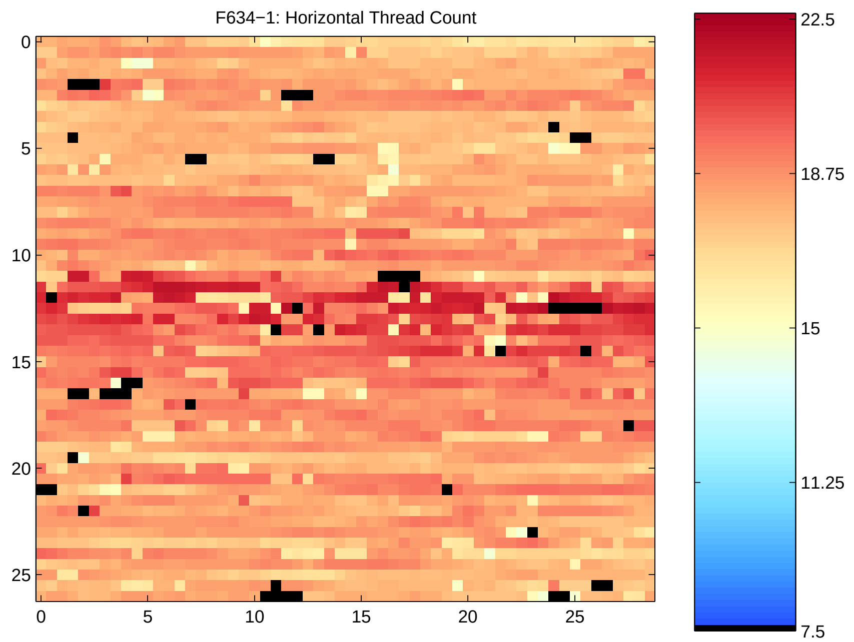


Figure 2: Density Map (Horizontal Threads): Film F634-1

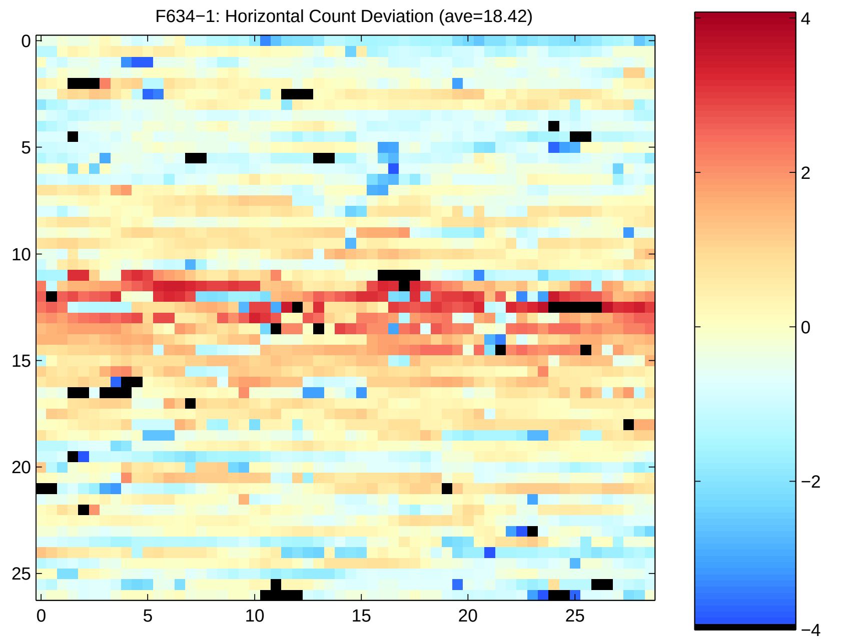


Figure 3: Density Deviation Map (Horizontal Threads): Film F634-1

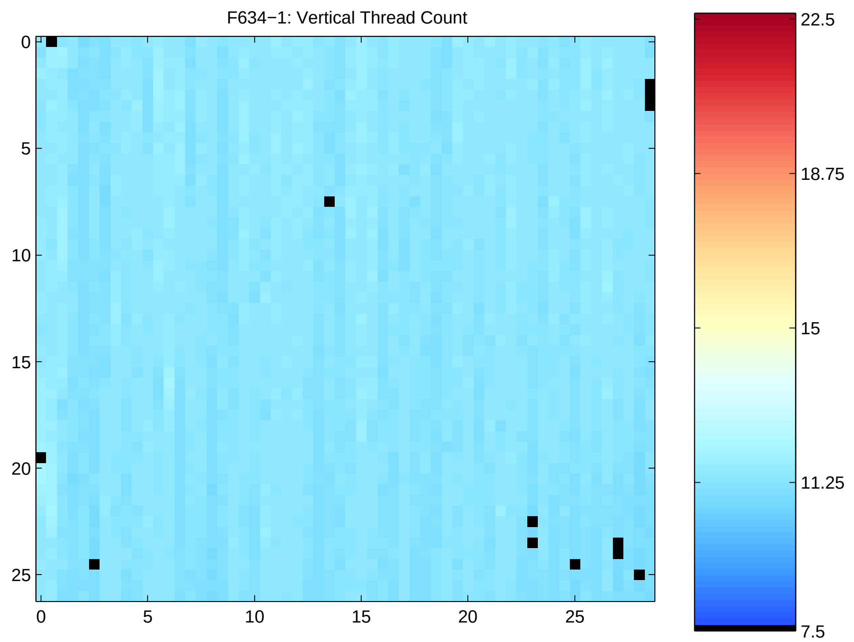


Figure 4: Density Map (Vertical Threads): Film F634-1

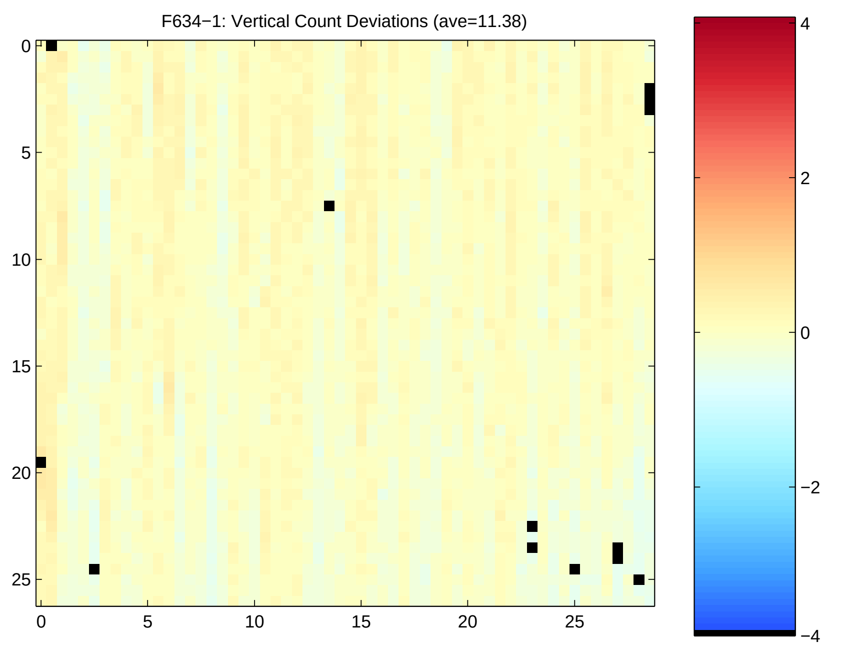


Figure 5: Density Deviation Map (Vertical Threads): Film F634-1

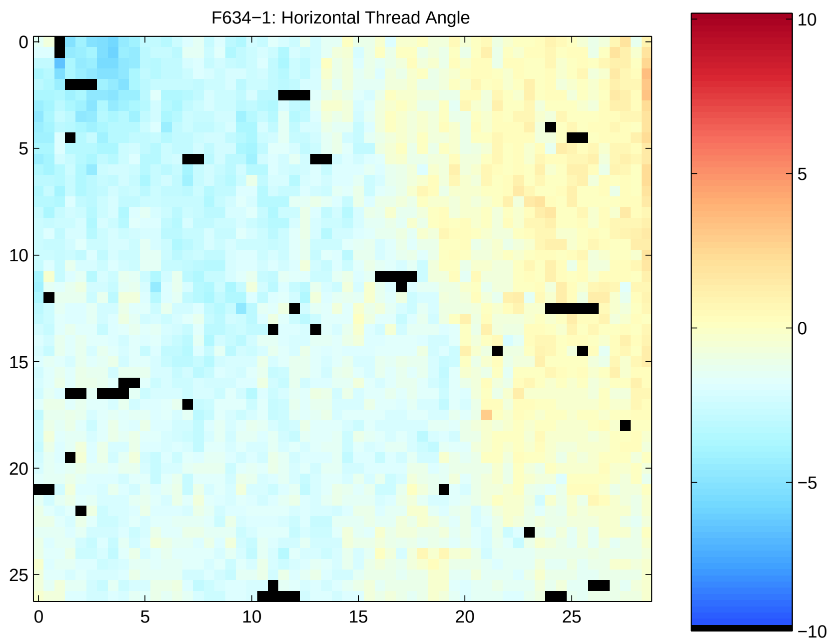


Figure 6: Angle Map (Horizontal Threads): Film F634-1

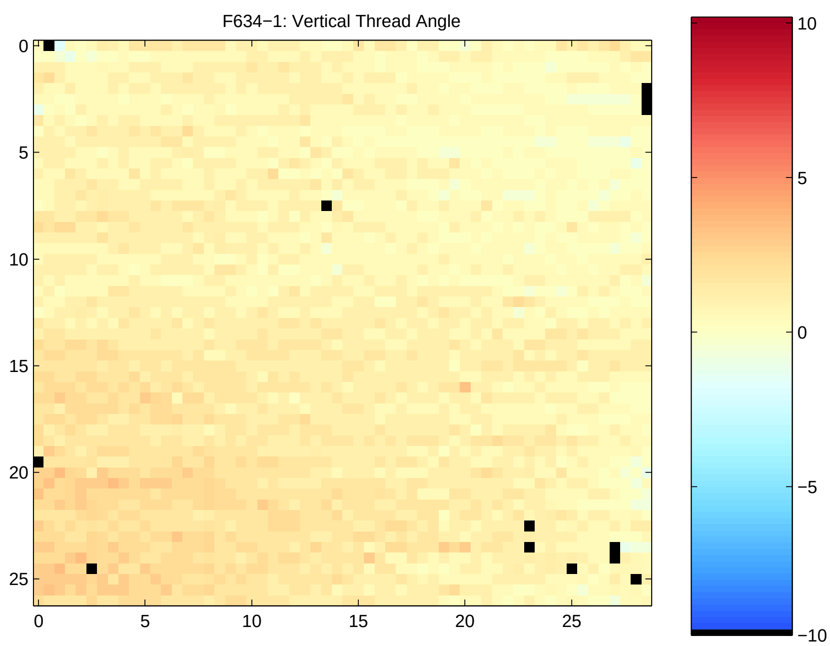


Figure 7: Angle Map (Vertical Threads): Film F634-1

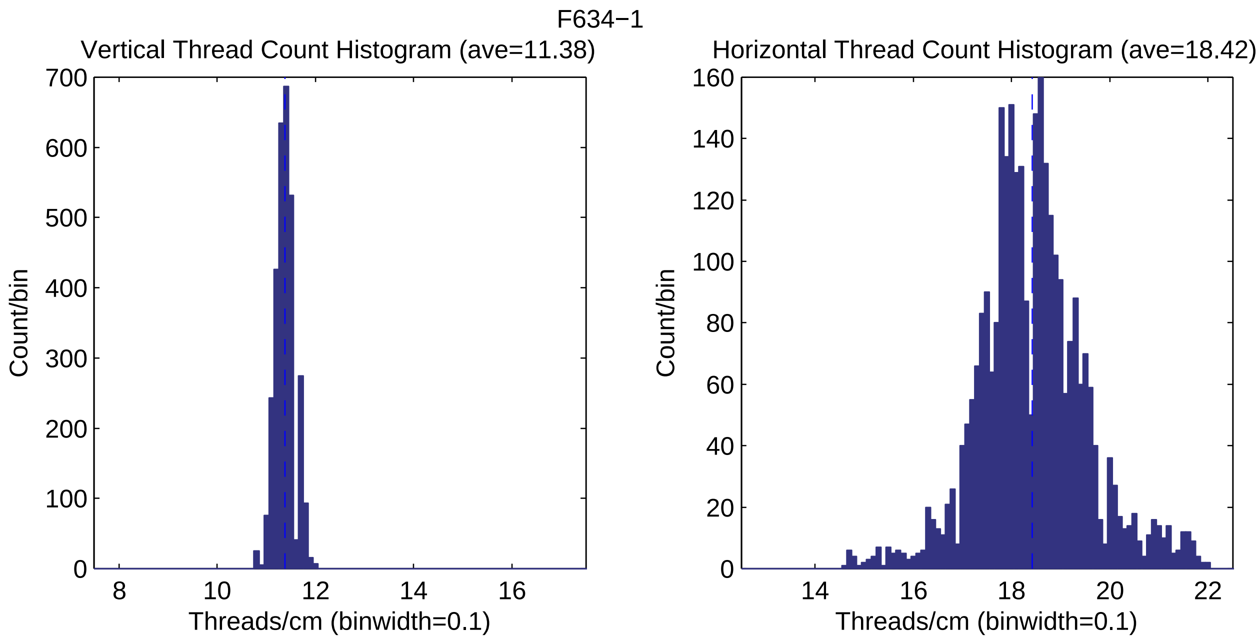


Figure 8: Thread density histograms: Film F634-1

F634-1	min	max	avg	σ
horizontal thread density (th/cm)	14.6	22.0	**18.4**	1.1
vertical thread density (th/cm)	10.8	12.0	**11.4**	0.2
horizontal thread angle (degrees)	-10.8	3.4	**-1.4**	1.3
vertical thread angle (degrees)	-3.5	1.8	**-1.0**	0.7

Table 2: Thread Counts and Angles: minimum, maximum, average, and standard deviation: F634-1

Figure 9: X-ray image: Film F634-2

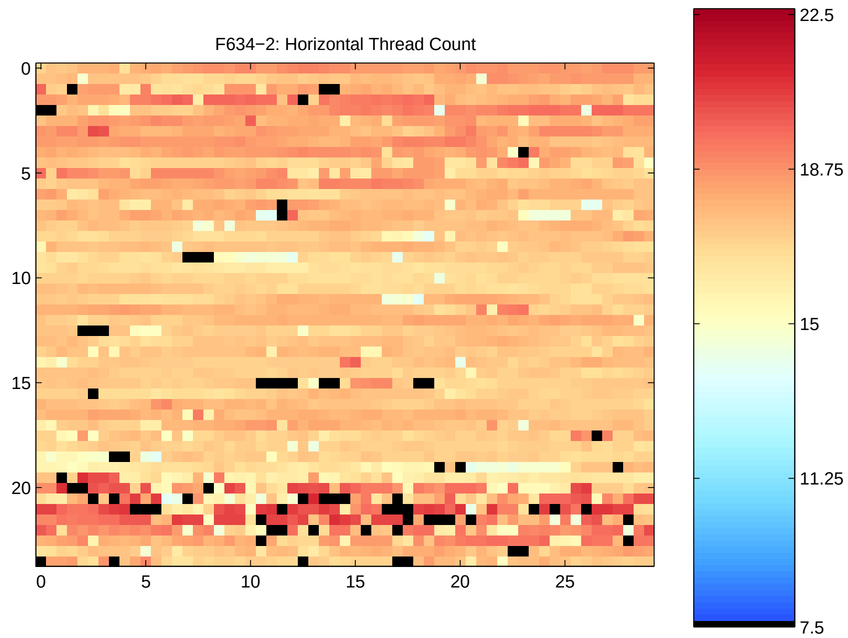


Figure 10: Density Map (Horizontal Threads): Film F634-2

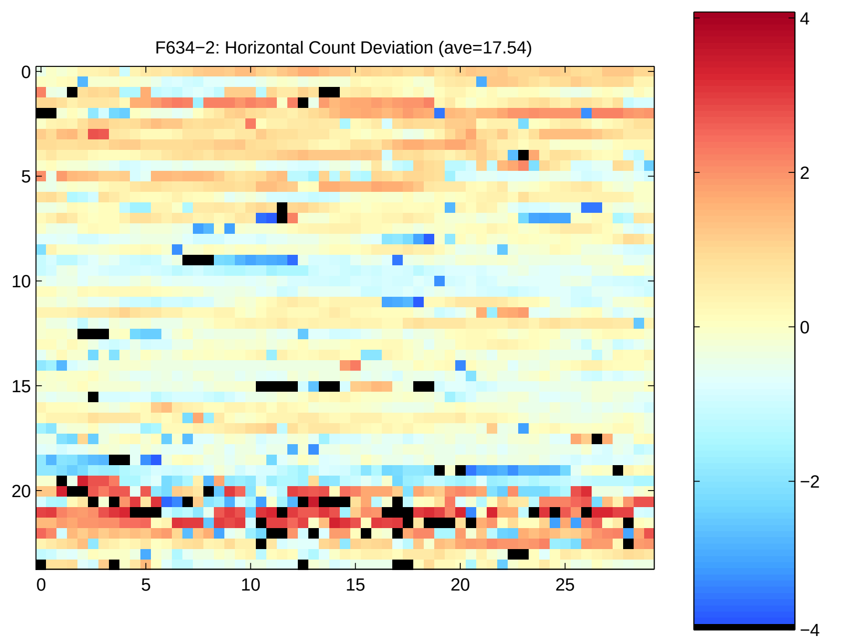


Figure 11: Density Deviation Map (Horizontal Threads): Film F634-2

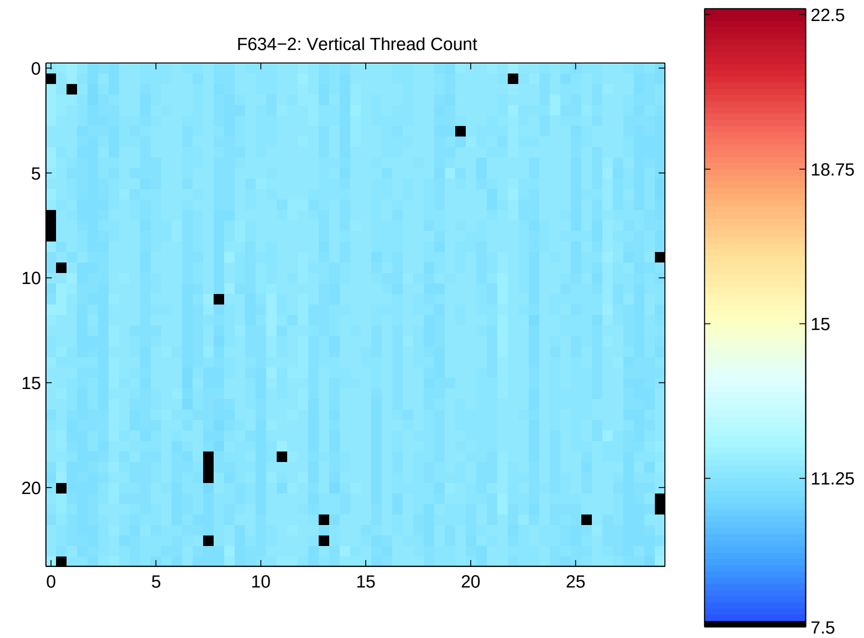


Figure 12: Density Map (Vertical Threads): Film F634-2

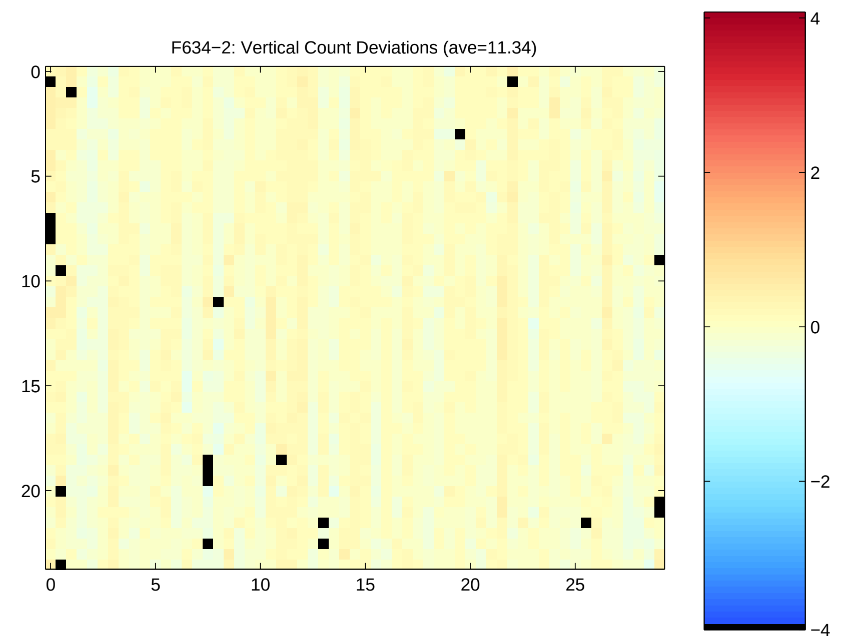


Figure 13: Density Deviation Map (Vertical Threads): Film F634-2

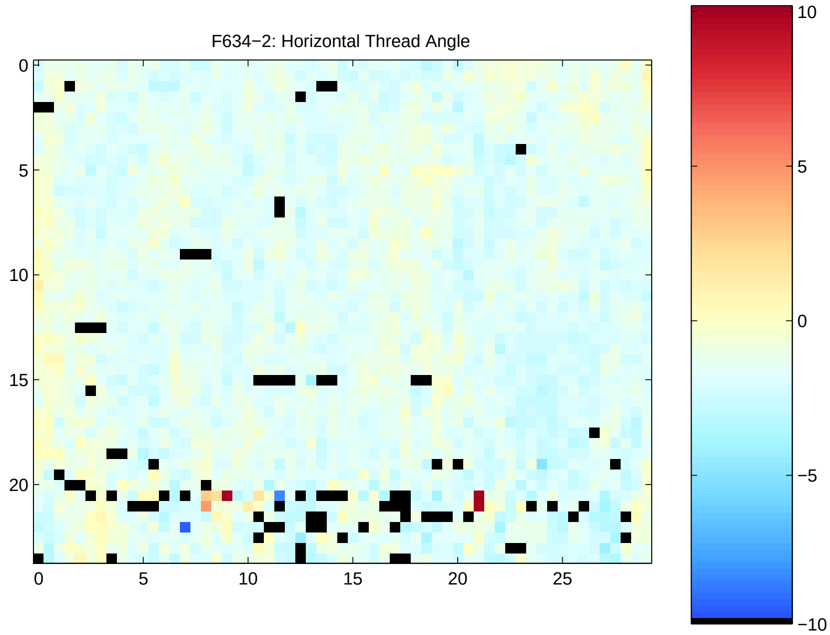


Figure 14: Angle Map (Horizontal Threads): Film F634-2

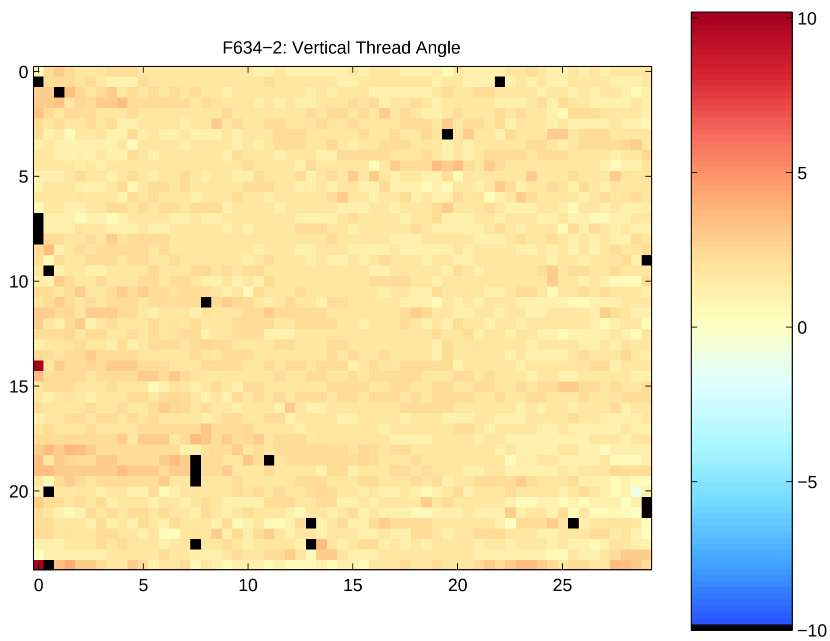


Figure 15: Angle Map (Vertical Threads): Film F634-2

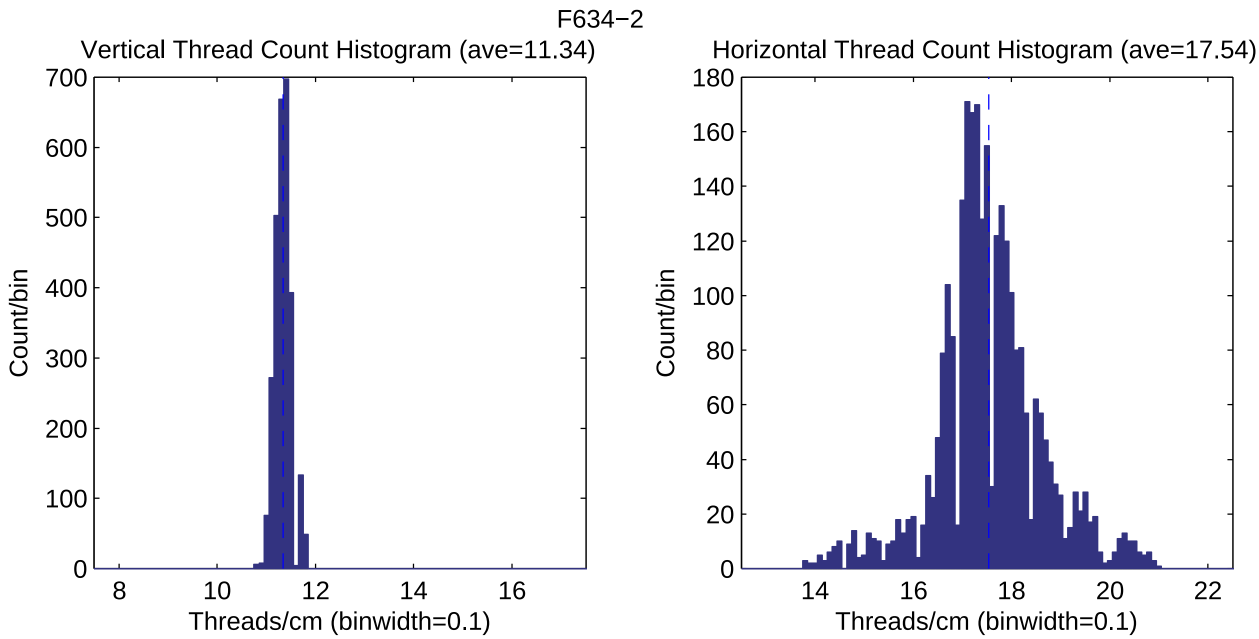


Figure 16: Thread density histograms: Film F634-2

F634-2	min	max	avg	σ
horizontal thread density (th/cm)	13.8	21.0	**17.5**	1.1
vertical thread density (th/cm)	10.8	11.8	**11.3**	0.2
horizontal thread angle (degrees)	-19.9	12.8	**-1.6**	1.2
vertical thread angle (degrees)	-12.7	1.2	**-1.8**	0.6

Table 3: Thread Counts and Angles: minimum, maximum, average, and standard deviation: F634-2