1983

Investigation of the radiometric integrity of the theogram after its raster scan lines are removed through spatial filtration

Joan Allamena

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INVESTIGATION OF THE RADIOMETRIC INTEGRITY OF
THE THEROGRAM AFTER ITS RASTER SCAN LINES
ARE REMOVED THROUGH SPATIAL FILTRATION

by

Joan A. Allamena

A thesis submitted in partial fulfillment
of the requirements for the degree of
Bachelor of Science in the School of
Photographic Arts and Sciences in the
College of Graphic Arts and Photography
of the Rochester Institute of Technology.

Signature of the Author.......................... Joan Allamena
Photographic Science and Instrumentation

Certified by........................................ Joseph D. Biejil
Thesis Advisor

Certified by........................................ Name Illegible
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Accepted by....................................... Ronald Frarini
Coordinator, Undergraduate Research
Title of Thesis: Investigation Of The Radiometric Integrity Of The Thermogram After Its Raster Scan Lines Are Removed Through Spatial Filtration.

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Date: ____________
INVESTIGATION OF THE RADIOMETRIC INTEGRITY OF
THE THERMOGRAM AFTER ITS RASTER SCAN LINES
ARE REMOVED THROUGH SPATIAL FILTRATION

by
Joan A. Allamena

Submitted to the
Phoptographic Science and Instrumentation Division
in partial fulfillment of the requirements
for the Bachelor of Science degree
at the Rochester Institute of Technology

ABSTRACT

Frequency content of the raster scan lines was removed
from the optical power spectrum of the thermogram by
spatial filtration. The back transform of the spectrum
resulted in a thermogram void of raster scan lines. A
linear relationship was established between the
densitometric characteristics of the filtered and
unfiltered thermogram. Within the scope of this
experiment, the radiometric integrity of the thermogram was
preserved.
ACKNOWLEDGMENTS

The author would like to thank Mr. Joseph Biegel for his guidance and patience throughout this thesis experiment, helping to improve the quality of this thesis. Thank you to Dr. Schott for his advice in several areas of the project.

Thanks to John D., Jim F., and John S. for their technical and moral support.

The author’s highest level of thanks goes to her family and to Charles Mondello and his family for their endless encouragement and support.

The author would especially like to give thanks to God, for without His presence it would not have been possible.
DEDICATION

The author would like to dedicate this work to her Mother, the one who encouraged her from the very start of life. Thank you for always being there and for your unfailing love and strength.
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INTRODUCTION

Thermograms are records of density levels which correspond to apparent temperatures. The process of thermographic imaging is based on Plank's law which relates temperature to radiance. It begins with the collection of quantum energy which is then converted to voltage. The voltage powers a light source to expose the recording material of the thermogram. Atmospheric effects must also be taken into consideration. The relationship which takes all variables into account can be found in appendix A.

The relationship between thermogram density and radiance is applicable for use in the field of energy conservation. Large data sets can be taken by an airborne imaging system in a very short time. One such use for aerial thermography is in the assessment of heat-loss levels for residential and commercial roof surfaces. A thermogram is made up of a series of adjacent lines of imaged information. The gap between the lines of information are raster scan lines.

When densitometric data is collected from a thermogram, the scan lines are integrated into the results. If the raster scan lines were removed, the precision of densitometric data acquisition from the thermogram could be increased. The quality of the image also would increase because there would no longer be lines going through the imagery. A continuous image is much more desirable by the
consumer than a segmented one. The removal of the scan lines would only be beneficial if the radiometric integrity of the thermogram was preserved.

By comparing the densitometric characteristics of a thermogram void of scan lines to that of its reconstructed original, the preservation of the radiometric integrity is investigated.

The process of making an aerial thermogram begins when a photon detector located in an aircraft is directed towards the ground and detects radiation. The detector converts incoming energy into a proportional electric signal which is amplified and recorded on electromagnetic tape or photographic film. The processing of the film results in a thermographic image which displays the radiant "heat" energy as shades of grey. Thermograms do not directly display heat loss or temperature, but are records of density levels which correspond to radiance levels. They represent only surface or near surface radiance conditions. The 8-14 micron (um) spectral region is used because it is the area of peak radiation for a 300° kelvin blackbody. 300° kelvin is the temperature of most earth surfaces. This region is also an effective atmospheric window.

Thermograms were first used in 1956 in the health science field. In the early 1970's, thermography began to play a part in energy conservation. It was a rapid and
relatively inexpensive method to collect and analyze thermal data. Aerial thermal imaging surveys began in the mid-1970's. Paljak and Petterson\textsuperscript{7} published the first comprehensive manual describing the theory and techniques of an infrared imaging system in 1972.\textsuperscript{8} In 1978, the United States Department of Energy sponsored Dick and Schmer\textsuperscript{9} to author a "how to" manual of the technical information on the use of aerial infrared scanning systems. This was done to condense all information up to this point on the subject and to arouse the interest of potential users.\textsuperscript{10}

The photon detector used to make the thermograms of this experiment has a video signal output. The output voltage level is proportional to the amount of energy received. The video signal is amplified and used to modulate the intensity of a glow modulator tube. The output of the tube is projected onto a 120° scanning mirror that sweeps the image onto the film. As the film and aircraft advance simultaneously, a new line of data is swept on the film adjacent to the previous one. The raster scan line resulting is that area void of information between two adjacent raster lines.

A step wedge can be used to establish the relationship between thermogram density and photon detector voltage. The step wedge used in this experiment was produced by
inputing a particular voltage into the glow modulator tube and sweeping the image onto the film.

To use the thermogram for temperature analysis, the density value on the film must be converted to a radiometric value. The density is related to the photon detector voltage, which is then related to apparent temperature. The system gain is defined as the change in voltage associated with unit change in temperature.\(^1\)

To associate the system gain to the apparent temperature, the blackbody temperature must be calibrated. The scanner is allowed to view two temperature controlled standards and the blackbody. The corresponding film densities are then converted to voltage using the related density-voltage curve. Since the system's temperature response is linear with voltage and since two temperatures are known, it is possible to calculate the internal blackbody temperature. For proper calibration, corrections for emissivity must be made. Emissivity is the ratio of the energy radiated from a source to the energy radiated from a blackbody at the same temperature. The complete blackbody calibration is accomplished by plotting the control setting versus the calibration temperature for the range of temperatures of interest.\(^2\)

To regroup the information contained in the thermogram according to frequency and energy distribution, a simple diffraction pattern can be used. The diffraction pattern
also contains information such as the amplitudes of each of
the frequency components of the given wavefront. This
information is called the fourier transform of the object.
The diffraction pattern is sometimes called a power
spectrum because if the intensity integrated over a
specific area increases, the energy contained in the image
increases.\(^{13}\) If one is interested in filtering specific
frequency information or in altering the frequency spectrum
of the image, spatial filtration is performed. The
frequency of an object's component is proportional to the
distance from the central (zero order) of the power
spectrum to its node of equivalent frequency. D. Ansley
and W. Blikken\(^ {14}\), of the Conduction Corporation and
N.A.S.A., used spatial filtration to piece together a Lunar
Orbiter composite photo made up of several strips of film.

The Abbe-Porter experiment\(^ {15}\) is an excellent example
of the methodology of spatial filtration. See figure 1,
below for the image elements of the experiment.

\[\text{object} \quad \text{lens} \quad \text{focal plane} \quad \text{image}\]

Figure 1. The Abbe-Porter experiment.\(^ {16}\)
The components of the object are separated according to frequency. This reorganization of information is done by illuminating the object onto the lens which focuses the image's fourier transform on its back focal plane. The lens brings the diffraction pattern in from infinity.

The Abbe-Porter experiment visually shows the relationship between imagery and its power spectrum. It relates the horizontal components seen in the image to the vertical components of the transform plane. The mathematical representation of this experiment is the following:

Rules of fourier transform mathematics:
\[ f(x) \ast g(x) \rightarrow F(f) G(f) \quad \text{if} \quad f(x) \rightarrow F(f), \text{and} \]
\[ \text{convolution} \quad \text{transform} \quad g(x) \rightarrow G(f) \]

In one dimension, the vertical component of the mesh is:
\[ \text{comb}(x) \ast \text{rect}(x) \rightarrow \text{Comb}(f) \text{Sinc}(f) \]
\[ \quad \text{since} \quad \text{comb}(x) \rightarrow \text{Comb}(f), \text{and} \]
\[ \quad \text{rect}(x) \rightarrow \text{Sinc}(f) \]

\text{Comb}(f) \text{Sinc}(f)\) represents the amplitude of the frequency components of the object. The eye views power which is the autocorrelation of the amplitude function. If a function is symmetrical about the y-axis, power is the square of the function, \(\text{Comb}(f) \text{Sinc}^2(f)\) in this example. The final spectrum in one and two dimension looks like:
To filter out one set of components, a filter is needed to block out all but the dc term in that direction. An opaque image of the $\text{Sinc}^2(f)$ function would work well.
To quantify the effect of the raster scan line on the integrity of the radiometric characteristics of a thermogram, the raster scan lines must be filtered from the thermogram. The components of the thermogram can be separated according to frequency through the use of Fourier optics. As demonstrated in the Abbe-Porter experiment, components of different frequency and placement can be separated. The Abbe-Porter experiment used a grid pattered mesh composed of horizontal and vertical elements. The vertical components are related to the raster scan lines of the thermogram. Knowing the transform of the vertical pattern, the structure of the scan line's spectrum can be approximated. The mathematical representation of this filtration is the following:

If a raster scan line is depicted by:
$$\text{comb}(x/b) \cdot \text{rect}(x/b)$$

where \( b = \) scan line width, the power spectrum seen by the eye:
$$b^2 \text{comb}(b) \sin c^2(b) \quad b = 0.085\text{mm}$$

for imagery used. See figure 4 for diagram of power spectrum, where shaded areas represent the area to be filtered.

$$F(\xi) = b^2 \text{comb}(b) \sin c^2(b)$$

Figure 3. Scan line power spectrum and filter.
Densitometric analysis of specific sites on the recorded reconstructed original and on the improved thermogram will, after statistical examination, determine if radiometric integrity of the enhanced product has been perserved.
EXPERIMENTAL

The raster scan line was characterized with a microdensitometer to learn its period, frequency, image width, artifact width, maximum density, and minimum density. A frequency histogram of the densities was prepared.

The Abbe-Porter experiment was performed to become familiar with the relationship between imagery and its power spectrum. The optical apparatus was set up as shown in figure 4. Records of the reconstructed imagery were made.

Using the principles of fourier optics demonstrated in the Abbe-Porter experiment, filtration of raster scan lines from a thermogram was attempted. An enlarged power spectrum was recorded for insight into the structure to be filtered. An ideal filter to remove the raster scan lines of the thermogram would be a sinc²(x) function for x greater than π/L, where L is equal to scan line width. Three filter designs were tested for best approximation of the ideal filter.

Densitometric analysis of specific sites on the reconstructed unfiltered and filtered imagery was performed using a 1 millimeter (mm) aperture macrodensitometer. A 1mm aperture will integrate over approximately five raster line cycles on the magnified final image product. The densitometric data was statistically analyzed using a
linear regression and a test for lack of fit. The regression used the densities of the filtered thermogram as the independent variable on which to base a model. This model attempts to explain the variance of the dependent variable which is the density of the unfiltered thermogram.17

The preservation of the radiometric integrity of the thermogram, after its raster scan lines have been spatially filtered was based on the statistical analysis performed.

![Diagram of experimental setup](Image)

The purpose of each piece of apparatus is:

- **pin hole** - decreases size of illuminating beam
- **lens 1** - to expand beam
- **aperture** - to collimate light
- **object** - to be transformed and studied
- **lens 2** - brings power spectrum into focus
- **filter** - located in transform plane, blocks frequency information
- **image** - back transform of frequency components, final image used in densitometric comparison

Figure 4. Set up for optical apparatus.
RESULTS

The raster scan lines of a sample of imagery was characterized using the Ansco Automatic Recording Microdensitometer, Model 4. The density range of the raster line cycle was found to be 0.339, and its minimum diffuse density was found to be 1.878. The width of the image was 0.0293 mm. The width of the artifact was 0.0303 mm. No significant difference was found between the image width and the scan line width.

The Abbe-Porter experiment was successfully simulated using a wire mesh. Figure 5 shows the transmitted spectrum when a vertical slit is used. The corresponding reconstructed image contains only the horizontal structure of the mesh. When a horizontal slit is placed in the transform plane, the image contains only the vertical structure of the mesh.

The raster scan lines of the thermogram are vertical artifact. Figure 6 shows a sample of thermal imagery. Figure 7 shows the actual aerial thermogram used. To remove the scan lines, a horizontal filter was made. The first filter tested was a vertical slit with movable jaws. This filter took too much information out of the reconstructed image. A closer look at the thermograms power spectrum was necessary.
Figure 5. Results of the Abbe-Porter experiment.
Figure 6. Raster scan lines.
Figure 7. Results of imagery manipulation.
The next filter to be tested was a horizontal line of 0.5 mm graphic tape placed on a glass slide. The line had a 1 mm break at its center. The design of the filter was correct but the construction was faulty. The glass diffracted some of the frequency information of the spectrum. The last filter made consisted of two straight pins coated with india ink to minimize reflectance. The pins were placed point to point in the horizontal plane perpendicular to the optical axis. The filter passed through the center of the power spectrum, leaving a 1 mm gap between the points of the pins. The gap allows the transmission of the dc term of the spectrum which is where most of the image's energy is located. The artifact was filtered from the imagery along with fine detail information. Proper alignment of this and all filters was critical. This imagery was the best of the experiment and possibly the limit of this apparatus and filter design.

To study the radiometric intensity of the filtered versus unfiltered imagery, the densities of corresponding areas of the reconstructed imagery were compared. (See appendix B for the densitometric values of the imagery.) A linear regression as described in part two of this experiment, was performed on the data. The correlation coefficient for this set of results was 0.997. The standard deviation for the model was 0.035. (See appendix C for analysis.) The test for lack of fit was not significant at
a confidence level of 95%. This test result means that "there is no reason to doubt the adequacy of the model." ¹⁸

As a representation of the difference between the model and actual densities of the unfiltered reconstruction. The residual plot of the experimental data is shown in figure 8. From the groupings of data on the plot, it is shown that a wider range of object densities should have been used. By increasing the range of densities, the fit of the linear regression would have been more meaningful.

The results of the repeatability data set (see appendix D) had a correlation coefficient of 0.9988, and a standard deviation of 0.058. The test for lack of fit was not significant. (See appendix E for analysis of repeatability data.)
Residual plot of experimental data.

Density of unfiltered thermogram.
DISCUSSION

The simulation of the Abbe-Porter experiment strongly showed the relationship between an image and its Fourier transform or frequency components. This experiment gave insight into the concept of spatial filtration.

Spatial filtration of the raster scan lines from the thermogram was not quite as simple as the Abbe-Porter experiment. A thermogram contains more components than the two component mesh of the Abbe-Porter experiment. The primary problem with the first filter was that it was eliminating too much high frequency information and a portion of the dc term. High frequency information is recognizable by the sharpness of image edges. By taking a closer look at the power spectrum of the imagery, the author realized the importance of the information around the dc term. This information represents the random features of the imagery, such as agriculture. Internal reflection from the optical equipment became evident in the power spectrum plane.

Loss of high frequency information was also caused by the glass filter. The glass mount was believed to cause the root of the problem. Diffraction and reflection of the light may have caused the loss of high frequency information.

To resolve this problem of high frequency information loss, a pin filter was constructed. The images produced
were good compared to the others produced. In a subjective comparison of an enlargement of the original thermogram to the filtered thermogram, much detail has been lost. The roads of the filtered imagery have lost their sharpness as did the water tanks. It also appears that the raster scan lines were removed but information necessary for good image quality was also filtered out.

To determine the results of this experiment, the model was investigated. The linear regression performed on the densities of the filtered and unfiltered imagery was significant, and the test for lack of fit supported this model. The density of the unfiltered imagery can be predicted, knowing the density of the filtered because of their linear relationship. With a correlation coefficient of 0.997, it can be concluded that the radiometric characteristics of the reconstructed thermograms was linear. The density of each of the sites on the different imagery was within 0.05 neutral density units. This change in density is related to approximately a $0.67^\circ$C change in temperature.
CONCLUSION

The objective of this experiment was to determine if the radiometric characteristics of the thermogram were preserved when its raster scan lines are removed through spatial filtration. The regression model demonstrates that there is a linear relationship between the density of the filtered and unfiltered imagery. The radiometric integrity of the thermogram can be measured. Within the scope of this experiment, the radiometric integrity of the thermogram was preserved.

The accuracy of the results and limitation of image degradation could be increased by the improvement of the optical apparatus quality, the accuracy of densitometric data collection, and the filter construction.
REFERENCES


2. Ibid., p. 6.

3. Ibid., p. 4.


17. Schott, J. R., E. P. Wilkinson, J. D. Biegel, "Aerial


BIBLIOGRAPHY


APPENDIX A. Blackbody emittance associated with temperature.

\[ W(t) = (W - W(a) - (1-E)t F W(s) - t(1-E)(1-F) W(b))/t E \]

where: \( W(t) = 2 \pi h \frac{c^2}{\lambda^5} \left( e^{hc/\lambda kT} - 1 \right)^{-1} d\lambda \) is the observed blackbody emittance associated with an object with a kinetic temperature \( T \).

where:

- \( h \) = Plank's constant
- \( k \) = Boltzmann's constant
- \( c \) = speed of light
- \( \lambda \) = wavelength
- \( W \) = irradiance sensed by the line scanner associated with a brightness value on the recorded image
- \( W(a) \) = irradiance on the sensor associated with the atmospheric path radiance
- \( t \) = atmospheric transmittance
- \( E \) = object emissivity
- \( F \) = fraction of the incident radiance on the target coming from the sky
- \( W(s) \) = irradiance from the sky incident on the target
- \( W(b) \) = irradiance from the background objects other than the sky incident on the target.
APPENDIX B. Experimental data

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Each set of data pertains to a particular site on the imagery.
APPENDIX  C. Analysis of experimental data.

All point linear regression:  
\[ b, \text{slope} = 1.1248 \]  
\[ Y_{\text{inter.}} = -.1926 \]  
\[ R^2 = 0.9972 \]  
\[ s, \text{st.dev.} = 0.0348 \]

Test for lack of fit:  

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<td>2.06</td>
<td>2.06</td>
<td></td>
</tr>
<tr>
<td>Res.</td>
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<td>.075</td>
<td>.0012</td>
<td>17.17</td>
</tr>
<tr>
<td>LoF</td>
<td>32</td>
<td>.043</td>
<td>.0014</td>
<td></td>
</tr>
<tr>
<td>P.E.</td>
<td>30</td>
<td>.031</td>
<td>.0010</td>
<td>1.40</td>
</tr>
</tbody>
</table>

F regression at 95% confidence:  
\[ F_{\text{calc.}} = 17.17 \]  
\[ F_{\text{crit.}} = 4.0 \]  
therefore, the Ho hypothesis that the regression is not significant is rejected.

95% confidence limits for:  
\[ b = 1.125 \pm 0.054 \]  
\[ Y = -0.193 \pm 0.0887 \]  
\[ \text{point} = \text{pt.} \pm 1.96s \]

Lack of fit test at 95% confidence:  
\[ F_{\text{calc.}} = 1.40 \]  
\[ F_{\text{crit.}} = 1.84 \]  
therefore, the model is assumed to be adequate.
APPENDIX D. Repeatability data.

<table>
<thead>
<tr>
<th>density of filtered</th>
<th>density of unfiltered</th>
<th>density of filtered</th>
<th>density of unfiltered</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.79</td>
<td>0.93</td>
<td>1.28</td>
<td>1.38</td>
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<tr>
<td>0.87</td>
<td>0.93</td>
<td>1.36</td>
<td>1.41</td>
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<td>set #1 0.85</td>
<td>0.91</td>
<td>set #4 1.34</td>
<td>1.40</td>
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<tr>
<td>0.82</td>
<td>0.92</td>
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<td>1.37</td>
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<tr>
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<td>1.29</td>
<td>1.40</td>
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<tr>
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<td>1.46</td>
<td>1.51</td>
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<tr>
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<td>set #5 1.47</td>
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<td>1.00</td>
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<td>1.53</td>
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</tr>
<tr>
<td>1.19</td>
<td>1.28</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Each set of data pertains to a particular site on the imagery.
APPENDIX E. Analysis of repeatability data.

All point linear regression:
- \( b, \text{slope} = 0.884 \)
- \( Y_{\text{inter.}} = 0.216 \)
- \( R^2 = 0.998 \)
- \( \text{s, st.dev.} = 0.058 \)

Test for lack of fit:
- Source df SS MS F
  - Reg. 1 0.97 0.97
  - Res. 23 0.07 3.32 290.
- LoF 1 F calc = 1529
- F crit = 1.72

95% confidence intervals for:
- \( b = 0.884 \pm 0.11 \)
- \( Y = 0.216 \pm 0.127 \)
- \( \text{point} = \text{pt.} \pm 1.96s \)

The slope and intercept of the repeatability data is different from that of the experimental data. The variability is due to the changes in collection of the radiometric data, film exposure, and film processing.
VITA

The author was born in Albany, New York. While attending the Albany Academy for Girls, she became interested in photography. Upon graduation, she wished to pursue an education in engineering and photography. She spent two years in the optical engineering program at the University of Rochester before transferring into the Photographic Science and Instrumentation program at the Rochester Institute of Technology. Since that time, she has spent one summer working for the U.S. Central Intelligence Agency.