Multispectral Image (MSI) Processing for Cultural Heritage
(Examples, with some comments on imaging)

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Use Electromagnetic Radiation ("Light") to "Probe" Material Properties

- X rays ($\lambda \ll 200\text{nm}$, very large energies)
- Ultraviolet ($200\text{nm} \leq \lambda \leq 400\text{nm}$)
  - Stimulates fluorescence
- Visible Light ($400\text{nm} \leq \lambda \leq 700\text{nm}$)
- Near Infrared ($700\text{nm} \leq \lambda \leq 1100\text{nm}$)
  - "sees through" charring damage
- "Mid Infrared" ($3\text{\mu m} \leq \lambda \leq 5\text{\mu m}$)
- "Thermal Infrared" ($8\text{\mu m} \leq \lambda \leq 14\text{\mu m}$)
- "Submillimeter" or "Terahertz" ($100\text{\mu m} \leq \lambda \leq 1\text{mm} \Rightarrow 0.3 \times 10^{12} \text{ Hz} \leq \nu \leq 3 \times 10^{12} \text{ Hz}$)
- Radio wavelengths ($1\text{mm} \leq \lambda, \nu \leq 300 \times 10^9 \text{ Hz} = 0.3 \text{ THz}$)
Background Physics:

- Useful information about object is conveyed by both “visible” and “invisible” light

- Digital cameras made from silicon are sensitive to “invisible” wavelengths:
  - ultraviolet = “UV”
  - infrared = “IR”
Human Eye vs. Silicon Sensor

Sidebar #1: Value of (and need for) UV+VIS+IR Lens for Imaging of Cultural Heritage
Spectral Imaging with Lens Designed for Visible Light

Nikon 60mm f/2.8 “Micro-Nikkor”
(35mm format, ~ $500)

Examples from Archimedes Palimpsest
Spectral Imaging with Visible-Light Lens

\[ \lambda = 365 \text{nm} \]
Spectral Imaging with Visible-Light Lens

\[ \lambda = 570\text{nm} \]
Spectral Imaging with Visible-Light Lens

\[ \lambda = 625 \text{nm} \]
Spectral Imaging with Visible-Light Lens

\[ \lambda = 870\text{nm} \]

much less sharp
in infrared light
when focused for
visible light
Reason for “Fuzzy” IR Images: Nikkor apochromat is corrected for visible light ONLY
Spectral Imaging with "Spectral" Lens

60mm f/4 by Coastal Optics (now Jena)
(35mm format, ~ $6000)

coastalOpt® 60mm f/4 UV-VIS-IR

- Designed by J. Brian Caldwell
- “True Apochromat”
  - corrected at 3 widely spaced focus crossings in UV, VIS, IR spectrum
  - \( \lambda \approx 350\text{nm}, 450\text{nm}, 870\text{nm} \)
- 5 elements of CaF\(_2\), 12-layer coatings
  - Transmittance > 99% per surface
- Strehl ratio > 0.8, \( 365\text{nm} \leq \lambda \leq 900\text{nm} \)
  - Implies “ideal” imaging over full range of bands
Spectral Imaging with Spectral Lens

$\lambda = 365\text{nm}$
Spectral Imaging with Spectral Lens

\[ \lambda = 570\text{nm} \]
Spectral Imaging with Spectral Lens

\[ \lambda = 735\text{nm} \]
Spectral Imaging with Spectral Lens

“sharply” focused over wavelength range

$\lambda = 940\text{nm}$
Large-Format Spectral Lens

• MegaVision UV-IR 120mm f/4.5
• also designed by J. Brian Caldwell
  ➢ 6 elements of extra-low-dispersion glass
  ➢ 1 aspheric element
Sidebar #2: Different Imaging Modalities

- Reflection: Lots of Photons ("light")
- Transmission: Lots of Photons
- Fluorescence: Few Photons
Reflective Multispectral Imaging with Light-Emitting Diodes (LEDs)

Narrowband Light Sources (light-emitting diodes = LEDs)

Camera

Sensor

Lens

Object (Manuscript)

Lens must transmit and focus entire range of $\lambda$
Transmissive Imaging

New transmissive sources constructed from discarded LCD display panels

- Lightsheet (faceplate of flat-panel monitor)
- Manuscript with thickness variation

Camera

Sample Image
Fluorescence Imaging with Light-Emitting Diodes (LEDs)

Object (Manuscript)

U or B fluorescence

U reflectance

B fluorescence

G fluorescence

R fluorescence

Camera

Sensor

Lens

Filter

Object (Manuscript)
“Fluorescence”

⇒ Imaging of photons generated in parchment or ink

- Intrinsically fewer photons to image
- Statistical “uncertainty” in number counted
- Pixels that should count the same number of photons will count different numbers due to statistical variations
“Signal-to-Noise Ratio” for Fluorescence

• “Signal” = mean number $N$ of photons to count
• “Noise” = statistical variation = $\sqrt{N}$
• $SNR = \frac{N}{\sqrt{N}} = \sqrt{N}$

• $SNR$ increases with number of counted photons
  $\Rightarrow$ More fluorescent light or longer exposures
  $\Rightarrow$ Success of subsequent processing depends on GOOD $SNR$
Random variations in fluorescence affect success of processing

• SNR increases with number of counted photons
  ➢ Need to reduce “uncertainty” ⇒ “statistical noise”
⇒ More fluorescent light or longer exposures
⇒ Success of subsequent processing depends on GOOD SNR

• Sensors with larger pixels have less statistical noise
⇒ Spatial resolution ain’t everything...
VERY Brief History of Image Processing for CHI

http://www.cis.rit.edu/~rlepci/palimpsest_imaging/References_on_History_Palimpsest_Imaging.html

Historical References on Palimpsest Imaging (pdfs)

(English translations mostly by Google ... something desired is left)

Ernst Pringsheim and Otto Gradewitz
  1894: "Photographic Reconstruction of Palimpsests" (English + original)
  1900: "Photography as Aid to Paleography," by Hermann Schmauss (English)
  1901: "Photographic Reconstruction of Palimpsests" (English + original)

Raphael (Gustav) Kögel
  1912: "Photography of Palimpsests" from Studien und Mitteilungen zur Geschichte des Benediktinerordens, Bd. 33 (1912), S. 309-315 (English translation + original)
  1913: patent #274030 on "UV illumination of palimpsests" (English + original)
  1913: patent #283207 on "Photographic Recording of Palimpsests" (English + original)
  1914: "Gelatine or Cellite for Preservation," from "Studien und Mitteilungen zur Geschichte des Benediktiner-Ordens," Bd.35 1914, pp.353-358 (English + original)
  1914: patent #285154 on "Palimpsest Imaging using Two Transparencies" (English + original)

...
Basic Concept of MSI is NOT New

- William Henry Fox Talbot, 1840s
  - “The Pencil of Nature” 1844
- Ernst Pringsheim and Otto Gradenwitz, 1890s
- Fr. Raphael Kögel and Fr. Albert Dold, O.S.B., 1910s
  - Palimpsest Institute, Archabbey of St. Martin, Beuron
  - Kögel’s book “Die Palimpsestphotographie” (1920)

http://goobipr2.uni-weimar.de/viewer/resolver?urn=urn:nbn:de:gbv:wim2-g-2965569
"Experimenters have found that if (the solar) spectrum is thrown upon a sheet of sensitive paper, the violet end of it produces the principal effect [of exposure]: and, what is truly remarkable, a similar effect is produced by certain invisible rays which lie beyond the violet, and beyond the limits of the spectrum, and whose existence is only revealed to us by this action which they exert.

"Now, I would propose to separate these invisible rays from the rest, by suffering them to pass into an adjoining apartment through an aperture in a wall or screen of partition. This apartment would thus become filled (we must not call it illuminated) with invisible rays, which might be scattered in all directions by a convex lens placed behind the aperture. If there were a number of persons in the room, no one would see the other: and yet nevertheless if a camera were so placed as to point in the direction in which any one were standing, it would take his portrait, and reveal his actions.

"For, to use a metaphor we have already employed, the eye of the camera would see plainly where the human eye would find nothing but darkness.

"Alas! that this speculation is somewhat too refined to be introduced with effect into a modern novel or romance; for what a dénouement we should have, if we could suppose the secrets of the darkened chamber to be revealed by the testimony of the imprinted paper."

*The Pencil of Nature*, p. 30
http://www.thepencilofnature.com/
1890s, Photographic Image Processing

Collaborating scholars in Breslau

(Pringsheim’s measurements of light from different sources led to Planck’s hypothesis of light “quanta”)

Ernst Pringsheim (experimental physicist)
Otto Gradenwitz (religious studies)
Zen-like Goal

• “To remove the ‘overtext,’ subtract it!”

Photographische Reconstruction von Palimpseste
Von E. Pringsheim und O. Gradenzitz.
Jahrbuch für Photographie und Reproduktionstechnik für das Jahr 1901
Unter Mitwirkung hervorragender Fachmänner
Herausgegeben von Hofrath Dr. Josef Maria Eder,
pp. 52-55

(Available at: https://archive.org/details/jahrbuchfrphoto04edergoog/page/n75)
Combinations of Two Photographs

• Different conditions (emulsions, illumination, filtering, exposure), such that:
  A: shows both texts “well”
  B: shows only overtext
• Positive transparency of “A”
• Negative transparency of “B”
  \[ B' = B_{\text{max}} - B \]
• Align a sandwich of A and B’
  \[ A \cdot (B_{\text{max}} - B) = A \cdot B_{\text{max}} - A \cdot B \]
Transmission of Processed Transparencies for Different Features

<table>
<thead>
<tr>
<th></th>
<th>background</th>
<th>undertext</th>
<th>overtext</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transparency A</td>
<td>dark</td>
<td>dark</td>
<td>light</td>
</tr>
<tr>
<td>Transparency B'</td>
<td>light</td>
<td>dark</td>
<td>dark</td>
</tr>
<tr>
<td>Transmitted Light</td>
<td>dark + light = gray</td>
<td>dark + dark = black</td>
<td>light + dark = gray</td>
</tr>
</tbody>
</table>

Table from 1894 paper (after translation)

Borrowed precise translation table from Hermann Carl Vogel, astrophysicist at University of Potsdam to align ("register") images
Analog Photographic Method of by Pringsheim and Gradenwitz to Enhance Palimpsested Text, 1890s

Image A, (positive)
Analog Photographic Method of by Pringsheim and Gradenwitz to Enhance Palimpsested Text, 1890s
Analog Photographic Method of by Pringsheim and Gradenwitz to Enhance Palimpsested Text, 1890s
Analog Photographic Method of by Pringsheim and Gradenwitz to Enhance Palimpsested Text, 1890s
Kögel’s Imaging Technology in 1910s
(with ultraviolet illumination)

(a) ultraviolet absorbing filter
(c) condensing lens
(d) metal filament lamps (longer wavelength visible light)
(g-g') Hg vapor lamp (discrete lines with $253\text{nm} \leq \lambda \leq 579\text{nm}$)
(u) visible absorbing filter

Glass cuvette to hold liquid used as ultraviolet absorbing filter
Comparison of “Before” and “After” Images by Kögel

Approximate Visual Appearance  After Analog Processing
Spicilegium Palimpsestorum arte photographica paratum per S. Benedicti monachos Archiabbatiae Beuronensis, Volume I: Codex Sangallensis 193. Leipzig, Harrassowitz, 1913
1917 Advertisement for Imaging Services

PALIMPSEST INSTITUTE
THE ABBEY of BEURON in Province of HOHENZOLLERN.

The Institute offers its services to private owners of illegible palimpsests or public libraries to recover writings without the use of chemical reagents and therefore without harming the precious copies of the texts of scientific research. With the consent of the owner will result in a fine prospect, without making new cost him the photographs taken by a reproduction process as panel factory wider circles of interested users to. It is only to be hoped that as many Palimpsest will make this offer owners the benefits and what was previously difficult or impossible to decipher, make it usable for a broader scientific yield. (From the article: . Handwriting research and photographic art in de Theological Review, 1915, No. 1/2, of University Professor J. Götsberger, Munich)

•••

In this sense refers to the Palimpsest Institute Beuron be renewed Tender, contracts to take on palimpsest - photographic works on respective written request and commitment towards. In Format 9×12 cm photographs to M.3:50 executed in 12×18 format to M.5:50 with fluorescence techniques. Requires the size ratio of the manuscript larger formats or the condition of the primary font upper exposures with extra power consumption, as occurs corresponding increase in price.

Favorable results are to be expected when something primary font is still present and the Palimpsest leaves were not treated with oak gall tincture or other inhibiting reagent. The codices remain untouched, are not subject to chemical reagents of any kind and safe fire and theft proof.

Test shots at the same price as test panels to services.

End page of Prophetentexte in Vulgata-Ubersetzung
Nach Der Altesten Handschriften-Uperlieferung Der S. Galler Palimpseste No. 193 und No. 567, Fr. Alban Dold, Benediktiner der erzabtei beuron, 1917
Light-Emitting Diodes (LEDs) as Spectral Sources for MSI

• LEDs convert electricity to light by electronic process instead of as byproduct of heat generation
• Much more efficient (> 20%)
• Operating temperature is much lower
  ➢ Safer for object
• “Narrowband” (Δλ ~ 20-40 nm)
  ➢ Spectral filters for band selection often not needed
Prototype LED Illumination System, 2006

Monochrome Digital Camera
Manuscript
Optical Fibers
Light-Emitting Diodes (LEDs)

Keith Knox
“National Treasure: Book of Secrets,” 2007

“Imaging” of page fragment from “John Wilkes Booth’s diary” using prop system based on 2006 El Greco system

Justine Bartha  Nicolas Cage  Diane Kruger
Spectra of LEDs on Early Illumination Panel
Current System with LEDs ($\Delta \lambda \approx 40\text{nm}$)

16 LED bands in Reflection

- 365nm
- 420nm
- 450nm
- 470nm
- 505nm
- 530nm
- 560nm
- 590nm
- 615nm
- 630nm
- 655nm
- 700nm
- 735nm
- 780nm
- 850nm
- 940nm

2 LED bands for fluorescence + bandpass filters

- 365nm with 6 filters
- 450nm with 4 filters

Transmissive Bandpass Filters

- B47
- G58
- O22
- R25

- UVP (pass)
- UVB (block)

4 LED bands for transmission using *Lightsheet* illuminator

- 500nm
- 580nm
- 735nm
- 940nm

⇒ Total of 30 bands
Image Processing for MSI

- **Combinations** of image bands
  - (occasionally find a single band with useful information)

- Renderings
  - Pseudocolor
  - Band differences

- **Statistical Processing**
  - Principal Component Analysis (PCA)
  - Independent Component Analysis (ICA)
  - Minimum Noise Fraction (MNF)
  - Spectral Angle Mapping (SAM)
The Archimedes Palimpsest

- 12th-century prayer book
  - the “Euchologion”
- Written on top of erased manuscripts
  - Seven treatises of Archimedes
    - Copied in 10th century
    - only copy of “On Floating Bodies” in Greek
    - only known copy of “Method of Mechanical Theorems”
  - Two speeches by Hypereides
    - Athenian politician and lawyer
    - 4th century, BCE
  - Commentary on Aristotle’s “Categories”
Single Image Band: Unexpected Result

• Undertext on unidentified leaves appears “bright” on darker parchment at $\lambda = 870\text{nm}$
  • Fluorescence?

(contrast reversed from original image)
Images of Unidentified Leaves at Archimedes Conference, Budapest

László Horváth (then at University of Budapest)

Dr. Sophia Kapetanaki
University of Peloponnese
Kalamáta, Greece
Example: Images Under Two Illuminations

Archimedes 92v-93r

Tungsten

Ultraviolet

© Owner of the Archimedes Palimpsest
Pseudocolor Rendering of Spectral Fluorescence Image

Image under Red Illumination

Blue Fluorescence under Ultraviolet Illumination

© Owner of the Archimedes Palimpsest
Pseudocolor Rendering of Archimedes Palimpsest

• Analogous to monochromatic image combinations by Pringsheim/Gradenwitz and Kögel/Dold

• Became so popular with scholars that they wanted to see similar renderings of images generated by subsequent processes
Insert Normalized Separations into Color Channels

“Red”

“Blue” Fluorescence
Band Differences

- Evaluate and render difference of same two bands used to make pseudocolor image
  - Now analogy with renderings by Pringsheim/Gradenwitz and Kögel/Dold becomes “Almost Exact”

- Requested by the late Bob Sharples of University College London (“UCL”)
  - therefore dubbed “Sharpies”
had been oldest book on Google Books
Spectral Imaging in Transmission
Caucasian Albanian under Georgian Text

Georgian NF 13, folio 59r © St. Catherine’s Monastery of the Sinai, used with permission
Pseudocolor Image

Georgian NF 13, folio 59r © St. Catherine’s Monastery of the Sinai, used with permission
Reversed Contrast

Georgian NF 13, folio 59r  © St. Catherine’s Monastery of the Sinai, used with permission
Custom MSI Processing Based on Spectral Statistics
Statistical Processing

• Principal Component Analysis (PCA)
• Independent Component Analysis (ICA)
• Spectral Angle Mapping (SAM)
• Minimum Noise Fraction (MNF)
Principal Component Analysis (PCA)

• Assumes statistics of all spectral features are “Gaussian distributed” (“bell curve” of likelihoods)

• Evaluates an “equivalent set” of bands from N-band image
  ➢ “equivalent set” ⇒ transformation is invertible
  ➢ each output PC band is a weighted sum of the N original bands
  ➢ all PCA bands are “orthogonal” (“uncorrelated”)
  ➢ PC bands ordered by image variance
    ☑ PCA#1 exhibits largest variance (widest range of “contrast,” e.g., from “overtext” to “parchment”)
    ☑ PCA#2: “overtext” and “parchment” pixels collapsed to same gray value, other variation exhibits contrast (e.g., “undertext” to “parchment”)
    ☑ PCA #3: largest variance that is orthogonal to #1 and #2
Illustrative Example of PCA

• Synthetic **Two-Band** Image, e.g., “red” and “blue” light

• Two object features or classes: “A” and “B”
  - denoted in histograms by different symbols (circle ●, triangle △)
  - Class “A” could be “undertext”
  - Class “B” could be “parchment”

• Look at “histograms” of each band
  - graph of pixel population vs. gray value
  - estimate of probability of each gray value
Image Histogram, Band 1

- Graph of probability of pixel gray values

- Pixels in Class “A” not distinguished from those in Class “B” by gray value
Image Histogram, Band 2

- Again, pixels in Class “A” are not distinguished from those in Class “B” by gray value.
2-D Histogram of Bands 1,2

- "Simultaneous" probability of pixel gray values in two images
  - How many pixels have same pair of gray values in two images?

![Diagram of 2-D Histogram](image)

- Input Band 1
- Input Band 2
- Axis of PC1
- Histogram of PC1 (Classes Still Overlap)
- Pixel in Class A
- Pixel in Class B

White
Black

Input Band 1
Input Band 2

White
Black
1st Principal Component

- Project pixels onto axis with largest variance
- Map ends of axis to “black” and “white”
- Forms new image as weighted sum of constituent images
2nd Principal Component

- Project onto perpendicular axis with next largest variance
- Map ends of axis to “black” and “white”
- Forms new image as weighted sum of constituent images
  - enhanced contrast
Extend to $N$-Band Image

• PCA generates equivalent set of $N$ bands
  - Rendered on orthogonal axes
  - Sequenced by image “variance”
    - Roughly analogous to “contrast”
    - “lowest-order” PC bands have largest variance
      $\Rightarrow$ widest range of contrast
    - “highest-order” PC bands have least variance
      $\Rightarrow$ subtlest contrast differences
Example of PCA Processing, Reflectance: Whitewashed Greeting Card in "Cuaderno" Collage
Overpainted Greeting Card in “Cuaderno” Collage

PCA Band 6 from 12-band image
Overpainted Greeting Card in “Cuaderno” Collage

PCA Band 6 from 12-band image
Overpainted Greeting Card in “Cuaderno” Collage

PCA Band 6 from 12-band image
PCA of Spectral Fluorescence Imagery
Fluorescence Imaging with Light-Emitting Diodes (LEDs)

Lens must transmit and focus both UV and visible light

- U reflectance
- B fluorescence
- G fluorescence
- R fluorescence

Diagram:
- Camera
- Sensor
- Lens
- Filter
- Object (Manuscript)
Example from “Aristotle Commentary” in “Archimedes Palimpsest”

• Seven folios
• Commentary on “Categories” by Porphyry or Alexander of Aphrodisias
• Undertext was very difficult to recover
  ➢ PCA method by Kevin Bloechl, RIT 1st-year undergraduate
Little Benefit from Other Methods on Aristotle Commentary

- Spectrum of ink differs (somehow) from inks on leaves with Archimedes text
RGB Fluorescence Image under UV

f. 120v-121r
Subsequent Improvement

• Pseudocolor rendering of PCA bands with “hue-angle rotation”
  - dynamic change in rendering of same data
  - may reveal text more clearly

• Reasons:
  1. Text features rarely segmented into single PC band
  2. User can “tune” image to their own eye
Hue angle $\theta = 0^\circ$

AP f. 120v – 121r
Different sections of 120v-121r, Hue angle $\theta = 0^\circ$
Hue angle $\theta = 45^\circ$
Hue angle $\theta = 90^\circ$
Hue angle $\theta = 135^\circ$
Hue angle $\theta = 180^\circ$
Hue angle $\theta = 215^\circ$
Hue angle $\theta = 270^\circ$
Hue angle $\theta = 315^{\circ}$
Transmissive Imaging with PCA for Paper Watermarks

“Dunlap Broadside” Copy of Declaration of Independence
printed by John Dunlap on night of July 4, 1776
one of 26 surviving of estimated 200 printed
PCA of Transmissive Spectral Images
from 10 visible and infrared bands (365nm and 940nm deleted)
PC Band #1 shows widest range of gray value = printed text and paper
PC Band #2 “collapses” print and paper pixels to same level
⇒ remaining range of contrast shows watermarks
PCA on “Les Eschéz d’Amour”
Saxon State Library, Dresden, 2010

• “The Chess of Love”
  ➢ 30,000-line epic poem in Middle French
• Damaged by water from broken mains in Feb. ‘45
“Armorial Achievement” on f.1 of Les Eschéz d’Amour
RGB Contrast Enhancement

Pseudocolor From PCA bands
Identified Owner (Waldenfels Family in Bavaria)
Independent Component Analysis (ICA)

• Similar in concept to PCA, but with less-stringent assumptions and capable of better performance
  ➢ does not assume Gaussian statistics
  ➢ uses higher-order correlations to determine transformation

• Creates a model for the system that produces the observed data based on model of “linear mixing”

• Somewhat more capable of segmenting the feature(s) of interest into different output bands

• Image “variance” is not applicable, but ICA bands may be sorted by similar concept called “spatial coherence”
Linear Mixing Model in ICA

“Party Conversations Problem”

Microphone “A”

Conversation #1

Microphone “B”

Conversation #2

Microphone “C”

Conversation #3
Analogy of “Cocktail Party” to Imaging

• Each of $N$ microphones measures different mixture of $M$ “independent conversations”
  ➢ summed signals that differ in relative volume and temporal frequency

• ICA tries to “unmix” the $N$ microphone signals, with goal of segmenting into original set of $M$ independent conversations

• Imaging analogy:
  ➢ $M$ “conversations” ↔ $M$ “features” ( “overtext,” “undertext,” “parchment,” …)
  ➢ $N$ signals from microphones ↔ $N$ bands of spectral data
    □ include mixtures of the $M$ “features”
    □ need $N \geq M$ (at least as many “bands” as “features” to segment)
Example: ICA of Greek NF MG99, f. 1r
processing by David Kelbe
Segmented bands of each object class
Visual Appearance

© Holy Monastery of St. Catherine at Mount Sinai
Output Band: “Overtex” Class
Output Band: Rubric from other side

© Holy Monastery of St. Catherine at Mount Sinai
Output Band: Overtex from other side

© Holy Monastery of St. Catherine at Mount Sinai
Output Band: Parchment

© Holy Monastery of St. Catherine at Mount Sinai
Output Band: “Noise”
Output Band: “Undertext”

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Pseudocolor from ICA Bands
Syriac NF 2A f. 148r

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Double Palimpsest
Arabic NF 8, folio 20r (61.41)

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Double Palimpsest
Arabic NF 8, folio 20r (61.41)

ICA by David Kelbe showing one undertext

© Holy Monastery of St. Catherine at Mount Sinai
Double Palimpsest
Arabic NF 8, folio 20r (61.41)

PCA by Kevin Sacca
showing different text

© Holy Monastery of St. Catherine at Mount Sinai
World Map by Henricus Martellus (c. 1491)
imaged in 2014 at Beinecke Rare Book and Manuscript Library at Yale University
Martellus Map (c. 1491)

- by Henricus Martellus Germanus
- worked in Florence, Italy, 1480-1496
- Text written with pigments of several different colors
- Nearly all text is faded and now illegible
- Different colors of pigment $\Rightarrow$ different processing needed for different writings
Keystone Cartouche

Visible Light

Infrared

Color Ultraviolet
Keystone Cartouche

Spectral Image, Processed from Several Bands
India
Visual Appearance, showing little text
Text written in different pigments

• Different processing necessary to recover different texts
Pseudocolor Result 1, showing text at top (yellow ellipses), none in red ellipse
Result 2, showing no text in red ellipse
Pseudocolor Result 3, showing text in red ellipse
Spectral Angle Mapping (SAM)

• Considers the gray values of a pixel over the range of bands to form a vector \( r \)
  \[
  r = \begin{bmatrix}
  x_1 \\
  x_2 \\
  \vdots
  \end{bmatrix}
  \]

• Select pixel(s) already identified as belonging to feature of interest (e.g., erased text); these form the “reference” vector \( a \)
  \[
  \theta = \cos^{-1} \left( \frac{a \cdot r}{|a||r|} \right)
  \]

• Display angle \( \theta \) between each pixel vector \( r \) and the single reference vector \( a \) as gray-scale image
Value of SAM

• Rapid evaluation, see results quickly
• Gray values in output image determined ONLY by “color” of each pixel
  - insensitive to “lightness”
  - May show useful information from “faint” features in image
    □ e.g., erased text