

Imaging of the Archimedes Palimpsest: Lessons Learned

Roger L. Easton, Jr.

*Chester F. Carlson Center for Imaging Science
Rochester Institute of Technology*

Keith T. Knox

*Boeing LTS
Maui, HI*

William A. Christens-Barry

*Equipoise Imaging and Johns Hopkins University
Baltimore, MD*

Outline

- Task
- Exploratory Investigations
- Evolution of Ideas, Advances in Technology
- “Production” Multispectral Imaging
 - Constraints
 - Procedure
 - Results
 - Image Stitching
 - Access for Scholars

Task:

- Imaging Techniques to Recover Original Text
 - Collection of Images
 - Processing
 - Rendering
- Success Determined by Scholars
 - Improvement in Text “Readability”
 - Defer Efforts Toward “Reproduction”
- Importance of Cost
 - Equipment
 - Efficiency

Exemplars to Illustrate Scope of Task

Many Pages are in Good Condition



91v-94r

Some are not!



169v-164r

Mold Damage

- Adjacent pages of quire
- “Split” at fold due to age and use

173v-176r



- Mold has eaten through parchments “in parallel”

174v-175r



Forged Icons

- After Heiberg's examination, 4 leaves were "re-erased" and painted over with icons of the four Gospels

81r



81v



Text in Gutter is Degraded

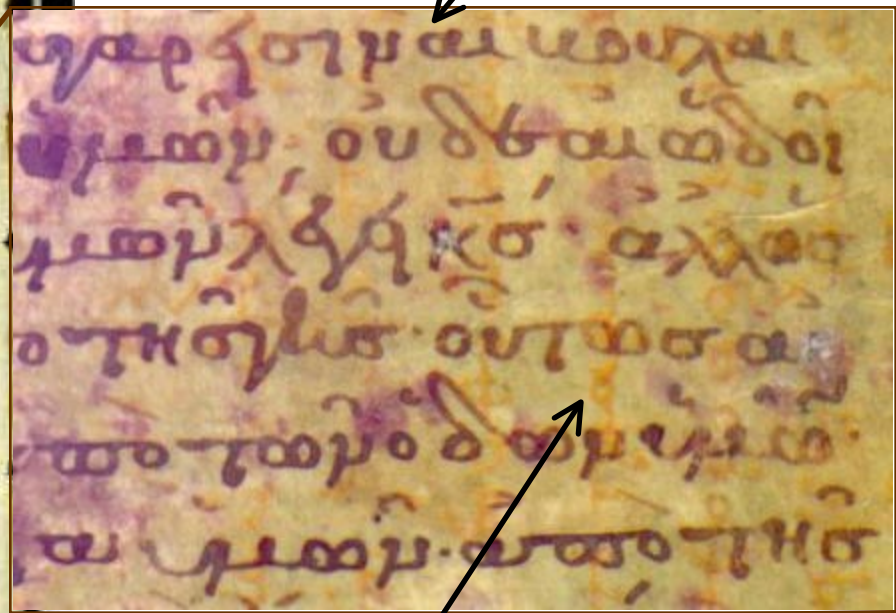


105v-110r

Leaf 28V



Prayer book
text

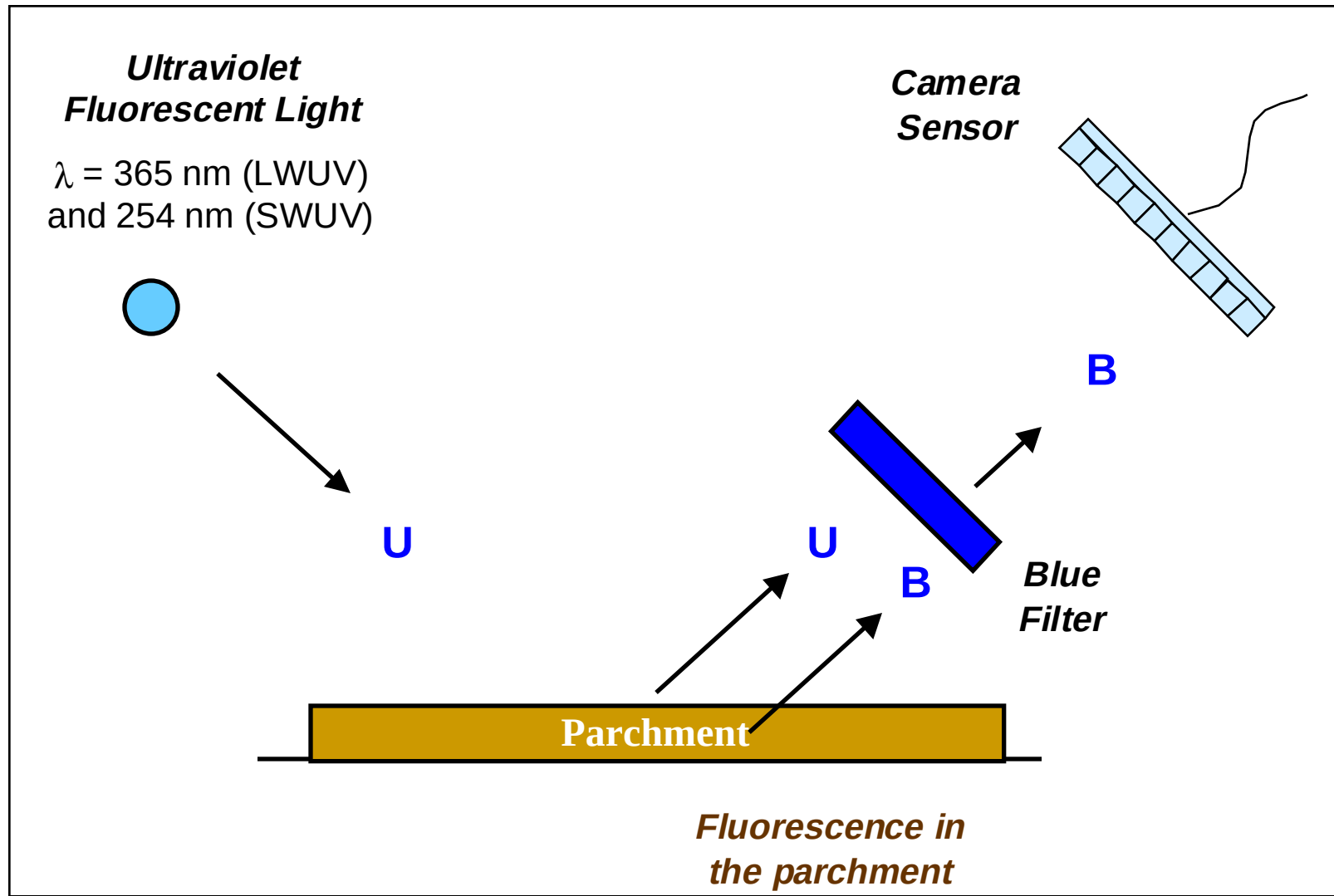


Archimedes text

Original Plan – Phase I, 2000

- Exploration of Task, Image 5 Single Leaves
- Propose Techniques to Apply in Phase II
 - RIT Team:
 - Multispectral Imaging + Image Processing to Distinguish Over- and Underwritings
 - JHU Team
 - Multispectral Imaging + Image Processing to Obscure Overwriting
- Both Teams Used Ultraviolet Illumination to Enhance Contrast of Underwriting

Ultraviolet Fluorescent Imaging



RIT Digital Camera



- *SenSys*[™] from Photometrics, now Roper Scientific
- Small Sensor (1536 × 1024 pixels)
- Filter Wheel
- Liquid-Crystal Tunable Filter (LCTF) from CRI
 - $\Delta\lambda \approx 10 \text{ nm}$
 - Measure Spectra of Object Classes

Experimental Image Collection Walters Art Museum, May 2000



Spectrometers

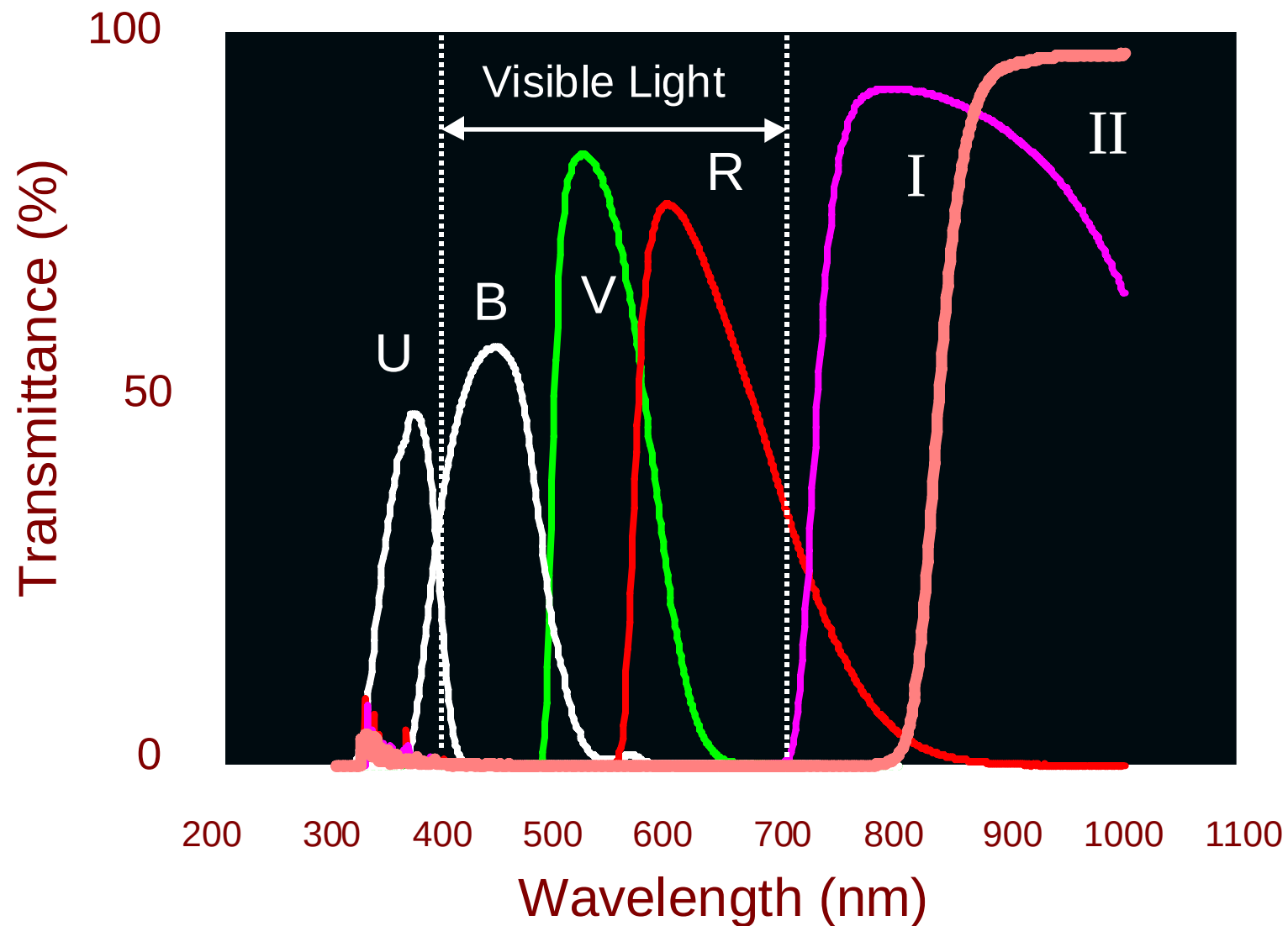
● 5 Glass Bandpass Filters

- Passband width = 100 nm
- Astronomical Filter set: UBV RIC, only BVRIC used
- Carried in “filter wheel” between lens and sensor

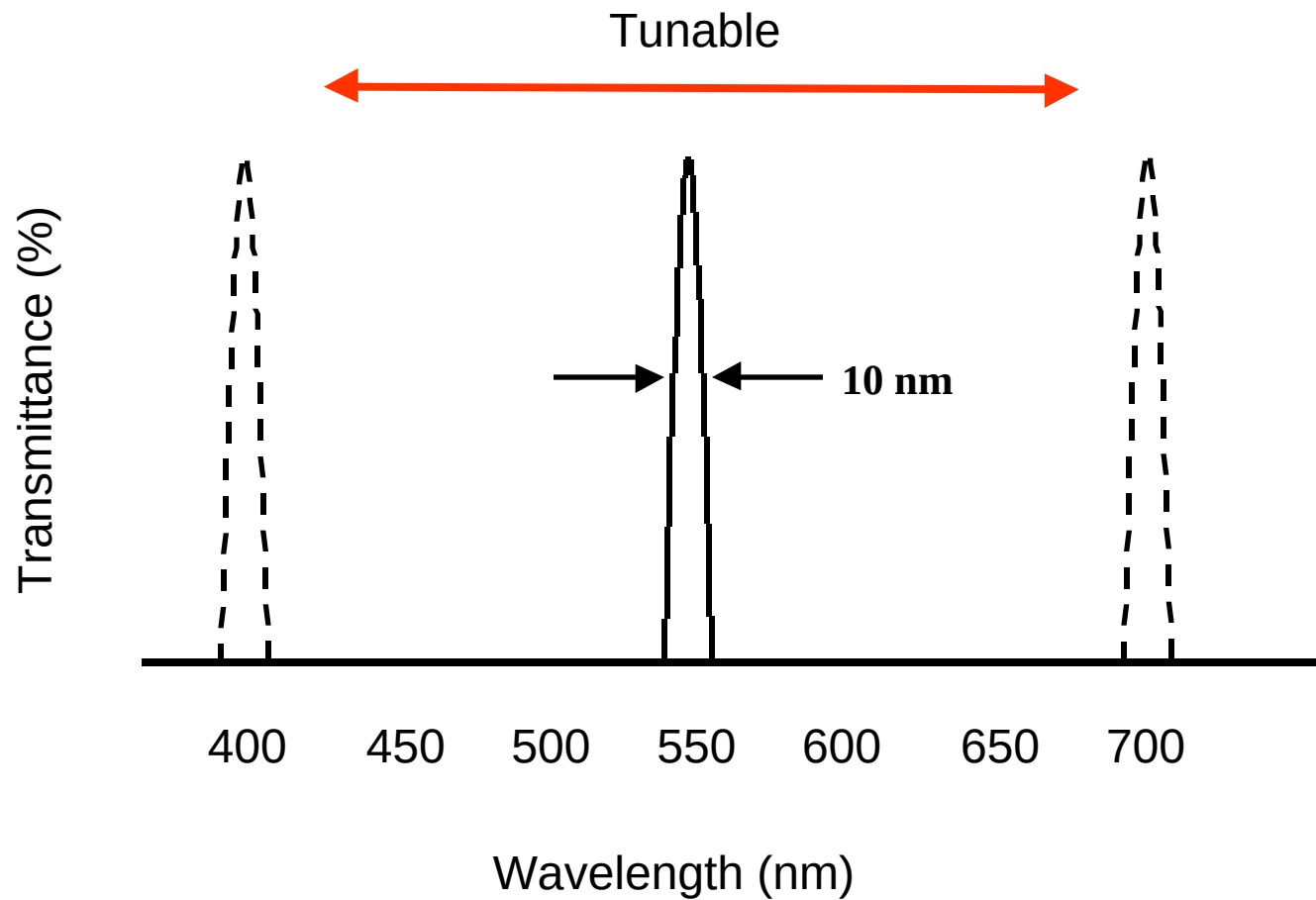
● Liquid-Crystal Tunable Filter (LCTF)

- Vari-SpecTM from *Cambridge Research and Instrumentation (CRI)*
- $400 \text{ nm} \leq \lambda \leq 720 \text{ nm}$, Passband $\Delta\lambda = 10 \text{ nm}$
- 18 mm aperture
- Mounted “in front” of camera lens

Filter Transmittances



Liquid Crystal Tunable Filter



RIT Phase-I Imaging

- Both Spectrometers, Three Illuminations
- Two Image Sections Per Page
 - Digitally “Stitch” to Obtain Image of Full Page
- Low Spatial Resolution
 - ≈ 9 pixels per mm = 220 dpi
- “Custom” Image Registration
 - Images at Each Wavelength

Multispectral Images from *SenSys*TM

CLEAR

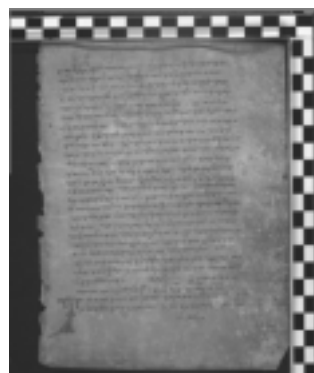
BLUE

GREEN

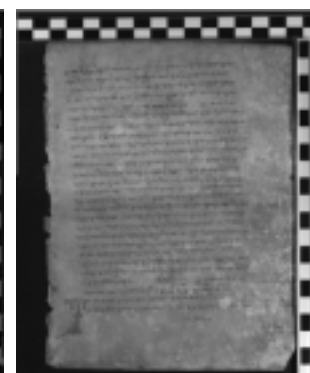
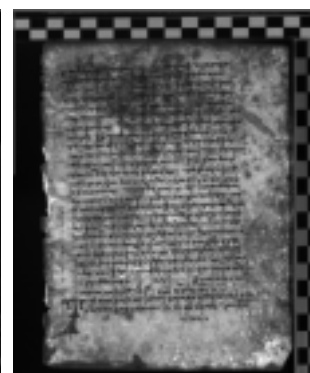
RED

IR

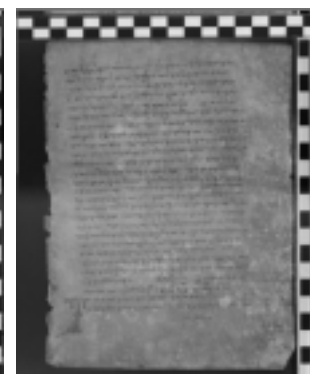
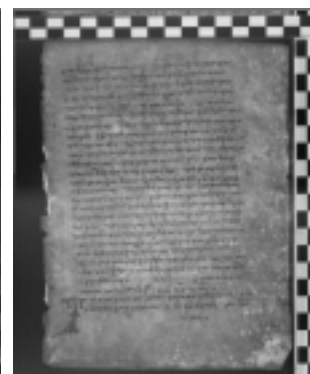
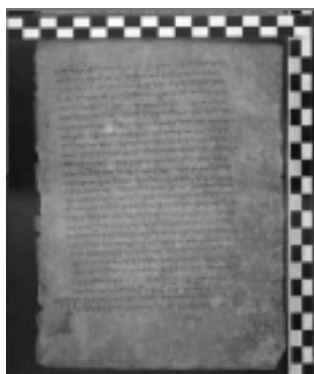
VIS



LWUV

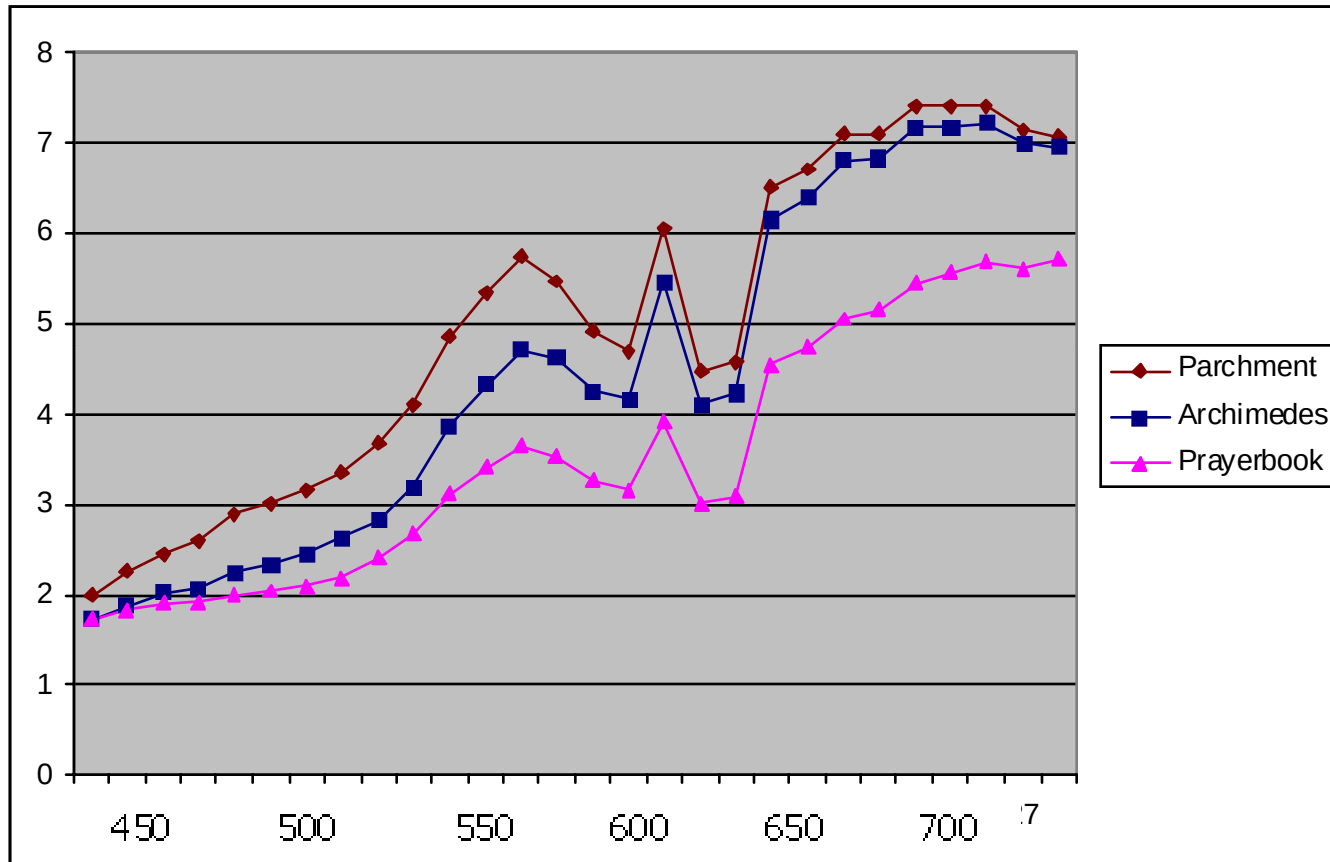


SWUV



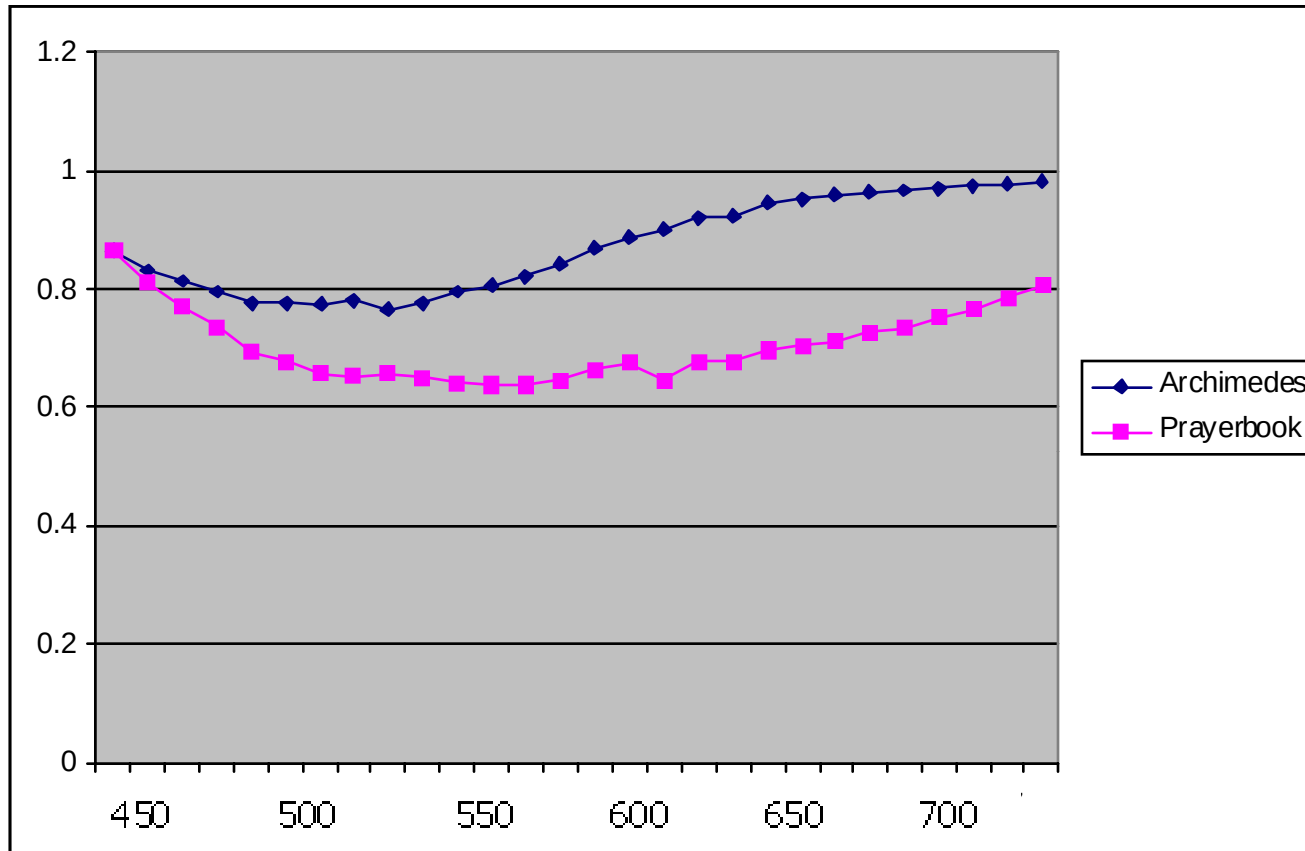
Spectral Responses

- Ink Spectra are Similar
- Parchment Spectrum Dominates Ink



Spectral Signatures of Two Inks

- Remove Parchment Spectrum (Normalize)
- Archimedes Ink is Brighter in “Red”



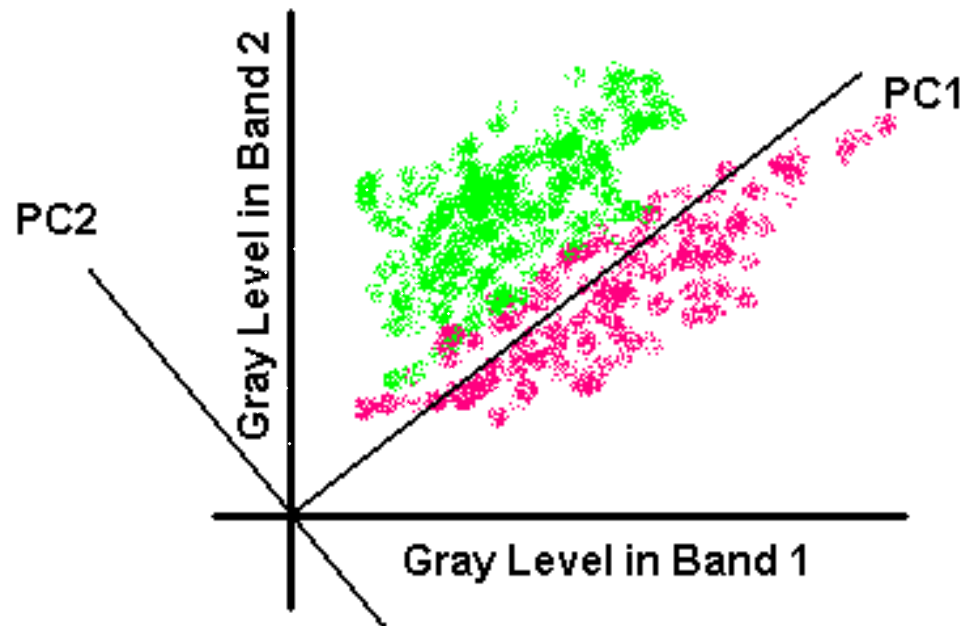
RIT Phase-I Image Processing Techniques from Remote Sensing

- Principal Components
- Matched Spectral Filtering
- Least-Squares Supervised Segmentation
 - Linear Mixing Model
 - Pixel Values are Mixtures of Spectra
 - Record Images in Many Spectral Bands
 - Spectral Unmixing
 - Determine Pixel Constituents
 - Measured Spectral Signatures
 - Pseudoinverse Solution

Principal Component Analysis in *ENVI*®

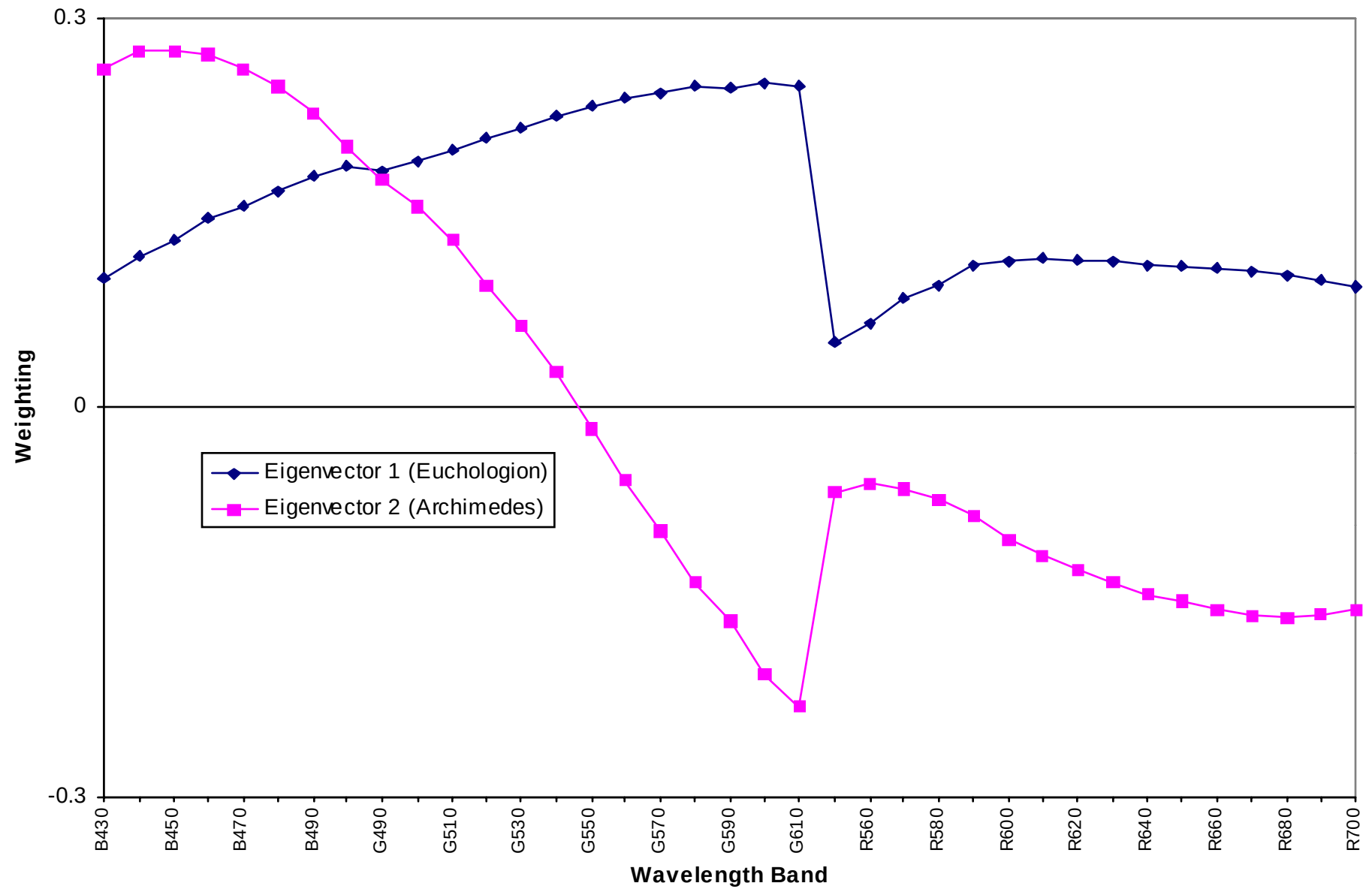
- Software computes weighted sums of the set of registered multispectral images
- Creates an “equivalent set” of 40 images ordered by the existing variance in the data
 - Band 1 of the PCA image exhibits most of the variation
 - Band 40 is the combination with the least variation (generally the “noise” in the scene)

Two-Band Example of PCA

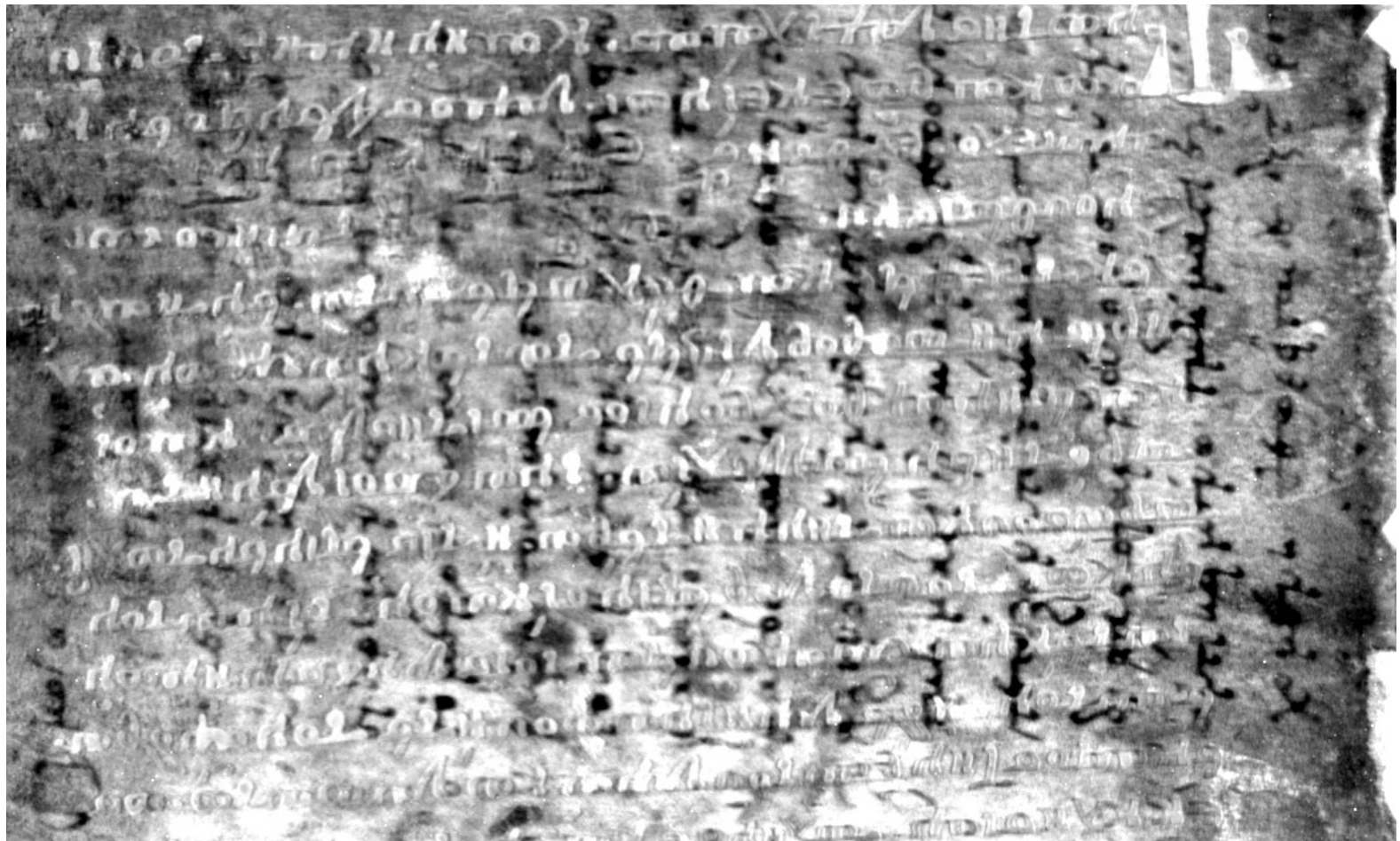


Projection of Data onto PC1 contains most image variance
Projection of Data onto PC2 distinguishes between classes

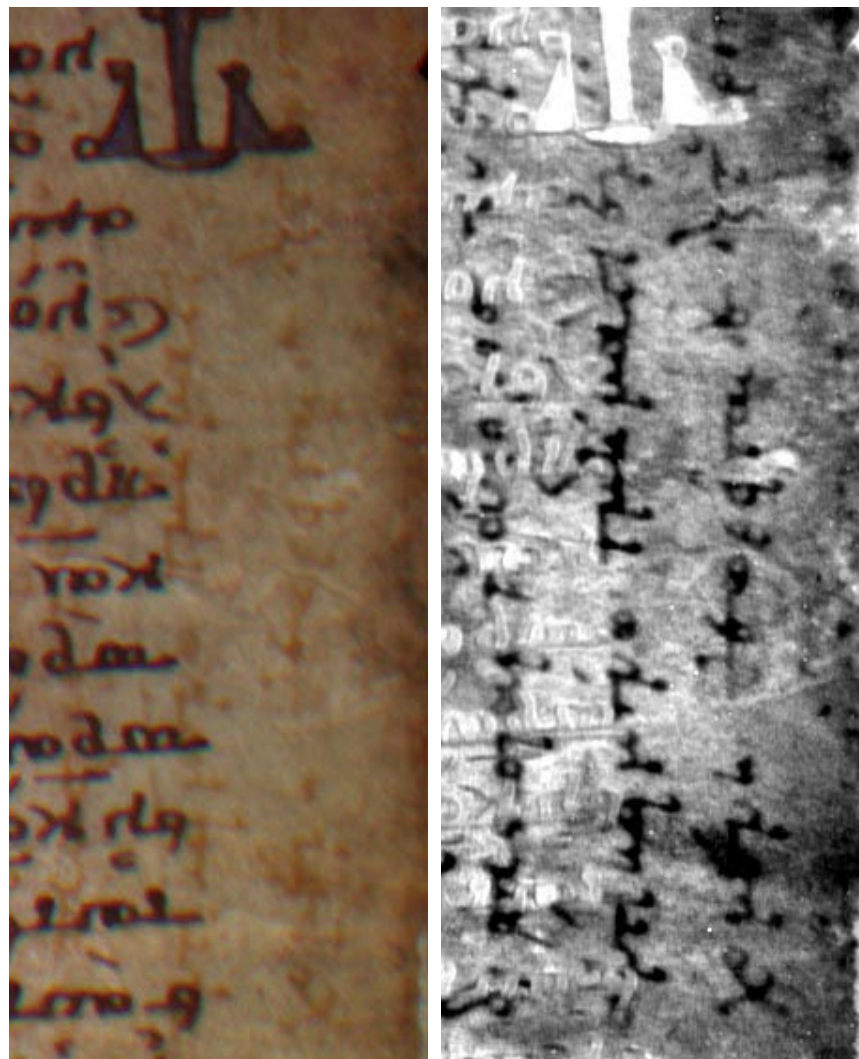
Eigenvector Weights



48R -- 2nd Principal Component



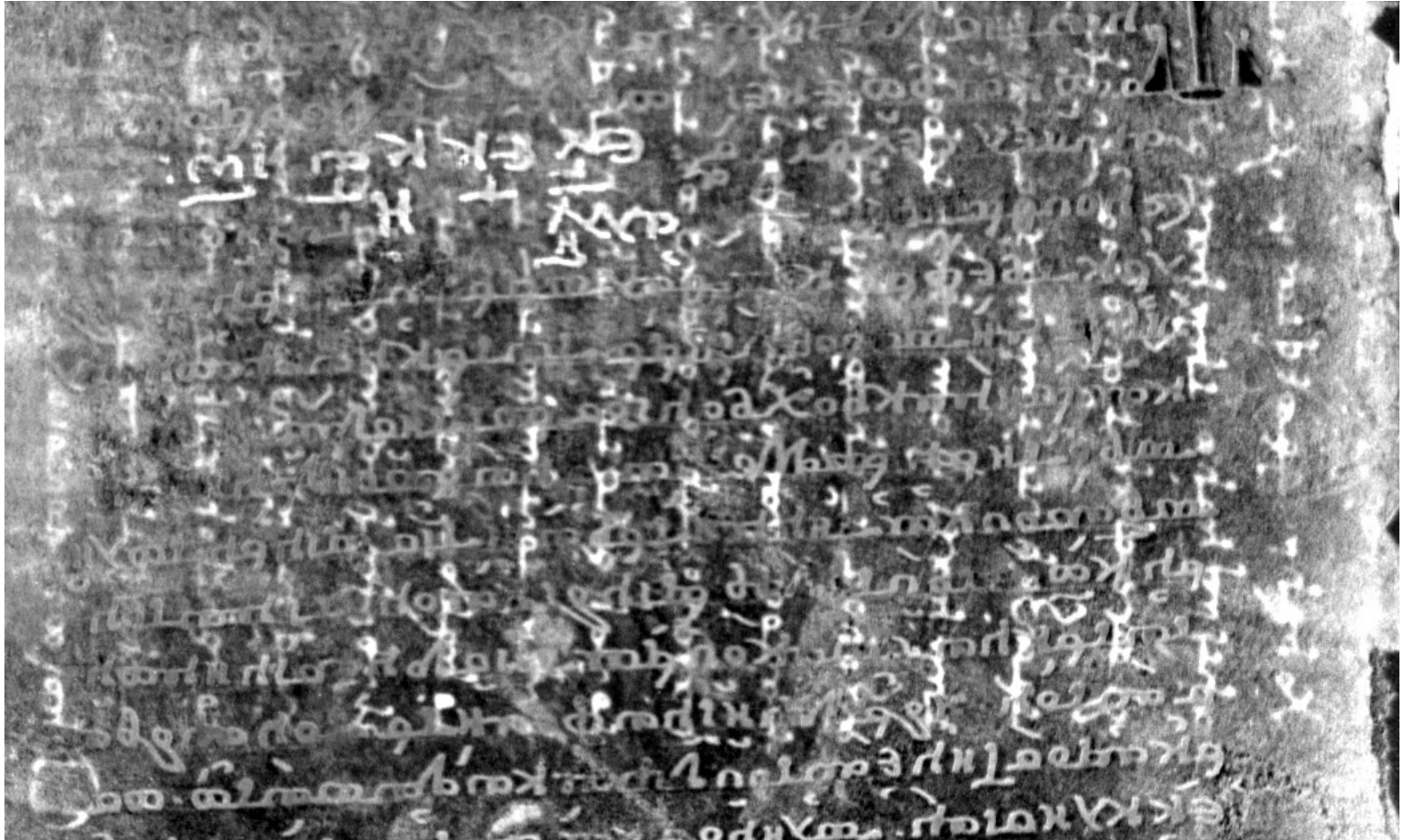
Comparison of “Uncalibrated” Color Image 48R to PC-2



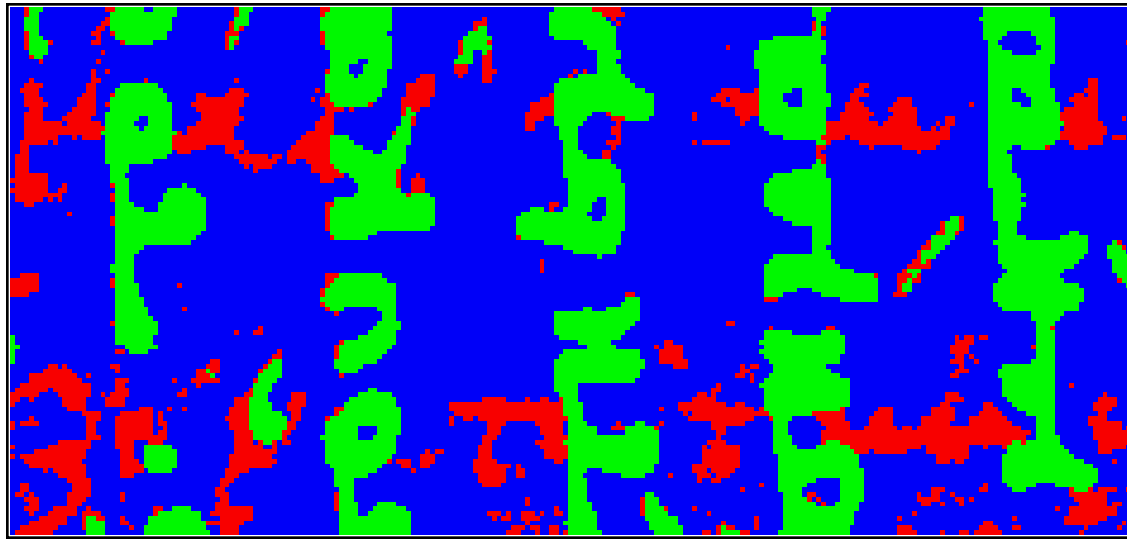
Minimum Noise Fraction

- Cascade of two PCAs
- Second “equates” parchment with noise

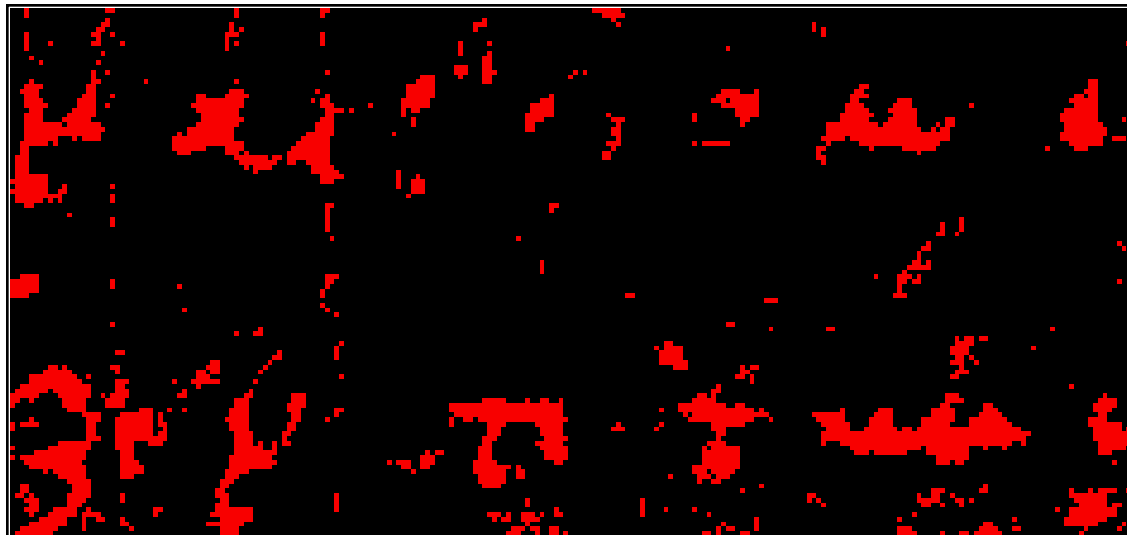
48R Minimum Noise Fraction



48R, Mahalanobis Classifier



Three Classes
(1) Parchment
(2) Euchologion
(3) Archimedes

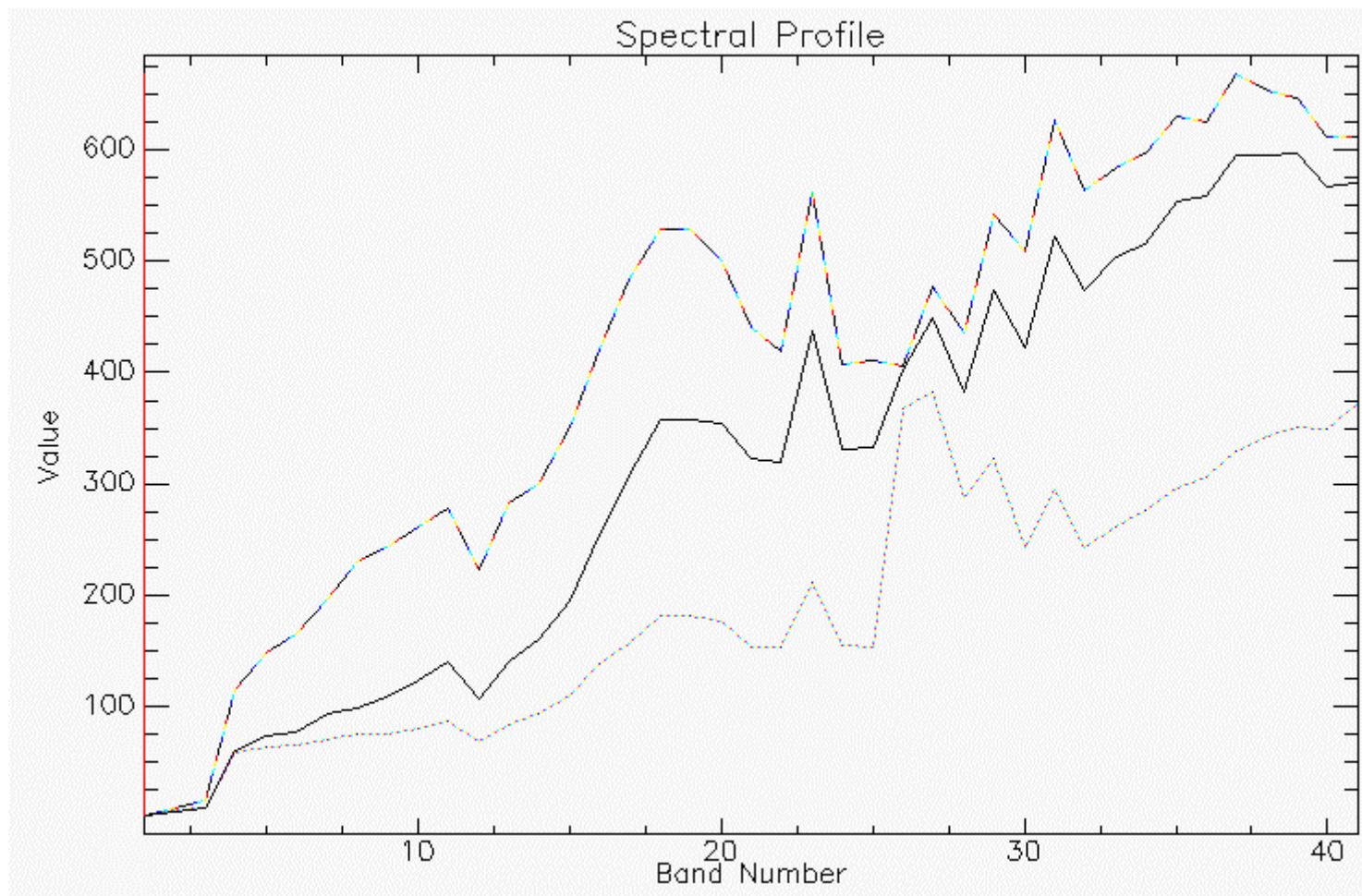


Two Classes
(1) Archimedes
(2) Other

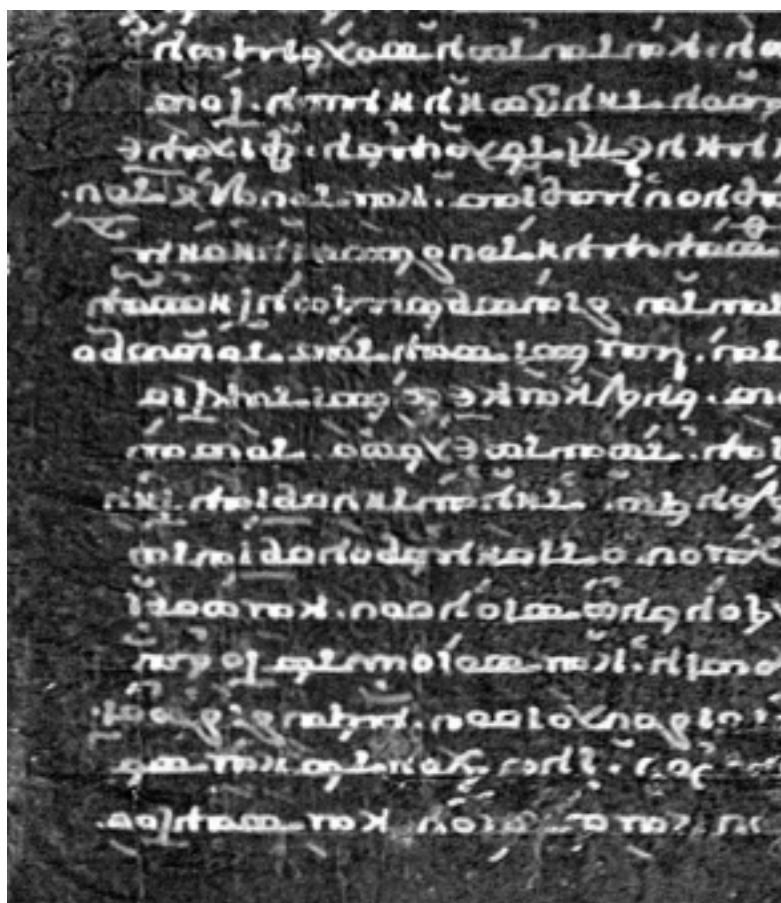
Spectral “Matched Filtering”

- “Supervised” Classification
 - Select Regions of Known
 - (1) Parchment
 - (2) Euchologion
 - (3) Archimedes Text
- Determine spectra for each known class
- Look for best “Match” of spectrum of each “unknown” pixel to the three “known” spectra
- Code each determined class as a “false color”

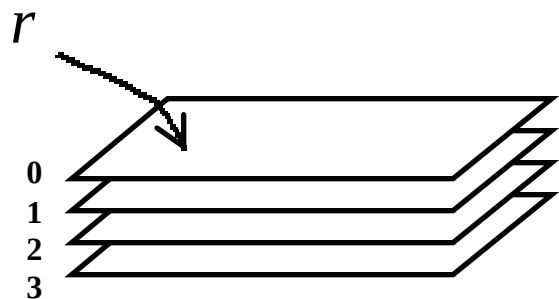
Preliminary Estimate of Spectra



70V

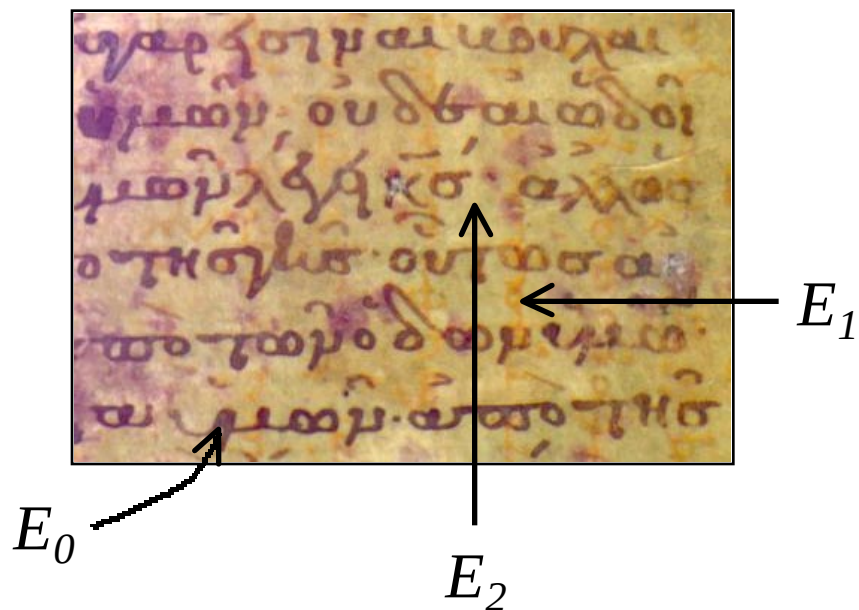


Linear Mixing Model



spectral bands

$$\begin{bmatrix} r_0 \\ r_1 \\ r_2 \\ \dots \end{bmatrix} = \begin{bmatrix} E_{00} & E_{01} & E_{02} \\ E_{10} & E_{11} & E_{12} \\ E_{20} & E_{21} & E_{22} \\ \dots & \dots & \dots \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \dots \end{bmatrix}$$



$$\underline{\mathbf{r}} = \underline{\mathbf{E}}\underline{\mathbf{a}}$$

Parchment/Ink Log Model

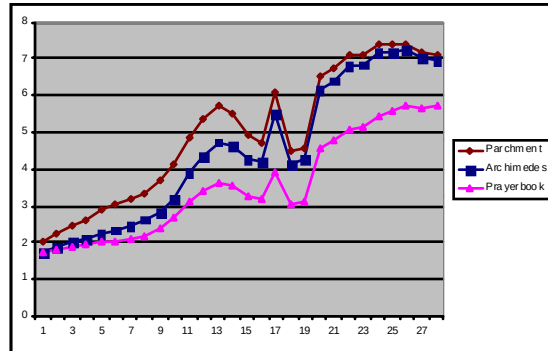
$$\text{pixel value} = \text{overwriting} \times \text{underwriting} \times \text{parchment}$$

$$\log(\text{pixel}) = \log(\text{overwriting}) + \log(\text{underwriting}) + \log(\text{parchment})$$

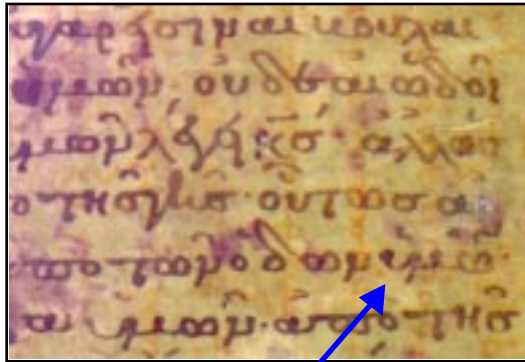
- $r_i = \log(\text{pixel value})$
- $E_{i0} = \log(\text{overwriting})$
- $E_{i1} = \log(\text{underwriting})$
- $E_{i2} = \log(\text{parchment})$

$$r_i = \sum E_{ij} \alpha_j$$

Least Squares Solution, Unconstrained



Spectral signatures



$\mathbf{r}$

$$\underline{\mathbf{r}} = \underline{\mathbf{E}} \underline{\boldsymbol{\alpha}}$$

Pixel Value is Linear Combination
of Spectral Signatures

$$\underline{\boldsymbol{\alpha}} = \left(\underline{\mathbf{E}}^T \underline{\mathbf{E}} \right)^{-1} \underline{\mathbf{E}}^T \underline{\mathbf{r}}$$

Determines Ink Fraction from Pixel
Value and Pseudoinverse Matrix

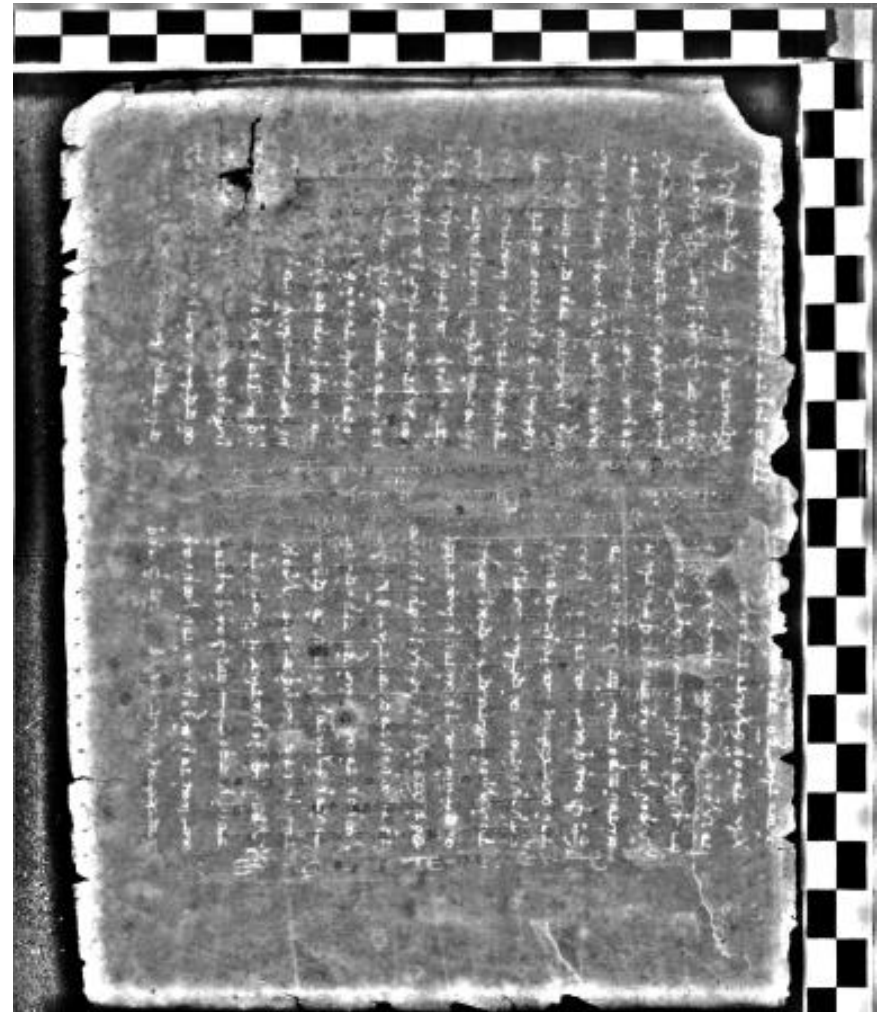
Output of Least-Squares Segmentation

- Images of Each Object Class
 - Parchment
 - Euchologion Text
 - Archimedes Text

70V Reconstructed Underwriting

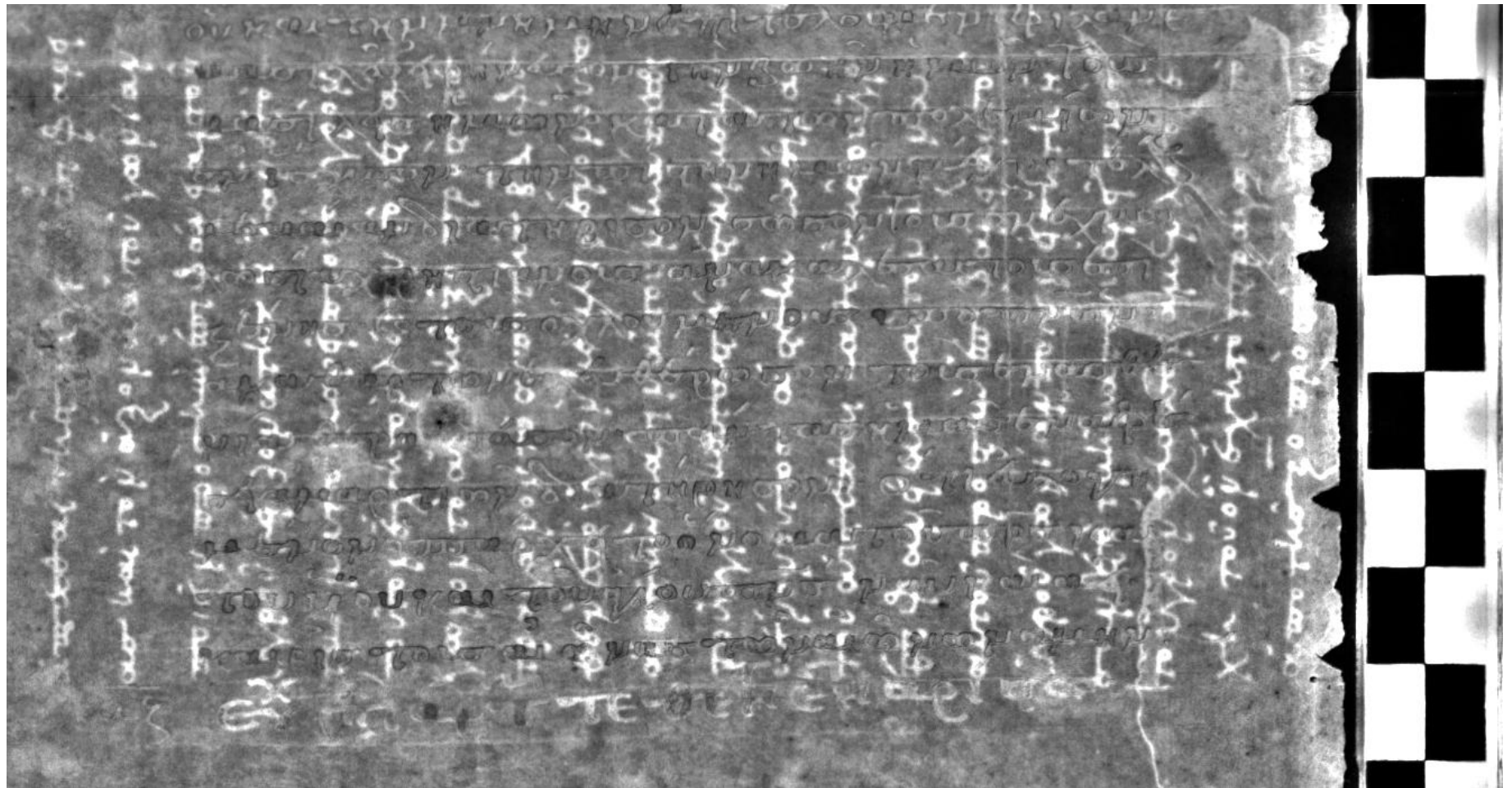


Visual Appearance



Archimedes Text Channel

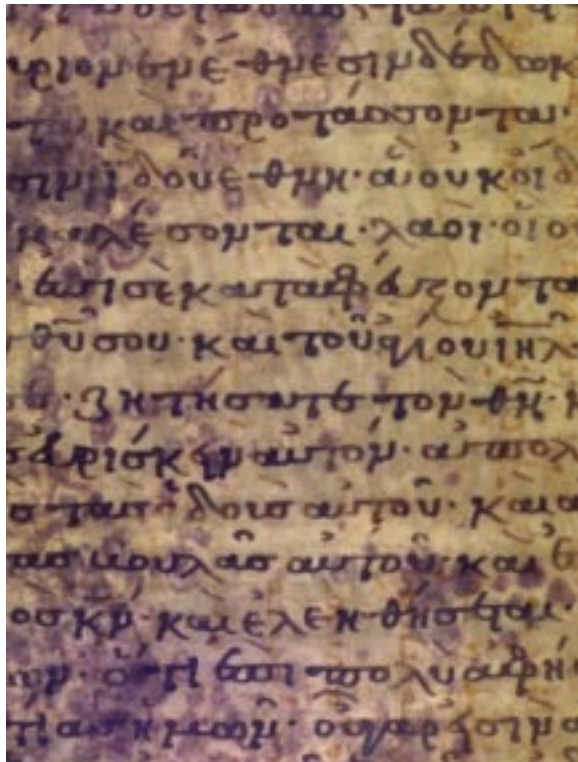
Underwriting on Leaf 70V



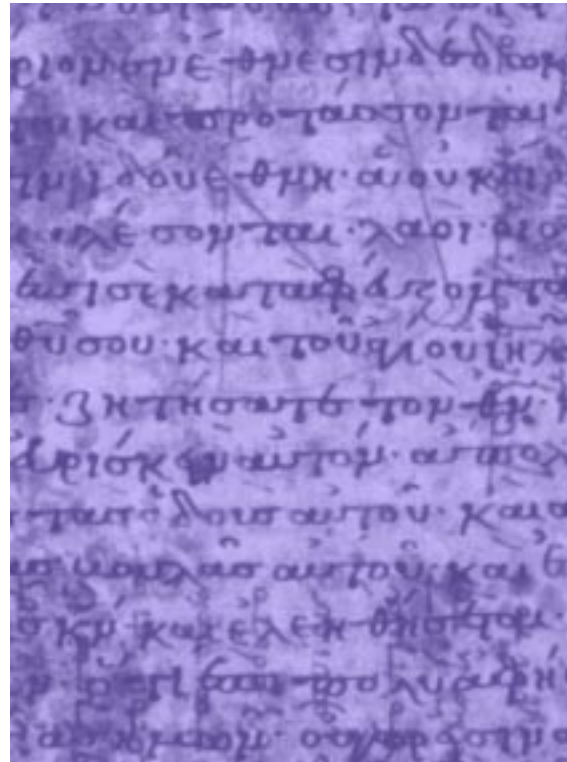
Underwriting “Channel” on Leaf 70V



Images of Leaf 28V



Visible illumination



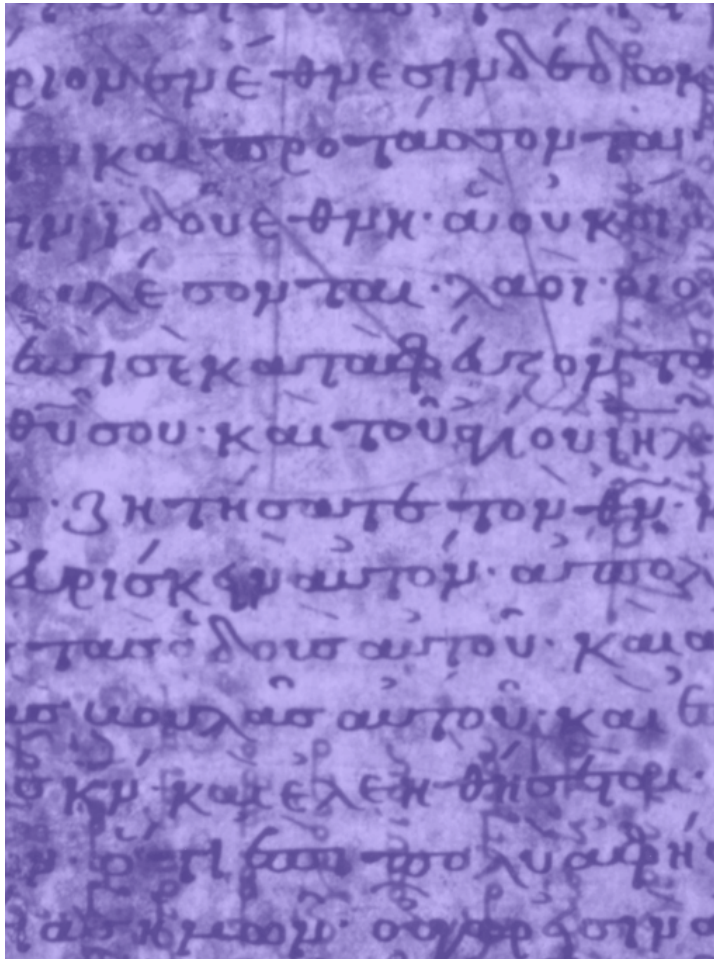
Ultraviolet illumination



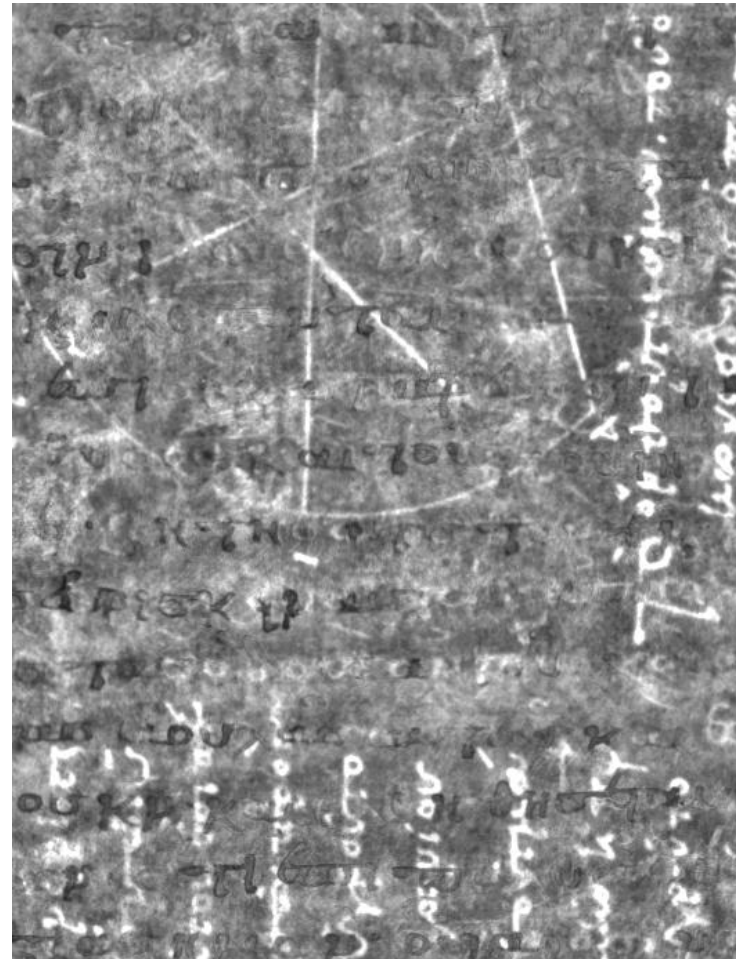
Pseudoinverse model

Scholars Preferred UV Images

no gaps
in text



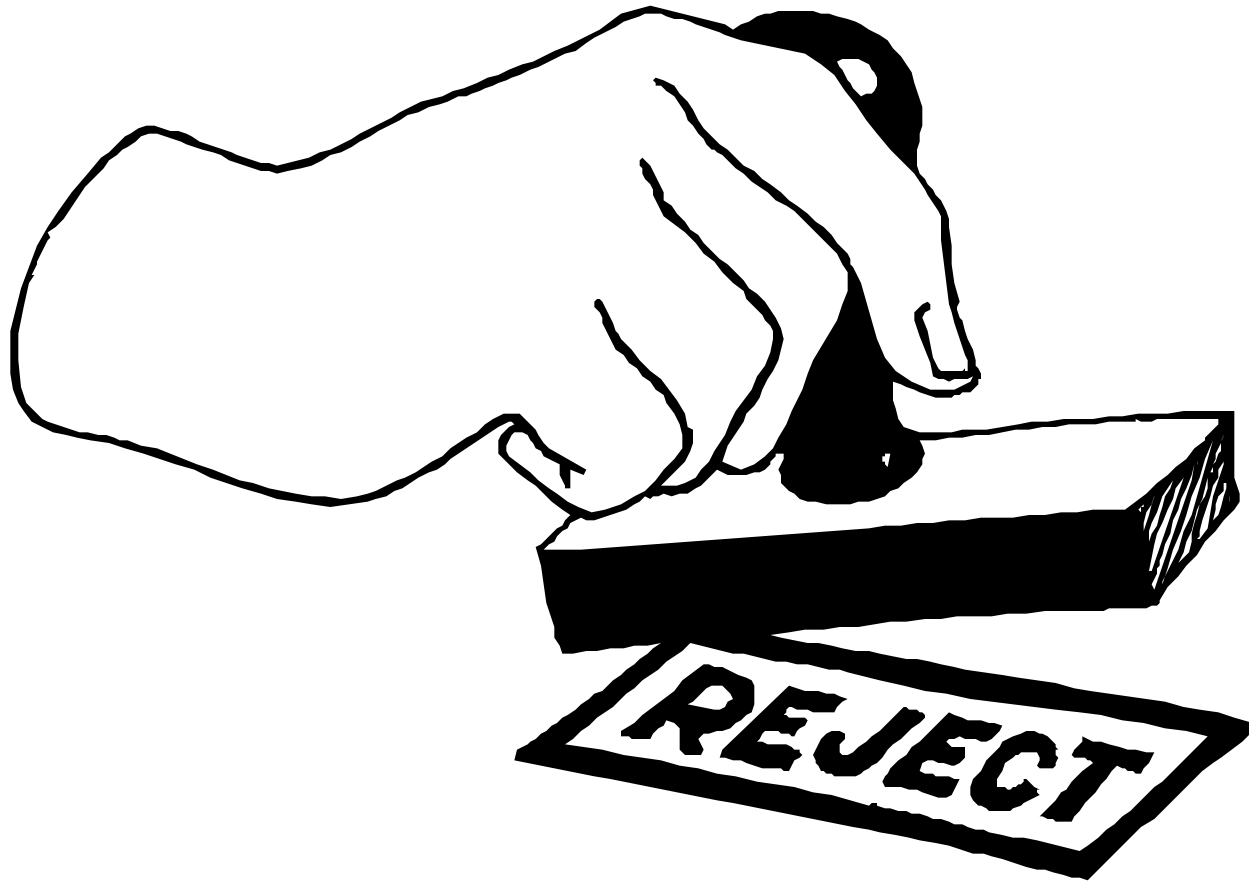
Ultraviolet illumination



noisy

Pseudoinverse Processing

Judgments of Scholars



Reason:

- Wished to See BOTH Texts
 - Distinguish Reason for Text “Gaps”
 - Want “Enhanced” Visibility of Undertext Rather than “Removal” of Overtext

JHU Phase-I Imaging



- Investigated Several Wavelength Bands
 - Different Cameras
- Success with RGB Digital Camera + Different Illuminations
 - No Registration Required

JHU Phase-I Image Processing

- Combinations of Principal Components
 - Euchologion Text in 1st Principal Component
 - Archimedes Text in PC #2+
- Use Thresholded PC#1 as Multiplicative “Mask”
 - Applied to Image with Archimedes Text
 - Fill in “Space” with Parchment
 - Produced a “Cookie-Cutter” Image

Proof of Concept, Early 2001

● Observations

- Tungsten “Red” Channel Shows Little Archimedes text
- Ultraviolet “Blue” Shows Both Writings

● Processing Strategy

- Encode Spectral Differences in Color to Create “Pseudocolor” Images

Images Under Two Illuminations

92v-93r



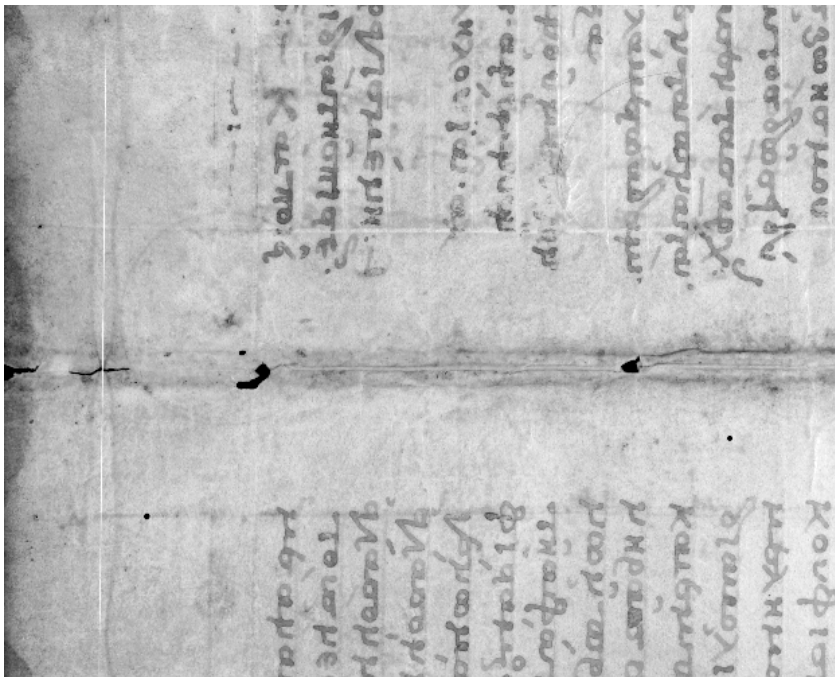
Tungsten



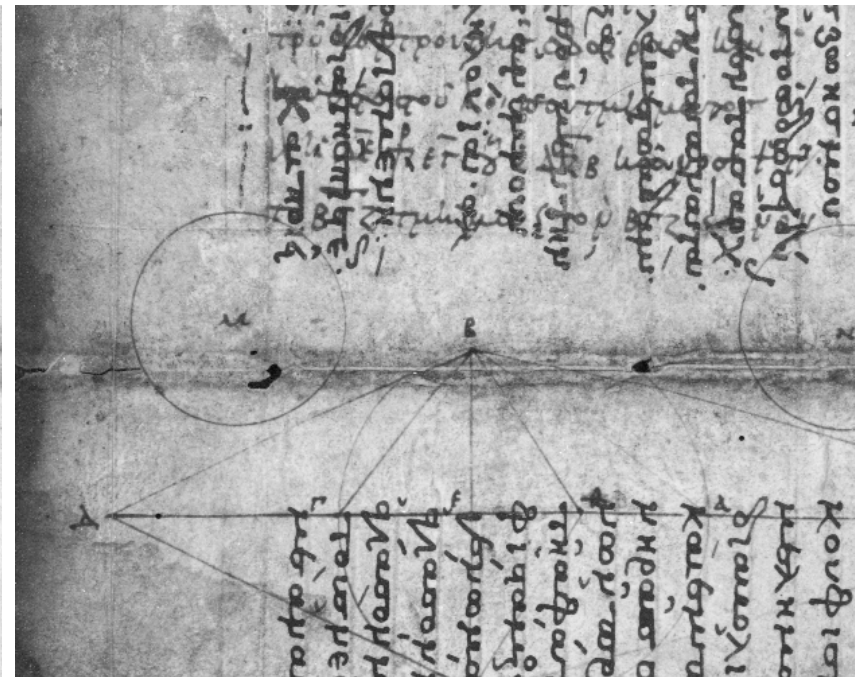
Ultraviolet

Color Separations

92v-93r



Tungsten **Red**



Ultraviolet **Blue**

“Pushbutton” Processing

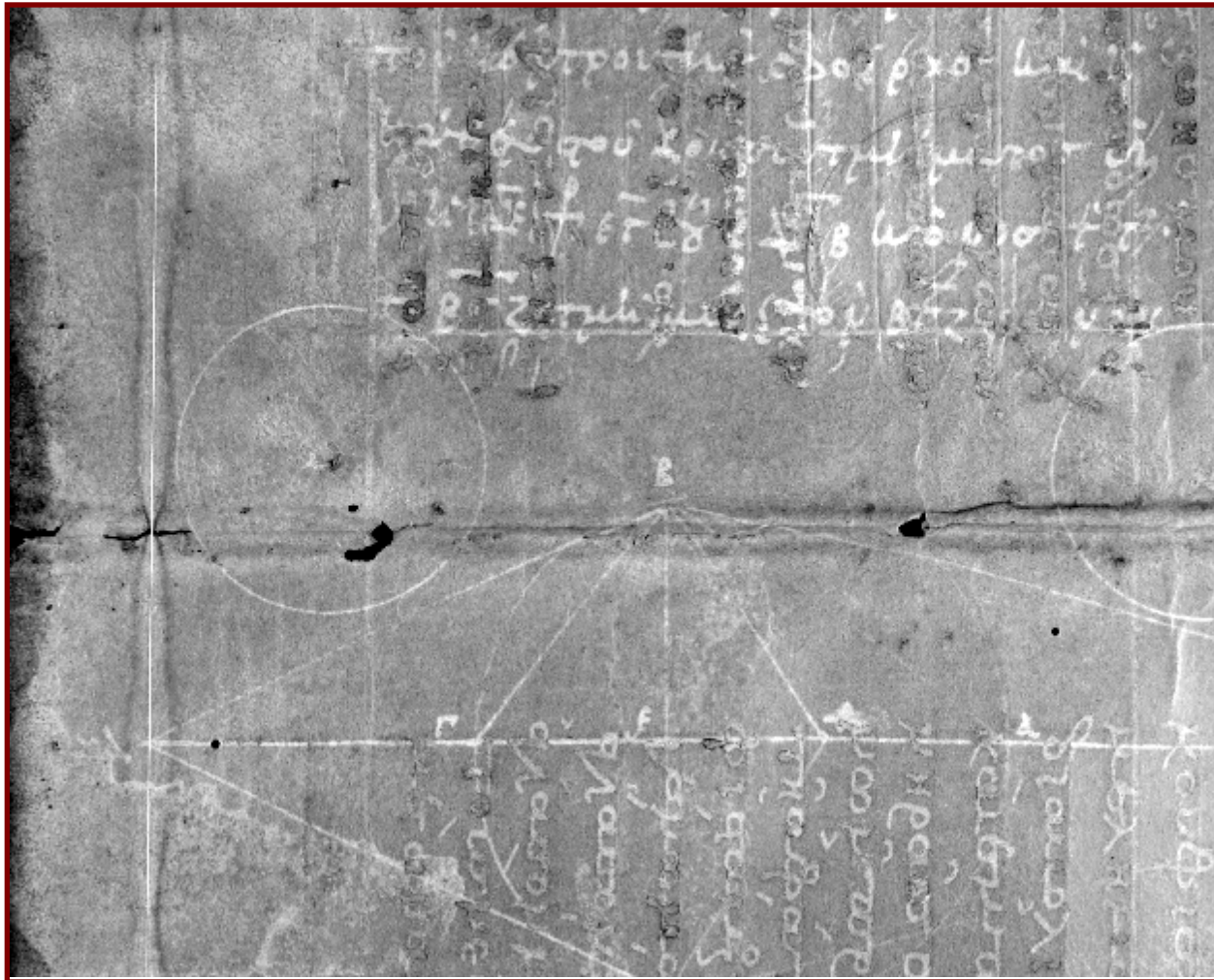
- Observations:

- Tungsten “Red” shows little Archimedes’ text
- Ultraviolet “Blue” shows both writings

- Processing Strategy:

- Scale color separations to “cancel” Prayer Book text
- Display difference of color channels as monochrome image

Difference Image, 93v-92r



- Similar to least-squares result
- “Gaps” where prayer book text removed

Production Imaging, Spring 2001+

- Image all leaves w/ “point-and-shoot” camera
 - Kodak DCS-760 professional digital camera
 - 3 illuminations
 - 3 spectral bands (Red, Green and Blue) per illumination
 - Sufficient for about 80% of text
- Remote sensing algorithms do not work
 - too few spectral bands
- Simpler processing method required

Production Imaging Goals (Phase II)

● Conserve Manuscript

- Disbind (to Reveal Archimedes Text in Gutter)
- Clean (Grime, Wax Droplets from Candles)
- Repair (Parchment Tears, Mold Damage)

● Image Entire Manuscript

- 177 Leaves
 - More than 5,000 digital images
- SIMPLIFY IMAGE PROCESSING
- Estimate Useful Results for 80% of Text

● Process to Reveal Erased Text for Scholars

- Images under Xenon Strobe to Record Visible Appearance
- Ultraviolet Images to Enhance Contrast of Erased Text
- Pseudocolor Combination to Highlight Erased Text

Phase-II Imaging

- RGB Digital Camera

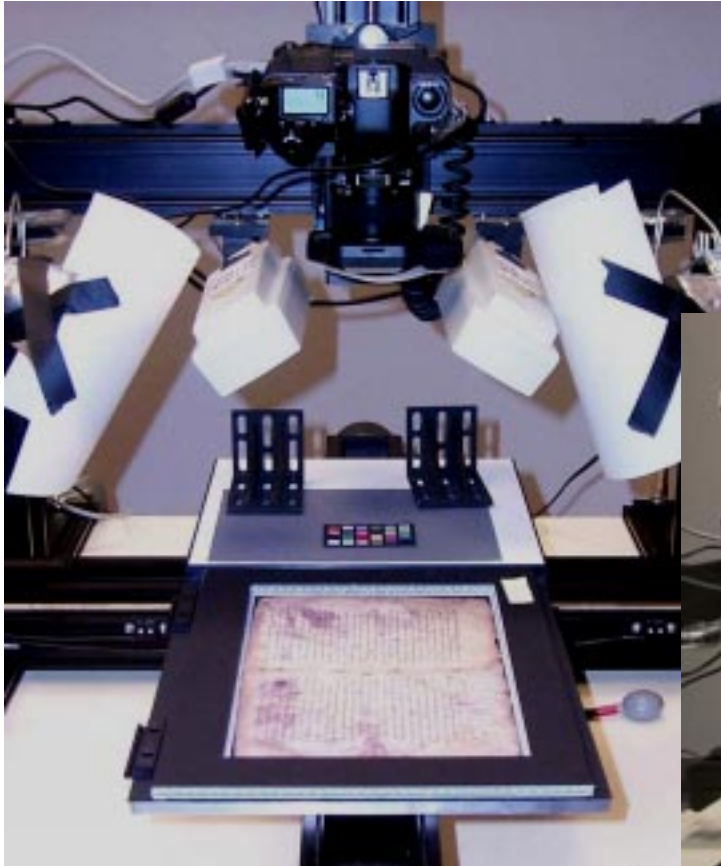
- “Large” Image Sensor ($3K \times 2K$)
 - Spatial Resolution ≈ 25 pixels per mm ≈ 600 dpi
 - $\Rightarrow \approx 7500 \times 5000$ pixels per bifolium
 - $\Rightarrow 10$ images per bifolium
- No Registration Problems

- Computer-Controlled Translation Table

- Three Illuminations

- Xenon Strobe, Documents Visible Appearance
- Low-Wattage Tungsten
- LWUV ($\lambda = 365$ nm)

Production Imaging



- Computer-Controlled Translation Table (XY + 2 Z Axes, for 2 Cameras)
- Custom Mattes
 - Black Backing to Minimize Reflection

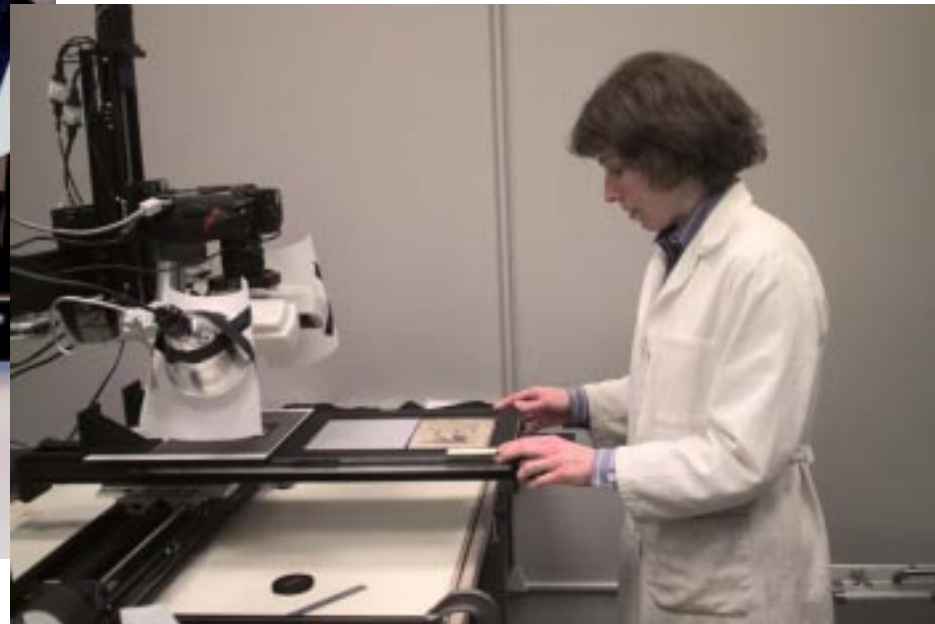
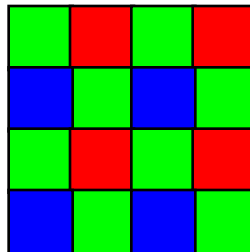
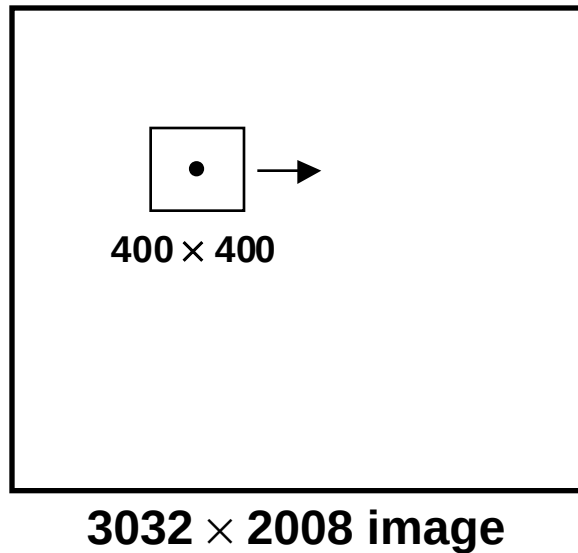
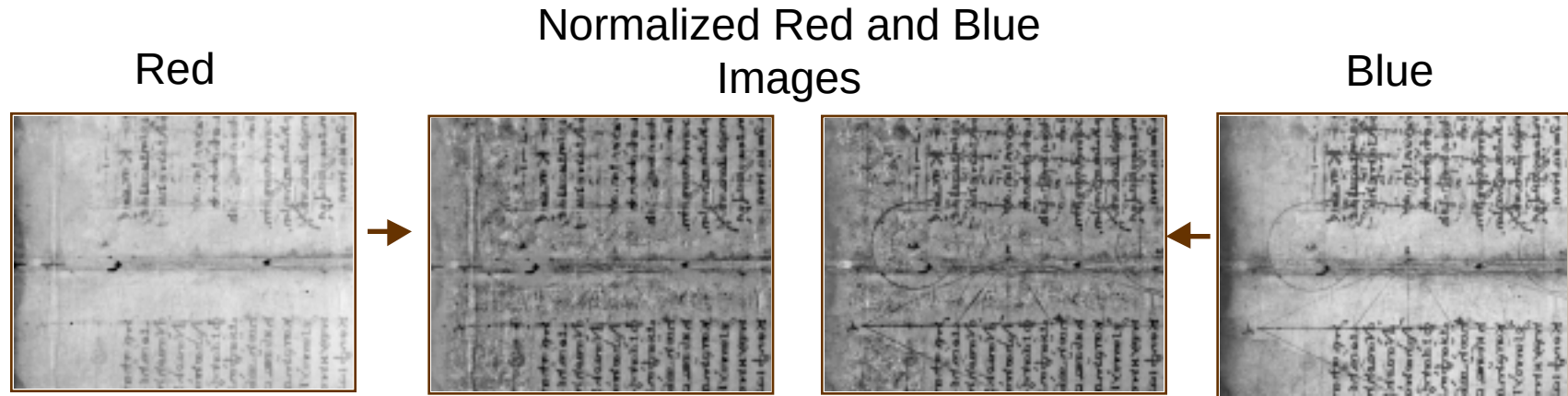


Image Capture

- Photojournalists' Digital Camera
 - Kodak DCS 760
 - RGB Color Filter Array over Sensor
 - 3 Illuminations: UV, strobe, tungsten
 - 10-bit TIFF Output
- Images are “Automatically” Registered
 - Combined to Enhance Visibility of Text
- Bayer Color Filter Array



Automatic Grayscale Normalization



Inside Sliding Window:
Change Value of Center Pixel to Equalize
Mean and Variance in Window

Fast Rectangular Average
Accesses Each Pixel Only 4 Times
Instead of 160,000

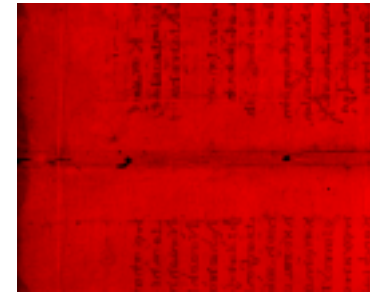
15 Seconds Instead of “Days”

Pseudocolor Image Processing

- Use same two separations as “Pushbutton”
- Encode differences in color
- Goal
 - Retain Prayer Book text
 - Eliminate gaps in text
 - Produce color difference between two texts
 - “pseudocolor” images

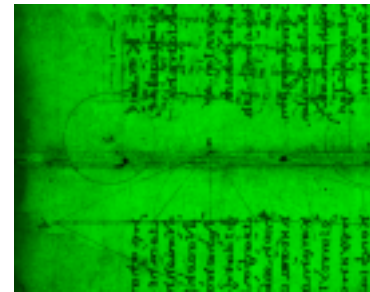
Separations $\Rightarrow$ Color Channels

Tungsten
"Red"
Channel

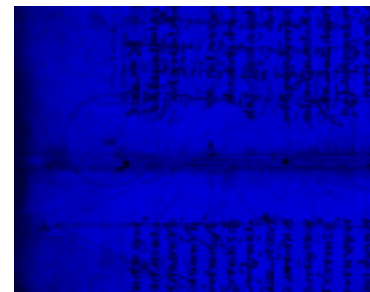


R

Ultraviolet
"Blue"
Channel



G



B

Difference Image vs. Pseudocolor



no gaps

Increased contrast

Pseudocolor Results

48r



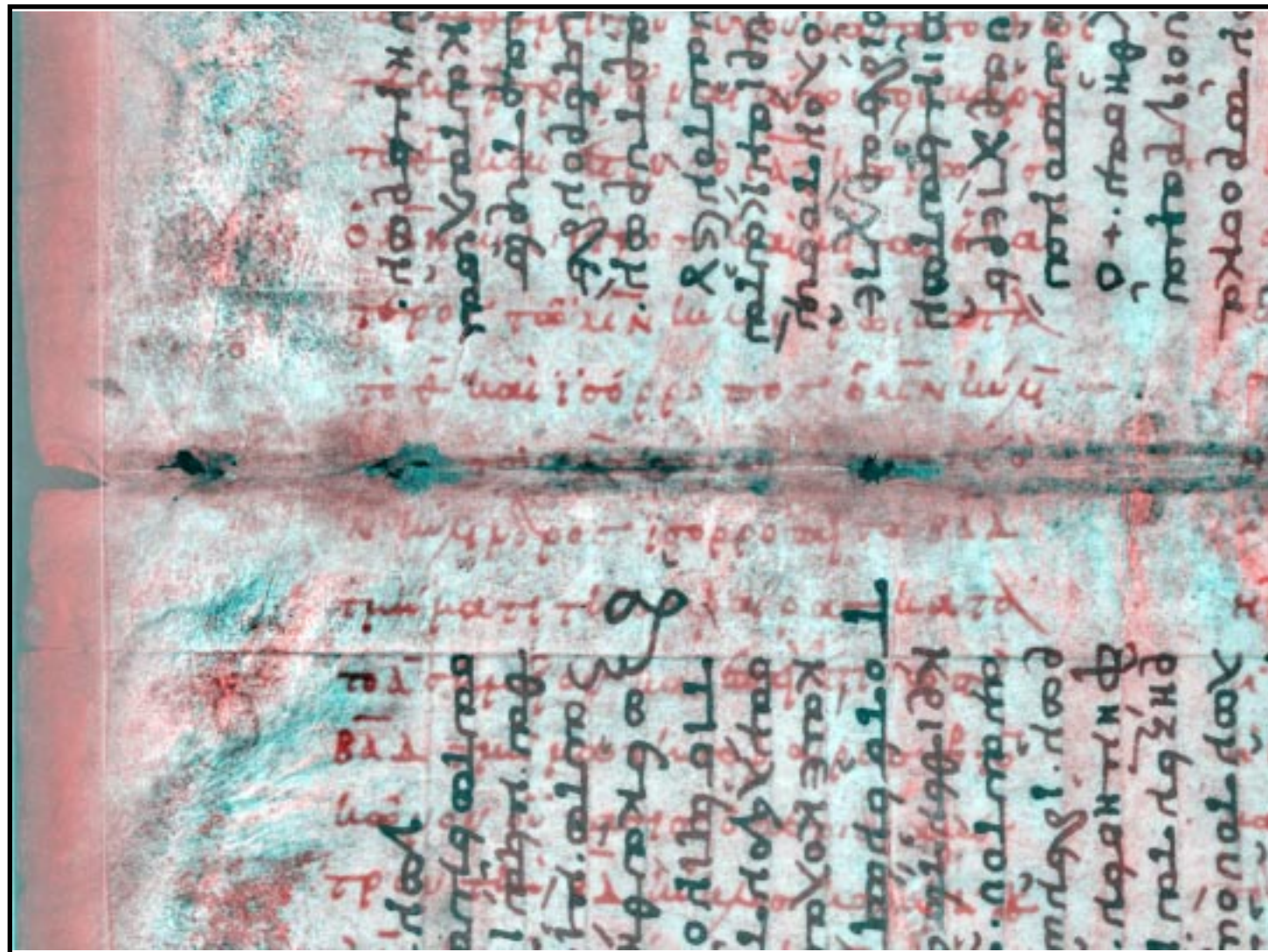
Text in Gutter of Prayer Book

166v-167r



Pseudocolor Processing

166v-167r



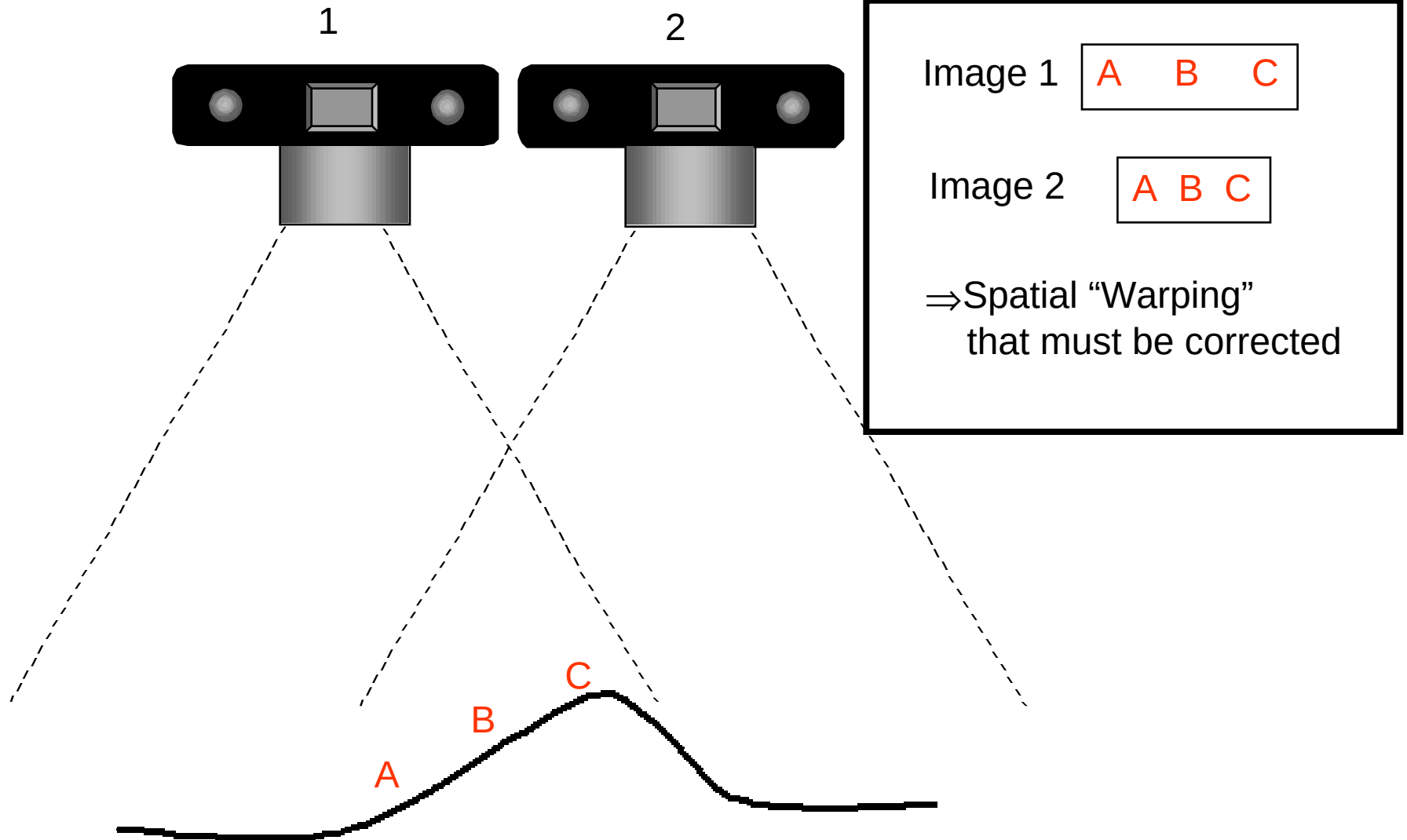
Summary of Pseudocolor Imaging

- Shows Both Texts
 - Scholars Can See Where Archimedes Text is Overwritten
- Different Texts Shown in Different Colors
 - Easily Distinguish Between Two Texts
 - Increase in Text Contrast
 - Both Color and Gray
- Scholars Use “Pseudocolor” Images to Read Erased Archimedes Text

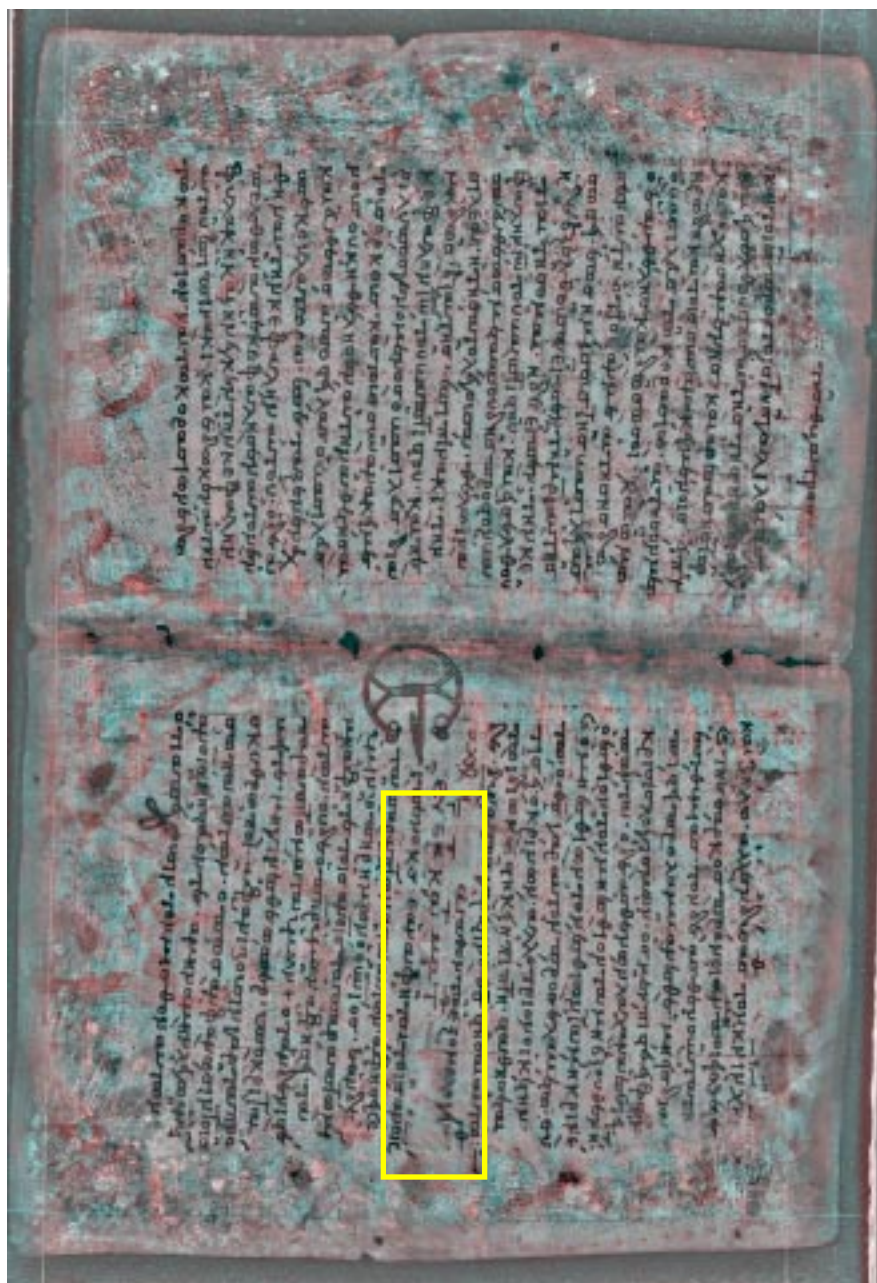
Stitching Software

- “Stitcher” (*RealViz*, France)
 - Intended for Electronic Media Industry
 - Simple and “Fast” ($\approx$ 20 minutes per page)
 - Rotates and Blends “Automatically”
- “DIME” (*Positive Systems*, Whitefish MT)
 - Developed for Remote Sensing
 - User Sets “Tie Points”
 - Image is “Warped” to Fit
 - User Intensive, Longer Time, More Expensive
 - “Pay by the Page”

Problem: “Topography” of Page

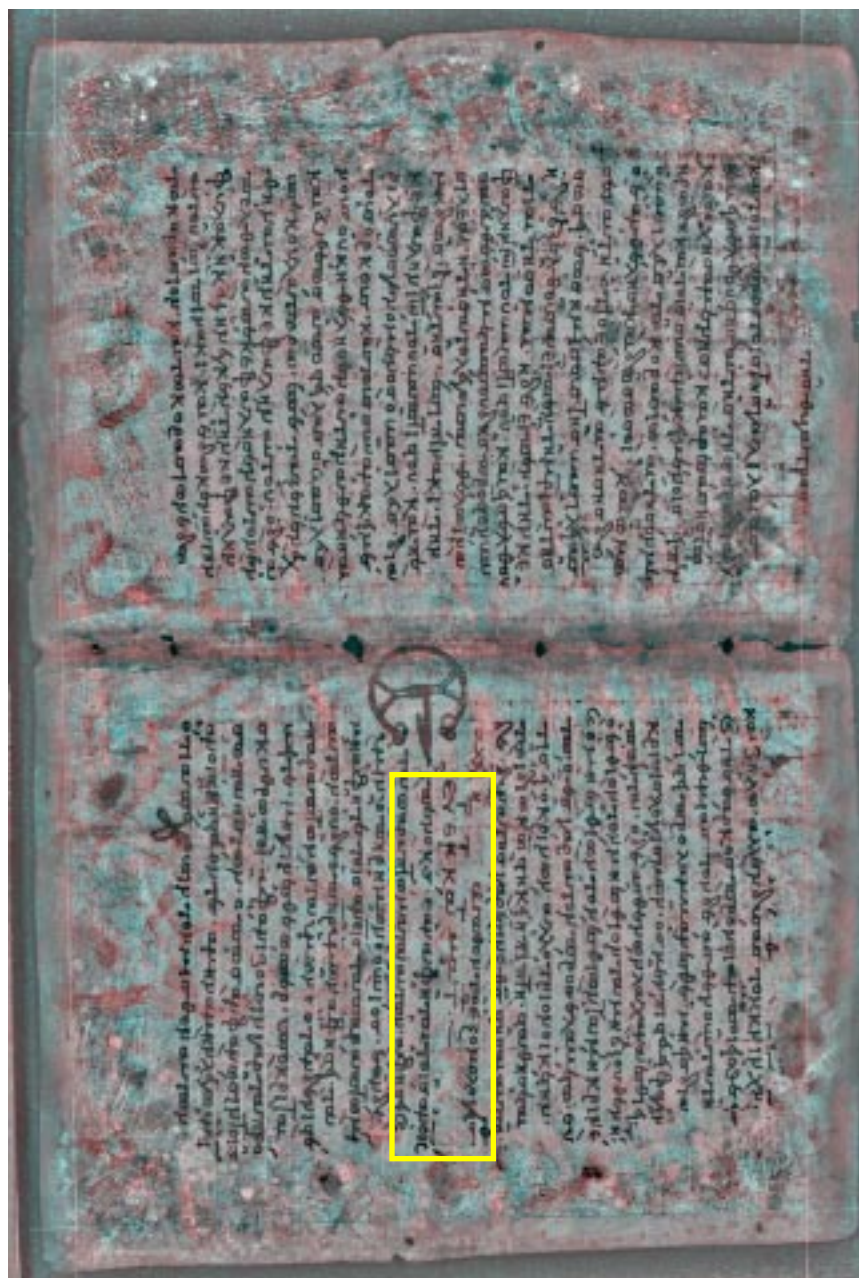


Stitcher

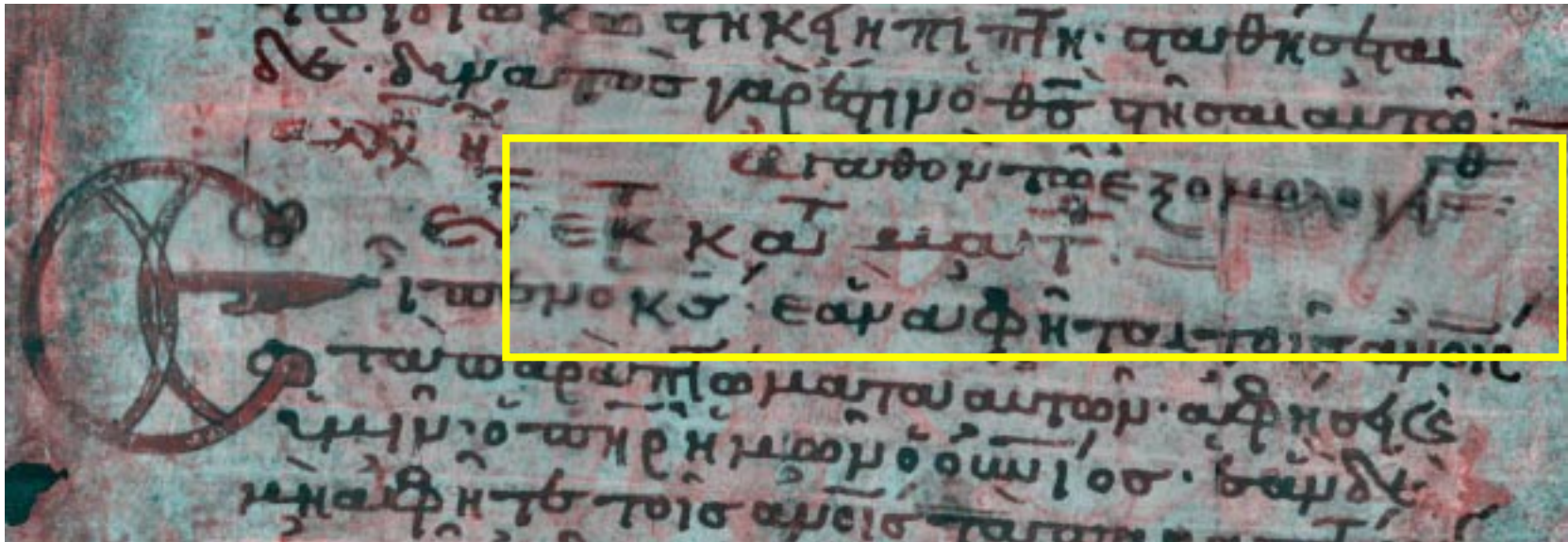


DIME

143r-146v

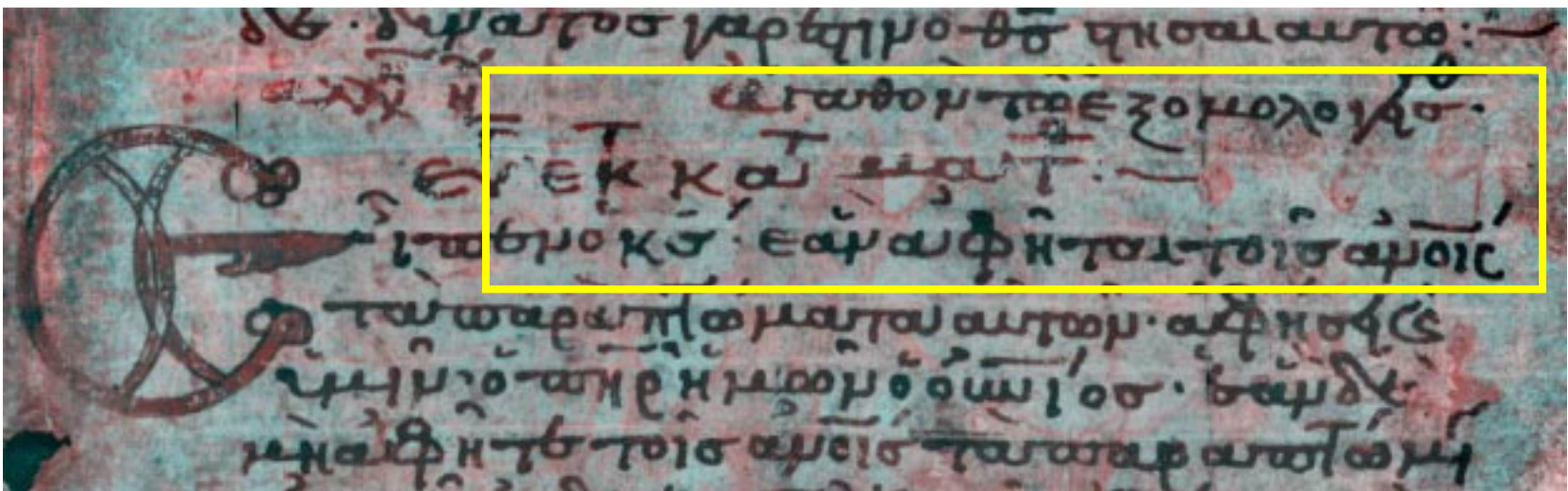


Effect of Topography on Stitching



Stitcher ↑

DIME ↓



Stitching Plans

- Restitch “bad” pages with DIME

Distribution of Images to Scholars

- 2002
 - 30 bifolia
 - 120 pages
 - 1.7 GBytes per bifolium
- Media
 - 11"×17" double-sided prints
 - CD-ROMs (90 per set!)
 - DVDs
 - Disk Drives
 - Web-based image navigator



New Web Browser

- Advantages:
 - Multiple Pages Open at Same Time
 - Direct Access to Other Side of Bifolium
 - Pan and Zoom Capability

New Browser Windows

The screenshot shows a web browser window with the title "Imaging Navigator for the ARCHIMEDES PALIMPSEST". The interface includes a navigation bar with buttons for "Archimedes Pagination", "Euclid's Page", "Collection Data", "Heiberg Images", and "Experimental Imaging". Below this, the "Archimedes Pagination" section is displayed, featuring two tables of manuscript folios. The first table, "Equilibrium of Planes", lists folios 007v-002r, 014v-019r, 081r, and 083r. The second table, "Floating Bodies", lists folios 083r, 056v-049r, 051v-050r, 055r, 082r, 087r, 017v-016r, 029v-021r, 028r, 069v-068r, and 129v-128r. Each entry is accompanied by a brief description of the content.

Imaging Navigator for the
ARCHIMEDES PALIMPSEST

Archimedes Pagination
Euclid's Page
Collection Data
Heiberg Images
Experimental Imaging

Archimedes Pagination

Equilibrium of Planes

007v-002r	022v-007r
014v-019r	019v-104r
081r	081v
083r	083v (Heiberg image only, 083v)

Floating Bodies

083r	083v (Heiberg image only, 083v)
056v-049r	049v-056r (Includes Heiberg images, 056v-049r, 049v-056r)
051v-050r	050v-051r (Includes Heiberg images, 050v-050r, 050v-050r)
055r	055v (Heiberg images only, 055r, 055v)
082r	082v (Heiberg images only, 082r, 082v)
087r	087v (Heiberg images only, 087r, 087v)
017v-016r	016v-017r (Includes Heiberg image, 016v-017r)
029v-021r	021v-029r (Heiberg image only, 021v-029r)
028r	028v (Includes Heiberg image, 028r, Phase II - 1B, November 2001)
028r	028v (Includes Heiberg image, 028r, Phase II - 3A, November 2003)
069v-068r	068v-069r (Heiberg images only, 069v-068r, 068v-069r)
129v-128r	128v-129r

Select

The screenshot shows the "ARCHIMEDES PALIMPSEST IMAGING" interface. It features a grid of blue circular buttons labeled "Individuals" and "Stitched". To the right of the grid, there are links for "Strobe Illumination", "Ultraviolet Illumination", "Pseudocolor Enhancement", "Heiberg Photographs", and "VASARI". Below the grid, the text "BIFOLIO: 016v-017r" and "TREATISE(S): Floating Bodies" is displayed. At the bottom, there are navigation buttons: "Information", "?", "Home", "Reverse Bifolio", and a circular arrow icon.

ARCHIMEDES PALIMPSEST IMAGING

Individuals Stitched

Strobe Illumination
Ultraviolet Illumination
Pseudocolor Enhancement
Heiberg Photographs
VASARI

BIFOLIO: 016v-017r
TREATISE(S): Floating Bodies

Information ? Home Reverse Bifolio

The screenshot shows the "WELCOME" page of the Archimedes Palimpsest Imaging interface. It features a background image of a manuscript page with a circular diagram. The text "WELCOME" is prominently displayed, followed by the instruction "Use the navigation bar on the left to select the images you wish to view". A large black arrow points to the left, indicating the direction to the navigation bar.

WELCOME

Use the navigation bar on the left to select the images you wish to view

Image Selection in New Browser

ARCHIMEDES PALIMPSEST IMAGING

Individuals Stretched

		<u>Strobe Illumination</u>
		<u>Ultraviolet Illumination</u>
		<u>Pseudocolor Enhancement</u>
		<u>Heiberg Photographs</u>
		<u>VASARI</u>

BIFOLIO: **016v-017r**
TREATISE(s): Floating Bodies

Information ? Home **Reverse Bifolio**