Seeing the Invisible Between the Lines

10+ Years of Imaging of the Archimedes Palimpsest

Archimedes Palimpsest

Appearance in 1998

- **Partial copies of seven treatises by Archimedes**
  - **copied in 10th century CE**
  - **only copy of "*On Floating Bodies*" in original Greek**
  - **only copies of leaves of "*Method of Mechanical Theorems*" ("*the Method*") and "*Stomachion*"**
- **Overwritten by "*Euchologion*" (Christian prayer book) in 1229 CE**
  - **177 parchment leaves, each 190mm x 150 mm**

\+ **leaves from other manuscripts**

- **Parts of two speeches by Hyperides, (5 leaves, discovered 2003)**
  - **"*Against Diondas*" and "*Against Timandros*"**
- **Commentary on Aristotle's "Categories," (6 leaves, discovered 2004)**
- **Life of a saint (2-7 leaves, 8/2007)**

Project Goals (from Day #1)

- Apply modern imaging technologies to enhance readability of original text in the *Archimedes Palimpsest*
  - Illumination
  - Cameras
  - Image Processing
  - Image Rendering
- Disseminate results to scholars
- Respond to their feedback

Original Plan, from Day #1

- Collect digital images at different wavelengths (different colors of illumination)
  - "Spectral Imaging"
- Combine images in computer to enhance readability of original text
  - deterministic: construct same combinations of bands for all leaves
  - statistical: different combinations for each leaf determined by conditions

Facts of Life:

- Project has spanned a period of relentless and rapid advance of technologies
  - tools for illumination, imaging, processing, and dissemination have changed and been enhanced
    - (some dramatically so)
    - ⇒ rapid obsolescence of imaging tools
- Began with commercially available cameras, illumination, and processing
  - to save time and money
- Evolved towards customized tools: LED illumination and processing software
  - to deal with leaves that did not respond to original tools

Imaging State of the Art, early 1990s

- little changed from 1930s: (*Scientific Aids for the Study of Manuscripts* by R.B. Haselden, Oxford University Press, 1935)
- Illumination
  - Reflected and transmitted imaging via tungsten incandescent lamps
  - Fluorescence imaging via ultraviolet lamps
  - Oblique lighting for indentations
  - Wratten gel filters for spectral information
- Optics
  - Microscopes
  - Hand magnifiers
- Photography
  - Panchromatic and color films
  - "Standard" cameras and lenses
  - Single copies, replication was difficult and expensive
  - Dissemination via mail/express carrier

State of the Art, mid-1990s

- First digital cameras
- 1.3-megapixel sensor (Kodak DCS 100)
  - 1320 × 1035 pixels, ~ $20,000 - $25,000
- Standard Lenses:
  - 60mm Micro-Nikkor (~ $400, but corrected for visible wavelengths only)
  - 105mm Nikkor telephoto (quartz lenses ⇒ transmits UV)
- Processing Tools:
  - Adobe Photoshop 4, custom software
- Dissemination via floppy disks

State of the Art, 2001

- 6-megapixel sensor (e.g., Kodak DCS 760)
  - photojournalist's camera
  - 3032 × 2008 pixels, ~$8000
- Standard Lenses
  - for imaging in visible light
- Spectral information obtained by filtering light into camera
  - source of some difficulty
- Processing Tools
  - Adobe Photoshop 6
  - Scientific toolboxes from remote sensing, medical imaging
  - Custom software
- Dissemination via external disk drives over "SneakerNet" (or, more accurately, "FedExNet")

State of the Art, 2015

- 50-megapixel sensor (8304 × 6220 pixels)
  - ~ $20,000
  - Silicon: sensitive from near-ultraviolet to near-infrared
    - 350nm ≤ λ ≤ 1050nm
- Illumination by light-emitting diodes (LEDs)
  - Many narrow wavebands
- Spectral lenses
  - corrected focus over bands from near-UV to near-IR
- Many processing tools now available
  - Photoshop (~$1K), GIMP ($0), ENVI ($7K), ImageJ ($0)
  - Some campuses have licenses that reduce direct cost
- New Imaging Modalities
  - Reflectance Transformation Imaging (RTI)
  - X-ray fluorescence (XRF) for obscured/faded text on high-value objects
- Dissemination over Internet

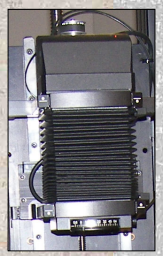
Digital Cameras Used

Kodak DCS-100, 1.25 MP, 1991
$20,000 - $25,000 new

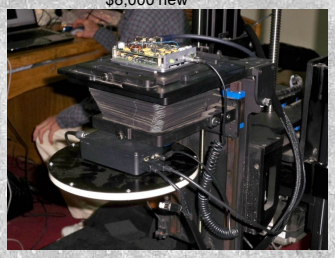
Photometrics *SenSys*, 1.5 MP, 1998
$25,000 new

Kodak DCS-760, 6 MP, 2001
$8,000 new

Photometrics *Quantix*, 6 MP, 2004
$25,000 new



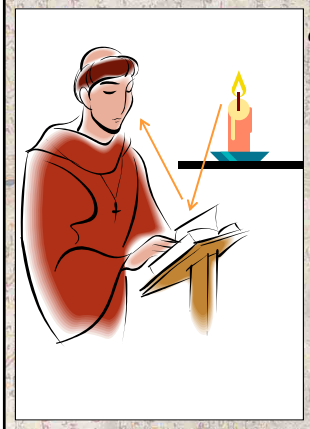
Sinar MP54, 22 MP, 2007
$15,000 new



Megavision, Kodak KAF39000 sensor
39 MP, 2009

Task: Recovery of Erased Text

How Do We Read Text?



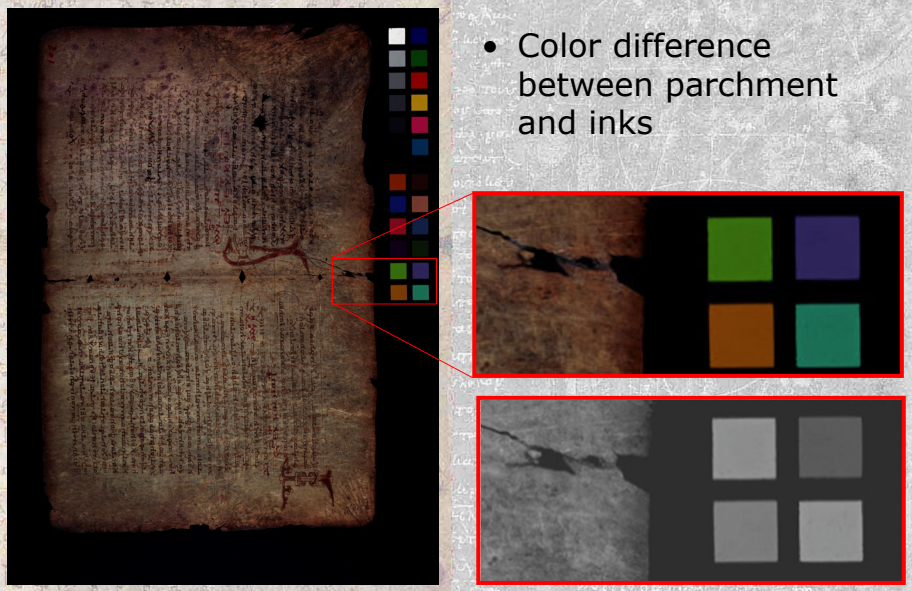
- Information conveyed from page to sensor (e.g., eye or camera) by light waves (electromagnetic radiation)
  - only visible light is "visible!"
  - visible *and* invisible light are measured by silicon sensors in digital cameras
    - a "bug" for snapshots (would add "invisible light" to images)
    - a "feature" for us ("invisible light" conveys useful text information)

Attributes of Handwritten Text

1. Chemical constituents of ink and parchment
   - e.g., iron in ink, calcium in parchment, …
   - (What we REALLY want to measure to locate ink on page)
   - Constituents are measured by X-ray fluorescence
2. Relative "lightness" of texts and parchment
   - described as "contrast" between ink and leaf
   - determined by material constituents, age, wear and tear, …
3. Colors of texts and leaf
   - "color contrast"
4. Depressions in parchment, due to:
   - Force of pen nib
   - Excavation of parchment by acid in ink
5. Character "shapes"

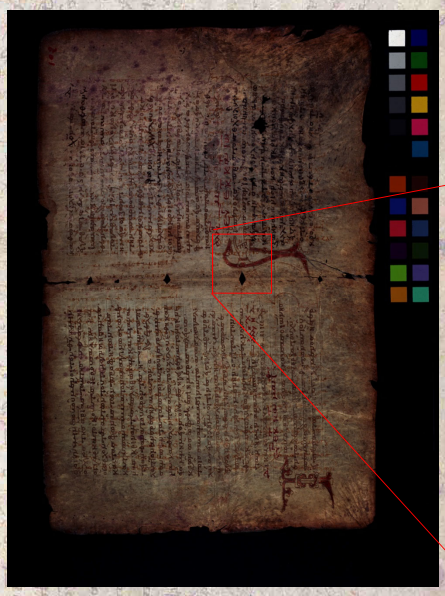
Each was useful for some text!

Color Contrast



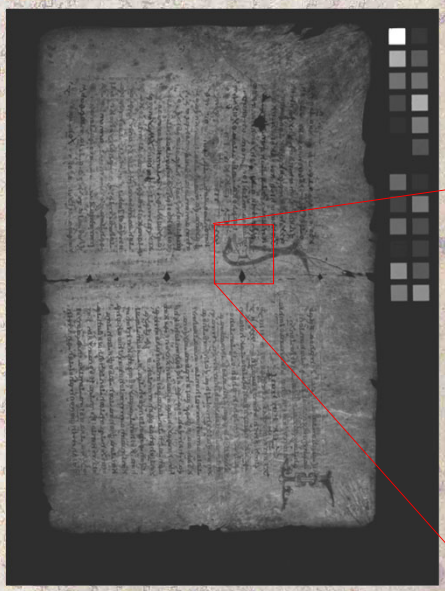
- Color difference between parchment and inks

Color Contrast



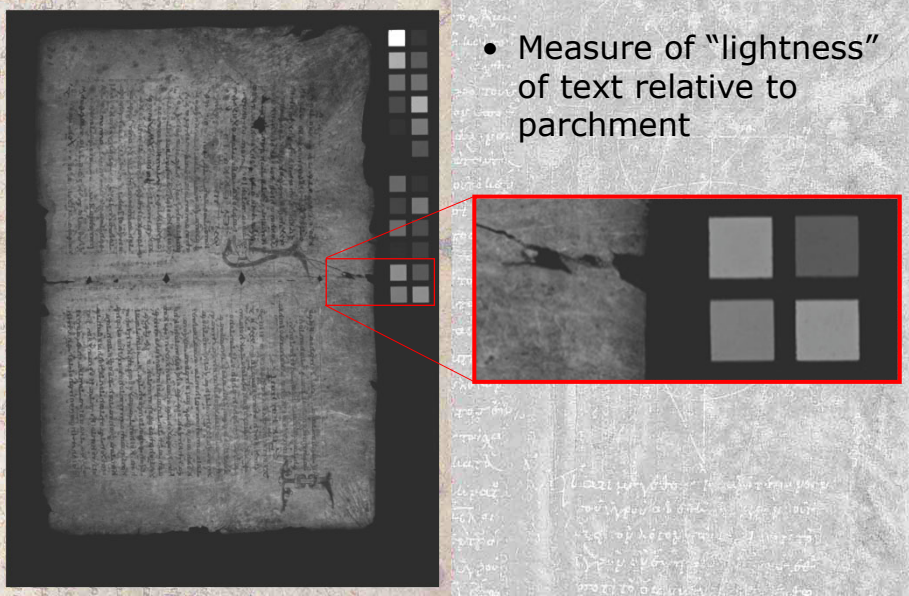
- Color difference between parchment and inks

Text Contrast



- Measure of "lightness" of text relative to parchment

Text Contrast



- Measure of "lightness" of text relative to parchment

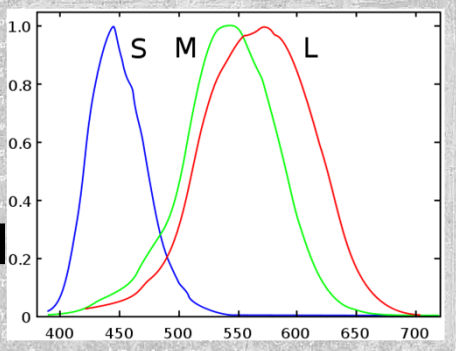
Use Color Contrast to Estimate Chemical Constituents of Ink and Leaf

- Measure "spectra" of objects on leaf
  - Spectrum: "amount" of light at each wavelength that was:
    1. Reflected from surface of leaf
    2. Emitted by objects after light from another source was absorbed ("fluorescence")
- Spectra are "fingerprints" of materials

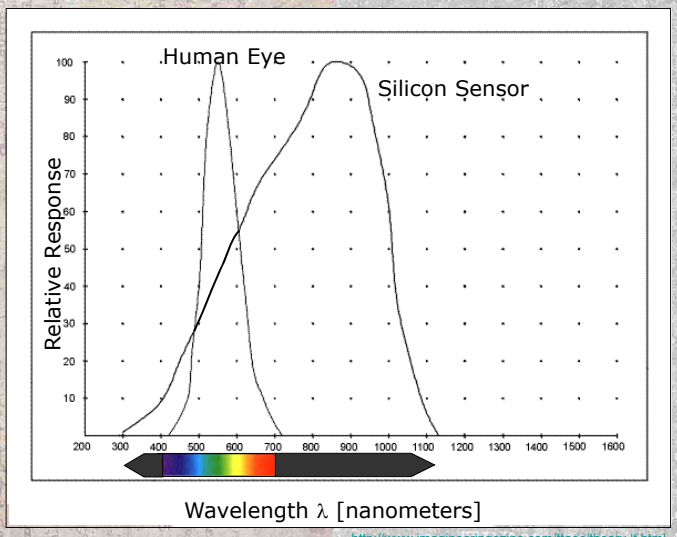
Collecting Spectral Images

Human Eye: Three Color Sensors

- "Cones"
  - "L," "M," "S" (long, medium, short)
  - Act like sensors with overlaid colored filters
- 3 types of cones ⇒ 3 primary colors
  - Additive Primaries
    - colored lights
    - **Red**, **Green**, **Blue**
  - Subtractive Primaries
    - colored pigments
    - **Cyan**, **Magenta**, **Yellow**



Comparison of Sensitivity Range of Human Eye and Camera Sensor



http://www.imagineeringezine.com/ttaoc/theory-lf.html

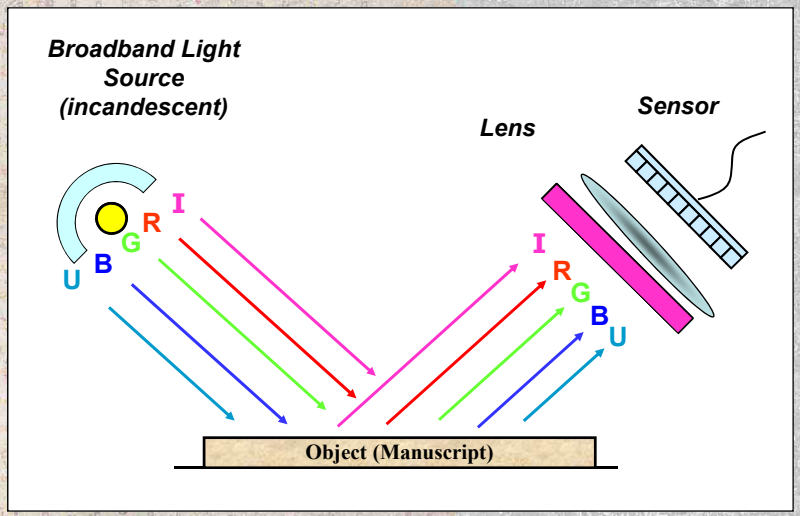
Different Information Conveyed by Different Wavebands

- Visible wavelengths
  - Colors of features (e.g., parchment, inks)
- "Near-Infrared" (NIR) wavelengths
  - "Sees through" darkened or charred parchment
    - reflectance of parchment remains large at infrared wavelengths
- "Near-Ultraviolet" wavelengths
  - Enhance visibility of faded text by fluorescence of parchment
- X rays
  - Can penetrate and escape obscurations
    - e.g., forged paintings in Archimedes Palimpsest
  - BUT: experimental setups (sources + detectors) are expensive

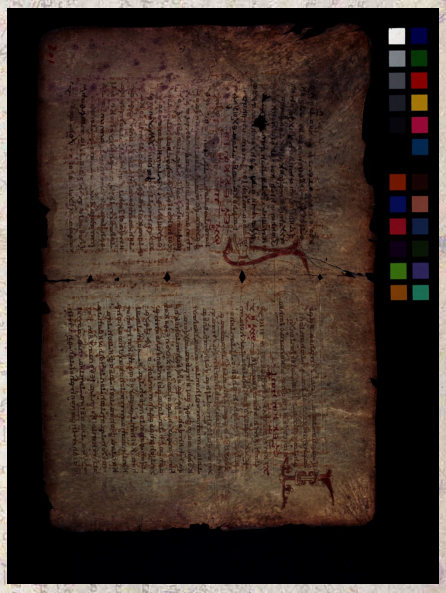
Reflectance Spectrum

- Percentage of light at each wavelength λ that is *reflected* by material (e.g., inks, parchment)
- Depends on color and "density" of colorant
  - may see background through "sparse" colorant
- May be useful for classifying constituents at each pixel

Spectral Reflectance Imaging of Manuscript

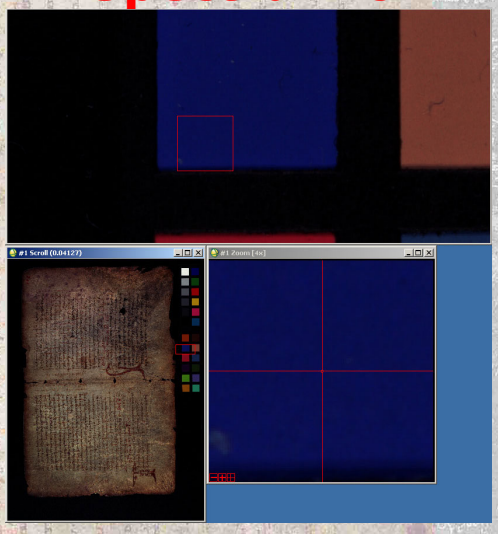


Spectrum of RGB Color Image



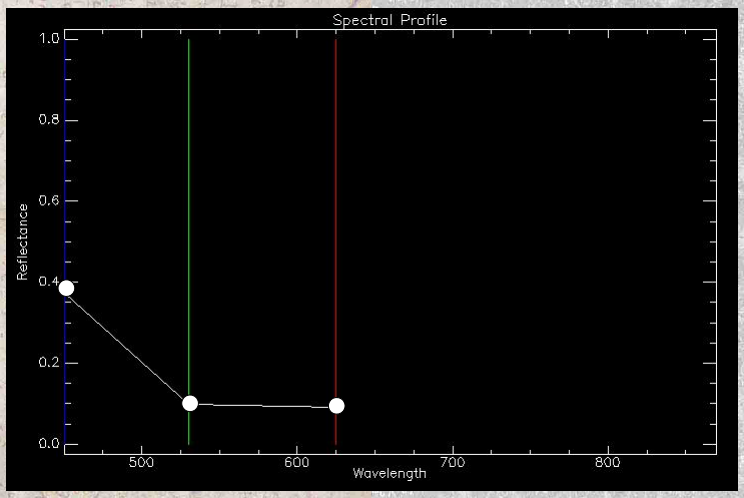
- Samples reflectance of materials in:
  - red light
  - green light
  - blue light

Measure RGB Reflectance Spectrum of "Blue Patch"

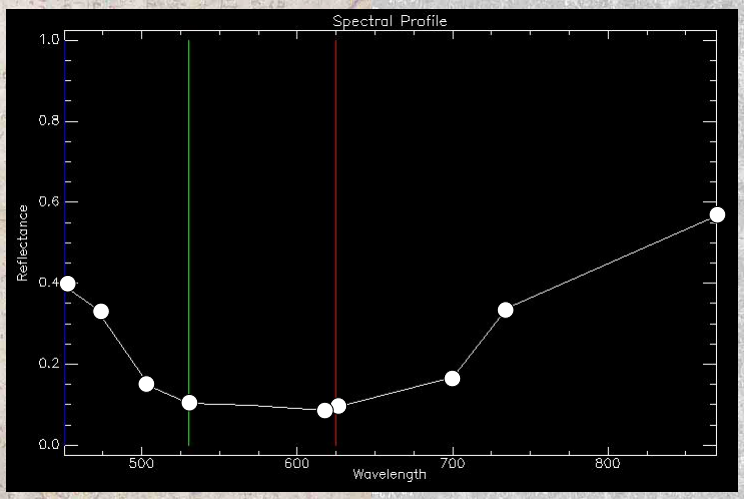


- Reflects blue light well
  - "brighter" at short wavelengths

RGB Measurements of Blue Square

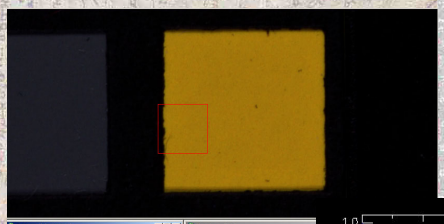


10-Band Measurements of Blue Square



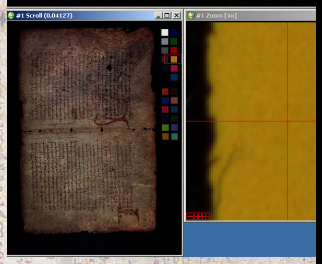
Low reflectance in green and red, large reflectance in blue and infrared

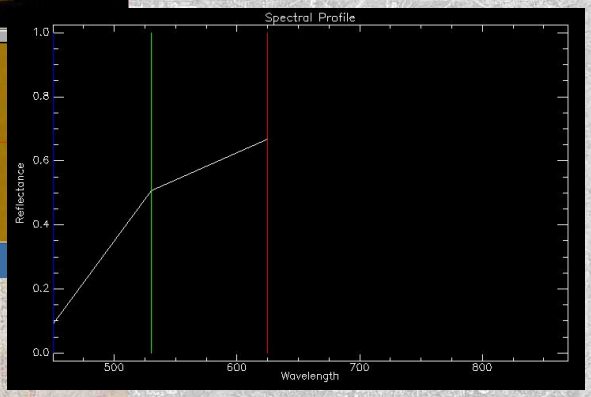
RGB Spectrum of Yellow Patch



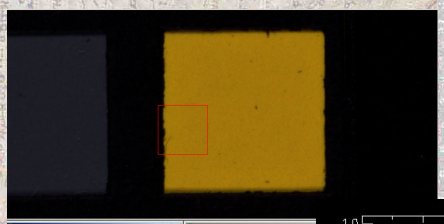
Yellow Patch:
- absorbs blue light
- reflects green and red light

Yellow = Red + Green

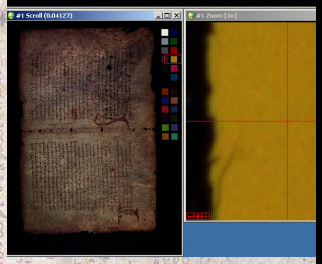


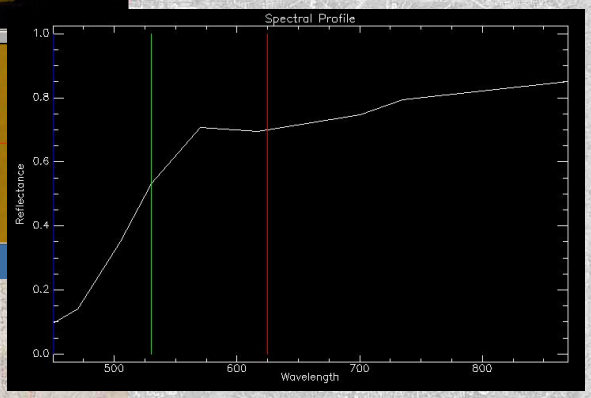


10-Band Spectrum of Yellow Patch

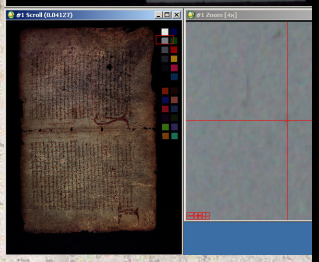


Large reflectance in Green, Red, Infrared

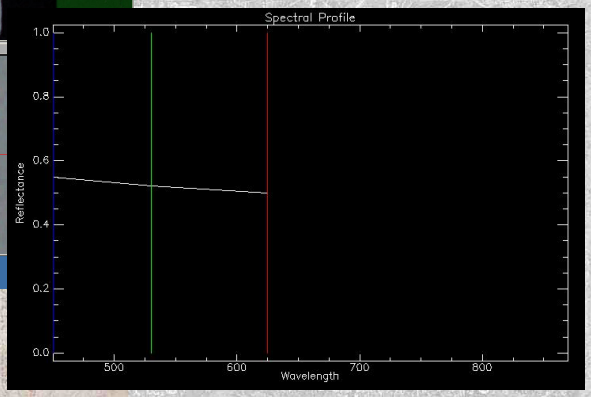




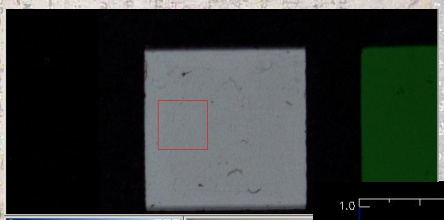
RGB Spectrum of Gray Patch

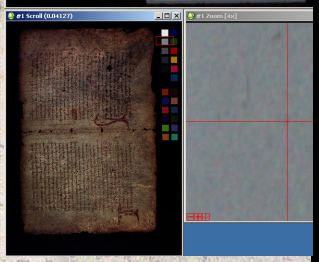


Gray Patch:
- reflects all visible light "about the same"

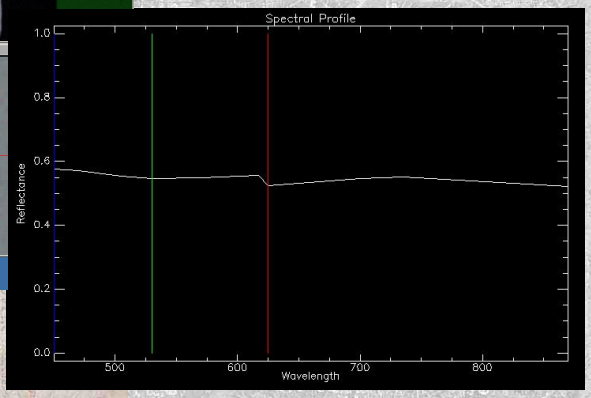


10-Band Spectrum of Gray Patch

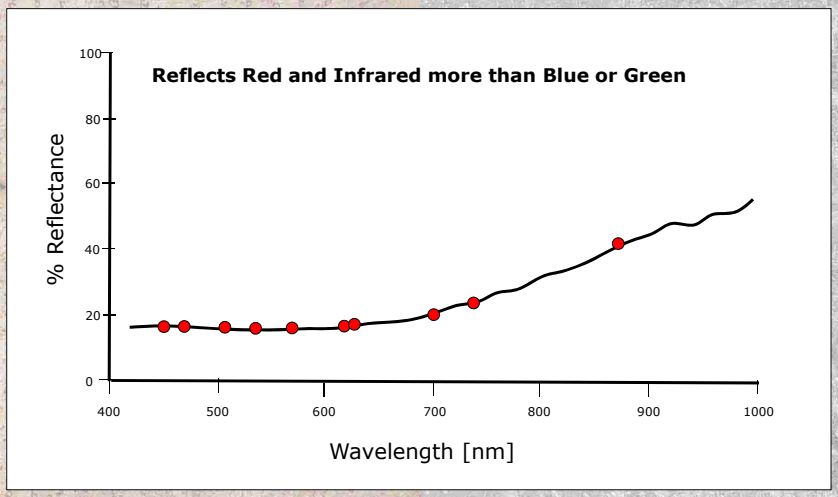




Gray Patch:
- reflects infrared as much as visible light



Spectrum of Sample of Iron Gall Ink

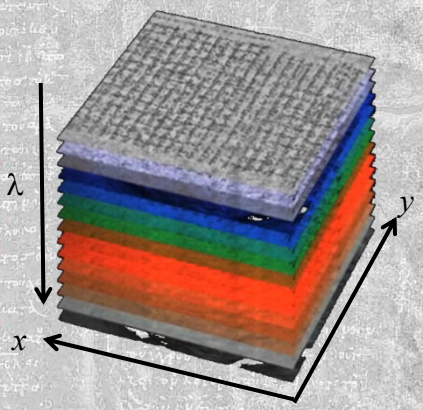


http://codexsinaiticus.org/en/project/conservation_msi.aspx

Measurements at Different Wavelengths ⇒ Image "Cube"

- "Stack" of images of same scene ordered by wavelength
- Images at different wavelengths in [x,y] plane
- Spectra of individual pixels parallel to λ axis

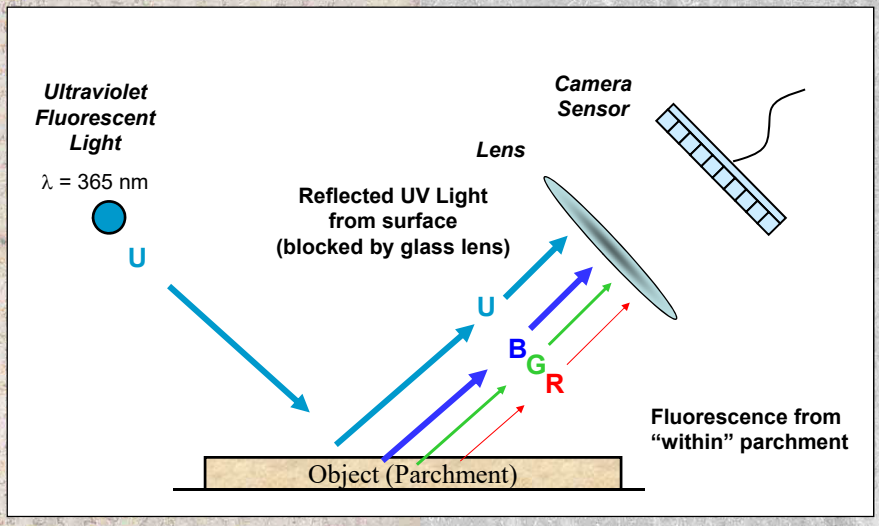
Image Cube, Sampled Spectra



"Fluorescence" Imaging

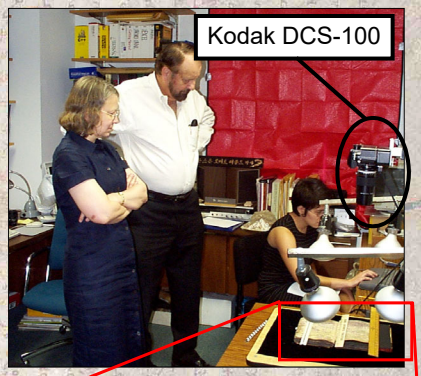
- Fundamentally different from reflectance imaging
- λ of incident light from source is "short" (often UV, can be X rays)
- Light is *absorbed* by object and *reemitted* with longer λ ⇒ less energy
  - incident ultraviolet light ⇒ emission from parchment dominated by blue
  - incident X rays ⇒ emits lower-energy X rays
- UV fluorescence has been used for many years to enhance faded text
  - Parchment/paper "glows" beneath absorbing ink

Fluorescence Imaging



Application of Imaging to the Archimedes Palimpsest

Imaging for Christie's Catalog, August 1998

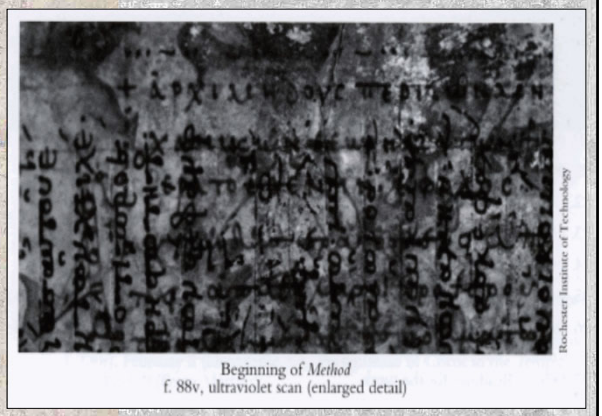


Hope Mayo Keith Knox Bob Johnston

Images for Christie's Catalog

Demonstrated benefit of modern imaging tools

©Christies



Beginning of *Method*
f. 88v, ultraviolet scan (enlarged detail)

p. 35, ©Christies

Archimedes Palimpsest Imaging 2001 – 2006

- "Production Imaging" of entire manuscript
  - 177 Euchologion leaves (~90 original leaves)
    - 3 illuminations (tungsten, Xenon strobe, ultraviolet)
    - Imaged at 600 ppi, 10 camera positions
    - > 5,000 digital images
- Process to enhance/reveal erased text for scholars
  - Strobe images to record visible appearance
  - Ultraviolet images to enhance contrast of erased text
  - Pseudocolor combination to highlight erased text
  - Stitch to create replicas of full leaves

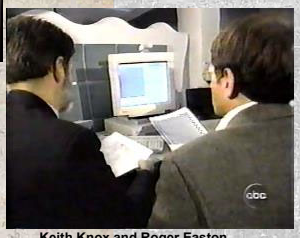
1998 Auction

- 29 October 1998
- Lawsuit by Government of Greece to prevent auction was denied just before
- Sold in a minute (or so) for $2 Million




Preliminary Imaging Session Summer 2000

Charles Dickinson (CIS M.S. Student)
organized and supervised competitive imaging session



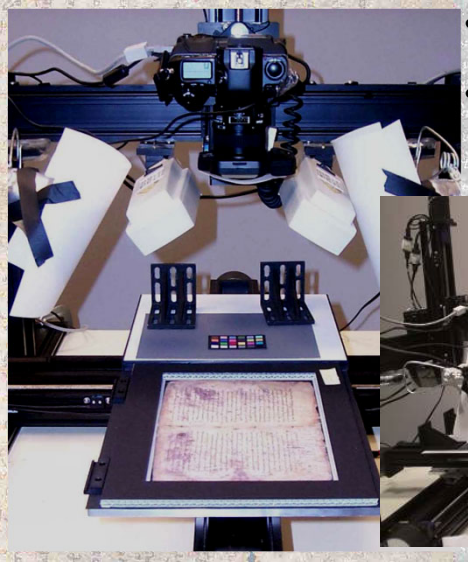
Keith Knox and Roger Easton

Camera for "Production" Imaging

- Kodak DCS 760
  - Photojournalists' digital camera
  - Color filter array
  - 3032 × 2008 pixels ⇒ 6 megapixels
  - sensitive from blue to near IR
    - 400nm ≤ λ ≤ 1000nm
- State of the Art in 2001, ~ $7000
  - Comparable camera ≤ $1000 now

- Each bifolio imaged in 10 sections and digitally stitched
  - 3 illuminations (tungsten, UV, Xenon strobe)
  - Stitched images ~ 5000 × 7000 pixels
  - final resolution ~ 600 dpi (25 mm^{-1})

"Production Imaging" (2001 – 2006)



- Computer-controlled RGB digital camera and XYZ table
- Custom black mattes
  - minimize "show through"

Combine Reflectance and Fluorescence Images

- Observations:
  - Archimedes text has faded and appears "reddish" under white light
  - Archimedes text appears "black" or "gray" under ultraviolet light
  - Euchologion text is "black" or "gray" under both illuminations
- Strategy to enhance undertext:
  - Combine images taken under two illuminations
    - Low-wattage tungsten
    - Ultraviolet

Processing Algorithm

- Readily automated
- "Fast"
- Combination of two image bands:

1. Red channel of image under visible light
   - erased undertext "disappeared" into parchment
   - "neutral" overtext readily visible
2. Blue channel of image under ultraviolet light
   - enhanced visibility of both undertext and overtext

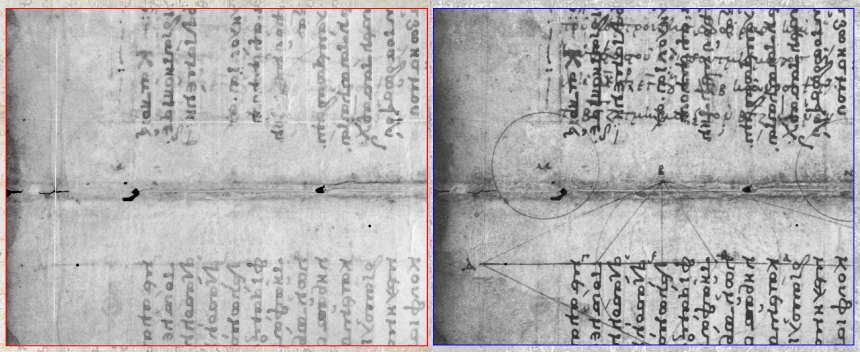
Images Under Two Illuminations

f. 093v-092r

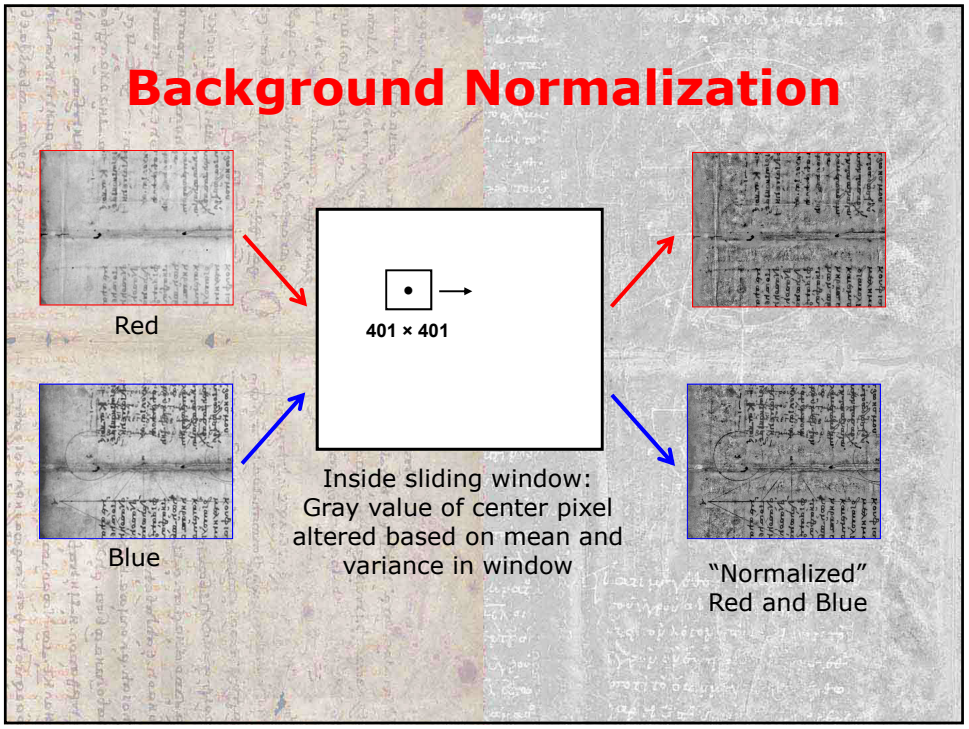
Tungsten | Ultraviolet

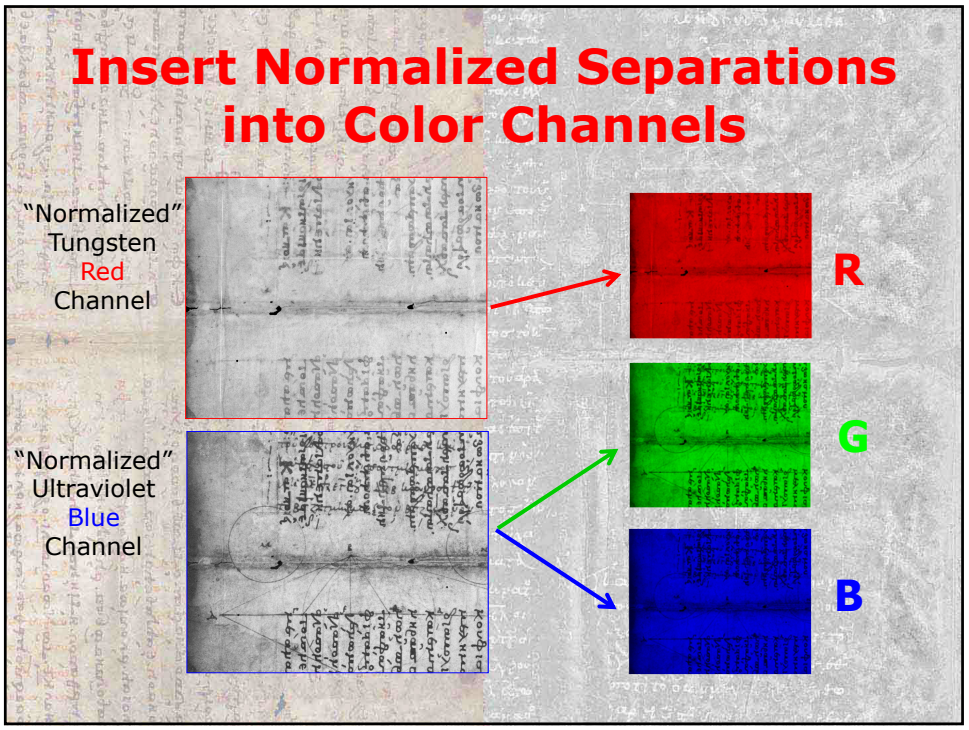
Individual Bands of Images Under Two Illuminations

f. 092v-093r

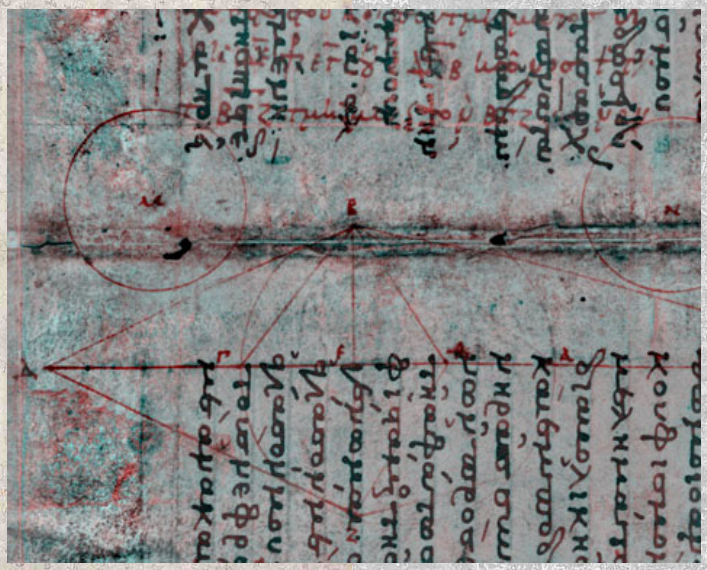


Tungsten **Red** | Ultraviolet **Blue**


Background Normalization
Red
Blue
401 × 401
Inside sliding window:
Gray value of center pixel
altered based on mean and
variance in window
"Normalized"
Red and Blue


Insert Normalized Separations
into Color Channels
"Normalized"
Tungsten
Red
Channel
"Normalized"
Ultraviolet
Blue
Channel
R
G
B

Pseudocolor Result



f. 093v-092r

Another Example

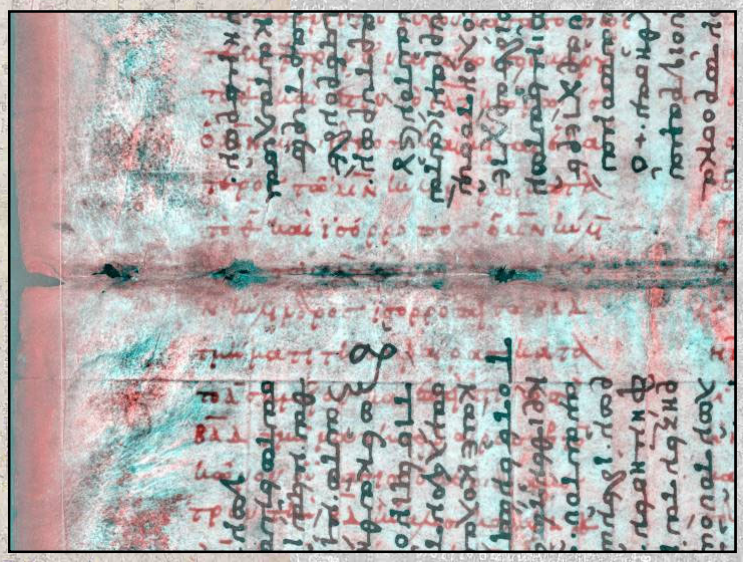
f. 048r

Example of Text in Gutter

166v-167r

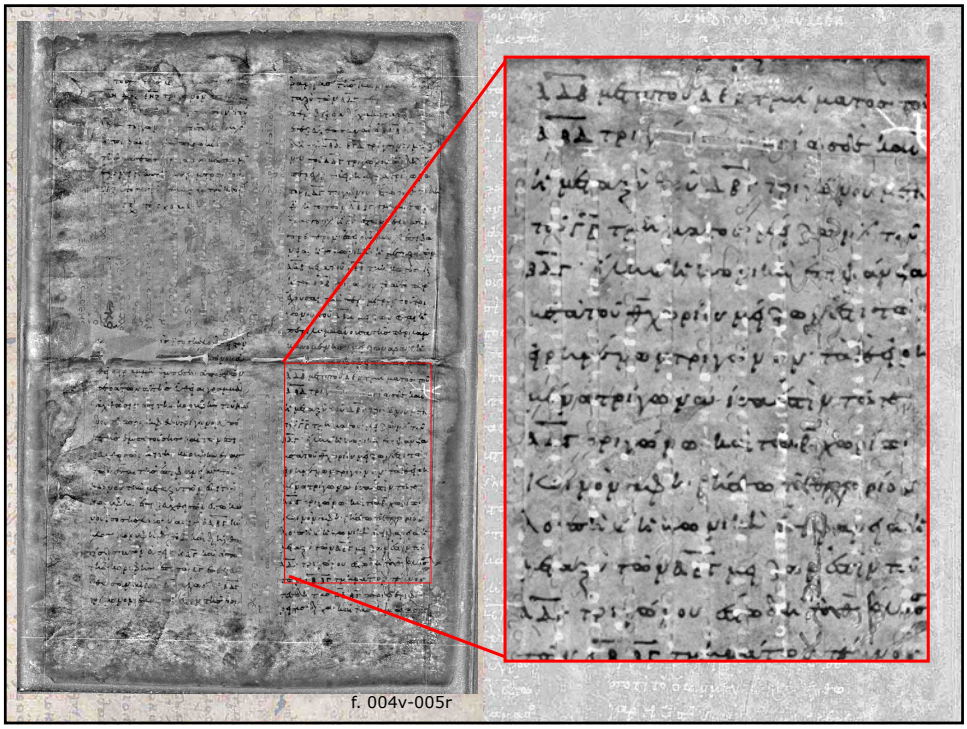
Pseudocolor Processing

166v-167r

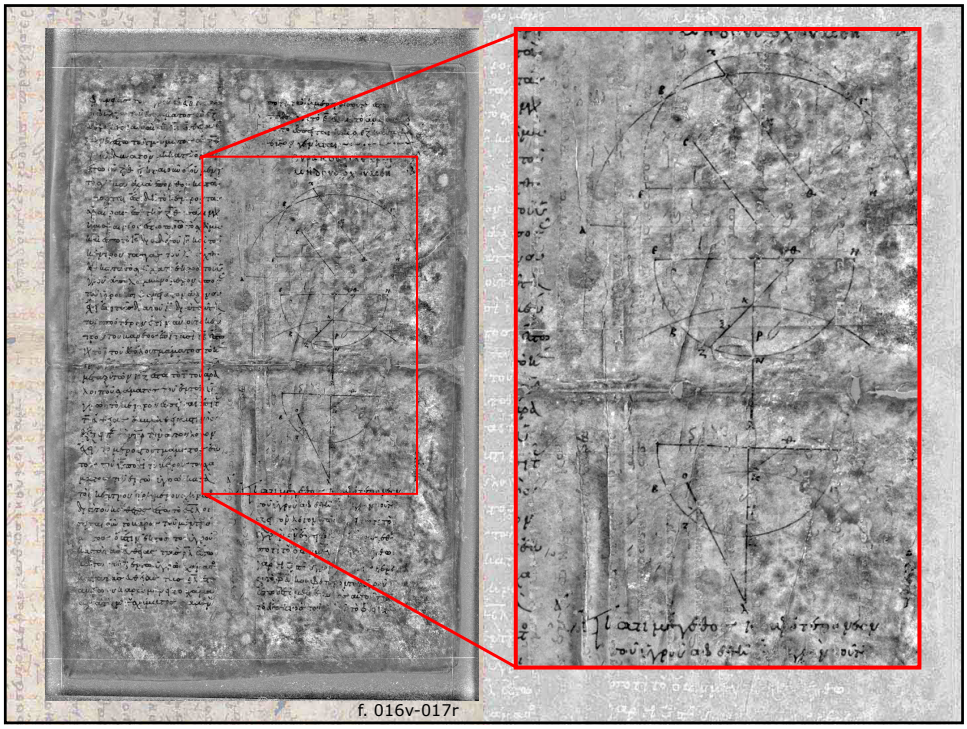


Alternative Rendering:
Difference of Pseudocolor Channels

- Compute difference of pseudocolor channels:
  (visible/red) – (UV/blue) = output gray
- Overtext and parchment exhibit same levels in both UV/blue and visible/red
  - subtract to "0" (dark pixels)
  - Undertext is brighter in visible/red
    - subtracts to "positive" numbers (bright pixels)
- Overtext "disappears" from difference image
- Thought to be easier to read at some locations
  - Good indication of locations of undertext
- Requested by the late Bob Sharples, UCL
  - hence given the nickname "sharpies"



f. 004v-005r



f. 016v-017r

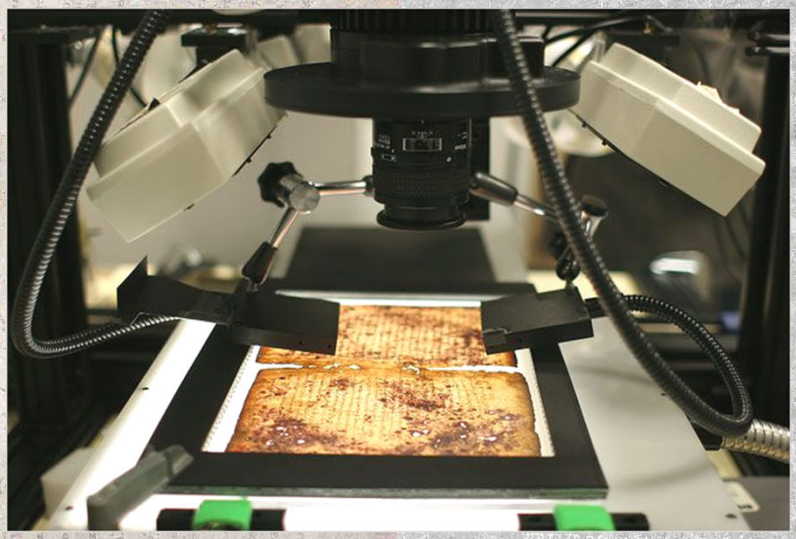
Assessment of "Production" Imaging

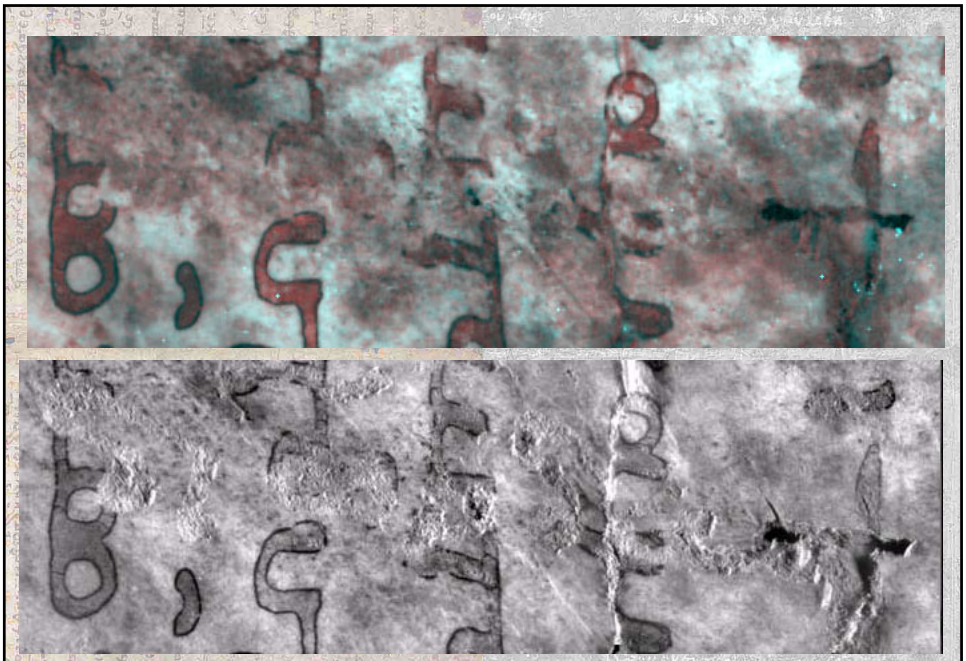
- Enhanced readability of **~80%** of text
- Little (if any) help on some leaves
  - painted icons and colophon of *Euchologion*
- 2004 Conference to hear suggestions
  - X-Ray Fluorescence (XRF)
  - Character recognition: Derek Walvoord (Ph.D.)
  - High-resolution multispectral (*"El Greco"*)
- Other methods developed during imaging
  - raking illumination, 11/2006, Jud Herrman
- New multispectral system, August 2007
  - Large-format digital camera
  - LED illumination

Jud Herrman's 2006 Observation

- Could read "vanished" text with low-angle ("raking") illumination
- Imaging of impressions in parchment
  - erosion of parchment by acid in ink

Raking-Incidence Illumination November 2006



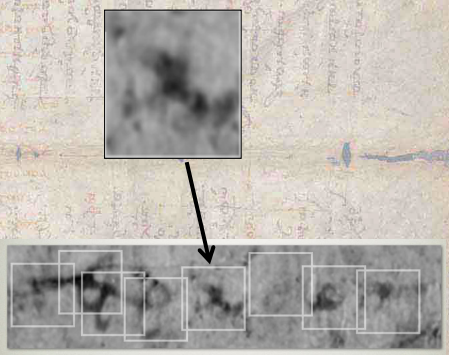


Character and Word Recognition Tool

based on character "shapes" and vocabulary

Derek Walvoord, Ph.D., 2008

Partial Characters in Images



- How to use context of adjacent "known" characters to help read partial or missing characters

"Optical" Character/Word Recognition

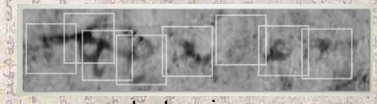
- Analyze images to help scholars identify "partial" or faded characters and words
- Based on:
  1. Image Statistics
     - Correlation pattern recognition
  2. Transcription Statistics
     - Probability distribution of words
  3. Context
     - User-supplied input

Inputs to OCR Algorithm

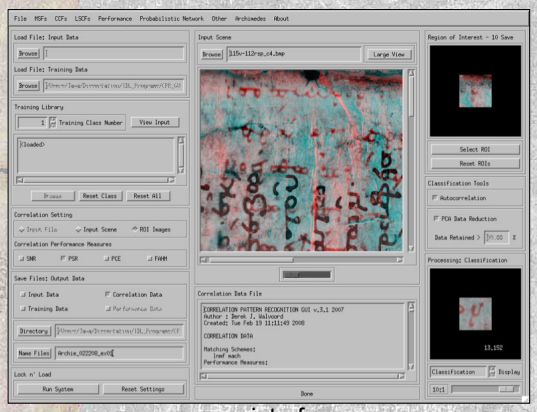
1. Pseudocolor image
   - User-specified Regions of Interest (ROIs)
2. Library of unobscured characters
3. Archimedes word dictionary file
   - 1730 words
4. User-supplied context

Character Recognition Tool

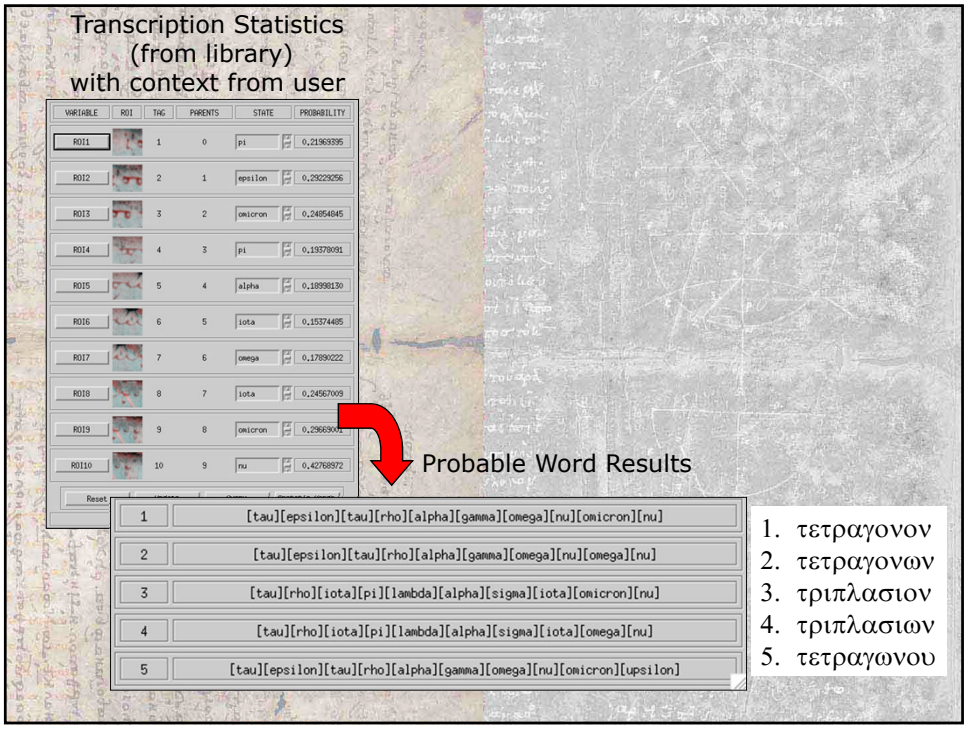
character libraries



test regions



user interface



Reviel Netz's Assessment

"I was much surprised when the machine actually did paleographic work - we gradually moved to more and more difficult areas until we looked at fragmentary words for which I had guesses, no more, at 158-159. The machine reached my guesses independently. … This means either that I think like the machine and that we both can be outperformed by better paleographers, or that the machine is in fact making informed paleographic judgments."

21 September 2006

Reimaging of Entire Codex 2007

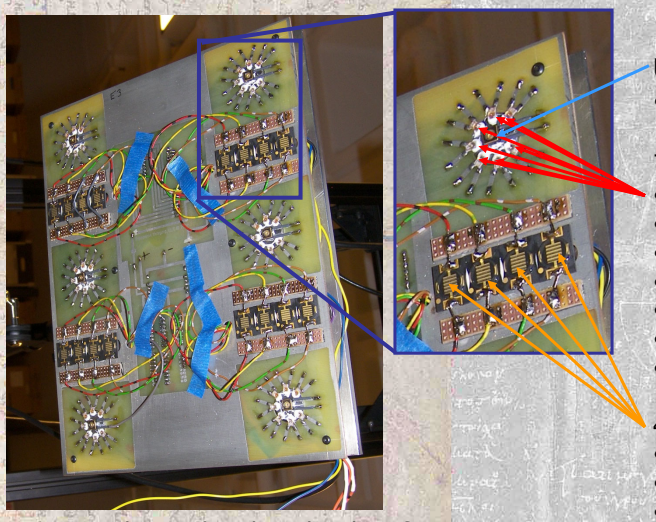
2007 Spectral Imaging

- Advances in camera technology
  - Sensors then available up to 39 megapixels (now 50+ MP)
- Illumination from light-emitting diodes (LEDs)
- Combine higher-resolution camera + LEDs to obtain registered spectral images at more wavelengths
- Goal: to produce better output images from combinations of spectral images

Illumination by Light-Emitting Diodes (LEDs)

- Generate light from electronic transitions
  - not from heat
  - less potential for damage to parchment
- Electrically efficient
  - most electrical energy converted to light
- Inherently "Narrowband"
  - Measure reflectance over narrow range of wavelengths
  - $\Delta\lambda \sim 25 - 40$ nm
- Available in wide range of spectral bands, with more being added

2007 LED Illumination Panel



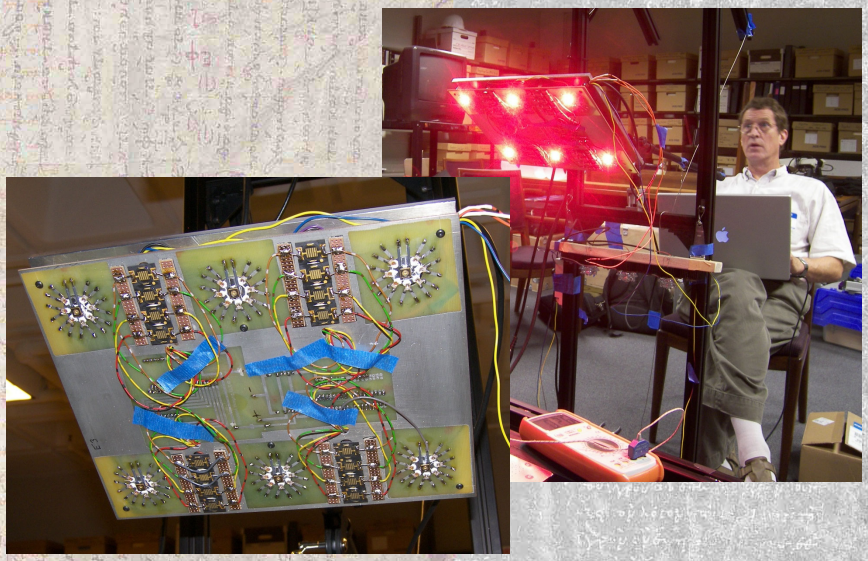
UV LED
- λ_0 = 365 nm

7 visible LEDs
- 445 nm
- 470 nm
- 505 nm
- 530 nm
- 570 nm
- 617 nm
- 625 nm

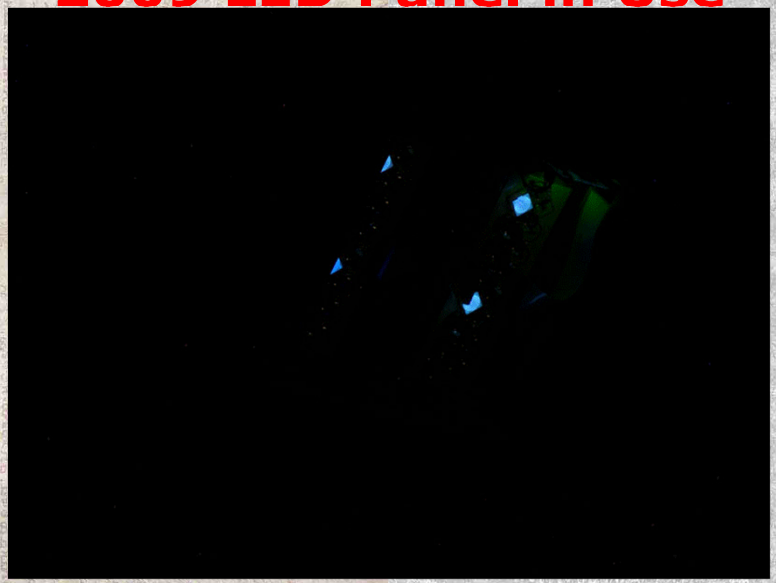
4 Infrared LEDs
- 700 nm
- 735 nm
- 780 nm
- 870 nm

Two Panels, each w/ six banks of
12 visible and UV LEDs + two banks of 4 IR LEDs

LED Illumination Panel

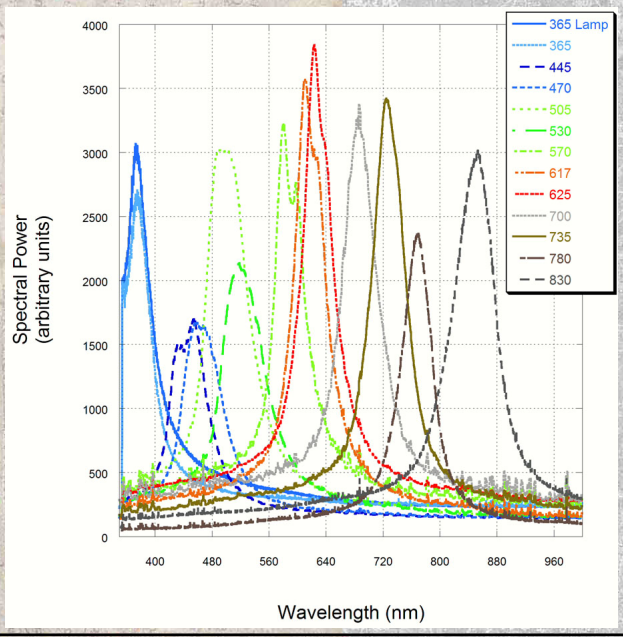


2009 LED Panel in Use



EurekaVision™ System by Megavision, Inc.

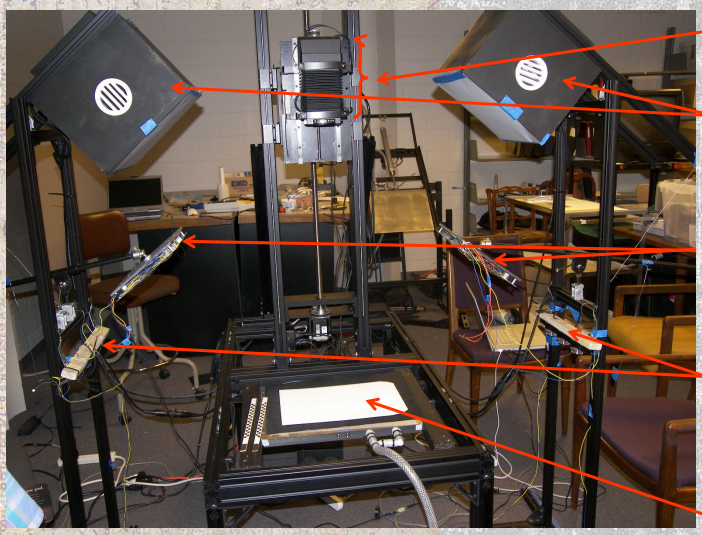
Spectra of LEDs on 2007 Panel



High-Resolution Digital Camera

- Planned: monochrome sensor
  - 4992 × 6668 pixels ~ 32 Megapixels
  - failed to arrive in time
- Fallback: Sinar 54H digital sensor
  - 4080 × 5440 pixels ~ 22 Megapixels
  - Cooled to reduce thermal noise
  - RGB array ⇒ color sensor
    - Not desired (considered to be a "bug")
    - Proved to be serendipitous (a "feature"); essential for the *Aristotle Commentary*
  - Half-pixel translations ⇒ 88 MP

2007 Spectral Imaging System



LED Images

Ultraviolet

365 nm

Visible Wavelengths

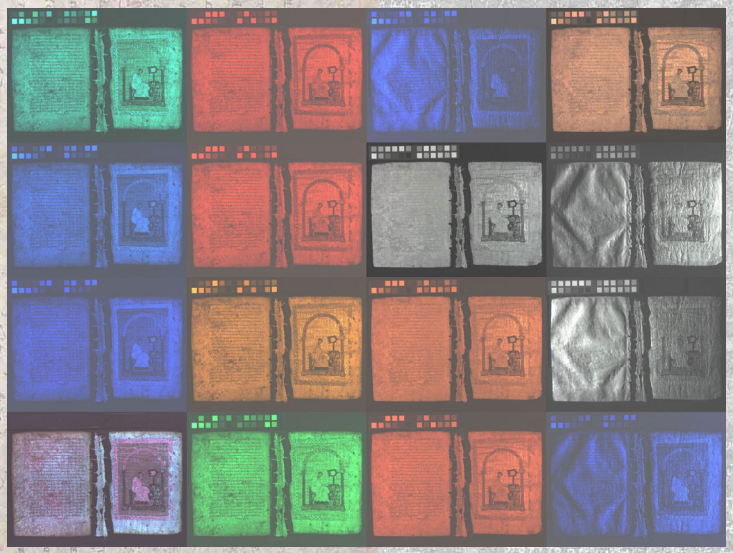
445 nm 470 nm 505 nm 530 nm 570 nm 617 nm 625 nm

700 nm 730 nm 870 nm

Infrared

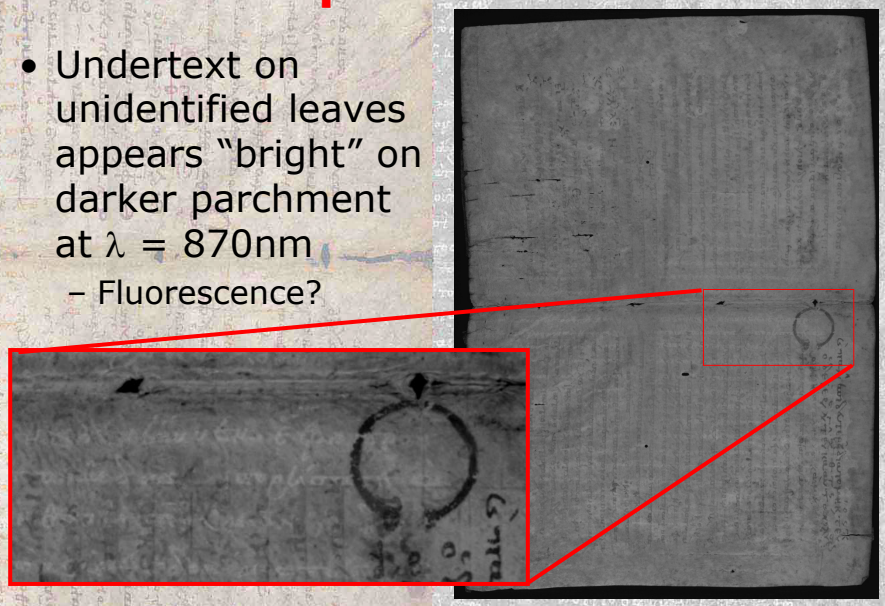
n.b., false colors due to infrared transmittances of RGB filters

LED Images of Manuscript (including raking incidence)



Unexpected Result

- Undertext on unidentified leaves appears "bright" on darker parchment at λ = 870nm
  - Fluorescence?



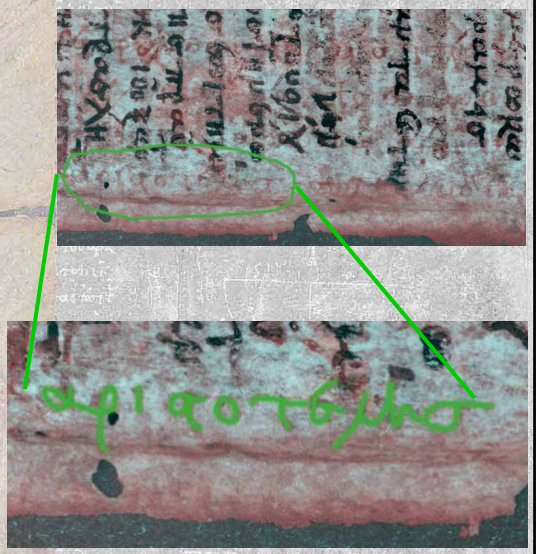
Second Surprising Result on New Images of "Aristotle" Treatise

Sent: Saturday, June 11, 2005, 2:24 PM

"Dear Will,

"Excellent news. The hard-drive and photos came safely this week. ***A first glance suggests that there is no more Hyperides, but several leaves of the philosophical text, on one of which I read the name Aristotle clearly enough.***

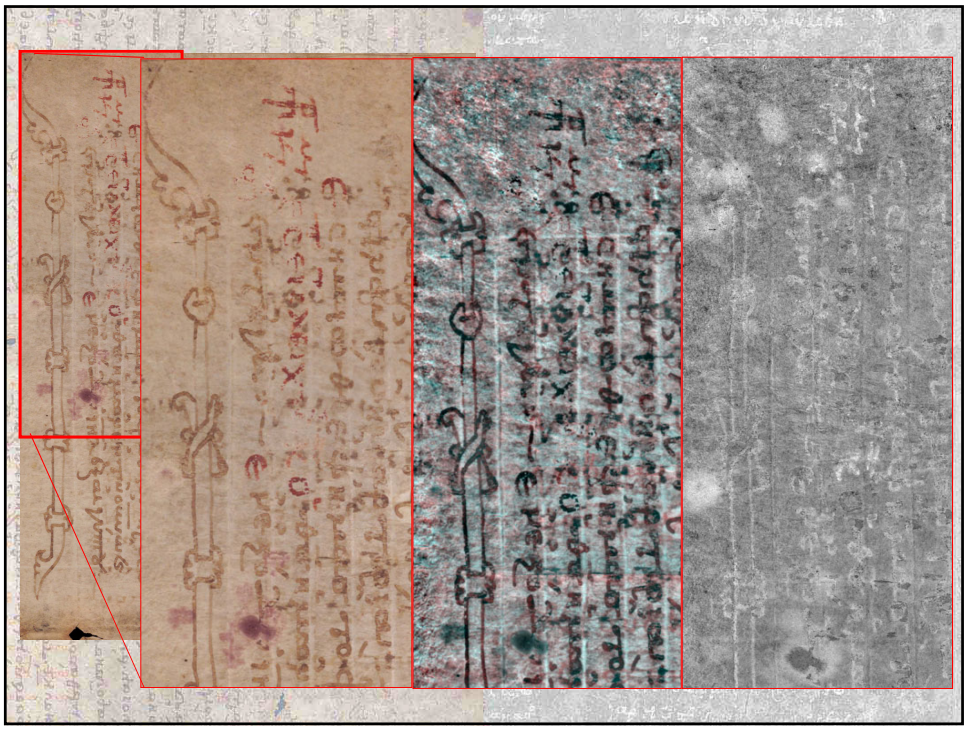
All the best,
Nigel



Gutter of 080v-073r

Little Benefit of Pseudocolor Rendering on Alexander Pages

- Spectrum of ink differs (somehow) from inks on leaves with Archimedes text
- Frustrating for Scholars



Will Noel's 2008 *Christmas Challenge*

12:13 PM EST, 13 December 2008

Guys

On December 6th, Nigel Wilson, Bob Sharples, Marwan Rashed, and Natalie met in London to have a further "group" crack at the Alexander text, and amazingly, made really exciting progress. They think about ten further meetings and they will have a text that is worth publishing - and that it will be important. This is cool.

As you know, this is a really tricky philological task, and **any help you can give to them as they work by processing the images further might just pay huge dividends**.

If your idea of a fun vacation is to play with tricky images (and I know it is), then **the bit of Alexander to try to make more legible is the bottom third of 120r-121v, and all of 120v-121r**. The philosophers are next meeting on January 31.

First contact person for Alexander is Bob Sharples at UCL, whom I copy on this email. I know that he would be delighted to inspect any images that you wouyld be kind enough to generate, and that he would share them with all those who work on this text.

With warmest regards for the holiday season.

Will

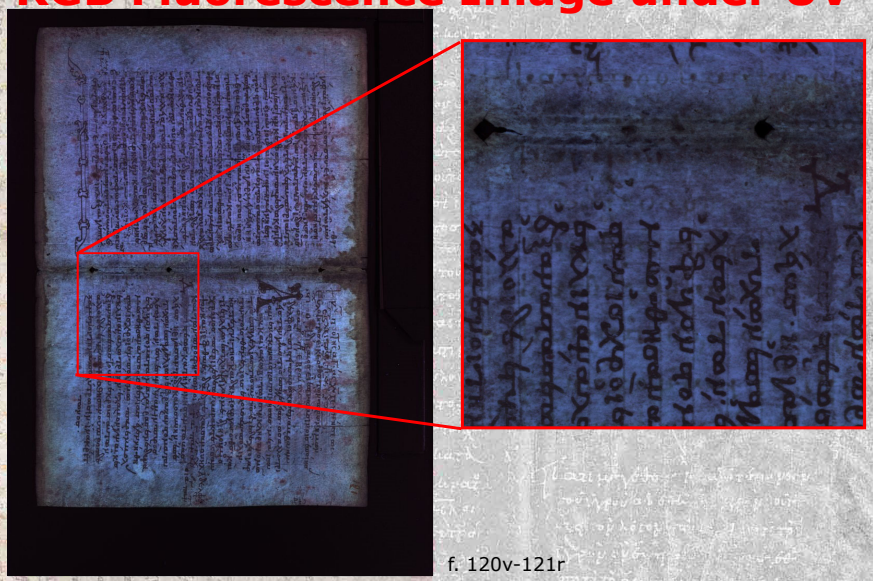
Response to Challenge

- Principal Component Analysis (PCA) of spectral images
  - For N-band image, PCA calculates an equivalent set of N orthogonal bands
    - each is weighted sum of N original bands
    - arranged in order of decreasing image variance

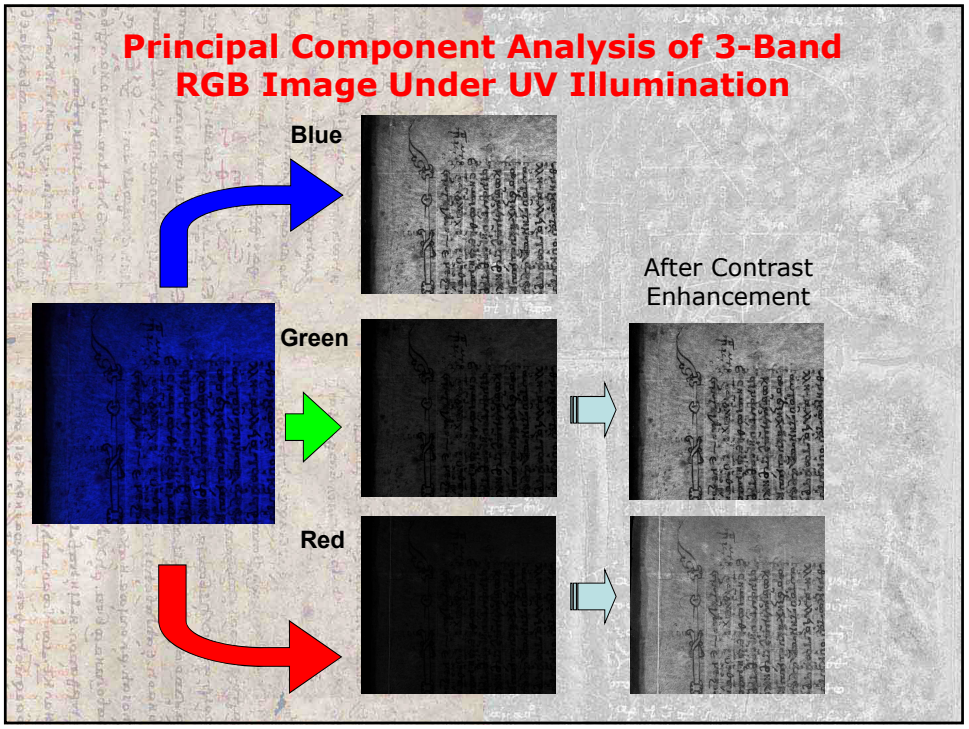
Principle of Principal Component Analysis of N-Band Spectral Image

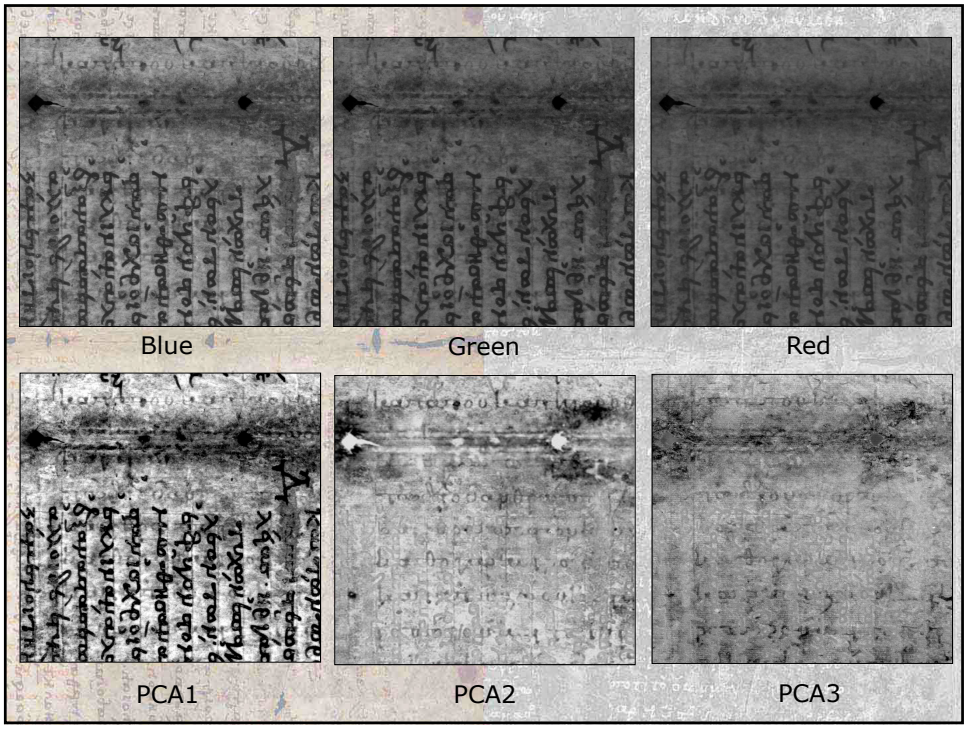
- Find combinations of the original image bands ordered by "variance" of image data
  - 1st Principal Component (PC1) exhibits largest possible variance of image data
  - Axis of PC2 is "orthogonal" (perpendicular) to PC1 and exhibits next largest variance
  - Axis of PC3 is orthogonal to PC1 AND PC2
  - Repeat to construct N principal component images

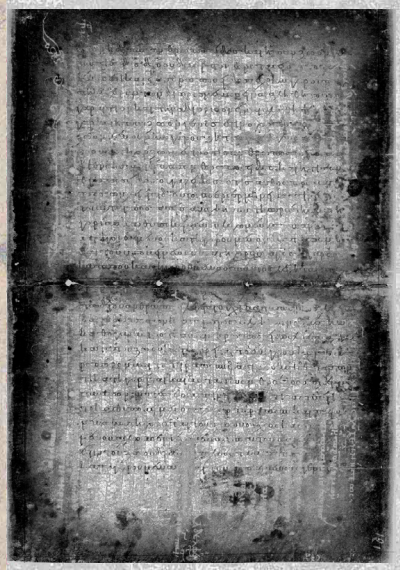
RGB Fluorescence Image under UV



f. 120v-121r


Principal Component Analysis of 3-Band
RGB Image Under UV Illumination
Blue
Green
Red
After Contrast
Enhancement


Blue
Green
Red
PCA1
PCA2
PCA3



25 January 2009

Response from Scholars

Dear Will,

I got out the provisional transcription that the team had produced so far and began to check it against the image. **It is clear that the new picture is a real step forward, and someone deserves to be congratulated. I was able to make several alterations in the space of about half an hour! So let's have some more leaves done the same way....**

...

All the best,

Nigel

Oxford, University, 29 December 2008

Dear all,

it appeared clearly in the last days that the new images on the website are incomparably better than everything we had until now. Contrarily to my first impression, it is somewhat miraculous to be now able to read portions which seemed lost for ever. I thus pray those of you who have some influence on Will to ask for images of this type for the rest of Alexander's commentary.

best,

Marwan Rashed

Professor, École Normale Supérieure, Paris, 27 January 2009

Subsequent Observation

- PCA Band 1 is dominated by blue fluorescence emission

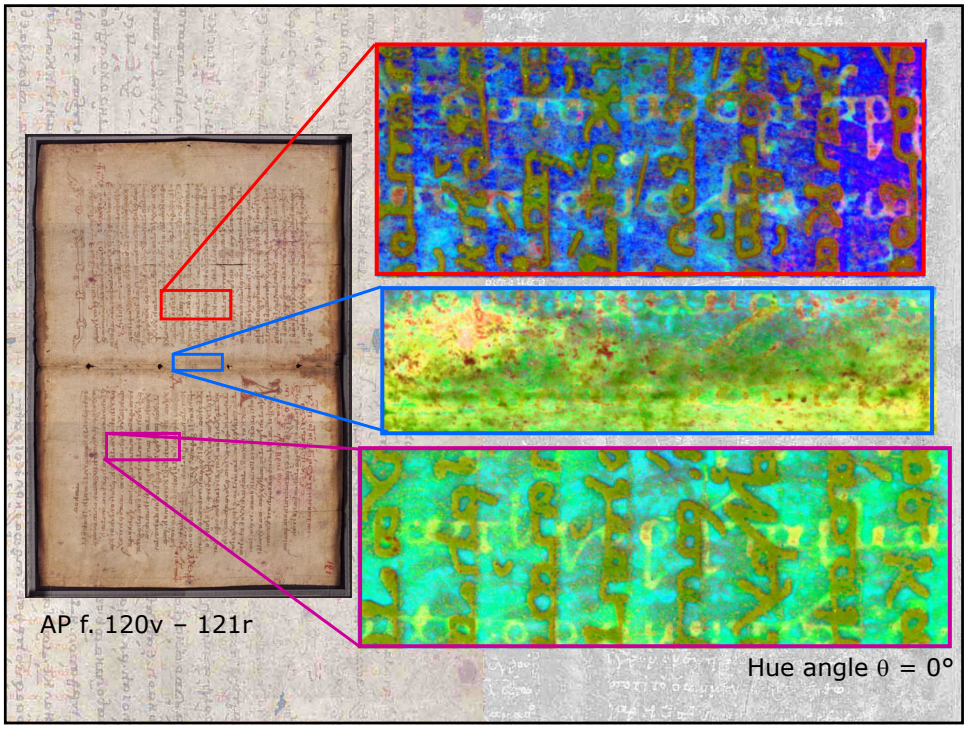
⇒ Bands 2 and 3 must be dominated by combinations of green and red emission

- Undertext appears at different locations on leaf in PC2 and PC3

⇒ **Optimum rendering may be different at different locations**

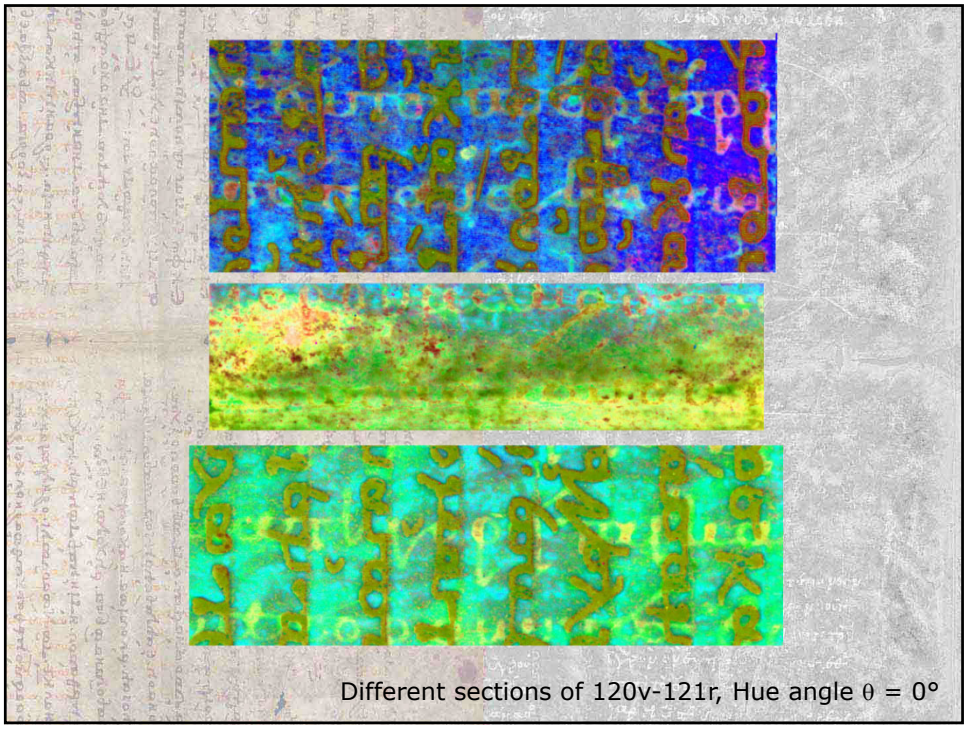
Pseudocolor Rendering of 3-Band PCA Images

- Dynamic rendering of pseudocolor mapping of 3-band PCA
  - PC1 → Red
  - PC2 → Green
  - PC3 → Blue
- Text on leaf appears with different color renderings at different locations
- Rotate hue angle to "optimize" rendering for different locations
  - (and perhaps for different viewers)

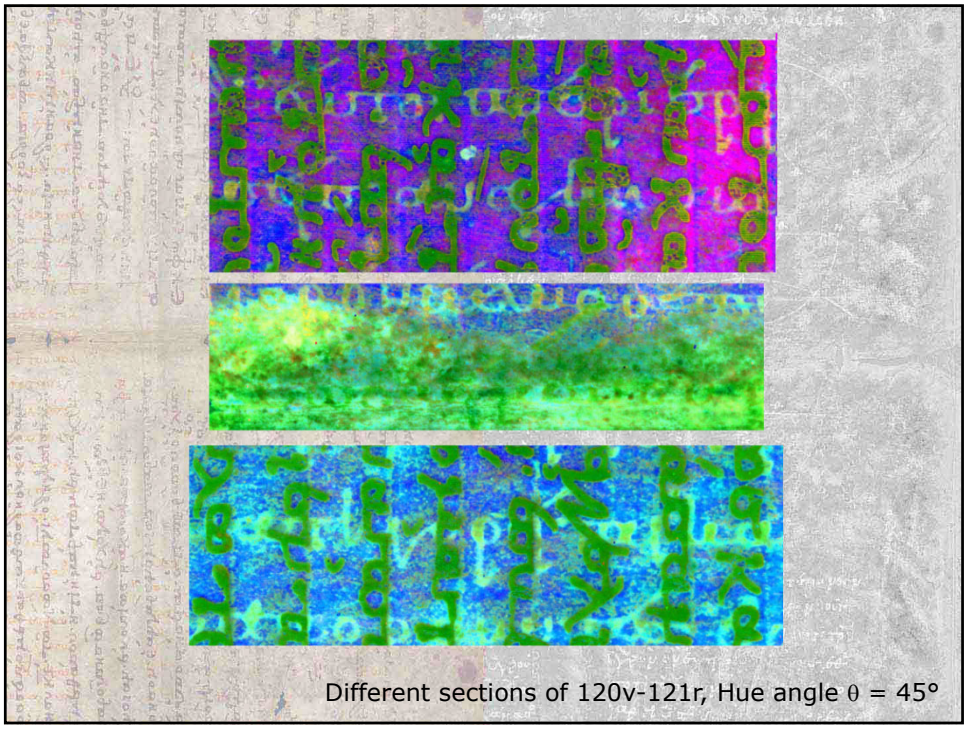


AP f. 120v – 121r

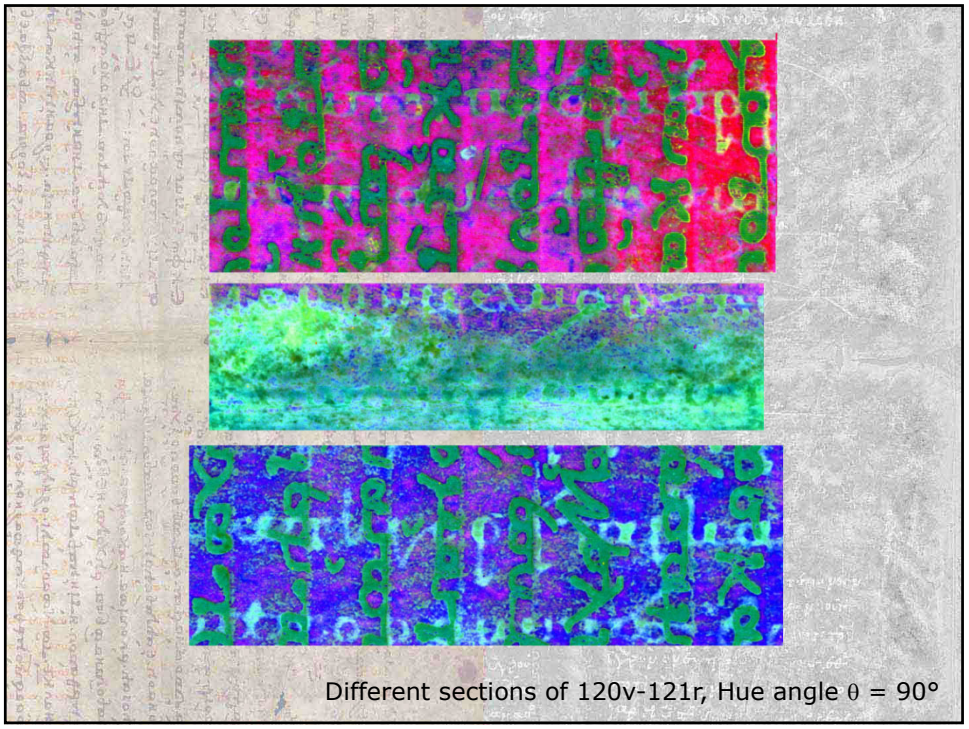
Hue angle θ = 0°



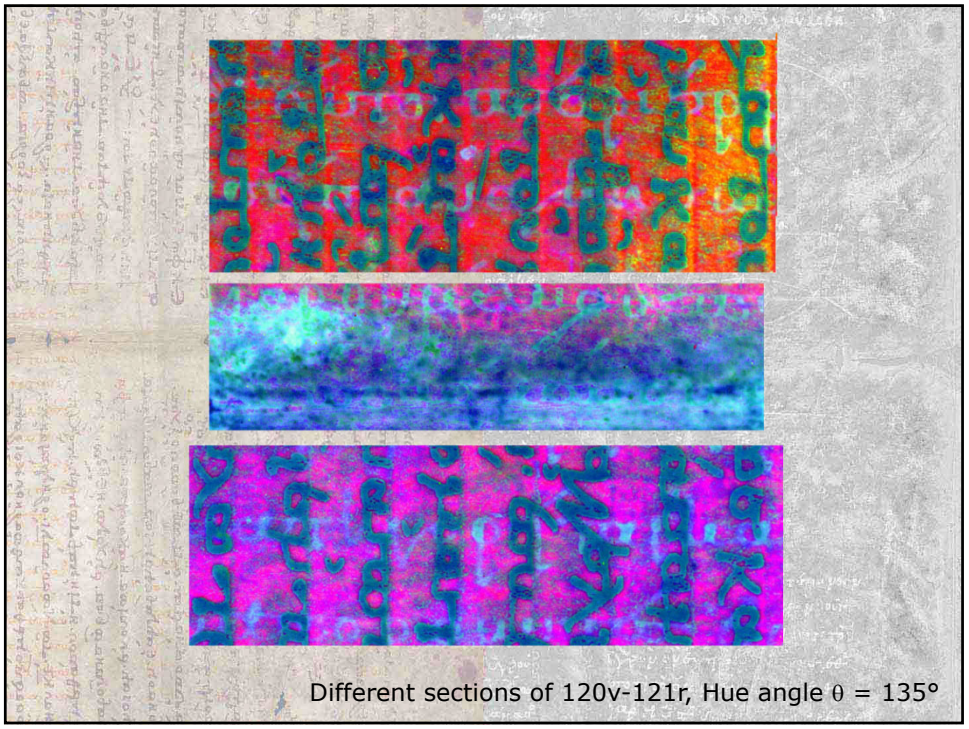
Different sections of 120v-121r, Hue angle θ = 0°



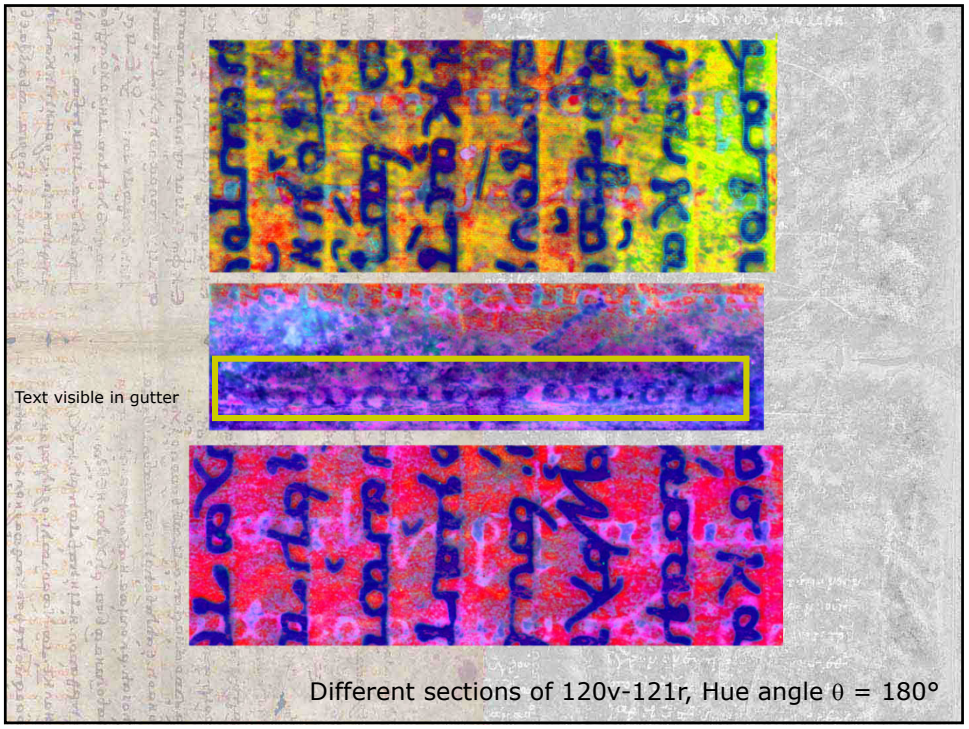
Different sections of 120v-121r, Hue angle θ = 45°



Different sections of 120v-121r, Hue angle θ = 90°



Different sections of 120v-121r, Hue angle θ = 135°

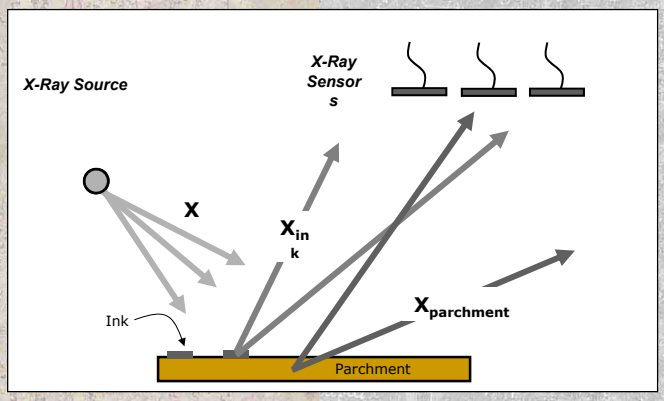


Different sections of 120v-121r, Hue angle θ = 180°

X-Ray Fluorescence Imaging

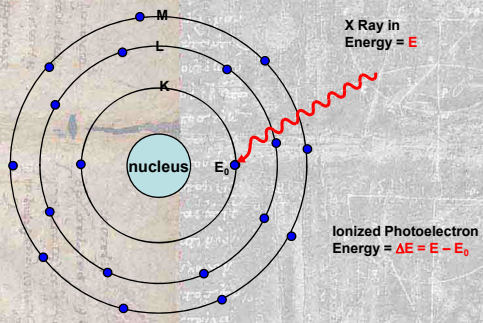
- Same idea as UV fluorescence, but much shorter wavelengths
- Can penetrate through overtext

X-Ray Fluorescence Imaging



X-Ray Fluorescence - 1

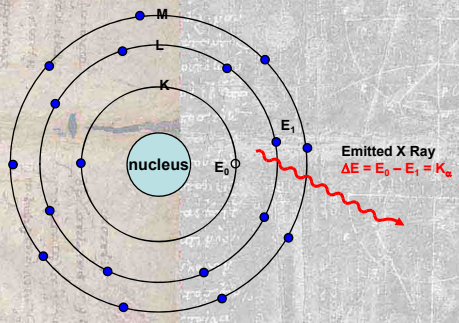
Energy-Level Diagram of Atomic Electron Shells



Absorbed X-ray photon liberates a "photoelectron"

X-Ray Fluorescence – 2a

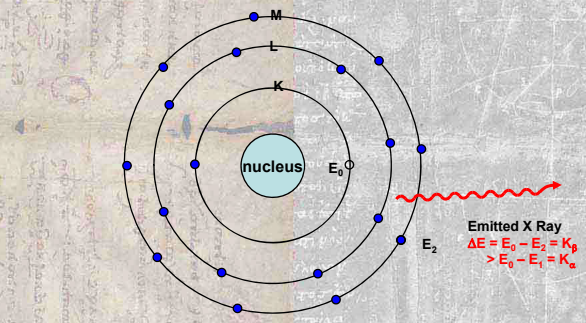
"Alpha Emission"



Electron from second shell drops into inner shell; releases longer-wavelength X-ray photon.

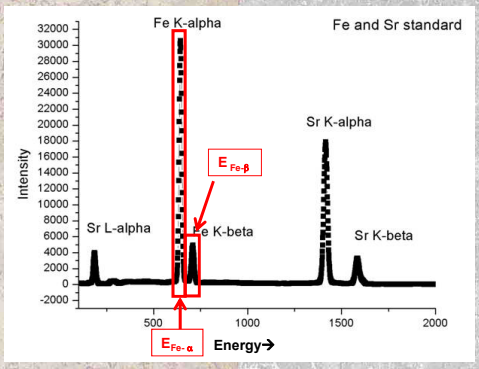
X-Ray Fluorescence – 2b

"Beta Emission"



Electron from third shell drops into first shell

XRFi Spectral Lines



- X-ray detector "tuned" to energy for "Iron" emission
- Signal strength proportional to amount of Iron at that location

XRFi of Archimedes Palimpsest

- Suggested and implemented by Uwe Bergmann, Stanford Synchrotron Radiation Laboratory
- Applied to 4 leaves overpainted with forged icons and dirty leaves at beginning and end of codex

Post-1938 "Vandalism" of AP

- Paintings of icons of four Gospels, perhaps during WWII
  - One pigment first produced commercially in 1938

St. Luke on f. 021r over *"Floating Bodies"*

St. Matthew on f. 064v over *"Method"*

St. John on f. 057r over *"Method"*

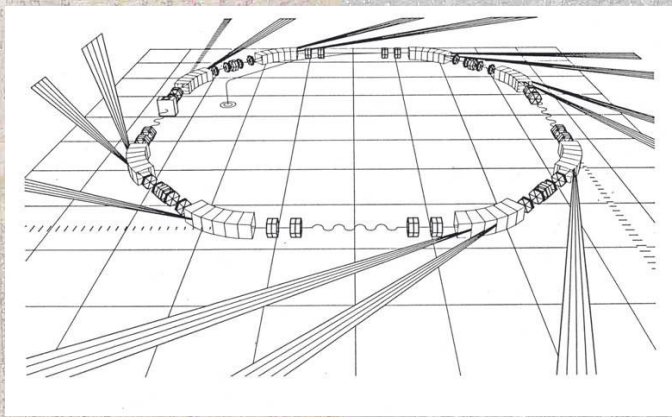
St. Mark on f. 081r over *"Floating Bodies" & "Equilibrium of Planes"*

- **Apparent attempt to increase sale value of book**
  - **books with art more valuable than text manuscripts**
- **Other pages with painted forgeries are still missing**

Need Large Flux of X rays at each "Pixel"

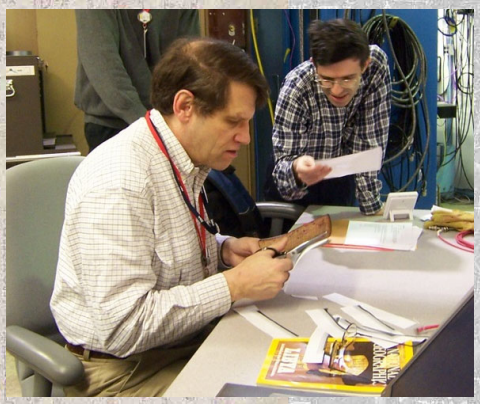
- Uwe Bergmann, Staff Scientist at *Stanford Synchrotron Radiation Laboratory* ("SSRL")
  - now at University of Wisconsin
  - SSRL is part of *Stanford Linear Accelerator Center* ("SLAC")

XRF Imaging at SLAC-SSRL

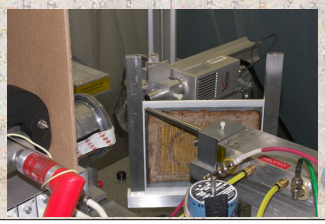


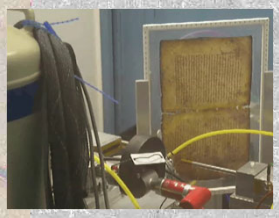
Embarrasing (and perhaps incriminating) Snapshot

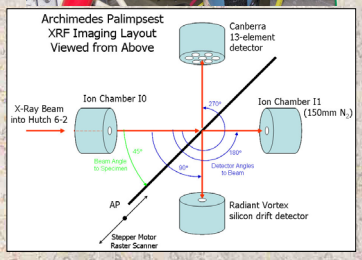
Reviel Netz



XRF Imaging at SSRL

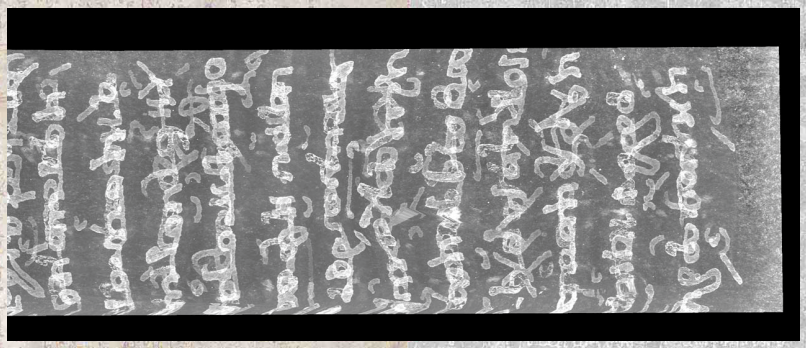




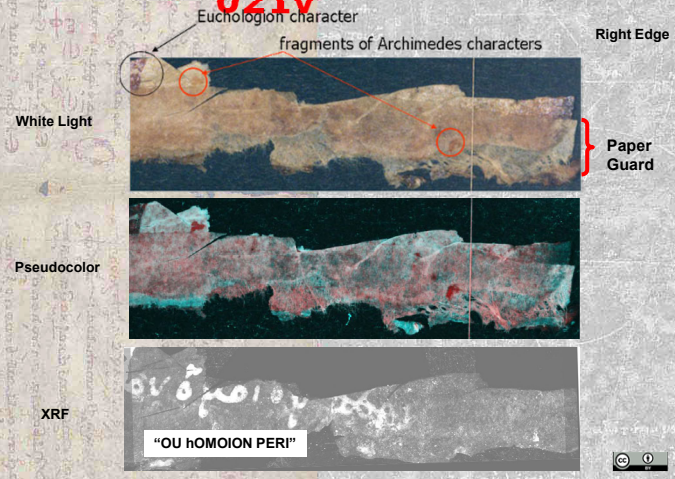


- Scan page through narrow X-ray beam
  - diameter ~ 50μm
- Measure intensity of energy spectrum of scattered radiation
- Construct image(s) of number of X rays at energies characteristic of different materials
  - iron, calcium
- Use to read faded and obscured text

XRFi ⇒ Up to 4 Palimpsest Texts Visible



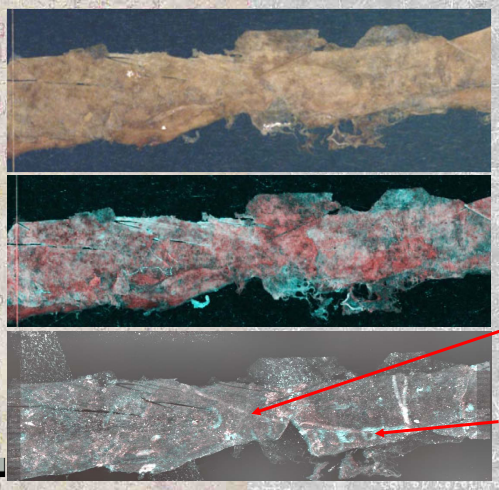
Result: Verso Side of Stub of f.028r-021v



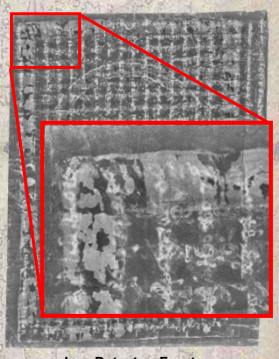
Pseudocolor Rendering of XRF

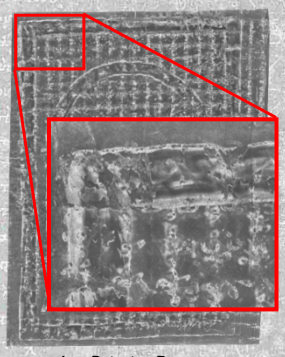
- Signals from iron atoms measured by detectors in front and behind page
  - Signal "strengths" differ
  - Use difference to distinguish the two texts
- Blue: iron image measured by "front" detector
- Green and Red: iron image

Stub of f.028r-021v



Front and Rear Images, f. 81v


Iron Detector, Front


Iron Detector, Rear

XRF Pseudocolor

Iron Detector (Front)

Iron Detector (Rear)

Pseudocolor: (Front text in blue) (Rear text in yellow)

Colophon Reading from XRF

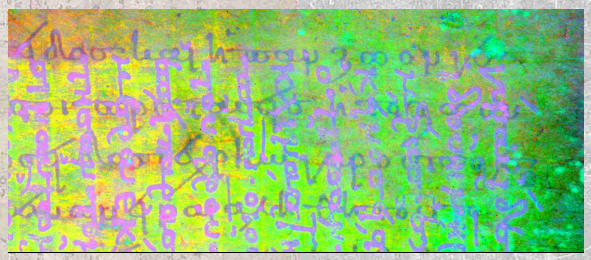
Subject: RE: colophon
From: "Lowden, John" <John.Lowden@courtauld.ac.uk>
Date: Thu, 16 Mar 2006 15:31:35 -0000
To: "William Noel" <wnoel@thewalters.org>, "Georgi Parpulov" <gparpulov@thewalters.org>, <nigel.wilson@lincoln.ox.ac.uk>,
<netz@stanford.edu>
CC: <bergmann@slac.stanford.edu>, <mbt.rbtoth@starpower.net>, <knox@cis.rit.edu>, <easton@cis.rit.edu>

Have just received this on return from Dublin.
The improved legibility is astonishing.
First impression is that the name (refining Georgi P) is *Iw(annou) iere(os) tou Murwna*
I would check *Ioannes Myronas iereus* as scribe.
But maybe I should check first and communicate after!
Yours (too hastily?)
John
Professor John Lowden
Courtauld Institute of Art
London WC2R 0RN

XRF Imaging Assessment

- Essential to read text through forged paintings and on colophon of *Euchologion* in Archimedes Palimpsest
- Expense and utility constrained its use to special cases
- Now MUCH more common
  - Just used to identify ink constituents in Vinland map

XRFi is NOT a Panacea



120v-121r (Aristotle 02r) XRF Iron Front
120v-121r (Aristotle 02r) UV PCA + Hue Angle