# Targeted Anomaly Detection in Hyperspectral Imaging for Cultural Heritage Applications – Finding a Needle in a Haystack

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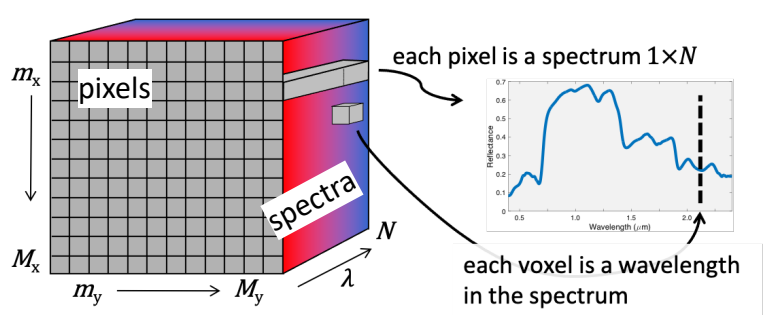
1

## What is Hyperspectral Imaging?

- Hyperspectral imaging measures a spectrum at many pixels
  - Provides good sampling for exploratory analysis, detection and classification
  - Rapid and non-invasive (good for cultural heritage and archeological samples)
  - Images can be big!
- Provides
  - Spatial statistics
  - Chemical Information




https://eigenvector.com/wp-content/uploads/2020/12/IntroHSIandMIA.pdf

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3

# Hyperspectral (HSI) Applications

- Good for heterogeneous samples
  - Although quantities of analytes may be low on a volume basis, signal in individual pixels can be dominated by an analyte of interest
  - Good for detecting a needle in a haystack and finding rare signals
  - In contrast, destructive wet chemistry methods can be hampered by dilution effects
- Chemical Sensing, Standoff Sensing and Remote Sensing
- Many algorithms available
  - Depends on the sensing objective and how the signal manifests

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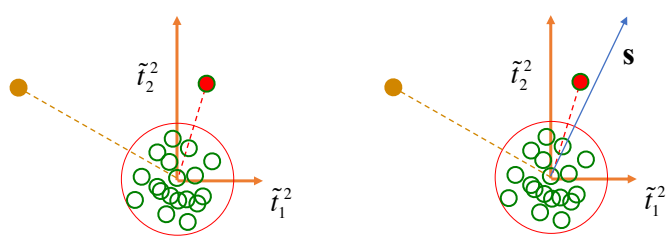
# Detection Algorithms

- Anomaly detection finds unusual signal
- Target detection finds unusual signal that matches a specific spectrum
- Targeted anomaly detection finds unusual signal that matches a specific anomaly in an image
  - Once a strong anomaly is found, weaker anomalies that match it can be found

anomalies are found in any direction




target signal is found in a specific direction, **s**

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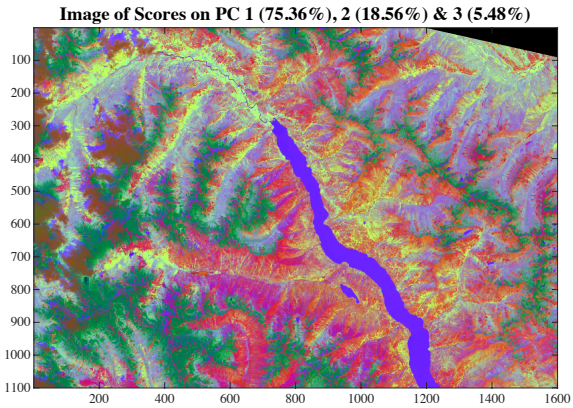
# Anomaly Detection Example

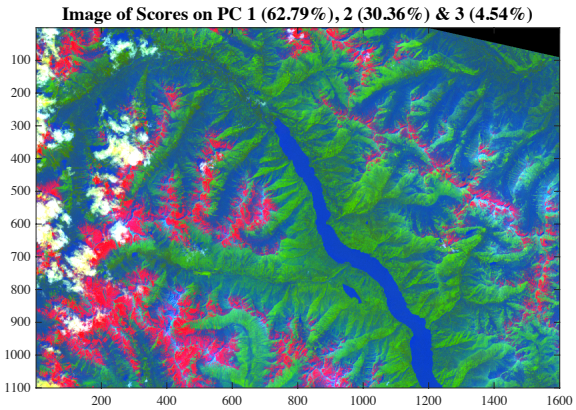
- Landsat 8 image of the NW end of Lake Chelan, WA USA
  - 1100 x 1600 pixels x 8 wavelength bands
  - 1760000 total pixels
- Principal Components Analysis (PCA)
  - Ubiquitous tool for multivariate analysis
  - Outliers can be found using:
  - Scores t
  - Hotelling's T2 (distance from data origin)
  - Q residuals (lack of fit)
  - This example modeled the entire image

6

# PCA of a Landsat 8 Image




Preprocessing: 1-norm, mean-center.
Image: autocontrasted.

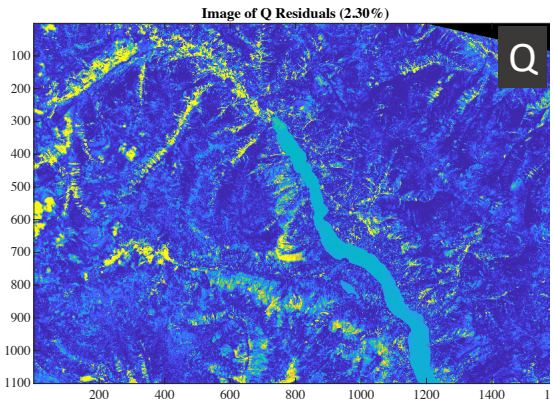


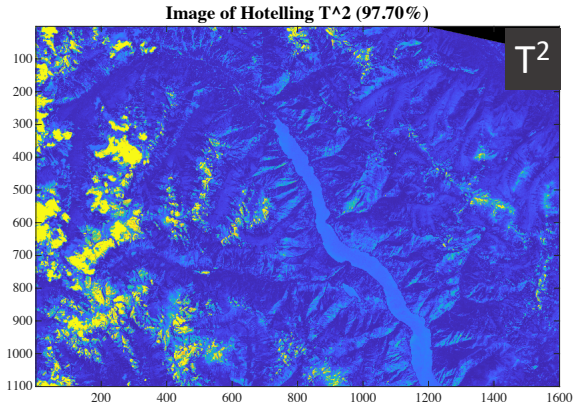

Preprocessing: autoscale.
Image: autocontrasted.

Data preprocessing can have a significant impact on the ability to detect outliers

7

# Examine Q and $T^2$ for Outliers




Preprocessing: autoscale.
PCA: 3 principal components.
Image: autocontrasted.

Inspection of images can show where anomalies may be but can be difficult to see small anomalies

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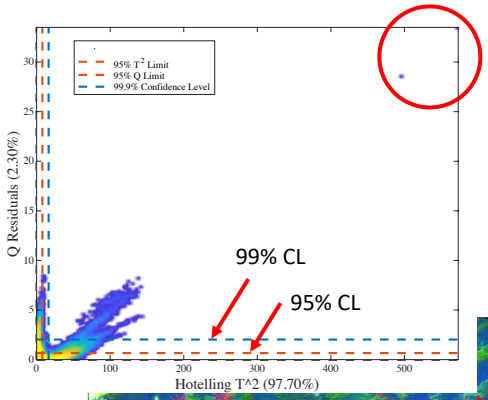
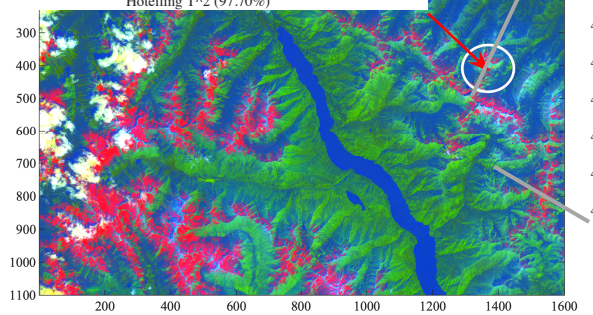
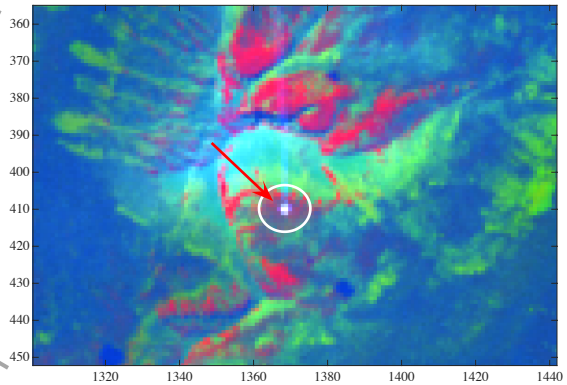



2 pixels at [1368 410] & [1369 410]

Plot of Q vs T2 can help identified truly unusual signal.
Changing color schemes and contrast can help explore the signal.





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# Examine Region Local to the Anomaly

Image of Scores on PC 1 (17.23%)

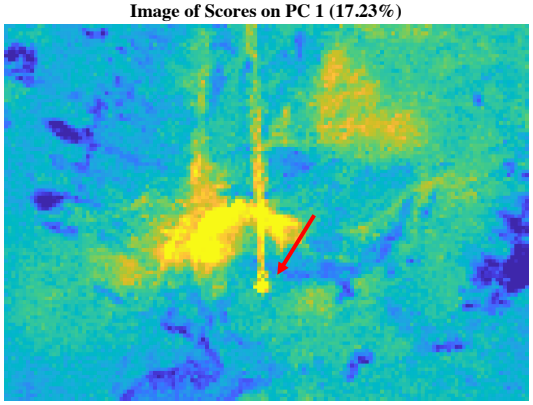
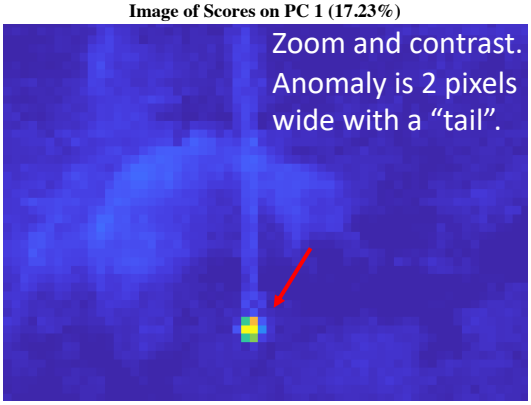
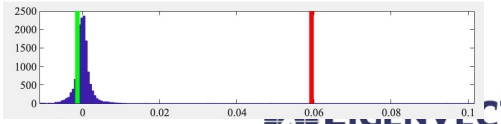


Image of Scores on PC 1 (17.23%)




Preprocessing: autoscale, glsw de-cluttering.
Image: autocontrasted.

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# Is It a Bird? A Plane?

- The pixel resolution for the image was 30 m.
  - The anomaly is ~2x2 pixels
- A 747 is 68.4 m wide and 76.3 m long
  - https://www.boeing.com/commercial/747/

Landsat 8 satellite

| Band Number | Wavelength Range (µm) | Resolution (m) |
|---|---|---|
| 1 | 0.433-0.453 | 30 |
| 2 | 0.450- 0.515 | 30 |
| 3 | 0.525- 0.600 | 30 |
| 4 | 0.630- 0.680 | 30 |
| 5 | 0.845- 0.885 | 30 |
| 6 | 1.560- 1.660 | 30 |
| 7 | 2.100- 2.300 | 30 |
| 8 (not used) | 0.500- 0.680 | 15 |
| 9 | 1.360- 1.390 | 30 |
| 10 (not used) | 10.6 -11.2 | 100 |
| 11 (not used) | 11.5 -12.5 | 100 |

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# Anomaly Detection Example

NIR reflectance image of a cellulosic swipe.

a) is an anomaly apparent?
b) where is it?
c) if seen, can the analyte be identified?

apparent anomaly observed – what is it?

Image of Scores on PC 1 (97.73%), PC 2 (1.28%) & PC 3 (0.56%)

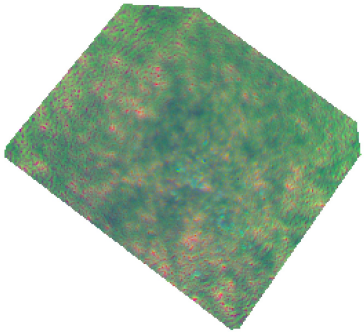
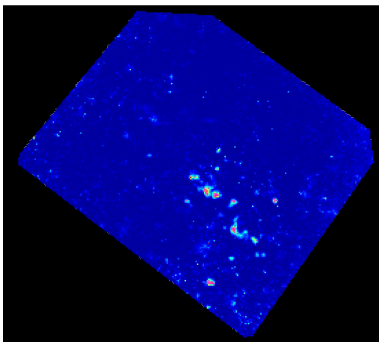


Image of Hotelling T^2 (99.83%)



data set: courtesy OPOTEK, Inc., Carlsbad, CA

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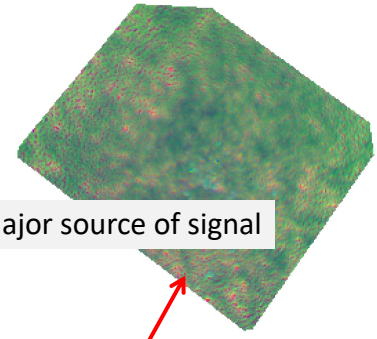
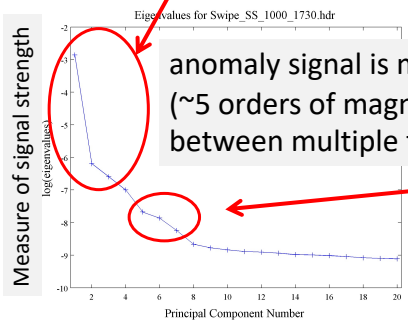
13

# Anomaly Detection Example

Image of Scores on PC 1 (97.73%), PC 2 (1.28%) & PC 3 (0.56%)



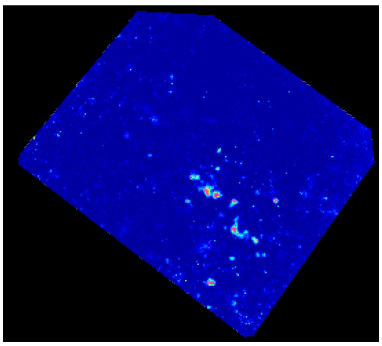
major source of signal




anomaly signal is minor (~5 orders of magnitude) and spread between multiple factors

apparent anomaly observed – what is it?

Image of Hotelling T^2 (99.83%)



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# Anomaly Detection Summary

- Flexible - finds unusual signal
- Minor anomalies may be difficult to detect
  - Could appear like random noise
- Doesn't identify the signal
  - Library search
    - Spectra in library not relevant? Matrix, environment,…
    - Additional processing may be needed for impure signal to remove background

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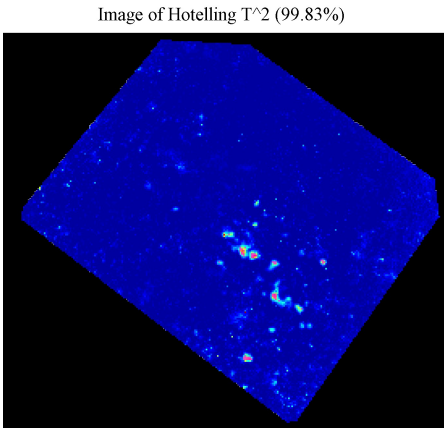
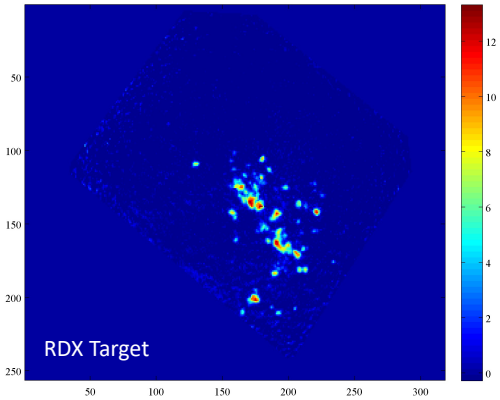
# Target Detection Example

Anomaly detection




Target detection
(also uses clutter suppression)

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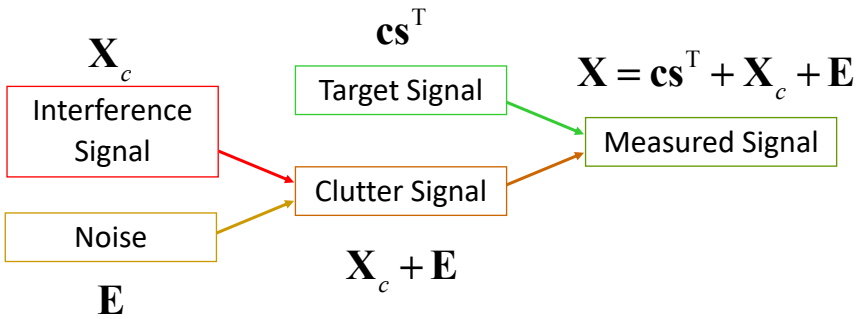
# Measured Signal – What is Clutter?

- Clutter is present in all measurements
  - clutter = interferences + noise not of interest

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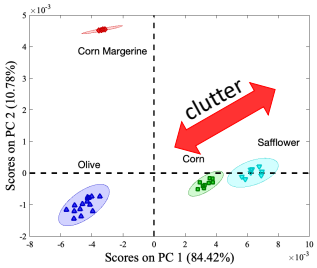
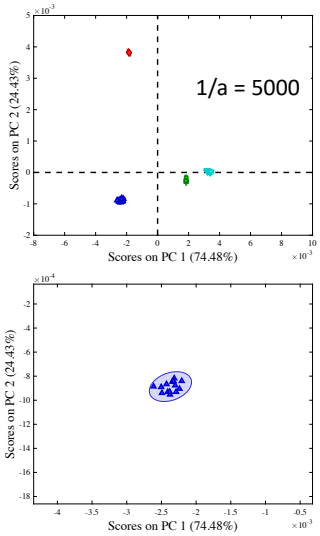
What does "decluttering" do?




generalized least squares weighting is a form of "de-cluttering" - increases inter- to intra-class variance. Increasing 1/a increases the weighting strength.

Paradigm Shift:
Maximize: signal-to-noise → signal-to-clutter

GLSW (weighting 1/a)

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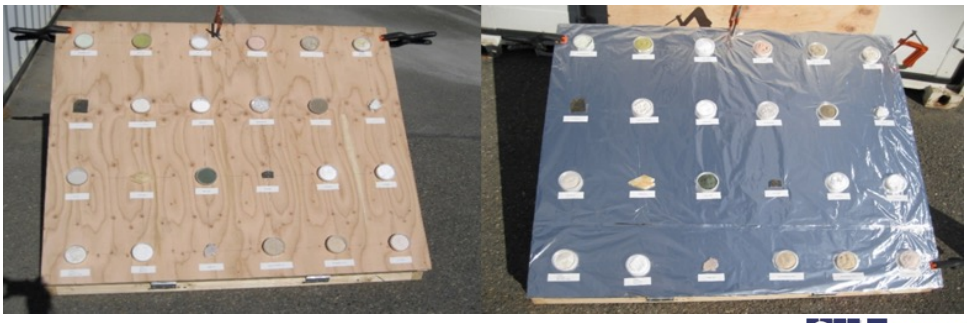
18

# Target Detection Example Minerals on Plate

- Rock and Minerals (ground in Nalgene cup)
  - Samples: 8 inch columns, 11.3 inch rows
  - Bare plywood and aluminum foil surfaces at 45º at 14 m
  - Rudimentary atmospheric correction



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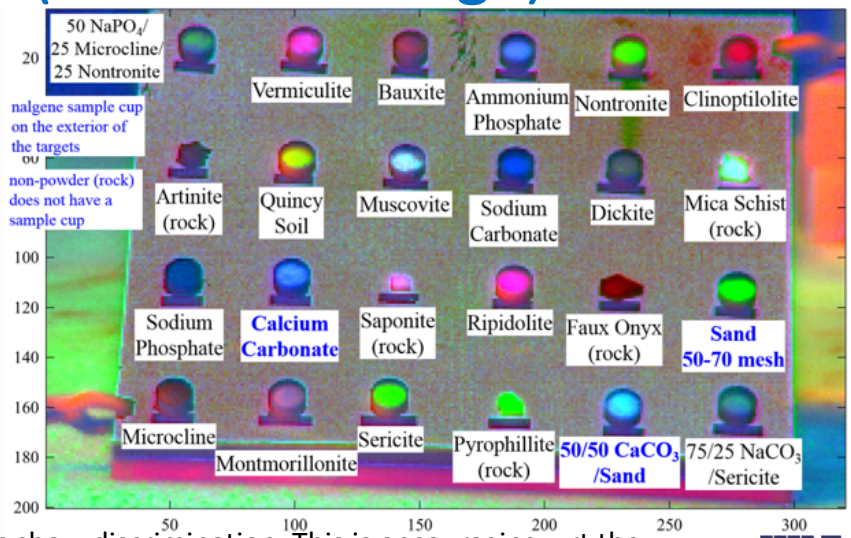
19

# PCA (PC Scores Image)




Scores images show discrimination. This is encouraging wrt the objective of detection and classification.

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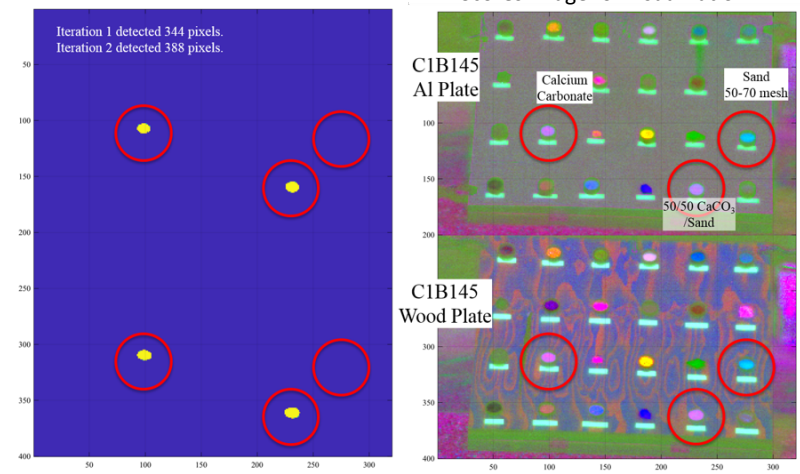
20

# Target Detection for $CaCO_3$

Scores image for visualization




Only $CaCO_3$ is detected (including the 50/50 mixture)!

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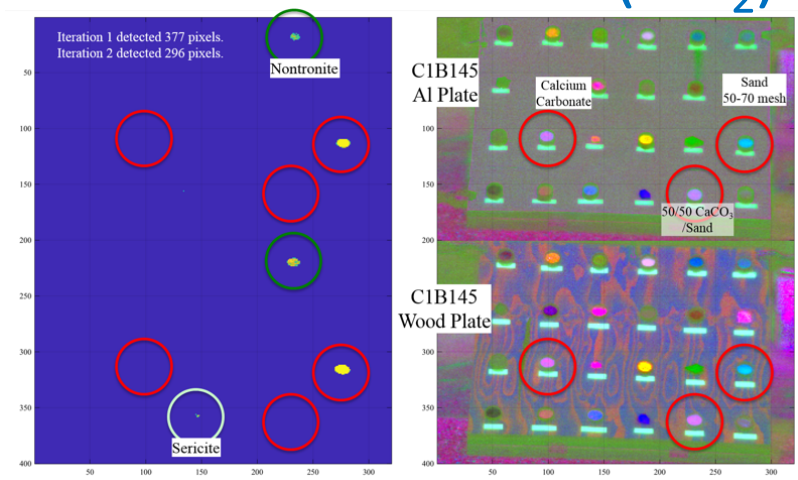
21

# Target Detection for Sand ($SiO_2$)




Sand is detected (none in the 50/50 mixture with $CaCO_3$).
Nontronite is a false alarm. Sericite has a minor false alarm on the wood plate.

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# Targeted Anomaly Detection

- Target detection finds unusual signal that looks like a target spectrum.
  - Targets are often from a library and may not correspond to a measured image
  - Requires atmospheric correction for remote sensing applications
  - Requires selectivity between targets for accurate detection and classification

- Targeted Anomaly Detection
  - Start with library, anomaly or other knowledge of a target of interest
  - Use first detections as new target signal – it is image specific and relevant
  - Find unusual signal in an image likely related to the desired target

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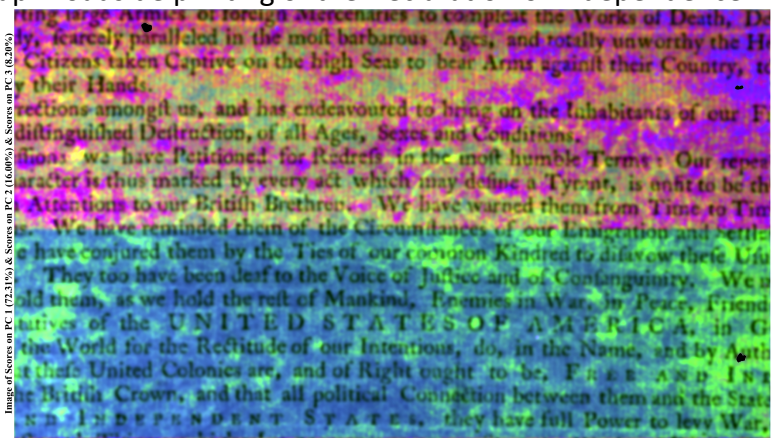
# Hidden Watermark

Dunlap Broadside printing of the Declaration of Independence




- Two major sources of clutter
- Hint of watermark used as the target

Thank you, Library of Congress
Meghan Wilson, Preservation Science Specialist
Fenella France, Chief of Preservation Research and Testing Division

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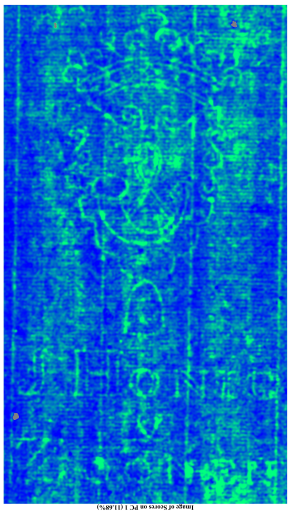
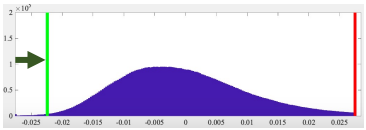
24

# Watermark



colormap winter
enhanced contrast
decluttering (1/α=100)
decluttering (1/α=10)
decluttering (1/ α=1)
decluttering (1/α=0.1)
no decluttering

- GLSW, mean-centering
  - 1/α larger is stronger de-cluttering
- Scores on PC 1
  - autocontrasted
    - mean-centered & saturated at ±2 std



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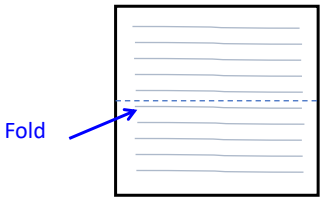
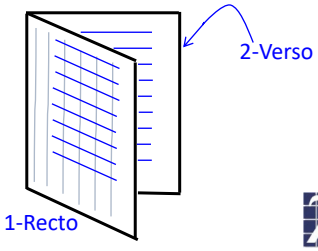
# This 15th Century Palimpsest

- Originally had writing on one side
- The ink was washed off
- The document was folded in half with the fold parallel to the original text yielding four sides for the new writing.
- The underwriting ended up on sides 1-Recto and 2-Verso, perpendicular to the overwriting.

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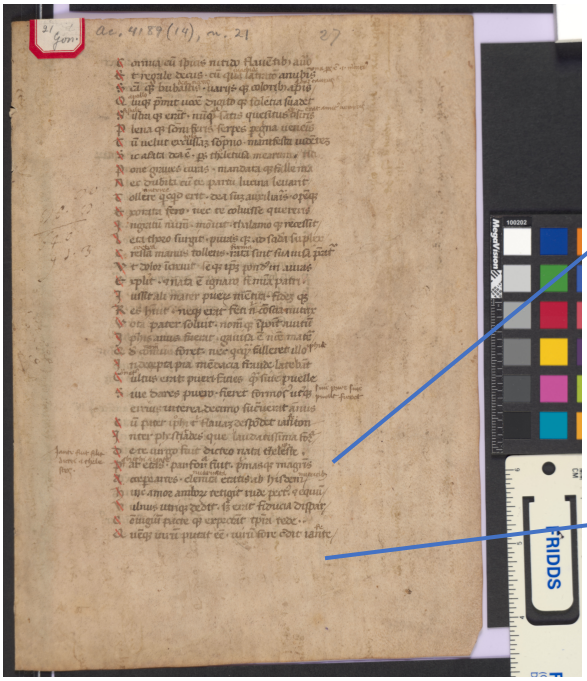
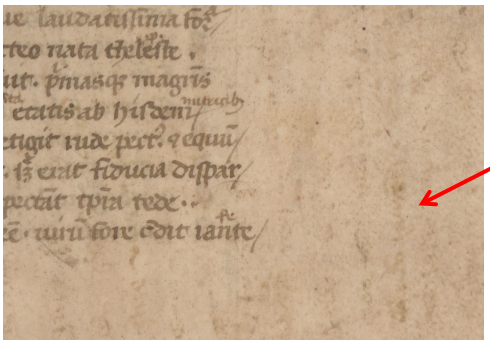
26



# Hints of Older Writing



Thank you, Library of Congress
Meghan Wilson, Preservation Science Specialist
Fenella France, Chief of Preservation Research and Testing Division

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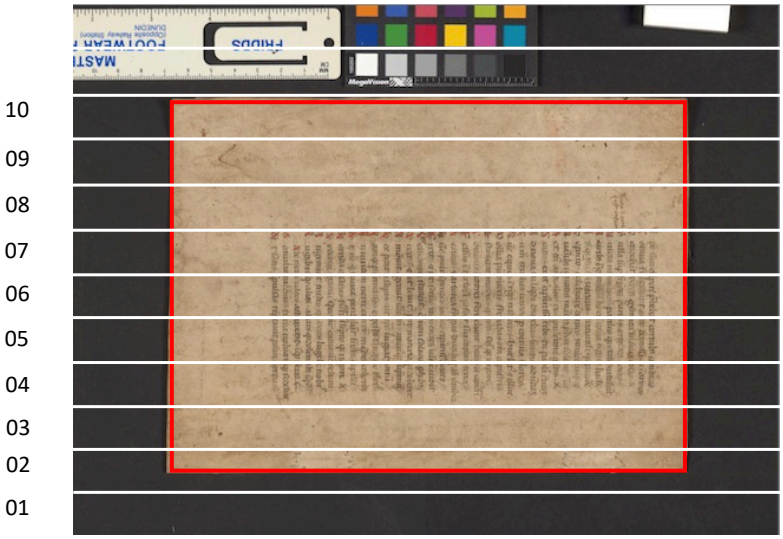
# Section into segments for Analysis




Analyzed segments 10, 09 & 08

Dahlberg, D., Gallagher, N., Wilson, M., France, F., "Revealing the Hidden Writing of a 15th Century Palimpsest Using Hyperspectral Imaging Analyzed by Principal Component Analysis and Generalized Least Squares Weighting", EAS15, Somerset, NJ, Nov 16-18 (2015). https://eigenvector.com/wp-content/uploads/2020/09/EAS15_Palimpsest-Analysis.pdf

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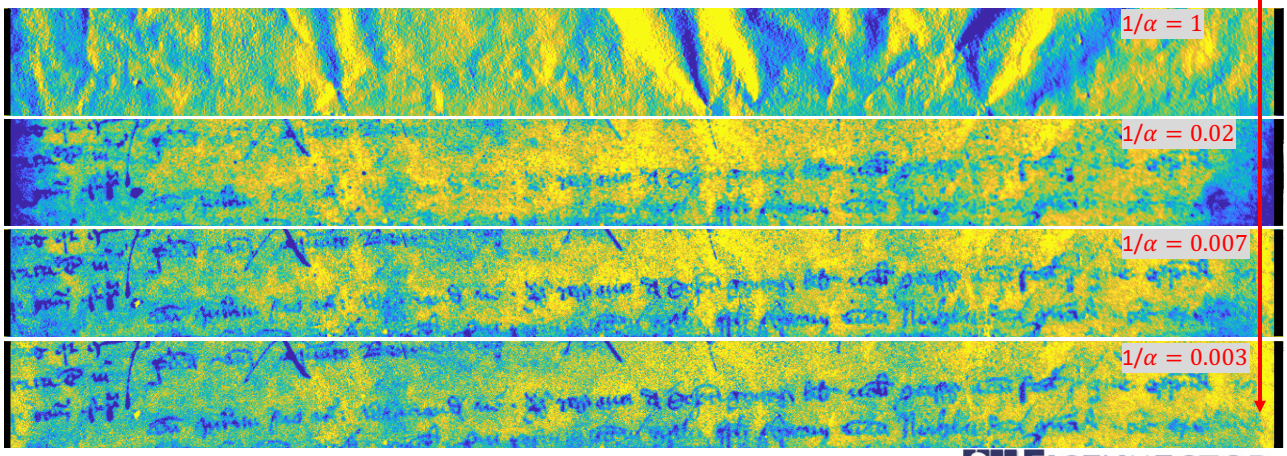
28

# Section 10

Scores on PC 1

increasing de-weighting

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29

# Section 10

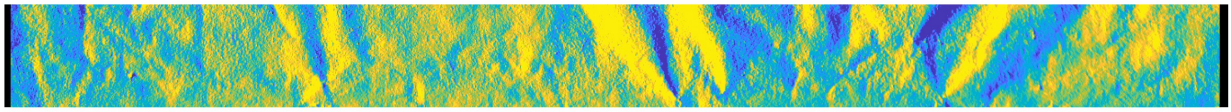
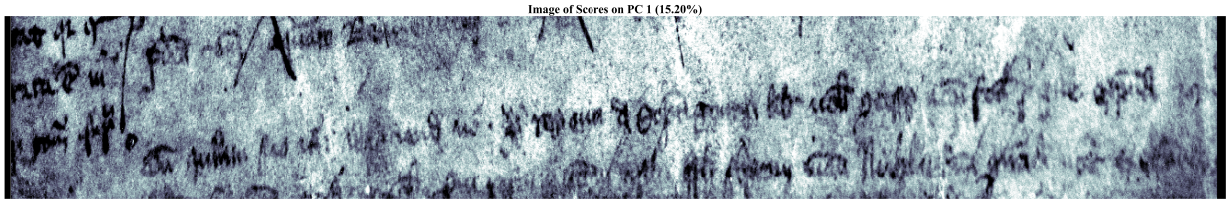


Image of Scores on PC 1 (15.20%)



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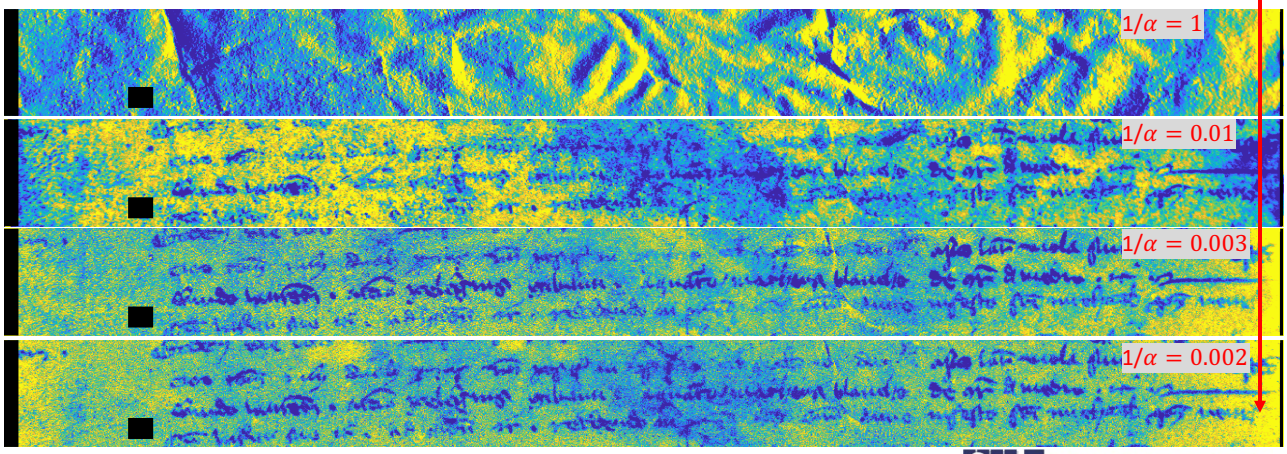
30

# Section 9

Scores on PC 1

increasing de-weighting

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31

# Section 9

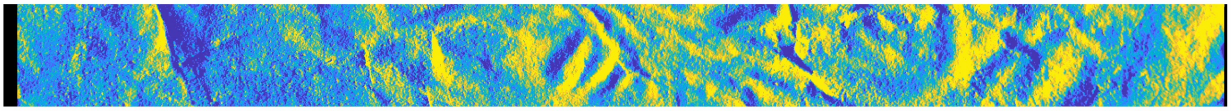
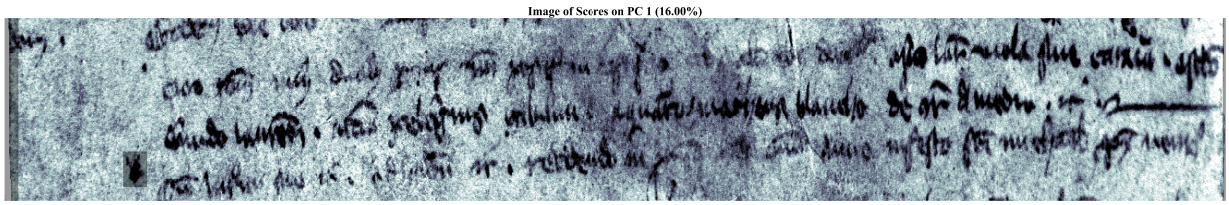


Image of Scores on PC 1 (16.00%)



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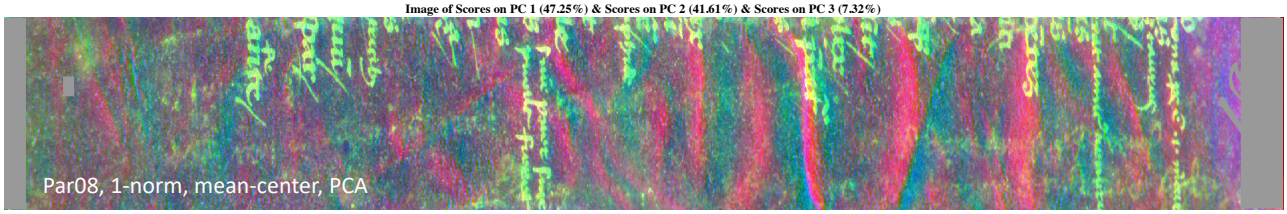
32

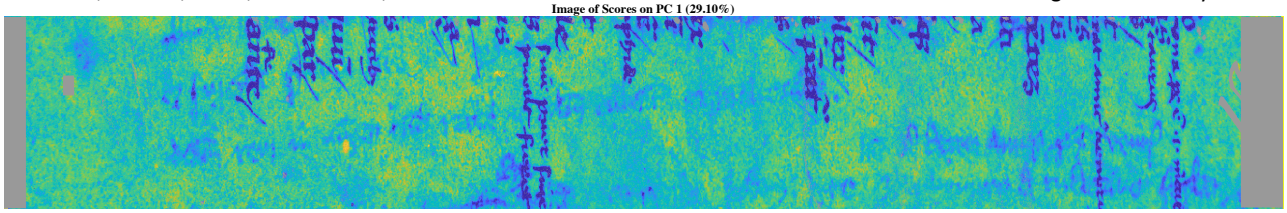
Image of Scores on PC 1 (47.25%) & Scores on PC 2 (41.61%) & Scores on PC 3 (7.32%)




Par08, 1-norm, GLSW, mean-center, PCA

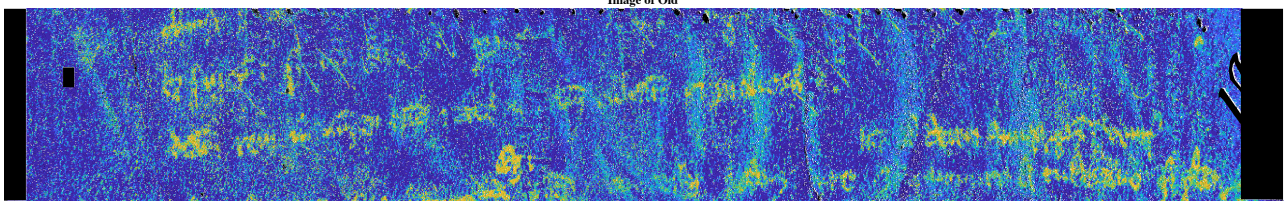
Section 8 – Some times things aren't as easy…..

Image of Scores on PC 1 (29.10%)



Par08, 1-norm, ELS, GLSW, NNLS, CLS (matched filter)

Image of Old



33

# De-Cluttering: GLSW Summary 1/2

- GLSW de-weights variations in the clutter class – e.g., paper signal.
  - Signal important to wrinkles, paper texture, uneven lighting (and overwriting) were de-weighted.
- The objective is to suppress signal not of interest (clutter) to enhance signal of interest
  - Maximize signal-to-clutter

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34

# De-Cluttering: GLSW Summary 2/2

- GLSW de-weighting works to remove spectral shape not magnitude
  - E.g., use row normalization to minimize magnitude effects
- The weighting finds 'directions' of correlated clutter
  - Due to interferences
  - Significant differences in noise between spectral channels
- The weighting is characterized with data that does not contain target signal

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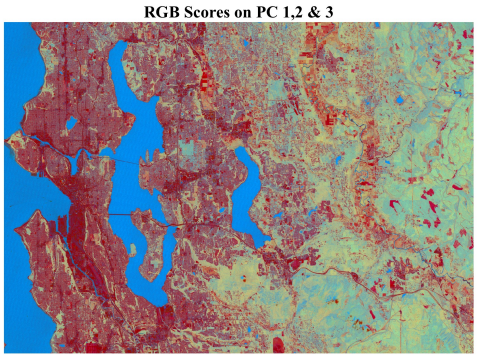
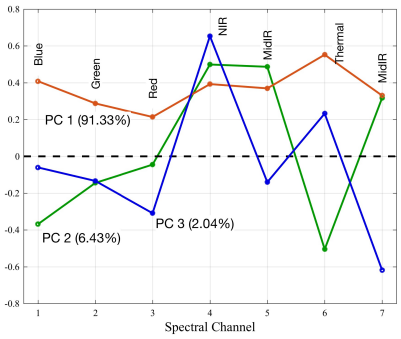
35

# PCA Scores and Loadings

Landsat of Seattle and surrounding area

**water signal is minor (it's in PC 3)**
**Can we discriminate Puget Sound from fresh water lakes?**




Seattle Landsat, USGS/NASA

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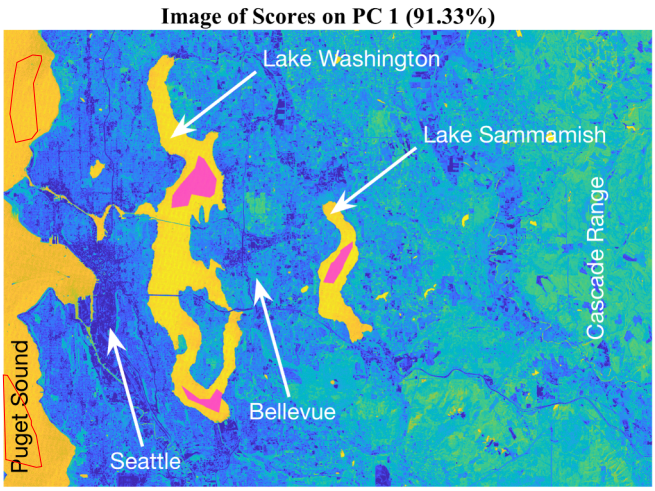
36

# Target Detection Example: Multiple Targets




- Two-target GLS
  - Target: "Lakes" magenta
  - Interference: "Puget Sound"
- Extended Mixture Model + Generalized Least Squares
  - Can improve discrimination over the single target GLS approach

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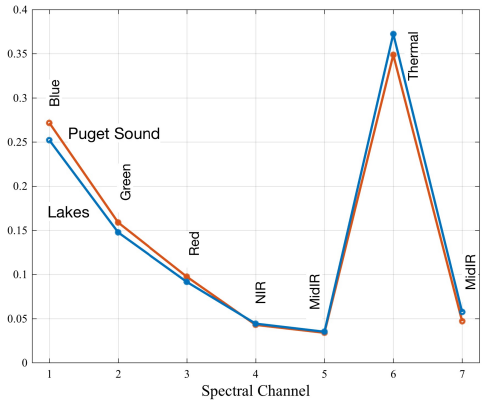
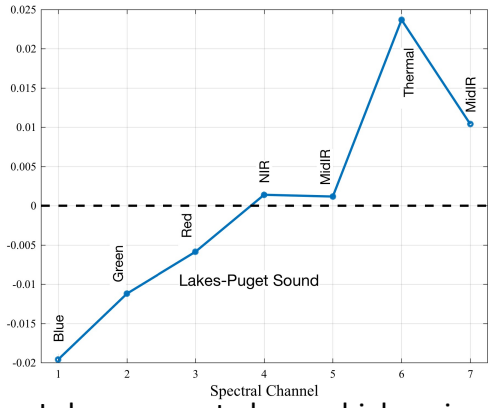
37

# Targets




The target signals are *very* similar

Differences between the two targets




Lakes appear to have a higher signal on the Thermal channel relative to the Blue channel.

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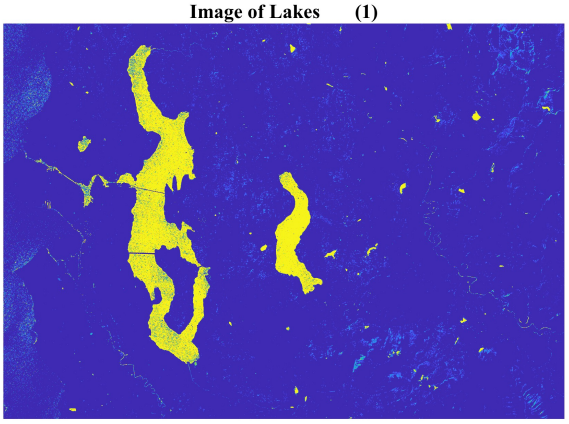
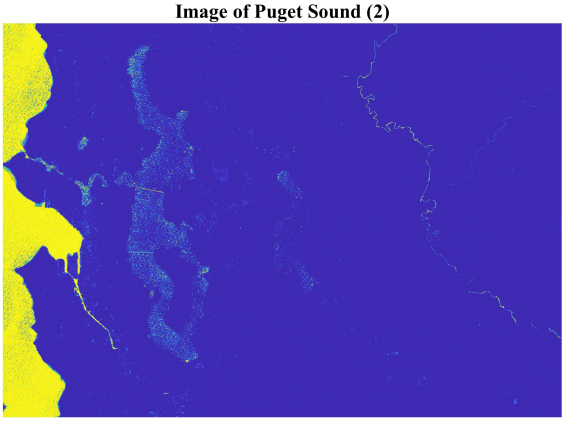
38

Image of Lakes (1)



Lakes

Image of Puget Sound (2)



Sound

Lakes are discriminated from the Sound but ….

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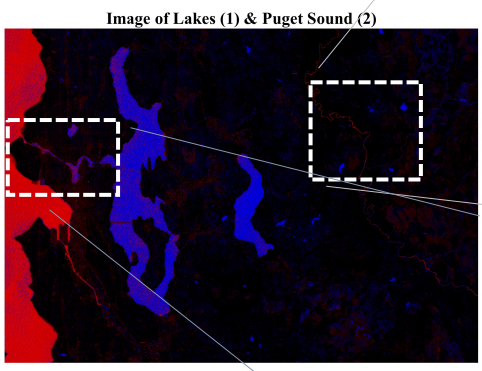
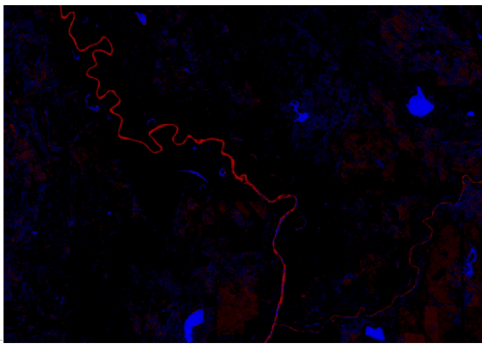
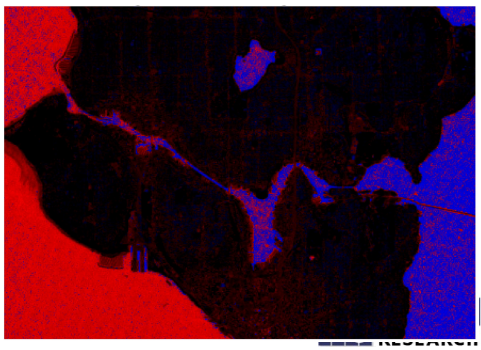
… It looks like temperature is a major driver for the difference.

Image of Lakes (1) & Puget Sound (2)







Discrimination is sometimes due to physics and not chemistry.

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41

# Conclusions

- The examples differed are in how "signal" and "clutter" are defined depending on the desired signal to enhance and signal to suppress
  - One man's clutter is another's target.
- Anomaly and Target Detection can be used synergistically to find signal of interest
  - signal that may be missed when used independently
  - the result is Targeted Anomaly Detection
  - very flexible approach to targeted image exploration

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42

# Additional Information

Myers, T.L., Johnson, T.J., Gallagher, N.B., Bernacki, B.E., Beiswenger, T.N., Szecsody, J.E. Tonkyn, R.G., Ashley M. Oeck, A.M., Su,Y.-F., Danby, T.O., "Hyperspectral Imaging of Minerals in the Longwave Infrared: The Use of Laboratory Directional-Hemispherical Reference Measurements for Field Exploration Data," *J Appl Remote Sens*, **13**(3), 034527 (2019). DOI: 10.1117/1.JRS.13.034527.

Gallagher, N.B., Shaver, J.M., Bishop,R., Roginski, R.T., Wise, B.M. "Decompositions with Maximum Signal Factors," *J. Chemometr.*, **28**(8), 663-671 (2014). DOI: 10.1002/cem.2634.

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Blake, T.A., Kelly, J.F., Gallagher, N.B., Gassman, P.L., Johnson, T.J., "Passive Detection of Solid Explosives in Mid-IR Hyperspectral Images," *Anal. Bioanal. Chem.* **395**(2), 337-348 (2009), DOI 10.1007/s00216-009-2907-5.

Gallagher, N.B., "Classical Least Squares for Detection and Classification," in Hyperspectral Imaging, Vol 32 (Data Handling in Science and Technology) 1st Ed, J. Manuel Amigo editor, Elsevier, 231-246, Oct 1 (2019) ISBN: 9780444639776. https://doi.org/10.1016/B978-0-444-63977-6.00011-0

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43