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

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

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

\[ \text{anomalies are found in any direction} \quad \text{target signal is found in a specific direction, } s \]
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 $T^2$ (distance from data origin)
    - Q residuals (lack of fit)
  - This example modeled the entire image

PCA of a Landsat 8 Image


Data preprocessing can have a significant impact on the ability to detect outliers.
Examine Q and $T^2$ for Outliers


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

Plot of Q vs T2 can help identify truly unusual signal. Changing color schemes and contrast can help explore the signal.
Examine Region Local to the Anomaly

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

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/

<table>
<thead>
<tr>
<th>Band Number</th>
<th>Wavelength Range (µm)</th>
<th>Resolution (m)</th>
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<tbody>
<tr>
<td>1</td>
<td>0.43 - 0.453</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>0.45 - 0.515</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0.52 - 0.600</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>0.63 - 0.680</td>
<td>30</td>
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<tr>
<td>5</td>
<td>0.84 - 0.885</td>
<td>30</td>
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<tr>
<td>6</td>
<td>1.56 - 1.660</td>
<td>30</td>
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<tr>
<td>7</td>
<td>2.10 - 2.300</td>
<td>30</td>
</tr>
<tr>
<td>8 (not used)</td>
<td>0.50 - 0.680</td>
<td>15</td>
</tr>
<tr>
<td>9</td>
<td>1.36 - 1.990</td>
<td>30</td>
</tr>
<tr>
<td>10 (not used)</td>
<td>10.6 - 11.2</td>
<td>100</td>
</tr>
<tr>
<td>11 (not used)</td>
<td>11.5 - 12.5</td>
<td>100</td>
</tr>
</tbody>
</table>
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?

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

Anomaly Detection Example

apparent anomaly observed – what is it?

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

major source of signal
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

Target Detection Example

Anomaly detection
Image of Hotelling $T^2$ (99.83%)

Target detection
(also uses clutter suppression)

RDX Target
Measured Signal – What is Clutter?

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

![Diagram of signal components]

What does “decluttering” do?

Generalized least squares weighting is a form of “decluttering” - increases inter- to intra-class variance. Increasing 1/a increases the weighting strength.

Paradigm Shift: Maximize: signal-to-noise $\rightarrow$ signal-to-clutter
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

Scores images show discrimination. This is encouraging wrt the objective of detection and classification.
Target Detection for CaCO₃

Only CaCO₃ is detected (including the 50/50 mixture)!

Target Detection for Sand (SiO₂)

Sand is detected (none in the 50/50 mixture with CaCO₃). Nontronite is a false alarm. Sericite has a minor false alarm on the wood plate.
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

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
Watermark

- GLSW, mean-centering
- $1/\alpha$ larger is stronger de-cluttering
- Scores on PC 1
- autocontrasted
- mean-centered & saturated at $\pm 2$ std

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.
Hints of Older Writing

Thank you, Library of Congress
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Fenella France, Chief of Preservation Research and Testing Division

Section into segments for Analysis

Section 10

Scores on PC 1 increasing de-weighting

\[
\frac{1}{\alpha} = 1
\]

\[
\frac{1}{\alpha} = 0.02
\]

\[
\frac{1}{\alpha} = 0.007
\]

\[
\frac{1}{\alpha} = 0.003
\]

Section 10

Image of Scores on PC 1 (15.2%)

Eigenvector Research Incorporated
Section 9

Scores on PC 1

increasing de-weighting

$1/\alpha = 1$

$1/\alpha = 0.01$

$1/\alpha = 0.003$

$1/\alpha = 0.002$
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
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

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
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

The target signals are very similar

Lakes appear to have a higher signal on the Thermal channel relative to the Blue channel.
Lakes are discriminated from the Sound but ... .

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

Discrimination is sometimes due to physics and not chemistry.
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

Additional Information


https://doi.org/10.1016/B978-0-444-63977-6.00011-0