Hyperspectral Feature Detection Onboard the Earth Observing One Spacecraft

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Agenda

Why onboard hyperspectral analysis?

Enabling techniques
1. Superpixel segmentation
2. Endmember detection

EO-1 experiments
Imaging spectrometers are important tools for exploration

- Moon (M³)
- Mars (OMEGA, CRISM)
- Jupiter (Galileo NIMS)
- Saturn (Cassini VIMS)
- Vesta (Dawn VIR)
- Comets (Rosetta)
- In-situ
- Terrestrial applications

Images courtesy NASA/Brown/JPL and other missions
Challenge: bandwidth constraints limit duty cycle

MRO/CRISM coverage by full-resolution images

images courtesy NASA / Brown University. Online map: http://crism-map.jhuapl.edu/
Challenge: respond to targets of opportunity

Mt. Erebus thermal anomaly

Hartley 2 morphology, plumes
Solution: onboard spectral discovery and mapping

CRISM interpretation
[Gilmore et al., JGR 2011]
Onboard analysis is hard

1. Planetary spectral data can be noisy
2. Signals are subtle, difficult to interpret
3. Targets are often unknown in advance
4. Very limited onboard computation

![Graph showing spectral data with annotations for instrument noise, unanticipated atmospheric distortion, and unique & subtle mineralogy.]
Superpixel representations exploit the spatial dimension

- Spatially contiguous, homogeneous regions
- Improves robustness to artifacts
- Reduces noise by $\sqrt{n}$
- Reduces data set by 75x for later processing

Taylor glacier (EO-1)

<3500 superpixels

260,000 pixels
Superpixel representations exploit the spatial dimension

[Thompson et al., TGARS 2010]
Superpixel representations exploit the spatial dimension

- Felzenszwalb graph partitioning algorithm [2004]
- Compute spectral distances between neighbors
- Agglomerative clustering grows minimum spanning trees
Endmember detection finds spectrally distinct superpixels

Linear mixing model: spectra are convex combinations of a small number of endmembers

Endmembers often correspond to unique materials

- Magnesite
- Phyllosilicate
- Olivine
Endmember detection finds spectrally distinct superpixels

Linear mixing model: spectra are convex combinations of a small number of endmembers

Endmembers often correspond to unique materials

\[ \rho_j = Qa_j + \mathcal{N}(0, \sigma^2) \]

- \( m \times n \) matrix of endmembers
- Gaussian measurement noise
- Measurement at superpixel \( j \)
- \( n \)-vector of nonnegative mixing coefficients

Endmembers:
- Magnesite
- Phyllosilicate
- Olivine
Superpixel endmember detection

SMACC endmember detection in CRISM 3e12
[Thompson et al., TGARS 2011]
Summary Classification

Spectral angle map for fast, fully automatic scene classification

CRISM interpretation
[Gilmore et al., JGR 2011]
Agenda

Why onboard hyperspectral analysis?

Two tricks to make it work

1. Superpixel segmentation
2. Endmember detection

EO-1 experiments
The EO-1 Spacecraft

- Currently in an “extended mission” phase
- Used in sensorweb and autonomous science operations since 2004 [Chien et al., 2005]
- Detects transient events such as floods and volcanoes
- Mongoose-V 32-bit microprocessor for onboard data analysis
  - 12MHz clock speed
  - No hardware floating-point arithmetic
  - Limited memory (16 MB application max)

EO-1 Selective downlink of volcanic activity “hot spot” in thermal imagery [Davies et al. 2005]
The Hyperion imaging spectrometer

- High resolution hyperspectral imager
- 220 spectral bands from 0.4 to 2.5 µm
- 30 meter spatial resolution, provides 7.5 x 100 km land area per image
- A reflectance product is available for onboard use
  - 12 bands selected in advance (once per observation)
  - 256x1024 pixel subframe

Gold Standard Cuprite maps [Kruse et al., IEEE TGARS 2003]
Uplink

Bands, lat, lon

Acquisition, T = 0

Downlink
~5 days, 760 Mb

3900 x 256 x 220 image
Uplink

Bands, lat, lon

Acquisition, T = 0

Reflectance conversion, band selection

1024 x 256 image

Superpixel Segmentation

~3000 superpixels

Endmember (EM) detection

30 EM spectra

SAM Match to endmembers

1024x256 EM map

EM locations and spectra

3900 x 256 x 220 image

Telemetry
~6 hours, 160 Kb

Downlink
~5 days, 760 Mb
Cuprite NV, USA – Sept. 2011

Credit: nvghosttowns.com
Cuprite NV, USA – Sept. 2011

Sept. 19, 2011 Overflight

Sept. 27, 2011 Overflight

Gold Standard Cuprite maps
[Kruse et al., IEEE TGARS 2003]
Cuprite NV, USA – Sept. 2011

Endmember spectra

Full spectrum

Kruse et al. manual analysis (Hyperion)
Steamboat Springs, USA – 3 Oct 2012

Credit: NREL
Steamboat Springs, USA – 3 Oct 2011

Endmember spectra

Compositional map generated onboard

Authoritative version of [Kruse et al., 2003]
Blood Falls, Taylor Glacier – 7 Feb 2012

Credit: USAP
Hyperspectral image

Spectral endmember

Blood Falls, Taylor Glacier – 7 Feb 2012
Mammoth Springs, MT - 20 Oct 2011
Rio Tinto, Spain- 25 May 2012

Credit: Carol Stoker (AMES) / Wikicommons
Clouded over?
Rio Tinto, Spain - 25 May 2012

Credit: Jesús Municio
Summary

• Automatic onboard mapping summarizes a 1024 x 256 x 220 scene using 20kB
• Runs onboard, using a fraction of a 12MHz processor
• Requires <16MB of volatile memory
• Identifies pure features and returns exemplar spectra
• Operating regularly on EO-1
Future directions

Autonomy can be enabling for hyperspectral imagers

More sophisticated detection algorithms are possible

- Follow up on signatures in a library
- Follow up on signatures **not** in a library
- Linear unmixing

Multi-core architectures and FPGAs can provide faster, full-spectrum analyses
References

- B. Bue, D. R. Thompson. Multiclass Continuous Correspondence Learning. NIPS Domain Adaptation Workshop 2011
- B. Bornstein, D. R. Thompson, S. Chien, R. Castano and B. Bue. Efficient Spectral Endmember Detection Onboard the EO-1 Spacecraft. IEEE WHISPERS, June 2011
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Extra slides
Automatic onboard analysis

Uplink

Bands, lat, lon

Acquisition, $T = 0$

Reflectance conversion, band selection

1024 x 256 image

Superpixel Segmentation

~3000 superpixels

Endmember (EM) detection

30 EM spectra

SAM Match to endmembers

Telemetry ($T = \sim 6h$)

1024x256 EM map

EM locations and spectra

Downlink ($T = \sim 5d$)

3900 x 256 x 220 image
EO-1 Thermal signature detection

Black Body model used to trigger a second observation [Chien et al. 2005]

- ASE images Erebus Night
- ASE initiates band extraction
- ASE runs thermal classifier
- THERMAL TRIGGERED
- Planner selects reaction observation (Stromboli observation replaced)
- Thumbnail downlinked (S-band)

13:40 GMT
} +10 min
} +28 min
} +29 min
} +20 min

15:58 GMT

20:10 GMT + 06:30

ASE Onboard Thermal Classifier Thumbnail

ASE Onboard Thermal Classifier

ASE images Erebus again
Cuprite NV

Kruse et al. (AVIRIS)

Kruse et al. (Hyperion)

EO-1 Onboard

endmember
Superpixels via graph partitioning

- Posit spectral distances \( d(v_i, v_j) \) between neighbors
- Agglomerate minimum spanning trees [Felzenswalb 2004]
- Merge based on largest internal distance

\[
\text{Dif}(S_a, S_b) > \text{MInt}(S_a, S_b) = \min \left( \text{Int}(S_a) + \frac{k}{|S_a|}, \text{Int}(S_b) + \frac{k}{|S_b|} \right)
\]
EO-1 Onboard
Sept. 21, 2011

Kruse et al. manual analysis (Hyperion)

EO-1 Onboard
Sept. 27, 2011

endmember 2
Alunite

15 (spurious)
3 Muscovite

27 Calcite

28 Kaolinite/Muscovite

29 Kaolinite/Alunite?

2 Alunite

21 Muscovite

16 Muscovite

7 Calcite

Kruse et al.