# Hyperspectral Feature Detection Onboard the Earth Observing One Spacecraft


David R. Thompson
Steve Chien
Benjamin Bornstein
Brian Bue[1]
Becky Castaño
Damhnait Gleeson[2]
Aaron Noell
Steve Schaffer
Daniel Tran

Jet Propulsion Laboratory,
California Institute of Technology
david.r.thompson@jpl.nasa.gov

1 Rice University
2 Centro de Astrobiologia (CSIC-INTA)
Madrid Area, Spain



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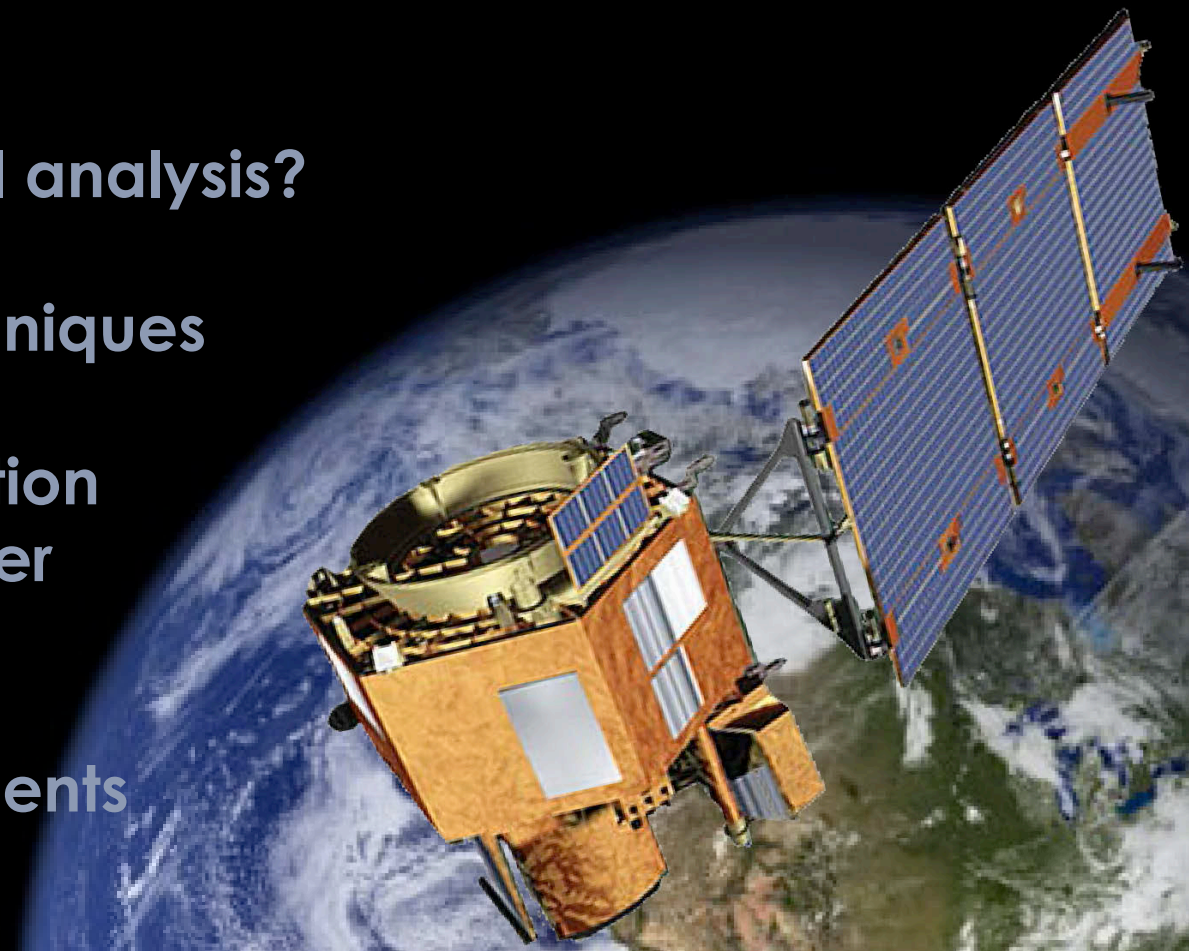
# Agenda

Why onboard hyperspectral analysis?

Enabling techniques

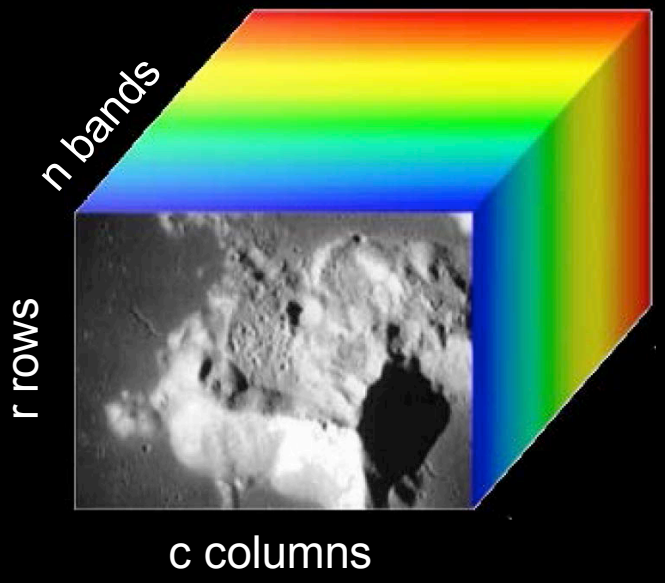
1. Superpixel segmentation
2. Endmember detection

EO-1 experiments



# Imaging spectrometers are important tools for exploration

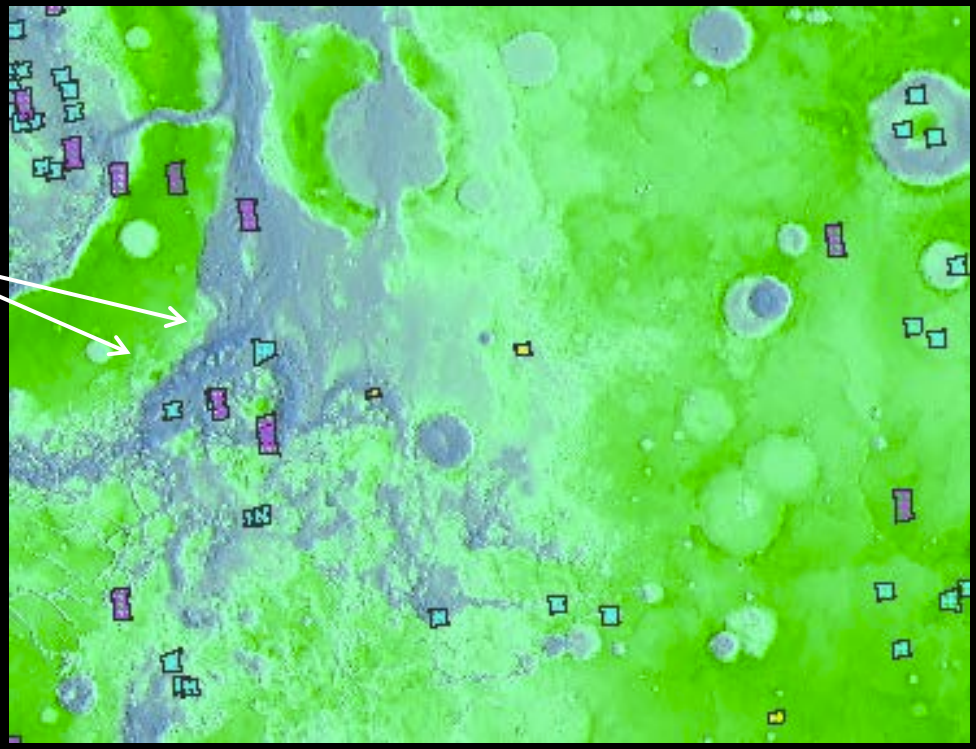
- Moon ($M^3$)
- Mars (OMEGA, CRISM)
- Jupiter (Galileo NIMS)
- Saturn (Cassini VIMS)
- Vesta (Dawn VIR)
- Comets (Rosetta)
- In-situ
- Terrestrial applications




Images courtesy NASA/Brown/JPL and other missions

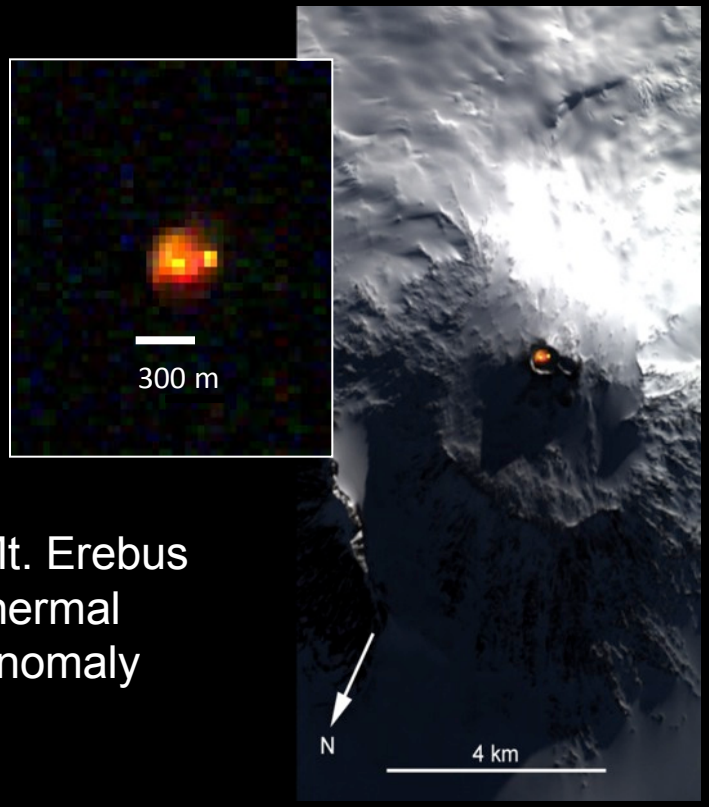
# Challenge: bandwidth constraints limit duty cycle

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

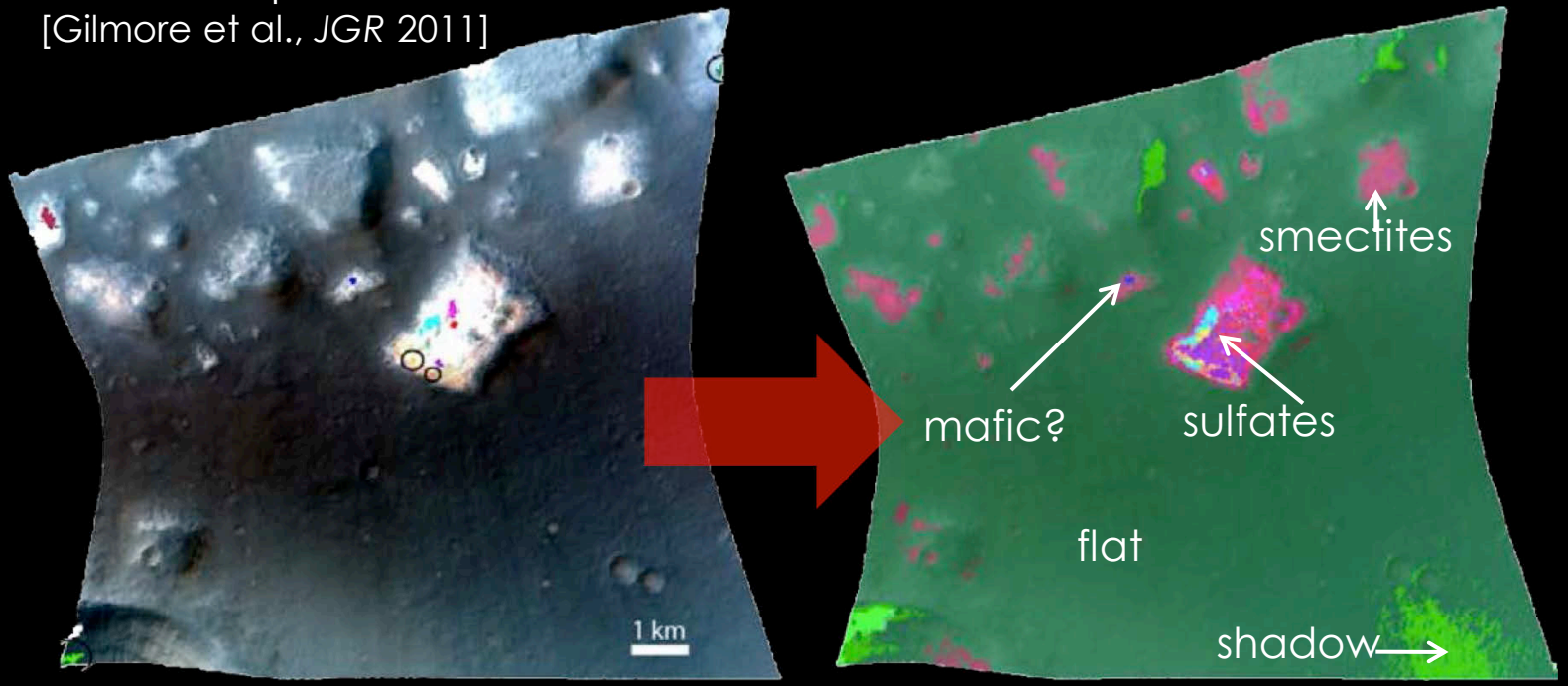



Mt. Erebus thermal anomaly

Hartley 2 morphology, plumes

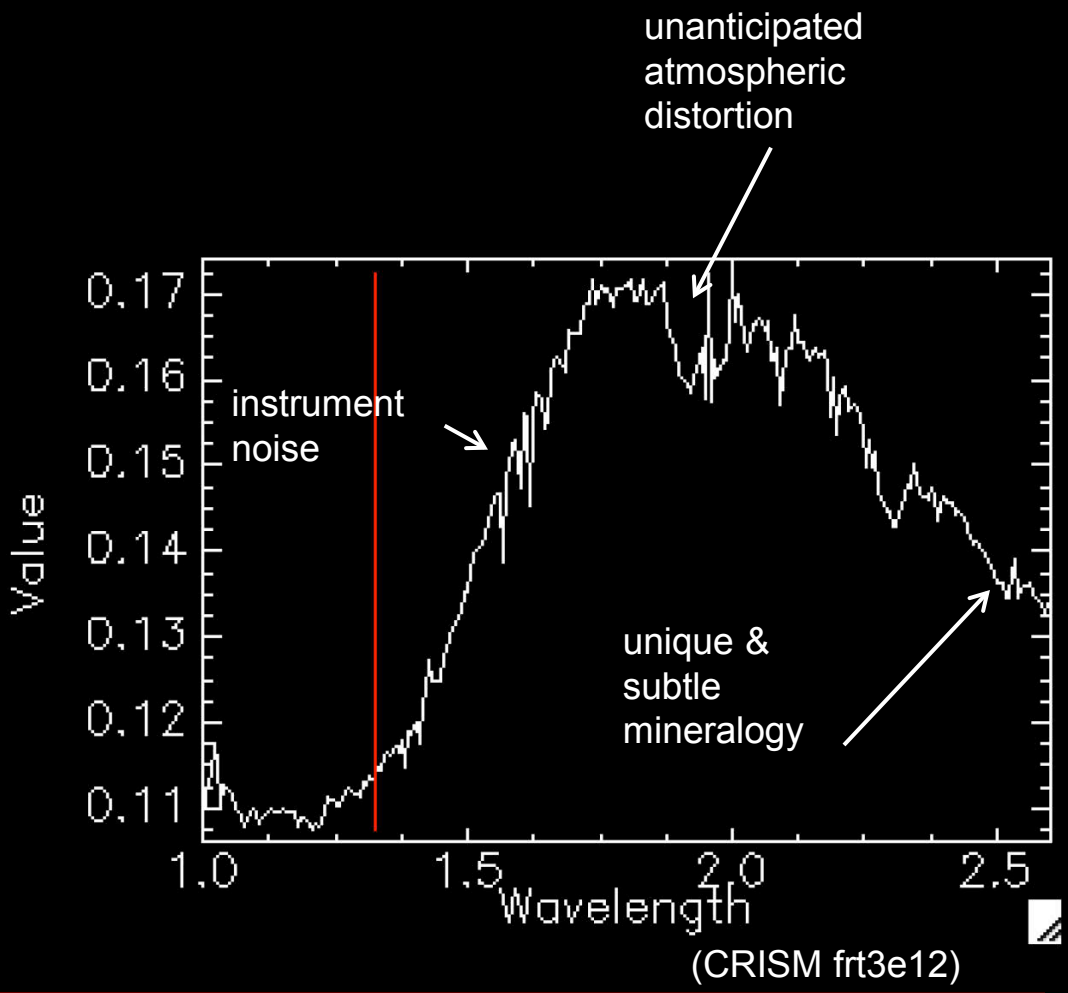
# Solution: onboard spectral discovery and mapping

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



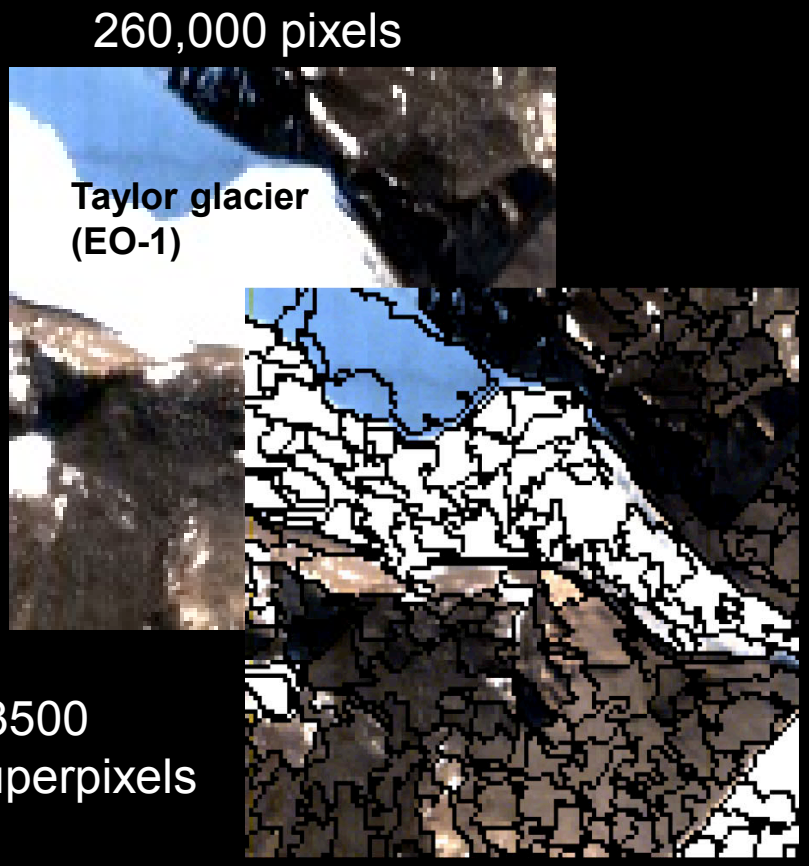
# Onboard analysis is hard

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

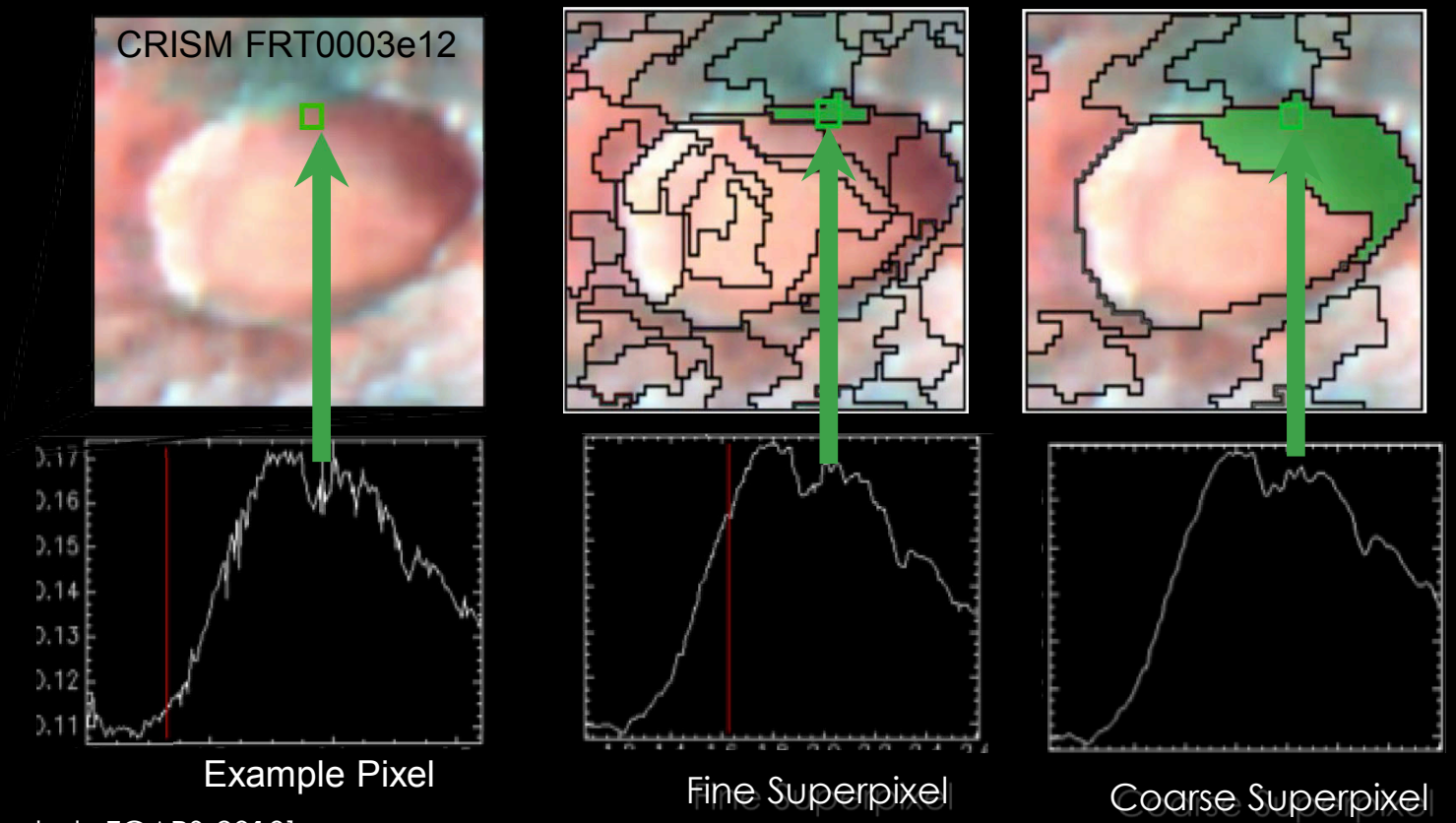


# Superpixel representations exploit the *spatial* dimension

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



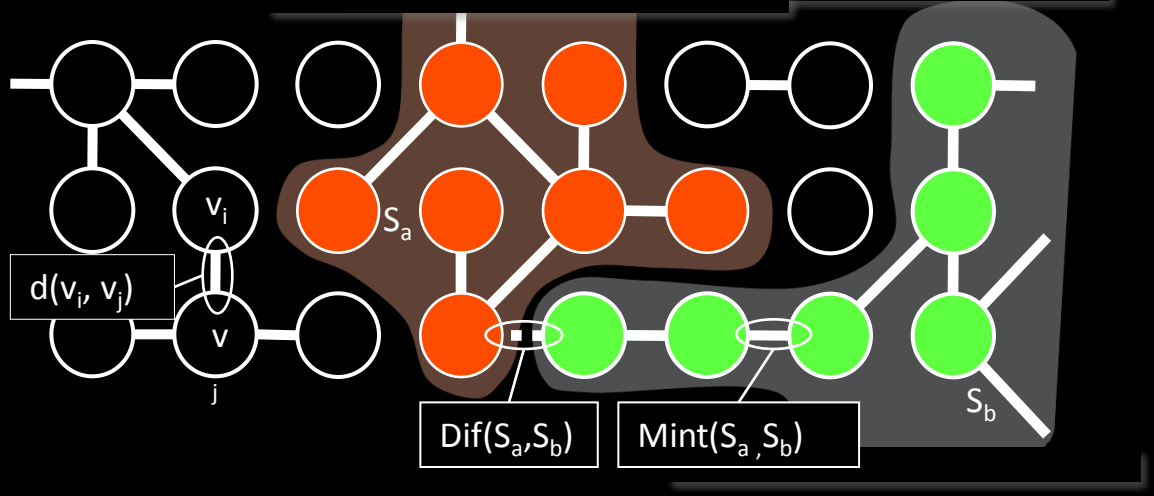
# Superpixel representations exploit the *spatial* dimension




[Thompson et al., TGARS 2010]

# Superpixel representations exploit the *spatial* dimension

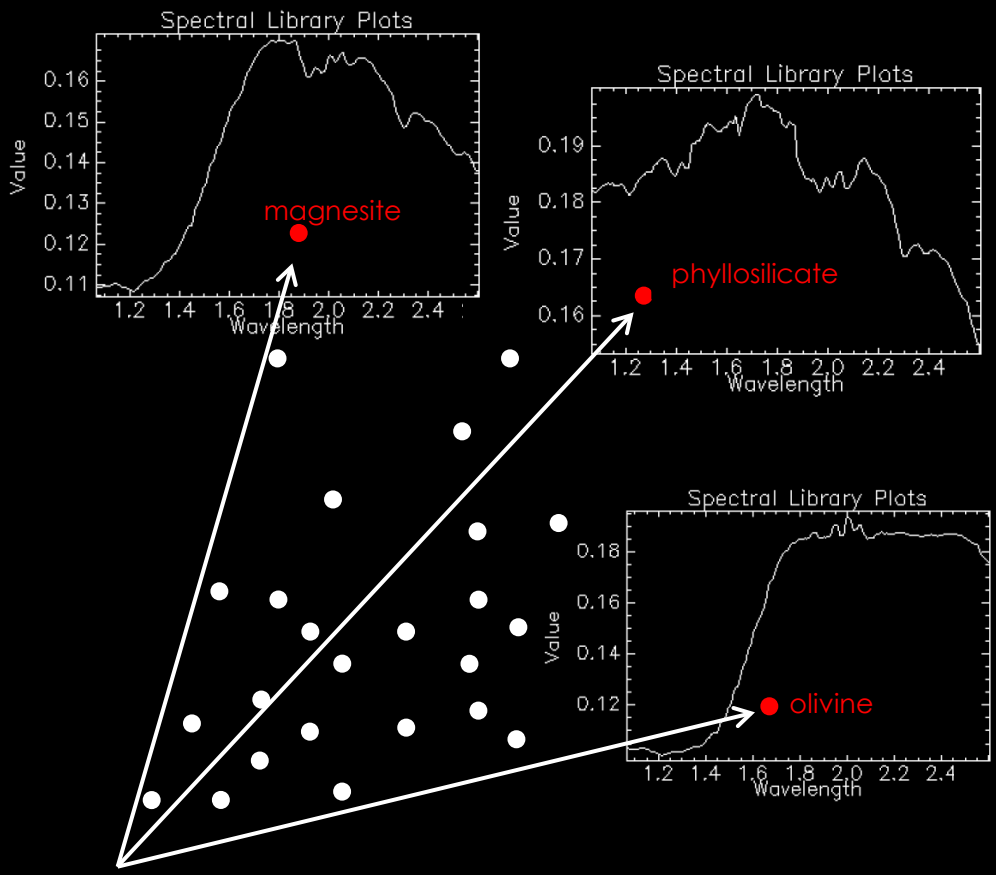
- Felzenszwalb graph partitioning algorithm [2004]
- Compute spectral distances between neighbors
- Agglomerative clustering grows minimum spanning trees



# 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



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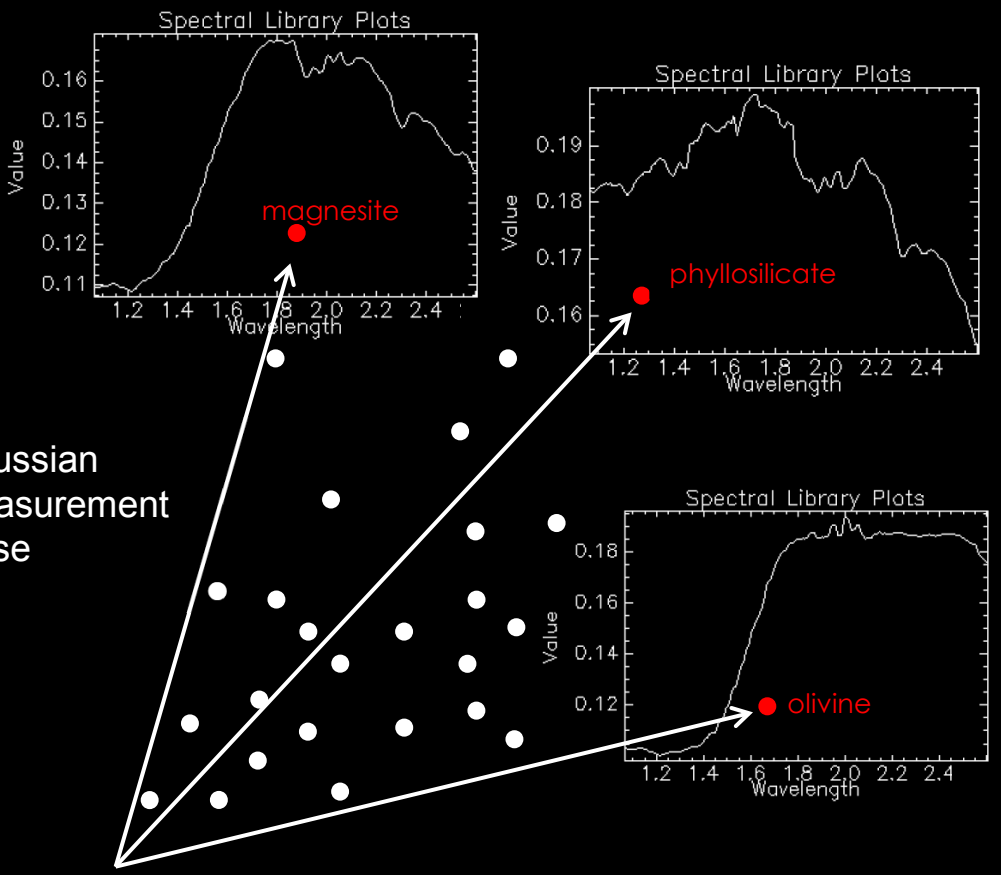



m x n matrix of endmembers

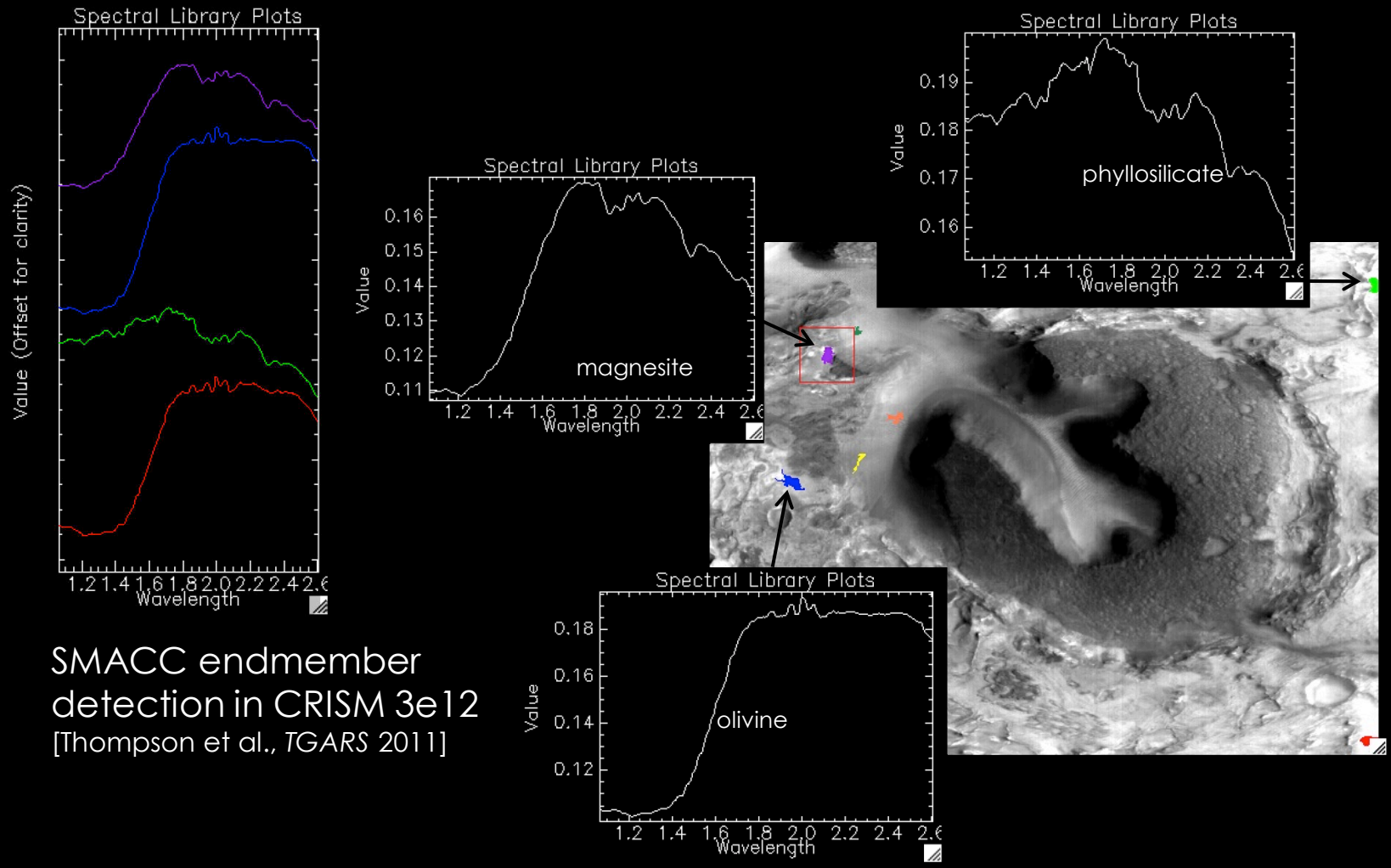
Gaussian measurement noise

$$\rho_j = \mathbf{Q}\mathbf{a}_j + \mathcal{N}(0, \sigma^2)$$

measurement at superpixel j

n-vector of nonnegative mixing coefficients

# Superpixel endmember detection

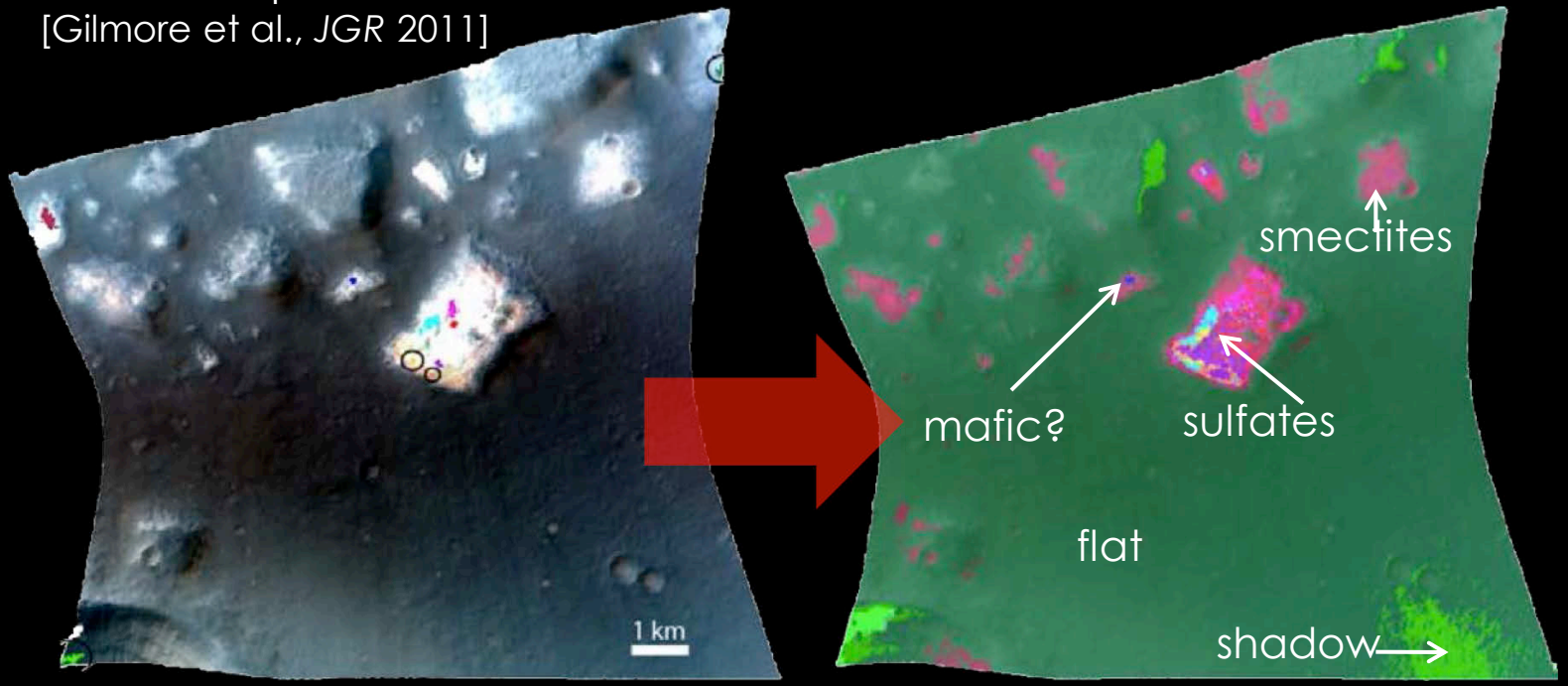



SMACC endmember detection in CRISM 3e12
[Thompson et al., *TGARS* 2011]

# Summary Classification

Spectral angle map for fast, fully automatic scene classification

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



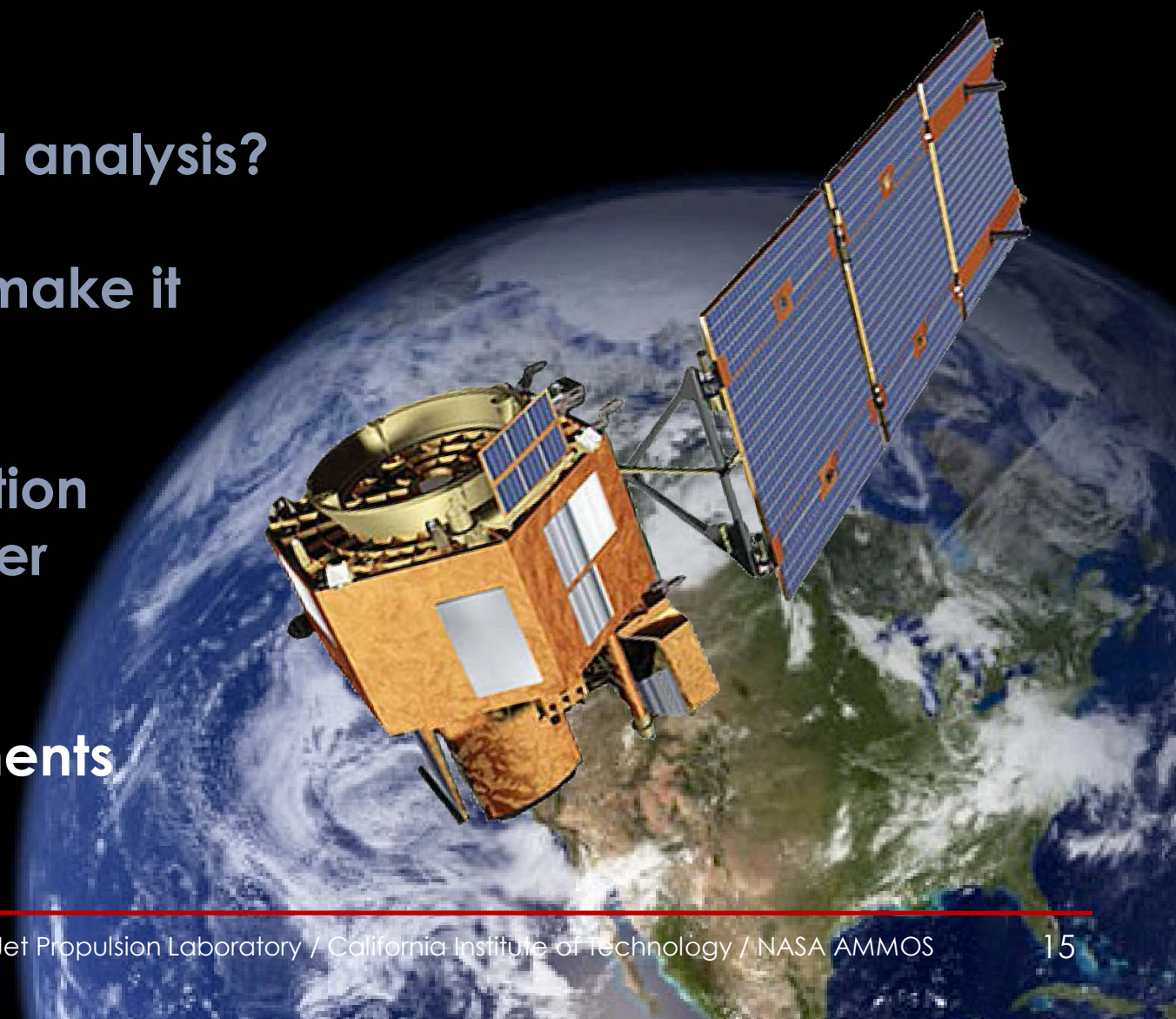
# Agenda

Why onboard hyperspectral analysis?

Two tricks to make it work

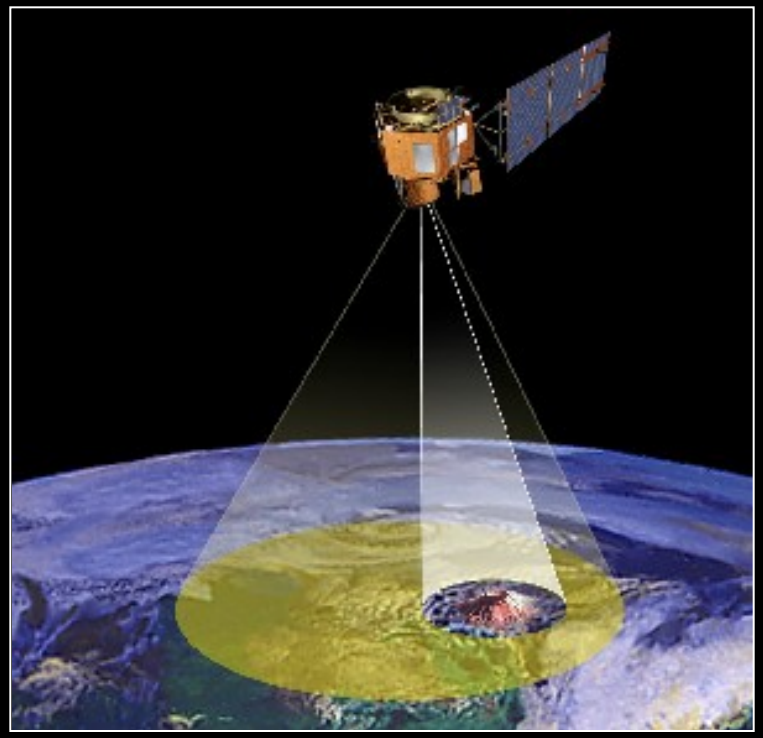
1. Superpixel segmentation
2. Endmember detection

**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)



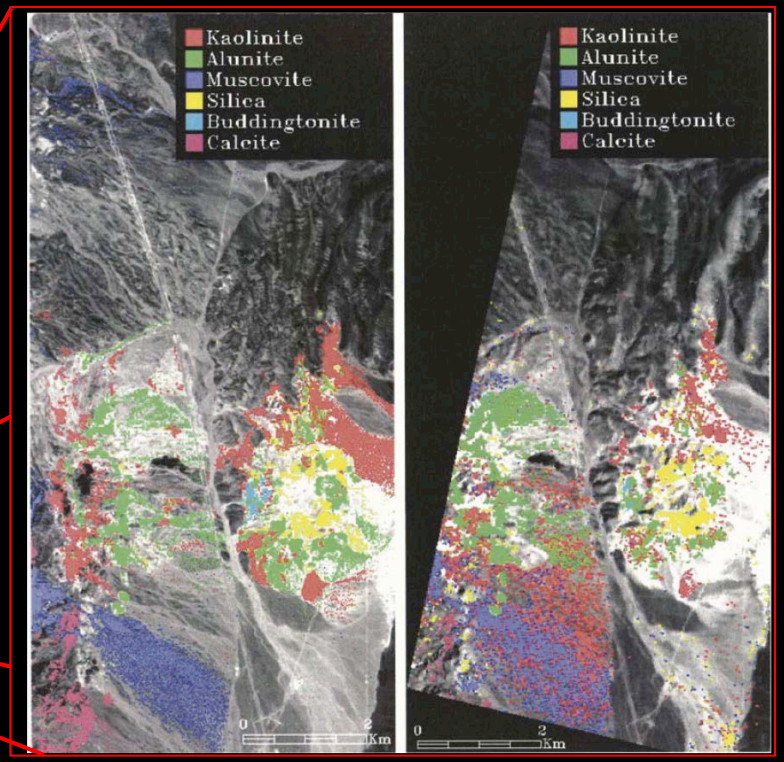
EO-1 Selective downlink of volcanic activity "hot spot" in thermal imagery [Davies et al. 2005]

# The Hyperion imaging spectrometer

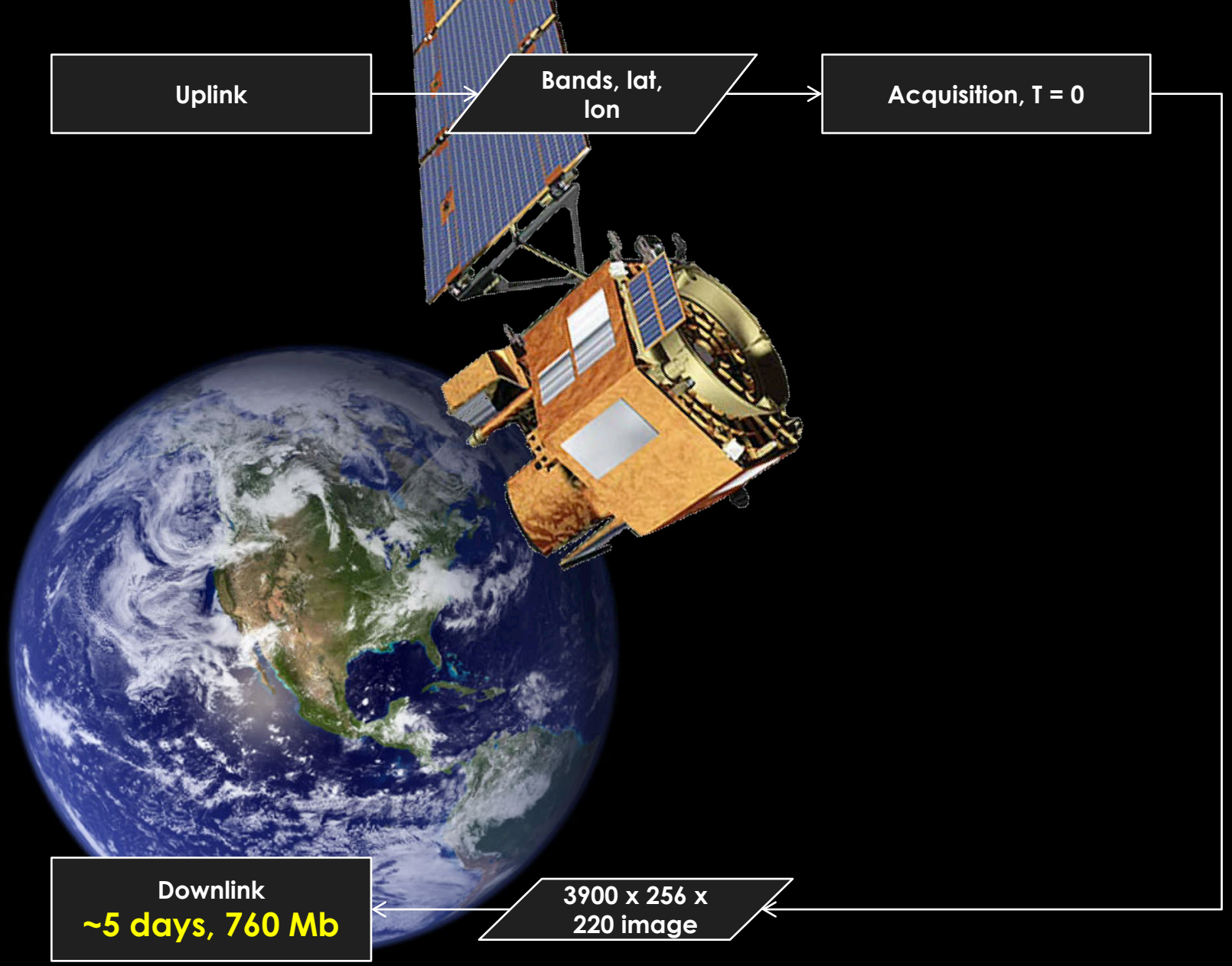
- High resolution hyperspectral imager
- 220 spectral bands from 0.4 to 2.5 µm
- 30 meter spatial resolution, provides 7.5 x 100 km land area per image
- A reflectance product is available for onboard use
  - 12 bands selected in advance (once per observation)
  - 256x1024 pixel subframe

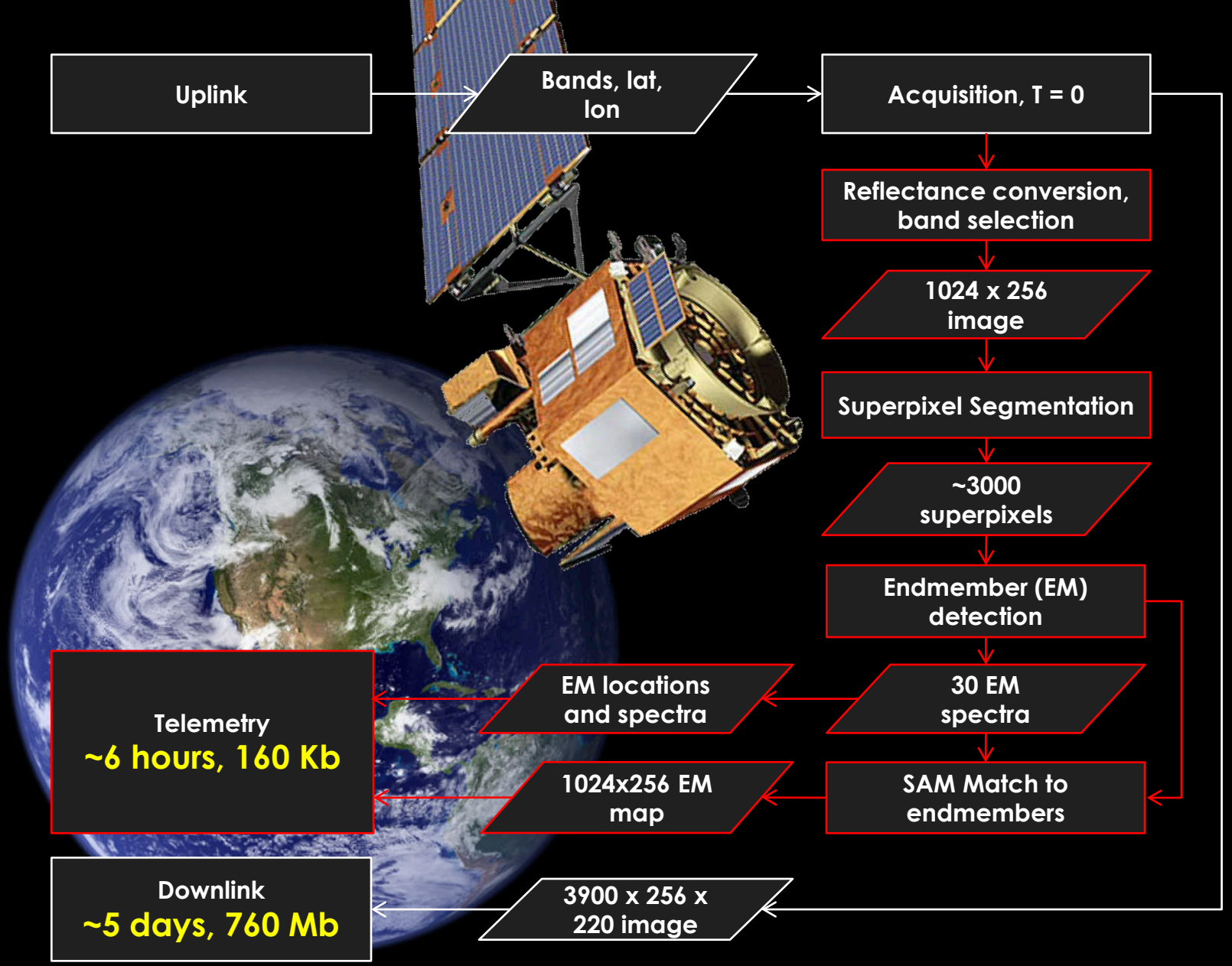

Hyperion view of Cuprite, NV

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




AVIRIS Hyperion


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
EM locations and spectra
1024x256 EM map
3900 x 256 x 220 image
Telemetry
~6 hours, 160 Kb
Downlink
~5 days, 760 Mb

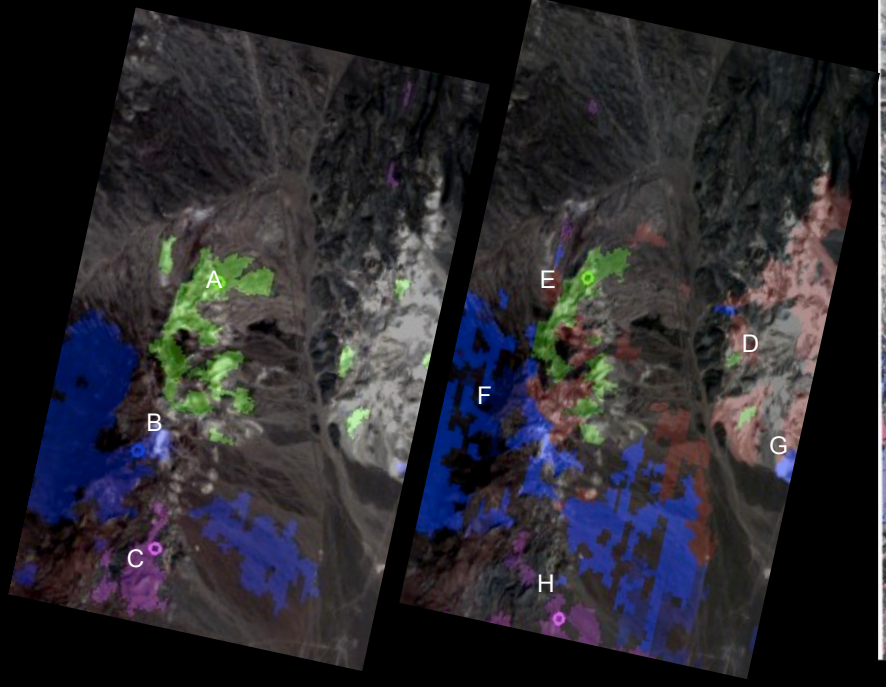
# Cuprite NV, USA – Sept. 2011

Credit: nvghosttowns.com

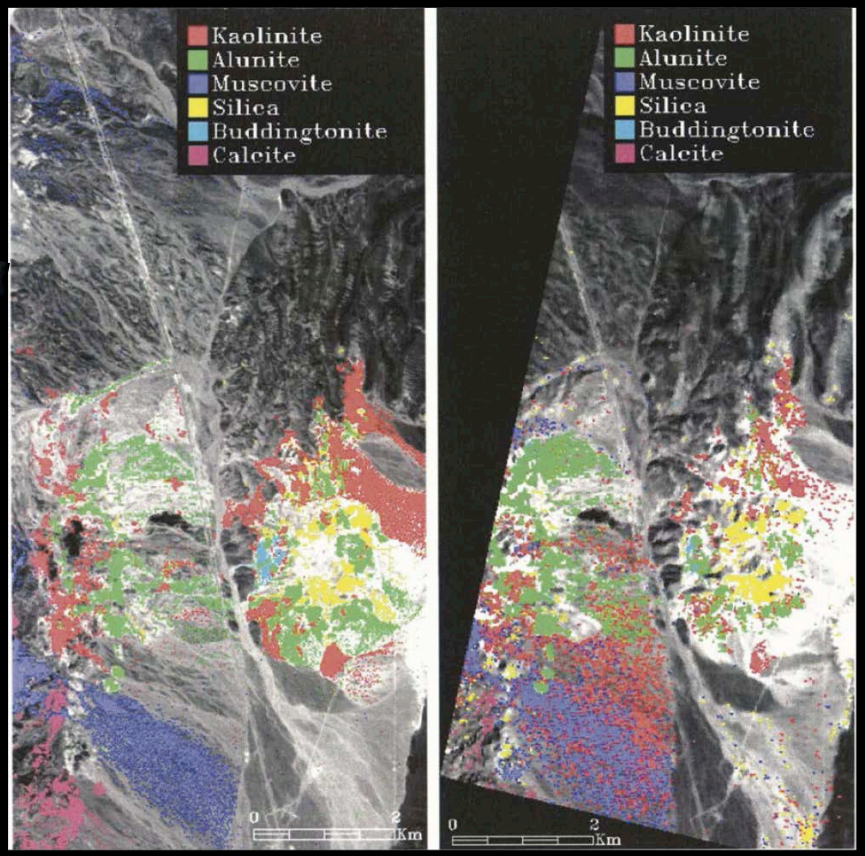
# Cuprite NV, USA – Sept. 2011

Sept. 19, 2011
Overflight

Sept. 27, 2011
Overflight




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

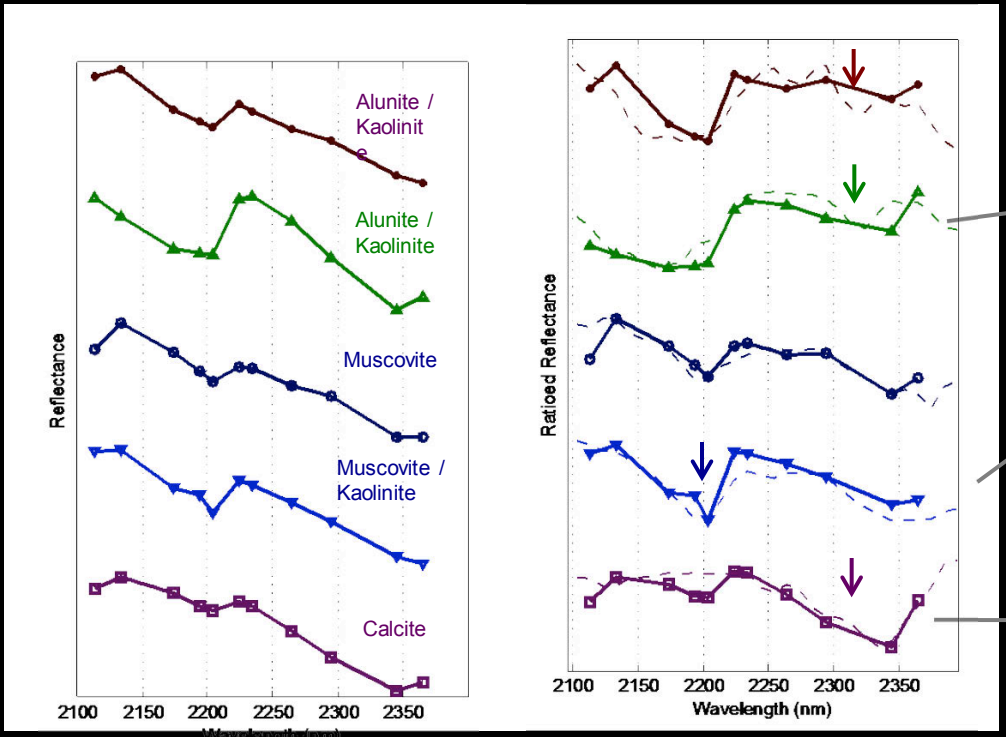


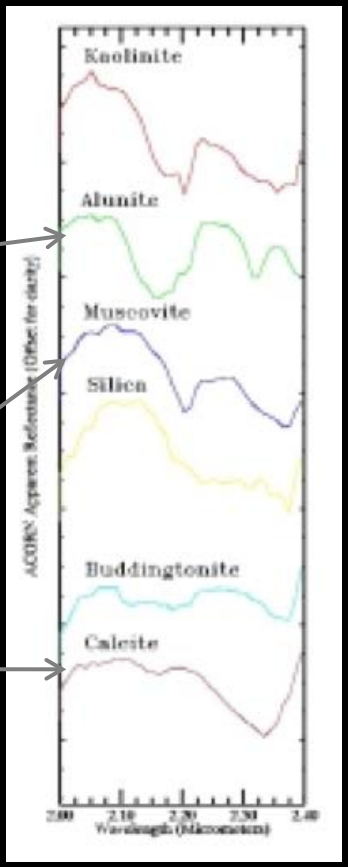
# Cuprite NV, USA – Sept. 2011

Kruse et al. manual analysis (Hyperion)

Endmember spectra

Full spectrum



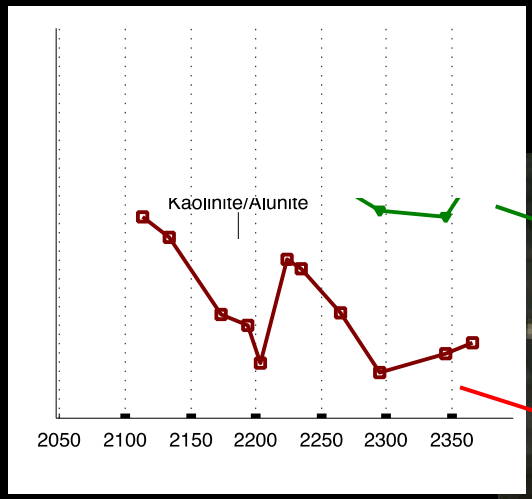



# Steamboat Springs, USA – 3 Oct 2012

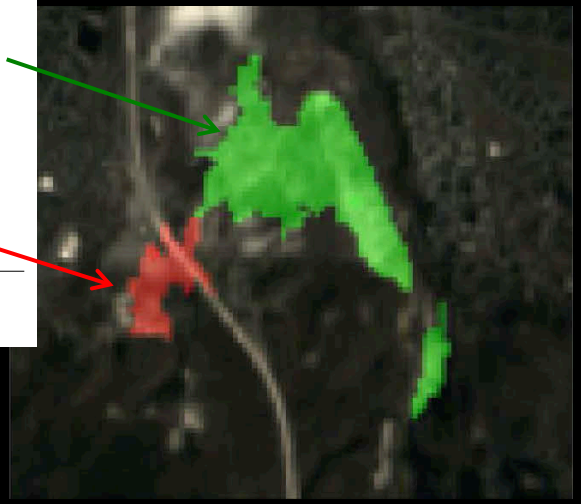
Credit: NREL

# Steamboat Springs, USA – 3 Oct 2011

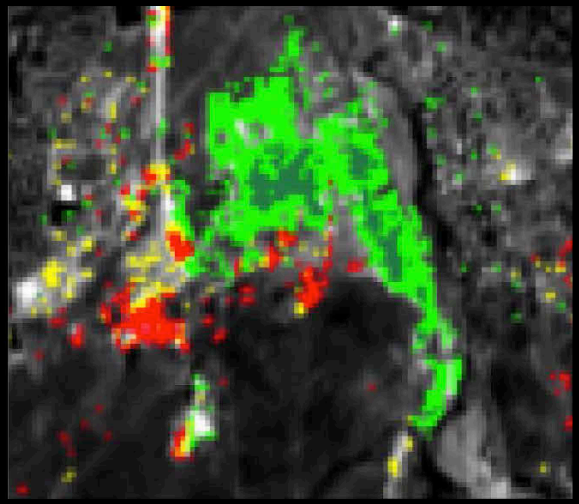
Endmember spectra



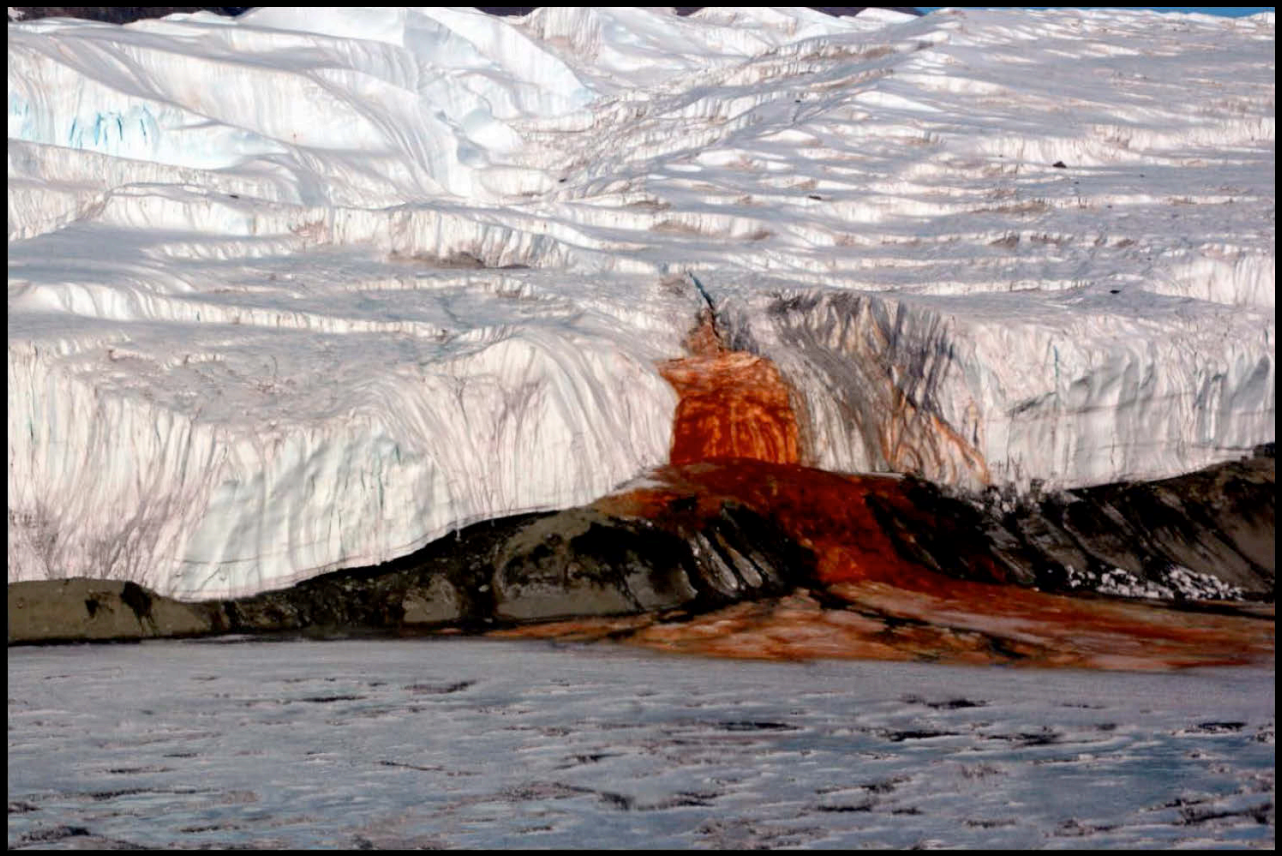

Compositional map generated onboard



Authoritative version of [Kruse et al., 2003]



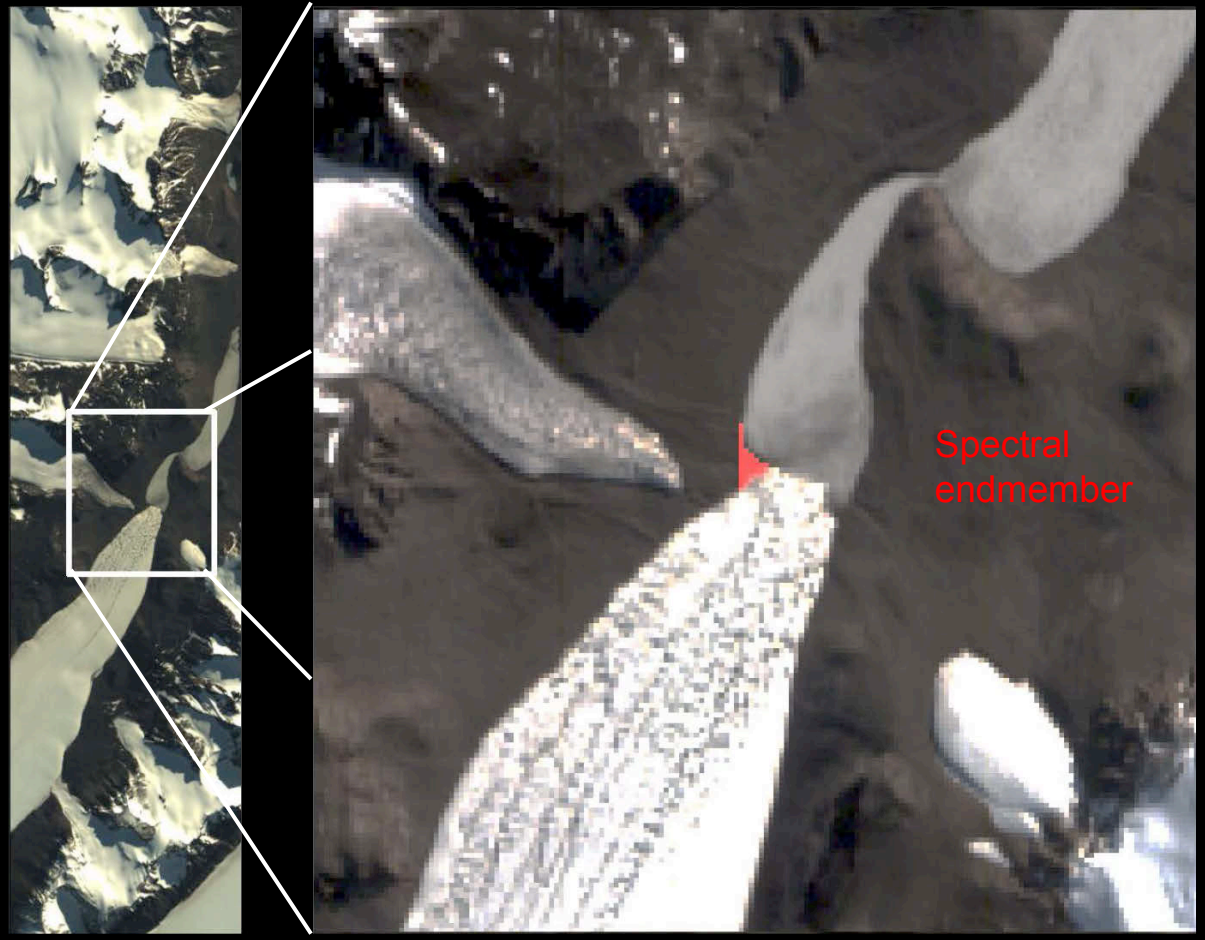
# Blood Falls, Taylor Glacier – 7 Feb 2012



Credit: USAP

# Blood Falls, Taylor Glacier – 7 Feb 2012

Hyperspectral image



# Mammoth Springs, MT - 20 Oct 2011

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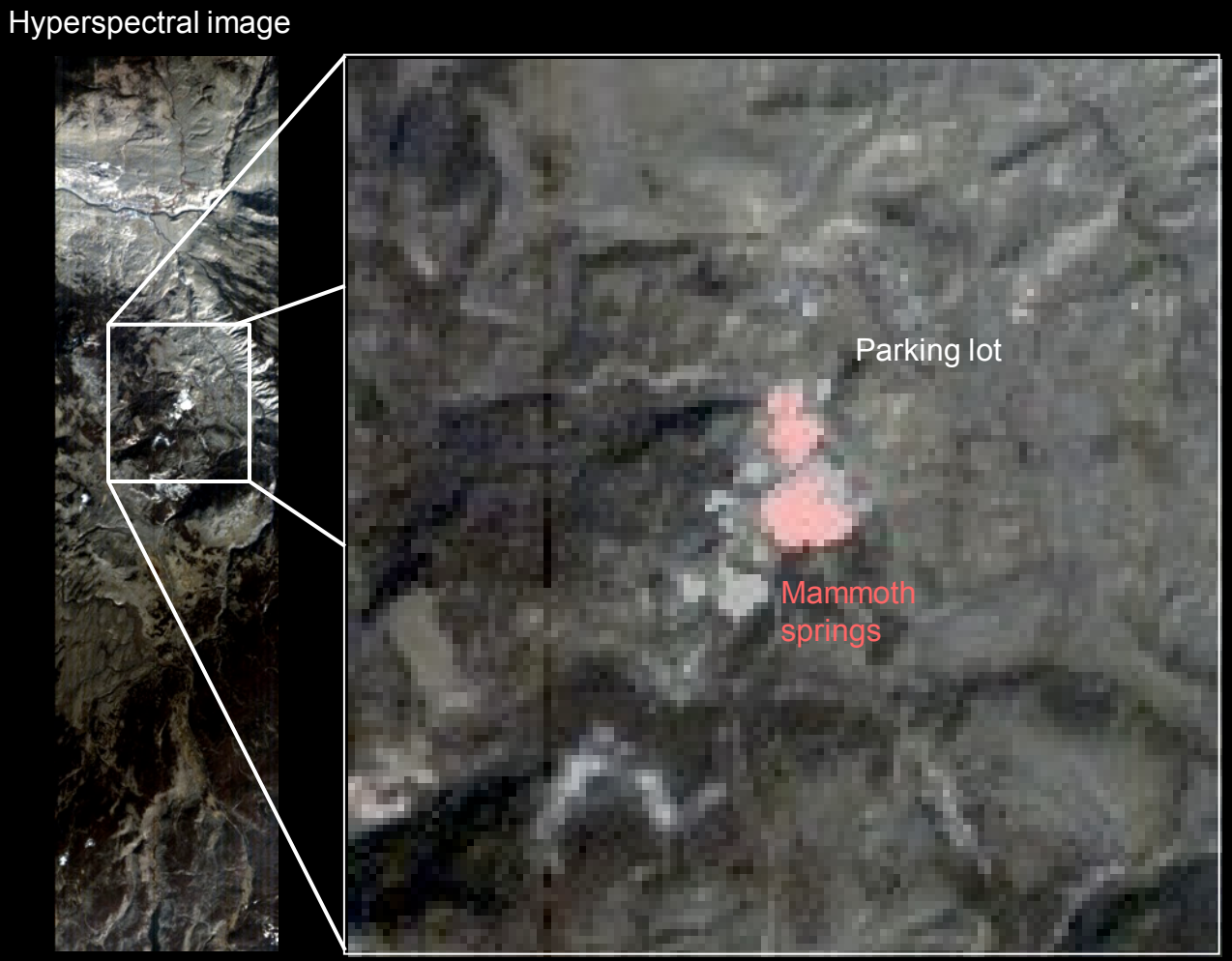
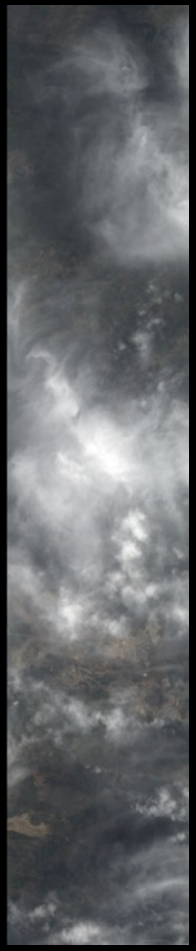


# Rio Tinto, Spain- 25 May 2012

Credit: Carol Stoker (AMES) / Wikicommons

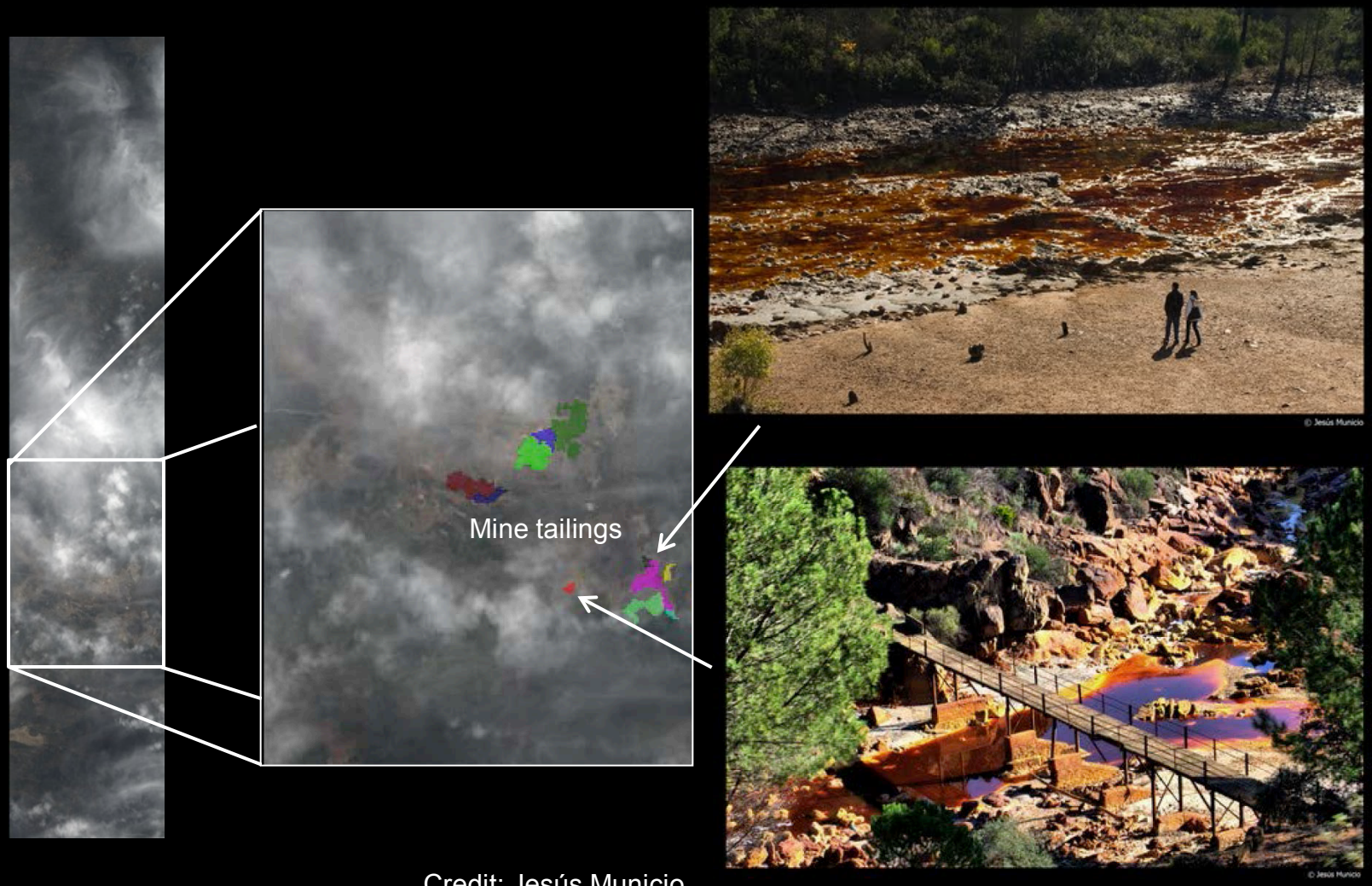
# Rio Tinto, Spain- 25 May 2012



Clouded over?

Credit: Carol Stoker (AMES) / Wikicommons

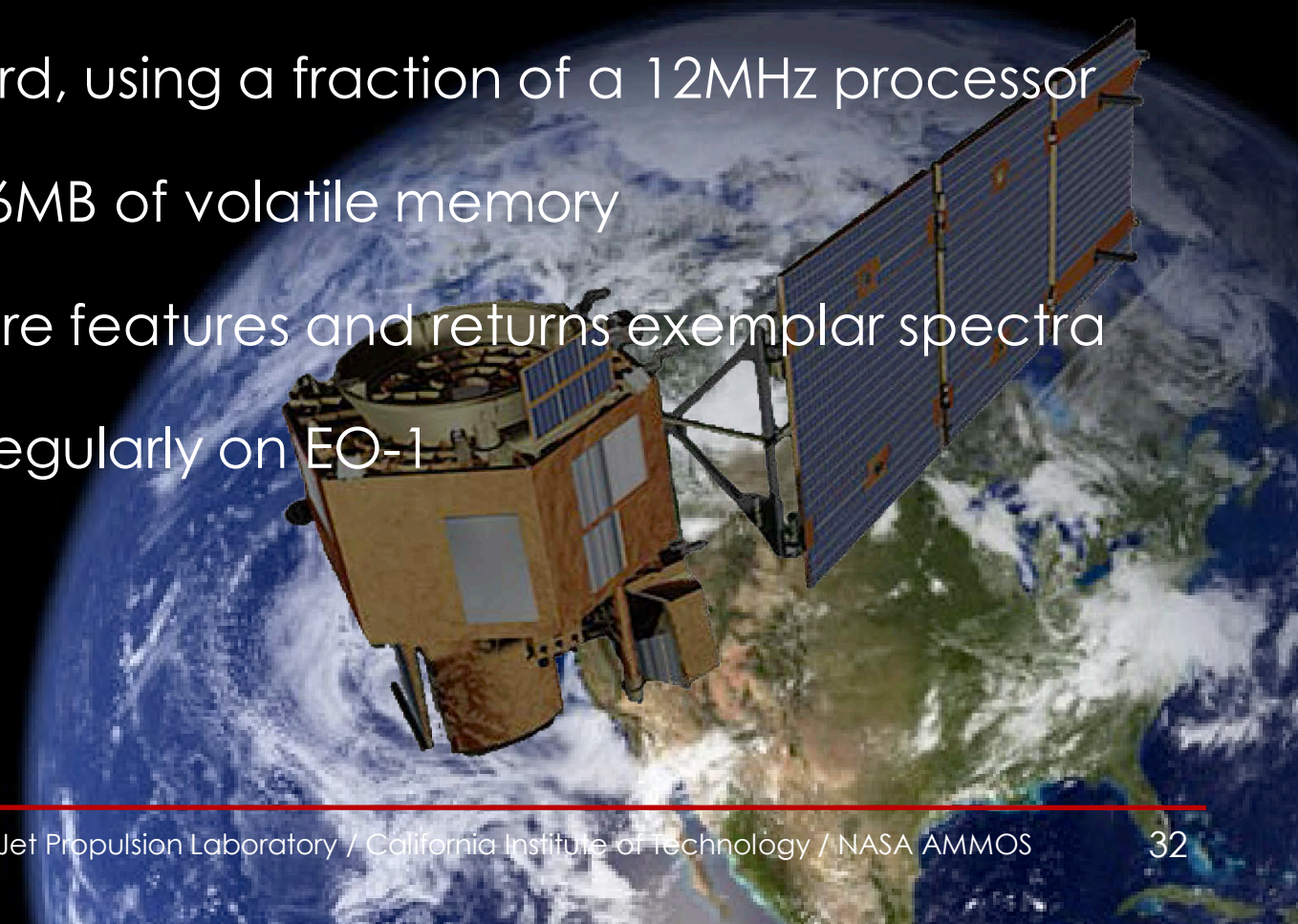
# Rio Tinto, Spain- 25 May 2012




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



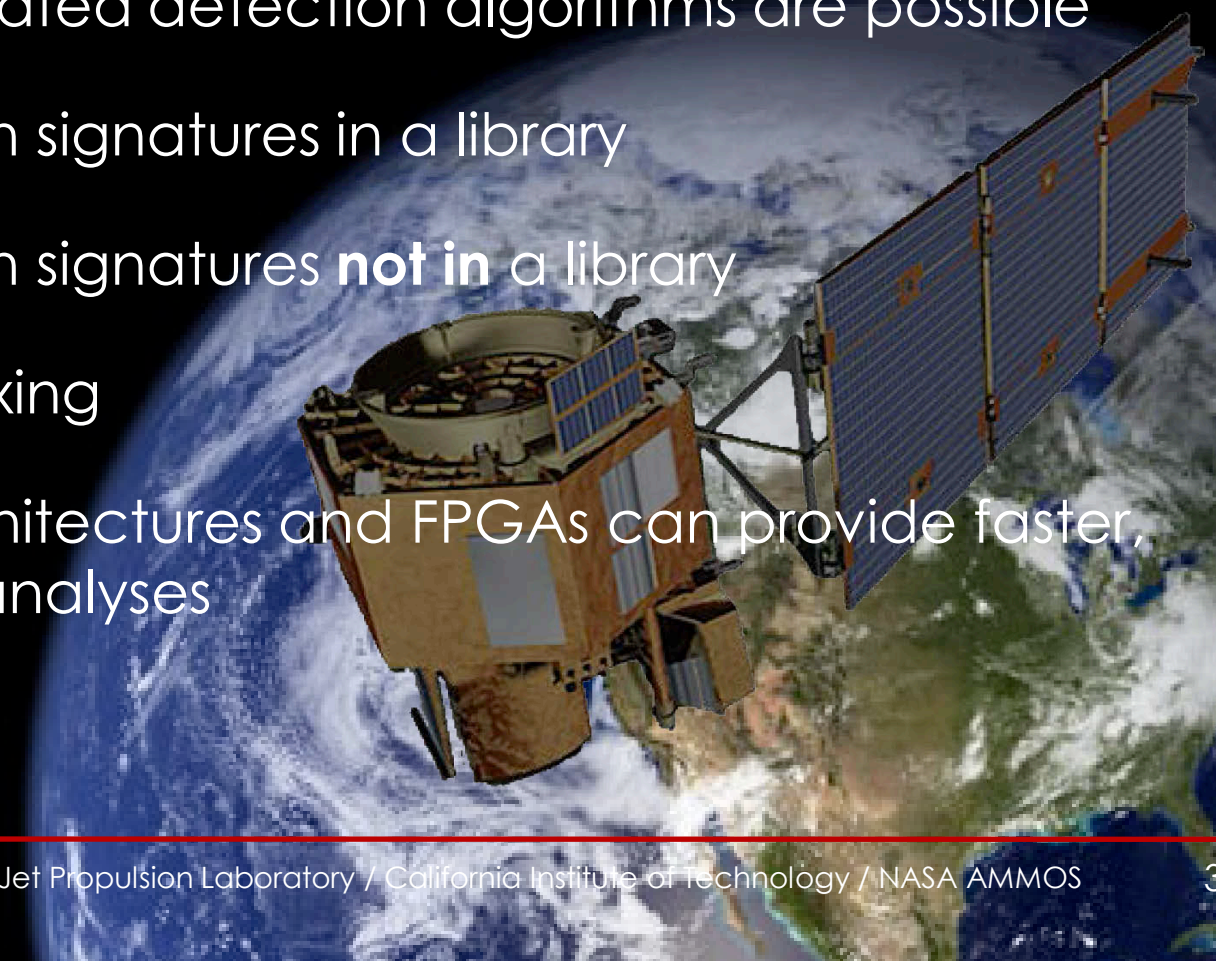
# Future directions

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



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Jesús Municio por el uso de sus fotos de Río Tinto

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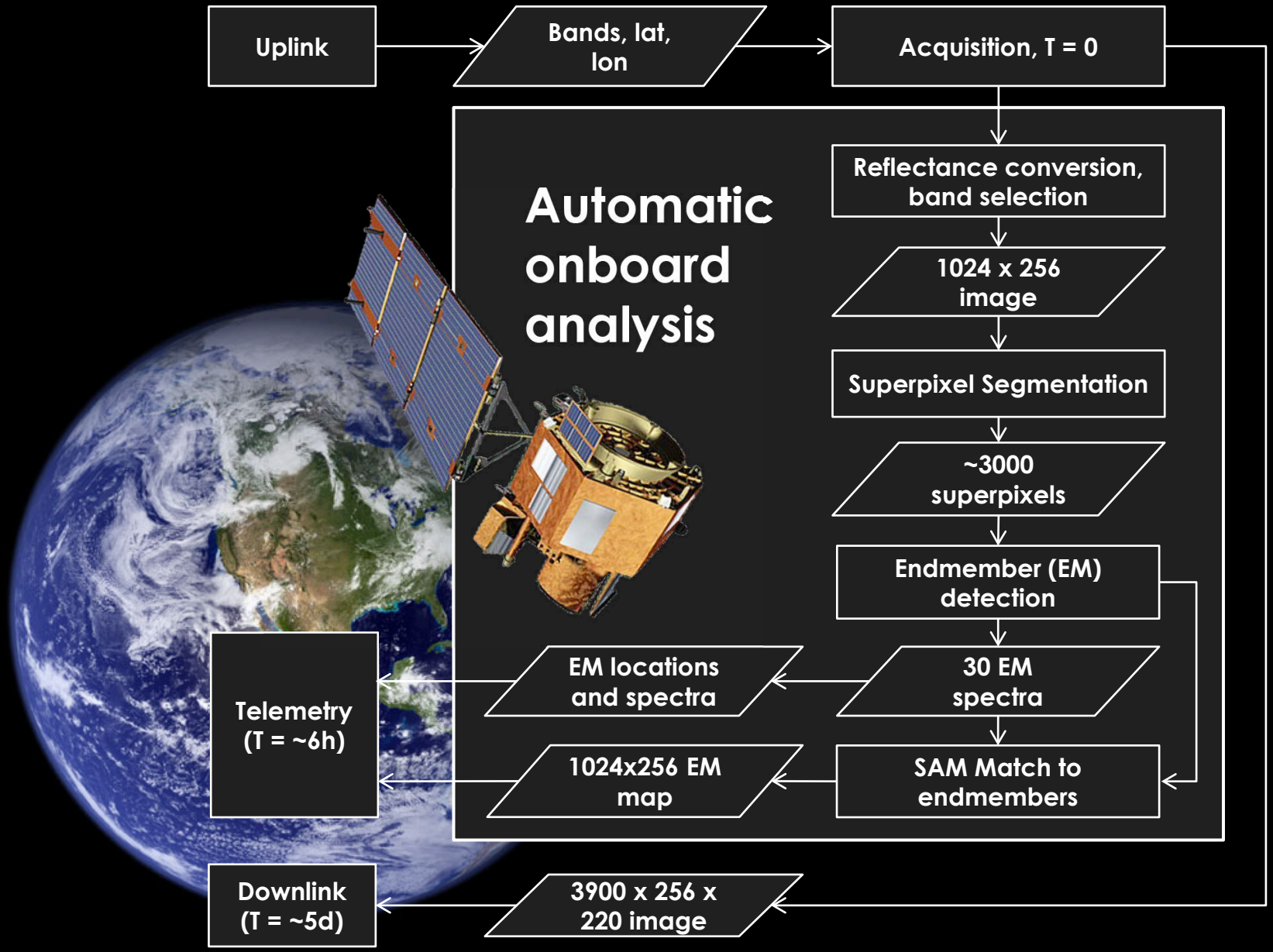
# Extra slides


Uplink
Bands, lat, lon
Acquisition, T = 0
Automatic onboard analysis
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
Telemetry (T = ~6h)
3900 x 256 x 220 image
Downlink (T = ~5d)

# EO-1 Thermal signature detection

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

ASE images Erebus Night — 13:40 GMT

} +10 min

ASE initiates band extraction

} +28 min

ASE runs thermal classifier

} +29 min

THERMAL TRIGGERED

Planner selects reaction observation (Stromboli observation replaced) — } +20 min

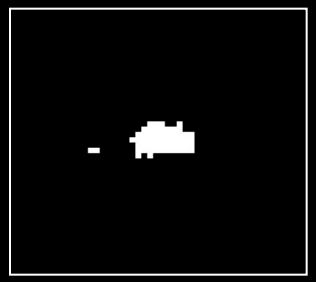
15:58 GMT

Thumbnail downlinked (S-band)

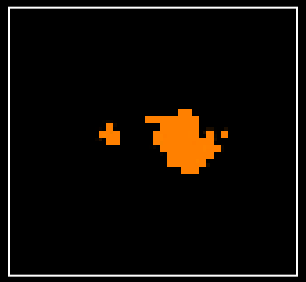
20:10 GMT + 06:30

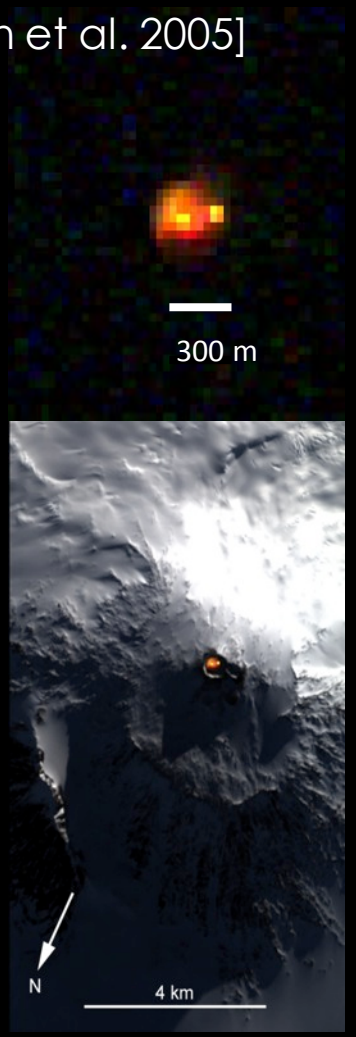
ASE images Erebus again

ASE Onboard Thermal Classifier Thumbnail



ASE Onboard Thermal Classifier

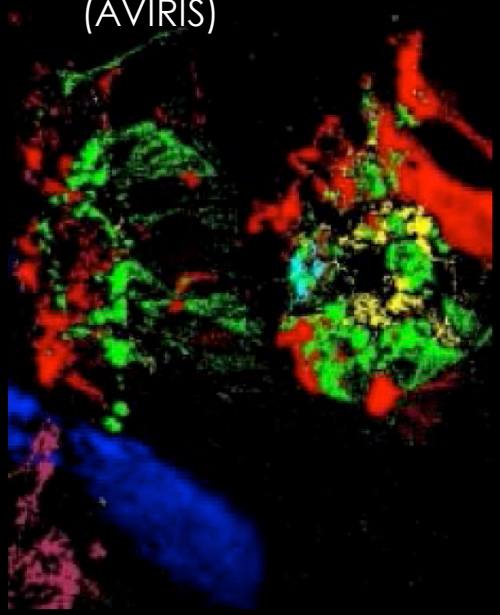




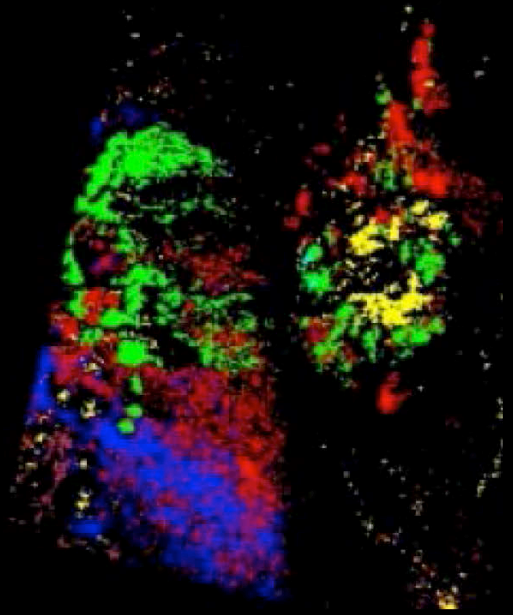
# Cuprite NV

Kaolinite
Alunite
Muscovite
Silica
Buddingtonite
Cacite

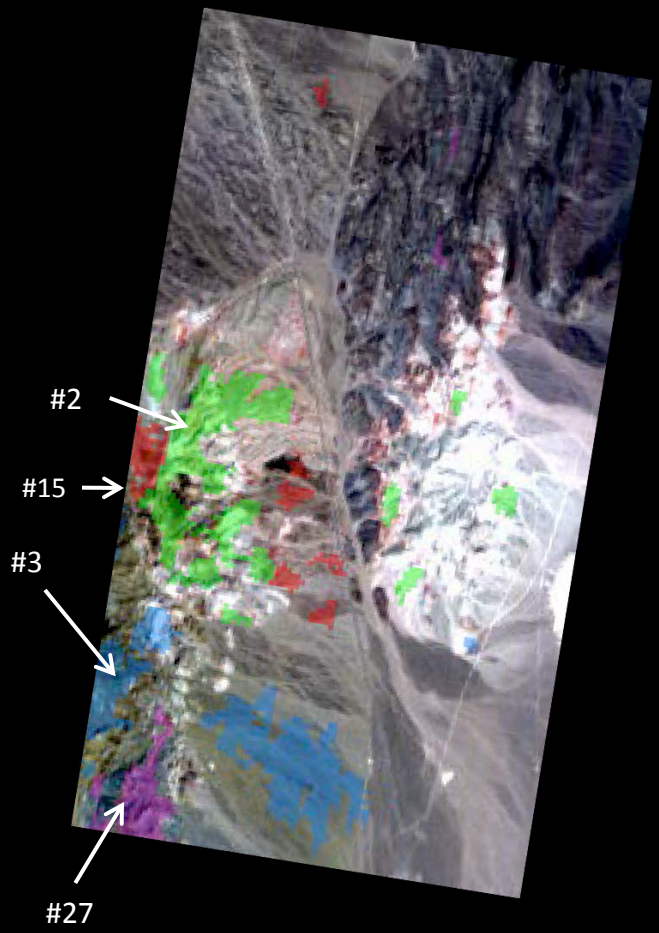
Kruse et al. (AVIRIS)



Kruse et al. (Hyperion)



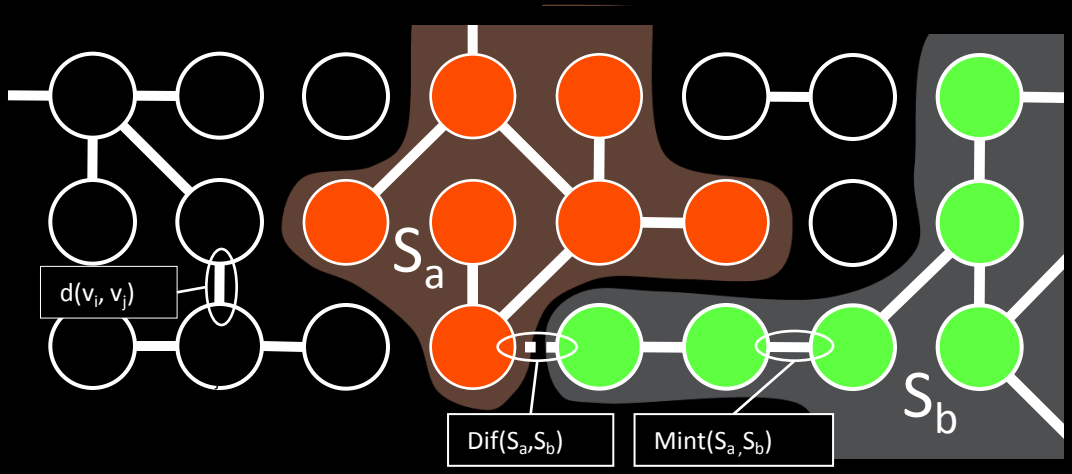
EO-1 Onboard




EO-1 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

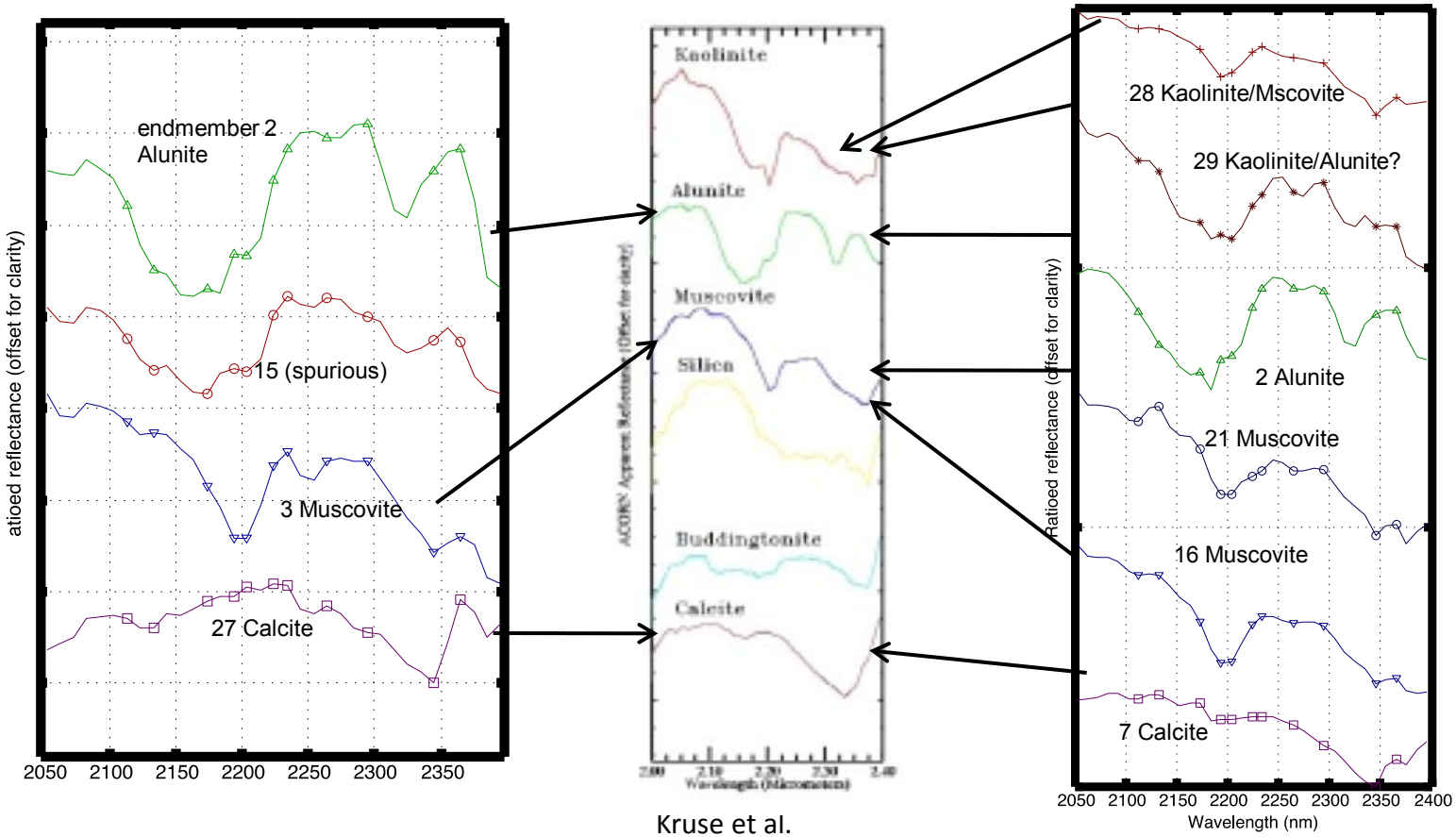



$$\mathrm{Dif}(S_a, S_b) > \mathrm{MInt}(S_a, S_b) = \min\left(\mathrm{Int}(S_a) + \frac{k}{|S_a|},\ \mathrm{Int}(S_b) + \frac{k}{|S_b|}\right)$$

EO-1 Onboard
Sept. 21, 2011

Kruse et al. manual
analysis (Hyperion)

EO-1 Onboard
Sept. 27, 2011




Kruse et al.