Spectral Anomaly Detection for the Mapping Imaging Spectrometer for Europa (MISE)

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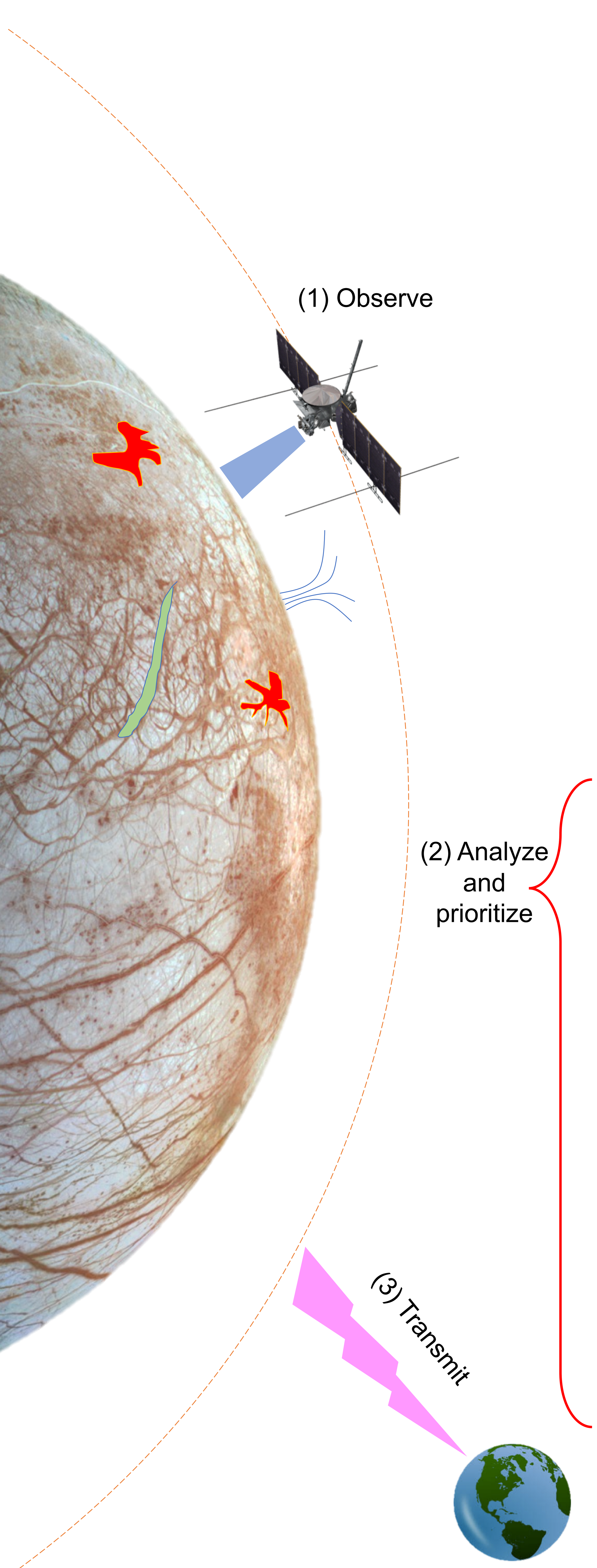


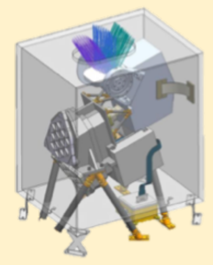
Goal: Develop and evaluate **spectral (compositional) anomaly detection** methods for use by the Mapping Imaging Spectrometer for Europa (MISE) on the Europa Clipper spacecraft. MISE [1] will observe the surface of Europa with **greater coverage and higher spectral resolutio**n than existing observations of Europa from the Galileo NIMS imaging spectrometer.
Anomaly detection methods can:
1) Enable **content-based data prioritization** onboard Europa Clipper
2) Analyze downlinked products to **accelerate mission planning** and **enable content-based search**.

Europa Clipper

- Expected launch in 2023, headed for Jupiter orbit
- Trajectory includes 40+ flybys of Jupiter's moon Europa

Mapping Imaging Spectrometer for Europa (MISE)

- Dyson imaging spectrometer
- Spectral coverage: 480 spectral bands from 0.8 to 5.0 μm
- Spatial resolution: 25 m/pixel at 100 km range



Why Search for Spectral Anomalies?

- Europa's surface composition is not yet well characterized
- Expected: Organics, salts, sulfates, fresh ice or surface deposits, radiation-altered materials
- MISE may discover other rare or unanticipated materials
- Rare / anomalous mineralogy = high priority for downlink and analysis

Anomaly and Mineral Detection Methods

- **Reed-Xiaoli (RX)** [2] – Model the spectral "background" of the cube and score each pixel x_i by its difference from the background (covariance) Σ after subtracting mean pixel μ. Rank all pixels by (decreasing) anomaly score.

$$A_{RX}(x_i) = (x_i - \mu)^T \Sigma^{-1} (x_i - \mu)$$

- **Discovery via Eigenbasis Modeling of Uninteresting Data (DEMUD)** [3] – Iteratively select the pixel most different from the ones previously selected using a singular value decomposition (SVD) to model previously seen data with principal component vectors U. This method emphasizes diversity of selected anomalies and provides an "explanation" that highlights which spectral features caused a pixel x_i to be chosen.

$$A_D(x_i) = ||x_i - (UU^T(x_i - \mu) + \mu)||_2$$

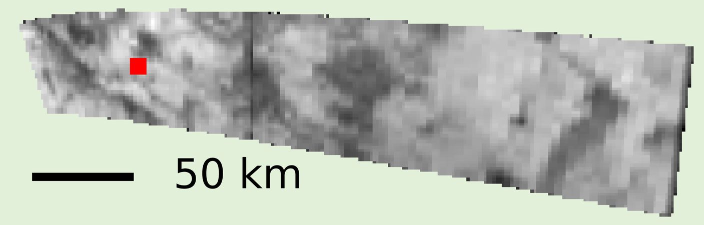
- **Matched filter (MF)** – Given a mineral spectrum of interest s, score each pixel x_i by its similarity to s. Rank all pixels by (decreasing) similarity score. This method provides an upper bound on detectability.

$$T_{MF}(x_i) = \frac{s^T \Sigma^{-1} x_i}{\sqrt{s^T \Sigma^{-1} s}}$$

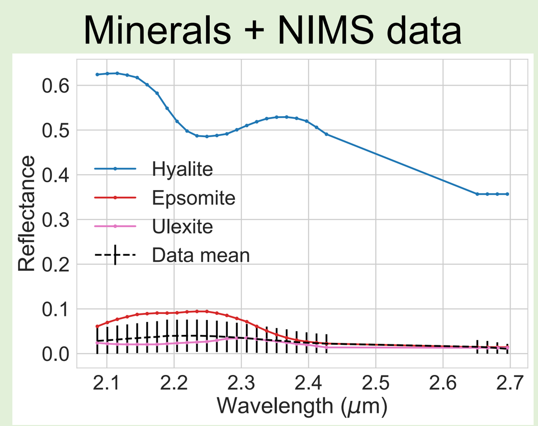
References:
[1] Blaney *et al.*, "The Mapping Imaging Spectrometer for Europa (MISE) investigation: Exploring Europa's habitability using compositional mapping," LPSC 48, Abstract #2244, 2017.
[2] Chiang and Chiang, "Anomaly detection and classification for hyperspectral imagery," *IEEE Trans. on Geoscience and Remote Sensing*, 40(6), 2002.
[3] Wagstaff *et al.*, "Guiding scientific discovery with explanations using DEMUD," *Proc. of the 27th AAAI Conference on Artificial Intelligence*, p. 905-911, 2013.

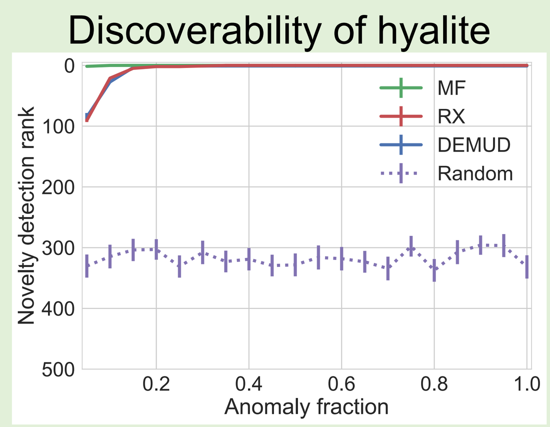
What Minerals are Detectable?

- Start with Galileo NIMS observation of Argadnel Regio on Europa (0.7-5.2 μm)
- For each mineral, select a random NIMS pixel and mix linearly with mineral's library spectrum
- Assess how quickly each anomaly detection method finds the perturbed pixel (100 trials)
- **Result**: Anhydrous minerals are detected more easily than hydrated minerals (as expected)



NIMS observation of Argadnel Regio on Europa (14ENSUCOMP01A). Red dot shows a randomly selected pixel where a synthetic anomaly was injected.





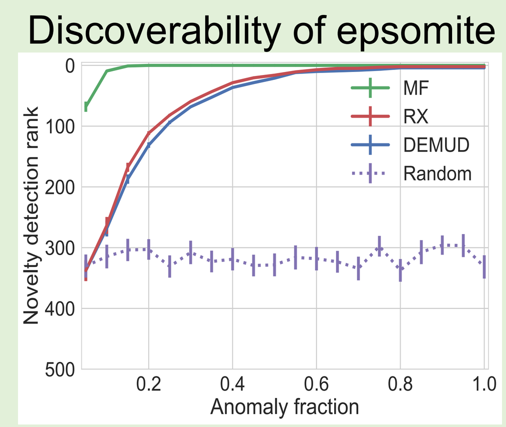


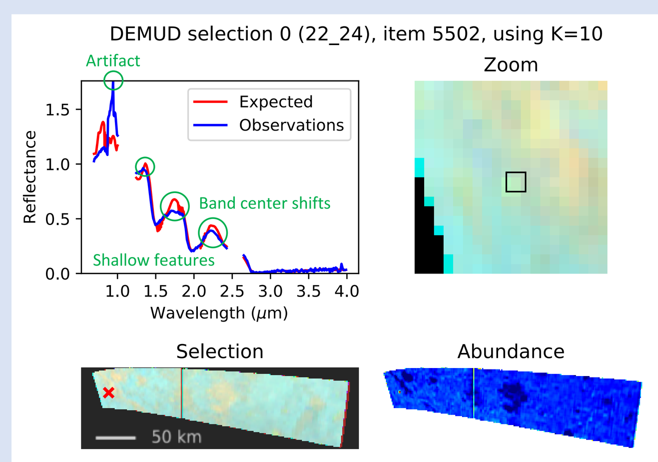
Table 1: Discoverability of different minerals injected into NIMS Europa observation 14ENEUR15H01B in terms of mean (and standard error of) novelty rank (lower is better) across all anomaly fractions (100 trials). A random baseline achieves a novelty rank of 317.41 (4.16) for all minerals. Hydrated minerals are marked with (H).

Mineral	RX	DEMUD	MF
Sulfates			
Sulfur	0.19 (0.01)	1.43 (0.04)	0.00 (0.00)
Polyhalite	1.63 (0.04)	3.55 (0.13)	0.03 (0.00)
Bloedite (H)	24.01 (0.92)	20.04 (0.83)	0.75 (0.18)
Epsomite (H)	58.52 (2.29)	64.52 (2.31)	3.91 (0.49)
Silicates			
Olivine	0.45 (0.01)	1.89 (0.07)	0.02 (0.00)
Pyroxene	1.11 (0.02)	3.24 (0.06)	0.05 (0.00)
Hyalite (H)	6.07 (0.16)	6.63 (0.39)	0.08 (0.01)
Opal (H)	256.55 (8.21)	197.12 (7.39)	32.33 (2.91)
Oxides			
Rutile	0.55 (0.01)	2.18 (0.08)	0.03 (0.00)
Cuprite	11.08 (0.34)	17.44 (0.74)	0.40 (0.10)
Chromite	66.22 (2.33)	92.23 (3.54)	5.65 (0.81)
Ulexite (H)	282.55 (8.37)	391.06 (9.60)	33.94 (2.88)

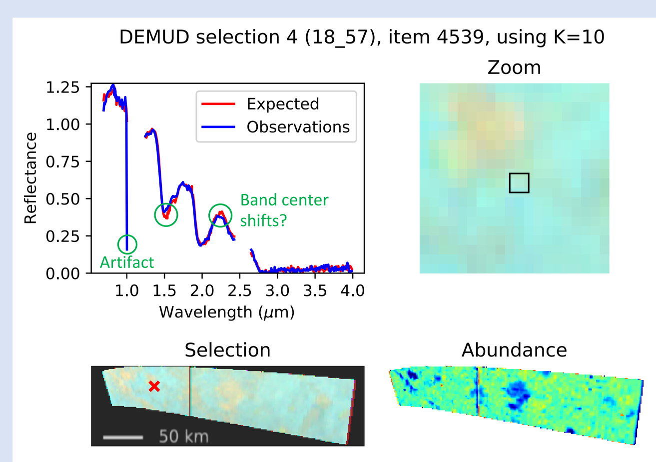
What Anomalies do We Find in Existing Europa Observations?

- DEMUD analysis of Galileo NIMS cube data using k=10 principal components to model the data

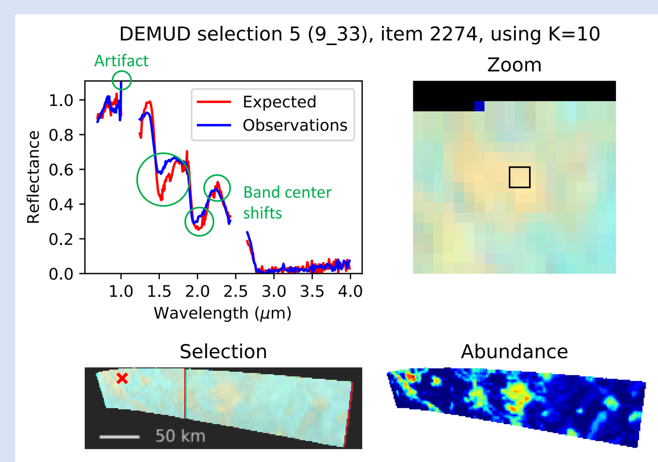
Argadnel Regio (14ENSUCOMP01A): an area of ice crust disruption, faulting, and lineae



Shallow features with band center shifts near 1.4, 1.8, 2.3 μm possibly related to water-containing compounds or grain size

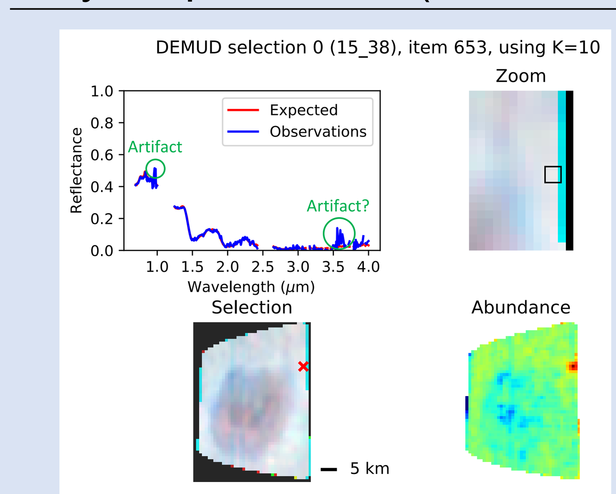


Artifact near 1.0 μm dominates result (edge of filter), with minor band center shifts near 1.5, 2.3 μm

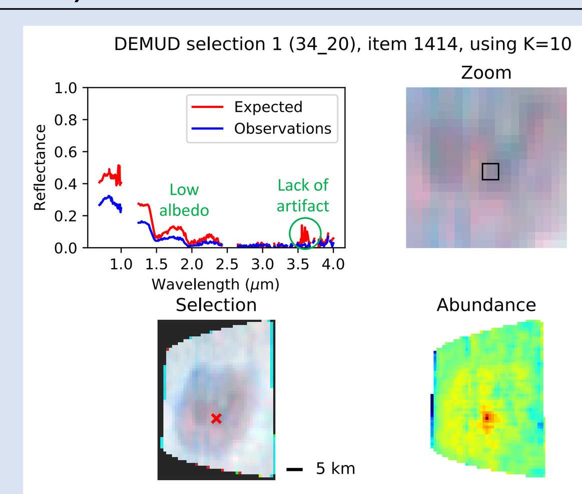


Shallow absorption features and band center shifts at 1.6, 2.0, 2.3 μm

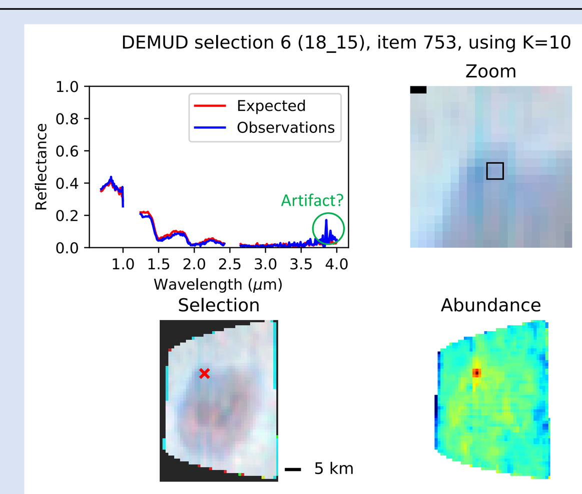
Pwyll impact crater (12ENCPWYLL01A): sub-surface material is redistributed across the surface



Pixel is near edge of image (known to be noisy)



Low-albedo material with mild band asymmetry near 1.5, 2.0 μm



Reflectance increase near 3.9 μm under investigation

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