Pluto surface composition from New Horizons LEISA data

Applying cross-disciplinary methods to planetary cartography

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What maps do we still need to produce from the *New Horizons* flyby data?

Pluto datasets

Products published to date:

Panchromatic reflectance (Schenk et al., 2018)	LORRI, MVIC	global
DEM (Schenk et al., 2018)	LORRI, MVIC	encounter hemisphere
Spectral slope (Earle et al., 2018)	MVIC	global
980 nm CH_4 band (Earle et al., 2018)	MVIC	global
Spectral index maps for CH_4, N_2, CO, H_2O, red material (Schmitt et al., 2017)	LEISA	encounter hemisphere
Hapke modeling of same (Protopapa et al., 2017)	LEISA	encounter hemisphere

Pending work:

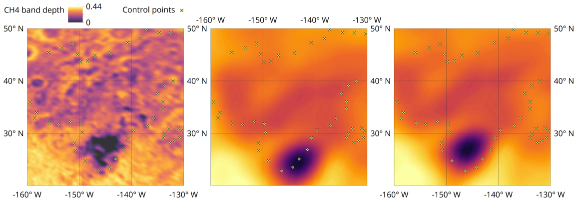
- Global spectral index maps from LEISA
- Global quantitative composition maps from LEISA and inverse modeling

How do we make the global LEISA maps?

- LORRI and MVIC-based global maps were produced using feature-based registration
- LEISA datasets have much lower resolution and fewer identifiable sharp-edged features

Intensity-based registration

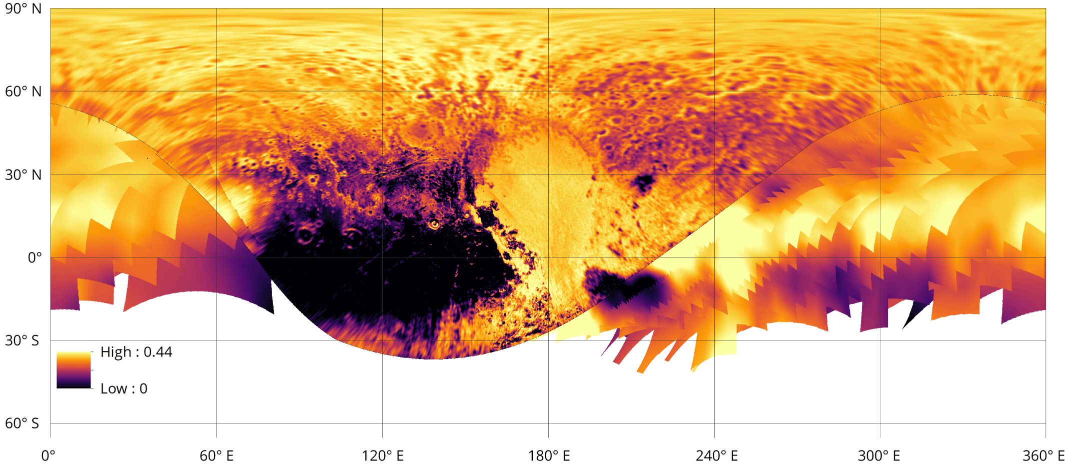
Method often used for medical imagery; compares intensity patterns in the images to be registered with different metrics (cross-correlation, mutual information etc).



Validating LEISA registration: a) high-resolution data; b) misregistered low-resolution data; c) registered low-resolution data

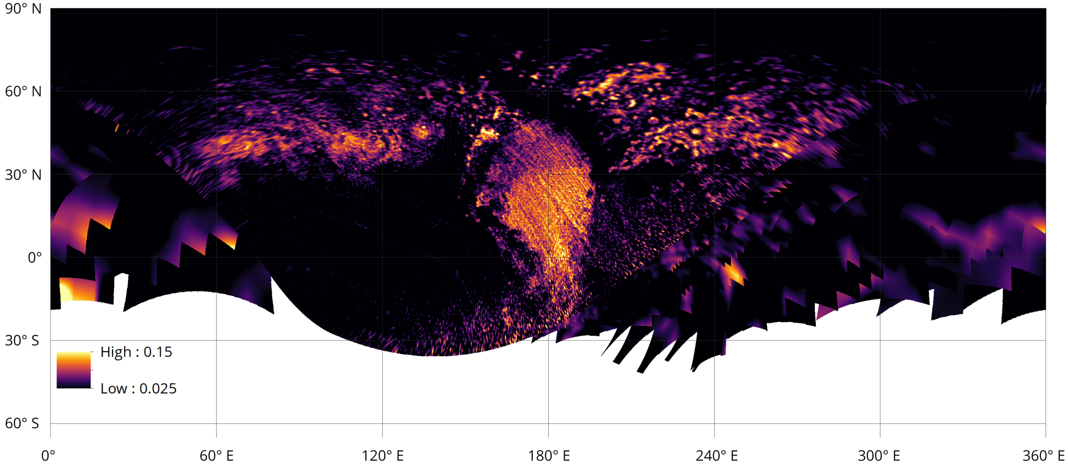
For more detail on intensity-based registration, refer to: Gabasova et al. 2019, Pluto System After New Horizons abstract #7029, and upcoming Icarus special issue

Global spectral index and band depth maps



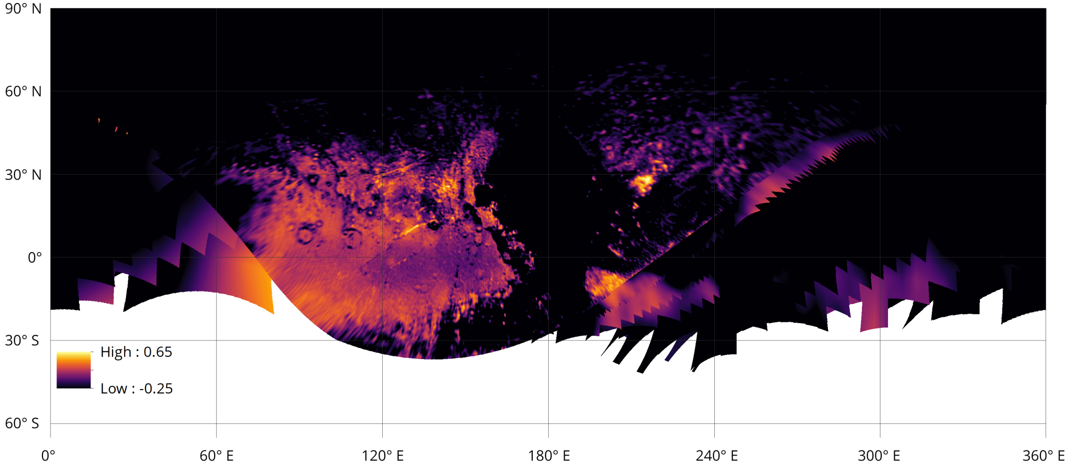
1.7-μm CH_4 integrated band depth map

Global spectral index and band depth maps

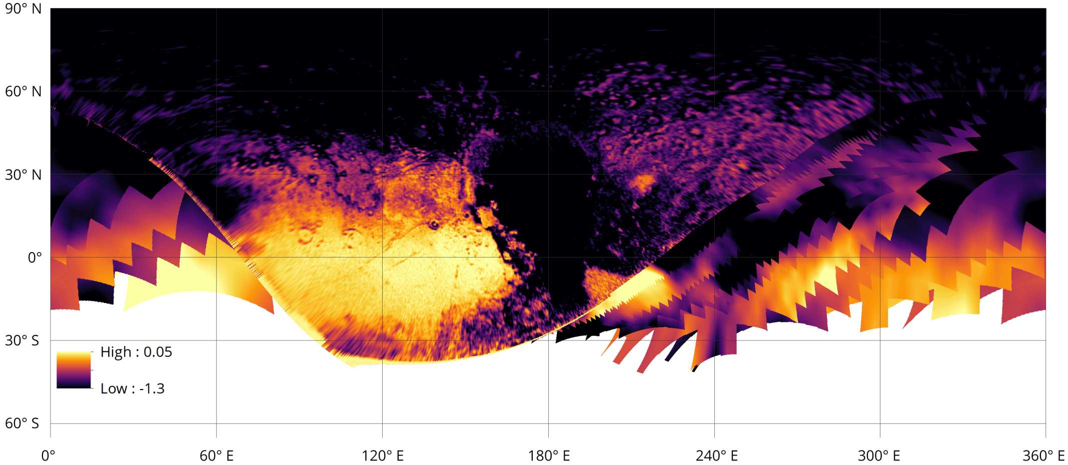


2.15-μm N_2 integrated band depth map

Global spectral index and band depth maps

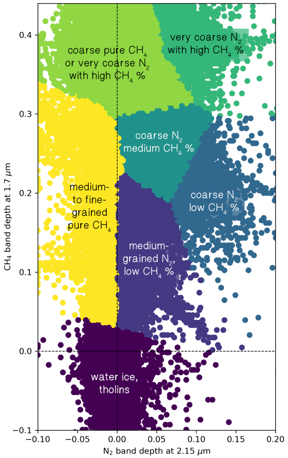


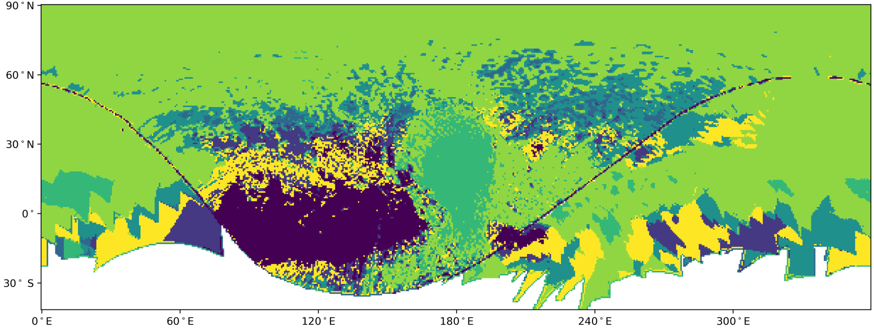
H_2O spectral index map (from wavelength bands centred around 1.39 and 2.06 μm)



Red material spectral index map (from wavelength bands around 1.44 and 1.66 μm)

Qualitative classification of N_2:CH_4 ice terrains





Terrain classes calculated with a Gaussian mixture model from 1.7 μm CH_4 band depth vs 2.15 μm N_2 band depth

Summary of observations from LEISA maps:

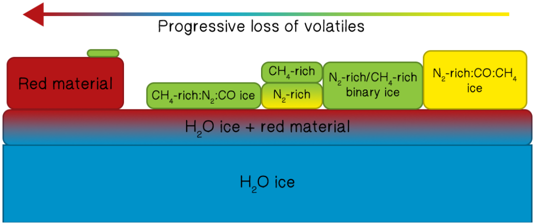
- a global methane belt in the 0-30°N latitude range
- diffuse methane presence in high latitudes
- N_2 presence in the 0-30°N belt, in Sputnik Planitia, and in medium-latitude uplands
- red material presence in a near-global 0-30°S belt, interrupted by SP
- strong correlation between: a) N_2 and CH_4, b) H_2O and red material

Correlating LEISA maps with MVIC and LORRI datasets suggests the following:

- CH_4-rich dissected/eroded terrain with N_2 infill in high latitudes
- a largely continuous equatorial belt of CH_4- and N_2-rich bladed terrain
- an equatorial belt of dark organic tholin-type material, deposited by atmospheric haze
- H_2O ice in longitudes outside Sputnik Planitia corresponding to exposed substrate

Quantitative surface modeling is required to validate these interpretations.

- 6 components with independent grain sizes
- 4 mixing modes (areal, vertical, granular, molecular)



Schematic representation of the various materials present on Pluto and their possible mixing states (adapted from Schmitt et al., 2017)

→ approx. 45-dimensional problem

- Lowest-resolution exhaustive computation time of all the spectra = 1500 years on 1000-core cluster
- Simple iterative optimization e.g. gradient descent not possible: too many local minima

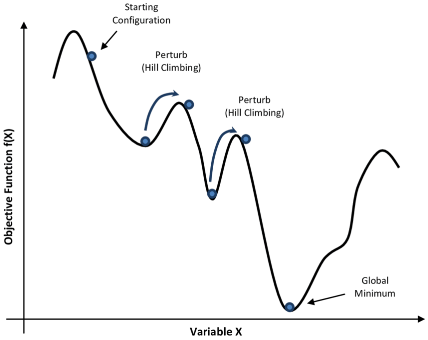
What are metaheuristics?

High-level heuristics designed to find a sufficiently good global solution to a complex problem.

Simulated annealing

An algorithm inspired by annealing in metallurgy, which combines gradient descent with stochastic perturbations (slowly decreasing in probability over time) to escape local minima.

For details of SA algorithm adapted to radiative transfer modeling, refer to: Gabasova et al, 2018, EPSC abstract #537 (http://www.koliaza.com/files/EPSC_2018_Gabasova.pdf)



Schema showing the concept behind simulated annealing (Ghasemalizadeh et al., 2016)

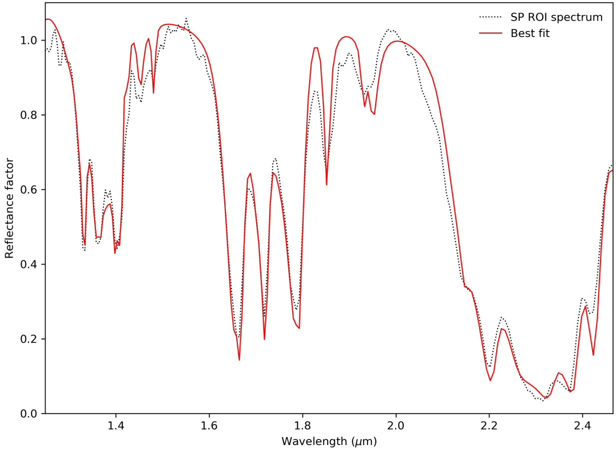
Recent modifications to inverse fitting model

- Initial radiative transfer model (RTM) backend in 2018 was Spectrimag as developed by Douté and Schmitt (1998)
- Now replaced with DISORT (originally developed by Stamnes et al., 1988, rewritten for C with efficiency improvements by Buras et al., 2011)

Advantages of new backend:

- Vertical stratification support
- Open source code, permitting the project to be shared with all dependencies
- Guarantees more accurate results; DISORT is frequently used as a reference model for RTM testing (e.g. in Wang et al., 2015)

Simple test case: Sputnik Planitia



Simulated annealing/DISORT fit of LEISA ROI located in Sputnik Planitia

RMSE over absorption bands: 5%

Coarse-grained CH_4:N_2 binary ice, covered with thin layer (100 μm) of pure CH_4 ice

Layer	1	2
Composition	Pure CH_4	N_2-rich ice + dilute CH_4 (0.7%)
Grain size	100 μm	25 cm
g	0.4	0.4

Compromise between accuracy, correctness and efficiency; given indefinite time, the model will converge accurately, but practical constraints apply.

1. How close must the initial spectrum be to allow the model to converge in a reasonable time?
2. On which part of the spectrum is accuracy most critical?
3. How badly does the error grow with inaccuracies?

If error grows slowly enough, focus on efficiency with different strategies:

- Seed the annealing with computed solutions for nearby points
- Create a dictionary of seeding points

Validate at each step by using maps of fake spectra of progressively reduced accuracy