Étude de la surface de Mars par techniques de séparation de source appliquées sur des images hyperspectrales de télédétection

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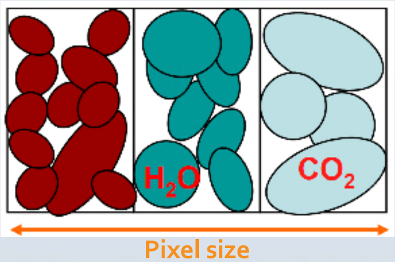
Projet Vahiné – ANR/CNES

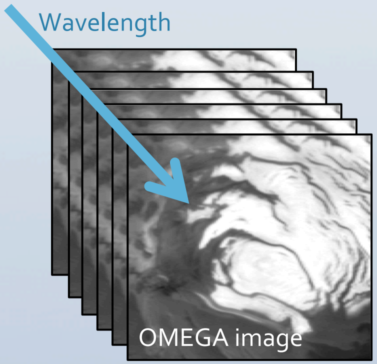
Background

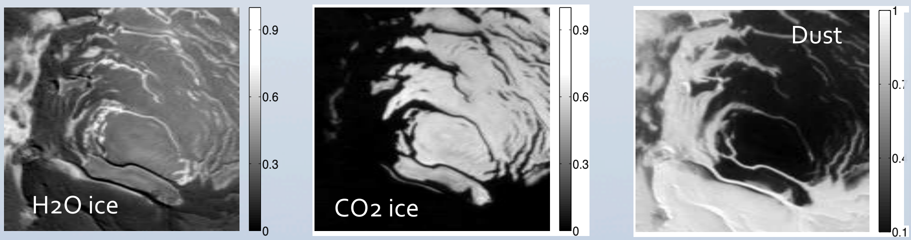
- **Imaging spectroscopy** in **planetary sciences**
  - Imaging spectrometers around **Mars**:
    - OMEGA/MEX, 2004
    - CRISM/MRO, 2006
- Increasingly **voluminous** collections of **data**…
  - Need for efficient yet accurate analysis algorithms!
  - **Unsupervised linear spectral unmixing**
    - Decomposition of a hyperspectral image into a few data sources
  - Example on OMEGA data:


Mars observed by Viking Orbiters

Geographical linear mixture







(a) H_2O ice (b) CO_2 ice (c) dust

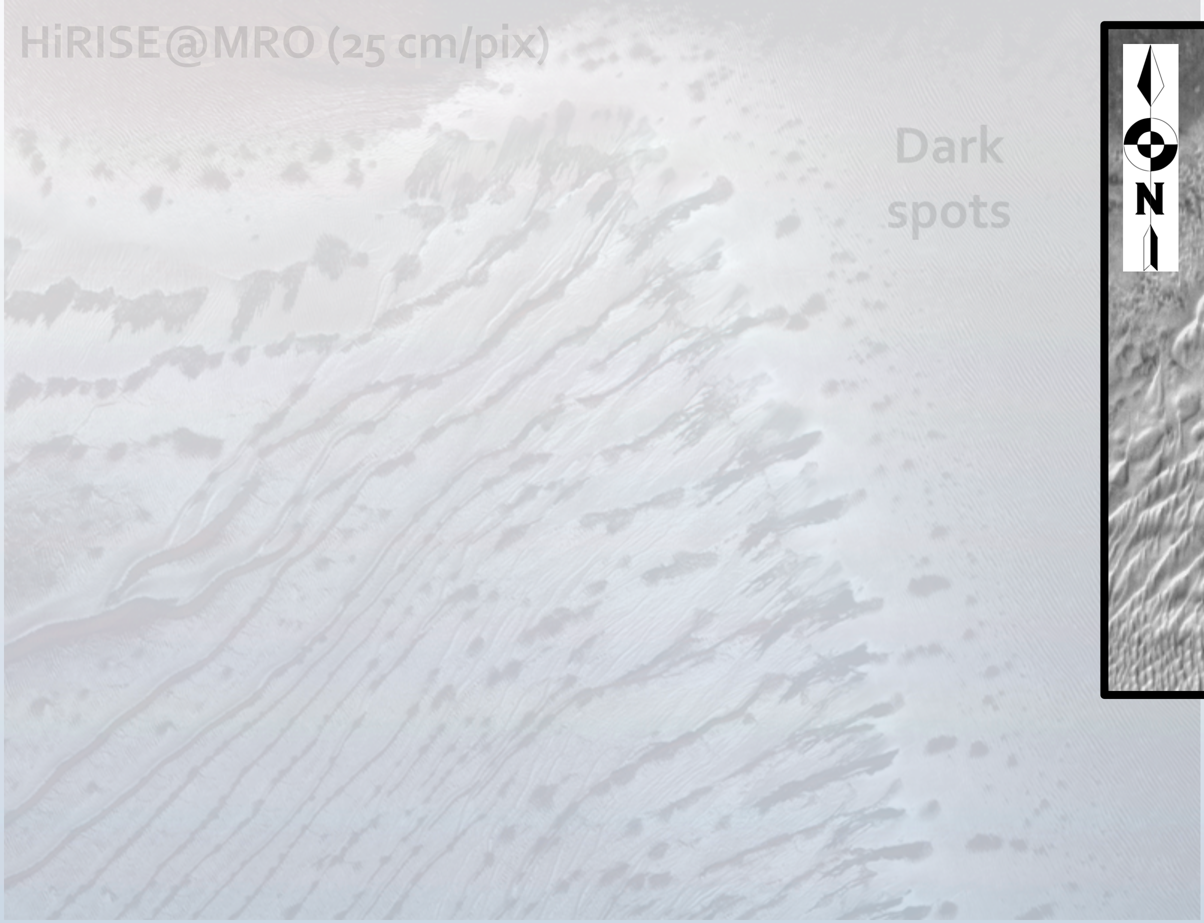
Estimated abundances of three physical sources from the South Polar Cap of Mars observed by OMEGA. *Moussaoui 2007*

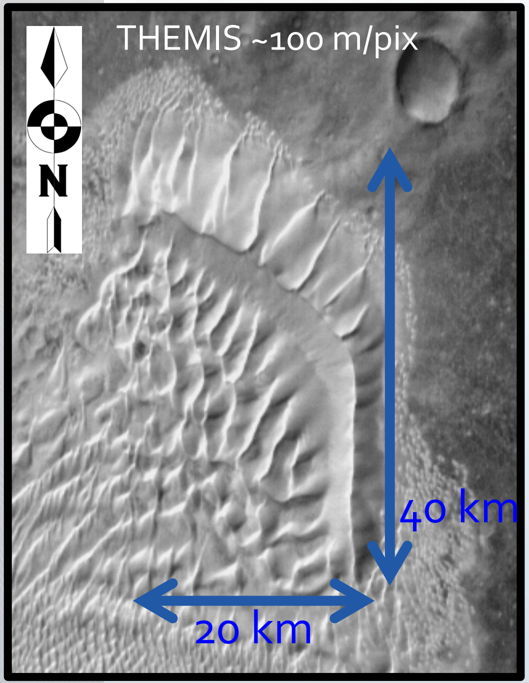
Outline

- Background
- **The Russell crater megadune**
- Experiments
- Validation
- Conclusions

The Russel crater megadune

Coexistence of **seasonal ice** and **dusty dark features** in late winter

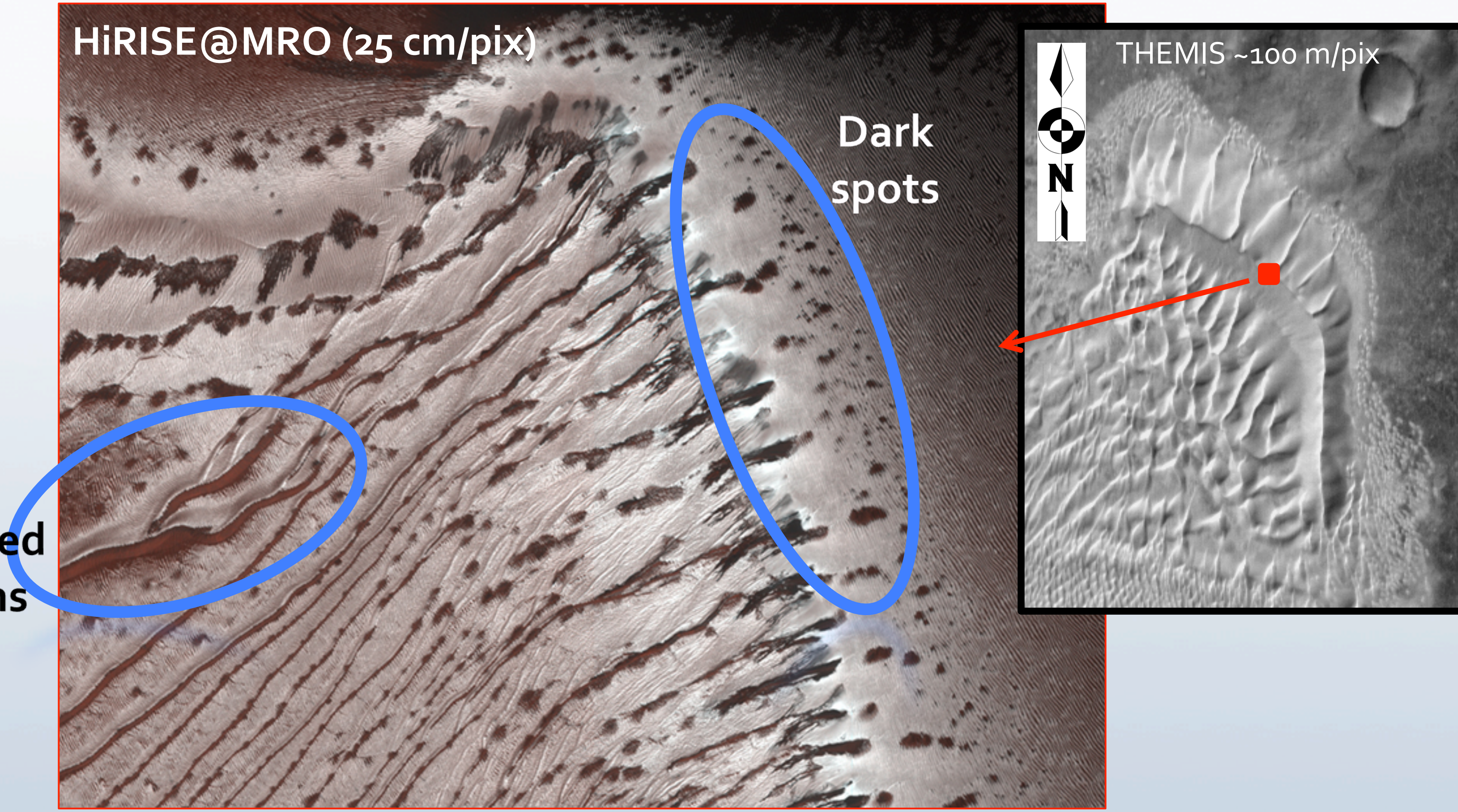




Dark defrosting features appear before complete defrosting!

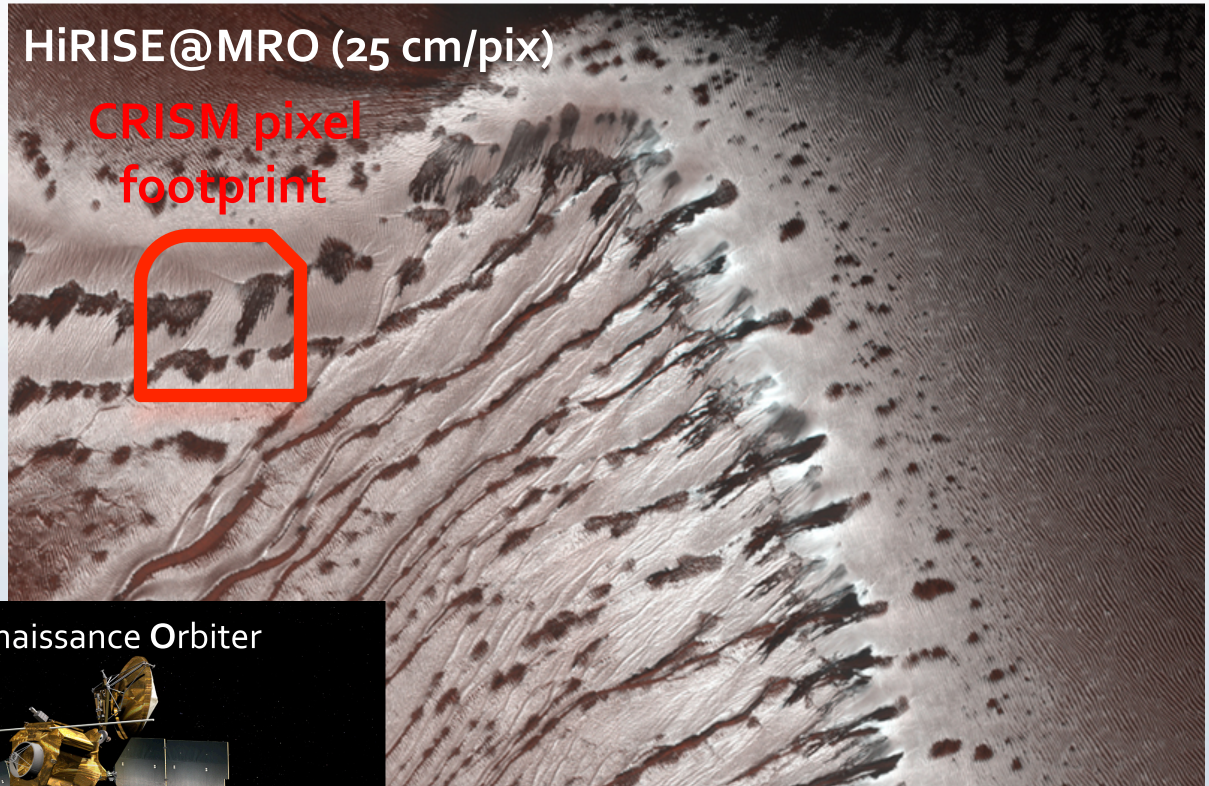
The Russel crater megadune

Coexistence of **seasonal ice** and **dusty dark features** in late winter



The Russel crater megadune

Coexistence of **seasonal ice** and **dusty dark features** in late winter



Appropriate scene for linear unmixing: **geographic mixtures may exist within a CRISM pixel!**

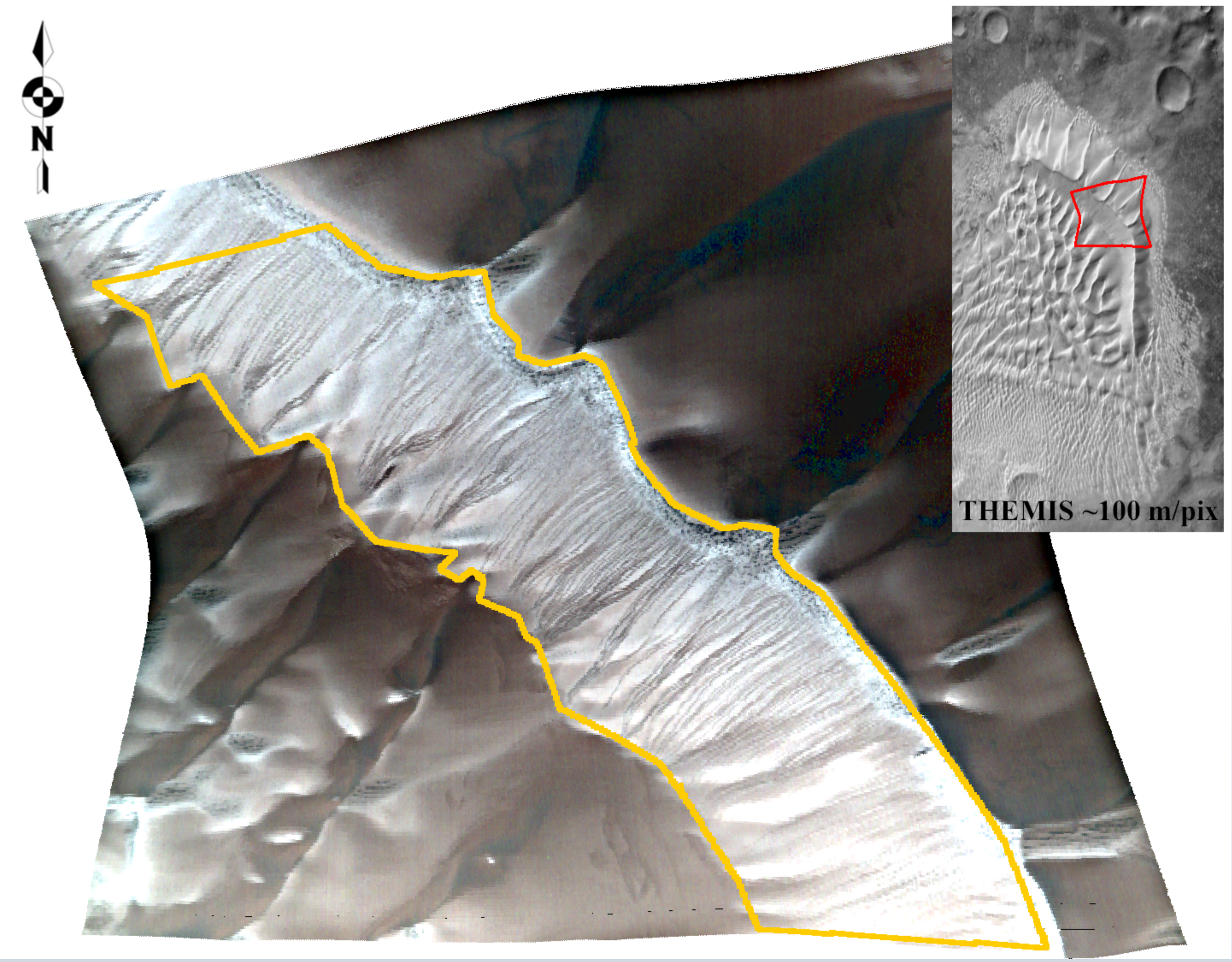
Compact **R**econnaissance **I**maging **S**pectrometer for **M**ars

- **362 – 3920 nm (544 channels)**
- **15-19 m/pix**

The Russel crater megadune

CRISM *frt000042aa*

- Late southern winter
- Near IR : 1 – 2.5 µm
- 18 m/pix
- Region Of Interest



IPAG CRISM pipeline

Raw image
↓
Artifact cleaning
↓
Photometric correction
↓
Atmospheric correction
↓
Clean image

Outline

- Background
- The Russell crater megadune
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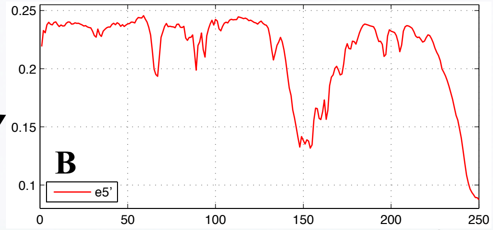
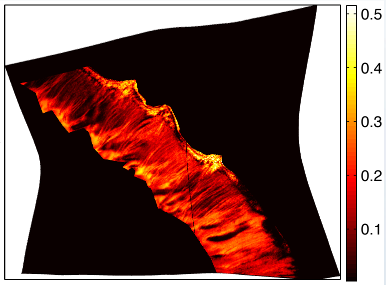
Experiments

Unsupervised spectral unmixing

- **Linear** mixing model : $\mathbf{X} = \mathbf{M} \cdot \mathbf{S} + \mathbf{e}$
  - $\mathbf{X}=\{\mathbf{x}_1,\ldots\mathbf{x}_{Np}\}$: hyperspectral image
  - $\mathbf{M}=\{\mathbf{m}_1,\ldots\mathbf{m}_{Nc}\}$: mixing matrix
  - $\mathbf{S}=\{\mathbf{s}_1,\ldots\mathbf{s}_{Nc}\}$: source matrix
  - $\mathbf{e}$: additive noise



$\mathbf{m}_n$: spectral signature of endmember $\mathbf{n}$



$\mathbf{s}_n$: abundance map of endmember $\mathbf{n}$

- Two main steps:
  1. Estimation of the number Nc of endmembers
     - ELM (*Luo'09*)
  2. Endmember extraction to obtain $\mathbf{M}$ and $\mathbf{S}$
     - Selection of four state-of-the-art algorithms

	VCA (Nascimento'05)	MVC-NMF (Miao'07)	spatial-VCA (Zortea'09)	BPSS (Moussaoui'06)
First principle:	Geometric	Geometric	Geo. + spatial	Statistical
Advantage:	Fast	Less-prevalent endmembers	Homogeneous endmembers	Bayesian framework
Drawback:	Less-prevalent endmembers	False spectra	Less-prevalent endmembers	Computational time

Experiments

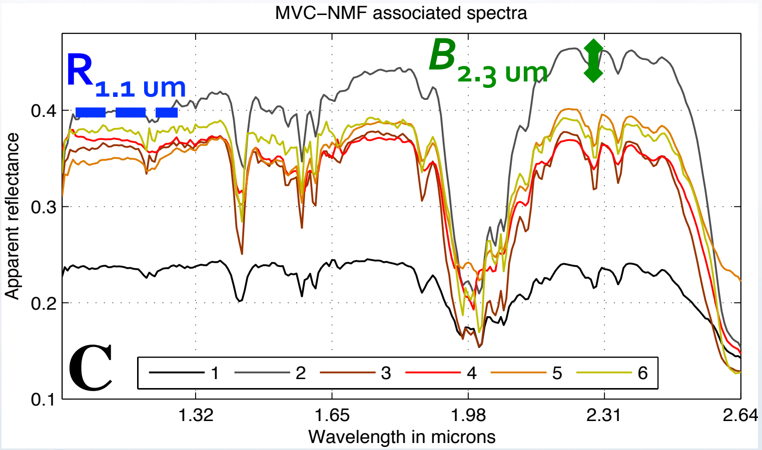
Spectral unmixing of CRISM image *frt42aa*

1. **Estimation of the number of endmembers**
- ELM: **Nc = 6** endmembers
2. **Endmember extraction**
- VCA, BPSS, MVC-NMF & *spatial*-VCA: **6 spectra** and **6 abundance maps**
3. **Planetary interpretation**
- **Similar** for all methods
- Defined by **3 physical sources**:
  - Dark source: presence of dark features
  - Strong bright source: high content of CO_2 ice
  - Weak bright source: highest content of CO_2 ice
- Nonlinear contributions generate **source splitting effects**

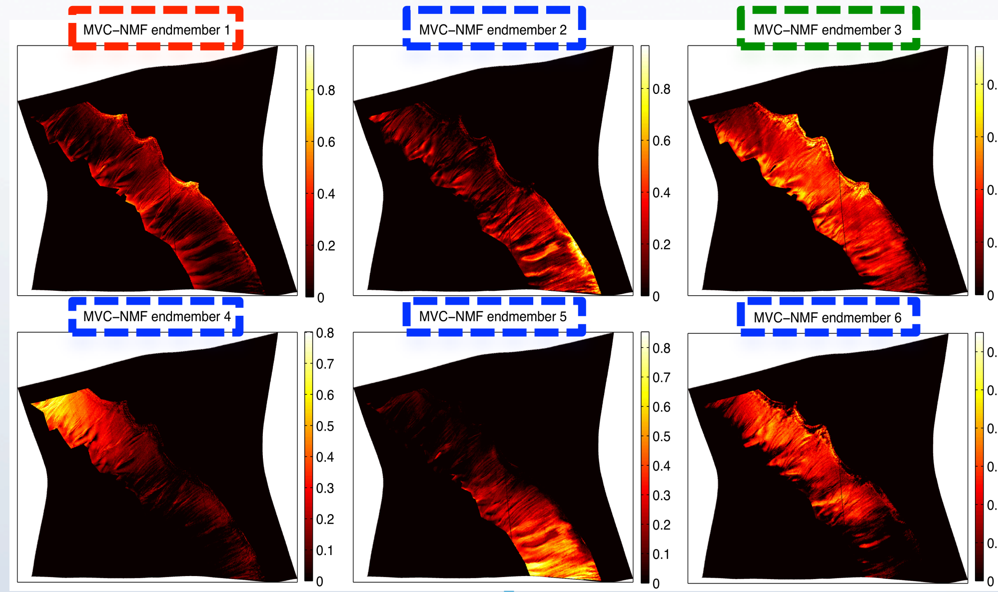
Experiments

- Recombination process for MVC-NMF

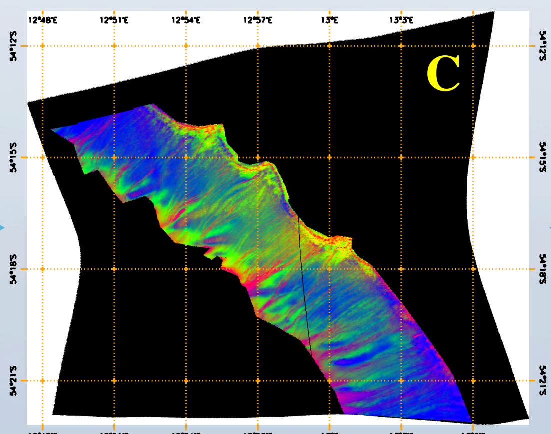
Spectral product: extracted spectra



Spatial product: abundance maps



Dark
Strong bright
Weak bright

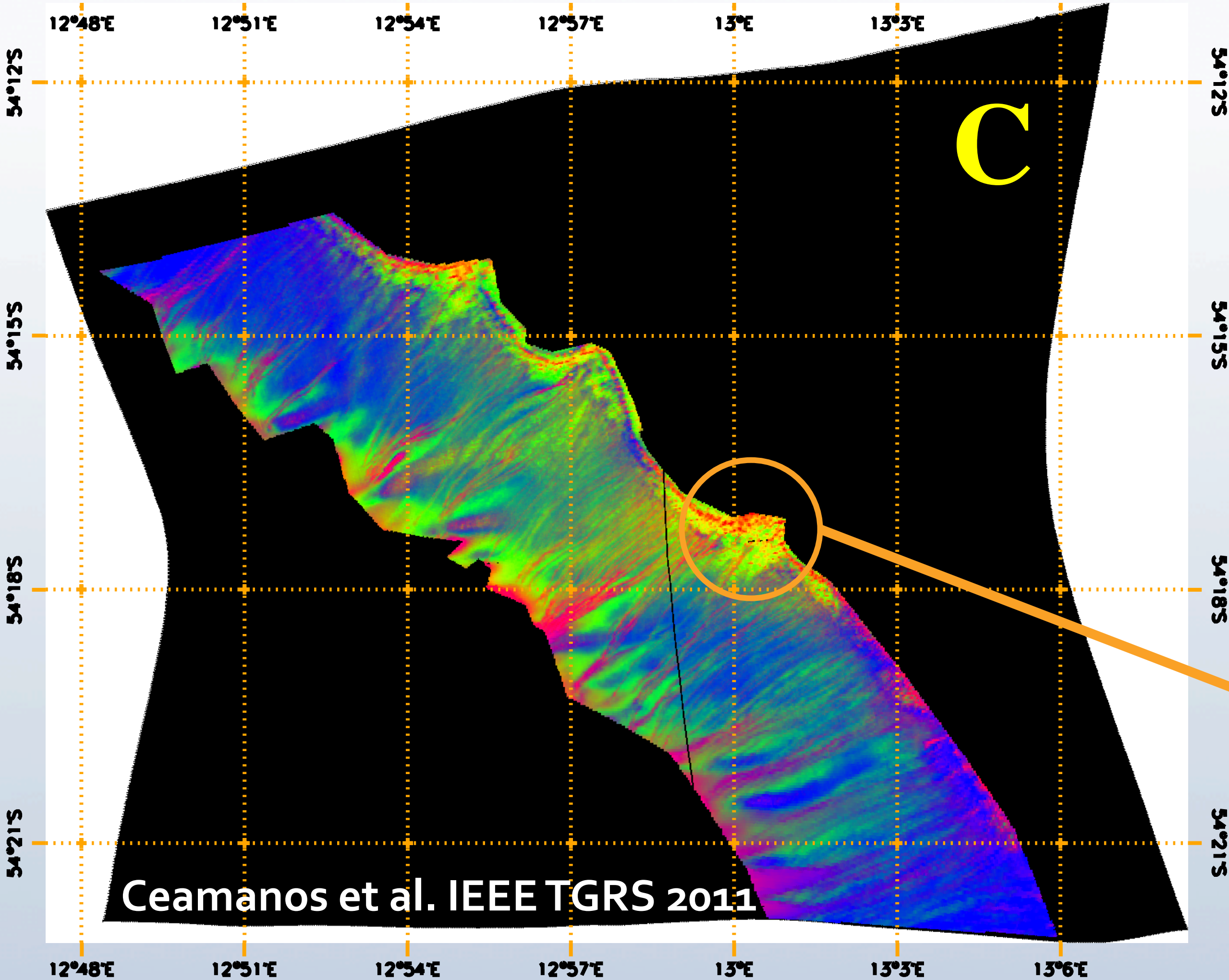


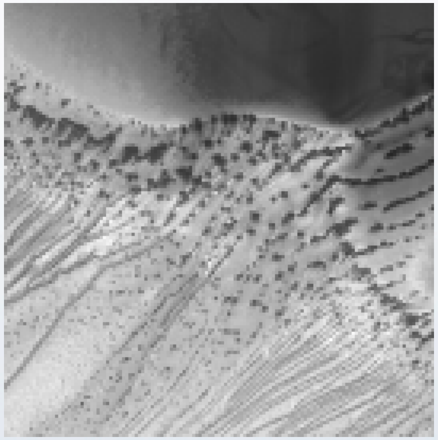
Final product: composite abundance map!

Experiments

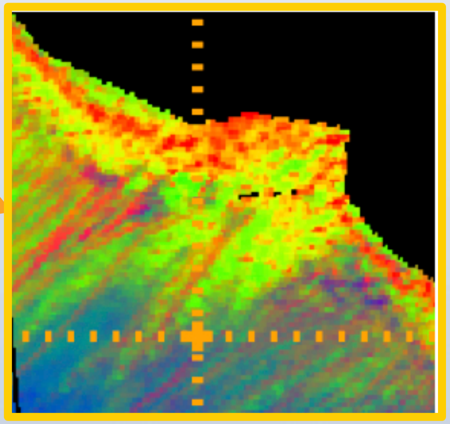
- **MVC-NMF:** composite map

Sources: Dark, strong bright, weak bright





HiRISE image

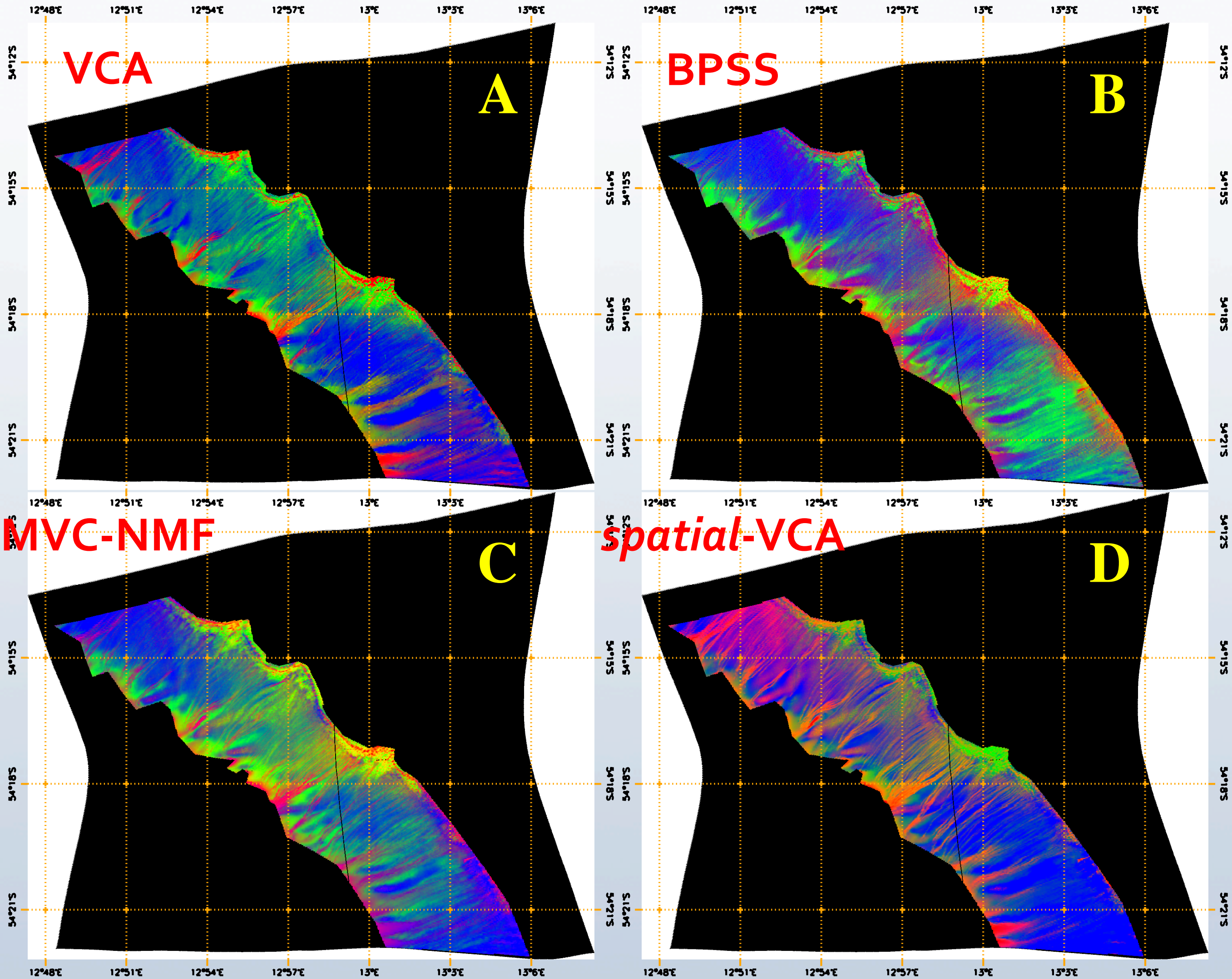


VCA abundance map

Experiments

- Composite maps

Sources: Dark, strong bright, weak bright



Outline

- Background
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- **Validation**
- Conclusions

Validation

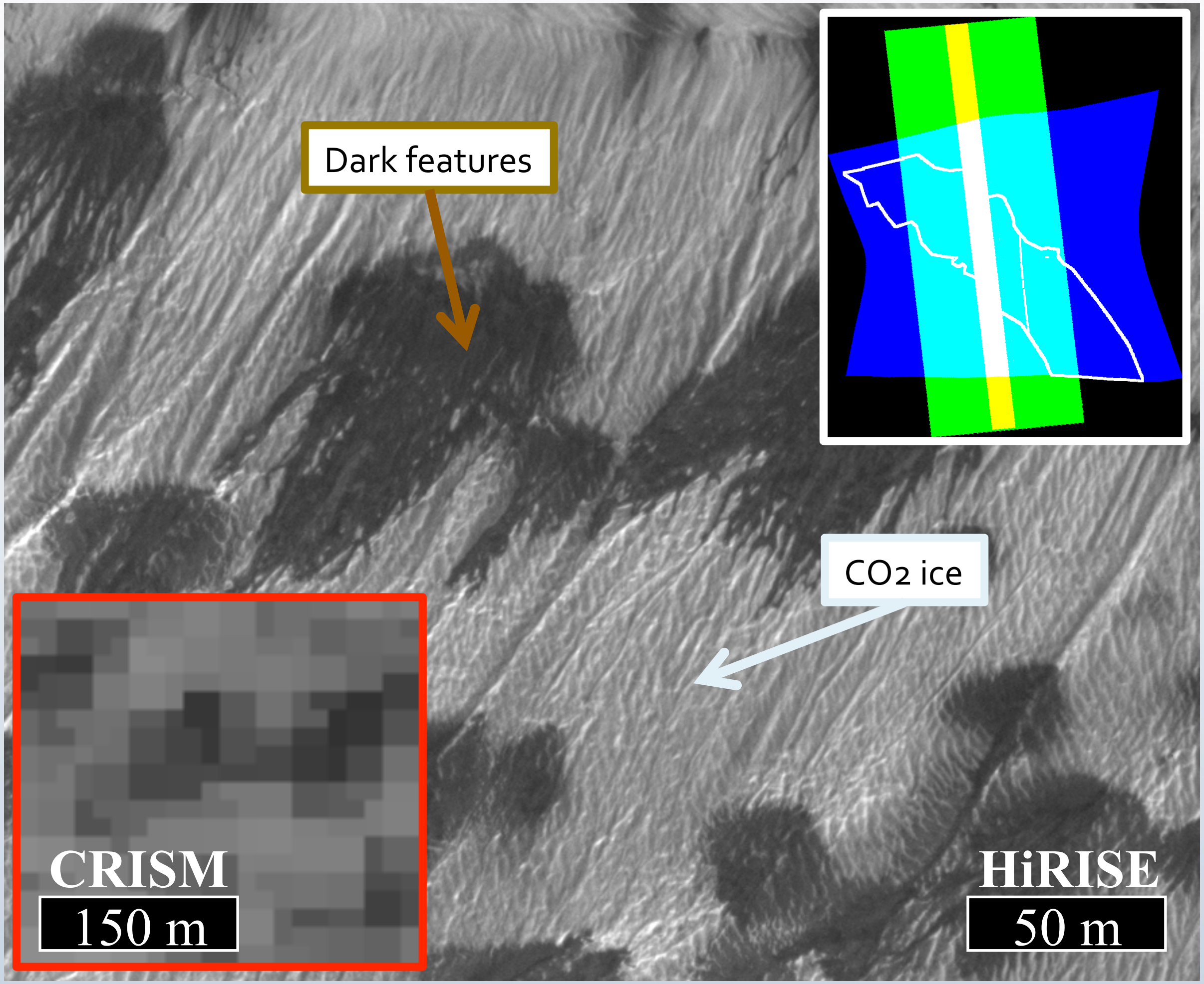
- Validation of spectral unmixing techniques in the literature?
  - ✔ Spectral signatures
    - Reference data bases? ➡ **Ground truth is very scarce on Mars!**
    - Simulated data? ➡ **Limitations of the simulation models!**
  - ✖ Abundance maps

Validation of spectral unmixing by evaluation of abundance maps using HiRISE imagery

- **H**igh **R**esolution **I**maging **S**cience **E**xperiment
  - Red band: 550-850 nm; 0.3 m/pix
  - Aboard MRO and **coordinated with CRISM!**

Validation: **ground truth**

HiRISE *PSP_002482_1255* :

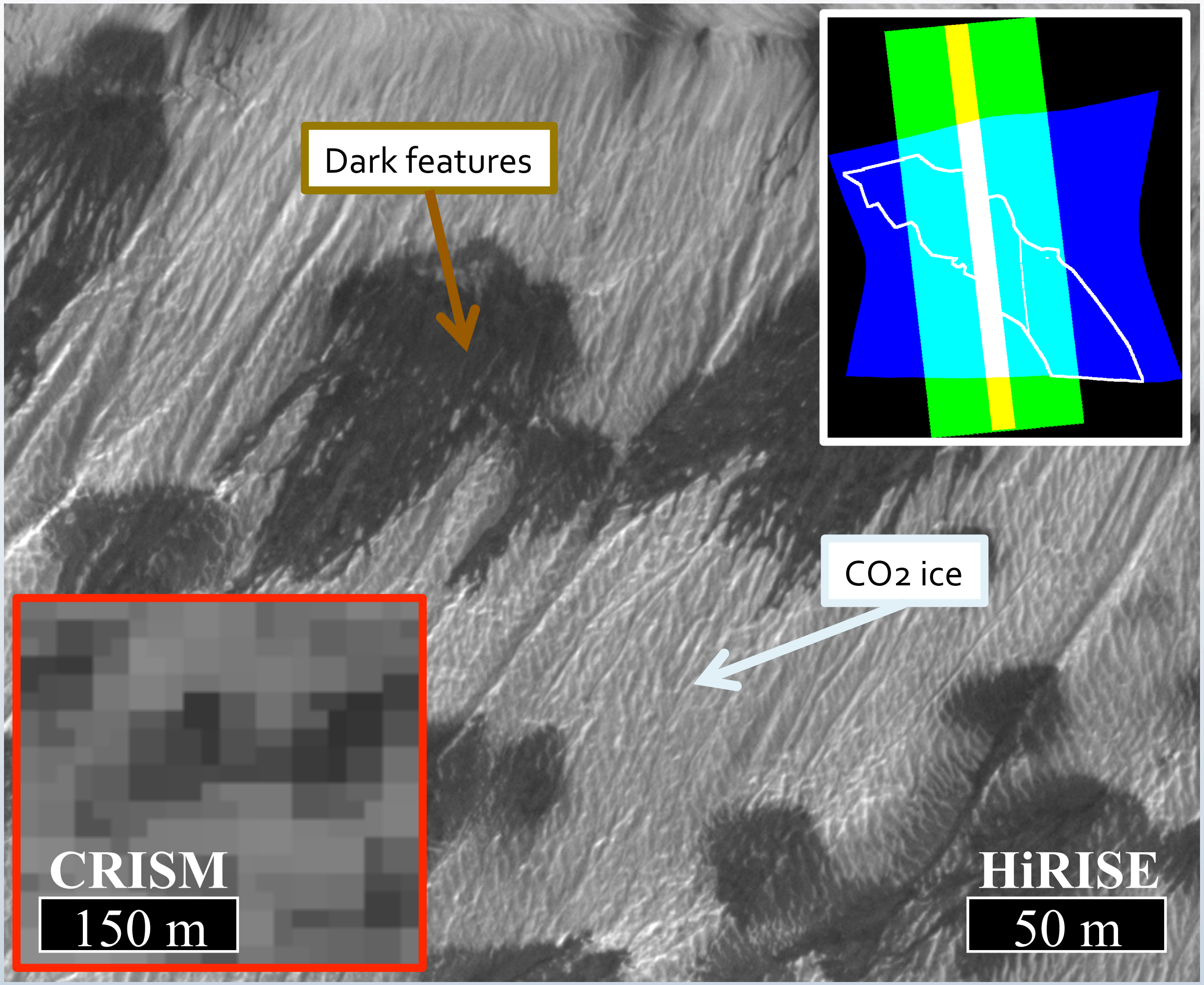


Detail of the Russell dune observed by the CRISM and the HiRISE instruments. CRISM *frt42aa* in blue, HiRISE *PSP_002482_1255* in green

A **reference abundance map** of the dark features can be built from HiRISE imagery!

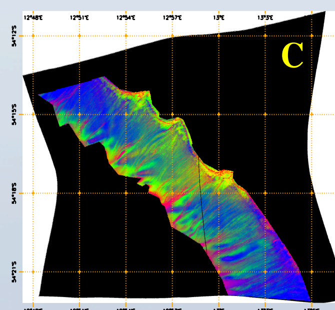
Validation: **ground truth**

HiRISE *PSP_002482_1255* :



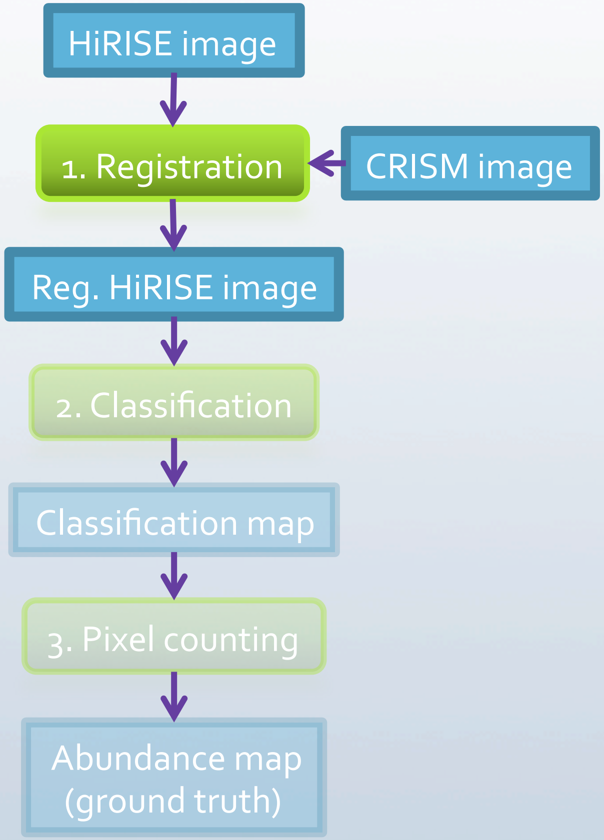
Detail of the Russell dune observed by the CRISM and the HiRISE instruments. CRISM *frt42aa* in blue, HiRISE *PSP_002482_1255* in green

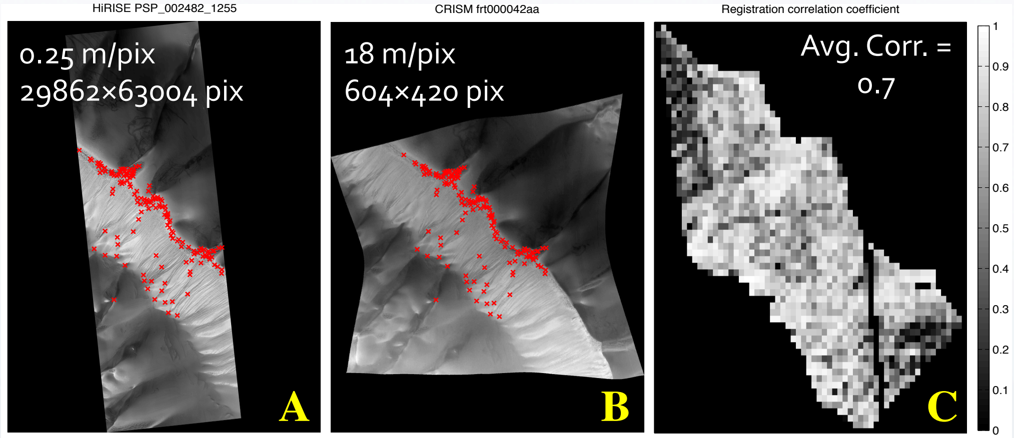
The **reference abundance map** may be used to validate the dark source



Validation: **ground truth**

Ground truth generation

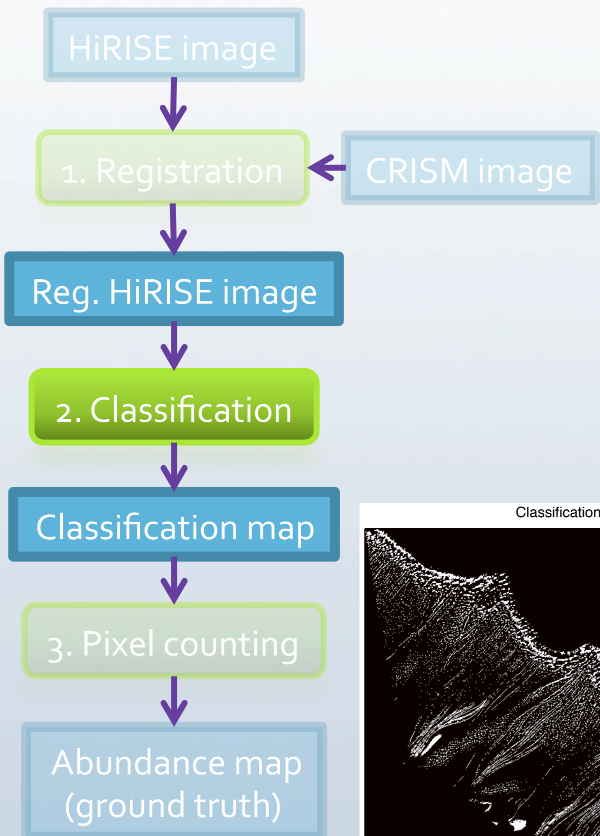


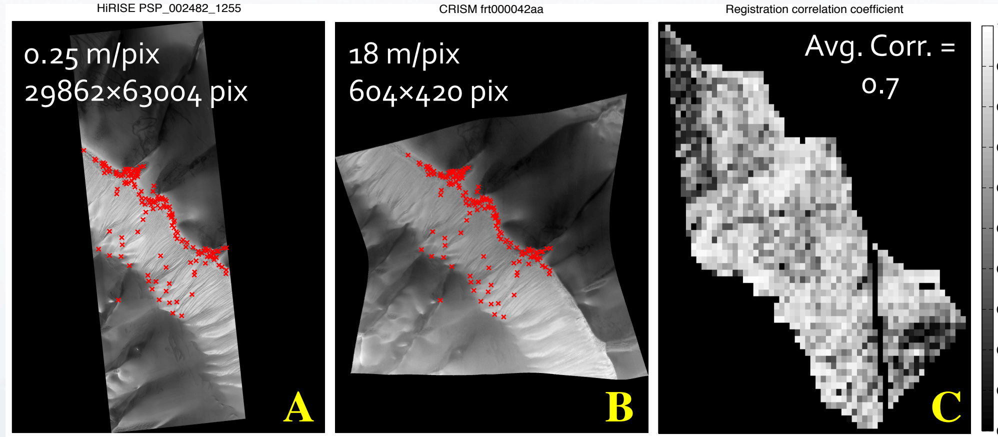


1. Registration of CRISM and HiRISE images
2. Classification (*k*-means strategy)
3. Pixel counting

Validation: **ground truth**

Ground truth generation





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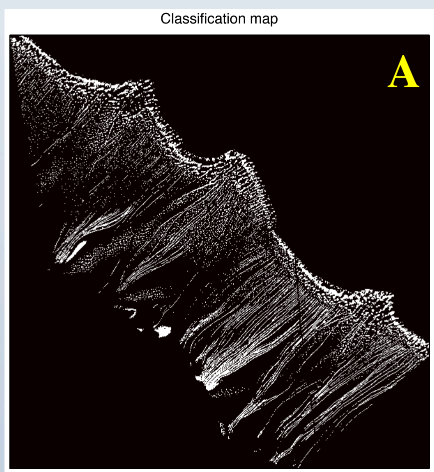
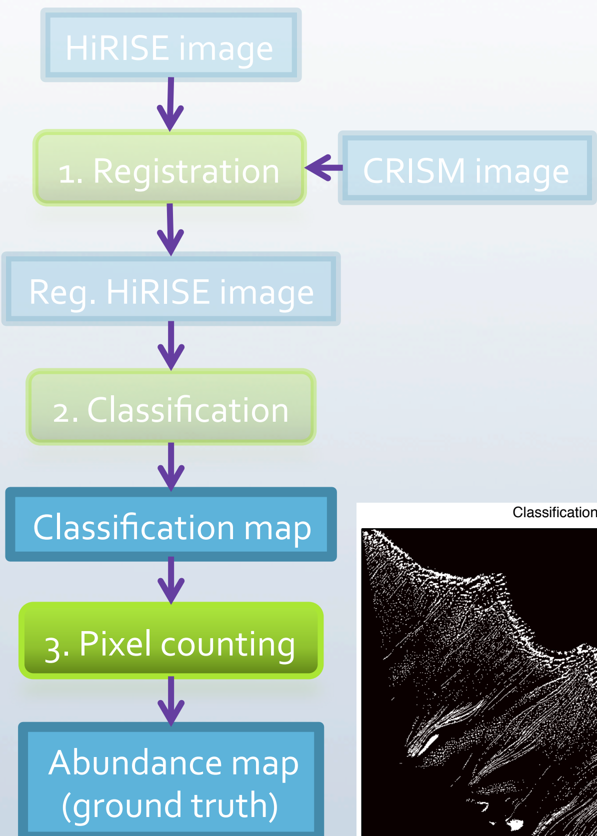
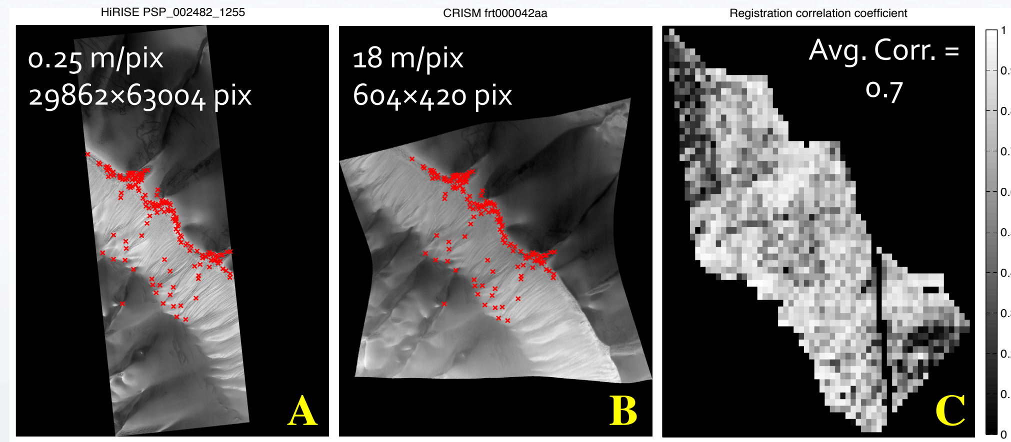


Validation: **ground truth**

Ground truth generation





1. Registration of CRISM and HiRISE images
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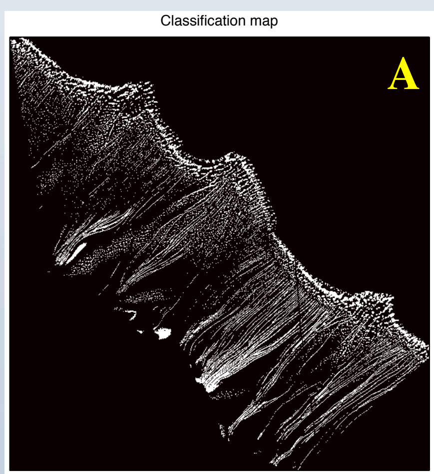
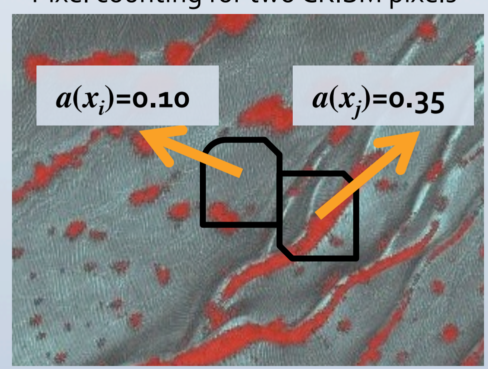
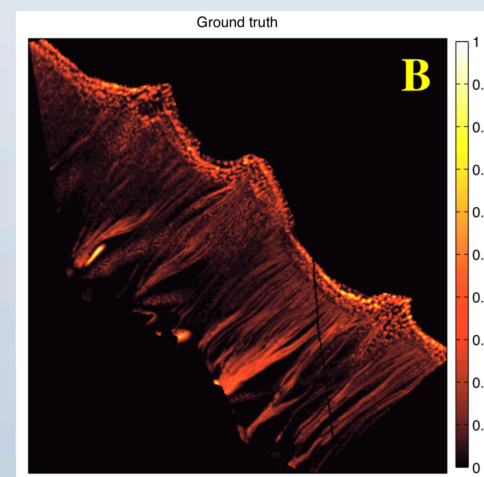


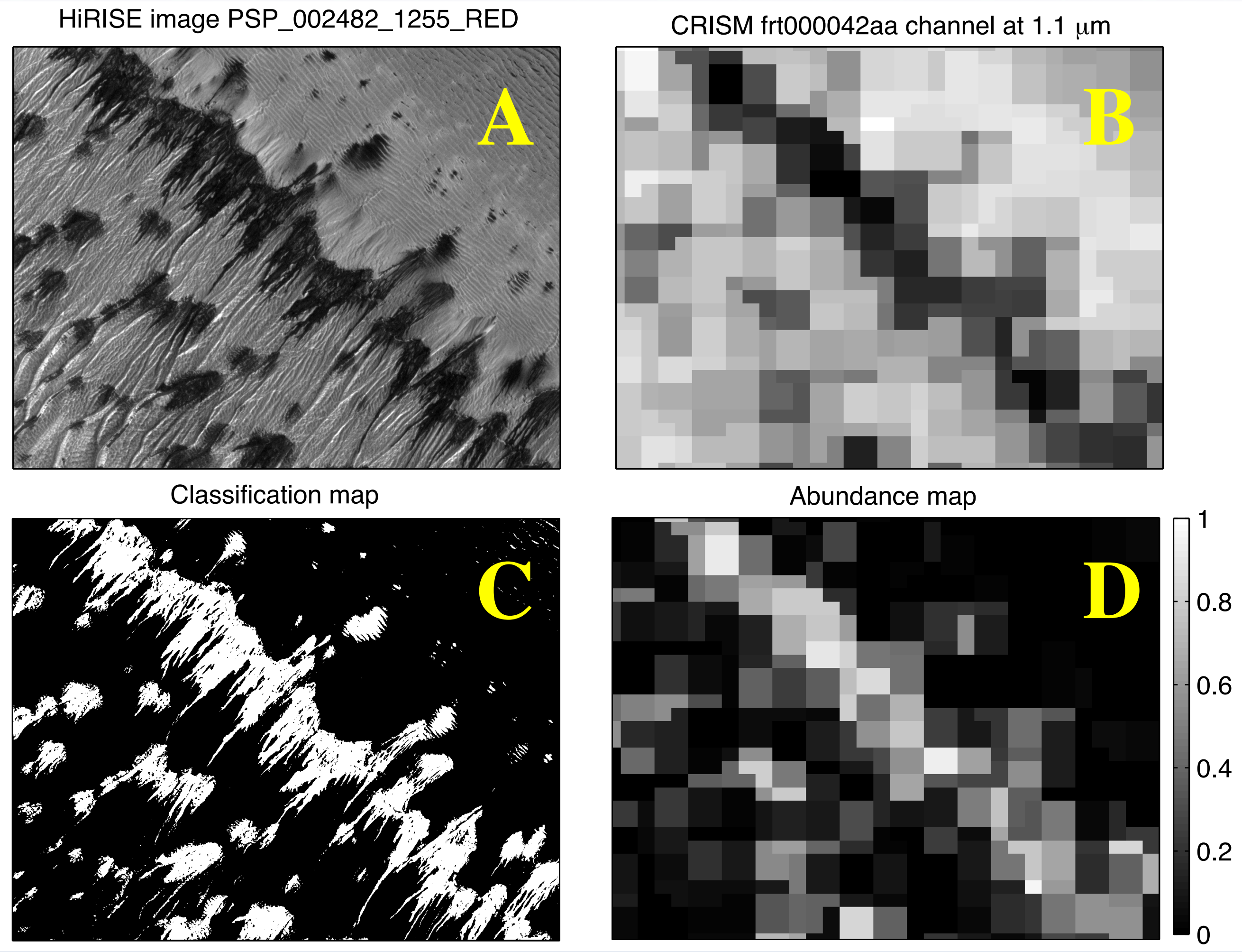
Pixel counting for two CRISM pixels



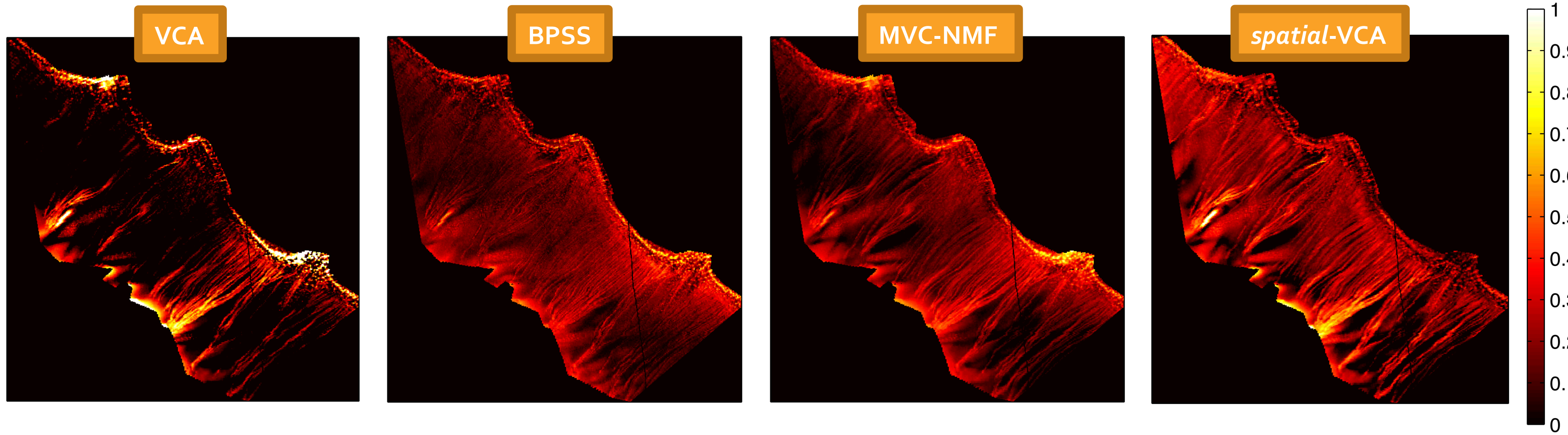


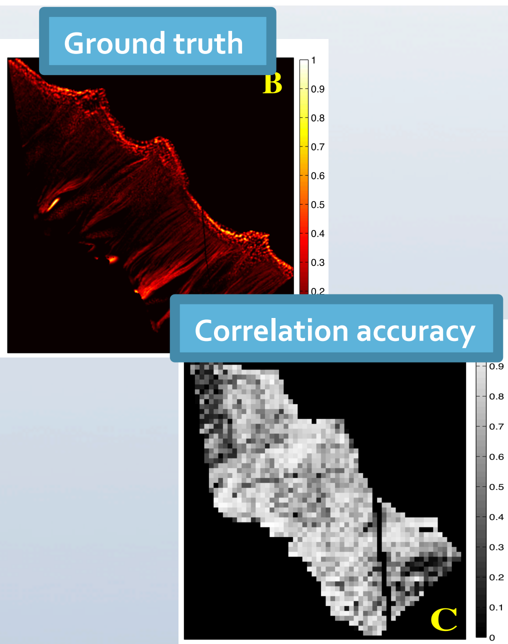
Validation: **ground truth**

Ground truth generation: detail



Validation of **dark source**



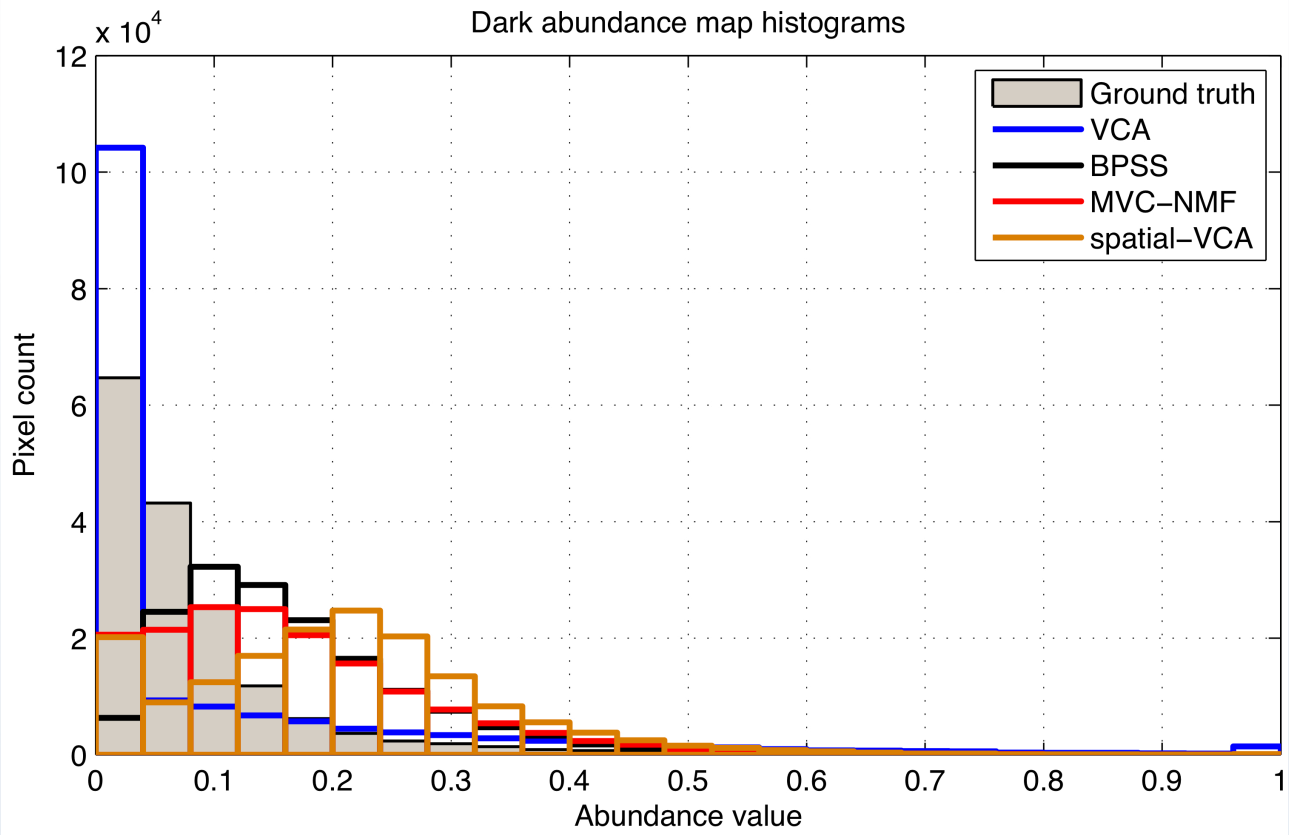


Method	VCA		BPSS		MVC-NMF		*spatial*-VCA	
Indicator	r	ϵ	r	ϵ	r	ϵ	r	ϵ
(1) All pixels	0.68	0.08	0.57	0.10	0.69	0.09	0.50	0.14
(2) Accurate registration	0.73	0.08	0.59	0.09	0.72	0.08	0.56	0.13
(3) Best registration	0.81	0.19	0.80	0.13	0.83	0.14	0.77	0.33

- Misregistration is the main cause of inaccuracy
- MVC-NMF and VCA obtain the best r **= 0.83** and ε **= 0.08**
- *spatial*-VCA does not extract the dark source satisfactorily

Validation of **dark source**

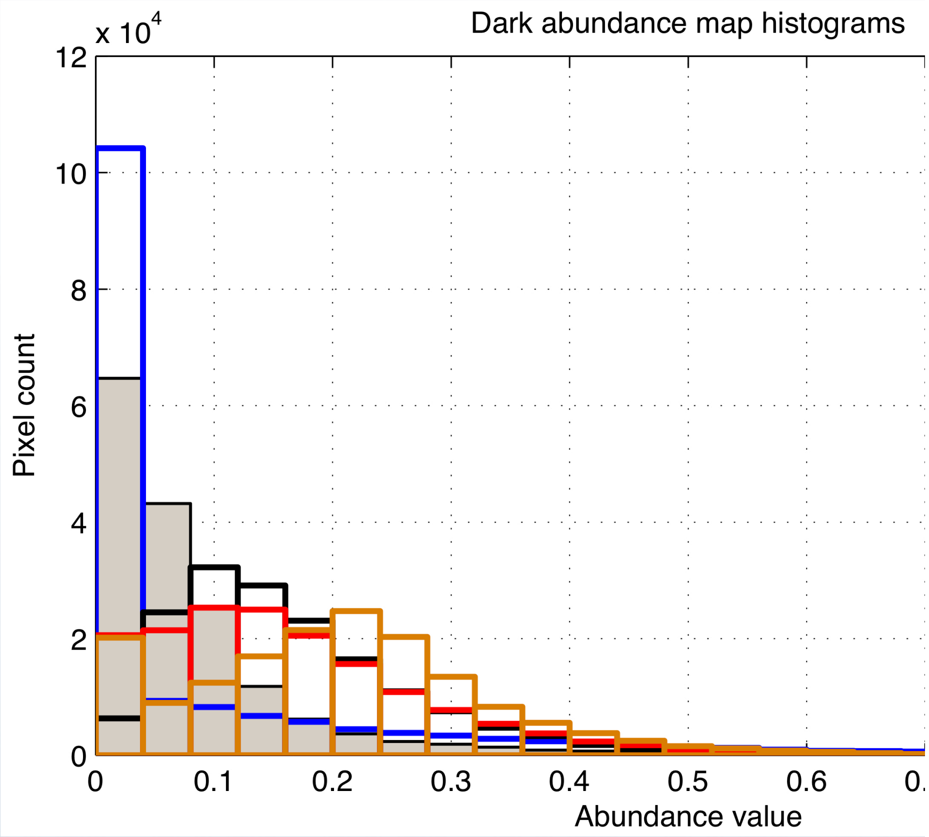
Abundance distribution for all pixels

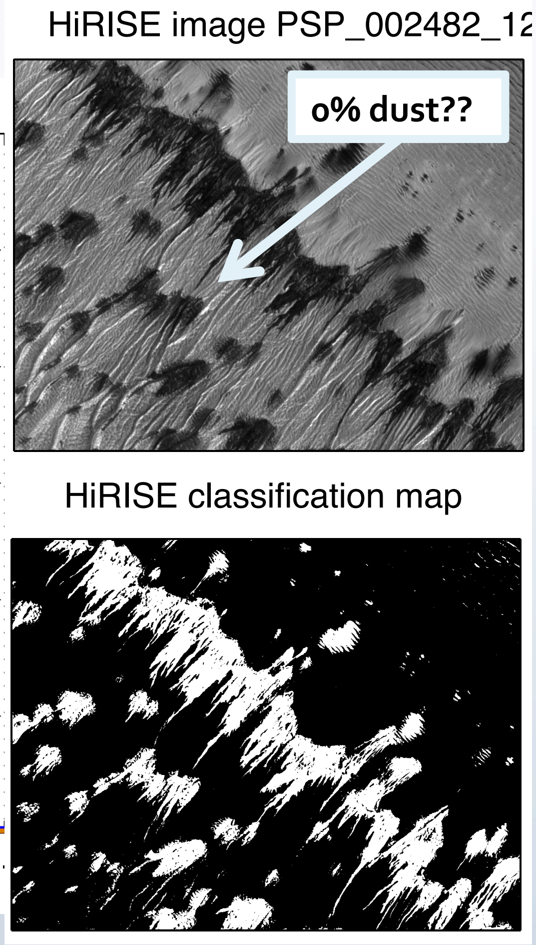


- BPSS obtains the most accurate abundances along with MVC-NMF
- VCA abundances are underestimated
- General overestimation?

Validation of **dark source**

Abundance distribution for all pixels

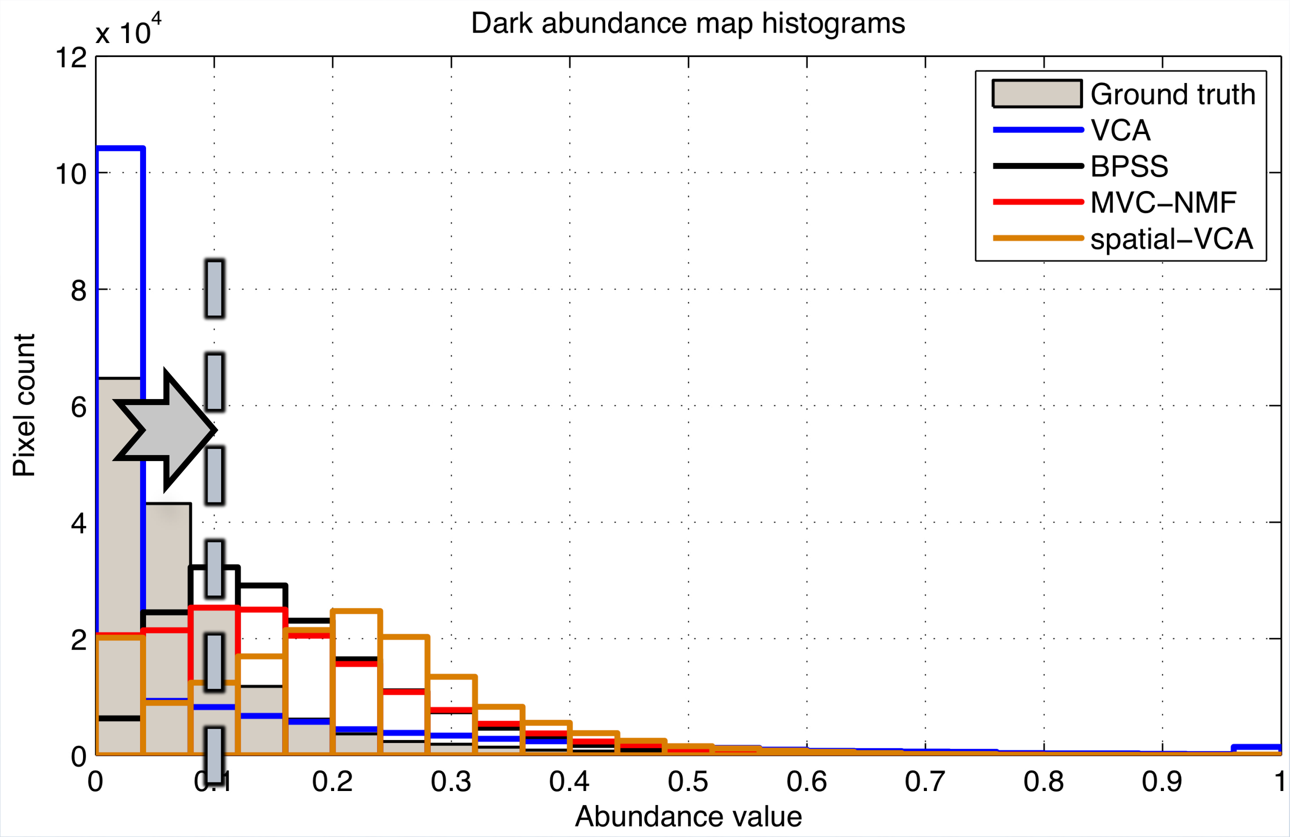




- BPSS obtains the most accurate abundances along with MVC-NMF
- VCA abundances are underestimated (unmixing constraints?)
- General overestimation?

Validation of **dark source**

Abundance distribution for all pixels



BPSS and MVC-NMF results are expected to improve significantly!

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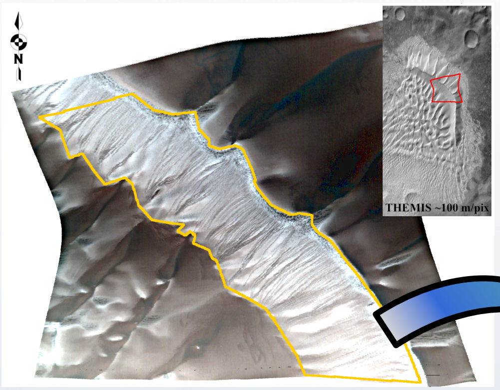
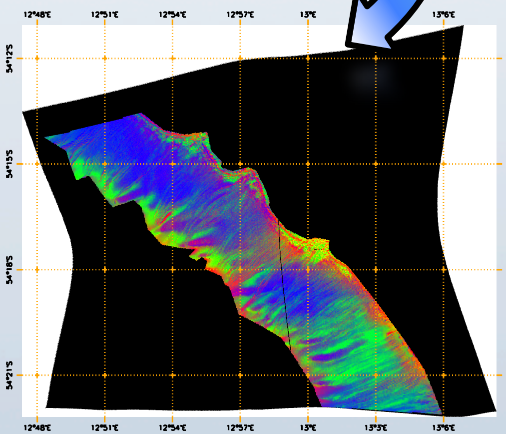
Conclusions

1. Spectral unmixing is suitable for **planetary exploration**
   - A meaningful planetary scenario is revealed



2. Validation of abundance maps using an independent **ground truth**
   - ✔ Suitability of the linear mixing model



3. **Intercomparison** of endmember extraction algorithms
   - **MVC-NMF** and **BPSS** obtained the best results
   - **MVC-NMF** & **VCA** may be used as quick look

- **Future work:**
  - Full inversion fed by unmixing abundances

Thanks for your attention!

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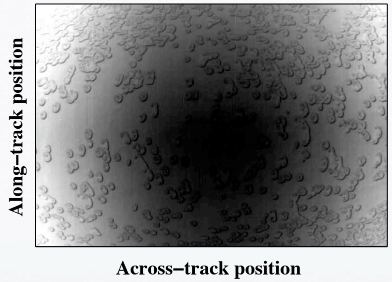
Projet Vahiné – ANR/CNES

Science case: **CRISM data pipeline**

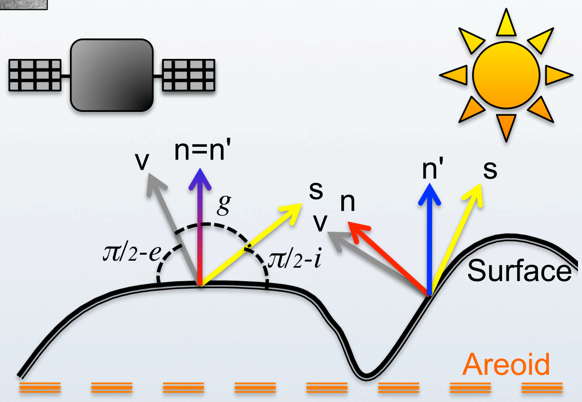
- **Artifact correction**
  - Stripes + spikes + **smile effect**
  - CRISM toolkit + LPG algorithms
  - *frt42aa* is very challenging!



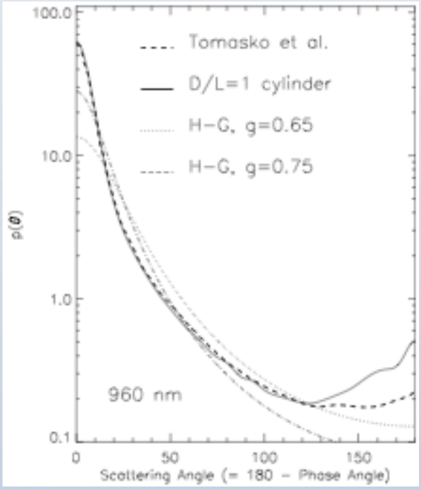
Typical smile artifact affecting CRISM bands

- **Photometric correction**
  - Heterogeneous illumination
  - Digital Terrain Model
  - Noisy DTM for the Russell dune!

Illumination conditions depend on surface inclination



- **Atmospheric correction**
  - Gases & aerosols
  - $I(x;\lambda) = t_{GAS}(x;\lambda)^{\varepsilon(x;\tau_{aero})} R(x;\lambda)$
  - Inaccurate aerosol phase function



Martian aerosol phase functions

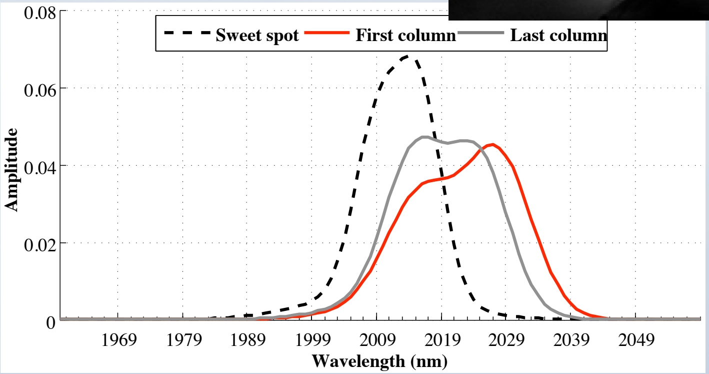
Potential non-linear contributions!

Data pipeline: **artifact correction**

- **Stripes**
  1. Random column-dependent error bias
  2. Electronic miscalibration
  3. *Parente 2007*

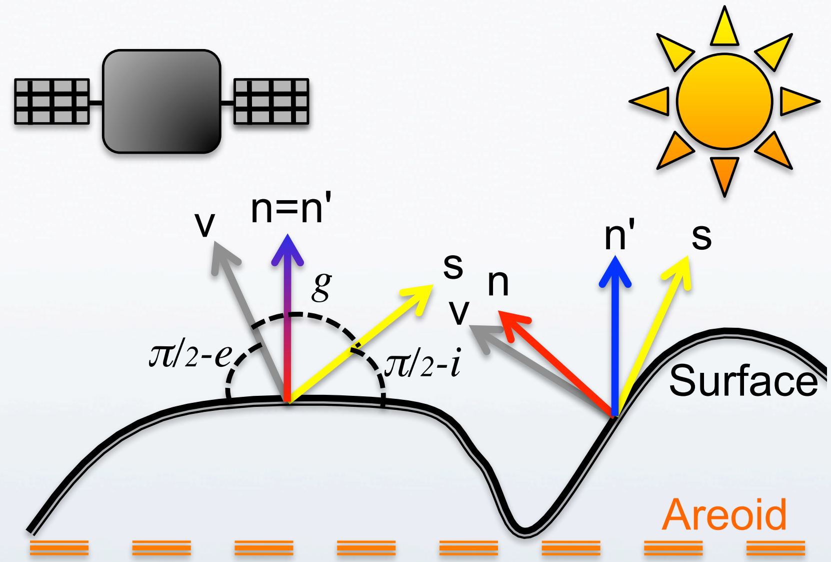
- **Spikes**
  1. Aberrant error bias affecting single pixels
  2. Cosmic rays or bit errors
  3. LPG homemade algorithm

- **Spectral smile**
  1. Column-dependent artifact
  2. Non-uniform spectral response
  3. *Ceamanos and Douté 2010*



CRISM spectral response changes according to column. *Ceamanos 2010*

Data pipeline: **photometric correction**

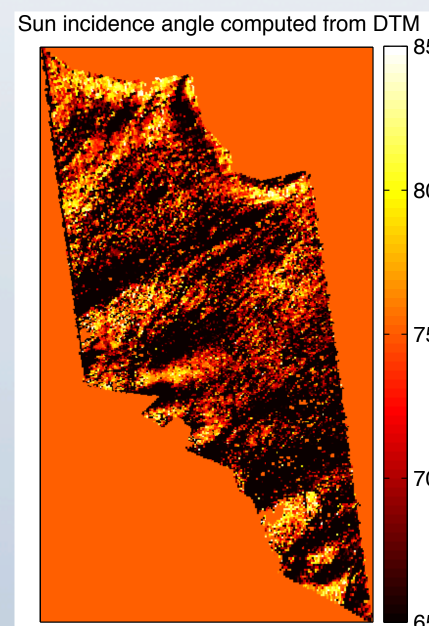


- CRISM data come in I/F units
- Reflectance units (ρ)

$$\rho(i,e,g) = \frac{I}{\pi \cdot F}$$

$$REFF = \frac{\pi \cdot \rho(i,e,g)}{cos(i)} = \frac{I}{cos(i) \cdot F}$$

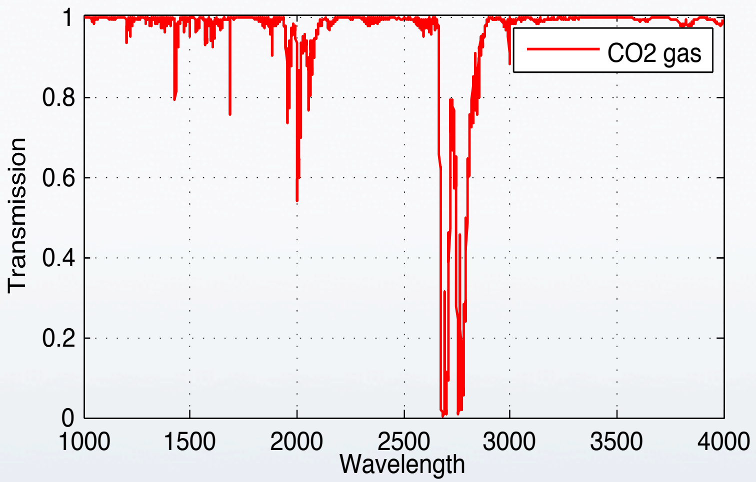
- General procedure: $i \approx i' = <n', s>$
- Digital Terrain Models to determine $i = <n, s>$
  - ~~MOLA DTM at 400 m/pix~~; HiRISE DTM at 1 m/pix
  - **Drawback**: noisy DTM generates bad i values
- **Assumption**: $i \approx \bar{\imath}_{DTM} = 75^{\circ}$



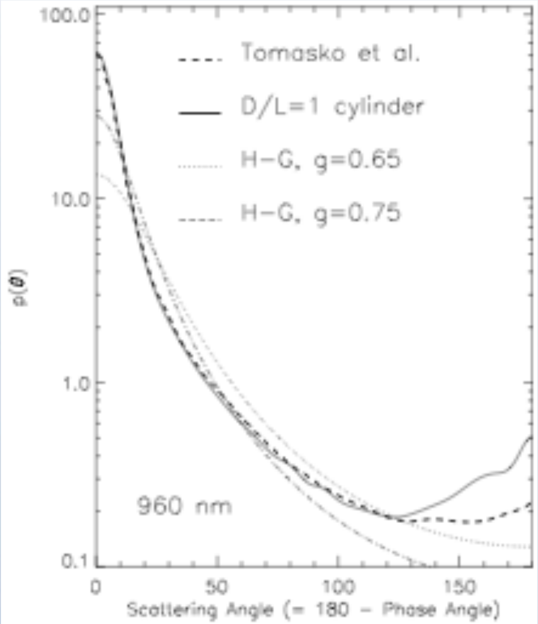
Data pipeline: **atmospheric correction**

- Faint atmosphere
  - **Gases**: 98% of CO_2 (strong absorption bands in NIR)
  - **Aerosols**: mineral particles (anisotropic contribution)

- $I(x;\lambda) = t_{GAS}(x;\lambda)^{\varepsilon(x;\tau_{aero})} R(x;\lambda)$
  - $t_{GAS}(x)$: gas transmission (radiative transfer model)
  - $\varepsilon(x;\tau_{aero})$: coupling between aerosols and gases
  - $R(x;\lambda)$: surface reflectance
  - τ_{aero} : aerosol optical thickness
    - estimated at 1 µm
    - $P(\theta,\lambda)$?



Atmospheric CO_2 gas absorption bands in the near infrared



Martian aerosol phase function of *Tomasko 1999*, *Vincendon 2008* and *Wolff 2009*

Spectral unmixing: **number of endmembers**

- Eigenvalue Likelihood Maximization (ELM) *Luo 2009*
  - z_l: the difference between the l^{th} sorted eigenvalues of the correlation and covariance matrices
  - If z_l corresponds to noise $z_l = 0$, otherwise $z_l > 0$
  - the distribution of z_l can be asymptotically modeled by:

$$\begin{array}{ll} z_i \sim \aleph(\mu_i, \sigma_i^2), & i \leq N_c \\ z_i \sim \aleph(0, \sigma_i^2), & i > N_c \end{array}$$

  - Likelihood function:

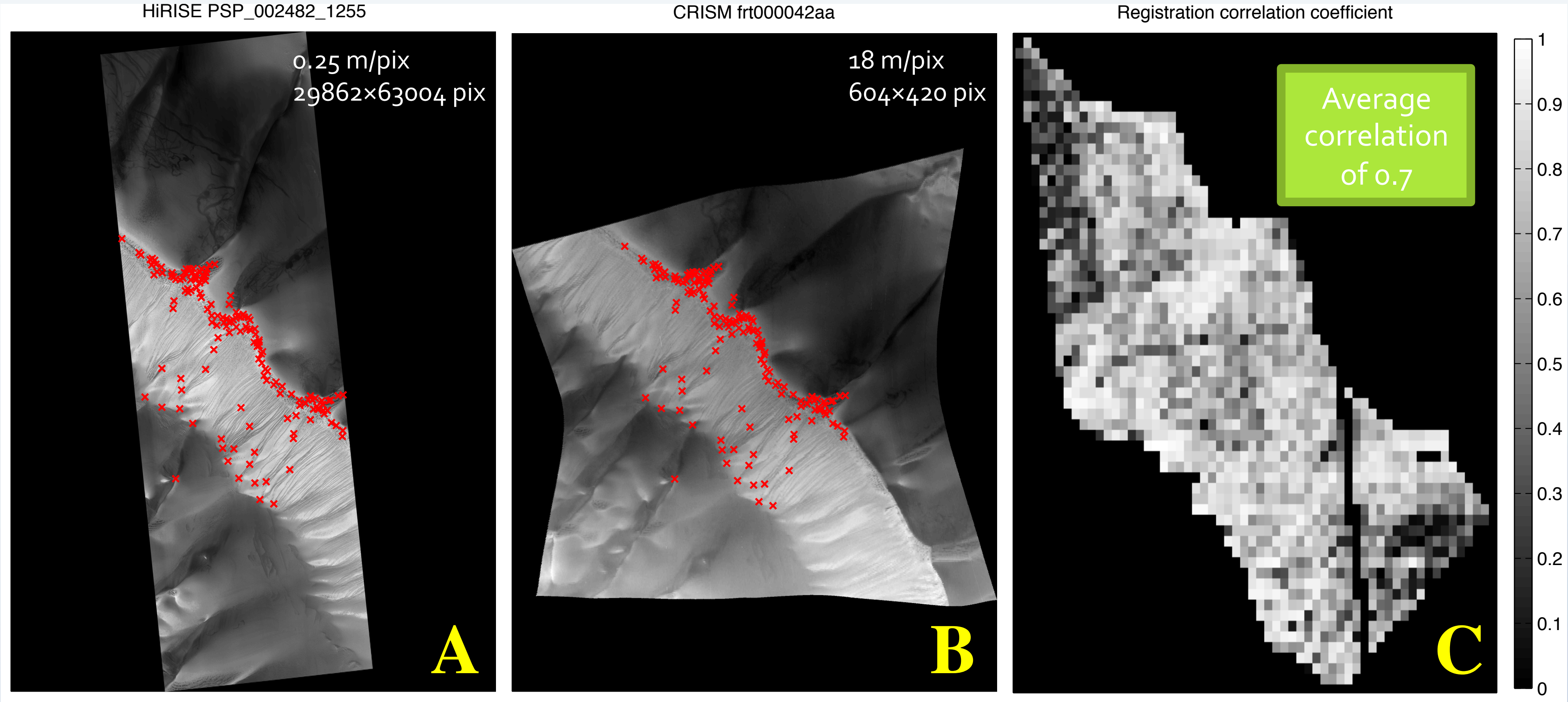
$$\tilde{H}(i) = -\sum_{l=i}^{N_s} \frac{z_l^2}{2\sigma_l^2} - \sum_{l=i}^{N_s} \log \sigma_l,$$

  - The number of endmembers is defined such that

$$N_c = \arg\max_i \{\tilde{H}(i)\} - 1.$$

Ground truth: **registration**

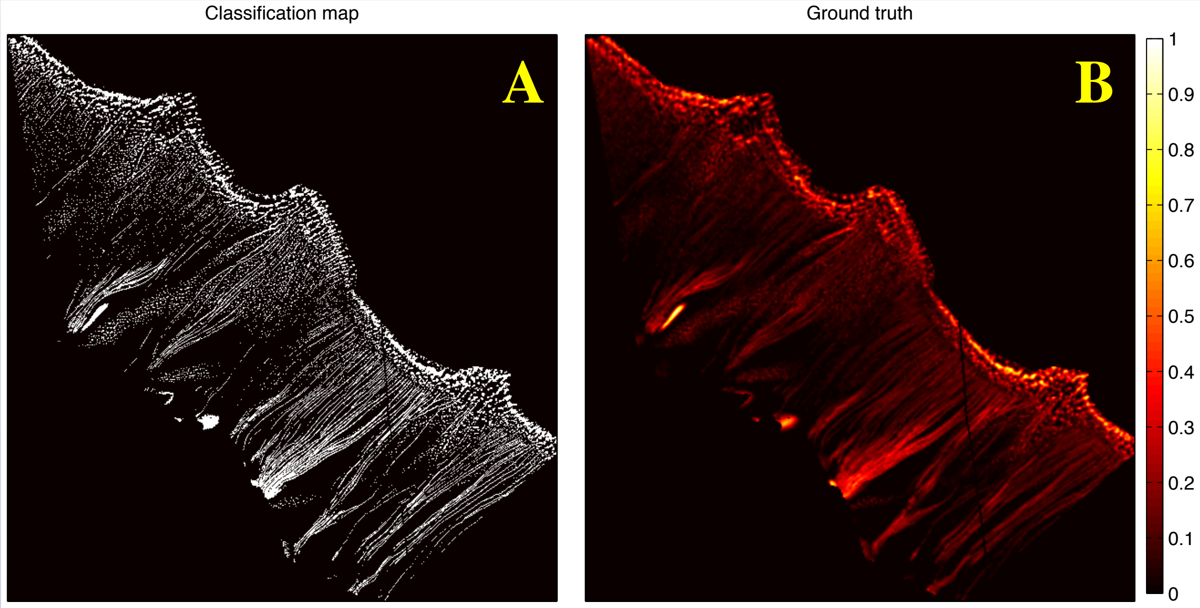
- Registration of CRISM and HiRISE images is challenging
  1. Different spatial resolution **=>** projection of CRISM image onto HiRISE geographic space
  2. Different geographic model **=>** Coarse registration + Delanauy triangulation
- Innacuracies caused by manually selected control points



Ground truth

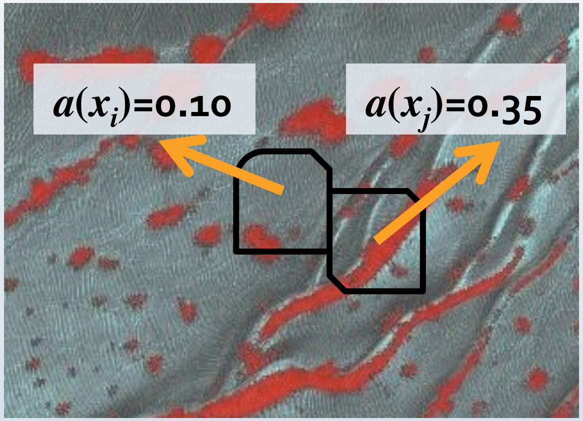
Classification

- Classification approach based on k-means clustering
  - the **darkest cluster** encompasses the **dark features**
  - results are improved to account for shadows and local photometry



Pixel counting

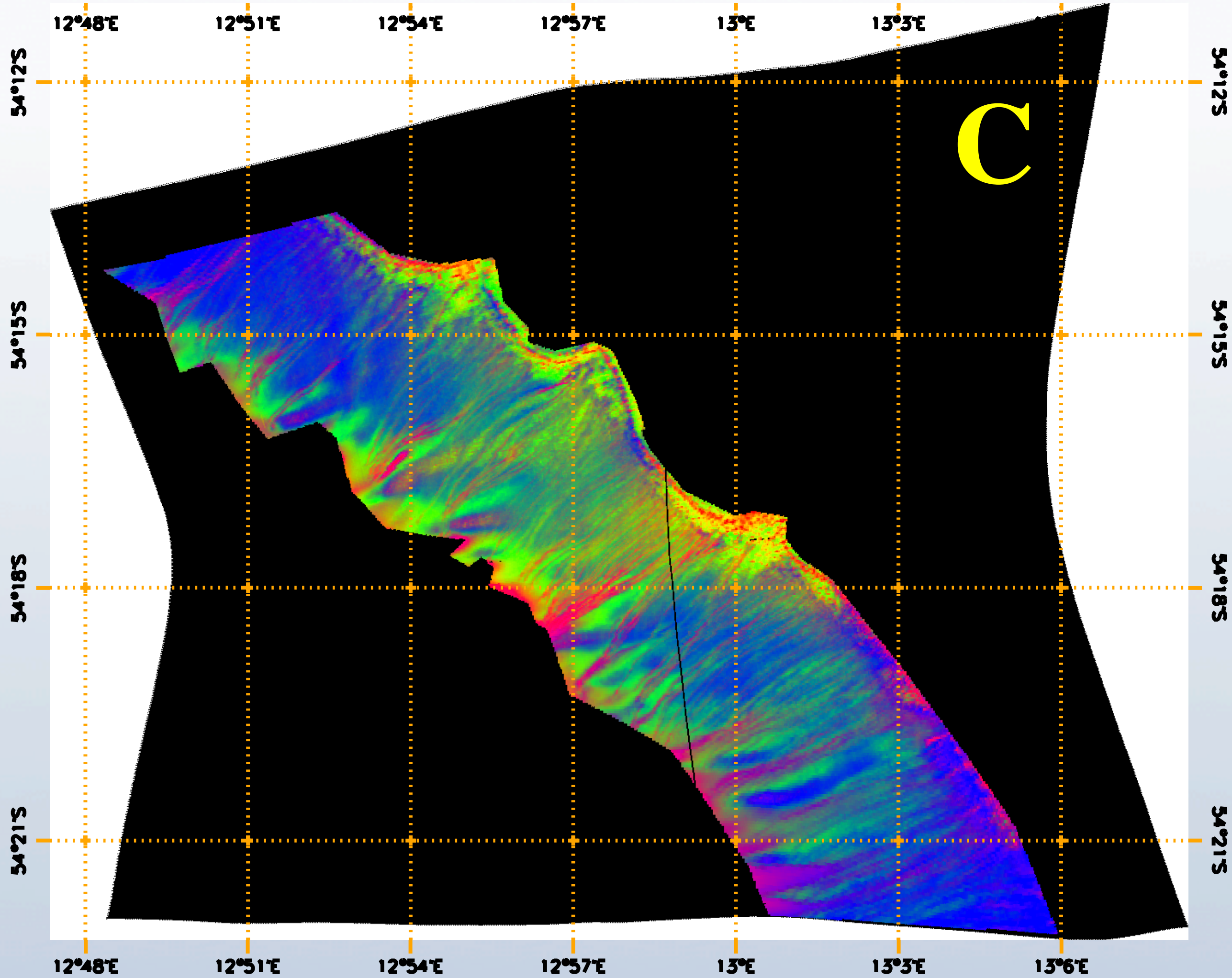
- Transformation of the **classification map** into **abundance map**
  - $a\,(pix_C) = dark\,(pix_H)\,/\,total\,(pix_H)$



Dark label counting of two CRISM footprints over the HiRISE classification map

Future work

Final reflection: **where do gullies come from?**



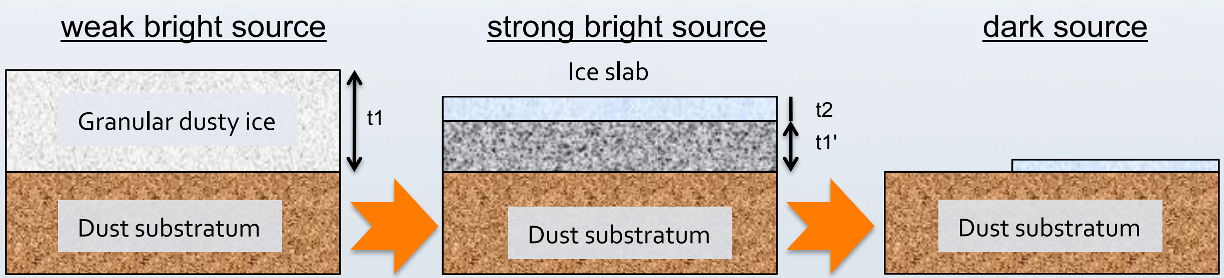
Does dust in the gullies come from avalanches starting in dune ridge?

OR

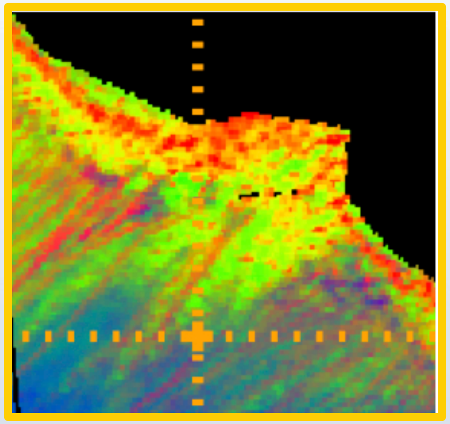
Is it revealed after ice sublimation?

Future work

- Full data inversion:
  - Abundance maps can be used as ***a priori* information**
- Possible defrosting scenario:



Sources: Dark, strong bright, weak bright



  - First **tests with synthetic data** seem to confirm this scenario
  - To be tested on a **temporal series** of observations!