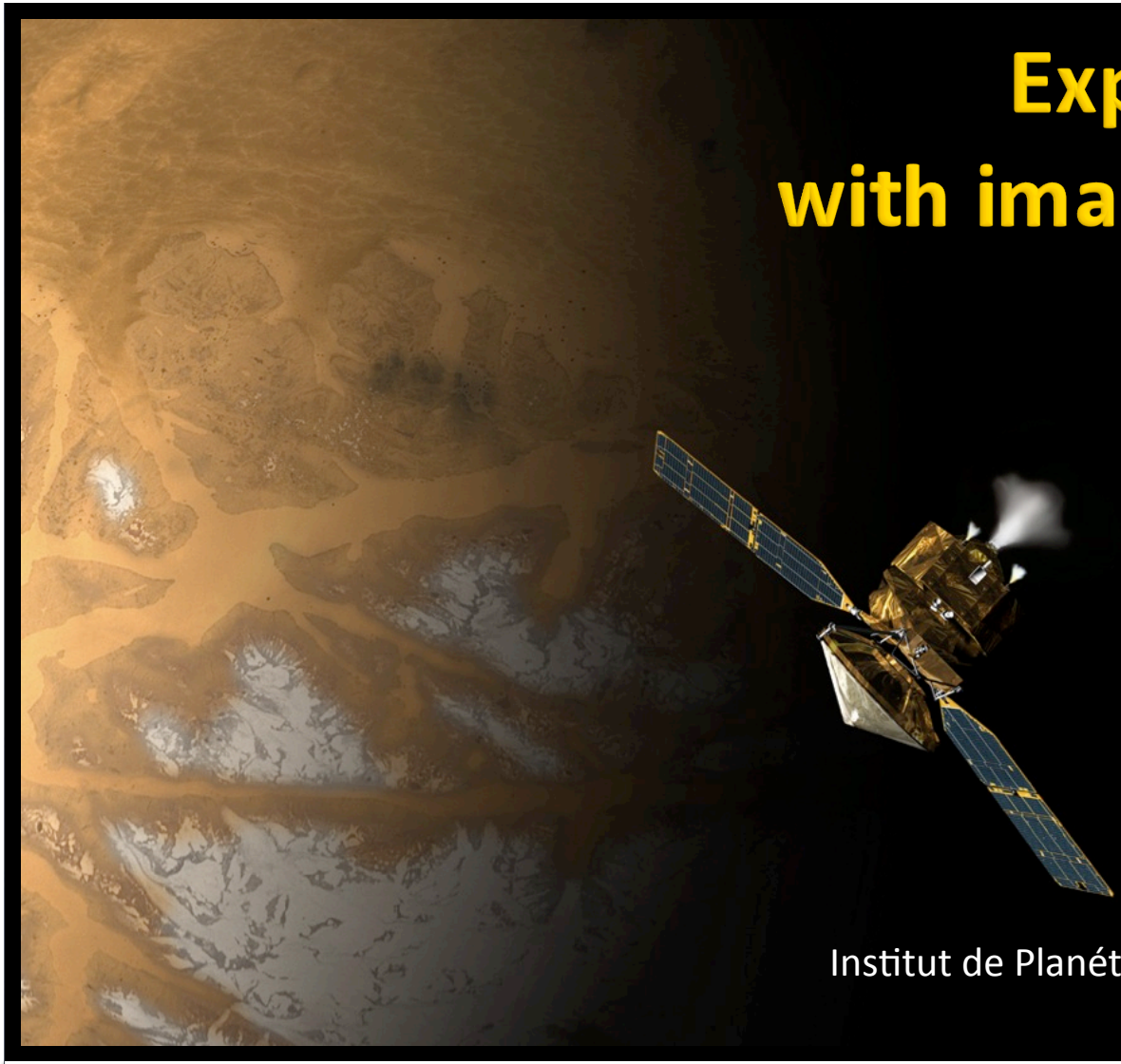
Exploring Planet Mars with imaging spectroscopy :

methods and algorithms



Dr. Sylvain DOUTÉ

Institut de Planétologie et d'Astrophysique de Grenoble (IPAG)

IPAG:

Institut de Planétologie et d'Astrophysique de Grenoble

Université Joseph Fourier GRENOBLE

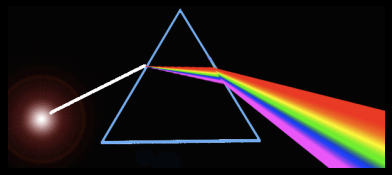
cnrs advancing the frontiers

Financement:

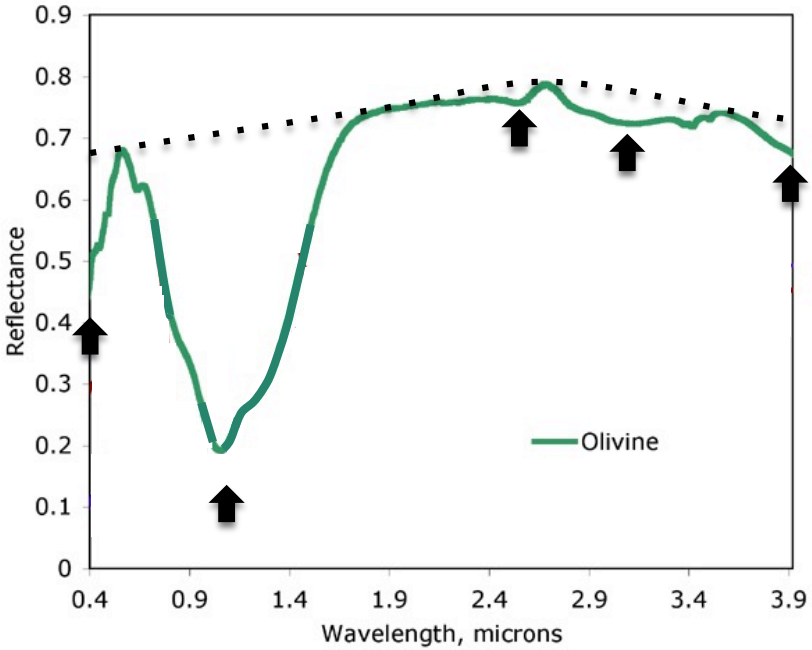
Agence Nationale de la Recherche ANR

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

Imaging spectroscopy



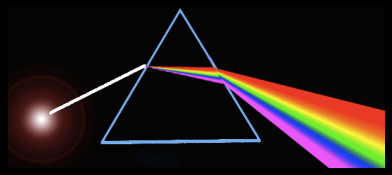
- Observing Mars with…
  - Imaging spectrometers
- Reflectance (emission) Spectroscopy
- Spectral range: visible, near-infrared, and short-wave infrared



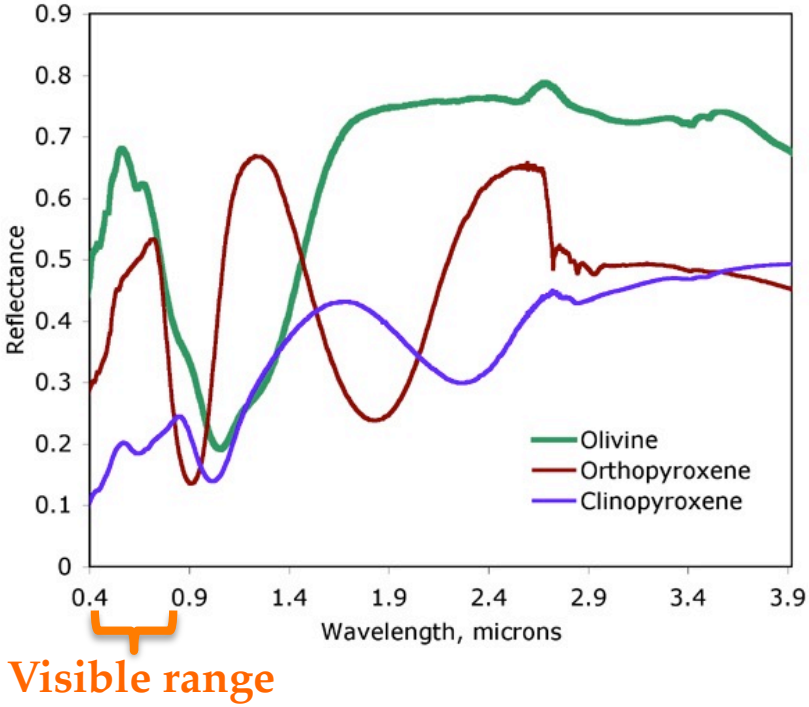
. . . . : spectrum continuum

⬆ : absorption band

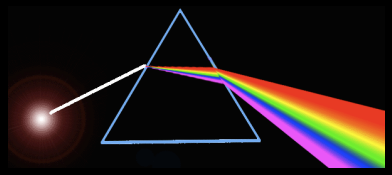
Imaging spectroscopy



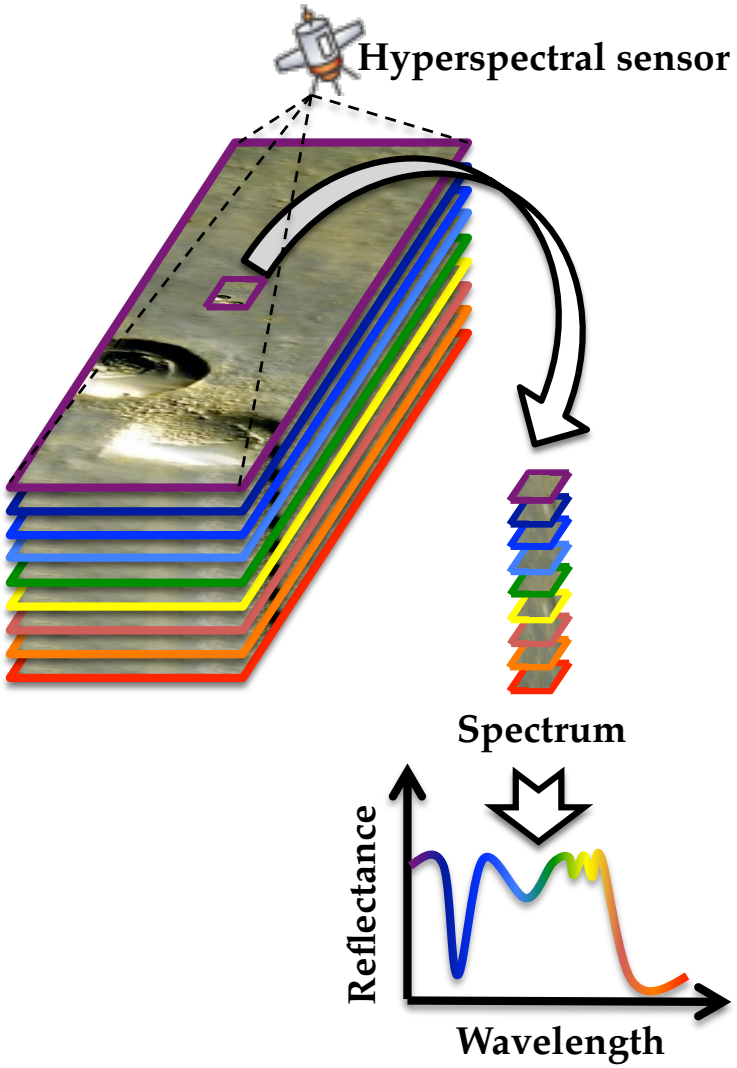
- Observing Mars with…
  - Imaging spectrometers
- Reflectance (emission) Spectroscopy
- Spectral range: visible, near-infrared, and short-wave infrared
- Mineralogical discrimination



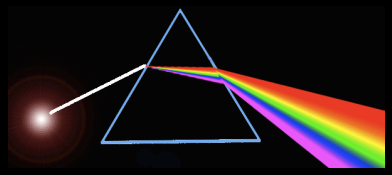
Imaging spectroscopy



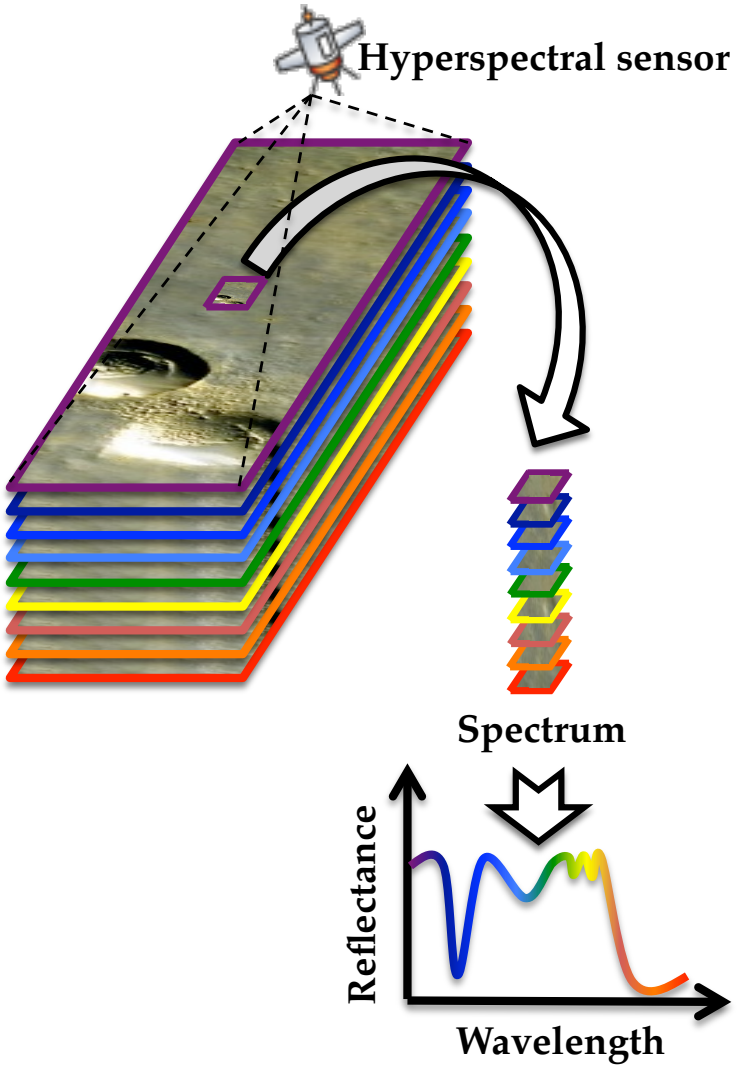
- Key remote sensing technique
  - Goal: Detect, characterize, and map mineralogical units on planetary surfaces
  - Around Mars: ISM/Phobos 2, 1988 … OMEGA/MEX 2003; CRISM/MRO, 2005



Imaging spectroscopy



- Key remote sensing technique
  - Goal: Detect, characterize, and map mineralogical units on planetary surfaces
  - Around Mars: ISM/Phobos 2, 1988 … OMEGA/MEX 2003; CRISM/MRO, 2005
- Challenges
  - Hundred thousands spectra!
  - Spectrum -> atmosphere, surface, several mineralogical units, …

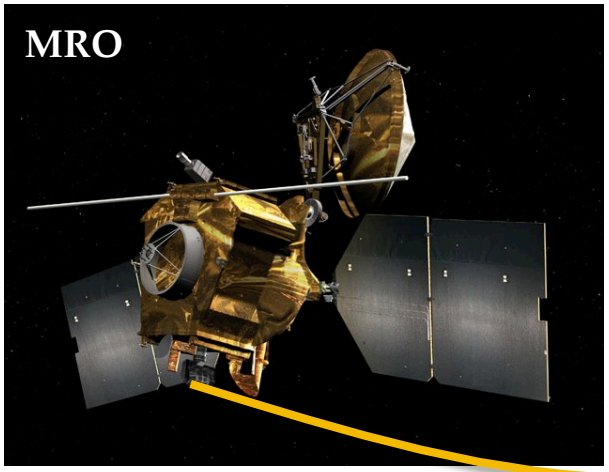


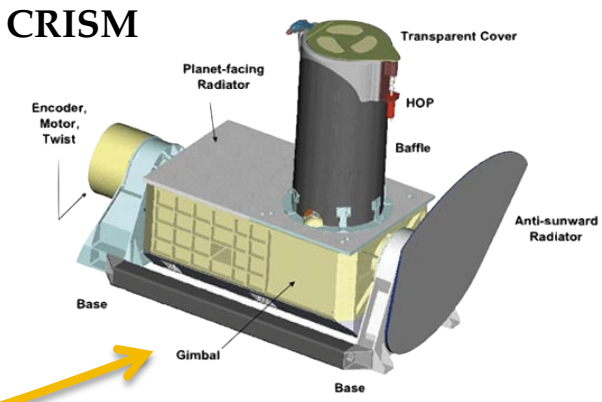
CRISM essentials

- Compact Reconnaissance Imaging Spectrometer for Mars[1]
  - Mars Reconnaissance Orbiter (MRO), Aug. 2005, NASA/JPL

Attribute	CRISM/MRO
Spectral range	0.36-3.92 µm
Spectral sampling	6.5 nm (544 bands)
Spectral resolution	FWHM = 8-15 nm
Spatial resolution	> 18 m/pixel

Two separated channels: VNIR and IR





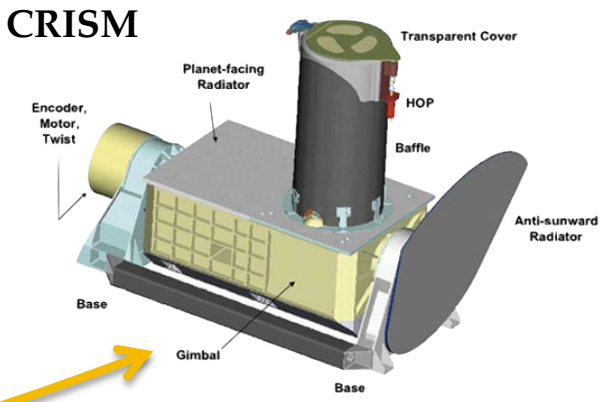
[Murchie et al. 2007]

CRISM essentials

- Compact Reconnaissance Imaging Spectrometer for Mars[1]
  - Mars Reconnaissance Orbiter (MRO), Aug. 2005, NASA/JPL

Attribute	CRISM/MRO	OMEGA/MEX
Spectral range	0.36-3.92 µm	0.38-5.10 µm
Spectral sampling	6.5 nm (544 bands)	13.4 nm (352 bands)
Spectral resolution	FWHM = 8-15 nm	FWHM = 7-20 nm
Spatial resolution	> 18 m/pixel	> 350 m/pixel

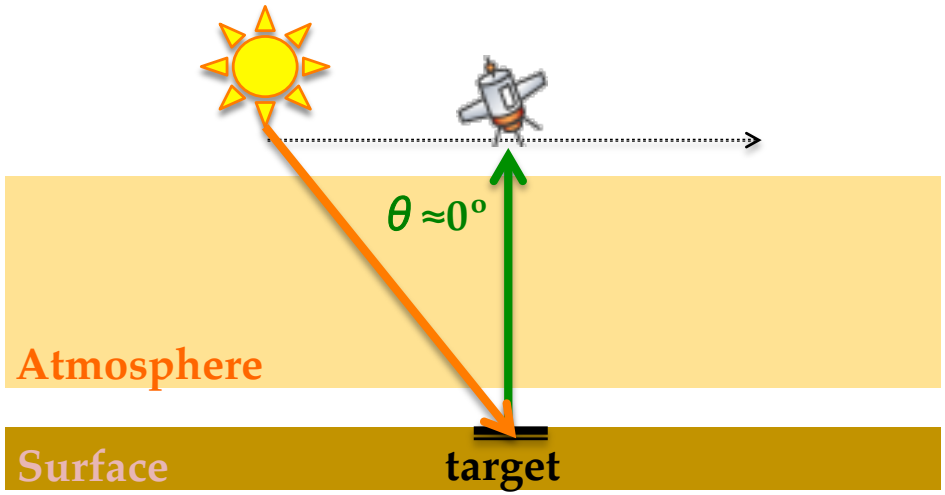




[Murchie et al. 2007]

CRISM essentials

- Compact Reconnaissance Imaging Spectrometer for Mars[1]
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  - Targeted mode
    - Multi-angle observations:
      - 1 x quasi-nadir scan at 18 m/pix



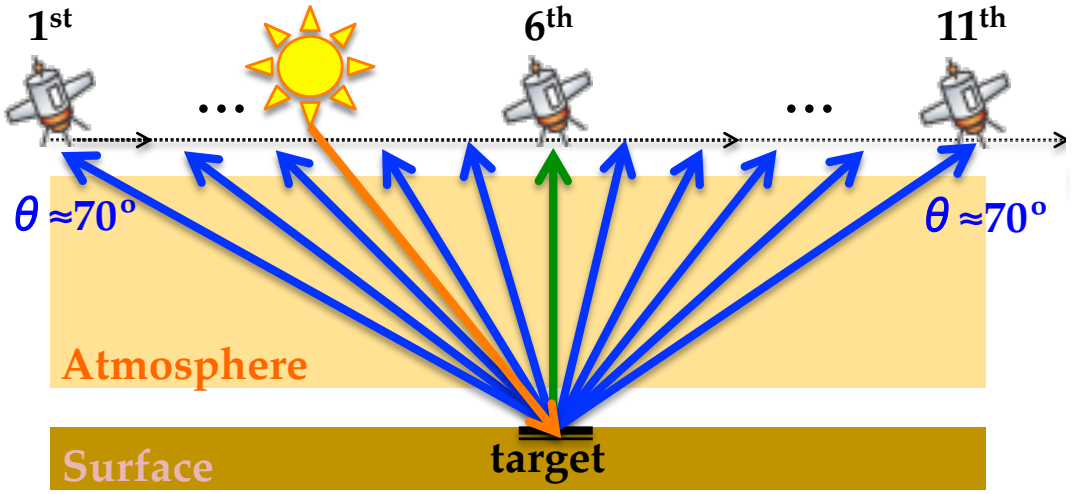


Superposition of the eleven footprints of a CRISM observation

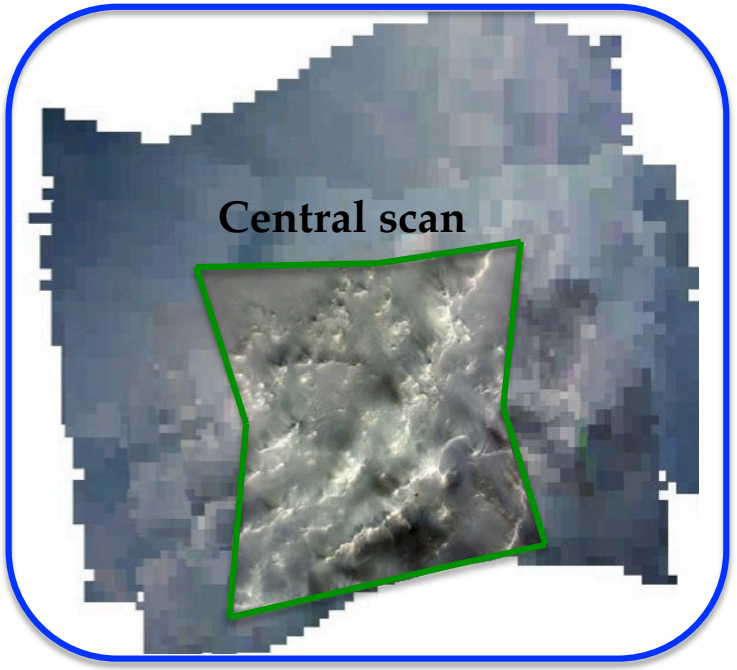
[1][Murchie et al. 2007]

CRISM essentials

- Compact Reconnaissance Imaging Spectrometer for Mars[1]
  - Mars Reconnaissance Orbiter (MRO), Aug. 2005, NASA/JPL
  - Targeted mode
    - Multi-angle observations:
      - 1 x quasi-nadir scan at 18 m/pix
      - 10 x off-nadir scans at 180 m/pix



Emission Phase Function (EPF)



Superposition of the eleven footprints of a CRISM observation

[1][Murchie et al. 2007]

Methodological objectives

- Image restoration
- Separating the atmospheric and surface contributions
- Constraining surface photometric properties
- Detecting components
- Mapping component abundances as well as the granularity, porosity and thickness of the materials
- Feature extraction and indexing

Outline

- Background

① Post-processing CRISM data

② Unsupervised spectral unmixing

③ Physical analysis by RT model inversion

④ Future prospects

Outline

- Background

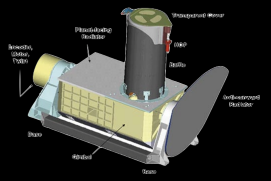
① Post-processing CRISM data
  - Correction for spectral smile

② Unsupervised spectral unmixing

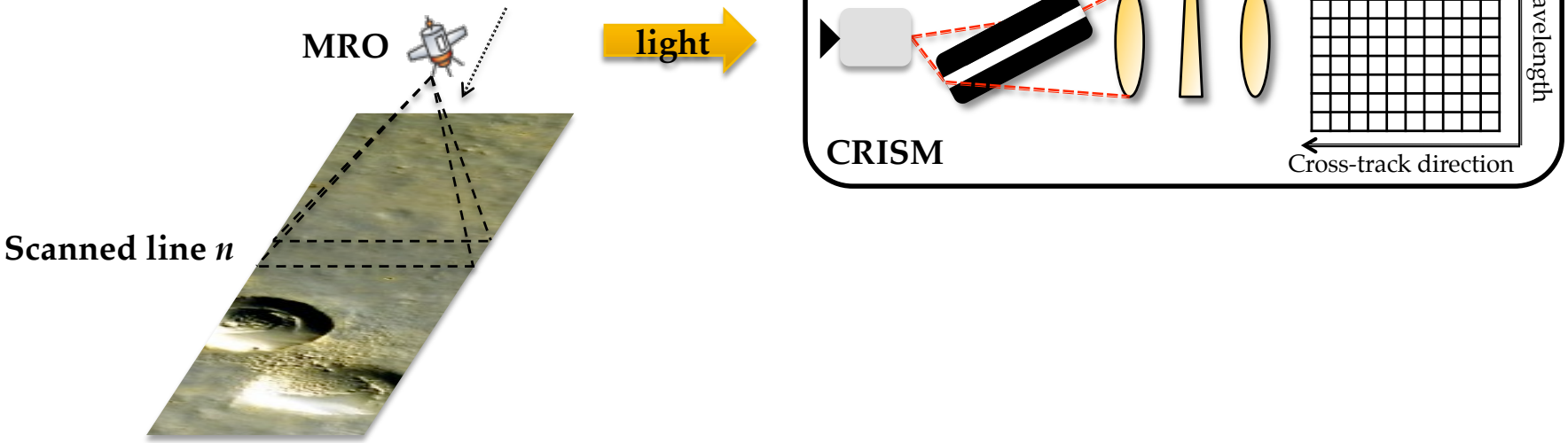
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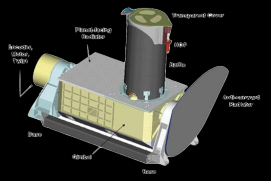
CRISM functioning



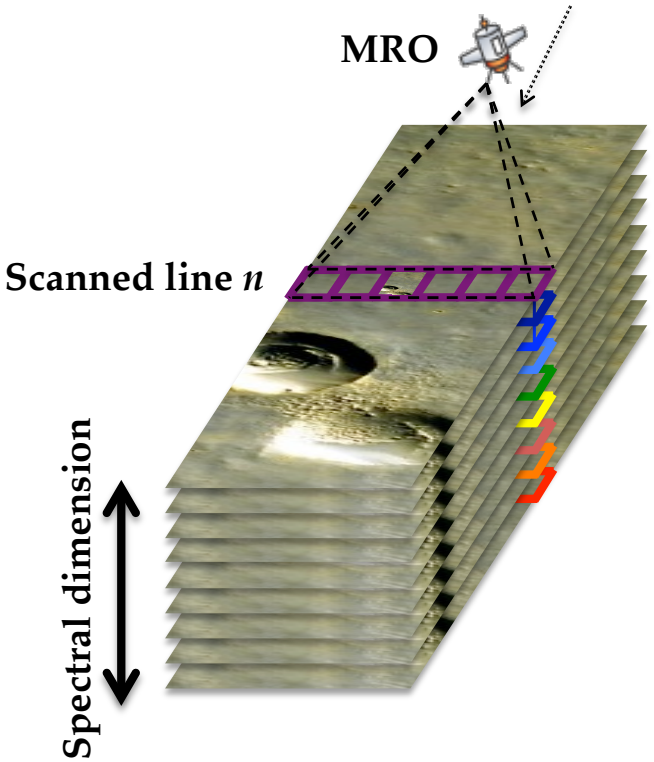
- Acquisition of hyperspectral images by CRISM
  - Push broom scanner

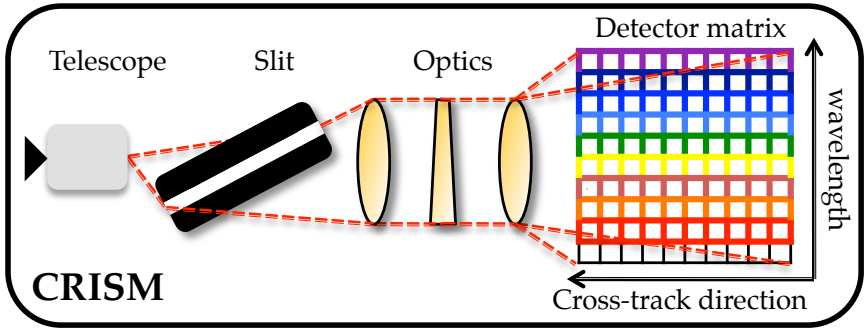


CRISM functioning

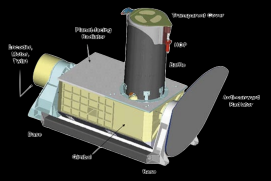


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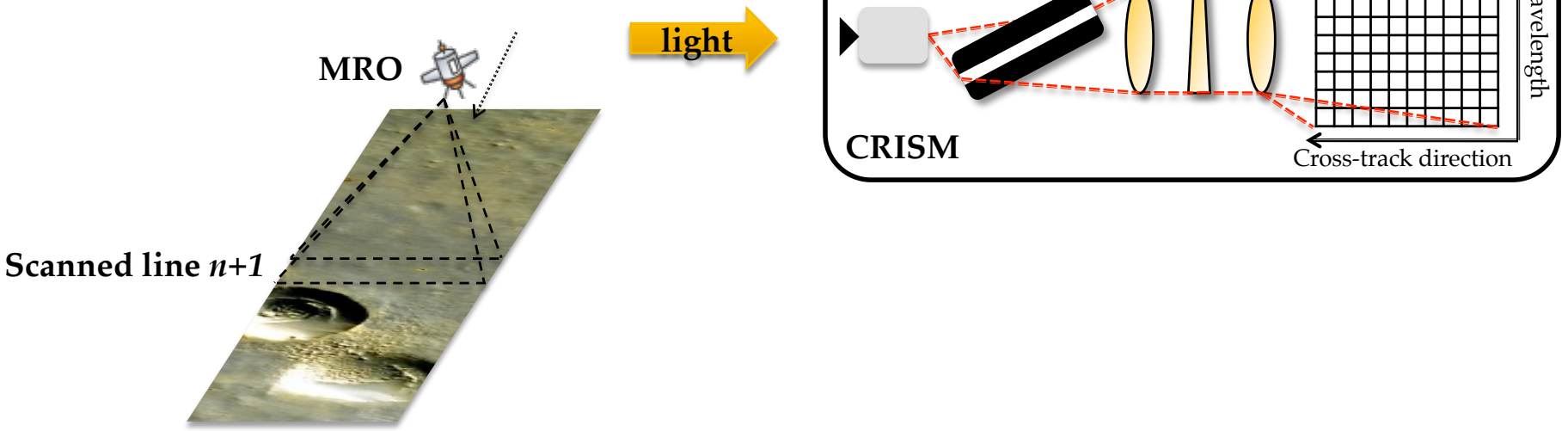




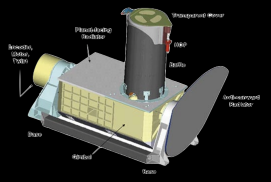
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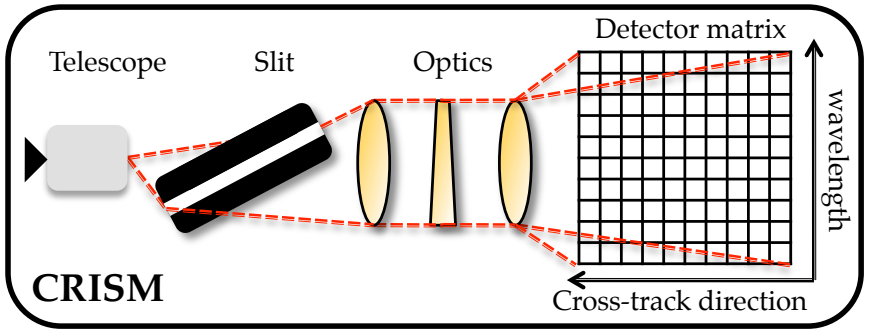
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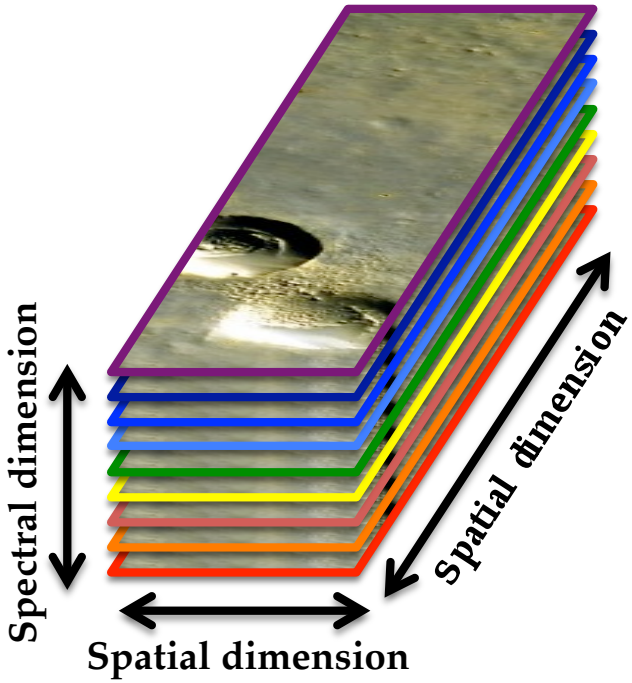


CRISM functioning



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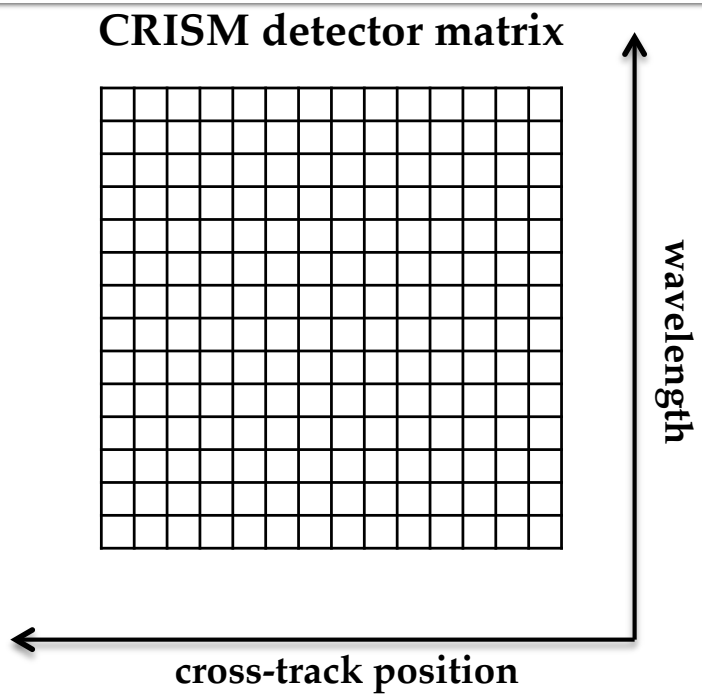
Pros: high SNR and resolution

Cons: Non-uniformities among the elements of the detector matrix

Spectral smile

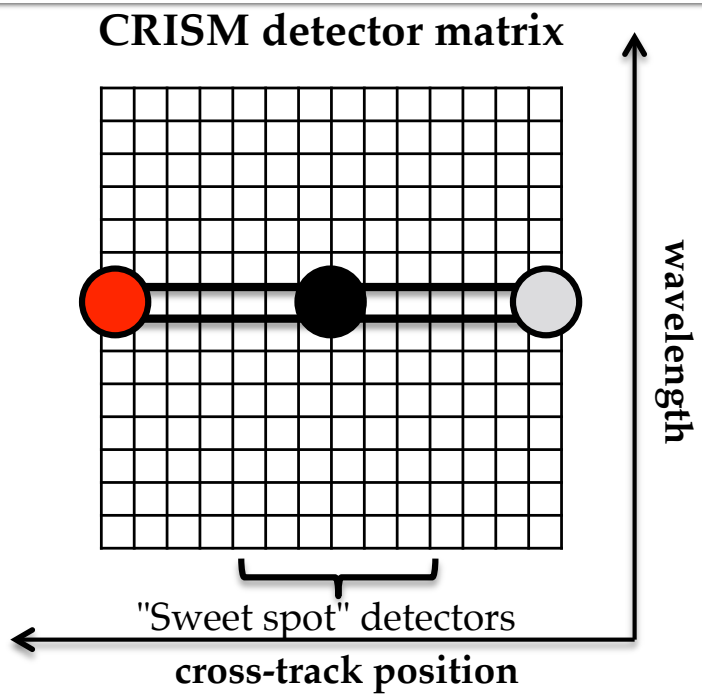


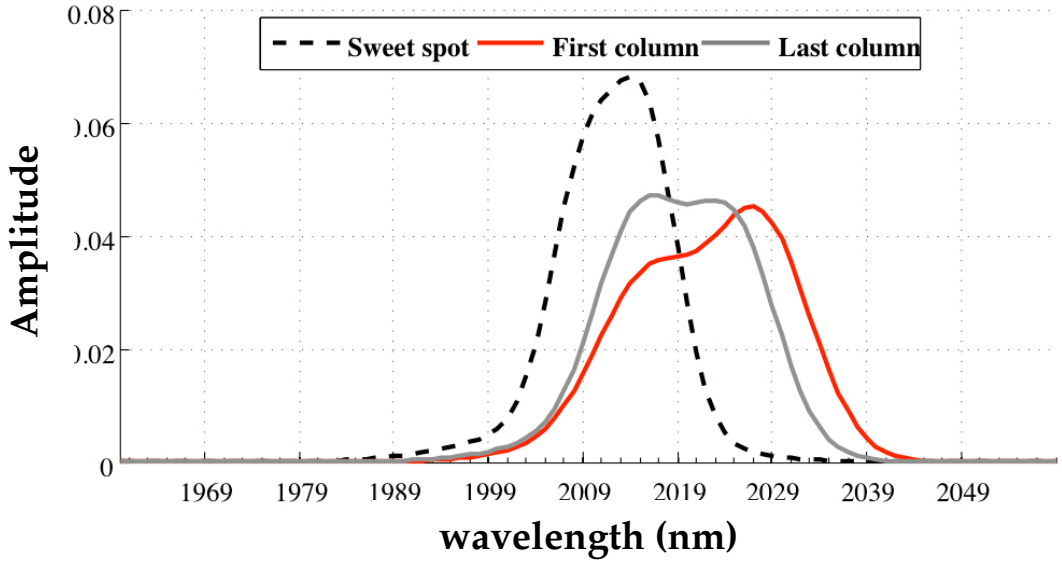
- Due to optical aberrations…
  - Non-uniform spectral response along the number of column



Spectral smile

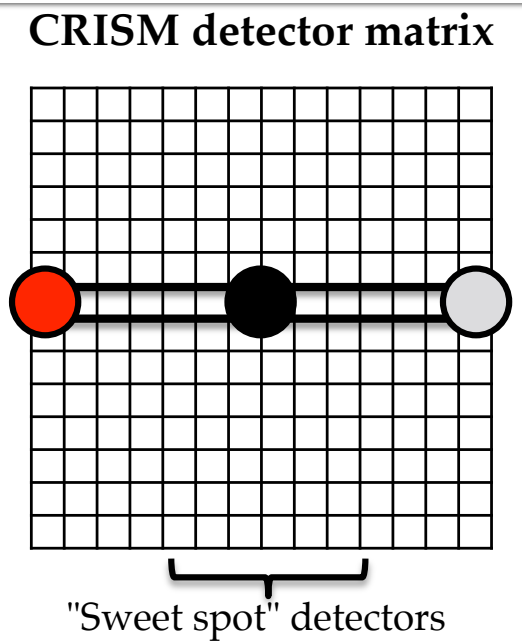
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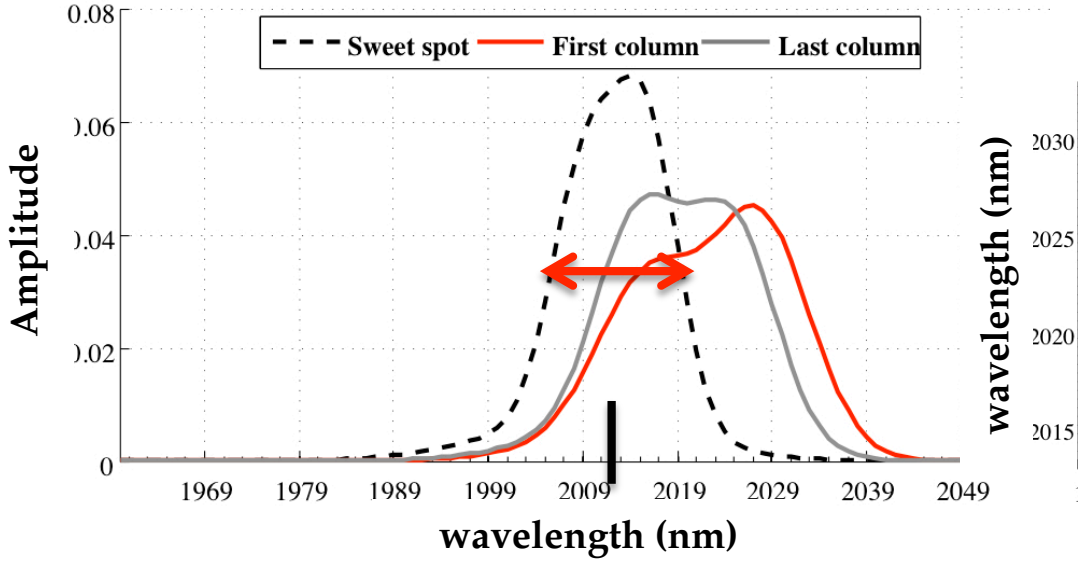


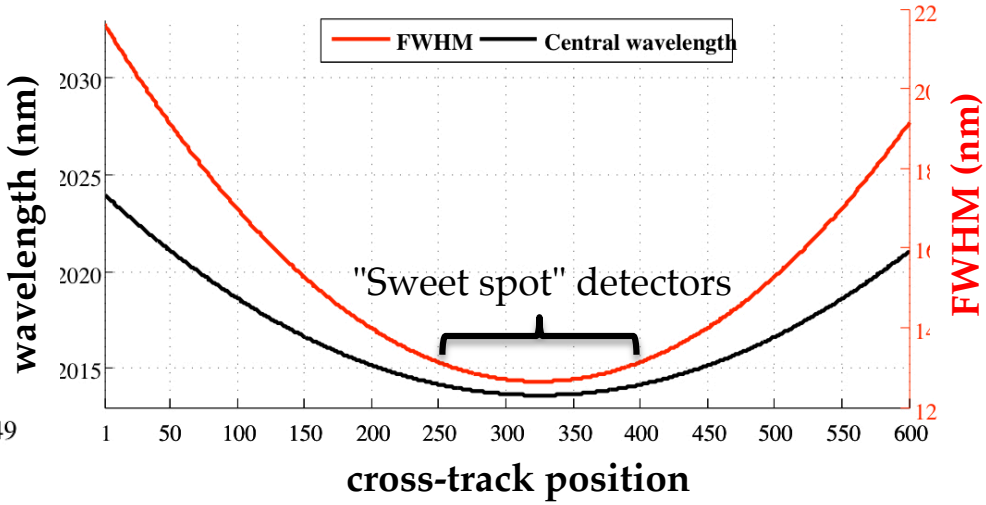


Spectral smile

- Due to optical aberrations…
  - Non-uniform spectral response along the number of column
  - **Central wavelength** and **spectral width** are degraded for extreme columns





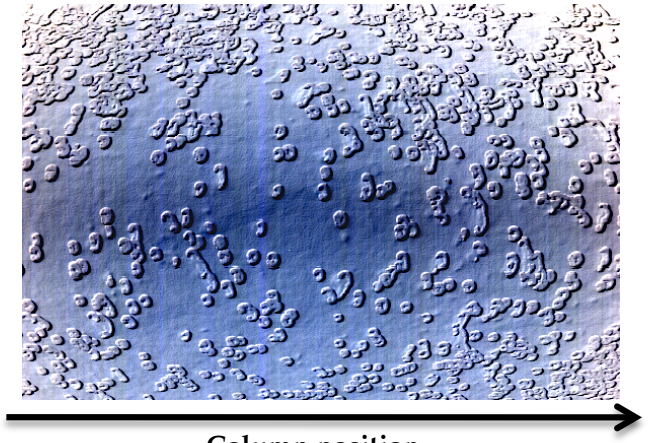


Spectral smile



- Impact on CRISM data: spatial and spectral distortions

Central scan FRT5AE3:

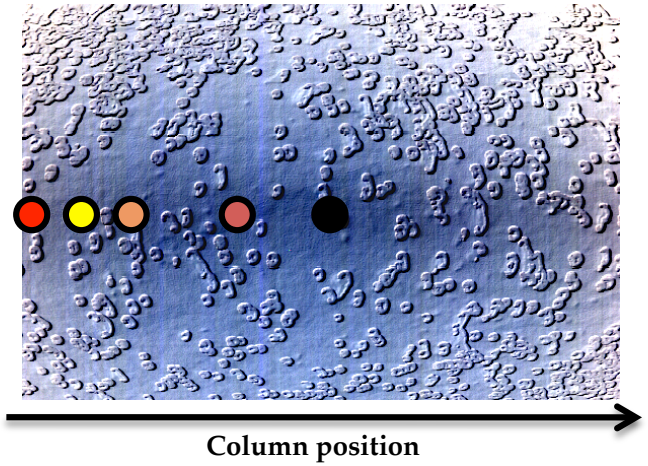


Spectral smile

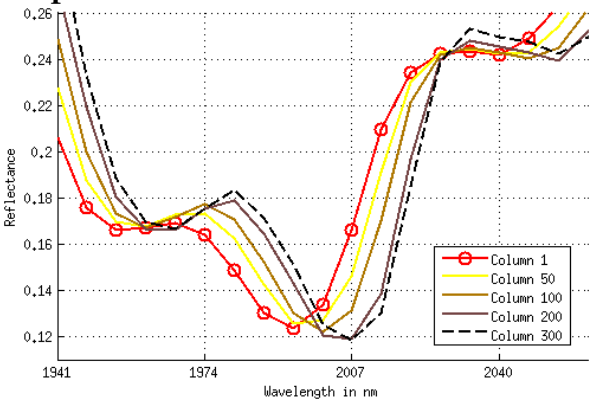


- Impact on CRISM data: spatial and spectral distortions

Central scan FRT5AE3:



Spectra (1940 – 2070 nm):



Absorption bands related to CO_2 gas and CO_2 ice

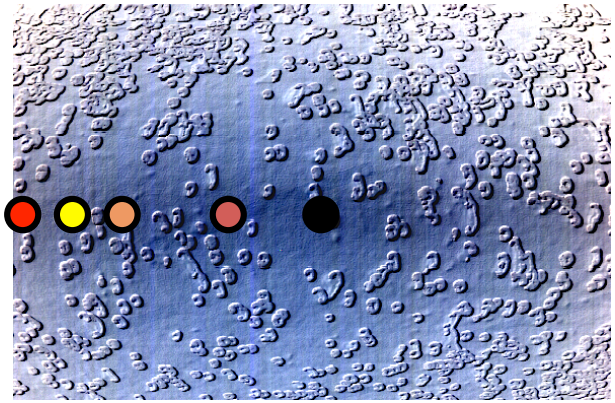
- **Spectral:** absorption bands are shifted and smoothed

Spectral smile



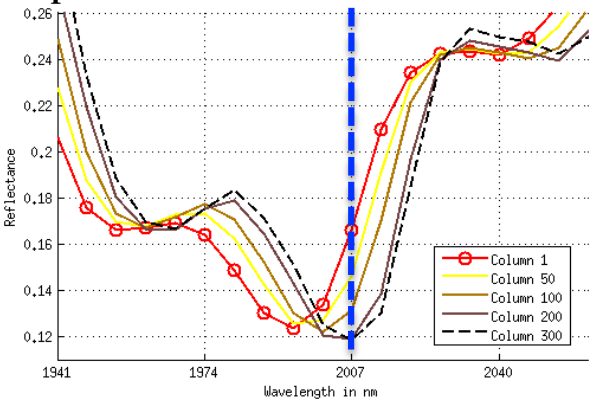
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Central scan FRT5AE3:



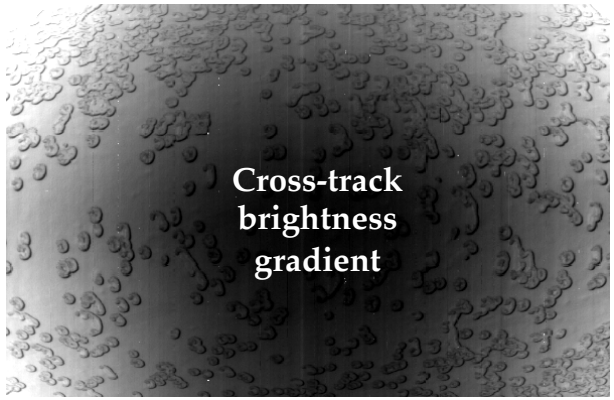
Column position

Spectra (1940 – 2070 nm):



Absorption bands related to CO_2 gas and CO_2 ice

Band IR 155 (≈2007 nm):



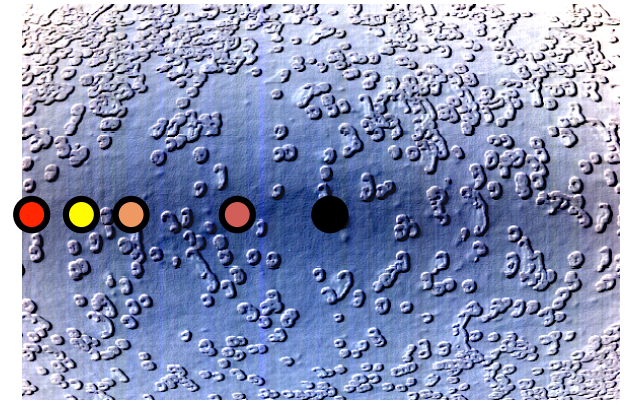
Column position

- **Spectral:** absorption bands are shifted and smoothed
- **Spatial:** cross-track gradient depending on sensed spectra

Spectral smile

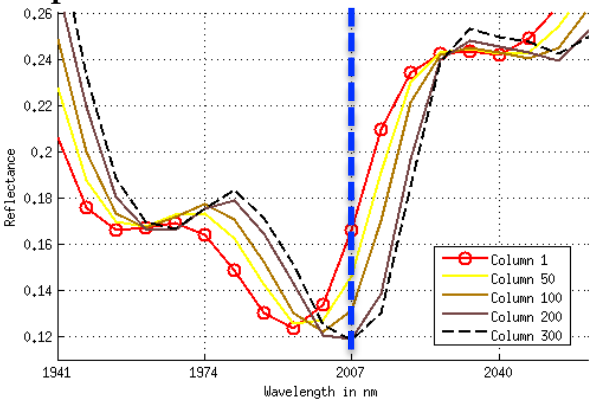
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Central scan FRT5AE3:



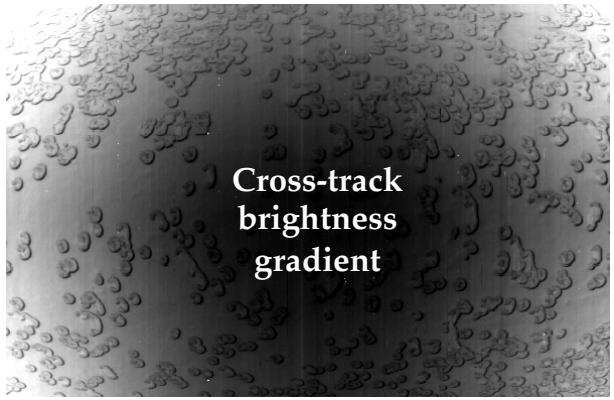
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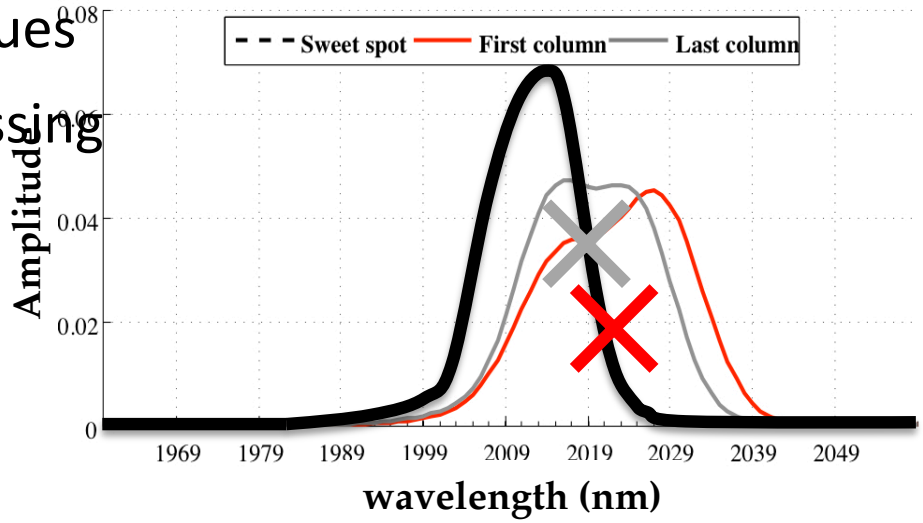
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Analysis of CRISM data becomes challenging!

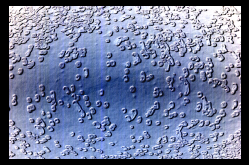
Desmiling method



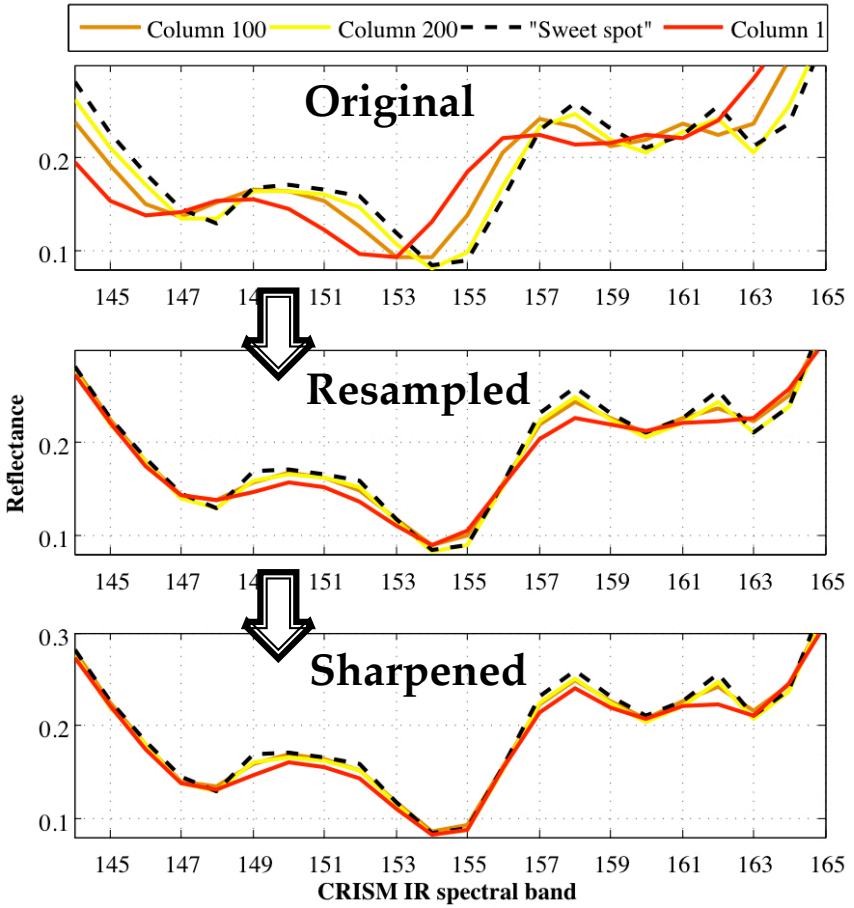
- hybrid and based on the instrumental attributes originating the spectral smile and the spectral properties of the materials at the surface
  - **Goal:** normalizing the spectral response of CRISM to its best attributes
- Correction for spectral smile
  - Robust desmiling technique driven by instrumental attributes
  - Appropriate for other pushbroom-type sensors
  - **Cons**: sensitive to calibration issues
  - **Pros**: key for further data processing



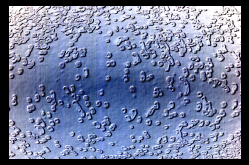
Experiments



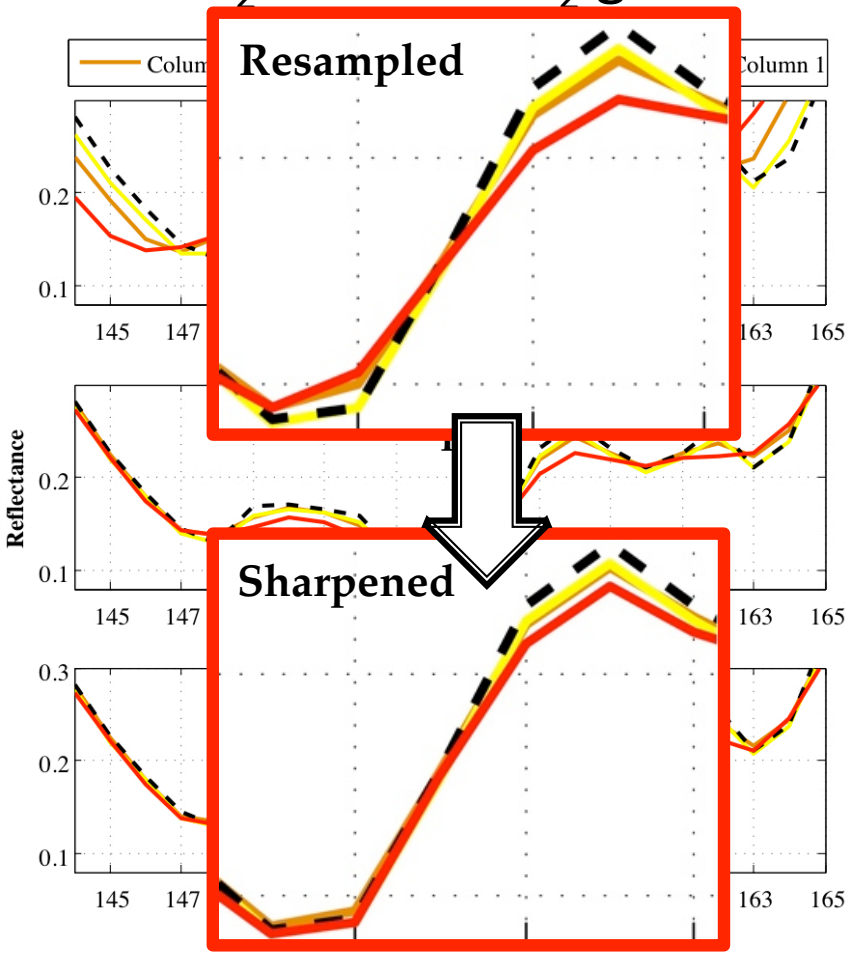
- Application to central scan of FRT5AE3
  - South polar cap: steep spectra due to CO_2 ice and CO_2 gas
- Benefits of desmiling method
  - Minimal shift and smoothness



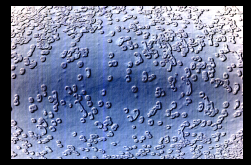
Experiments



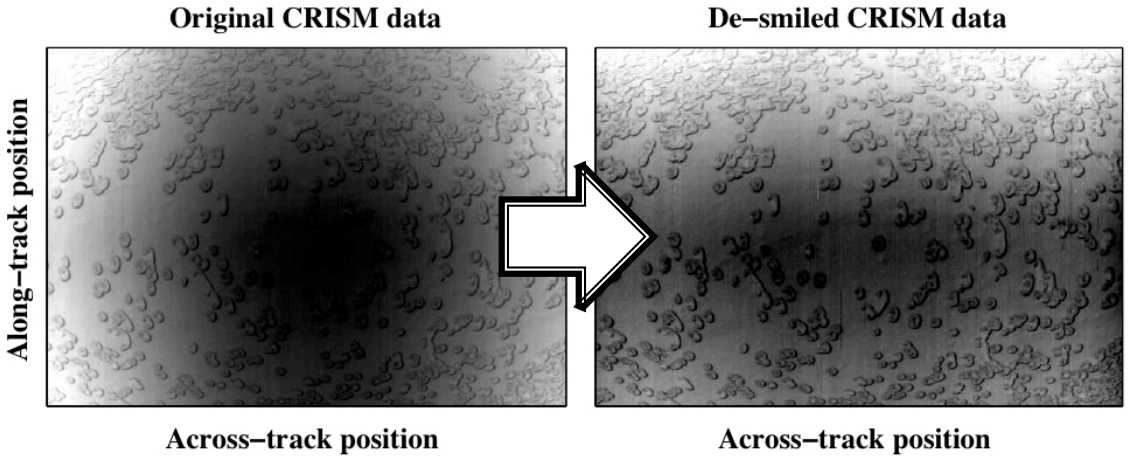
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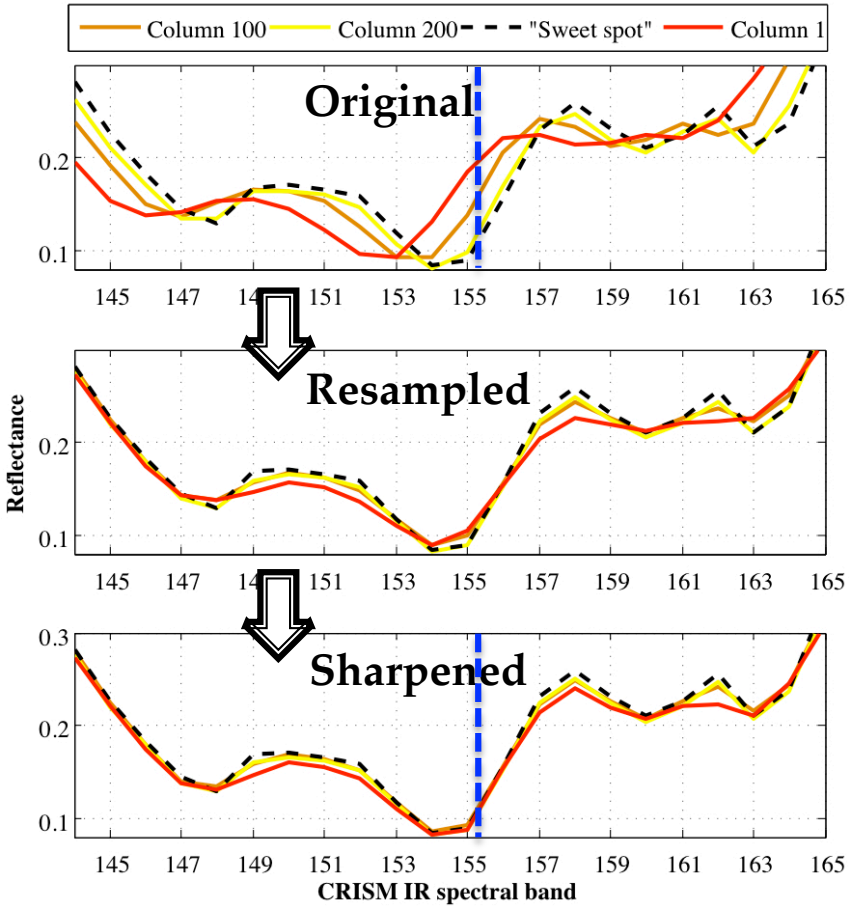


Experiments



- Application to central scan of FRT5AE3
  - South polar cap: steep spectra due to CO_2 ice and CO_2 gas
- Benefits of desmiling method
  - Minimal shift and smoothness
  - Greatly reduced spatial artifact





Outline

- Background

① Post-processing CRISM data

② Unsupervised spectral unmixing

③ Physical analysis by RT model inversion

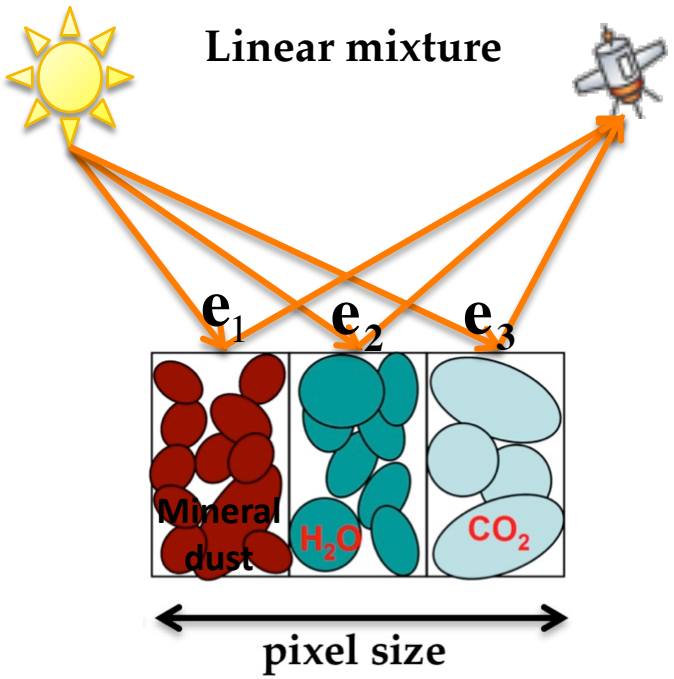
④ Future prospects

The standard linear mixture model

- Due to limited spatial resolution, light reflected by different materials is linearly integrated by the sensor inside a given pixel

- **Linear** unmixing: $\mathbf{X} = \mathbf{E} \cdot \mathbf{P} + \mathbf{e}$
  - $\mathbf{X}$: hyperspectral cube
  - $\mathbf{E}$: mixing matrix
  - $\mathbf{P}$: source matrix
  - $\mathbf{e}$: additive noise

$$\mathbf{x}_j = \sum_{k=1}^{M} p_{jk} \mathbf{e}_k + \varepsilon_j$$



- 3 main steps:
  1. Estimation of the number M of endmembers
  2. Endmember extraction $\mathbf{E}$
  3. Linear unmixing of the image to obtain $\mathbf{P}$: least square error estimation subjected to

$$\hat{P} = \arg\min_{P} \|X - EP\|^2 \qquad \sum_{k=1}^{M} p_{kj} = 1, \forall j$$

$$s.t.\ P \geq 0$$

Methods

1- Estimation of the number of endmembers

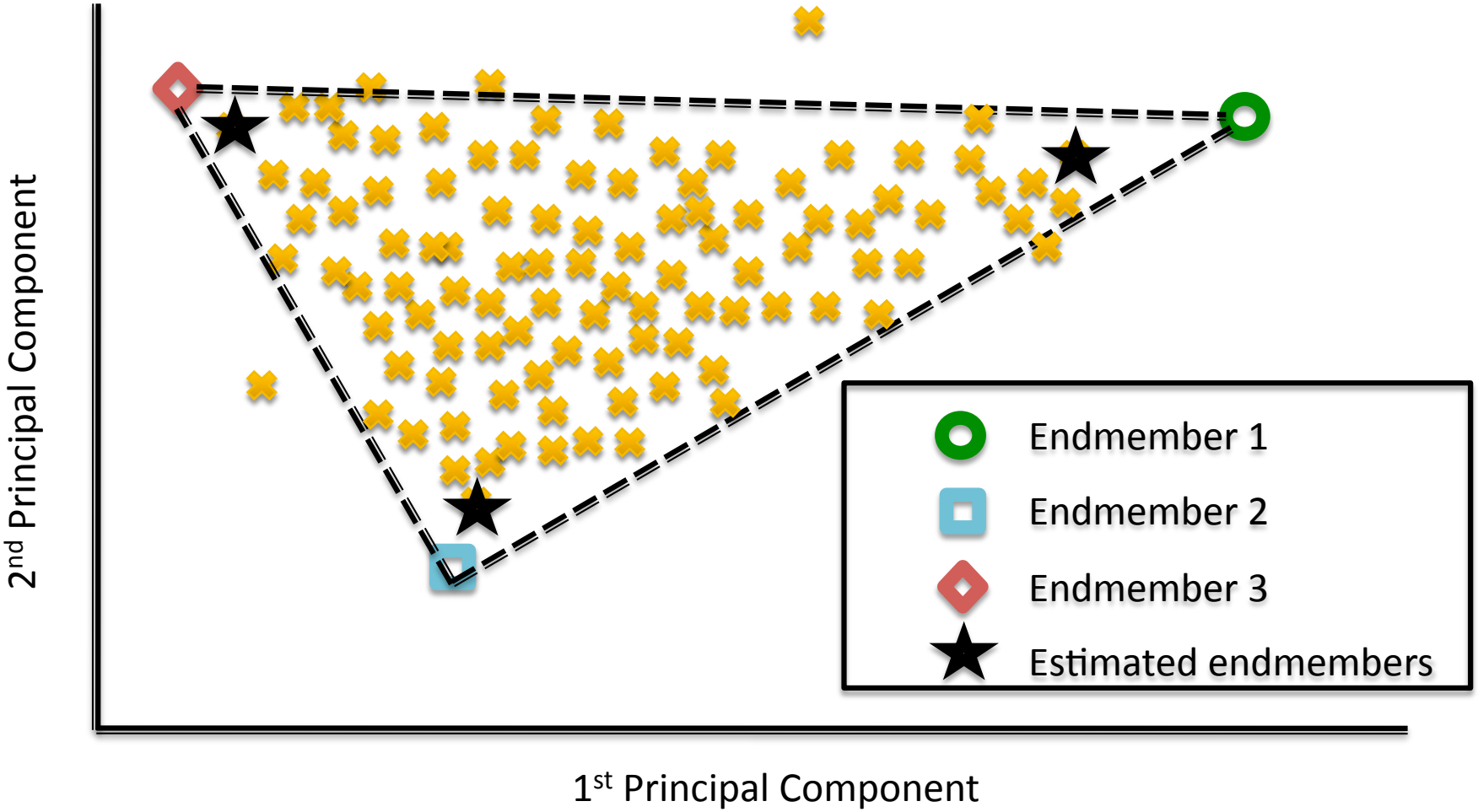
- **ELM [*Luo'11*]:** based on eigenvalues of the corr. and cov. matrices

2 - Endmember extraction

	VCA [*Nascimento'05*]	MVC-NMF [*Miao'07*]	*spatial*-VCA [*Zortea'09*]	BPSS [*Moussaoui'06*]
First principles:	Geometric method with pure pixel assumption	Minimum volume constraint	Incorporation of spatial information	Statistical approach
Advantages:	- Fast & efficient - Endmembers are physical	- Highly mixed scenes	- endmembers: objects	- Bayesian framework - intrinsic variability
Drawbacks:	- Impact of noise - Highly mixed scenes	- Risk of non-physical spectra	- Spatially-confined and less-prevalent endmembers	- Non-physical spectra - High computational time

Geometric method

- Pure pixel assumption



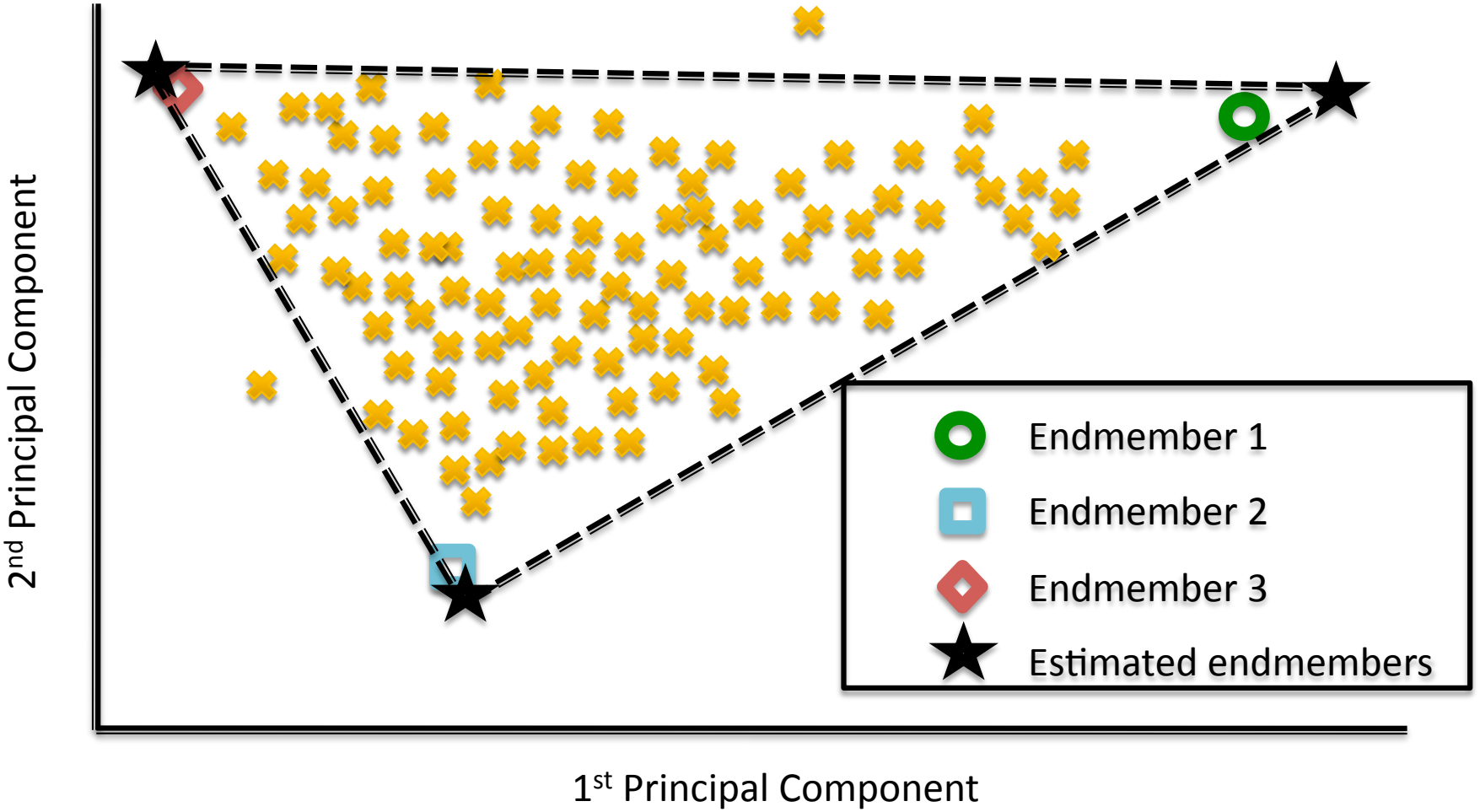
Methods

2 - Endmember extraction

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Geometric method

- Minimum volume constraint



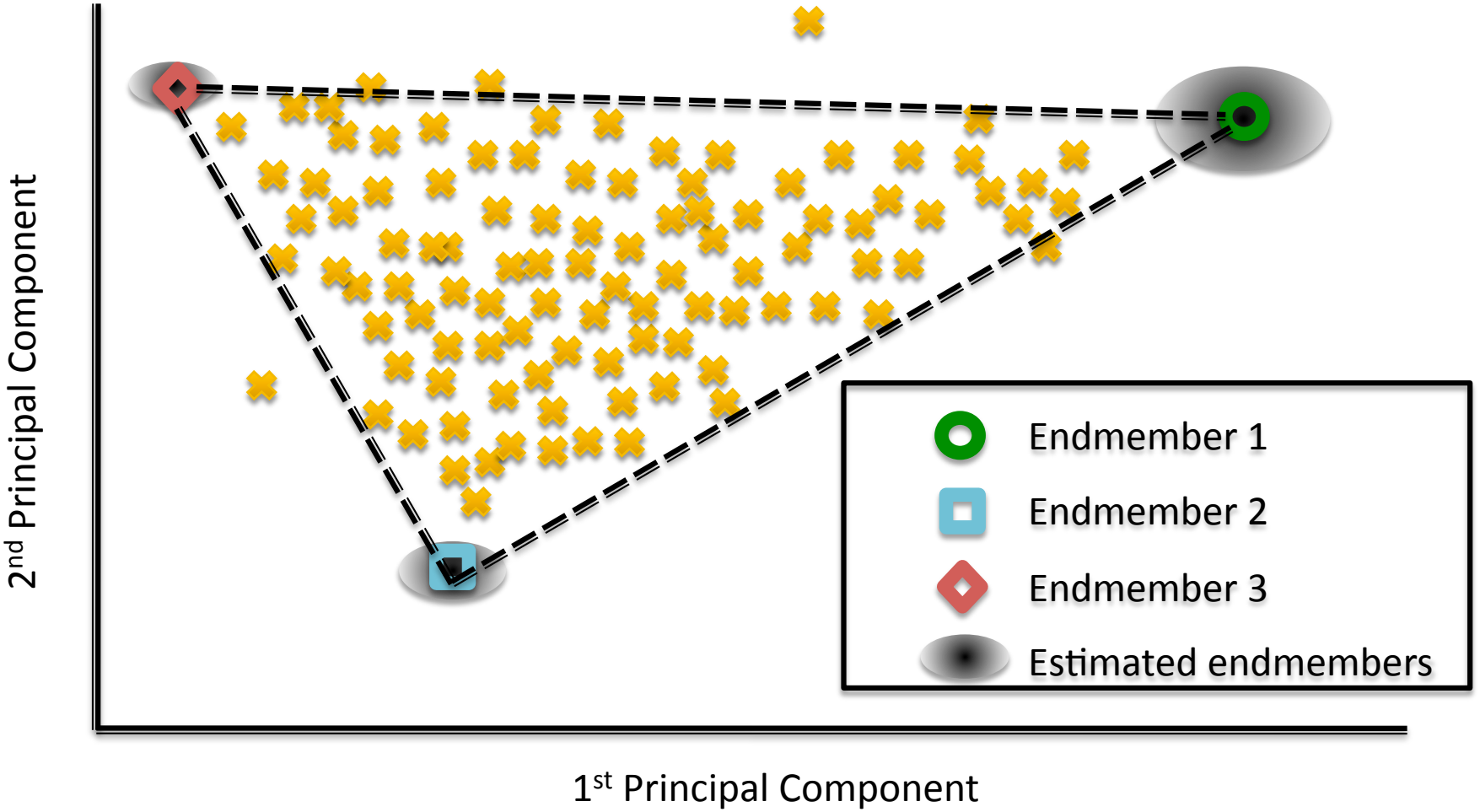
Methods

2 - Endmember extraction

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Statistical method

- Endmembers : probability distrib. functions



Methods

2 - Endmember extraction

	VCA [*Nascimento'05*]	MVC-NMF [*Miao'07*]	*spatial*-VCA [*Zortea'09*]	BPSS [*Moussaoui'06*]
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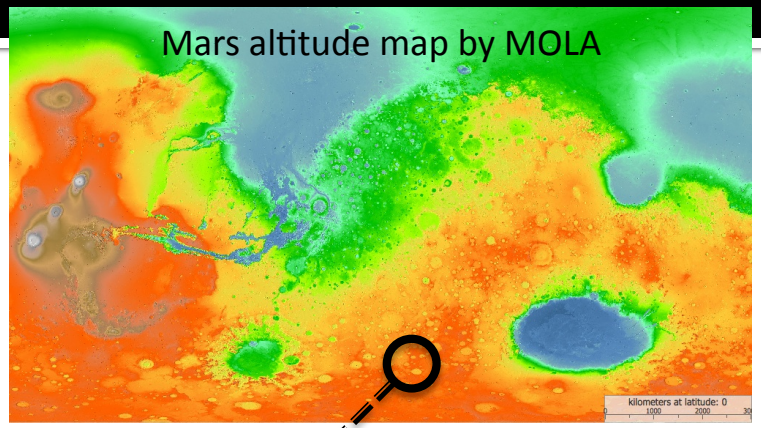
Science case: **description of the area**

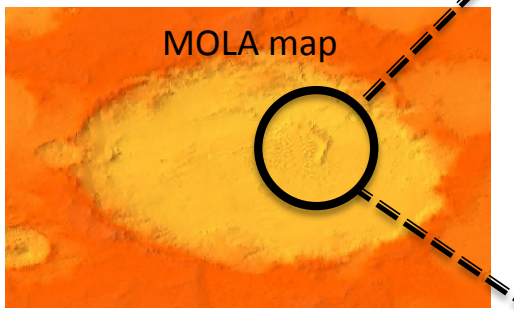
RUSSELL CRATER

- 54.6°S; 12.4°E
- 134 km diameter

DUST MEGADUNE

- NE boundary
- 1704 km^2
- 500 m high, 20 x 40 km.
- **SW-facing scarp**

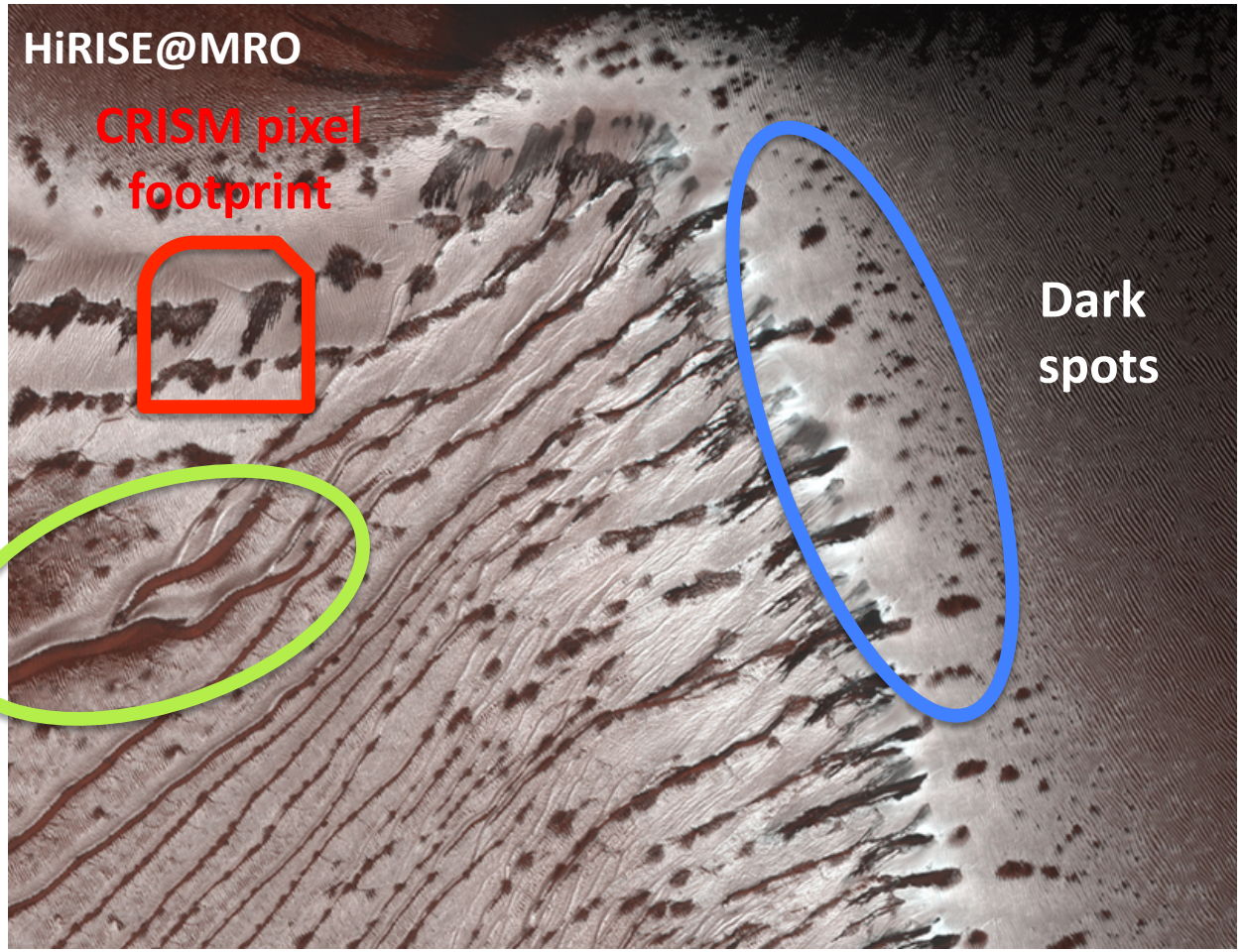






Science case: **description of the area**

DEFROSTING FEATURES DURING LATE WINTER



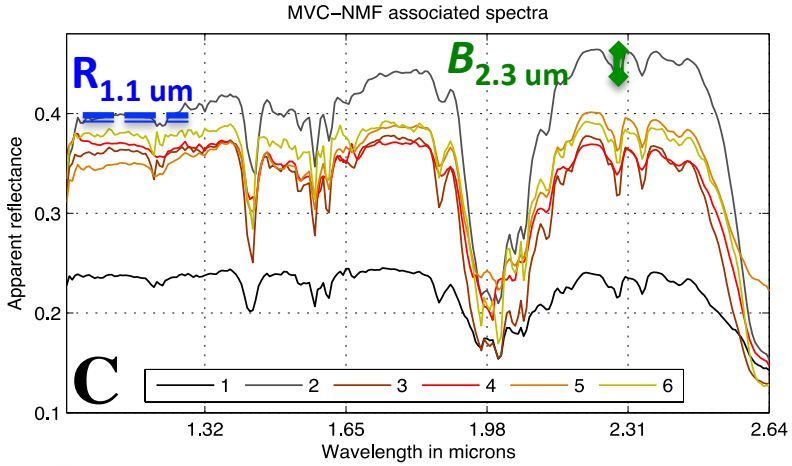
POTENTIAL LINEAR MIXTURES OF ICE AND DUST!

PRIOR STEP TO COMPLETE DEFROSTING

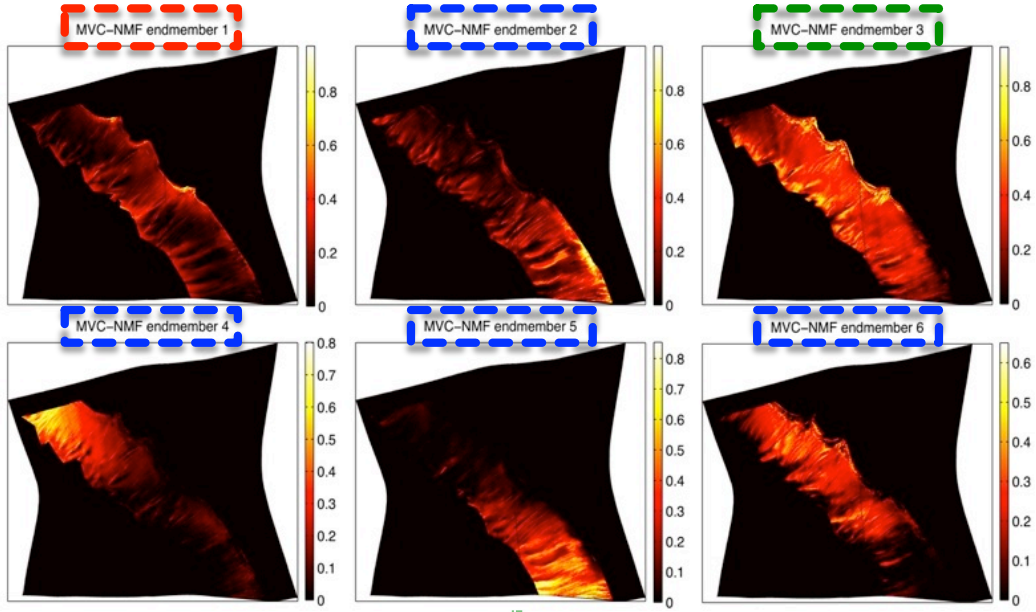
Experiments

- **Recombination process for MVC-NMF**

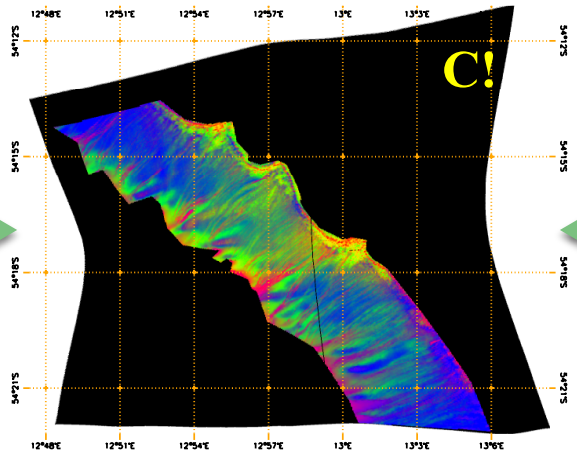
Spectral product: spectral signatures



Spatial product: abundance maps



Dark
Strong bright
Weak bright

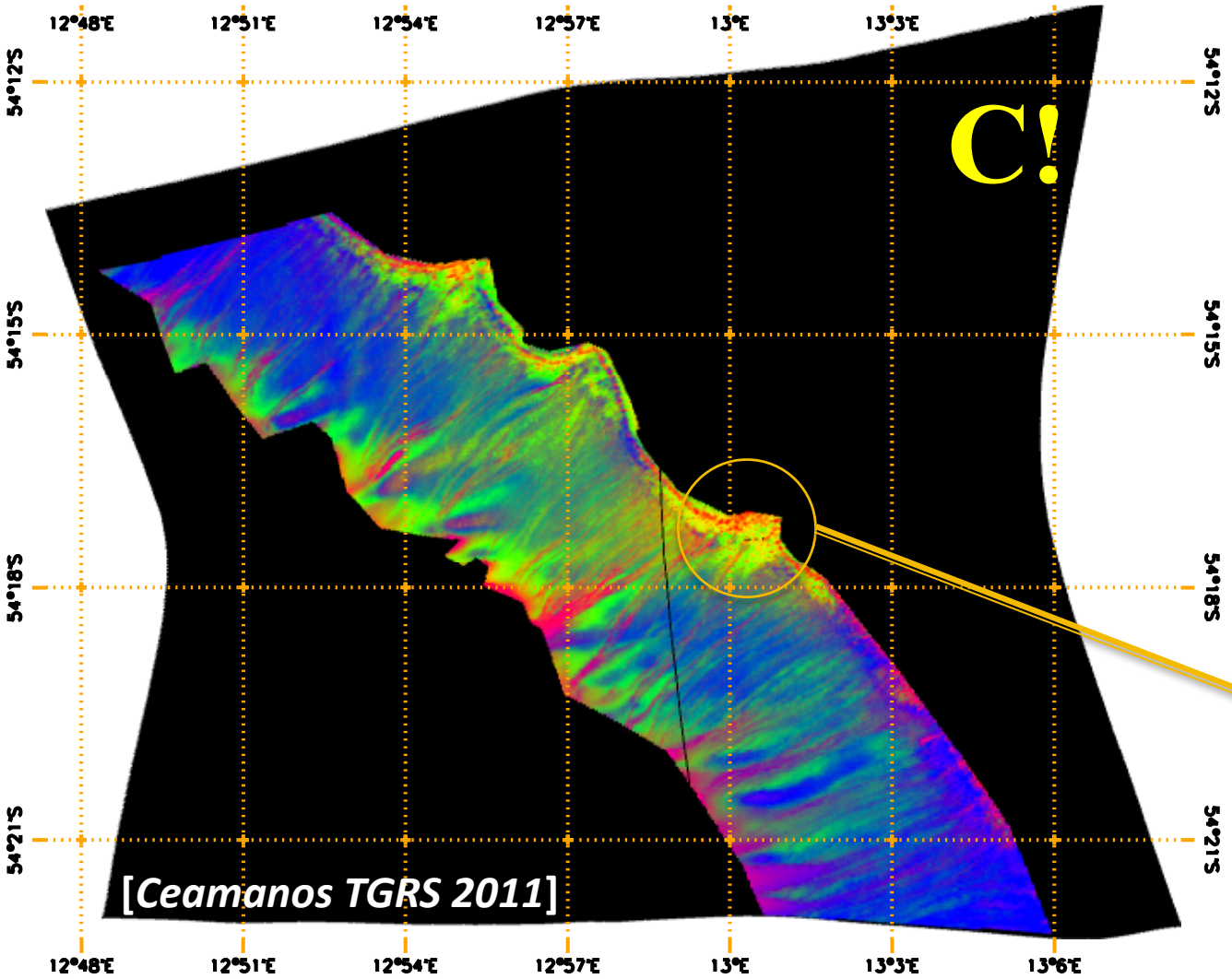


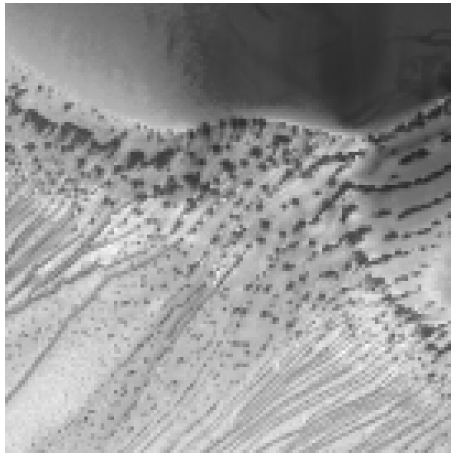
Final product: composite abundance map!

Experiments

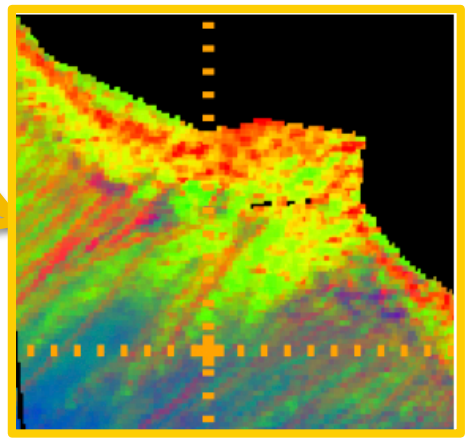
- **MVC-NMF:** abundance composite map

Sources: Dark, strong bright, weak bright





HiRISE image

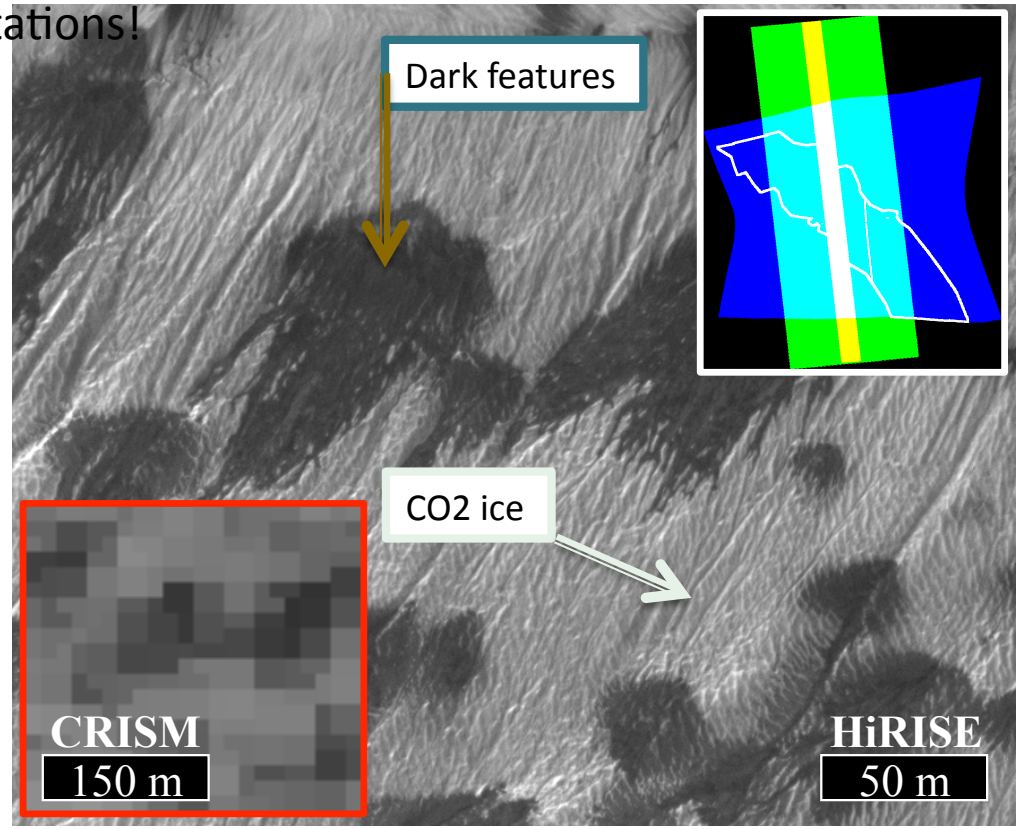


MVC-NMF composite map

Validation: **Ground truth**

- **Unmixing results** : abundance maps of physical sources
- **How can we perform the validation of the method**
  1. ~~Ground truth~~ **=>** very scarce on Mars!
  2. ~~Synthetic data~~ **=>** model limitations!
  3. Other type of imagery

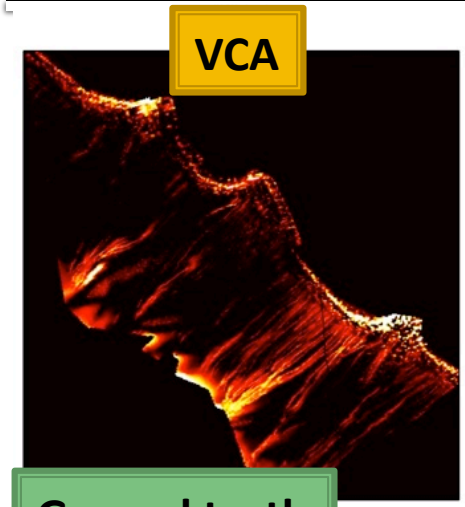
Detail of the Russell dune observed by the CRISM and the HiRISE instruments.

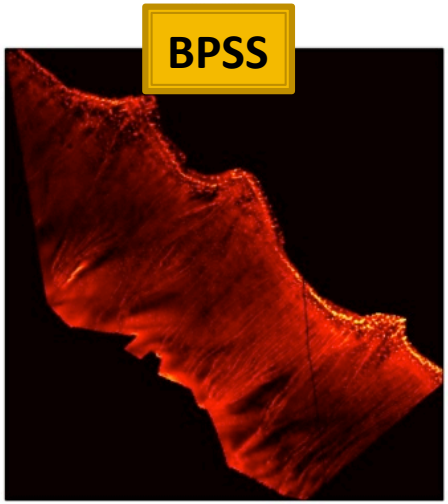


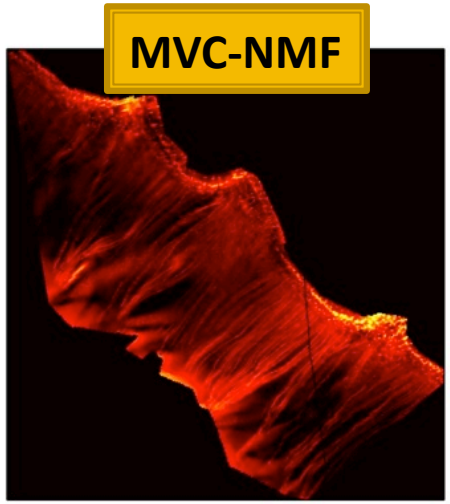
HIRISE

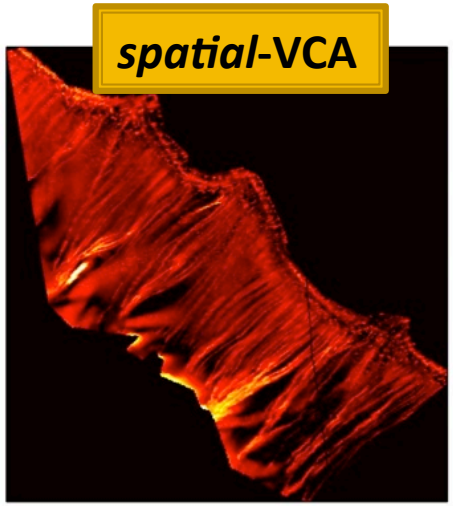
- Red band: 550-850 nm; 0.3 m/ pix
  green footprint
- **Coordinated with CRISM!**
  blue footprint

Validation



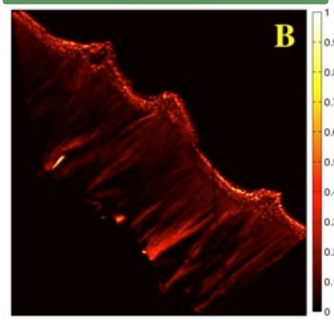


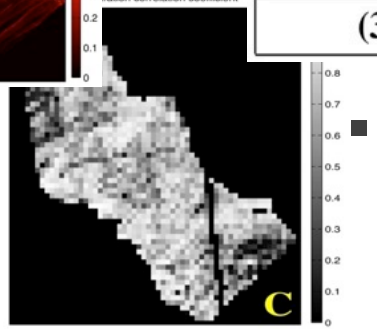






Ground truth





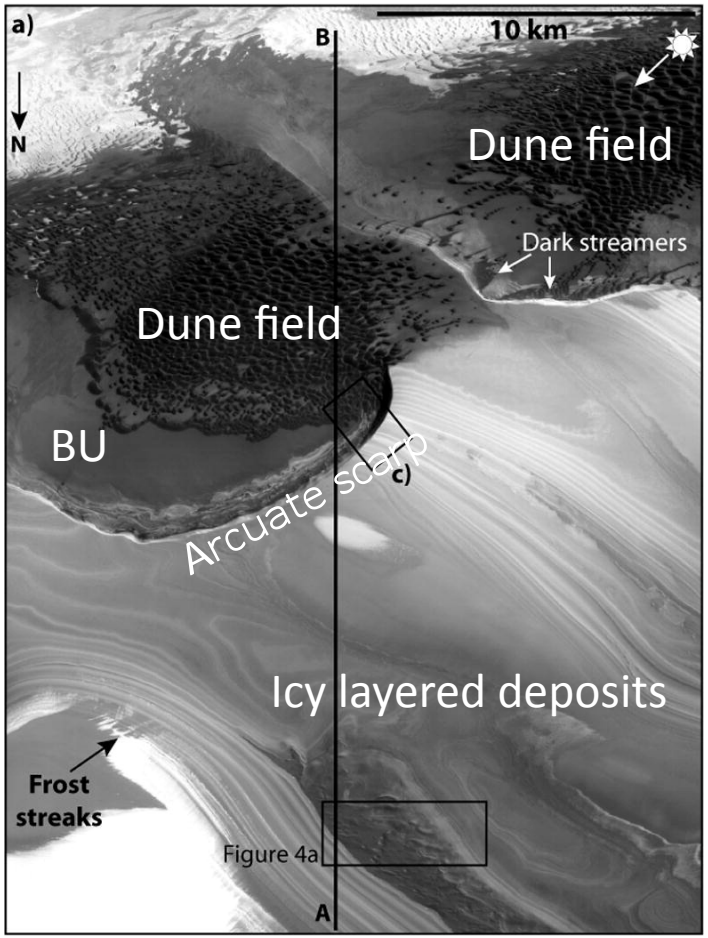
Registration accuracy

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

- **10% error** between ground truth and unmixing results
  - **MVC-NMF** obtains the best r = **0.83** and ε = **0.08**
  - **BPSS** provides **accurate abundances**
  - **VCA** provides **underestimated** abundances
  - ***spatial*-VCA** does not extract the dark source satisfactorily

The piece-wise convex multiple model

- The scene can contain multiple distinct regions that do not share common materials



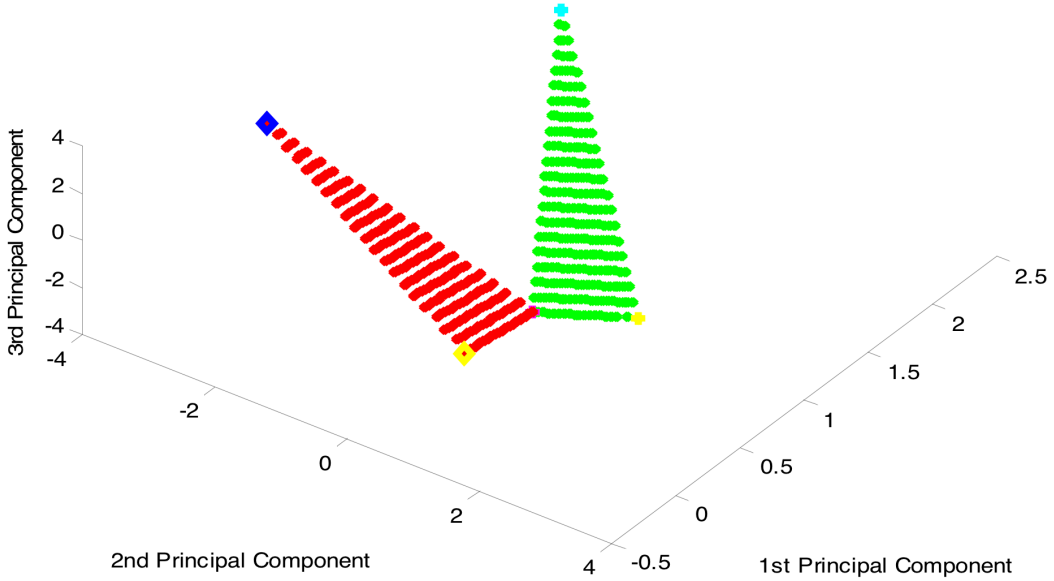


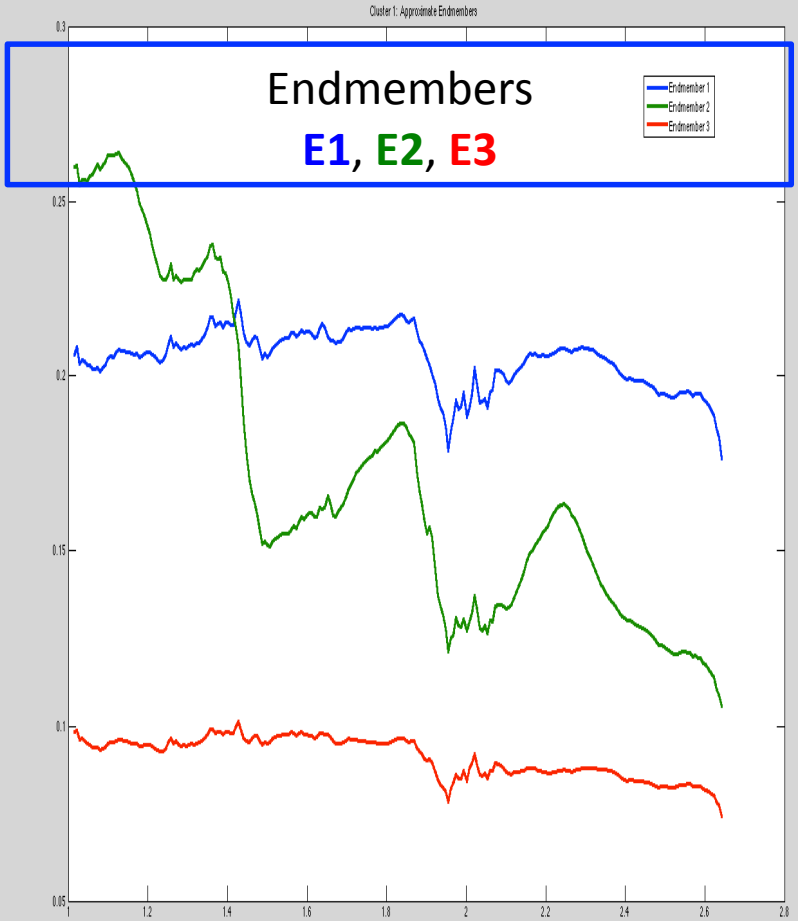
Figure 2-1. Two linear simplexes formed from macroscopic mixtures of five endmembers with uniform proportions.

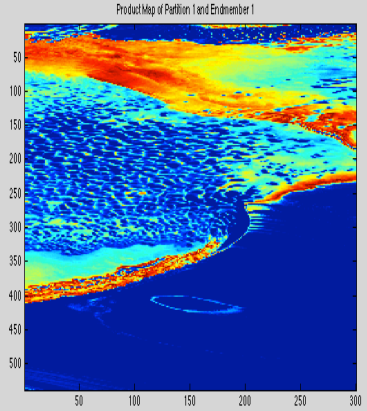
$$J(E,P,U)=\sum_{i=1}^{C}\left(\sum_{j=1}^{N}u_{ij}^{m}\left(\mathbf{x}_j-\mathbf{E}_i\mathbf{p}_{ij}\right)^T\left(\mathbf{x}_j-\mathbf{E}_i\mathbf{p}_{ij}\right)+\alpha\sum_{k=1}^{M-1}\sum_{j=k+1}^{M}\left(\mathbf{e}_{ik}-\mathbf{e}_{ij}\right)^T\left(\mathbf{e}_{ik}-\mathbf{e}_{ij}\right)\right)$$

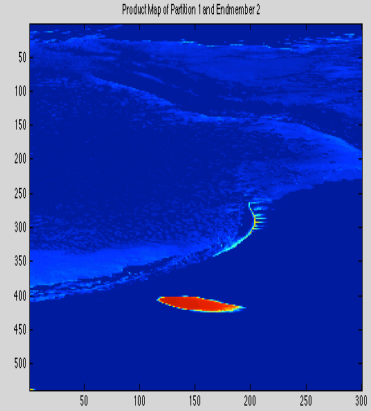
$$p_{jk}\geq 0\ \forall k=1,\cdots,M;\quad \sum_{k=1}^{M}p_{jk}$$

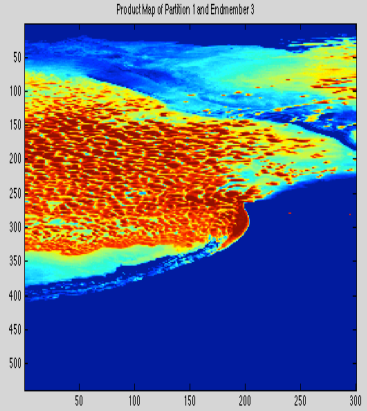
$$u_{jk}\geq 0\ \forall k=1,\cdots,M;\quad \sum_{k=1}^{M}u_{jk}$$

Experiments : cluster #1



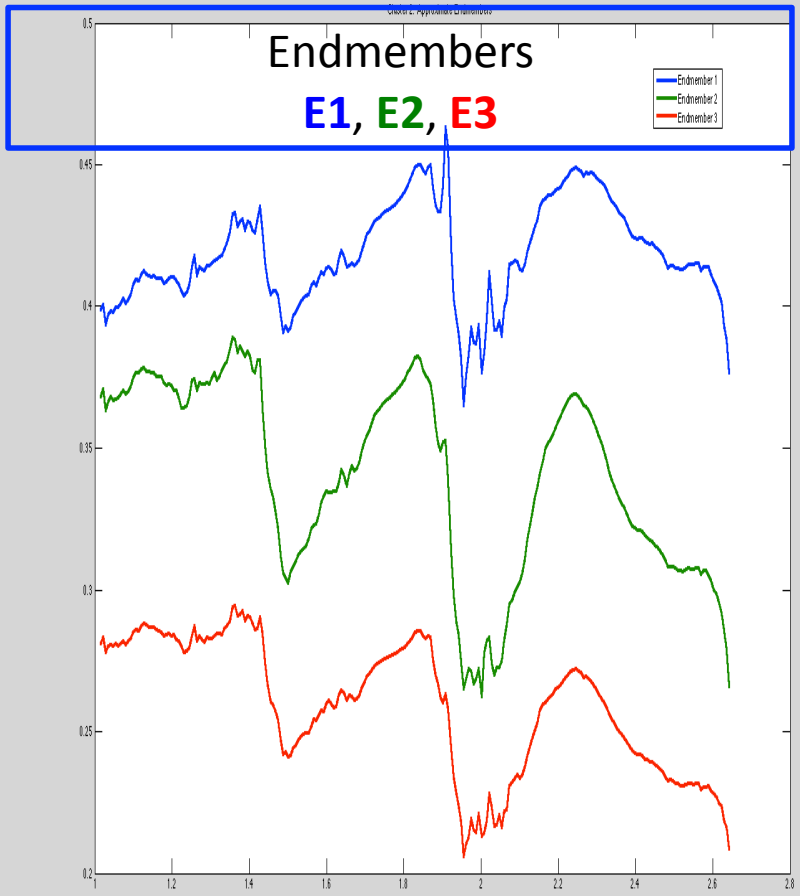


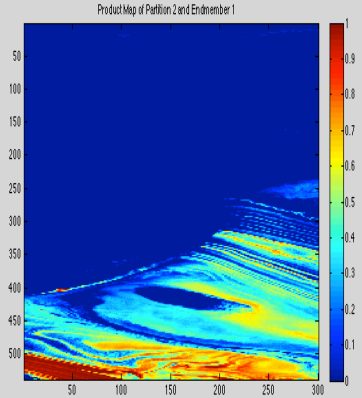


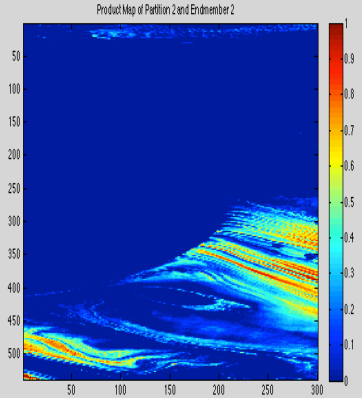


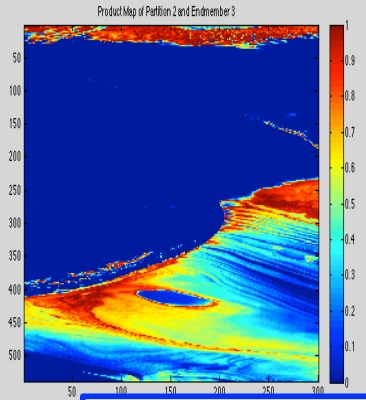
Membership x Proportion Maps

Experiments : cluster #2



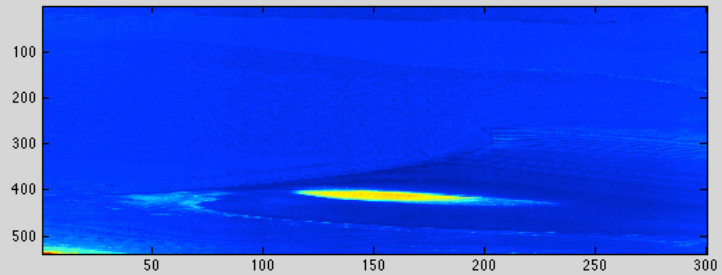


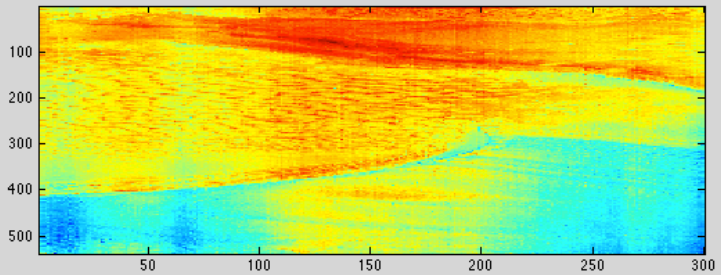


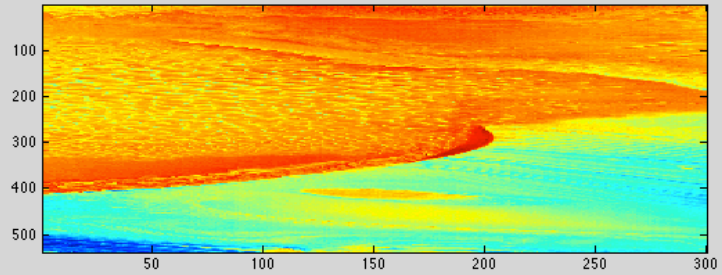


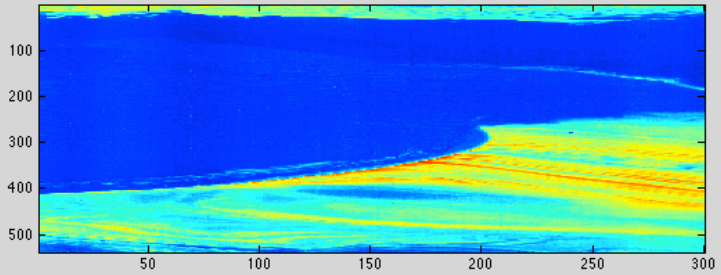
Membership x Proportion Maps

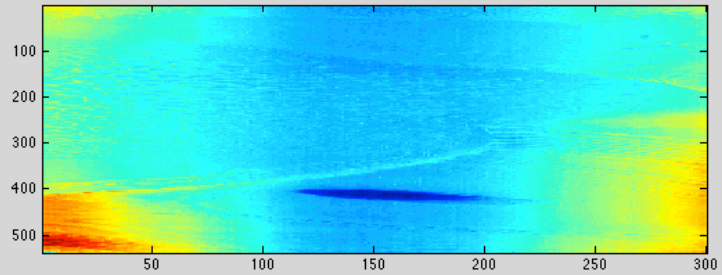
Experiments : VCA results

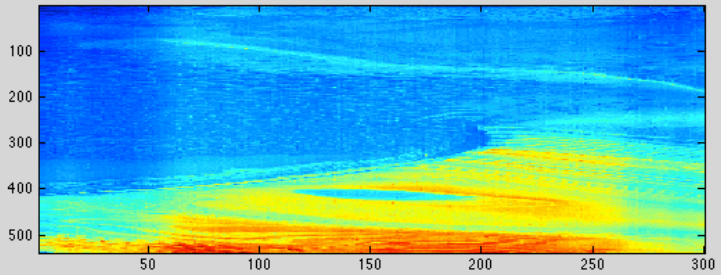












Outline

- Background

① Post-processing CRISM data

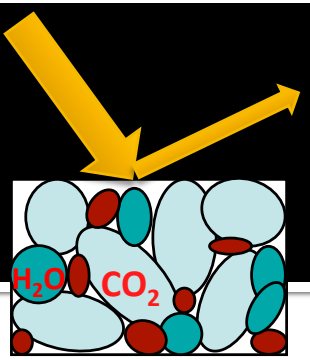
② Unsupervised spectral unmixing

③ Physical analysis by RT model inversion

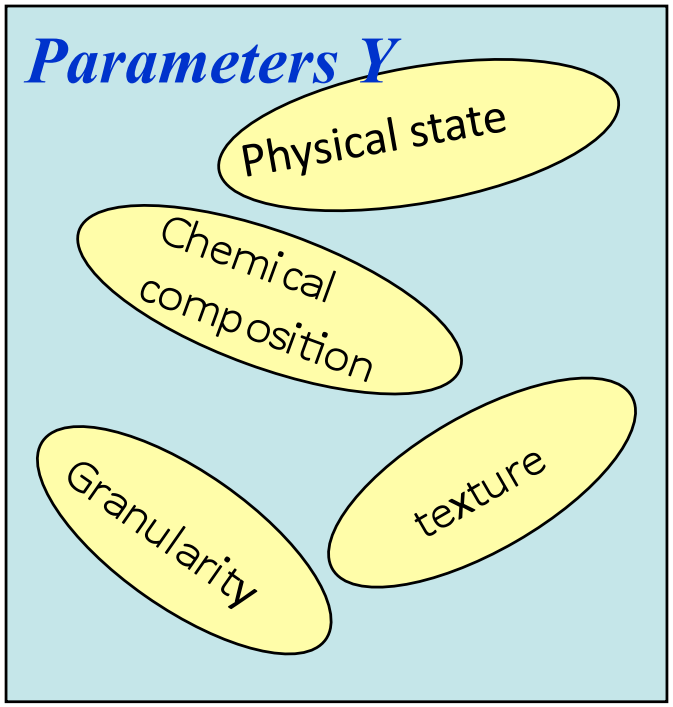
GRSIR method

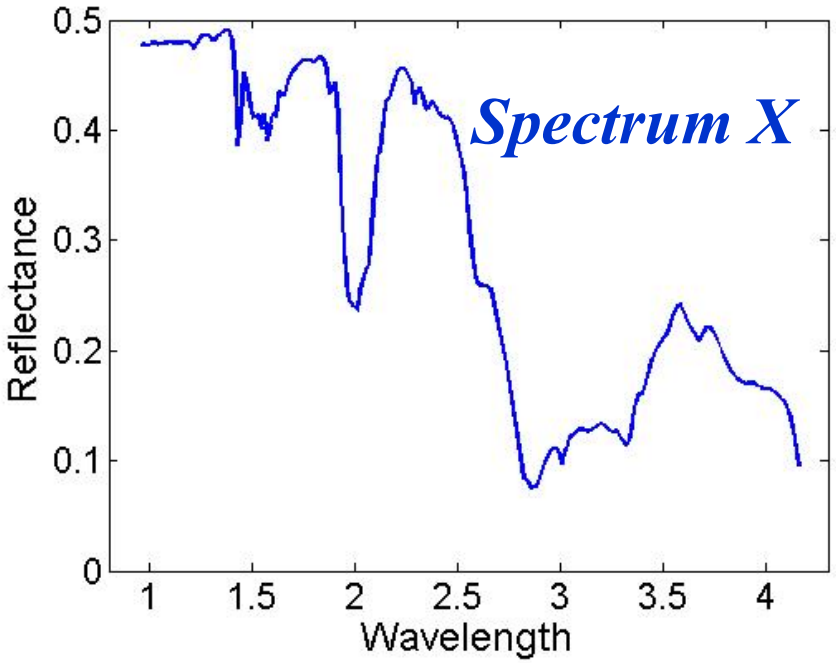
- Future prospects

Direct Problem



Physical model G

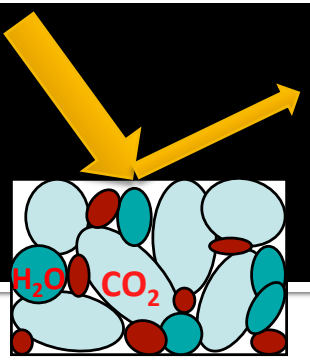




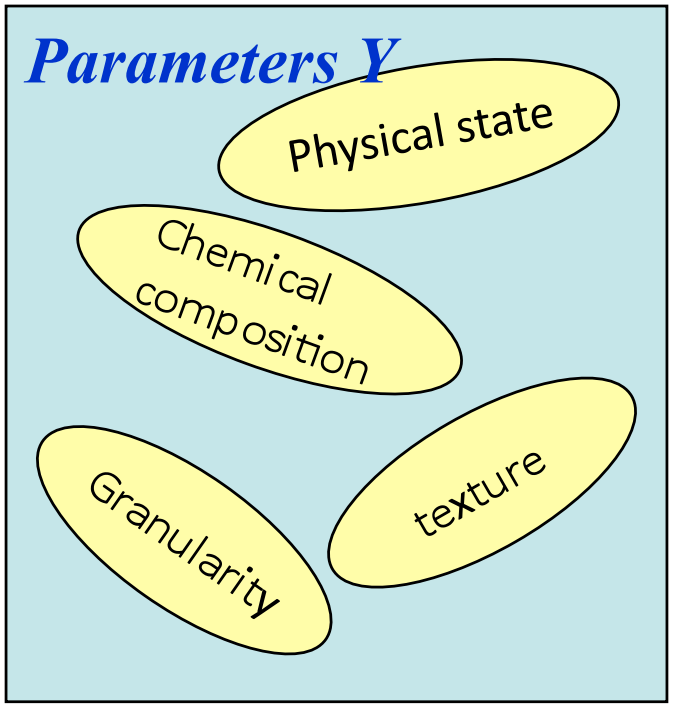
Direct Problem :

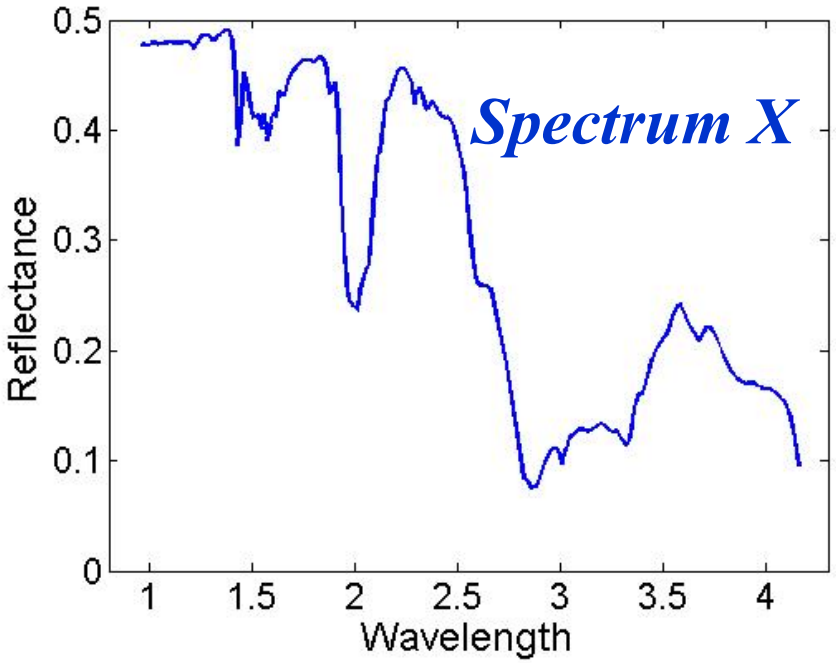
Calculating spectrum *X* from a combination of parameter values *Y* with a numerical radiative transfer model *G*

Inverse Problem



Physical Model G





Inverse Problem:

Estimating parameter values *Y* from the spectrum *X* knowing *G*

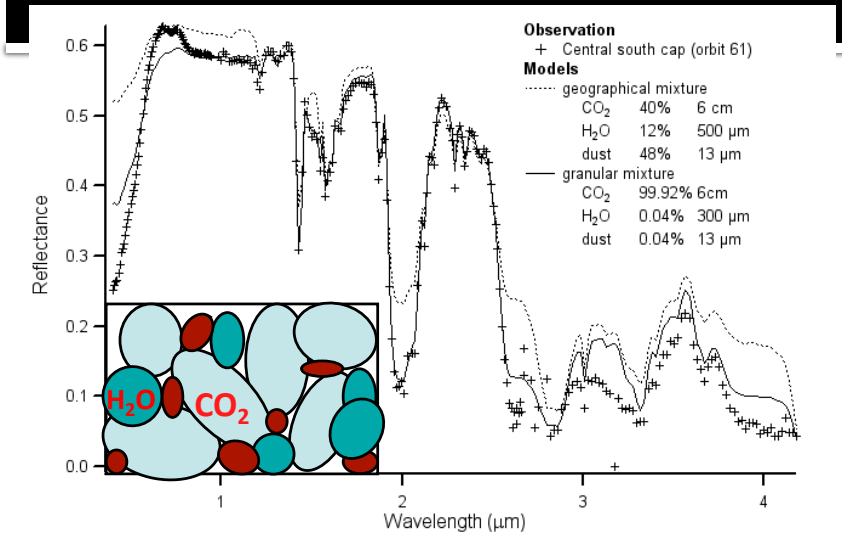
Physical analysis of planetary hyperspectral images by inversion :

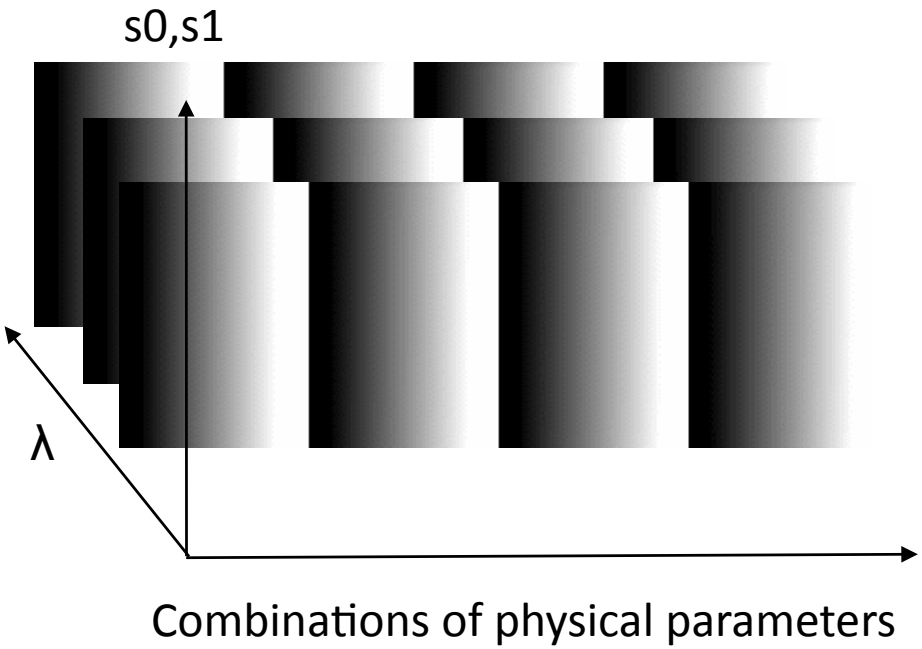
- Constrains:
  - Huge collections of images
  - A large variety of physical models
  - Data of high dimensionality
    (problem of the empty space)
  - Observed spectra are always affected by noise

Solutions for solving the inversion problem

- Optimization algorithms:
  - Minimizing a cost function (quality of fit)
  - methods powell, Simplex, quasi-Newton, etc.
  - Non stable solutions if ill-conditioned problem
  - Highly computer intensive
- Approach “Look-up table / K-NN”
  - Simulating a database of synthetic spectra for a large number of combinations of parameter values.
  - For each observed spectrum, seeking the K nearest neighbours (metric :cost function) in the database.
- Approach “Statistical learning”

Methods: GRSIR and SVM





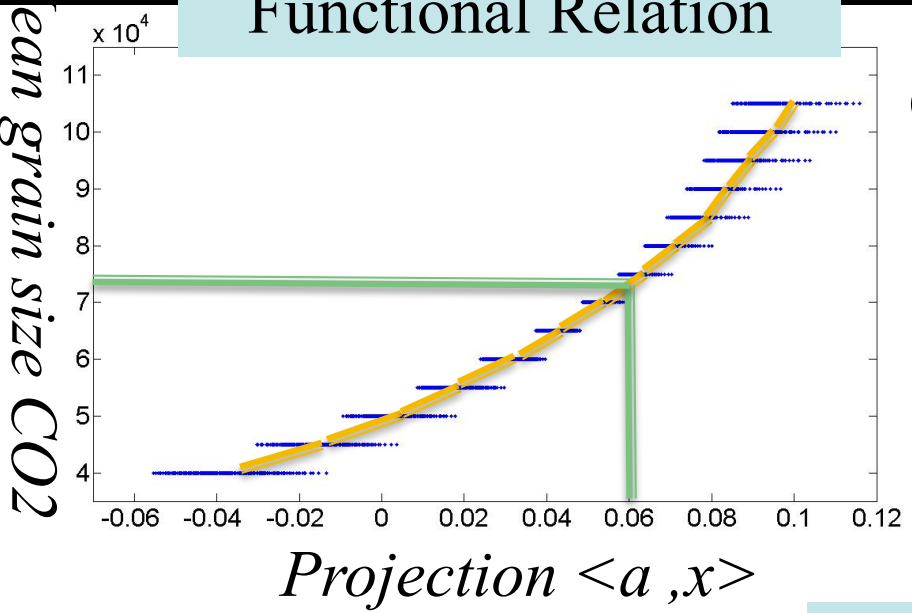
- Statistical learning techniques for the inversion of physical models of the spectral signal
  - generation of synthetic spectral databases
  - regularized learning of the functional Y=f(X)
    - Without dim. reduction: SVM regression
    - With dim. reduction: GRSIR

Bernard Michel, Douté et al. JGR 2009

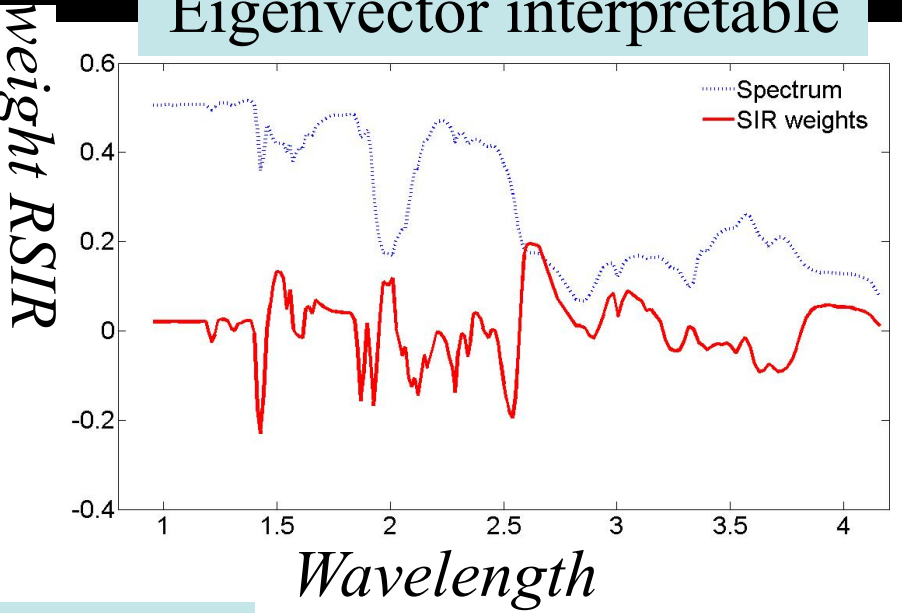
Fauvel, Douté et al. IEEE Whispers 2009

GRSIR in a nutshell

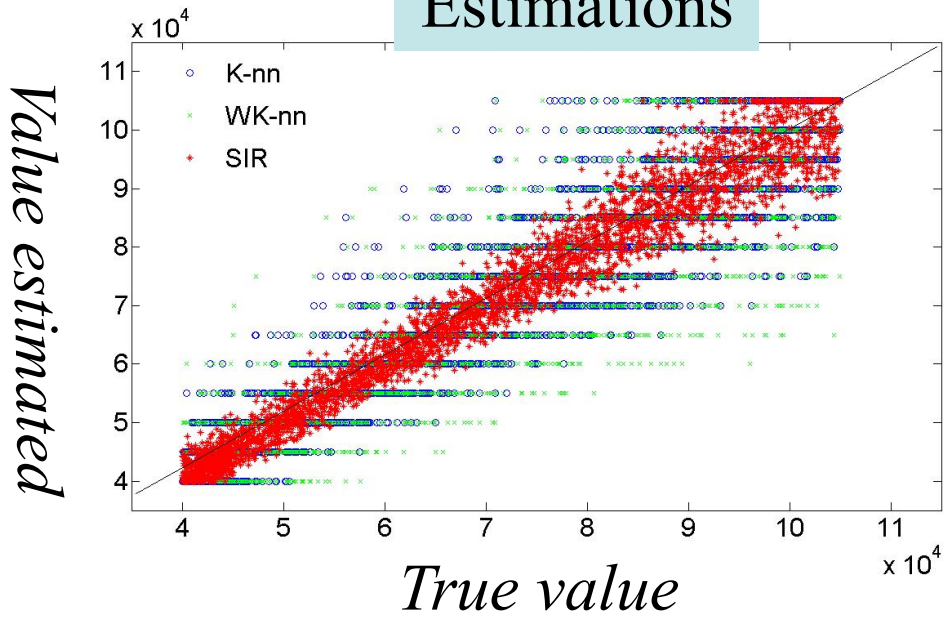
Functional Relation



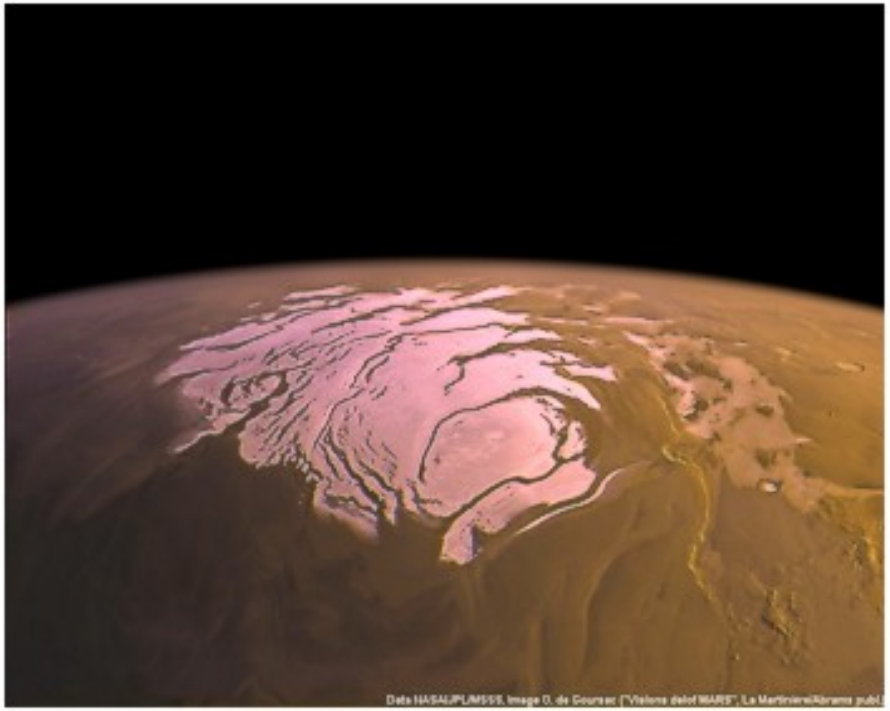
Eigenvector interpretable



Estimations



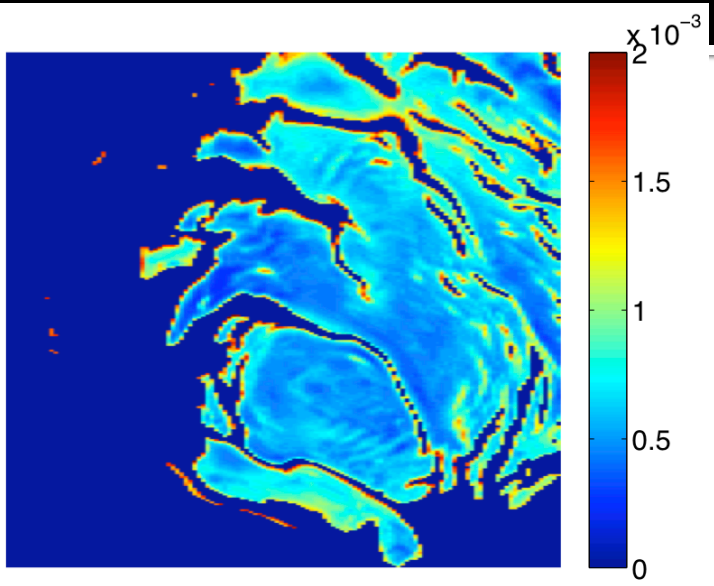
Application to Mars south permanent cap

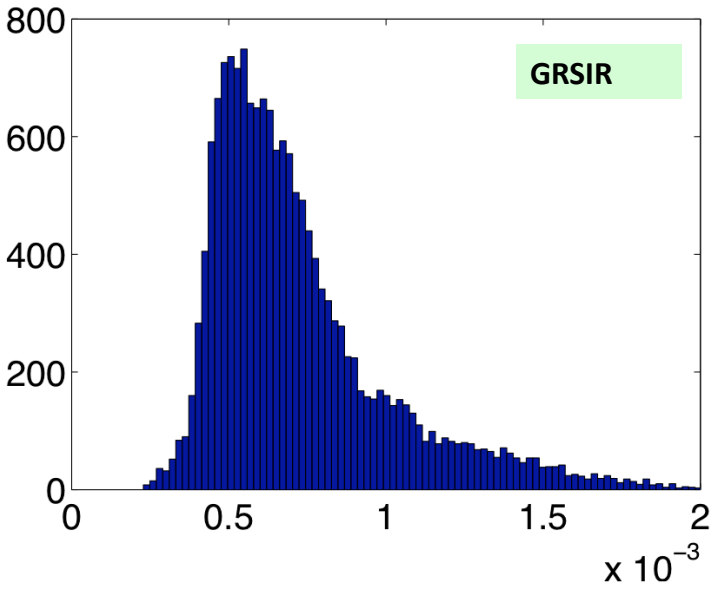


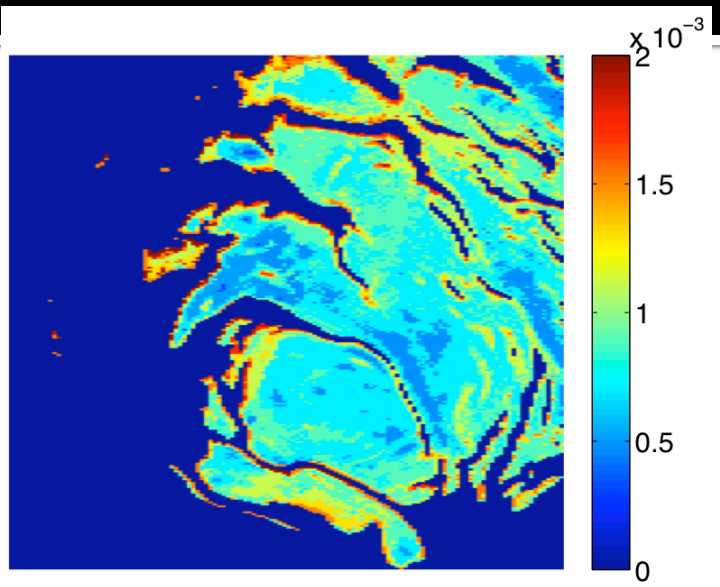
Source: "Visions de Mars" /eds: La Martinière

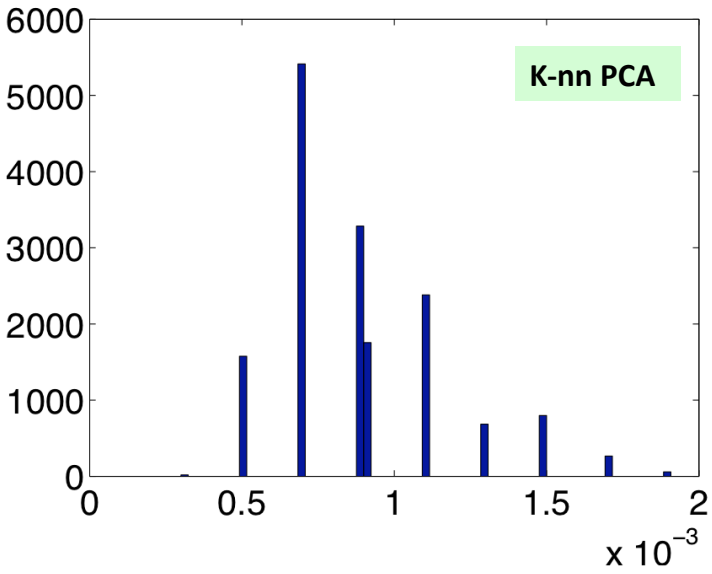
- Model: granular mixture dust + water ice + CO2 ice (Douté et al. 2007, PSS)
- Orbits 30, 41, 61 and 103
- ~ 10000-20000 spectra to be inverted by image
- 184 wavelengths
- Learning dataset generated by a radiative transfer model
- 5 parameters: abundance of dust, CO2 and water, mean grain sizes of CO2 and water.

Dust maps
from OMEGA Observation ORB41

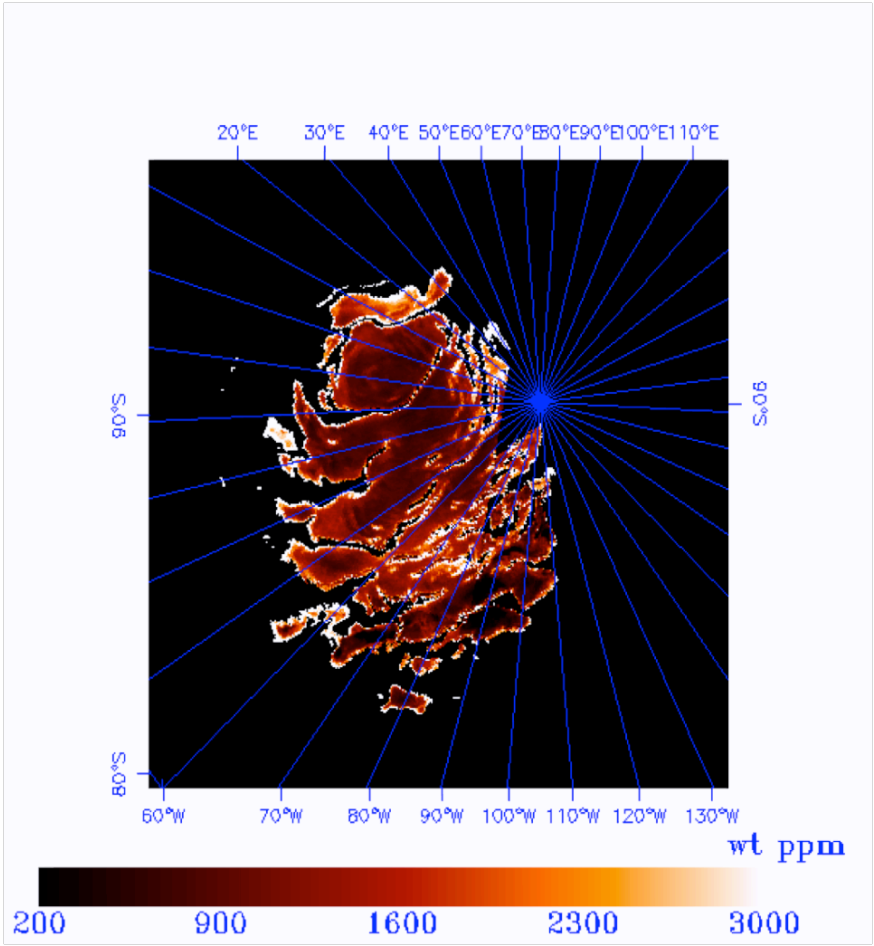


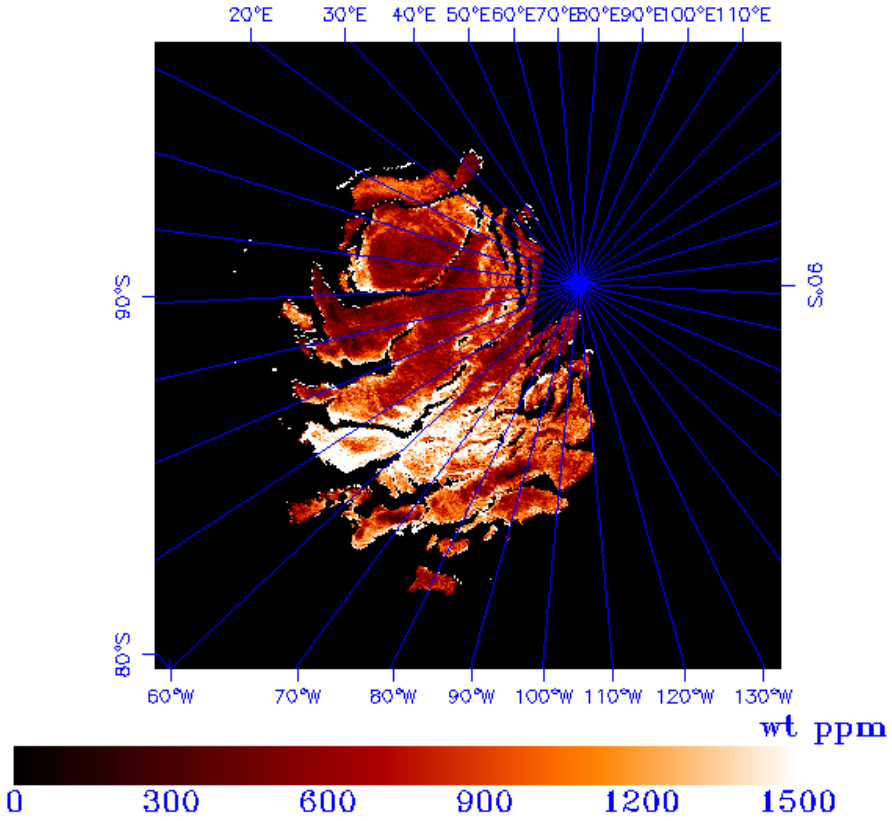






Contamination of CO2 ice





by dust and water ice

Outline

- Background and summary

① Post-processing CRISM data

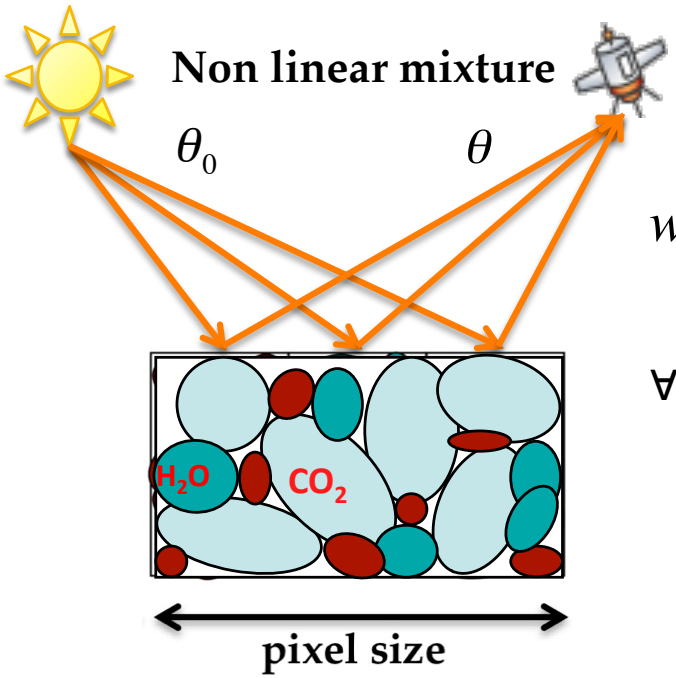
② Spectral unmixing

③ Physical analysis by RT model inversion

- Future prospects

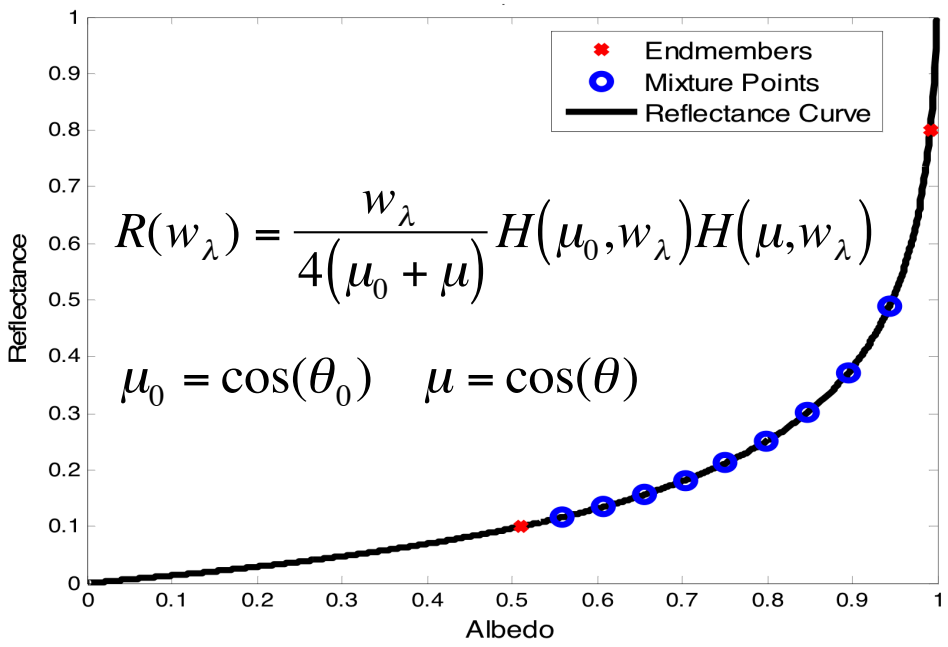
The microscopic mixture model

- Components appear generally in intimate mixtures of grains crossed by the solar light which then undergoes multiple scattering before being reflected towards the sensor.

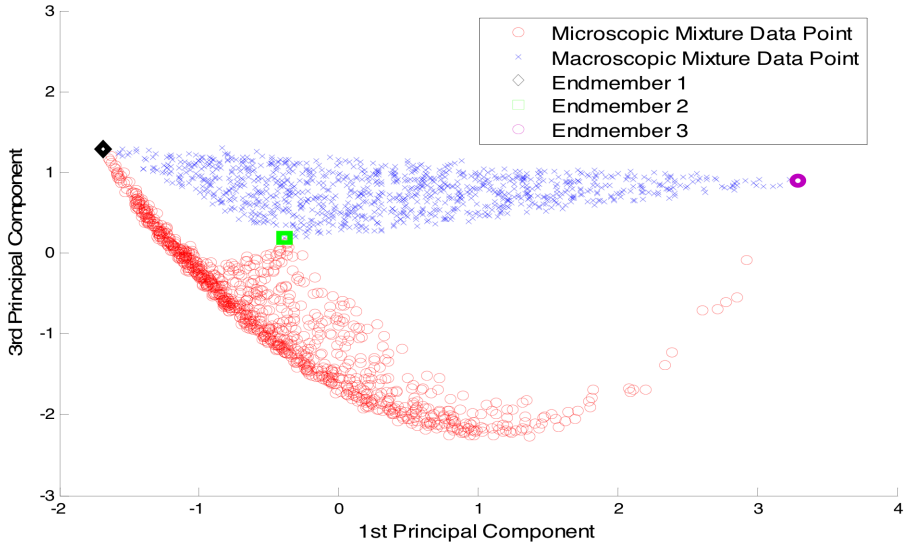


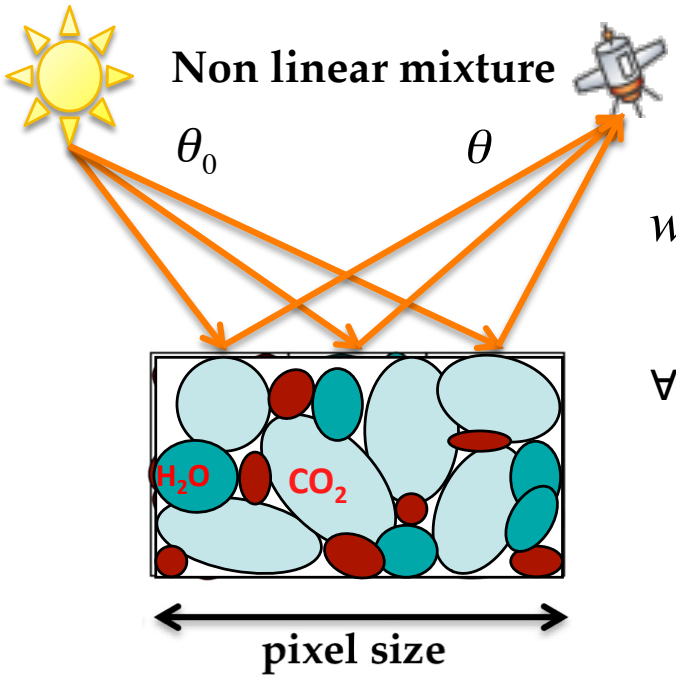
$$w_\lambda = \sum_{k=1}^{M} f_k w_{k\lambda}$$

$$\forall k \; f_k \geq 0 \qquad \sum_{k=1}^{M} f_k = 1$$



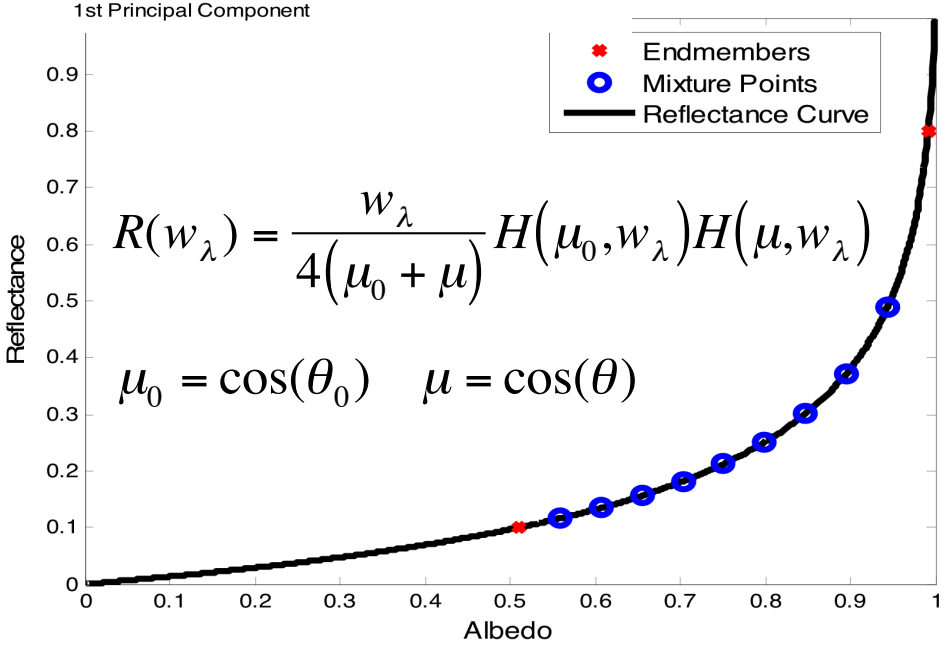
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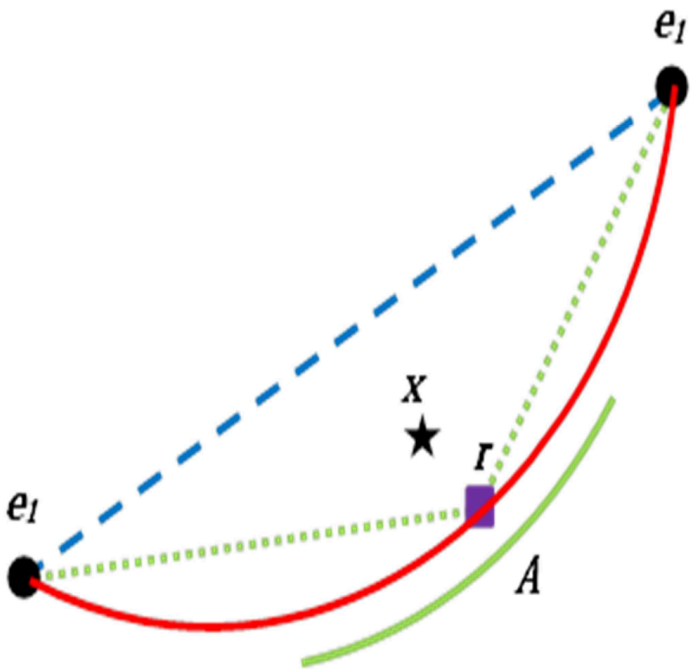
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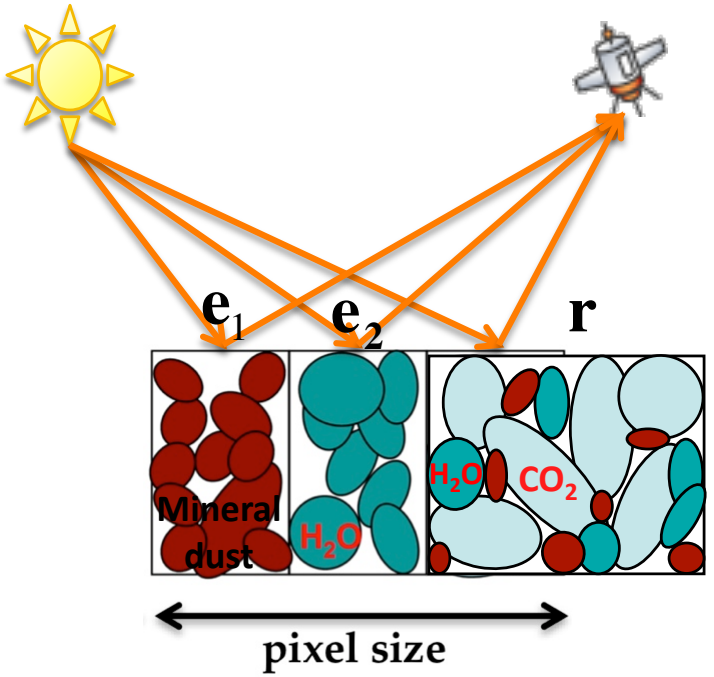


The multi-mixture pixel model

- A pixel may be composed of a macroscopic mixture, a microscopic mixture, or a combination of the two mixtures.

$$\mathbf{x}_j = \sum_{k=1}^{M} p_{jk}\mathbf{e}_k + p_{jM+1}R\left(\sum_{k=1}^{M} f_{jk}\mathbf{w}_k\right) + \varepsilon_j$$





Thank you for your attention!



Site Web http://vahine.gforge.inria.fr/

IPAG

Institut de Planétologie et d'Astrophysique de Grenoble

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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:

$$\begin{aligned} z_i &\sim \aleph(\mu_i, \sigma_i^2), \qquad i \le N_c \\ z_i &\sim \aleph(0, \sigma_i^2), \qquad i > N_c \end{aligned}$$

  - Likelihood function:

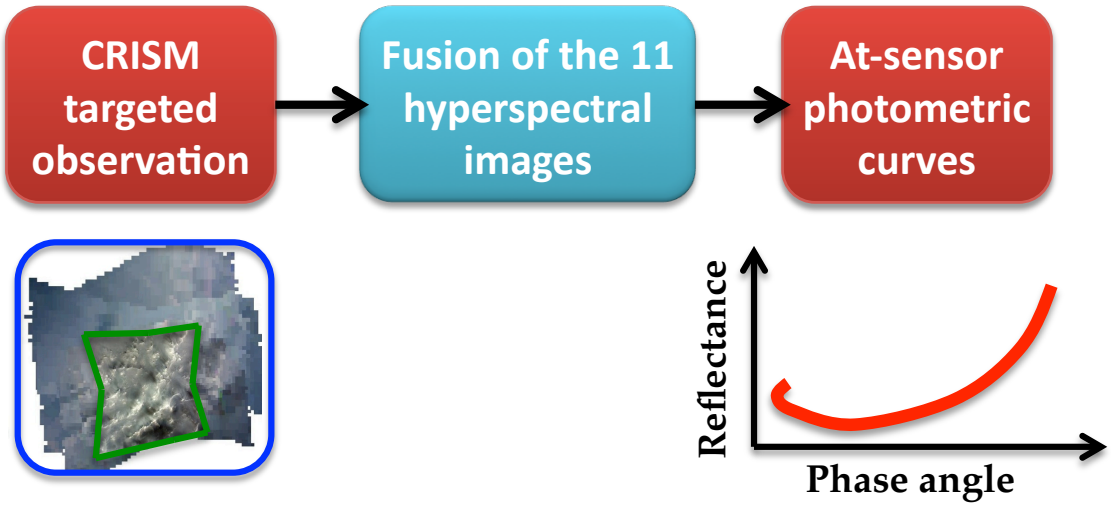
$$\tilde{H}(i) = -\sum_{l=i}^{N_s} \frac{z_l^2}{2\sigma_l^2} - \sum_{l=i}^{N_s} \log \sigma_l,$$

  - The number of endmembers is defined such that

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

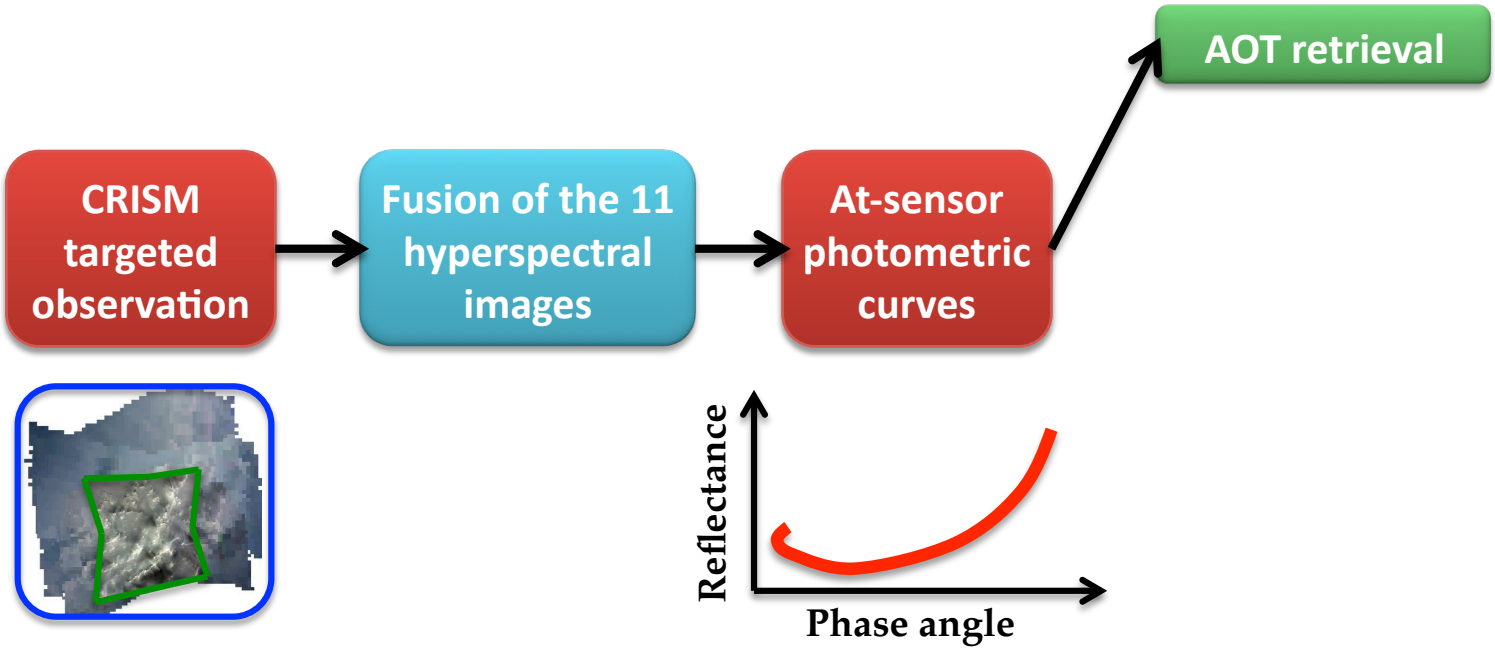
Atmospheric correction

- Atmospheric correction chain for CRISM observations
  1. Generation of multi-angle product by data pipeline



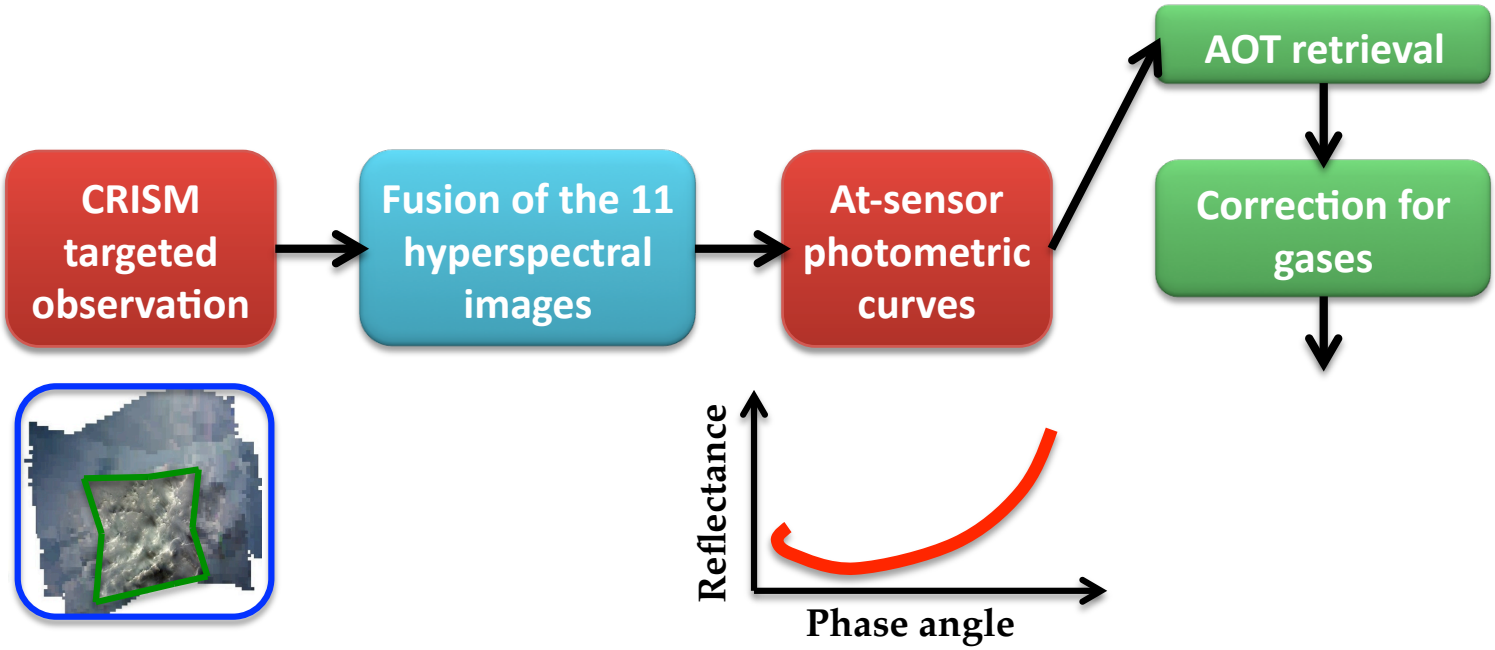
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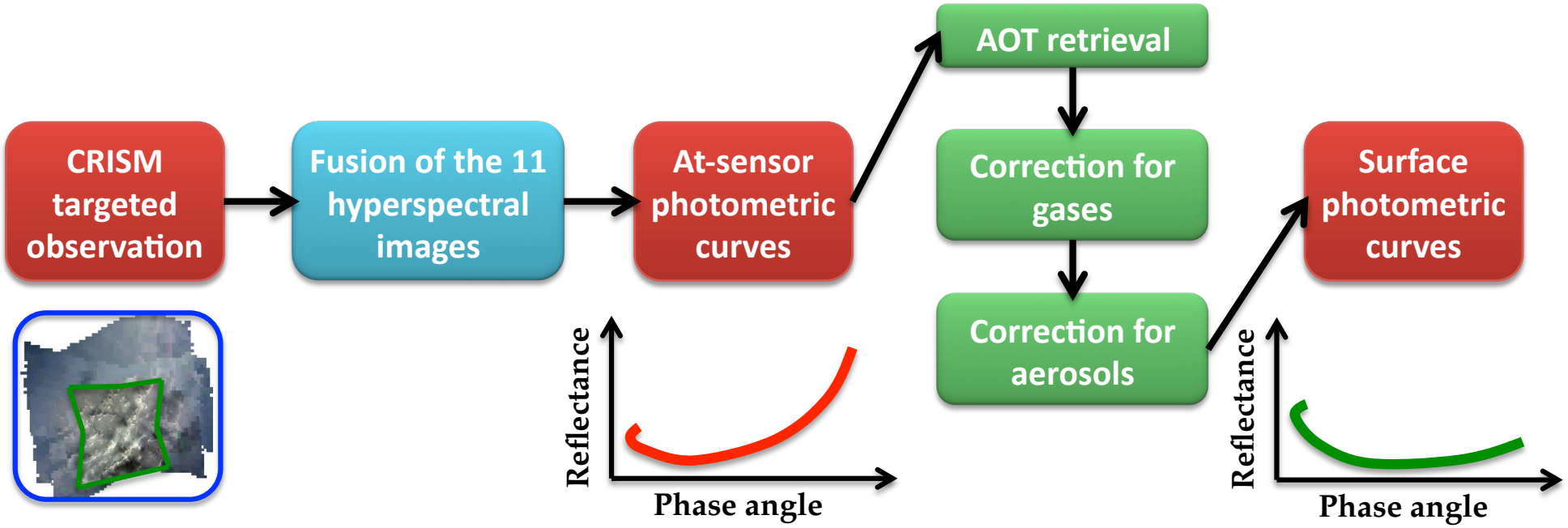
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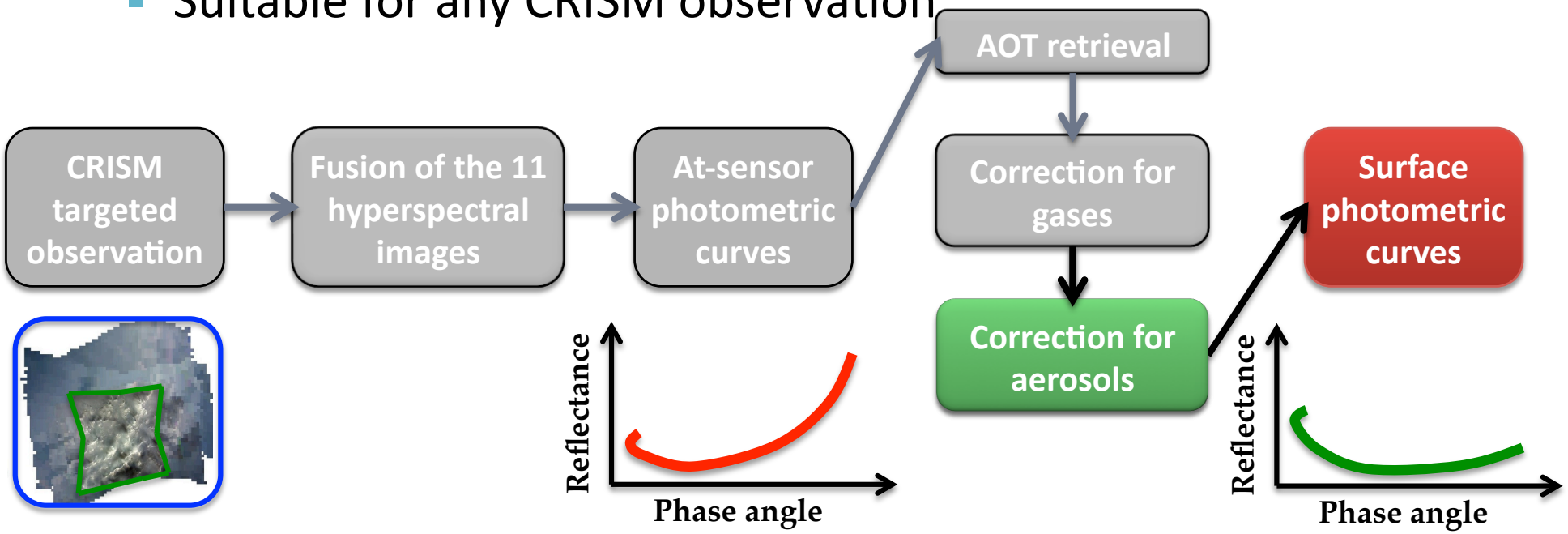
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  4. Correction for aerosols: MARS-ReCO

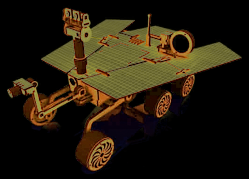


Atmospheric correction

- **MARS-ReCO**: Multi-angle Approach for Retrieval of Surface Reflectance from CRISM Observations
  - Correction for aerosol contribution considering the anisotropic scattering properties of the surface
  - Inspired by work done on Earth observation [Lyapustin 2011]
  - Suitable for any CRISM observation



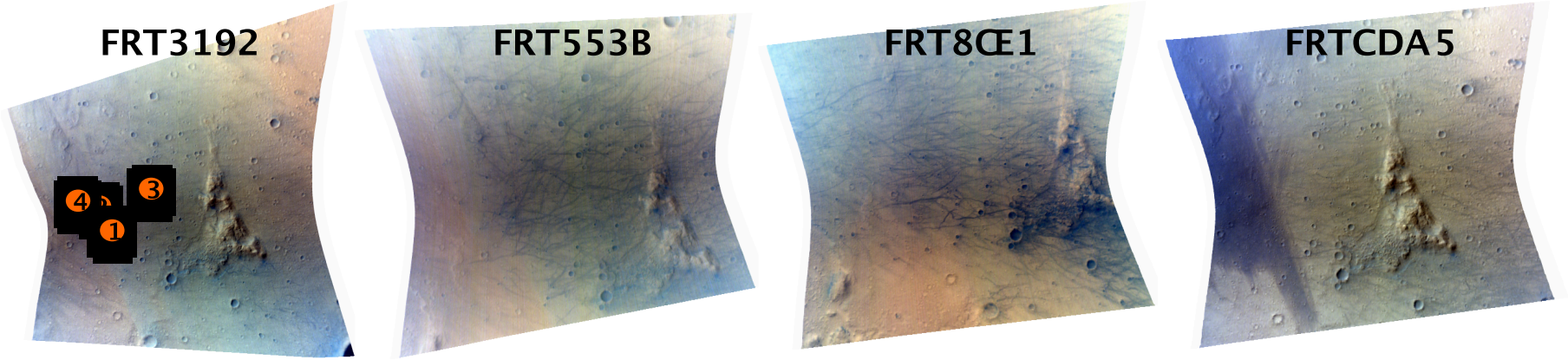
Validation on CRISM data



- Retrieval of surface BRDF from Gusev crater[1]
  - **Reference**: surface photometry measured on ground by PanCam on the rover "Spirit" [Johnson et al. 2006]

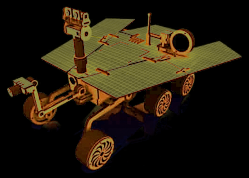


- Selection of 4 observations to improve angular sampling

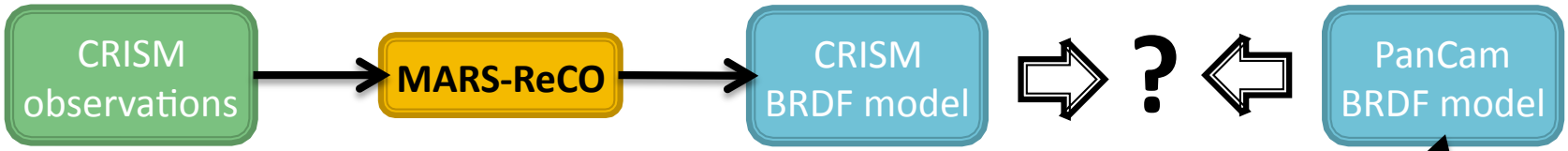


[1]: [Fernando et al. EPSC 2011]

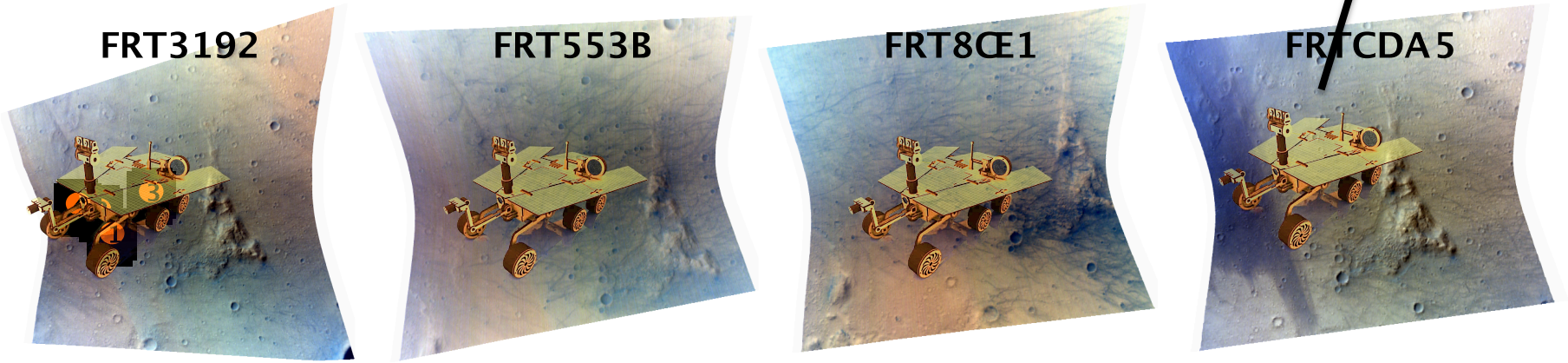
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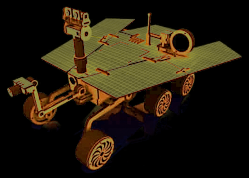


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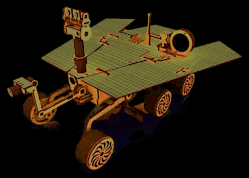
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$$\rho_{Hapke}(\theta_0,\theta,g) = \frac{\omega}{4}\frac{1}{\mu_{0e}+\mu_e}\left\{\left[1+B(g)\right]p(g)+H(\mu_{0e})H(\mu_e)-1\right\}S(\theta_0,\theta,g)$$

Hapke scattering parameters

Meas.\Param.	w	θ	b	c
CRISM MARS-ReCO	0.69-0.72	18-19	0.22-0.25	0.46-0.57
Spirit "**Soil**" [Johnson 2006]	0.69	11	0.24	0.48

Validation on CRISM data



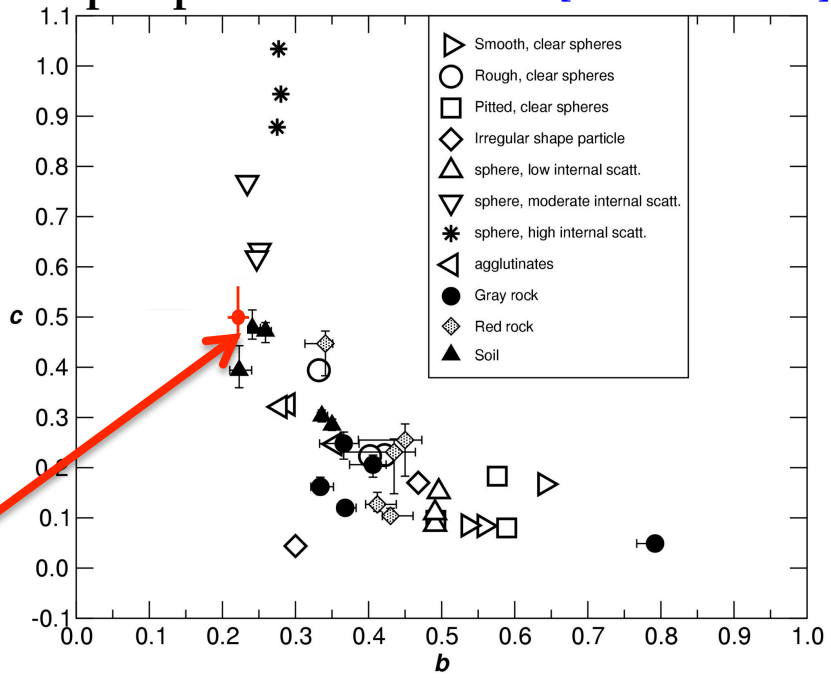
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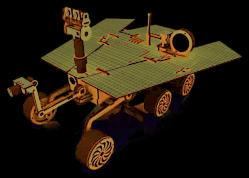
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Hapke parameters *b* and *c* [McGuire 1995]



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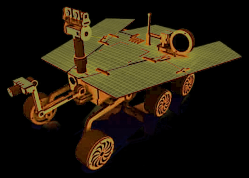


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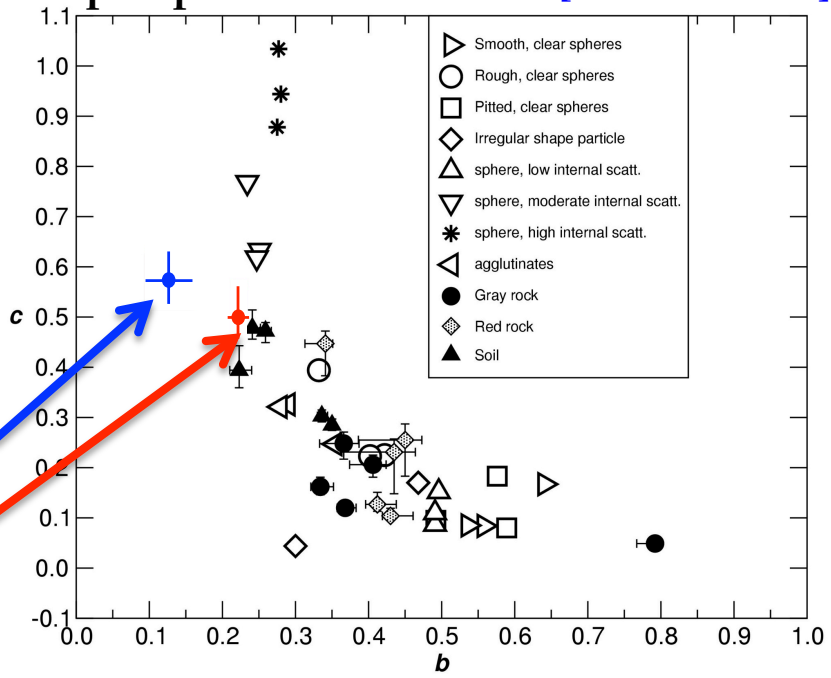
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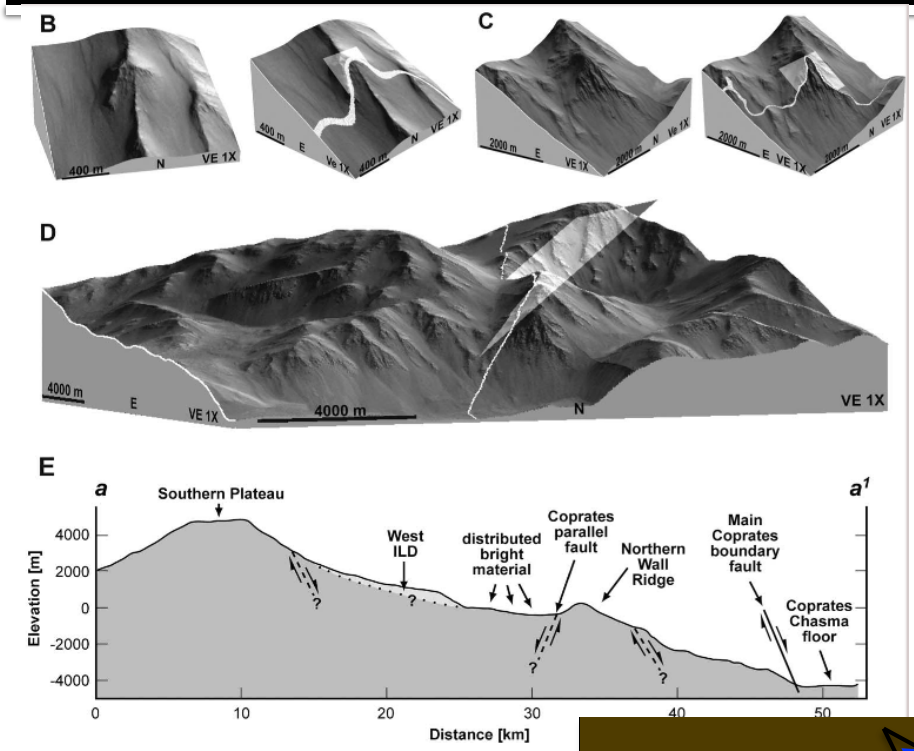
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Correction with Lambertian assumption

MARS-ReCO

The importance of accurate DTM



- Structural geology
- Atmospheric and environment radiative effect corrections
- Radiometric calibration

