EPSC Abstracts
Vol. 10, EPSC2015-676, 2015
European Planetary Science Congress 2015

Multi-angle Approach for Coherent Retrieval of Surface Reflectance and Atmosphere Optical Depth from CRISM Observations

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Abstract

This paper addresses the correction for aerosol effects in near-simultaneous multi-angle observations acquired by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) aboard the Mars Reconnaissance Orbiter. In the targeted mode, CRISM senses planet Mars from the top of the atmosphere (TOA) using 11 viewing angles in 437 visible and infrared wavelengths, which allow it to provide unique information on the scattering properties of surface materials and atmospheric aerosols. In order to retrieve these data, however, appropriate strategies must be used to model the signal sensed by CRISM and compensate for aerosol contribution. In [2] we put forward an innovative inversion scheme of the model named Multi-angle Approach for Retrieval of Surface Reflectance from CRISM Observations (MARS-ReCO). Nevertheless this first version of MARS-ReCO requires a priori information about the scattering properties and the abundance of the atmospheric aerosols prior to the inversion. The proposed method retrieves conjointly the atmosphere optical depth (AOD) and the bidirectional reflectance factor (BRF) of surface materials as a function of wavelength. MARS-ReCO represents a substantial improvement regarding previous techniques as it takes into consideration in a coherent way the anisotropy of both the surface and the atmosphere scattering. Thus it provides more realistic surface and atmospheric products. Furthermore, MARS-ReCO is fast and provides error bars on the retrieved parameters.

1. Method

MARS-ReCO performs the atmospheric correction of each TOA photometric curve $\mathbf{R}^C = \left\{R_1^C, \ldots, R_{Ng}^C\right\}$ extracted from a targeted observation where Ng is the number of available angular measurements. Following [3] signal sensed by CRISM can be decomposed as a sum of the atmospheric path radiance (D), and the radiance reflected by the surface before being directly ($L_s e^{-\tau_0/|\mu|}$) and diffusely (L_s^d) transmitted through the atmosphere. The surface anisotropy is taken into account through its BRF expressed using a semi-empirical Ross-Thick Li-Sparse (RTLS) model:

$$\rho\left(\mu_0, \mu, \varphi\right) = k^L + k^G f_G\left(\mu_0, \mu, \varphi\right) + k^V f_V\left(\mu_0, \mu, \varphi\right) \quad (1)$$

The subscripts refer to Lambertian (L), geometric (G) and volumetric (V) components with f_G and f_V predefined geometric kernels. The substitution of the RTLS model into the surface-atmosphere radiative transfer scheme provides a quasi-linear expression for the TOA signal : a linear combination of kernels.

$$\begin{aligned} R\left(\mu_o, \mu, \varphi\right) \quad = \quad & R^D\left(\mu_o, \mu, \varphi\right) + k^L F^L\left(\mu_o, \mu\right) + k^G F^G (\\ & + k^V F^V\left(\mu_o, \mu, \varphi\right) + R^{nl}\left(\mu_o, \mu\right) \end{aligned}$$

The kernels $\left\{F^L, F^G, F^V\right\}$, the path radiance R^D, and the surface dependent nonlinear term R^{nl} can be conveniently stored in reference look-up tables. In [1], assuming the AOD is known, an iterative inversion strategy of the TOA model is proposed based on an unconstrained linear inversion procedure. The method we propose in present paper is based on the evolution of the previous scheme with the AOD now a free parameter. Since our model of the TOA radiance already contains an additive atmospheric term in addition to the linear combination of surface kernels, we can define an atmospheric kernel which linear coefficient is the AOD. $R^D\left(\mu_o, \mu, \varphi\right) = k^T F^T\left(\mu_o, \mu, \varphi\right)$ where $F^T\left(\mu_o, \mu, \varphi\right) = R^D\left(\mu_o, \mu, \varphi\right)/k^T$. Then we have a pseudo linear model relating (k_L, k_G, k_V, k_T) with the vector of the observables. A first guess for the AOD, which is assimilated to k_T, allows to calculate the atmospheric kernel F^T. The latter is refined iteration after iteration along with the solution for k_T.

Second we borrow a Kalman filter based method presented by [2]. We adapt this procedure to the processing of multi-angle CRISM data in order to enhance the robustness of the inversion since our model, with 3 surface and one atmosphere free parameters, is not well constrained. We consider that the atmosphere opacity is usually more stationary than the properties of the martian surface in the spatial dimension because of the reduced size of the CRISM scenes (15x15 km). Thus the spatial dimension is exploited for simultaneous retrieval of the surface BRF and AOT. The solution is obtained through the unconstrained linear inversion procedure but perpetuated in space using a Kalman filter. Practically the solution k_{sol} and a posteriori covariance matrices $\mathbf{C}_{kp}$ for pixel $J-1$ are used to calculate a prior C_x and k_p for super-pixel J according to a prognostic model operator:

$$k_p = k_{sol} \tag{4}$$

$$C_x = (1+\delta)\mathrm{diag}(\mathrm{C_{kp}}) \tag{5}$$

The transition probabilities for the variances are described by vector :

$$\delta = \left(2^{2/t_1}-1,\ 2^{2/t_2}-1,\ 2^{2/t_3}-1,\ 2^{2/t_4}-1\right) \tag{6}$$

Then the iterative inversion scheme described above is applied to super-pixel J with the following regularized first guess and a priori covariance matrix:

$$C_k = \left(C_x^{-1} + C_{reg}^{-1}\right)^{-1} \tag{7}$$

$$k^{(0)} = C_k \left(C_x^{-1} k_p + C_{reg}^{-1} k_{reg}\right) \tag{8}$$

C_{reg} and k_{reg} are respectively a fixed regularization matrix and vector. One must note that the retrieval of the RTLS kernel weights and AOD by the previous scheme with two nested iterative loops is performed independently for each wavelength.

2. Numerical experiments and results

Validation of our method has been performed on a selection of 40 CRISM observations with different surface, atmospheric, and geometrical conditions. The chosen characteristic "times" (going from one pixel to the next) for the Kalman transition are t1=2; t2=10; t3=10 for the surface model and is variable for the AOD (a decreasing function of the number of valid CRISM geometries). For each observation, we assess the quality of the solution generated by MARS-ReCO by considering the behavior kT in the spatial and spectral dimensions (Fig. 1). First we have at a wavelength of 1.1 micron the evolution of the AOD as a function of the pixel sequence number in the inversion spatial path through the scene. This evolution allows us to estimate the quality of the convergence since the optical thickness should be spatially homogeneous in most cases. Second we consider the kT spectra of a series of pixels to assess the mean spectral dependance of tau as well as the variance around this mean. Note that the mean spectral slope is indicative of the aerosol size distribution. Based on a compilation of the obtained results for the selection of CRISM observations we conclude that the algorithm produces very satisfactory results except when the phase angle range is limited, the incidence angle is higher than 70, the topography is accuentuated or perhaps a combination of these three factors.

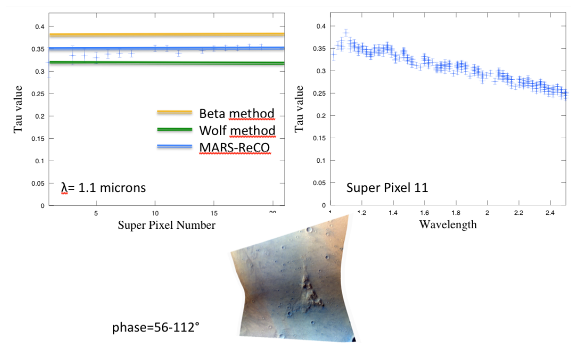

Figure 1: Behavior of the AOD solution as a function of the pixel sequence number and of the wavelength. For observation FRT3192 convergence of the MARS-ReCO algorithm is very satisfactory and the dispersion of the k_T spectra is weak.

Acknowledgements

This work is supported by a contract with PNTS and ANR.

References

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