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Retrieving atmospheric dust opacity on Mars by imaging spectroscopy at large angles

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ABSTRACT

We propose a new method to retrieve the optical depth of Martian aerosols (AOD) from OMEGA and CRISM hyperspectral imagery at a reference wavelength of 1 μm. Our method works even if the underlying surface is completely made of minerals, corresponding to a low contrast between surface and atmospheric dust, while being observed at a fixed geometry. Minimizing the effect of the surface reflectance properties on the AOD retrieval is the second principal asset of our method. The method is based on the parametrization of the radiative coupling between particles and gas determining, with local altimetry, acquisition geometry, and the meteorological situation, the absorption band depth of gaseous CO_2. Because the last three factors can be predicted to some extent, we can define a new parameter β that expresses specifically the strength of the gas–aerosols coupling while directly depending on the AOD. Combining estimations of β and top of the atmosphere radiance values extracted from the observed spectra within the CO_2 gas band at 2 μm, we evaluate the AOD and the surface reflectance by radiative transfer inversion. One should note that practically β can be estimated for a large variety of mineral or icy surfaces with the exception of CO_2 ice when its 2 μm solid band is not sufficiently saturated. Validation of the proposed method shows that it is reliable if two conditions are fulfilled: (i) the observation conditions provide large incidence or/and emergence angles (ii) the aerosols are vertically well mixed in the atmosphere. Experiments conducted on OMEGA nadir looking observations as well as CRISM multi-angular acquisitions with incidence angles higher than 65° in the first case and 33° in the second case produce very satisfactory results. Finally in a companion paper the method is applied to monitoring atmospheric dust spring activity at high southern latitudes on Mars using OMEGA.

1. Introduction

Visible and near infrared imaging spectroscopy is a key remote sensing technique to study and monitor the planet Mars. Although its atmosphere is much fainter than Earth's, its composition dominated by CO_2 gas implies numerous and strong absorption bands that often overlap with spectral features coming from the surface. Furthermore small mineral particles or H_2O ice clouds often drift over Martian surfaces at various altitudes. These aerosols have also a strong, spatially and temporally varying influence on the morphology of the acquired spectra. As a consequence accurate analysis for the study of surface materials requires the modeling and the correction of the atmospheric spectral effects. The first step in this matter consists in retrieving the aerosol optical depth (AOD) over the scene.

Since 2004 the imaging spectrometer OMEGA aboard Mars Express performs nadir-looking and EPF (emission phase function) observations in the VIS (visible) and the SWIR (short wave infrared) (920–5100 nm at 14–23 nm spectral resolution) for the study of the surface and the atmosphere of the red planet. See Clancy and Lee (1991) for the definition of the EPF mode. The spatial resolution of OMEGA typically varies between 300 and 2000 m/pixel due to its eccentric orbit. The authors in Vincendon et al. (2007) have developed a method to quantify the contribution of atmospheric dust in SWIR spectra obtained by OMEGA regardless of the Martian surface composition. Using multi-temporal observations at nadir with significant differences in solar incidence angles, they can infer the AOD and retrieve the surface reflectance spectra free of aerosol contribution. However, this method relies on the very restrictive assumption that the atmosphere opacity remains approximately constant during the time spanned by the employed acquisitions.

In Vincendon et al. (2008) the same authors map the AOD in the SWIR above the south seasonal cap of Mars from mid-spring to

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early summer. This mapping is based on the assumption that the reflectance in the 2.64 μm saturated absorption band of the CO_2 ice at the surface is mainly due to the light scattered by aerosols above most places of the seasonal cap. In this case, one geometry is sufficient for the AOD retrieval. Nonetheless, this method is restricted to the area of CO_2 deposits that are not significantly contaminated by dust nor water ice.

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) is a hyperspectral imager on the Mars Reconnaissance Orbiter (MRO) spacecraft. In targeted mode, a gimballed optical sensor unit (OSU) removes most along-track motion and scans a region of interest that is mapped at full spatial and spectral resolution (18 or 36 m/pixel, 362–3920 nm at 6.55 nm/channel). In the targeted mode, 10 additional, spatially binned images (180 m/pixel) are taken over the same region before and after the main image at 10 emergence angles ranging from -70° to 70°. They provide the so-called emission phase function (EPF) for the site of interest that is intended for atmospheric study and correction of atmospheric effects.

Regarding the atmospheric correction of CRISM data, McGuire et al. (2009) adapted and improved the so-called volcano-scan technique (Langevin et al., 2006). This method removes the CO_2 gas absorption bands of any spectrum of interest after division by a scaled reference spectrum (i.e. the ratio between the atmospheric transmission at the summit and the base of Olympus Mons evaluated on a Martian sol when the amounts of ice and dust aerosols were minimal). This simple technique works reasonably well for surfaces spectrally dominated by minerals, water ice, and sometimes CO_2 ice but does not correct for aerosol effects.

In McGuire et al. (2008), a DISORT-based model retrieved the dust and ice AOD, the surface pressure and temperature from previous experiment products as well as the acquisition geometry, and the measured I/F spectrum as inputs. Then, a surface Lambertian albedo spectrum is computed as the output. However, this algorithm does not retrieve the AOD directly from the images nor does it take advantage of the EPF measurements of the CRISM targeted mode.

Brown and Wolff (2009) proposed a first attempt in that direction by using the DISORT algorithm to model the signal at one wavelength (i.e. 0.696 μm). They iteratively adjust three parameters (surface albedo, dust and ice opacity) in order to achieve a close fit at five points spread across the EPF curve. Nevertheless the method is time consuming and the surface albedo is assumed to be Lambertian. It has been proved that this assumption bias the AOD and surface estimation (Lyapustin, 1999).

In this paper, we propose an original method that overcomes the previous limitations to retrieve the optical depth of the Martian dust from OMEGA or CRISM data at the reference wavelength of one micron. The method is based on a parametrization of the radiative coupling between aerosol particles and gas that determines, based on the local altimetry and the meteorological situation, the absorption band depth of gaseous CO_2. We consider the intensity of the absorption feature at 2 μm as a proxy of the AOD, provided that the other influencing factors have been taken into account. Our method relies on radiative transfer calculations that assume Lambertian properties for the surface even though, as demonstrated in this paper, the influence of the latter hypothesis is minimized by considering the effect of the aerosols on the gaseous absorption and not the total signal. When processing OMEGA observations, we are complementary to the method of Vincendon et al. (2008) since our approach processes pixels occupied by a wider variety of materials – pure mineral or water ice as well as CO_2 and H_2O deposits contaminated by a large amount of dust – while being observed at a fixed geometry. When processing CRISM observations we take full advantage of the top of the atmosphere spectral EPF measured by the instrument for the retrieval of the AOD.

This paper is organized as follows. In Section 2 we describe the post-processing and the formatting of the sequence of EPF calibrated image cubes accompanying the high resolution CRISM observation. In Section 3, we give insights about Martian atmospheric properties and radiative transfer (RT) in the SWIR range. Furthermore we describe models that calculate the spectral radiance coming from Mars and reaching the sensor at the top of the atmosphere. In Section 4 we expose the basic assumptions, RT parametrization, and properties on which relies the method for retrieving the AOD from the images. In addition we describe how we implement the method that is then validated on synthetic data. Finally, in Section 5, we present and discuss results obtained for representative observations, one from OMEGA and the others from CRISM. Conclusions are eventually drawn in the last section.

2. Post-processing and formatting of CRISM EPF observations

Due to the composite nature of CRISM EPF acquisitions, such data need some post-processing prior to AOD retrieval. First of all, CRISM data are transformed from apparent I/F units (i.e. the ratio of reflected radiance to incident intensity of sunlight) to reflectance units. A Lambertian surface is supposed and data are divided by the cosine of the solar incidence angle (Murchie et al., 2007).

CRISM data are corrected for artifacts caused by non-uniformities of the instrument, residuals of the radiometric correction or external sources. First, hyperspectral images are corrected for striping and spiking effects. Corrections for both distortions have been proposed by Parente (2008). Secondly, the CRISM spectrometer is affected by a common artifact to "push-broom" sensors, the so-called "spectral smile" effects. Smile effects refer to the artifacts originated by the non-uniformity of the instrument spectral response along the across-track dimension, i.e., the horizontal axis that corresponds to the data columns. The mitigation of smile effects is crucial since the spectral band corresponding to the absorption maximum of the CO_2 gas at 2 μm is particularly affected by spectral smile. We remember that the proposed AOD retrieval method is based on this spectral feature. As a matter of fact, the estimation of the AOD might be biased if smile effects are not addressed. Ceamanos et al. developed a twofold method that corrects CRISM observations for smile by mimicking an optimal smile-free spectral response (Ceamanos and Doute, 2010). Nevertheless since uncertainties associated to the method itself might propagate to the AOD retrievals we conservatively restrict the use of each spatially binned image to the central columns that own the best spectral response the so-called "sweet spot" columns. This decimation of the data is not a problem because the EPF sequence provides plenty of points for each 11 geometries.

CRISM observations are spatially rearranged to evaluate the atmosphere optical depth of a given terrain position depending on geometry. First, the central image that owns the highest spatial resolution is binned by a factor of 10 to match the spatial resolution of the EPF series. After that, all images are projected onto the same geographical space. At this point, CRISM observations showing a high overlap of the 11 acquisitions can be discriminated. In fact, a good overlap assures the existence of a high number of terrain units that have been sensed from many geometries. In a single hyperspectral data set that gathers all EPF images and the central scan (hereafter called CSP, Cube Spectro-Photometric), each super pixel conjugated to a given terrain unit gathers up to 11 spectra depending on the completeness of the overlap. More details can be found in Ceamanos et al. (2013).

3. Mars atmospheric radiative transfer

In the present section we give insights about Martian atmospheric properties and radiative transfer (RT) in the SWIR range.