RADIATIVE TRANSFER MODELING OF THE EMPIRCAL 'VOLCANO SCAN' ATMOSPHERIC CORRECTION: DISCUSSION OF ARTIFACTS.
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Introduction: Atmospheric correction of spectra acquired by the MRO CRISM spectrometer is important for interpretation of surface spectral reflectance properties because of scattering and absorbing aerosols and absorbing gases in the Martian atmosphere. Intense CO_2 absorptions occur in portions of the VNIR spectrum where vibrational features produced by OH and H_2O in hydrated minerals occur (Fig. 1). H_2O vapor in the atmosphere produces broad spectral features whose strength varies as a function of water vapor abundance. Dust aerosol contributions are highly variable and are most pronounced at shorter wavelengths (< 700 nm) and modulate spectral amplitude and slope at longer wavelengths (Fig. 1). Water ice aerosols (not discussed) can also influence spectra.

We use Discrete Ordinate Radiative Transfer (DISORT) modeling to simulate the commonly used empirical volcano scan correction method, which employs division by a scaled transmission spectrum derived from high and low altitude observation on Mars. DISORT model results are used to identify potential artifacts induced by the commonly utilized empirical volcano scan correction.

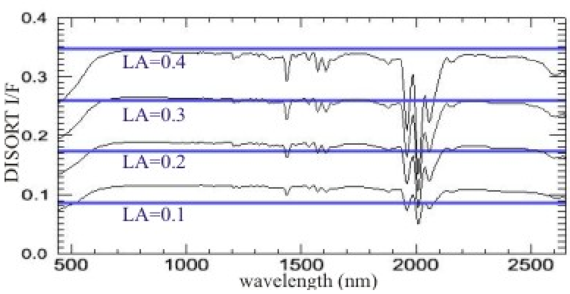

Figure 1. DISORT generated synthetic I/F spectra (black) that would be observed at the top of the Martian atmosphere for multiple spectrally neutral Lambertian surfaces (blue). Gases (CO_2, CO, and H_2O) and dust were modeled. Dust opacity = 0.6 at 900 nm, i = g = 30°, and e = 0°.

Dataset: The CRISM spectrometer [1] operates between 360 and 3960 nm and is capable of acquiring targeted hyperspectral images at 20 m/pixel. CRISM I/F (radiance (I) at sensor divided by the solar irradiance (F) divided by π) data and ancillary data products are available through the PDS at http://geo.pds.nasa.gov/missions/mro/crism.htm.

The CRISM spectrometer uses 2-D detector arrays and acquires data over 640 across track pixels for each channel (central wavelengths vary across columns, up to ± 7 nm). A relatively small (< 1.5 nm) temperature dependent wavelength shift also occurs [2].

Empirical Volcano Scan Correction: The volcano scan correction was originally implemented by the MEX OMEGA team to remove large atmospheric gas absorption features with minimal computational investment [3]. This method uses a scaled transmission spectrum derived from low and high altitude observations in which different path lengths through the atmosphere are measured. Transmittance between the base and summit of Olympus Mons, T_v, is determined using the integrated form of the Beer-Lambert Law,

$$T_v\ (\lambda) = I_\lambda(s_{0\to2})\ /\ I_\lambda(s_{0\to1}) = e^{-ks_{1\to2}},$$

where I_λ is equivalent to CRISM I/F at some wavelength (λ), k is the absorption coefficient of the optically active species, $s_{0\to1}$ and $s_{0\to2}$ are distances traversed through the atmosphere, and $ks_{1\to2}$ is the opacity (τ). It is implicit that the surface contribution to $I_\lambda(s_{0\to1})$ and $I_\lambda(s_{0\to2})$ is identical. In the presence of both scattering and absorbing molecules, the opacity is the sum of the absorbing (τ_{abs}) and scattering (τ_{scat}) optical depths, $\tau = \tau_{abs} + \tau_{scat}$. For the calculation of the transmission spectrum, τ is assumed to result entirely from τ_{abs}.

To perform the volcano scan correction, a target CRISM spectrum acquired through an arbitrary atmospheric path length (s_3) is divided by an exponentially scaled version of the transmission spectrum, T_v. The exponential scaling factor is calculated as the ratio of the band depth (BD) of a strong absorption feature in the target spectrum to the band depth of the same feature in the transmission spectrum. These band depths are proxies for the transmittance that occurred over the atmospheric path lengths of the two observations (assuming T=1 on the continuum), such that

$$BD_{targ} = I_{feature}(s_{0\to3})/I_{continuum} = e^{-ks_{0\to3}} \text{ and}$$

$$BD_{trans} = I_{feature}(s_{1\to2})/I_{continuum} = e^{-ks_{1\to2}}.$$

The exponential scaling factor is determined by taking the natural logarithm of the band depths,

$$\ln(BD_{targ})/\ln(BD_{trans}) = \ln(e^{-ks_{0\to3}})\ /\ \ln(e^{-ks_{1\to2}}) = s_{0\to3}/s_{1\to2}.$$

Band depth estimates that use two slightly different formulations have been evaluated [4]. One estimate, BD1, results in slightly higher exponential scaling factors than the other estimate, BD2. Applying the volcano scan correction to the target spectrum results in

$$I_{feature}(s_0)e^{-ks_{0\to3}}/(e^{-ks_{1\to2}})^{s_{0\to3}/s_{1\to2}} = I_{feature}(s_0),$$

where $I_{feature}(s_0)$ is the CRISM I/F value corrected for gas absorption, provided that all assumptions implicit in the volcano scan correction were met.

Modeling: We simulated the volcano scan correction using synthetic I/F spectra generated for conditions appropriate for the base and summit of Olympus Mons using DISORT [5, 6, 7]. Transmission spectra were generated from these synthetic I/F spectra using the technique described above. Multiple simulations were performed in which aerosol and surface parameters were adjusted. Exponential scaling factors calculated using BD1 and BD2 estimates were applied.

Results: CRISM volcano scan correction results are compared to analogous DISORT simulated volcano scan correction results (Fig. 2). Residual features near gas bands are evident in both the CRISM and DISORT simulated volcano scan corrected spectra (Fig. 2a-f). Applying a larger exponential scaling factor (BD1) results in 'hash' near 2000 nm caused by over correction of strong CO_2 bands and under correction of weaker CO_2 bands (Fig. 2c). Using a smaller scaling factor (BD2) results in under correction of CO_2 bands near 2000 nm that has the appearance of a broader feature (Fig. 2d). The addition of noise to the simulation (Fig. 2e-f) reduces the structured appearance of the residual features and looks more similar to the CRISM example (Fig. 2a-b), in which noise is inherent.

Residual gas features are also evident in DISORT simulated volcano scan corrected spectra in which all assumptions in the volcano scan correction were met, (e.g., the surface contribution to the low and high altitude spectra used to generate the transmission spectrum were identical and the aerosol opacity equals 0 so that the total opacity (τ) results only from gas absorption) (Fig. 2g-h). The residual gas features are affected by the choice of the constant exponential scaling factor used during the volcano scan correction (Fig. 2g-h).

The volcano scan correction does not address aerosol contributions. This results in slope differences between the input surface spectrum and the volcano scan corrected spectrum (Fig. 2c-e). In addition, aerosols affect the total opacity in the gas bands and using transmission spectra to correct target spectra with significantly different opacities alters gas band residuals.

Based on our comparison of volcano scan corrected and DISORT simulated volcano scan corrected spectra, we conclude that the residual features near gas bands in volcano scan corrected CRISM spectra are dominated by artifacts induced by applying the volcano scan correction. These artifacts occur as a result of scaling the transmission spectrum used in the volcano scan correction by a constant exponential factor, which is not physically correct. The absorption coefficient (*k*) changes as a function of column density. In the weak line limit (τ << 1), or linear regime, the absorptance (1-*T*) is proportional to the amount of absorbing molecules. In the strong line limit (τ >> 1), or saturated regime, there is a square root dependence on the column density [8]. In between these two limits, *k* is constant and a logarithmic relationship between absorptance and column density occurs. For pressures in the Martian atmosphere and gas line strengths in the NIR, linear and logarithmic regimes are important (Fig. 2i).

Artifacts induced by the empirical volcano scan correction can potentially be reduced with modifications to the method that include a wavelength dependent exponential scaling factor [9]. Artifacts induced by using a scaled transmission spectrum to perform atmospheric correction are avoided in more computationally intensive radiative transfer methods that calculate aerosol, gas, and surface contributions simultaneously (e.g., modeling using DISORT [5, 6, 7]).

References: [1] Murchie S. M. et al. (2007) *JGR*, 112. [2] Smith M. D. et al. (2009) *JGR*, 114. [3] Langevin Y. et al. (2005) *Science*, 307. [4] McGuire P. et al. (2009) *Planet. Spac. Sci.*, accepted. [5] Stamnes K. et al. (1998) *Appl. Opt*., 27. [6] Wolff M. J. et al. (2009) *JGR*, 114. [7] Wiseman S.M. et al. (2010) *JGR*, in prep. [8] Thomas G.E. and Stamnes K. (2002) *Radiative Transfer in the Atmosphere and Ocean*. [9] Morgan F. (2010) *JGR,* in prep.

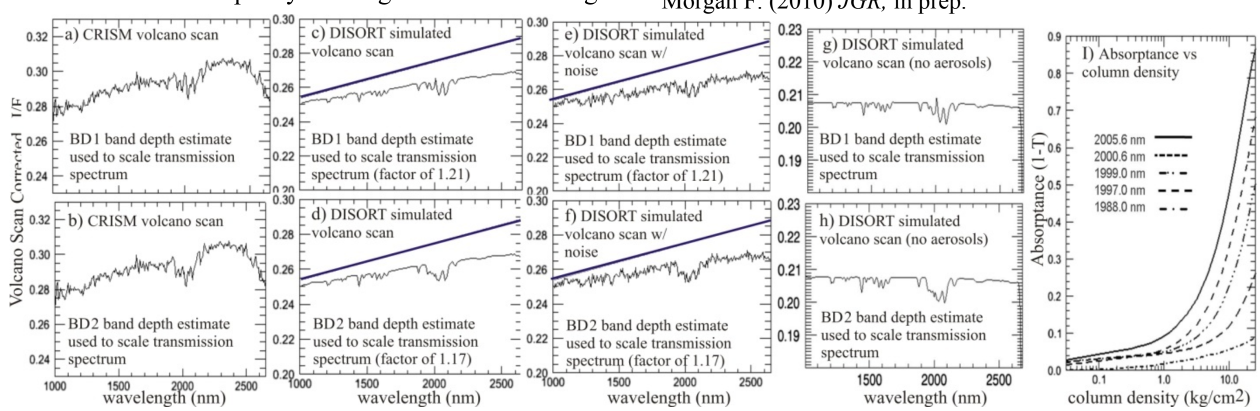

Figure 2. a, b) Volcano scan corrected CRISM spectra in which the target spectrum was extracted near the base of Olympus Mons from the same observation (FFC00008608) that the transmission spectrum was derived (avoids the temperature dependent wavelength shift). c, d) DISORT simulated volcano scan corrected spectra (black) for the surface spectrum shown in blue. Note - a perfect atmospheric correction would result in the black spectrum plotting on top of the blue spectrum. f) Same as c, d but with random Gaussian noise added. g, h) Same as c, d but with no aerosol contributions and modeled for a spectrally neutral surface. i) DISORT modeled absorptance vs column density for selected wavelengths.