THE EFFECTS OF ICE AND DUST AEROSOLS, AND SURFACE SCATTERING ON THE INTERPRETATION OF THE MARTIAN NORTH POLAR ICE CAP SURFACE CHARACTERISTICS USING CRISM VNIR-SWIR DATA. A. C. Pascuzzo[1], T. Condus[2], J. F. Mustard[1] and R. E. Arvidson[2], [1]Dept. of Earth, Environmental, and Planetary Science, Brown University, RI, USA (alyssa_pascuzzo@brown.edu), [2] Dept. of Earth and Planetary Sciences, Washington University in St. Louis, MO, USA.

Introduction: Martian atmospheric aerosols affect the spectral radiance properties of icy/dusty surfaces measured by remote VNIR-SWIR spectrometers and produce artifacts in spectral slope, albedo, and absorption strength of spectral data. Additionally, the unknown scattering properties of these icy surfaces add complexity to deciphering the radiance contributions from surface and atmosphere. This work demonstrates that rigorous atmospheric-surface corrections influence interpretations of surface properties in analyses of VNIR-SWIR data from CRISM at the north polar region of Mars, specifically of the North Polar Residual Cap (NPRC) and North Polar Layered Deposits (NPLD). We have assessed the sensitivity of single-scattering albedo (SSA) and reflectance retrievals, from discrete-ordinate radiative transfer modeling (DISORT), under different aerosol and surface scattering parameters to answer the following:

- What is the approximate surface scattering behavior of the ice cap?
- How do untreated aerosols affect spectral characteristics and interpretation of the surface through typical analyses such as H_2O Index parameters and Hapke mixture modeling?
- How does assuming Lambertian versus non-Lambertian scattering affect spectral characteristics and interpretation of the surface?

Background: CRISM full-resolution targeted (FRT) observations (18 m/pixel) have the potential to retrieve spatial and temporal variability of ice and dust abundance and grain size. However, CRISM FRTs have been minimally utilized over the ice cap to quantify the surface ice and dust [1,2]. This is partly due to the complex but necessary correction for the variable state of ice and dust aerosols in the atmosphere and surface scattering properties of icy and dusty surfaces.

Previous studies have used band depth parameters, such as the H_2O ice index [3]. The H_2O index uses the band depth of the 1.5 μm ice absorption and has been used to investigate seasonal ice changes of the NPRC [4,2,5]. [2] estimated the H_2O index of icy spectra changes ~0.01-0.02 due to modest ice aerosol opacities for clear atmospheric conditions. However, this error estimate did not model the effects of dust aerosols on the H_2O index or the effects of surface scattering (typically assumed to be Lambertian to simplify the modeling). [6] investigated the effects of treating or not treating dust aerosols on OMEGA data over the north polar region and found that changes in seasonal ice albedo are partially controlled by dust aerosols (second to the removal of surface dust). Although some previous spectral studies have attempted to account for aerosols, the sensitivity of the aerosol optical depth and surface scattering assumptions in atmospheric radiative transfer models has not been well characterized.

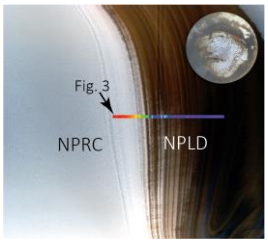

Figure 1. A true color image of the CRISM scene, not map projected, used in this study (FRT0000BEB8). The rainbow inset is a 2,000 pixel spatial subset used in spectral analysis after DISORT due to the computational expense of applying Hapke non-linear unmixing to the entire scene.

Methodology: *Radiative modeling of aerosols and surface scattering.* We used CRISM observation FRT0000BEB8, located at trough site N0 [7,8], 87°N 96°W (Fig. 1). This image captures a portion of the NPRC, the NPLD exposed along a trough wall, and the floor of the trough. The observation was acquired during optimal instrument operating temperatures (-152°C), providing high signal-to-noise, and in martian northern summer (L_s=108°) to avoid the seasonal CO_2 frost and dusty atmospheric conditions.

Attenuation and scattering of light due to aerosols in the atmosphere and scattering from the surface are accounted for using DISORT [9–11]. Atmospheric effects from CO_2 gas are removed using the standard volcano-scan correction before the DISORT modeling [12]. Atmospheric aerosols were modeled using the full range of viewing geometries covered by the emission phase function (EPF) observations for the CRISM data (phase angles range from 45°-120°). We also model variations in incidence and emergence angles.

Four parameters were adjusted within DISORT: atmospheric dust (τ_d) and water ice optical depths (τ_i), fraction of forward scattered light off the surface (*c*), and the width of the scattering lobe (*b*). We adjusted these parameters until the retrieved SSA at a given wavelength is constant for the same targeted point on the surface regardless of the viewing angle. We deemed the set of parameters closest to meeting this criterion as the best SSA retrieval. Within DISORT, surface scattering is defined by the Hapke bidirectional reflectance function and two-term Henyey-Greenstein

Table 1. Correction Parameters	τ_d (@ 9.3 μm)	τ_i (@ 12.1 μm)	*b*	*c*
#1 lambert, aerosols not treated	-	-	0	-
#2 wide backscattering	0.124	0.0	0.1	0
#3 broad, modestly-forward scattering	0.124	0.0	0.25	0.6
#4 narrow forward scattering	0.124	0.0	0.5	0.8
#5 minimum summer dust	0.100	0.0	0.25	0.6
#6 maximum summer dust	0.130	0.0	0.25	0.6
#7 MCD dust estimate + ice	0.124	0.05	0.25	0.6

**opacity ranges typical for over the north polar cap during the summer (estimated range from the MCD). #3 uses MCD dust estimate*

function, which contains *b* and *c*, which we use to retrieve surface SSA at every wavelength and CRISM pixel. These variables were varied to test the effects of wide vs. narrow backscattering and forward surface scattering assumptions (Table 1). Additionally, 3 different aerosols optical depths were assessed. The dust optical depth (τ_d) for #3 parameters was estimated from the Mars Climate Database [13] for the date, time, and location that the image was acquired* (Table 1).

The DISORT and SSA retrieval process produced denoised SSA image cubes [14] that were then converted to reflectance using the Hapke radiance coefficient equation [15]. The reflectance data were used to calculate H_2O index maps of each correction. The SSA data were used to solve for abundance and grain sizes using a non-linear unmixing model assuming intimate mixtures of water-ice [16], dust and palagonite [17,10].

Results: For this CRISM observation, the best SSA estimates are retrieved under a broad, modestly-forward surface scattering behavior (i.e., particles with moderate internal structure), using the MCD τ_d estimate, and τ_i of 0 (Table 1; #3). When a narrow forward scattering assumption is applied, the SSA retrievals are > 1.0 in the visible, thus an unrealistic scattering behavior for the polar ice cap. Additionally, when a τ_i of 0.05 is used, the retrievals at ice absorptions are below 0.0. Therefore, it's best to assume negligible ice aerosols in this scene.

Leaving dust aerosols untreated causes ice absorptions to be weaker and spectral slope redder (Fig. 2), resulting in underestimation of the H_2O index values up 8% for the ice-rich NPRC (Fig. 3). Uncertainty in the true τ value at the time of data acquisition, as assessed through #5 and #6, results in negligible variation in both the H_2O index and non-linear unmixing results, < 3% and < 2% (Fig. 3).

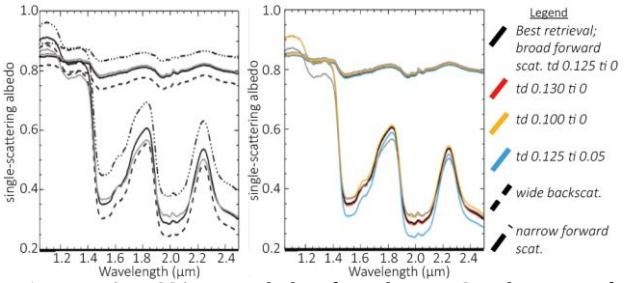

Figure 2. Ave. SSA spectral plots from the NPRC and NPLD Left: showing the spectral effects of assumed scattering behavior. Grey spectrum is from the simplified 'lambert-aerosols not treated' data. Right: effects of ice and dust aerosols versus no aerosols.

Changing the surface scattering parameters affects the spectral albedo (Fig. 2), but not the absorption strength (Fig. 3). This is expected since *b* and *c* are independent of wavelength in DISORT. The scattering parameters also affect the relative ice abundance from non-linear unmixing. The maximum ice difference is 8% for DISORT runs #2 and #4, while the maximum ice difference exceeds 20% between the best DISORT-SSA retrievals and the Lambertian/no-aerosols data.

Conclusions: Dust aerosols cause significant changes in retrieved surface spectra. Left untreated they can lead to error in analysis and interpretation of reflectance and SSA data. Future studies, especially those investigating seasonal changes of the NPRC, should prioritize corrections for the variable state of aerosols in the atmosphere to minimize uncertainty. Error due to τ_d uncertainty is minimal as long as the estimated τ_d is within ~0.05 of the true τ_d.

Although surface scattering behavior does not affect interpretations of H_2O index, accounting for the appropriate surface scattering behavior is needed to retrieve the most accurate SSA and reflectance values, decreasing errors in estimated abundances and grain sizes via non-linear radiative transfer modeling.

References: [1] Calvin, W. M. et al. (2009) *JGRP*, *114*; [2] Brown, A. J. et al. (2016) *Icarus*, *277*, 401–415; [3] Langevin, Y. et al. (2005) *Science*, *307*, 1581–1584; [4] Brown, A. J. et al. (2012) *JGRP*, *117*; [5] Appéré, T. et al. (2011) *JGRP*, *116*; [6] Vincendon, M. et al. (2007) *JGRP*, *112*; [7] Fishbaugh, K. E. et al. (2010) *GRL*, *37*; [8] Becerra, P. et al. (2016) *JGRP*, *121*; [9] Stamnes, K. et al. (1988) *Appl. Opt.*, *27*, 2502–2509; [10] Wolff, M. J. et al. (2009) *JGRP*, *114*; [11] Arvidson, R. E. et al. (2006) *JGRP*, *111*; [12] McGuire, P. C. et al. (2009) *PSI*, *57*, 809–815; [13] Madeleine, J.-B. et al. (2009) *Icarus*, *203*, 390–405; [14] Kreisch, C. D. et al. (2017) *Icarus*, *282*, 136–151; [15] Hapke, B. (1993) *Theory Reflectance Emit. Spectrosc. 2nd Ed.*; [16] Warren, S. G. and Brandt, R. E. (2008) *JGRA*, *113*; [17] Wolff, M. J. et al. (2006) *JGRP*, *111*.

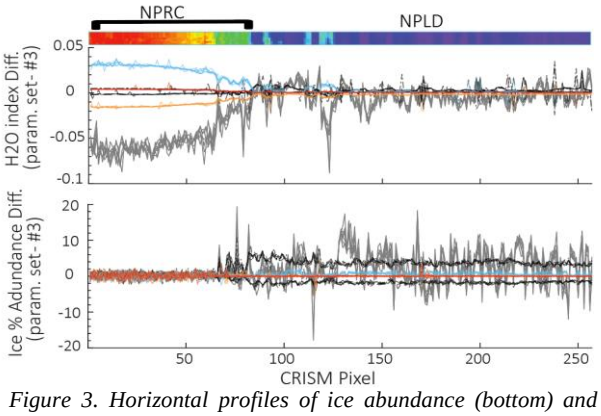

Figure 3. Horizontal profiles of ice abundance (bottom) and H_2O index values (top) from the spatial subset (Fig 1). Y-axis is the difference between the results from each parameter set and the #3 parameter set (most accurate SSA retrieval). For legend, refer to Fig 2 or Table 1.