Determining Water Ice Content of the Martian Regolith by Nonlinear Spectral Mixture Modeling

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Background

- Icebreaker life—a proposed Martian Lander—seeks to drill into the regolith to collect samples.
- These samples will then be analyzed for biomarkers.
- Drilling into the subsurface provides the opportunity to assess the vertical distribution of water ice to one meter.
- We want to understand the uncertainty involved in using a three-color imaging system to constrain the abundance of water ice in regolith samples.

Methodology

- We acquire the spectrum of a icy regolith sample, let the ice sublimate, and take another spectrum of the dehydrated sample under the same viewing geometry.
- The spectrum of the dehydrated sample is used to obtain the optical constants of the regolith (see below).
- Shkuratov modeling is then used to model mixtures of regolith and water ice to constrain the abundance of water ice in the original icy sample.
- The real and imaginary indices of refraction are derived using an initial estimate for the index of refraction, assumed regolith grain size, and porosity; and iterating through Equations 13 and 14.
- The assumed regolith grain size and porosity does not matter so long as these same parameters are used in the modeling of the regolith mixed with water ice.
- We performed a case study and an experiment in order to understand the uncertainties involved in the process.

Lab Experiment: Three types of soil were mixed with water at different abundances and frozen. Spectra were take, the sample was allowed to sublimate, then more spectra were taken.

Case Study: Phoenix data of the Snow White Trench between Sol 45 and 50 of Phoenix's mission were analyzed. The time between the observations allowed for sublimation of ice.

Mixture Modeling

-We used Shkuratov et al (1999) instead of Hapke (1981) because the viewing geometry is not used to calculate the albedo, and it is reversible—one can determine the imaginary indices of refraction from a measured reflectance.
- Shkuratov mixing takes into account the components' concentration c, its effective optical pathlength (size) S, real index of refraction n, and imaginary index of refraction κ at a wavelength λ. It also accounts for the volume fraction filled with particles q.

$$r_b = R_b + \frac{1}{2}T_eT_iR_i\frac{e^{-2\tau}}{1-R_ie^{-\tau}} \qquad (1)$$

$$\tau = \frac{4\pi\kappa S}{\lambda} \qquad (2)$$

$$r_f = R_f + T_eT_ie^{-\tau} + \frac{1}{2}T_eT_iR_i\frac{e^{-2\tau}}{1-R_ie^{-\tau}} \qquad (3)$$

- Here r_b and r_f represent the angularly averaged light scattering indicatrix of a particle.
- R_b and R_f are the average backwards and forwards reflectances, respectively, and are functions of the real index of refraction n. Meanwhile, R_i and R_e are the average internal and external reflectances, respectively.
- T_e and T_i are the average transmittances:

$$R_e = R_b + R_f \qquad (4)$$

$$R_i = 1 - \frac{1-R_e}{n^2} \qquad (6)$$

$$T_e = 1 - R_e \qquad (7)$$

$$T_i = 1 - R_i \qquad (8)$$

- ρ_b and ρ_f represent the one-dimensional indicatrix of a layer, where the layer is a coarse mixture of components.

$$\rho_b = q\sum_j c_j r_{b,j} \qquad (9)$$

$$\rho_f = q\sum_j c_j r_{f,j} + 1 - q \qquad (10)$$

- The 1D indicatrix is then used to model the albedo.

$$A = \frac{1+\rho_b^2-\rho_f^2}{2\rho_b} - \sqrt{\frac{1+\rho_b^2-\rho_f^2}{2\rho_b} - 1} \qquad (11)$$

- This A is the hemispheric or integral albedo A_{int} and is related to the bidirrectional reflectance at an incidence angle 30° and emission angle 0°(Shkuratov & Grynko, 2005):

$$\log R(30°) = 1.088 \log A_{int} \qquad (12)$$

- The Shkuratov mixture model is also reversible:

$$\kappa = \frac{-\lambda}{4\pi S}\ln\left[\frac{b}{a} + \sqrt{\left(\frac{b}{a}\right)^2 - \frac{c}{a}}\right] \qquad (13)$$

$$a = T_eT_i(yR_i + qT_e) \qquad b = yR_bR_i + \frac{q}{2}T_e^2(1+T_i) - T_e(1-qR_b)$$

$$c = 2yR_b - 2T_e(1-qR_b) + qT_e^2 \qquad y = (1-A)^2/2A$$

Subtractive Kramers-Kronig

$$n(\lambda_0) = n(\lambda_v) + \frac{2}{\pi}(\lambda_v^2-\lambda_0^2)\,P\int_0^\infty \frac{\lambda^2\kappa(\lambda)}{(\lambda_0^2-\lambda^2)(\lambda_v^2-\lambda^2)}d(\ln\lambda) \qquad (14)$$

- Given the imaginary component of a complex number (such as the index of refraction), one can derive the real component. If one only has a limited range of data, subtractive Kramers-Kronig Analysis is used—which assumes one knows the real index of refraction at one wavelength.
- In Equation 14, P denotes the Cauchy Principal part of the integral, λ_v is the wavelength for which you know the real index of refraction, and λ_0 is the wavelength for which one is determining the real index of refraction.

Results

- Observations and models are shown in Figures 1 and 2.
- Changes in porosity do not vary modeled albedos by more than a 0.1 albedo from 0-99% porosity.
- Thicker ice grains will simply increase absorption in the near infrared. 100 µm ice grains produce nearly identical plots to those shown in figures 1 and 2. Ice grains of greater magnitudes would simply produce dirty ice—which would be modeled in another fashion entirely.
- Raising the assumed index of refraction of the regolith lowers the albedo of a modeled mixture.

Lab-Experiment

- In the lab experiment, the dessicated baseline is from only the less icy of the two samples of each soil type.
- **Soil** (Fig 2A): The 0.15 water-ice soil is darker when it is icy than when the ice has been dessicated. As mixing in ice only serves to make a mixture more reflective, the modeled mixtures will always have a greater albedo by at least 0.05-0.15.
- The 0.2 water-ice soil had a modeled albedo within 2% of the observed albedo.
- **Silicate Sand** (Fig 2B): For both samples, modeled mixtures have albedos within 3% of that observed.
- As higher n lowers the albedo, can infer the index of refraction of silicate sand is close to 1.4.
- **Basaltic Soil** (Fig 2C): The far higher albedo of the model of the 0.22 water-ice soil is likely a result of using the dessicated 0.059 as the baseline.

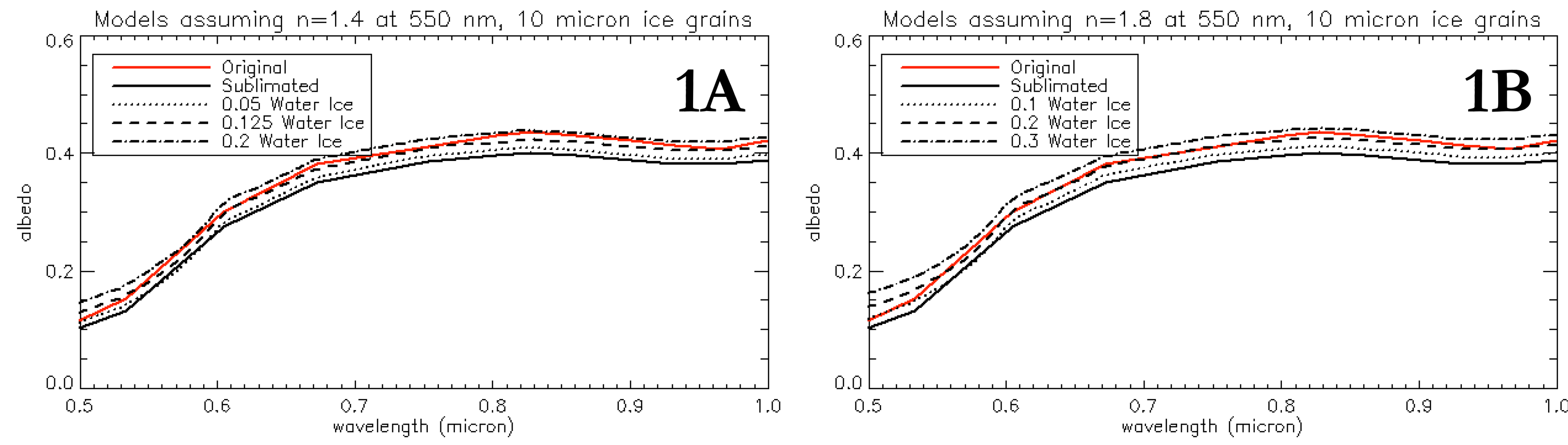

Figure 1: Modeled mixtures overlaid on actual spectra of the Snow White Trench before and after sublimation. Assumed a regolith grain size of 60 µm, ice grain size of 10 µm, and a porosity of 0.15. **(A):** Assumed n=1.4 at 550 nm, **(B):** n=1.8 at 550 nm.

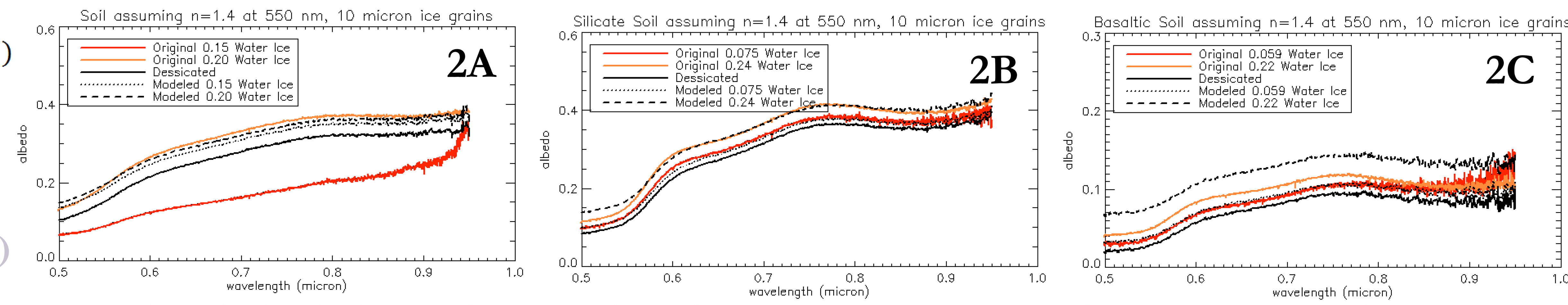

Figure 2: Observed and modeled spectra of icy samples. Assumed n=1.4 at 550 nm, sample grain size of 100 µm, porosity 0.15, and ice grain size of 10 µm. **(A):** Soil **(B):** Silicate Sand **(C):** Basaltic Soil

Case-Study

- Not exactly the viewing gemoetry for Eq. 12, but will remain accurate within a few percent.
- Real index was assumed to range between n=1.4-1.8, resulting in a spread of water ice abundance from 5-30% (Fig 1). This is consistent with emplacement by vapor diffusion, rather than melting.

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