Nonlinear Spectral Mixture Modeling to Estimate Water-Ice Abundance of Martian Regolith

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Abstract

We present a new technique to estimate the abundance of water-ice in the Martian permafrost using Phoenix Lander Surface Stereo Imager (SSI) multispectral data. Past work estimated this abundance by employing radiative transfer methods to model the spectra of ice and regolith mixtures using the optical constants of water-ice and a Martian-analogue soil. Our technique removed the uncertainty of using an analogue (or of estimating a regolith composition) by deriving the optical constants directly from observations of icy regolith acquired before and after sublimation of the ice at similar viewing geometries. Laboratory spectral measurements of known mixtures of water-ice and dry soil at controlled viewing geometries allowed us to constrain the uncertainty in our technique. We found that model fits across the observational uncertainty will contain the actual water-ice fraction. We then applied the technique to Phoenix SSI observations of Snow White trench and Dodo-Goldilocks trench. For the Snow White Trench we estimated water-ice abundances consistent with pore-fill in the near-surface ice, consistent with atmospheric diffusion. For the Dodo-Goldilocks Trench we estimate water-ice abundances larger than pore-fill would allow. These results have implications to our understanding of the history of water-ice on Mars and the role of the regolith at high latitudes as a reservoir of atmospheric H\textsubscript{2}O.

Key Words: Ices; Mars; Spectroscopy

1 Introduction

One of the key goals of the Mars Exploration program is understanding the history and state of water on Mars. Although the past decade has seen significant advances in this field, important questions remain pertaining to the emplacement of water in the late Amazonian. In this context, the northern lowlands are particularly intriguing because significant amounts of ice may be shallowly buried at mid- to high-latitudes \cite[e.g.][]{Boynton2002, Mellon2004, Mellon2009, Diez2008, Plaut2009, Dundas2014, Dundas2018}.

Much of the Martian regolith’s upper few meters are thought to be in diffusive equilibrium with the atmosphere, meaning water-ice would merely fill the pore-space between regolith grains \cite{Mellon2004}, and therefore constrains the volume of ice that can be stored. Indeed, experiments by \cite{Hudson2009} and \cite{Siegler2012} demonstrate pore-fill from water vapor diffusion under Mars surface conditions. Porosity in the uppermost desiccated layer of the regolith was estimated to vary between 25-60\% at the Viking landing sites \cite{Moore1987}, and between 50-55\% at the Phoenix landing site \cite{Zent2010}. Ice-abundances greater than pore-fill fraction would suggest another emplacement mechanism, such as the freezing of a body of surface water \cite{Carr1990}, subsurface growth of an ice lens \cite{Konrad1993}, snowfall \cite{Mischna2003, NoeDobrea2018}, or buried pack ice \cite{Prettyman2004}.

The Mars Phoenix lander provided an opportunity to compare ice emplacement models \cite{Mellon2004} and remote sensing observations of Martian ground ice \cite{Boynton2002,
Following this introduction is Section 2: a short review of the theory behind how we model spectra of mixtures as well as derive the necessary optical constants. In Section 3 we detail our methodology in applying these techniques to samples in the lab, as well as the results of these experiments. We then apply the methodology to data from the Phoenix Mars lander in Section 4. We discuss the results of that analysis and implications in Section 5 before our concluding remarks in Section 6.

2 Theory

The strong optical constants of most geologic materials in the visible-to-near-infrared (VNIR), and the resulting high reflectance values, result in a significant contribution of multiple scattering to the spectrum of an intimate mixture. Radiative transfer techniques (e.g. [Hapke, 2012, and the resulting high reflectance values, result in a significant contribution of multiple scatter-

The method of [Shkuratov et al., 1999] models a one-dimensional albedo. [Shkuratov & Grynko, 2005] expand upon this model and provide a relationship between the bi-directional reflectance at a phase angle of 30° ($R(30°)$) and the one-dimensional albedo ($A_{int}$):

$$\log_{10}(R(30°)) = 1.088 \log_{10}(A_{int})$$

(2)
<table>
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<tr>
<th>JSC Mars-1 (g)</th>
<th>H₂O ice (g)</th>
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<th>vol% ice</th>
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<tr>
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<tr>
<td>4.937</td>
<td>1.439</td>
<td>22.6</td>
<td>37.8</td>
</tr>
</tbody>
</table>

Table 1: Water-ice fraction of each of our sample mixtures.

While relationships for other viewing geometries can be derived [Shkuratov & Grynkó, 2005], we constrained our laboratory work to a viewing geometry of 30° incidence and 0° emission since this relationship is already known. This viewing geometry is also less prone to background scatter we observed at greater phase angles.

Our primary motivation to utilize [Shkuratov et al., 1999] over other spectral mixture models is that it is invertible, meaning we can compute optical constants of a material given its reflectance, porosity, and grain size $S$. This method requires the assumption of a real index of refraction and generates only the imaginary index of refraction $k$ at a specific wavelength $\lambda_i$:

$$k(\lambda_i) = -\frac{\lambda_i}{4\pi S} \ln \left[ \frac{b}{a} + \sqrt{\left(\frac{b}{a}\right)^2 - \frac{a}{b}} \right]$$  \hspace{1cm} (3)

where $a$, $b$, and $c$ encompass properties such as grain size and real index of refraction.

Subsequently, Kramers-Kronig analysis is used to find the index of refraction $n$ at a specific wavelength $\lambda_i$ by integrating over the imaginary index of refraction over all wavelengths:

$$n(\lambda_i) = n_{vis} + \frac{2(\lambda_{vis}^2 - \lambda_i^2)}{\pi} P \int_0^\infty \frac{\lambda^2 k(\lambda)}{(\lambda_i^2 - \lambda^2)(\lambda_{vis}^2 - \lambda^2)} d(\ln \lambda)$$  \hspace{1cm} (4)

where $P$ denotes the Cauchy principal part of the integral [Ahrenkiel, 1971, Dalton & Pitman, 2012].

We use equations 3 and 4 iteratively to converge on the optical constants of a material. However, subtractive Kramers-Kronig still assumes we know the real index of refraction at one wavelength $\lambda_{vis}$, so we estimate between a range (1.4-1.7) that is typical at 550 nm. We do not need to accurately extrapolate the spectrum from beyond our spectral range as subtractive Kramers-Kronig converges quickly [Ahrenkiel, 1971]. It is sufficient to assume a constant $k(\lambda)$ outside our spectral range.

3 Laboratory Methodology and Results

In order to determine the uncertainty of the methods discussed above, we tested them on mixtures of JSC Mars-1 (a Martian soil simulant [Allen et al., 1998]) and water ice grains. These mixtures contained known concentrations of the two components (Table 1). We produced water-ice grains by grinding water-ice in a mortar and pestle within a freezer at about -20°C. Still within the -20°C freezer, we sieved both components to a size-range of 150-250 µm and measured the mass of each portion of the mixture before mixing carefully and thoroughly with a small spoon. In order to transform between wt.% and vol.%, we assumed mean particle densities of 1.91 g cm$^{-3}$ [Allen et al., 1998] and 0.9167 g cm$^{-3}$ [Lide, 2005] for JSC Mars-1 and water ice, respectively.

As Shkuratov and Grynkó provide Equation 2 for converting from a bidirectional reflectance with a phase angle of 30° to integral albedo [Shkuratov & Grynkó, 2005], we set up our experiment such that light was incident at 30° and our spectrometer measured light emergent at 0°. Samples were measured on an adjustable stand, which ensured that both our white reference and our samples were measured at the same distance from the spectrometer.

After we measured spectra of a mixture sample, we needed to desiccate the sample. We were unable to place our samples in a Mars-like environment in order to sublimate the water ice, and placing the sample in a vacuum chamber at room temperature led to the water ice violently boiling and creating a rough surface texture. Instead, we placed the sample under a heat lamp to remove the ice via melting and evaporation. Once the sample was desiccated, we measured its spectrum again. All spectral measurements were performed at -20°C using an Analytic Spectral Devices, Inc. (ASD) FieldSpec 3 spectrometer, and reflectance was reported relative to our SpecTralon white reference. For each sample, we acquired 25 spectra at each of 5 points on the sample.
Figure 1: Top: Observed and modeled albedos of water ice grains. This paper’s model uses the optical constants derived from the observed albedo, and hence our model perfectly overlies the observed albedo. Assumed ice grain particle size is irrelevant as long as the same size is assumed for the derivation of the optical constants as for the generation of the model spectra (in this case 200 µm). The other model uses optical constants from [Warren & Brandt, 2008]. Middle: Real index of refraction that we derived for water ice versus values from [Warren & Brandt, 2008]. Note that while there is a difference in slope, the absolute difference in \( n(\lambda) \) between our optical constants and [Warren & Brandt, 2008]'s is less than 1%. Bottom: Imaginary index of refraction that we derived for water ice versus values from [Warren & Brandt, 2008].

We cannot ground-truth the water-ice grain sizes with Phoenix’s suite of instruments, however the effect of water-ice grain size on the model spectrum throughout the Phoenix SSI spectral range (450-1000 nm) only becomes significant for ice grain sizes exceeding 1 mm (Fig. 2).

As noted in [Poulet et al., 2002]'s comparison of [Shkuratov et al., 1999] and [Hapke, 1981] spectral mixture theories, there is only a weak dependence of porosity on model spectra produced by the Shkuratov et al. method. For instance, modeling a 50/50 mixture of JSC Mars-1 and water-ice produces only a 3-6% increase in albedo with a decrease in porosity from 50 to 25 vol.% (Figure 3), approximately the range of porosities expected on Mars.

We derived our own optical constants for water ice using a sample of pure ice grains (Fig. 1). We assumed the real index of refraction of water-ice to be \( n = 1.311 \) at 550 nm as per [Warren & Brandt, 2008].

Johnson and Grundy (2001) found JSC Mars-1 to have a real index of refraction \( n = 1.56084 - 0.052355 \lambda / \mu m \) [Johnson & Grundy, 2001]. Given that we would not have this information when deriving the optical constants of Martian regolith observed \textit{in situ}, we modeled JSC Mars-1 with test values of \( n \) ranging from 1.4 to 1.7 at 550 nm. This range brackets the index of refraction of most common minerals [Guinness et al., 1997].

We compare spectra of our icy soils (Table 1) to models generated using the optical con-
Figure 2: (Color) Modeled spectra of a mixture of JSC Mars-1 and water-ice for a range of water-ice grain sizes. The difference in spectra between water-ice at 20 and 200 µm is insignificant within the spectral range of interest. Significant effects on the spectra in the spectral region of interest only start occurring for grain sizes greater than 1 mm.

Figure 3: (Color) Modeled spectra of a mixture of 50 vol.% JSC Mars-1 and 50 vol.% water-ice (both with a grain size of 200 µm), assuming a range of porosities.
Figure 4: (Color) Reflectance spectrum of a mixture of 11.9 vol.% water-ice with JSC Mars-1 (solid black circles, thick error bars) and after desiccation (empty black circles, thin error bars), resampled to Phoenix SSI bandpasses. We use the standard deviation for our uncertainty. A solid blue line is our best fit model for the icy regolith assuming the real index of refraction $n$ at 550nm was 1.4, while the orange dashed line assumes $n(550\text{nm})=1.7$. The thin blue and orange error bars represent the best fit models at the extent of our uncertainties assuming $n(550\text{nm})=1.4$ and 1.7, respectively.

Figure 4, 5, and 6 show our observed and modeled spectra convolved with SSI filter responses. All other factors held constant, we fit for the concentration of water-ice grains iteratively and compare to the known original ice fraction (Table 2). In addition to the mean fit, we also fit our model to the mean albedo plus-or-minus the albedo’s standard deviation. In terms of absolute volume percent, our mean model fit underestimates the actual water-ice by up to half, depending on the mixture. However, spectral models using the actual water-ice fraction fall within the 1σ envelope defined by the spectral models derived from average albedo plus-or-minus the standard deviation. Unknown values of porosity and real index of refraction at 500 nm will contribute to the uncertainty but the uncertainty is dominated by the standard deviation of our observed reflectances.

$$T(\lambda) = e^{-\left(\frac{\lambda - \lambda_C}{W}\right)^4}$$  \hspace{1cm} (5)
Figure 5: (Color) Reflectance spectrum of a mixture of 20.6 water-ice with JSC Mars-1 (solid black circles, thick error bars) and after dessication (empty black circles, thin error bars), resampled to Phoenix SSI bandpasses. We use the standard deviation for our uncertainty. A solid blue line is our best fit model for the icy regolith assuming the real index of refraction $n$ at 550nm was 1.4, while the orange dashed line assumes $n(550 \text{ nm})=1.7$. The thin blue and orange error bars represent the best fit models at the extent of our uncertainties assuming $n(550 \text{ nm})=1.4$ and 1.7, respectively.

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<tr>
<th>Ice Fraction</th>
<th>Best Fit (vol.%)</th>
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<tr>
<td>vol.% ice</td>
<td>$n(550 \text{ nm})=1.4$</td>
</tr>
<tr>
<td>wt.% ice</td>
<td>$n(550 \text{ nm})=1.4$</td>
</tr>
<tr>
<td>---------------</td>
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</tr>
<tr>
<td>11.9</td>
<td>6.08</td>
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<td>37.8</td>
<td>22.6</td>
</tr>
</tbody>
</table>

Table 2: Water-ice fraction of each of our sample mixtures, both known values and best fit values.
Figure 6: (Color) Reflectance spectrum of a mixture of 37.8 water-ice with JSC Mars-1 (solid black circles, thick error bars) and after dessication (empty black circles, thin error bars), resampled to Phoenix SSI bandpasses. We use the standard deviation for our uncertainty. A solid blue line is our best fit model for the icy regolith assuming the real index of refraction $n$ at 550nm was 1.4, while the orange dashed line assumes $n(550 \text{ nm})=1.7$. The thin blue and orange error bars represent the best fit models at the extent of our uncertainties assuming $n(550 \text{ nm})=1.4$ and 1.7, respectively.

4 Application to Phoenix Data

4.1 Snow White Trench

Phoenix excavated Snow White Trench (Figure 7) to find water-ice mixed with the regolith. By Sol 45 (Figure 8), the same bright icy material appeared darker than the surrounding soil because the ice is forward-scattering [Cull et al., 2010] (see viewing geometries in table 3). On Sol 50, the water-ice had sublimated completely, such that the spectrum of the soil which used to contain water-ice matched the surrounding soil (Figure 9). Because these two spectra matched, we used the spectrum of the non-icy regolith acquired on Sol 43 to derive optical constants.

We used SSI $I/F$ (IOF) images where $I$ is radiance from the scene, and $\pi F$ is radiance from the Sun at the Martian surface, corrected for Sun angle (such that the light is incident perpendicular to the surface), atmospheric opacity, and dust [Drube et al., 2010]. Light reflected by Snow White Trench to SSI was at an emergent angle of approximately $47^\circ$, and not at $30^\circ$ for which we could use Equation 2. While Shkuratov and Grynko did not provide a relation between bidirectional reflectance at a $47^\circ$ phase angle and integral albedo, we derived a relation for reflectance at $50^\circ$ phase to integral albedo from a plot of this relationship in their paper [Shkuratov & Grynko, 2005]:

$$\log_{10}(R(50^\circ)) = 1.013 \log_{10}(A_{int})$$

Were the equation truly for a phase angle of $47^\circ$, we would expect a constant between 1.013 and 1.088 (Equations 6 and 2, respectively), but closer to 1.013. Nevertheless, we used equation 6 to transform SSI reflectance spectra into the integral albedo spectra used in the Shkuratov et al. methodology [Shkuratov et al., 1999].

To derive the regolith’s optical constants, we assumed a grain size of 60 $\mu$m [Goetz et al., 2010] and a porosity of 0.5 (for the dessicated regolith, following [Zent et al., 2010]'s porosity measurement of 50-55% in the upper 15 mm of the Martian surface). Since the porosity range of dry regolith is only 5 vol.%, modeled albedo is not expected to vary by more than 1%. Ice grain size matters
Table 3: Viewing geometries of Phoenix Lander trench observations used in this study, where $i$ is the incidence angle of light upon the trench (90° - solar elevation angle), $e$ is the emergence angle of light from the trench (90° - SSI elevation angle), and $\psi$ is the azimuthal angle between the Sun and SSI. The IOF observations we used normalized incidence to $i = 0$. Note that although the three Snow White trench observations had different $e$, this is for the center of the image. Observations on Sol 43 and 45 were centered upon the trench, while the Sol 50 observation was centered on the near-side trench wall. For reference, we include the Planetary Data System (PDS) product ID of the first image in each set of SSI images we used for our analysis, and the activity under which these image products fall.

<table>
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<th>$e$</th>
<th>$\psi$</th>
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<td>48°</td>
<td>191°</td>
<td>ss043rad900005586_14b04l1m1 etc.</td>
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<td>45°</td>
<td>2°</td>
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<td>56°</td>
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<td>5°</td>
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<tr>
<td>Dodo-Goldilocks</td>
<td>24</td>
<td>56°</td>
<td>46°</td>
<td>76°</td>
<td>ss024rad898354633_12e50l1m1 etc.</td>
<td>12e5</td>
</tr>
</tbody>
</table>

Figure 7: (Color) SSI color image (RGB = SSI Filters RA, RB, RC) of Snow White Trench on Sol 43, from activity 14b0 (e.g. PDS product ID ss043rad900005586_14b04l1m1). TEGA analysis confirms the bright portion of the trench contains water ice [Smith et al., 2009].
Figure 8: (Color) SSI color image (RGB = SSI Filters RA, RB, RC) of Snow White Trench on Sol 45, from activity 1503 (e.g. PDS product ID ss045rad900218012_150301l1m1). The dark material at the bottom of the trench is the bright material from Figure 7.
Figure 9: (Color) The spectrum of regolith after ice sublimation from Sol 45 to 50 (solid red line to dotted orange line) matches the spectra of the non-icy regolith both before (Sol 45, solid blue line) and after (Sol 50, dashed blue line) the icy in the regolith beside it has sublimated.

Figure 10: (Color) The spectrum of regolith before ice sublimation from Sol 45 to 50 (solid red line to dotted orange line) matches the spectra of the non-icy regolith both before (Sol 45, solid blue line) and after (Sol 50, dashed blue line) the icy in the regolith beside it has sublimated.

very little until beyond the wavelength range of Sol 43 observations (Fig. 2), so we also assumed 60 µm ice grain size for simplicity. We used water-ice optical constants from [Warren & Brandt, 2008] for our models, as we could not independently measure the water-ice optical constants like we did in the lab. This left our greatest uncertainty to be the real index of refraction of the Martian regolith at 550 nm, so we estimated a value between \( n = 1.4 \) to \( n = 1.7 \) (Fig. 10) as we did for our experiments with JSC Mars-1. Holding all other values constant, we found a best-fit model varying water-ice concentration. Depending on our assumed real index of refraction at 550 nm, our models fit best for 24-27 vol.% water-ice within the icy regolith exposed at Snow White Trench. We also fit models to the mean albedo with the addition or subtraction of its standard deviation, and found the best-fit water-ice concentration varies up to 12 vol.%.

4.2 Dodo-Goldilocks Trench

Phoenix excavated Dodo-Goldilocks trench (Figure 12) on Sol 24 to expose bright water-ice. Dodo-Goldilocks was viewed at an emergent angle of 44°, so we again used equation 6 to convert from IOF bidirectional reflectance to integral albedo before applying our model. As was the case with Snow White Trench, we expect the conversion coefficient to be between those of Equations 2 and 6, but still closer to that of the latter. We again assumed regolith grain-size of 60 µm, with optical constants derived from non-icy soil observed on Sol 24. These optical constants are similar to those derived for the regolith on Sol 43 at the Snow White Trench (Figure 11), differing most at wavelengths where their albedos also differed.

Only large water-ice grains (relative to regolith grain size) can explain the observed drop in reflectance in the near-infrared of the icy soil spectrum (Figure 2), as this feature does not appear in the desiccated regolith spectrum (Figure 13). Indeed, when we fit for water-ice grain size and concentration with a least-squares method we find an ice grain size of 1.0-1.3 mm, with an abundance of 85-87 vol.% depending on whether we assumed \( n(550 \text{ nm}) = 1.4 \) or 1.7. As with the Snow White Trench, we also fit our model to the extents of the uncertainty in the albedo, finding concentration uncertainty of ±5 vol.% and grain size uncertainty of ±0.4 mm.
Figure 10: (Color) Reflectance spectra of the icy (solid black circles, thick error bars) and dry (empty black circles, thin error bars) regoliths. Best-fit modeled albedo spectra of mixtures of non-icy regolith with water-ice, assuming both regolith (optical constants derived from the non-icy regolith) and water-ice grains to be 60 µm, an initial volume-fill fraction without water-ice of 0.5, and the regolith’s real-index of refraction at 550 nm to vary from 1.4 (solid blue line) to 1.7 (orange dashed line). The thin blue and orange error bars represent the best fit models at the extent of our uncertainties assuming $n(550\text{ nm})=1.4$ and 1.7, respectively.

Figure 11: Top: Observed albedos of the Martian regolith in both the Snow White Trench (solid) and Dodo-Goldilocks Trench (dotted). Middle: Real index of refraction derived for the regolith at each site, assuming either that the real index of refraction is 1.4 (black) or 1.7 (grey) at 550 nm. Bottom: Imaginary index of refraction derived for the regolith at each site.
Figure 12: (Color) SSI color image (RGB = SSI Filters RA, RB, RC) of Dodo-Goldilocks Trench on Sol 24, from activity 12e5 (e.g. PDS product ID ss024rad898354633_12e50l1m1).
Figure 13: (Color) Observations of ice reflectance (solid black circles, thick error bars) and Martian regolith reflectance (empty black circle, thin error bars) in the Dodo-Goldilocks Trench on Sol 24. Regolith grains are assumed to be 60 µm, with optical constants derived from the non-icy regolith. Best-fit modeled albedo spectra of mixtures of non-icy regolith with water-ice vary the regolith’s real-index of refraction at 550 nm to from 1.4 (solid blue line) to 1.7 (orange dashed line). The thin blue and orange error bars represent the best fit models at the extent of our uncertainties assuming $n(550 \text{ nm}) = 1.4$ and 1.7, respectively. Water-ice grain size was allowed to vary.

5 Discussion

Our analysis found Snow White Trench to have 24-27±12 vol.% water-ice. Assuming the same densities as we did in our laboratory experiments [Allen et al., 1998, Lide, 2005], this translates into 14-15±7 wt.%. In our laboratory experiments, the actual water-ice fraction tended to be greater than the best-fit water-ice fraction, but was still within the uncertainty. This water-ice fraction is consistent with emplacement by vapor diffusion, wherein water-ice forms within the pore spaces of the Martian regolith, depositing from the atmosphere [Mellon et al., 2004, Hudson et al., 2009, Siegler et al., 2012]. This emplacement mechanism guarantees that ice grains are evenly mixed within the regolith. [Mellon et al., 2009] also concluded that Snow White Trench and similar trenches were the result of vapor diffusion, further citing that present atmospheric conditions enable vapor diffusion and that the soil did not collapse with the sublimation of water-ice. [Cull et al., 2010] used the methods within [Hapke, 2012] to model mixtures of water ice and palagonite [Clancy et al., 1995] in order to estimate the water-ice fraction of Snow White Trench, finding 30±20 wt.%, or ~ 53 ± 29 vol.% water-ice. Our results are broadly consistent with [Cull et al., 2010]’s.

Our models indicated that Dodo-Goldilocks Trench contains 85-87±6 vol.% water-ice, exceeding the estimated 50-55 vol.% porosity of Martian regolith [Zent et al., 2010]. These results led to our conclusion that the Dodo-Goldilocks trench must be largely ice, as the ice is far greater than pore-filling. [Cull et al., 2010] also modeled Dodo-Goldilocks and found that Dodo-Goldilocks Trench was >99 wt.% water-ice. While the water-ice fraction estimates between our studies differ, they both concluded that the ice in Dodo-Goldilocks Trench far exceeded pore-filling [Cull et al., 2010]. Alternate emplacement mechanisms include freezing of water in wet soil, or the formation of ice lenses or needles [Smith et al., 2009].

By choosing to use the [Shkuratov et al., 1999] model for its analytic inversion to solve for optical constants, we sacrificed the angular dependence given in other radiative transfer models (e.g. [Hapke, 1981]). This became problematic for Snow White Trench as ice grains could either brighten or darken a surface depending on the azimuthal angle between the observer and the Sun.
whereas our mixture model only brightened with ice grains. For observation conditions similar to $i = 0^\circ$ and $e = 30 - 50^\circ$, [Shkuratov et al., 1999, Shkuratov & Grynko, 2005] worked well, but other models may work better at other geometries. Regardless of the exact methods of deriving regolith optical constants or modeling spectra of ice-regolith mixtures, our technique still eliminates the need to know or assume what the regolith is made of in determining its water-ice content.

Ultimately, this technique will prove useful aboard future missions to the Martian permafrost, in that we can determine water-ice content of the surrounding regolith using only cameras—allowing smaller and cheaper spacecraft to still do this science. The methodology can also be adopted in other locales such as the permanently shadowed regions of the Moon. Future instruments may also consider examining regolith with filters in the 1.5 or 2.0 $\mu$m wavelength regions where water-ice absorption features are located. These methods might also find themselves useful examining ices of other volatiles on future landers visiting moons or other small bodies in the outer solar system.

6 Conclusions

Our laboratory experiments demonstrate our technique’s ability to estimate the abundance of water ice in ice-soil mixtures (with soil optical constants derived from the spectrum of the soil alone) to within the 1σ envelope defined by fitting mixture models to the observed albedo spectrum plus-or-minus uncertainty. This uncertainty was dominated by the uncertainty of the observed albedo itself. We applied this procedure to data from Phoenix lander SSI as an exercise and found Snow-White-trench ice to be pore-filling and Dodo-Goldilocks-trench ice to be relatively-pure ice, agreeing with the results of [Cull et al., 2010, Smith et al., 2009]. However, unlike the prior studies we did not need to assume regolith composition, and that offers a boon in determining water-ice content of regoliths for which we may not have exact analogues or optical constants for.

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References


