THE DISTRIBUTIONS OF RETRIEVED PROPERTIES FROM WATER ICE CLOUDS IN THE MARTIAN ATMOSPHERE USING THE OMEGA IMAGING SPECTROMETER.

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Introduction

Water ice clouds in the Martian atmosphere play vital roles in chemical cycles and radiative transfer. They have a direct impact on atmospheric temperature and dynamics, facilitate heterogeneous processes, and affect the transport of water between hemispheres. Accurate knowledge of the properties of water ice clouds is therefore needed to improve our understanding of, and ability to model, each of the processes affected by them. The OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) imaging spectrometer on Mars Express is a valuable tool for studying cloud properties. Its spectral range covers several strong water absorption bands and its measurement technique provides the coverage necessary to observe clouds over a wide spatial extent.

This work builds on that of Madeleine et al. (2012), wherein a technique was developed to retrieve the effective radius, r_{eff}, and optical depth at 0.67 μm, τ_{i}, by fitting a single OMEGA spectrum at several discrete wavelengths. Madeleine et al. (2012) presented the analysis of spectra selected from single OMEGA pixels for 14 OMEGA orbits. The selection of the pixels was carefully done by hand and ensured that the Martian surface was flat, did not contain strong features, such as crater rims, and that the cloud coverage was of a minimum thickness defined by the Ice Cloud Index (ICI). The ICI is an estimate of the slope of the 3.1 μm water absorption band, and reflects the presence and abundance of water ice aerosols (Langevin et al., 2007). In our work, the ICI is defined as the ratio of reflectances recorded by the OMEGA L channel at 3.4 and 3.52 μm.

The primary extensions to the work of Madeleine et al. (2012) that we have developed are: an automatic algorithm for selecting good pixels to analyze, that many pixels covering the same cloud formation are analyzed to enable the mapping of retrieved properties and a statistical approach to their interpretation, and the use of *a priori* information that was not available at the time of the publication of Madeleine et al. (2012). These *a priori* include a collection of pre-computed ICI maps for OMEGA observations and a database of cloud coverage fractions and minimum thicknesses, a climatological database of dust optical depths (Montabone et al., 2015), a newer version of the LMD Mars general circulation model (LMD-GCM) (Forget et al., 1999; Millour et al., 2015) through the Mars Climate Database V5.2, and a new set of maps of the multi-spectral albedo of the Martian surface retrieved from cloud-free OMEGA observations (Geminale et al., 2015). The primary barrier with performing the retrieval on several pixels for an OMEGA observation is computational cost: there are thousands of orbits featuring clouds, which may also have thousands of spectra to analyze. However, the current number of potential orbits that are available to us for analysis is currently limited by the coverage of the maps of multi-spectral albedo.

OMEGA

The OMEGA instrument records images where each pixel contains a spectrum, referred to as image cubes. It uses three channels with overlapping wavelength ranges and 352 spectral pixels (spectels). Depending on the characteristics of the Mars Express orbit at the time, OMEGA records images that are 16, 32, 64, or 128 pixels wide and that may be thousands of pixels long. The three channels are denoted the visible, C, and L channels, and extend between 0.35–1.05 μm, 1–2.77 μm, and 2.65–5.1 μm, respectively. Mars Express was launched in June 2003, arrived at Mars in December 2003, began returning OMEGA data in January 2004, and continues to do so, having completed over 14,000 orbits. Unfortunately, instrument degradation over time has led to the death of several spectels, and in September 2010 the coolant supply used by the C channel detectors was exhausted (OMEGA continues to record cubes with the visible and L channels).

Retrieval technique

The inversion method used here, as described in Madeleine et al. (2012), fits a computed spectrum at seven wavelengths which cover the 1.5 μm, 2 μm, and 3.1 μm water absorption bands. The spectels for two of the wave-

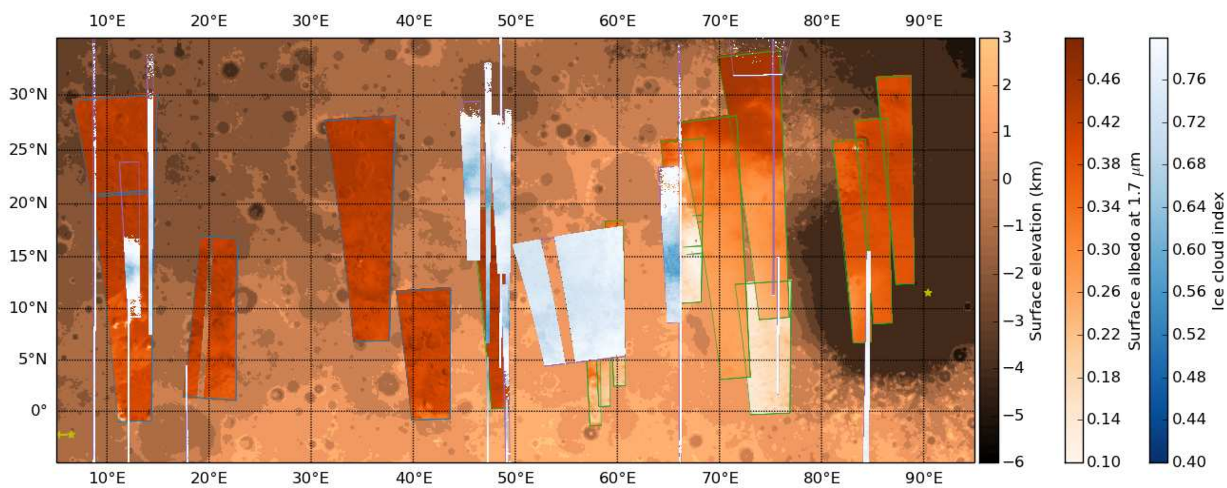

Figure 1: A map of Arabia Terra and Syrtis Major showing the multi-spectral albedo cubes derived from OMEGA image cubes, and the ICI maps from overlapping, cloudy OMEGA observations. The background relief is MOLA altitudes; the albedo data is shown in darker orange with blue of green outlines; and the ICI maps are white and blue, with darker blue indicating thicker clouds. The two stars indicate the landing sites of Opportunity (left) and Beagle (right).

lengths previously used became faulty during later orbits, so we have shifted them one spectel and compute spectral reflectances at 1.18, 1.49, 1.73, 2.23, 2.43, 3.40, 3.52 μm (previous spectels included 1.51 and 2.46 μm). Reflectances are computed using the DISORT radiative transfer code (Stamnes et al., 1988) and minimization is done using a Levendberg-Marqhardt least squares routine. In order to accurately retrieve information about the clouds, we require accurate *a priori* information about the temperatures of the surface and atmosphere, the quantity of dust suspended in the atmosphere, and the surface reflectance at the retrieval location. A major difference in our current implementation is that we no longer have to find a cloud-free OMEGA spectrum at the same location as a target pixel and use if to retrieve the surface albedo.

We begin with a set of cloud-free OMEGA image cubes which have been processed using principal component analysis to contain retrieved surface albedo for each spectel (Geminale et al., 2015). We then consider all OMEGA orbits that have been successfully analyzed to produce maps of ICI, and which have at least 10% cloud cover (which is 23% of analyzed image cubes, or 1430). We search for overlapping image cubes, and then find pixels whose centres are within 1.5 km of a cloud-free pixel with retrieved albedo. Before fitting spectra, we take the mean of that of the target pixel and those from the eight surrounding pixels. A database is built for each pair of cloudy and cloud-free albedo pixels that includes information about the pixel (location, time, ICI, etc.), the albedos for the spectels used in the retrieval, the dust condition of the atmosphere, the surface temperature, and the atmospheric state (temperature and pressure). The atmospheric state and surface temperature are taken from the latest version of the LMD-GCM (Forget et al., 1999; Millour et al., 2015), and the dust opacity is taken from a climatological reconstruction that is constrained by observations from the Thermal Emission Spectrometer (TES) aboard Mars Global Surveyor (MGS), the Thermal Emission Imaging System (THEMIS) aboard Mars Odyssey, the Mars Climate Sounder (MCS) aboard Mars Reconnaissance Orbiter (MRO), and the Mars Exploration Rovers (Montabone et al., 2015). In order to reduce errors between the C and L channels due to misalignment, the analyzed spectrum and the albedo spectrum are both corrected by shifting the L channel's pixel locations. With these parameters, spectral radiances are computed with DISORT and a best fit is found by varying the desired ice cloud aerosol properties: the effective radius, r_{eff}, and optical depth, τ_{i}.

Initial results were obtained by reanalyzing the OMEGA data presented in Madeleine et al. (2012) using the new *a priori* albedos, dust opacities, and surface temperatures. The resulting retrievals differed a small amount from the published results, but without any bias. Importantly, the χ^2 values were smaller in all cases, implying that the new *a priori* data result in a more accurate computed spectrum, validating our assumption that the *a priori* are improvements.

The parameter that the retrievals are most sensitive to is the surface albedo. This parameter also has a high un-

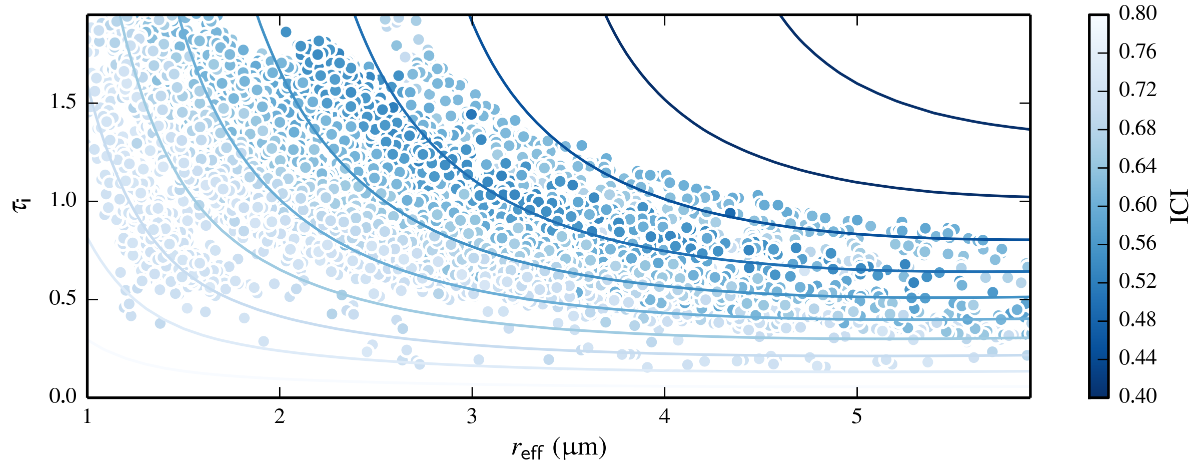

Figure 2: Distribution of the retrieved parameters from 12 OMEGA observations featuring thin clouds: effective radius, r_{eff}, and optical depth at 0.67 μm, τ_{i}. Each point represents the retrieval from a single OMEGA pixel and is shaded by the Ice Cloud Index (ICI) value for that pixel. Darker ICI values indicate thicker clouds. The parameter space was modelled by computing synthetic spectra for a set of r_{eff} and τ_{i} values, and then computing an ICI from the synthetic data. The model results are shown as contours of ICI.

certainty due to the observation footprint of the OMEGA spectrometer. The retrieval assumes a flat surface, so observations made over strong vertical surface features, such as crater edges, will have different reflectance characteristics than expected, such as a darker albedo than we expect. In regions featuring large crater features, the algorithm tends not to produce good fits (very large χ^2 values). The footprint of an OMEGA pixel will also be considered. The width of a pixel ranges between 0.3–5 km for both the retrieved albedo pixel and target pixel with clouds. Therefore, the retrieved albedo represents an average over a large area, while the fitted spectra are also averages over a large area, since we fit the mean of nine pixels, and the two areas will not necessarily overlap exactly. Finally, we assume that the surface albedo has not changed between when the cloud-free observation (albedo retrieval) was made and when the cloudy observation was made, between which there may have been two Mars years. The albedo can change over time from the overturning of surface regolith due to surface winds.

Observations

The initial set of OMEGA albedo image cubes we are working with partially covers the Mars Charts 12 and 13: Arabia Terra and Syrtis Major. Figure 1 shows the swaths for which multi-spectral albedo are available, and the ICI maps for cloudy, overlapping OMEGA observations. The albedo data set consists of 16 orbits, and our retrieval data set, overlapping OMEGA observations featuring clouds and a suitable number of matched pixels, consists of 14 OMEGA observations. The number of pixels on which we preformed retrievals ranges from 100–400 pixels, to upwards of several thousand pixels.

Results

For each overlapping orbit in Figure 1 we are able to explore the sensitivity of the retrieval by examining the distribution of results for each pixel. This allows us to estimate accurately mean values for r_{eff} and τ_{i}, but also to examine the distribution of results within the clouds. We find that the variability in the retrieved values, when overlaid on a map, is not random, but follows cloud features that are observable in the visible channel data and the ICI maps, implying that the retrieved parameters do vary within single cloud formations, and the variability of our retrievals is related to the physical properties of the clouds.

We have explored the parameter space of our retrievals by combing retrievals from each analyzed OMEGA image cube. The distribution of retrieved r_{eff} values as a function of retrieved τ_{i} values is shown in Figure 2, with colours indicating the ICI for each pixel. The relationship between r_{eff} and τ_{i} is a function of the extinction efficiency of the water ice aerosols, Q_{ext}, and the mass of the water ice column, M:

$$\tau_{\rm i} = \frac{3MQ_{\rm ext}}{4\rho r_{\rm eff}},$$

where ρ is the density of water ice. We can now develop an empirical relationship between the ICI, for which there is a large database covering the entire OMEGA mission, and can be easily computed without the need to an overlapping cloud-free observation (or C channel data after 2010), and the mass of water ice present in the clouds.

To validate our results, we modelled the parameter space by computing synthetic spectra for a set of $r_{\rm eff}$ and $\tau_{\rm i}$ pairs, given a surface albedo, temperature, and dust scenario from an OMEGA measurement. We then computed the ICI for each synthetic spectra, and the results are also shown in Figure 2.

All the clouds analyzed in this study are much thinner than those presented in Madeleine et al. (2012), pushing the sensitivity limits of the retrieval algorithm. This also limits our ability to investigate empirically a large portion of the parameter space with lower ICI values. We aim to move forward by obtaining a set of multi-spectral albedo cubes that will enable us to investigate thicker clouds.

For each of the cloud formations analyzed, our mean retrieved values agree with previously reported results, including those made using the Infrared Interferometer Spectrometer (IRIS) on Mariner 9 (Zasova et al., 2001); MGS TES (Wolff and Clancy, 2003); and previous work using OMEGA (Madeleine et al., 2012). Our mean $r_{\rm eff}$ results range from 1.8 to 3.6 μm, with an overall mean value of 2.33 ± 0.01 μm, while our mean $\tau_{\rm i}$ values fall within 0.6 and 1.4, and have an overall mean of 1.242 ± 0.006. Previous work found $r_{\rm eff}$ values between 2 and 5 μm. The OMEGA observations analyzed here were all made during the local afternoon, so we cannot infer diurnal cloud behaviour. However, they cover a range of solar longitudes, so we can explore the seasonal behaviour of cloud formation.

Acknowledgements

Funding for this research was provided by UPWARDS. We would like to thank the OMEGA science team for providing access to the spectral image cube data and for their support.

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