DEPTH AND DISTRIBUTION OF CO_2 SNOW ON MARS. Oded Aharonson, *Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena CA 91125, USA (oa@caltech.edu)*, Maria T. Zuber, *Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA (zuber@mit.edu)*, David E. Smith, Gregory A. Neumann, *Laboratory for Terrestrial Physics, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA (dsmith@tharsis.gsfc.nasa.gov, neumann@tharsis.gsfc.nasa.gov)*.

Introduction

The dynamic role of volatiles on the surface of Mars has been a subject of longstanding interest. In the pre-Viking era, much of the debate was necessarily addressed by theoretical considerations. A particularly influential treatment by *Leighton and Murray* [1] put forth a simple model relying on solar energy balance, and led to the conclusion that the most prominent volatile exchanging with the atmosphere over seasonal cycles is carbon dioxide. Their model suggested that due to this exchange, atmospheric CO_2 partial pressure is regulated by polar ice. While current thinking attributes a larger role to H_2O ice than did the occasional thin polar coating this model predicted [2], the CO_2 cycle appears to be essentially correct.

There are a number of observational constraints on the seasonal exchange of surface volatiles with the atmosphere. The growth and retreat of polar CO_2 frost is visible from Earth-based telescopes [3] and from spacecraft in Mars orbit, both at visible wavelengths and in thermal IR properties of the surface [4–6]. Recently, variations in Gamma ray and neutron fluxes [7, 8] have also been used to infer integrated changes in CO_2 mass on the surface. Measurements made by Viking's Mars Atmospheric Water Detector experiment were sensitive to atmospheric H_2O vapor abundance [9, 10]. Surface condensates and their transient nature were detected by the Viking landers [11]. The study here is motivated by recent data collected by the Mars Global Surveyor [12], affording the opportunity to not only detect the lateral distribution of volatiles [13, 14], but also to constrain the variable volumes of the reservoirs.

We elaborate on a technique first employed by *Smith et al.* [15]. By examining averages of a large number of topographic measurements collected by the Mars Orbiter Laser Altimeter (MOLA) [16], that study showed that the zonal pattern of deposition and sublimation of CO_2 can be determined. In their first approach, reference surfaces were fit to all measurements in narrow latitude annuli, and the time dependent variations about those mean surfaces were examined. In their second approach, height measurements from pairs of tracks that cross on the surface were interpolated and differenced, forming a set of crossover residuals. These residuals were then examined as a function of time and latitude. The initial studies averaged over longitude to maximize signal and minimize noise in order to isolate the expected small signal. In this follow-up study we now attempt to extract the elevation change pattern also as a function of longitude, and we focus on the crossover approach.

Data Quality and Processing

The accurate recovery of changes in elevation depends upon the quality of the range measurements from which the residuals are derived. Estimations of surface height are prone to error, introduced both by the range measurement itself, as well as from imperfect knowledge of the position and orientation of the spacecraft. The precision of the timing measurement is limited by the clock accuracy of $\sim$2.5 ns, corresponding to 37.5 cm, but suffers from systematic drifts in the clock frequency. These daily variations are estimated, and shown to be less than 1 part in 10^8 [17, 18]. Modeling of the instrument [19, 20] allows a correction to be applied, accounting for variability in shape and strength of return pulses that affects the instrument's triggering time. This correction, referred to as "range walk", is typically 1–3 m in amplitude, and has an uncertainty of approximately 30 cm [17].

In the final step of the processing the elevation measurements themselves are used to improve the orbital solutions. The elevations of locations where a pair of ground-tracks of measurements intersect (Figure 1), are interpolated and differenced to form a set of "crossover residuals". These residuals may include both real surface height changes, as well as systematic errors in the orbital position. To reduce the effect of systematic error sources the set of raw crossover residuals was adjusted by deriving a correction for each track such that the $\sim$ 9 million residuals, those equatorward of 57° latitude or occurring within 15 days of each other, were minimized, since no change is expected for these measurements. This minimization is carried out by least-squares fitting of orbital adjustment parameters, using three-dimensional, smooth (polynomial), functions of time [17, 18, 21]. In the preferred model, the fitting problem is over-constrained, as there are roughly 200 times as many measurements as fitted parameters. Applying these adjustments, and recomputing the crossover residuals, reduces their root-mean-square from the initial value of 8.303 m to 1.817 m [17]. The correction was then applied to all tracks and the entire set of $\sim$ 66 million residuals recomputed. Residuals resulting from less reliable measurements were excluded in order to minimize random errors. These include measurements obtained on slopes greater than 10%, off-nadir observations, and residuals $>$ 10 m. This criterion eliminates data collected in latitudes polewards of 87.3° (owing to the spacecraft's inclination angle of 92.7°), since these off-nadir polar observations are characterized by significant errors due to range walk.

Results & Summary

The intersections of MOLA ground-tracks (*i.e.* crossovers, as represented in Figure 1) provide a useful means of determining changes in the topography occurring during the time interval between the measurements. By averaging a large number of observations it is possible to isolate temporal height changes at an accuracy conservatively estimated to be at the $\sim$10 cm level [15]. In order to treat the data uniformly when forming averages, each crossover residual is counted twice: once with the time tag of the later track, and again, with the

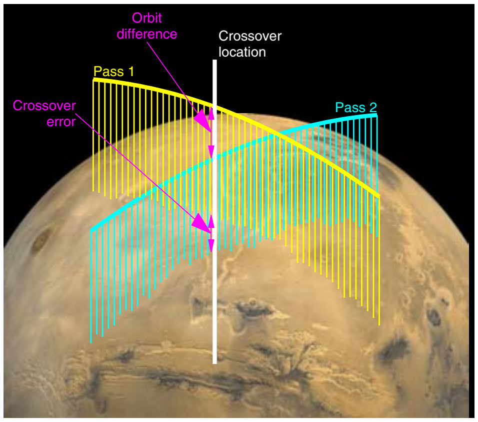

Figure 1: Crossover errors are determined by interpolation of crossing ground tracks. Removal of systematic orbit differences results in the change in surface height.

time tag of the earlier track (and an opposite sign).

In order to resolve the dependence of the pattern on longitude and time, a harmonic decomposition of the signal was carried out locally. Crossover residuals were sorted into spatial bins in latitude-longitude. Since MGS is in an approximately polar orbit, the number of elevation measurements in each bin is approximately uniform. However, since the number of crossovers increases as the square of the number of orbits, regular grids have cells with more crossovers near the pole, improving the statistical quality of high-latitude measurements with respect to low-latitudes.

In each spatial bin, we sorted the data in time (L_s), and applied a least-squares fit [22], to a function of the form

$$\delta z(L_s) = -\sum_{n=1}^{n_{max}} A_n \cos(nL_s - D_n). \qquad (1)$$

The coefficients A_n are the amplitudes, and D_n are the phases of the variations' minima. Initially we examine the first two terms, corresponding to the seasonal $n = 1$ and semi-annual $n = 2$ variations.

The annual component of the signal (A_1) is strongly correlated with the residual south polar cap deposits, and weakly with the north polar cap. Locally, the amplitude can be as high as 1 m (2 m peak-to-peak), but more typically it is 0.4-0.6 m on the caps and is reduced polewards. In areas on the dune-covered Olympia Planitia (82°N,166°E), where sand and dust transport may be important, the amplitude is $\sim$0.8 m. Our preliminary results indicate that in the north, the semi-annual component (A_2, D_2) correlates with the location of the ice deposits. The phase of the annual cycles (D_1) is in agreement with thermal observations of the timing of the annual disappearance of CO_2 frost from the surface at the high latitudes, as well as with predictions from global circulation models. At lower latitudes, frost sublimation predates the fitted minima due to the dependence of our procedure on the complete annual cycle.

It is worth noting that while unexpected from models and simple intuition, the observations of the "off season" component of the accumulation are statistically no different in quality from the annual component. The amplitude is only smaller by a factor of two, and the phase has a similar robustness and correlation with surface features.

Our results demonstrate that the large number of MOLA elevation measurements can be effectively corrected, averaged and fitted, to yield sensitive measurements of the changes in polar surface height as a function of both latitude and longitude over the Martian seasonal cycles. Accumulation is expected and observed to be maximum in late winter, and at high latitudes at both hemispheres. More perplexing deposition/sublimation episodes occur during warmer seasons as well, also visible in the zonally-averaged crossover analysis [15].

These results provide constraints that should be incorporated in future models of the Martian climate system and volatile cycles. In addition, the geographic correlations of the amplitude and phase of the signal with surface features, supports both the interpretation of the data as depositional in origin, and the utility of crossovers for analyses of subtle temporal changes of planetary elevation.

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