# Seasonal Changes in the Icecaps of Mars from Laser Altimetry and Gravity

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## Abstract

Using topography collected from the Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor (MGS) spacecraft, we have measured temporal changes in the elevation of the polar surface that correlate with the $CO_2$ seasonal exchange between the surface of the polar regions and the atmosphere. Further, using X-band radio tracking of the Mars Global Surveyor spacecraft, we have measured temporal changes in the long-wavelength gravity field of Mars that correlate, to first order, with the pattern expected due to the seasonal re-distribution of carbon dioxide between the atmosphere and surface. A comparison of very low degree gravity coefficients determined every 5 days shows an annual variation in the relative position of the center of the core-mantle component of Mars, represented as a degree 1 term, that is 3% smaller in amplitude and 22 different in phase compared to the signal predicted by a General Circulation Model (GCM) simulation of $CO_2$ exchange over a typical Mars year. The observed temporal change in the planetary flattening ($C_{2,0}$ spherical harmonic coefficient) displays both annual and semi-annual components that are more complex than predicted by the GCM.

## Introduction

The mass of Mars' thin carbon dioxide ($CO_2$) atmosphere varies seasonally by exchanges with the surface over the course of the planet's 687-(Earth) day year. Variations in solar insolation associated with the planet's orbital eccentricity [*Leighton and Murray*, 1966], coupled with a Hadley circulation pattern [*Richardson and Wilson*, 2002] driven by the planet's south-to-north elevation difference [*Smith and Zuber*, 1996; *Smith et al.*, 1999a], produce active atmospheric dynamics that drive the seasonal hemispheric transport of $CO_2$. Over the course of the Martian year about 18% of the total volatile mass will be exchanged between the atmosphere and the surface, resulting in a re-distribution of $1 \times 10^{-8}$ of the total mass of Mars. The seasonal transport of atmospheric mass and snow deposition will appear in the planetary gravitational field as temporal changes.

The Mars Global Surveyor (MGS) Altimetry [*Smith et al.*, 2001a] and Radio Science [*Tyler et al.*, 2001] investigations have now provided the first direct global-scale observations of the change in height of Mars' seasonal ice caps and of the seasonally exchanged mass [*Smith et al.*, 2001b]. Preliminary observations [*Smith et al.*, 2001a] displayed general patterns consistent with GCM predictions, but showed other features that were unexpected. This initial work demonstrated the feasibility of isolating small but important temporally varying geophysical signals on Mars from an orbiting spacecraft. In this study we discuss and analysis of MGS X-band Doppler and range tracking observations from the mission's Radio Science experiment [*Tyler et al.*, 2001] and show temporal changes in the degree 1 and 2 zonal terms of Mars' gravitational field, and show their relationship to the seasonal cycling of volatiles on Mars.

## MOLA Instrument Parameters

The topography of Mars has been measured by the Mars Observer Laser Altimeter (MOLA) (Figure 1) [*Smith et al., 2001*]. This MGS spacecraft instrument has a 50 cm primary mirror, a 1.064 ± .002 μm wavelength, an 8 nsec pulsewidth, operated at approximately 48 mJ, and a 10 Hz repetition rate. The range resolution is 37.5 cm. The hardware driven maximum range was 786 km, with a surface spot size of 168 m spaced at approximately 330 m [*Zuber et al., 1992*]. During the lifetime of the MOLA instrument, about 99% of the return pulses were detected, yielding 671,121,600 measurements to the surface of Mars.

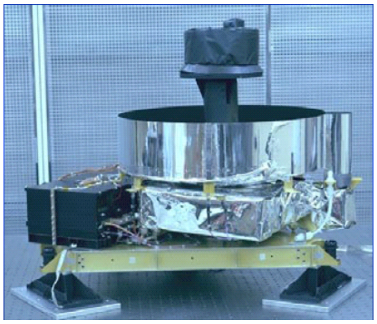

**Figure 1.** Mars Observer Laser Altimeter (MOLA)

## Mars Polar Topography from MOLA

MOLA elevation profiles in 0.05° deg. (3 km wide) latitudinal annuli between 60° and 87° North, and 60° and 87° South were analyzed to determine the seasonal elevation change of the Mars polar regions. In each annulus, an average reference surface was calculated by using a 25 point running median over the longitudinally ordered measurements in the annulus. The residual of the individual measurements to the median surface were calculated and time ordered. The time ordered residuals were averaged over 15 days and differenced from the median annulus for that hemisphere's 60° annulus. Selected profiles from these calculations are shown in Figure 2 [*Smith, et. al.*, 2001b].

The highest elevation changes observed in either hemisphere occurs when that polar region was not sunlit. The maximum elevation change occurred in late winter for that hemisphere. The pattern of the elevation change arises from the seasonal behavior of $CO_2$ exchange between polar ice and the atmosphere.

## Radio Tracking Observations

The MGS spacecraft is in a near-polar (inclination 92.8°), near-circular (altitude 400 km) orbit with a period of 117 minutes. The spacecraft utilized two-way and three-way ramped Doppler tracking. Observations are at X-band (4.2 and 3.6 cm wavelength corresponding to 7.2 and 8.4 GHz frequency) for the uplink from the ground and downlink from the spacecraft, respectively. In two-way tracking the signal is transmitted to the spacecraft, and transponded coherently back to the transmitting station on Earth. In three-way tracking the signal is transmitted and transponded from the spacecraft in the same fashion, however different stations are used to transmit and receive. Ramping of the Doppler signal refers to a piecewise linear change in the uplink reference frequency that facilitates locking onto the downlinked signal at the receiving station.

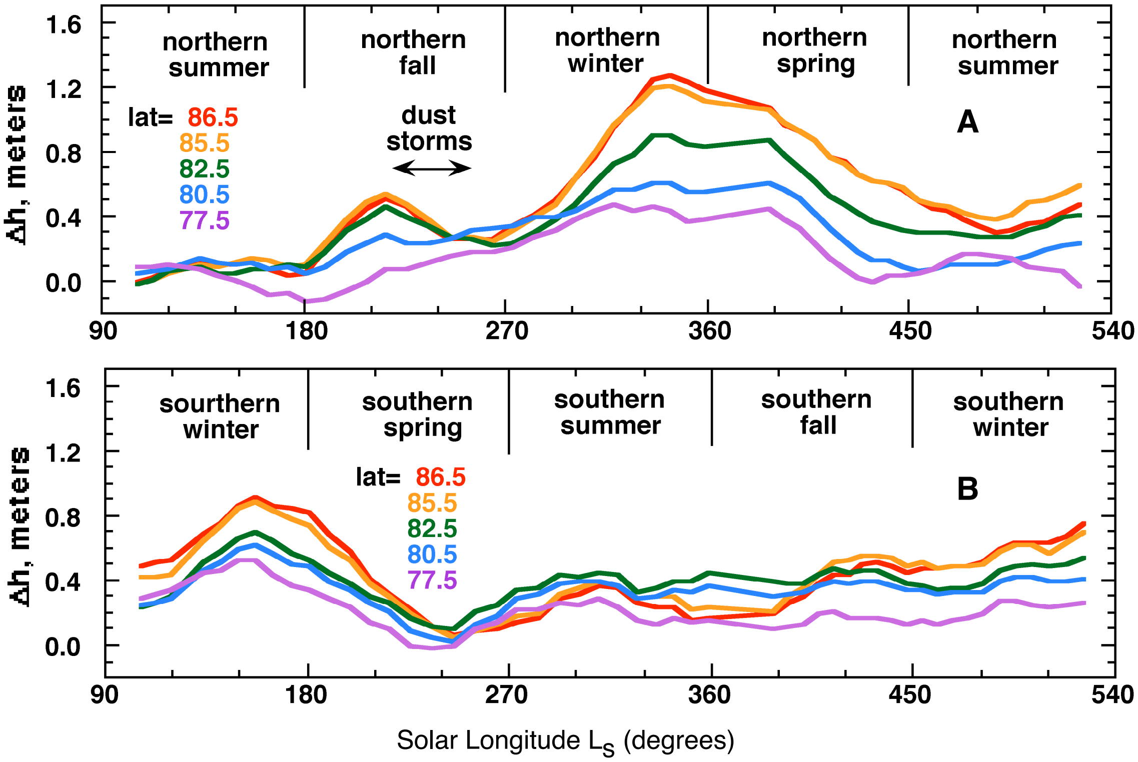

**Figure 2.** Latitudinal profiles of elevation change for the North and South polar regions of Mars as determined from MOLA measurements. The elevation changes are with respect to 60° North (A) or 60° South (B) latitude [*Smith et al.,* 2001b].

Transmission and reception of MGS radio signals utilizes tracking stations in the NASA Deep Space Network at Goldstone, CA, Madrid, Spain and Canberra, Australia. Typically, MGS is tracked for one 10-hour pass per day using the DSN's 34-m-diameter high efficiency or beam waveguide antennae. The range-rate observable is the Doppler shift of the tracking signal, which provides a measurement of spacecraft velocity. In the MGS mapping and extended missions, the Doppler tracking measurements are averaged in 10-second intervals and typically display an accuracy of better than 0.1 mm s-1 [*Tyler et al.*, 2001].

## Gravity from Radio Tracking

Doppler range rate and range in combination provide excellent constraints on the orbit of the MGS spacecraft [*Lemoine et al., 1999*]. This study examines the perturbations of the spacecraft in its orbit caused by Mars' long-wavelength gravitational field. Doppler tracking provides a measure of spacecraft velocity that is used to compute the orbits of MGS around Mars, based upon various a priori models and adjusted parameters. This orbital information is to estimate various orbital and geophysical parameters, including the spherical harmonics of the Mars gravitational potential.

The low-degree terms of the gravity field are of the greatest importance for the detection of temporal variability. The lowest degrees of the field correspond to the longest wavelength gravity signals, which are the most sensitive to global changes in the density distribution. The zonal terms are of key interest in the detection of $CO_2$ cycling, because they represent changes in the mass distribution along lines of longitude (i.e., from pole to pole). In general, the low-degree terms are the best constrained parameters in spherical harmonic models [*Lemoine et al.,* 2001]. Detecting these gravity field changes requires isolating perturbations in the velocity of the MGS spacecraft of 5 µm s-1.

On the basis of a simulation of gravity field changes associated with the cycle of $CO_2$ exchange on Mars, in a coordinate system centered on the solid part of the planet (core, mantle, crust), the largest term in the time-varying geopotential is a $C_{1,0}$ coefficient [*Smith et al., 1999b*]. For a static gravity field the $C_{1,0}$ term is identically zero because the center of mass and the center of figure are defined to coincide. However, the seasonal pole-to-pole transport of volatile mass can produce a $C_{1,0}$ term [*Smith et al., 2003*]. In a system with temporally varying mass, $C_{1,0}$ represents the pole-to-pole displacement of the volatile material with respect to the origin of the coordinate system. It is the few centimeter movement of the solid part of the planet required to maintain the center of gravity of the total planet (solid body + atmosphere + ice) in a fixed location. The internal redistribution of material within the planetary body does not change the location of the center of gravity of the total system. The components of the degree 1 term arising from the northern and southern hemispheres are in phase such that melting in one hemisphere has the same effect as deposition in the opposite hemisphere, and combine constructively to yield a quasi-annual variation. Figure 3 is a schematic diagram of this effect in the $C_{1,0}$ gravity term for Mars.

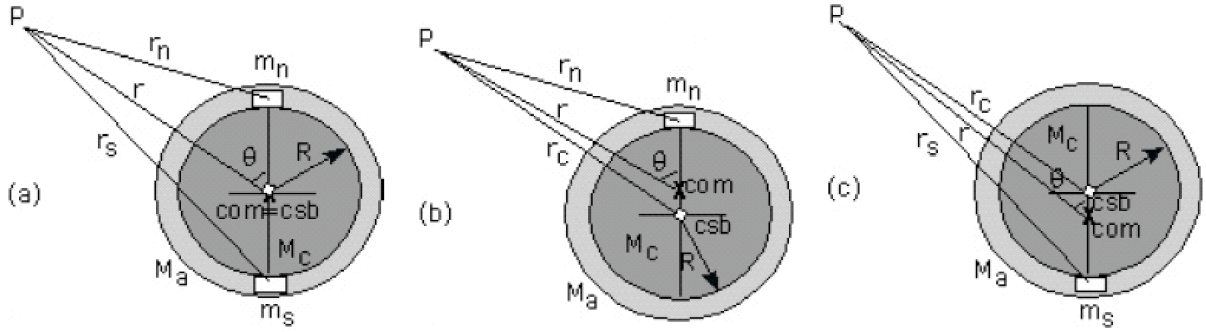

**Figure 3.** (a) Schematic showing the contributions to the gravitational potential at a point, P, exterior to the planet, due to mass contributions from the central solid body, Mc, the north and south seasonal polar caps, mn and ms, and the atmosphere, Ma. The center of the coordinate system about which the gravitational potential is expanded is the seasonally averaged planetary center of mass (com), shown as an X. In the case of seasonal averaging the com is coincident with the center of the solid body (csb). (b) and (c) Schematics illustrating how the center of mass of the solid planet, Mc, will shift along the polar axis over the course of a Martian year from the seasonally-averaged position in (a), due to alternating deposition of $CO_2$ frost during northern hemisphere (b) and southern hemisphere (c) winter seasons. In b and c the com and csb do not coincide [*Smith et al.,* 2003].

In contrast, the degree 2 terms are symmetric with respect to the equator and hence motion of material from the equator to either pole reduces the numerical value of the planetary flattening, i.e., the $C_{2,0}$ term. Since the annual deposition in the two hemispheres occurs in opposite seasons the result is principally a quasi-semiannual variation [*Smith et al., 1999b*].

## Ames General Circulation Model Prediction

Given the complicated processing involved in the recovery of temporal gravity signals, it is important to compare observations to a model of the predicted signals. To estimate the expected changes in Mars' gravitational field, we solved for changes in the mass distribution associated with the seasonal cycling of $CO_2$ predicted by a model of the Martian atmosphere over a "typical" year [*Smith et al.,* 1999b]. The simulation utilized the NASA Ames General Circulation Model (GCM) [*Pollack et al.,* 1990], a finite difference grid point model based on the "primitive equations". The derived variation of the $C_{1,0}$ and $C_{2,0}$ gravity terms as a function of Ls, the position of Mars in its solar orbit, are show by the red lines in Figure 4.

## Solution Strategy

We implemented our recovery of the temporal variations of the gravitational field by converging 240 orbital arcs each 5 days in length. Five days represents an MGS mapping cycle, and produces coarse global coverage. Our approach was to analyze the 240 orbital arcs simultaneously with some parameters being common to all the orbital data, such as the masses of Mars and Phobos, and other parameters, such as the MGS orbit and some low-degree time varying gravity coefficients, estimated in each arc.

Our initial solutions consisted of adjustments of the degree 1 coefficients along with the MGS orbit every 5 days. The results for $C_{1,0}$ show a signal similar to that predicted by the GCM [*Smith et al.,* 1999b]. Further, adjustments of the degree 2 coefficients along with the orbit also show patterns in the $C_{2,0}$ coefficient that, although not similar in appearance to the predicted GCM variation, had spectral components at the expected annual and semi-annual periods.

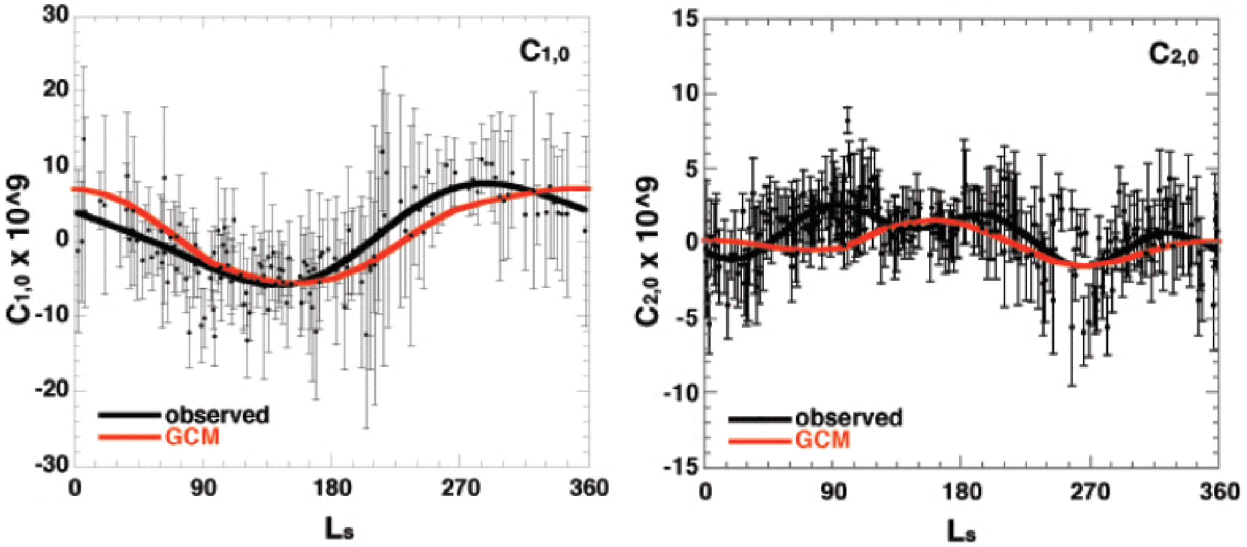

**Figure 4.** Comparison of observed temporal changes in the (left) $C_{1,0}$ and (right) $C_{2,0}$ terms of the Mars gravity field (points with best-fit black line) to those predicted from a General Circulation model simulation (red lines) from *Smith et al.* [1999b].

Figure 4 shows the resulting time series of the $C_{1,0}$ and $C_{2,0}$ gravitational terms in comparison with the results from the GCM simulation of $CO_2$ exchange as a function of Ls. In comparison to the model, the annual term of the $C_{1,0}$ term agrees in amplitude to within a few percent while the phase differs by about 22 percent. The result also agrees well in comparison to an independent analytical estimate of temporal changes in the COM/COF of Mars by *VanHoolst et al*. [2002]. The shift implied by $C_{1,0}$ term along the polar axis of Mars has a dynamic range of 7 cm corresponding to an exchange of $7x10^{15}$ kg of $CO_2$ between the atmosphere and surface.

## Summary

Topographic changes in the Mars polar caps derived from MOLA observations show the greatest surface elevation change occurs at latitudes above 80°, and is correlated with the $CO_2$ seasonal exchange between the surface of the polar regions and the atmosphere.

We have made a preliminary estimation of the variability of zonal terms of the Martian gravity field. When compared with the change predicted from the Ames GCM, we conclude that we are seeing similar order variations in the primary annual and semiannual components. But in each case we are seeing a phase difference of 20 to 30 expressed as degrees of Ls. We believe these differences are real atmospheric differences (compared to the "typical"

GCM year), but cannot rule out the possibility that they arise as a result of our approach or from systematics in our data.

## References

Leighton, R.B., and B.C. Murray, Behavior of carbon dioxide and other volatiles on Mars, *Science*, 153, 136–144, 1966.

Lemoine, F.G., D.D. Rowlands, D.E. Smith, D.S. Chinn, D.E. Pavlis, S.B. Luthcke, G.A. Neumann, and M.T. Zuber, Orbit determination for Mars Global Surveyor during mapping, AIAA Pap., 99-328, 1999.

Lemoine, F.G., D.D. Rowlands, D.E. Smith, D.S. Chinn, D.E. Pavlis, S.B. Luthcke, G.A. Neumann, and M.T. Zuber, An improved solution of the gravity field of Mars (GMM-2B) from Mars Global Surveyor, *J. Geophys. Res*., 106, 23,359–23,376, 2001.

Pollack, J.B., R.M. Haberle, and J. Schaeffer, Simulations of the general circulation of the Martian atmosphere, 1, Polar processes, *J. Geophys. Res*., 95, 1447–1473, 1990.

Richardson, M.I., and R.J. Wilson, A topographically forced asymmetry in the Martian circulation and climate, *Nature*, 416, 298–301, 2002.

Smith, D E., et al., The global topography of Mars and implications for surface evolution, Science, 284, 1495–1503, 1999.

Smith, D.E., et al., Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars, *J. Geophys. Res*., 106, 23,689–23,722, 2001a.

Smith, D.E., and M.T. Zuber, The shape of Mars and the topographic signature of the hemispheric dichotomy, Science, 271, 184–188, 1996.

Smith, D.E., M.T. Zuber, and G. A. Neumann, Seasonal variation of snow depth on Mars, *Science*, 294, 2141–2146, 2001b.

Smith, D.E., M.T. Zuber, P.J. Dunn, M.H. Torrence, J.J. McCarthy, and S.K. Fricke., Measurement of the Global-scale Seasonal Cycling of Volatiles on Mars from Temporal Change in the Low-degree Gravitational Field, *J. Geophys. Res*., manuscript in preparation, 2003.

Smith, D.E., M.T. Zuber, R.M. Haberle, D.D. Rowlands, and J.R. Murphy, The Mars seasonal $CO_2$ cycle and the time variation of the gravity field: A General Circulation Model simulation, *J. Geophys. Res*., 104, 1885–1896, 1999b.

Tyler, G.L., G. Balmino, D.P. Hinson, W.L. Sjogren, D.E. Smith, R.A. Simpson, S.W. Asmar, P. Priest, and J.D. Twicken, Radio science observations with Mars Global Surveyor: Orbit insertion through one year in mapping orbit, *J. Geophys. Res*., 106, 23,327–23,348, 2001.

VanHoolst, T., V. Dehant, O. de Viron, P. Defraigne, and J.-P. Barriot, Degree-one displacement of the center of Mars, *Geophys. Res. Lett.*, *29*, 10.1029/2002GL014,711, 2002.

Zuber, M.T., D.E. Smith, S.C. Solomon, D.O. Muhleman, J.W. Head, J.B. Garvin, J.B. Abshire, and J.L. Burfton, The Mars Observer Laser Altimeter Investigation, *J. Geophys. Res*., 97, 7781-7797, 1992.