The relationship between MOLA northern hemisphere topography and the 6.1-Mbar atmospheric pressure surface of Mars

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Abstract. To assist in targeting of landers and to enable comparison of new elevation data to previous topography models, we have re-determined the position of the 6.1-mbar atmospheric pressure surface on Mars with respect to surface topography from the Mars Orbiter Laser Altimeter (MOLA). The 6.1-mbar surface lies, on average, 1600 m below the zero level defined by MOLA topography, which occurs at an average pressure of 5.2 mbars at $Ls=0^\circ$. The elevation of the 6.1-mbar surface is expected to vary by 1.5-2.5 km over the Martian year due to the seasonal exchange of CO$_2$ between the atmosphere and polar caps. For average Martian atmospheric conditions, the pressure at the Mars Surveyor '98 landing site is expected to be -5.0 mbars during the lander science phase of the mission assuming an elevation of 1600 meters above the zero level defined by MOLA topography.

Introduction

A reference surface for atmospheric pressure provides a basis for understanding atmospheric structure and variability. On Earth the atmosphere is referenced to the pressure at sea level, but on Mars, which lacks such a convenient tie point, the atmosphere has traditionally been referenced to a prescribed surface of constant pressure, referred to as an areoid. An appropriate reference pressure for Mars is 6.1 mbars, which corresponds to the triple point of water and is close to the average atmospheric pressure on that planet. The particular utility of understanding the relationship between pressure and topography on Mars is that it provides an estimate of mass of the atmospheric column above a particular location, which is critical in the assessment of potential landing sites. Indeed, elevation relative to the 6.1-mbar surface is one of the key criteria in assessing whether an area of Mars will be safe to land at [Golombek et al., 1997].

Because initial determinations of the large-scale topography of Mars were based on atmospheric pressure measurements [Conrath et al., 1973; Hord et al., 1974], a surface of constant pressure has also been used as the reference for surface topography. Most historical models of Martian topography [Christensen, 1975; Wu, 1991; Batson and Eliason, 1995] adopted the 6.1-mbar pressure surface as the zero point of elevation. That reference surface was derived from a fitting pressure information from Mariner 9 occultations [Kliore et al., 1972; Kliore et al., 1973] to a degree-4 gravity model [Lorell et al., 1973].

During the Fall of 1997, the Mars Orbiter Laser Altimeter (MOLA) instrument on the Mars Global Surveyor (MGS) spacecraft provided 18 distributed topographic profiles across the northern hemisphere of Mars [Smith et al., 1998a]. These data are significantly more precise than previous observations of Mars topography and provide the impetus to re-define the position of the 6.1-mbar pressure surface to assist in atmospheric studies and in targeting future Mars landers. In this analysis we determine the elevation of the 6.1-mbar surface with respect to the Martian surface by relating the MOLA data to spacecraft occultations and comparing the position to that determined previously. In addition, using a model of the circulation of the Martian atmosphere [Pollack et al., 1990], we have assessed the effect of seasonal variations on the elevation of the pressure surface. We show that because of the seasonal variability of the Martian atmosphere, the 6.1-mbar surface varies significantly with respect to topography, and thus should not be used for studies of the planet that require a fixed reference. We also estimate the expected surface pressure at the Mars Surveyor '98 landing site.

Altimetry

We utilized topographic profiles of the northern hemisphere of Mars [Smith et al., 1998a] obtained from the MOLA altimeter during a 3-week period when the spacecraft was in a hiatus from atmospheric aerobraking [Albee et al., 1998]. The MOLA instrument [Zuber et al., 1992] provided measurements of the range from MGS to the Martian surface. Ranges were converted to planetary radius by correcting for the position of the spacecraft with respect to Mars' center of mass. Subtraction of the geoid (gravitational equipotential) radii from the planetary radii provided measurements of geopotential surface topography. The MOLA topography measurements are characterized by a vertical resolution of 37.5 cm and an absolute vertical accuracy with respect to Mars' center of mass of 30 m. The former number was dictated by the timing resolution of the instrument and the latter was controlled by the radial knowledge of the spacecraft orbit.

For the MOLA topography the zero-level contour represents a surface with a total potential (gravitational plus rotational)
that equals the potential of Mars’ mean equatorial radius, which was derived from the MOLA data and equals 3396.0 km ± 200 m [Zuber et al., 1998]. The radius and the GMM-1 gravity model [Smith et al., 1993], which was updated [Lemoine et al., 1994] with the most recent IAU coordinate system parameters for Mars [Davies et al., 1996], provided the potential of Mars’ mean equatorial radius. This equipotential surface was then extended to all latitudes as the zero-level reference for topography.

Occultations

Radio occultation measurements come from Doppler tracking as the signal from an orbiting or flyby spacecraft is lost (ingress) behind a planet and then re-acquired (egress) as viewed from Earth. The change in the frequency and intensity of the radio signal as it traverses through the atmosphere near the planetary limb provides measurements of atmospheric pressure and temperature as function of altitude above the surface. If the position of the spacecraft with respect to Mars’ center of mass is known, the timing of the loss (for ingress) and acquisition (for egress) of the radio signal provides measurements of planetary radius. Radio occultations thus provide a unique basis for relating planetary radius and atmospheric pressure. As for the altimetry, the radius from an occultation minus the geoid provides a measure of the topographic elevation.

We utilized occultation measurements from S-band tracking of the Mariner 9 and Viking 1 & 2 orbiters [Kliore et al., 1972; Kliore et al., 1973; Christensen, 1975; Lindal et al., 1979]. In a previous study we re-analyzed the Mariner and Viking occultations [Smith and Zuber, 1996] and produced 368 refined measurements of Mars’ planetary radius. We estimated the average absolute radial accuracy of these measurements to be ±500 m. New occultation measurements of Mars are now being collected from MGS. These measurements are from an X-band tracking system [Tyler et al., 1992] and are therefore lower in noise by about a factor of three compared to previous S-band measurements. The historical data were also limited in application to pressure variability by their spatial and temporal sampling. While the MGS occultation data are in an early stage of processing and are thus not incorporated here, preliminary analysis [Tyler et al., 1998] indicates that the new data confirm the accuracy of our re-processed Mariner 9 and Viking occultation radius values.

Comparison of Occultation and MOLA Elevations

To ultimately relate MOLA topography to atmospheric pressure it was necessary to first compare surface elevations obtained from the occultations to those from MOLA. Figure 1 shows a comparison of occultations that fall within 15 km of a MOLA track. For occultations that lie within 10 km of MOLA points the agreement is -18 ± 118 m. When the distance is extended to 20 km the misfit increases to +34 ± 106 m. Given the absolute accuracy of the occultation measurements, the MOLA and occultation elevations are indistinguishable within error bounds. The level of agreement is adequate for the purpose of relating MOLA elevations to occultation pressures. The close correspondence of MOLA elevations to those determined by pressure sensors on surface landers [Smith et al., 1998a] provides an independent check of the relationship of MOLA data to surface pressure.

Seasonal Variability

The occultations, which were collected throughout the Martian seasonal cycle, provide a pressure-radius relationship for Mars. However, measurements of surface pressure from the Viking [Tillman, 1988] and Pathfinder [Schofield et al., 1997] landers showed significant changes in pressure due to the exchange of CO₂ between the atmosphere and polar caps [Hess et al., 1980]. Pressure changes of 25%-30% occur over the course of the seasonal cycle, and as a consequence it is necessary to correct the pressures measurements to a single point in the year. It is convenient to utilize the seasonal argument, \(L_s\), which is defined from 0°-360° over a Martian year, where \(L_s=0°\) corresponds to the vernal equinox in the northern hemisphere.

We used the NASA/Ames’ General Circulation Model (GCM) [Pollack et al., 1990] to calculate the expected pressure change in a specified location at a desired \(L_s\) [Smith et al., 1998b]. The GCM is a finite difference grid point model based on the “primitive equations” that include horizontal momentum, thermodynamic energy, mass continuity, a hydrostatic approximation, and the equation of state for an ideal gas. The GCM’s diabatic routines incorporate the diurnal cycle and account for the radiative effects of CO₂ gas and dust aerosols, as well as the exchange of heat between the surface and atmosphere. GCM calculations were performed to yield temporal averages of pressure for twenty 33-day months, which corresponds to one Mars year (687 Earth days or 669 Mars days). The spatial grid of the GCM consists of 25 uniformly spaced points in latitude (7.5° resolution) and 40 uniformly spaced points in longitude (9° resolution), where on Mars one degree of latitude is approximately 60 km at the equator. The lower boundary of the model follows the geopotential topography [Smith and Zuber, 1996] and the upper extent of the model corresponds to the tropopause. The vertical mesh resolution is variable, with a closer spacing near
Figure 2. Seasonal pressure corrections at all latitudes as calculated by the Ames GCM. Corrections are relative to the expected pressure at $L_s=0^\circ$. Colors correspond to corrections for the 20 "months" in the Martian year.

Figure 3. Variation of surface pressure at the equator as calculated by the Ames GCM. Colors represent monthly corrections as given in Figure 2.

the surface where atmospheric density is greatest. The ability of the GCM to estimate surface pressures on Mars over a yearly cycle has been verified by comparison of model output to pressure measurements from the Viking landers.

We corrected all pressures to an arbitrary $L_s=0^\circ$. Figure 2 shows that the seasonal pressure correction has a maximum amplitude slightly in excess of 3 mbars. The dynamic range of the pressure variation corresponds to an altitude change of about 3.5 km over the course of the Martian year, which is nearly half an atmospheric scale height. Figure 3 shows the expected seasonal variability of surface pressure at the equator as calculated by the GCM. The longitudinal variation of the pressure is mostly a consequence of long wavelength topography, with greater variability in regions of low elevation. The location of the Tharsis rise centered on -110\(^\circ\) E is clearly evident. Pressure changes due to diurnal variations in the atmosphere are believed to be much less than seasonal effects [Leovy, 1982], so we did not make diurnal corrections to the pressure data. Atmospheric dynamics will further perturb the elevation of the pressure surface.

**Relationship of 6.1-mbar surface to MOLA Topography**

Figure 4 shows the pressure-elevation relationship derived from the occultations as compared to MOLA altimetry. The zero point of MOLA topography corresponds to an atmospheric pressure of -5.2 mbars at $L_s=0^\circ$. The 6.1-mbar pressure level occurs at approximately -1600 m relative to MOLA topography for $L_s=0^\circ$. The true height of the 6.1-mbar surface needs to be adjusted, depending on the date ($L_s$) and Figure 2 indicates that seasonal variations should produce vertical variations in the range of 1.5 to 2.5 km over the course of a Martian year.

**Comparison: MOLA Topography to USGS DTM**

The most widely used global topographic data set for Mars has been the USGS Digital Terrain Map (DTM) [Wu, 1991; Batson and Eliaison, 1995], which had the 6.1-mbar pressure surface as its zero elevation point. Because of the significant variation of atmospheric pressure due to the exchange of CO\(_2\) between the atmosphere and polar caps (Figure 2), it is now apparent that a pressure surface is an inappropriate choice for topographic studies that require a fixed reference level. However, because the DTM has been used extensively in previous analyses of Mars there is interest in comparing those elevations to MOLA's. This is possible using the topography-pressure relationship that we have established. Table I compares elevations from the 18 MOLA profiles with those from the DTM. The last column lists the root mean square (rms) deviation between the two after correcting for the mean difference. This residual misfit of the DTM elevations compared to MOLA is nearly a kilometer, and scrutiny indicates that the difference is not systematic on any scale. A formal error analysis was never performed on the DTM [S.S.C. Wu, pers. comm., 1996], in part because it was produced by combining several data types whose individual errors were not well understood. In contrast, radial errors in absolute elevations in the MOLA data have been thoroughly characterized and are approximately 30 m [Smith et al., 1998a]. We conclude that the kilometer-level misfit between MOLA and DTM elevations must be attributed mostly to random errors in the DTM elevations. The DTM cannot be corrected by applying a uniform constant offset.

Figure 4. Pressure-elevation relationship derived from MOLA topography and Viking and Mariner 9 occultations. Plotted as filled circles are ingress occultations only. Unfilled squares correspond to the Viking I & 2 and Pathfinder landing sites. All atmospheric pressures are corrected to $L_s=0^\circ$. The plot also shows the zero elevation points of MOLA topography and the USGS DTM, the 6.1-mbar surface and the expected pressure at the Mars Surveyor '98 landing site.
Landing Site Considerations

It is likely that knowledge of the relationship between surface topography and atmospheric pressure will be further refined as knowledge of Mars topography and gravity improves with the progress of the MGS mission. However, the initial improvement offered by the MOLA data is significant and relevant to current operational studies of targeting for the Mars Surveyor '98 and '01 landers. Mars Surveyor '98 (aka the Mars Polar Lander) is planned to land at a latitude of -72ø S, with longitude not yet specified. The landing is expected to occur at Ls-256 ø. Given typical targeting for the Mars Surveyor '98 and '01 landers. Mars improves with the progress of the MGS mission. However, refined as knowledge of Mars topography and gravity.

Acknowledgements. We thank Robert Haberle and James Murphy for performing the simulation on the Ames’ GCM. This work was supported by the NASA Mars Global Surveyor Project and Mars Exploration Program.

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Table 1. Difference between topographic elevations from the USGS DTM and MOLA. For each MOLA pass the table shows the minimum and maximum difference and mean and median deviation of the two data sets. The final column shows the rms misfit of the DTM minus MOLA after correcting for the different reference surfaces as discussed in the text.

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