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Vertical Roughness of Mars from the Mars Orbiter Laser Altimeter

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Abstract. The vertical roughness of the martian surface at ~250 m spatial scales has been determined in two global latitude bands: an equatorial and a high northern band acquired from 18 tracks of data by the Mars Orbiter Laser Altimeter (MOLA) during the Fall of 1997. The distribution of RMS vertical roughness, as derived from MOLA pulse widths, for the equatorial band is non-gaussian, with an overall mean of 2.8 m RMS, but with secondary populations at 1.5 m and 2 – 6 m RMS. The higher latitude northern plains of Mars are almost uniformly ~1 m RMS in their vertical roughness characteristics, suggesting that they are smoother than virtually any terrestrial deserts. We suggest that dust mantling has muted the local topography of Mars, rendering it as smooth as 1-2 m RMS. Heavily cratered uplands near the martian equator are noticeably rougher, indicating more rugged and less-mantled local topography.

Introduction and Background

The vertical characteristics of planetary surfaces are traditionally inferred from orbital images (Malin et al., 1998). Orbital radar altimeters and synthetic aperture radar systems, such as those that were deployed to characterize the global surface of Venus (Ford and Pettengill, 1992), have provided important insights into the local geomorphic characteristics of planetary surfaces. In order to quantify the vertical structure of local-scale landscapes, however, methods involving photoclinometry and stereogrammetry have been traditionally employed to yield the most geologically interpretable results.

The surface of Mars has been globally imaged at spatial scales as fine as 200-300 m by the Viking Orbiters, with higher resolution locally. There is considerable understanding of the vertical structure of landscape components at these length scales. However, until recently, there have been no direct mechanisms for determining the sub-hectometer spatial scale vertical roughness of the martian surface. Here we present preliminary results from the Mars Orbiter Laser Altimeter (MOLA) instrument (Zuber et al, 1992; Smith et al., 1998). MOLA provides a direct measure of the vertical variability of the local martian surface based upon the broadening of its laser pulse from interactions with the martian surface.

This new vertical roughness data provides a heretofore unavailable perspective on the spatial variability of the landform-scale surface of Mars. The MOLA pulse width data described here represents an independent assessment of the statistical properties of the martian surface texture and provides new information pertaining to the extent of dust mantling and other processes that serve to degrade landscape features. This type of information has proven to be of value in understanding the sub-kilometer properties of terrestrial landscapes (Garvin et al., 1998). In this report, we summarize the results of our preliminary assessment of the MOLA pulse width dataset.

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MOLA Pulse Width Data

The MOLA instrument measures the effective width of the backscattered laser energy at 1064 nm that is reflected at nadir off of the martian surface (Smith et al., 1998). It accomplishes this for every laser pulse emitted for which a reliable range value is recorded. The broadening due to martian surface characteristics can then be transformed into an RMS vertical roughness.

MOLA's pulse spreading is influenced by an ensemble of factors. The most important of these include the off-nadir pointing angle of the spacecraft platform, the footprint-scale slope of the surface, the local vertical distribution of relief elements (within the footprint), and the 1064 nm reflectivity of the surface (Gardner, 1992; Harding et al., 1994; Garvin et al., 1998). We have corrected for the effects of some of these factors in order to interpret the MOLA pulse width measurement in terms of the footprint-scale vertical variability of relief (i.e., the statistical equivalent to the RMS vertical distribution of detectable range levels within a 180-300 m diameter footprint). We have used the formulation of Gardner (1992) to effectively subtract the contribution due to along-track slope (S_X) under the assumption that the footprint-to-footprint slope is maximal in the along-track direction. We believe that applying the Gardner correction allows us to derive a systematic, internally-consistent measure of the RMS vertical roughness of the martian surface (Harding et al., 1994). This assertion is based on the statistical properties of the MOLA-derived parameter in comparison with RMS vertical roughness data measured for terrestrial surfaces with a MOLA-like laser altimeter system (i.e., the Shuttle Laser Altimeter or SLA) which included a full waveform analysis capability (Garvin et al., 1998).

Another problem is signal saturation, which is observed for those MOLA measurements which approach periapsis (approximately 30° N latitude). MOLA is optimized for observations in circular, polar orbit at a nearly constant altitude of 400 km. When MOLA is operated below about 380 km with respect to the martian surface, its signal strength exceeds the dynamic range of the altimeter receiver and saturation occurs. The effect of saturation on the corrected pulse width data is serious and because of ringing effects in the MOLA detector, all pulse widths acquired when MOLA is in saturation are spurious and must be discarded. We have isolated and removed all saturated MOLA pulses from our consideration by examining simultaneously the MOLA pulse energy and uncorrected pulse width parameter as a filter. Most of the measured MOLA pulse widths between about 50°N and 10°N are saturated and do not allow for derivation of a valid RMS roughness statistic. Nonetheless, over 40% of the laser pulses emitted by MOLA over the 18 tracks resulted in valid RMS vertical roughness values.

It is also necessary to correct pulse widths for the effect of changing footprint size, which is due to varying spacecraft altitude above the surface. The MOLA surface footprint varies from nearly 300 m in diameter at 80°N and 12°S (i.e., at the most distant altitudes in the Mars Global Surveyor orbit during the Hiatus Orbit period) to ~ 180 m diameter before the sensor saturates (i.e., approaching periapsis). We have attempted to normalize the pulse width and hence the RMS vertical roughness by scaling all values to that which would be observed at the mapping altitude (i.e., 150 m diameter footprint). Emulation experiments involving airborne laser altimeter footprints at 30 m, 70 m, and 150 m diameters conducted over martian analogue terrains in Iceland (i.e., volcanoes, glacial outwash plains, icecaps) did not result in appreciable changes in the RMS pulse width statistics.

Vertical Roughness

During the Fall 1997 observation period (i.e., the Hiatus Orbit period), unsaturated roughness values were measured in the near-polar latitudes (50-80°N) and in the equatorial region (5°N to 12°S). Figure 1 illustrates the spatial pattern of the corrected RMS vertical roughness. We have superimposed the MOLA ground tracks on top of the shaded relief derived from the pre-MOLA martian Digital Topographic Model (USGS DTM). The magnitude of the RMS vertical roughness data is color-coded from brown to red/white, corresponding to the plot of vertical roughness in meters shown below. Most of the values are brown-dark blue, corresponding to RMS vertical roughness values between 0.5 m and 2.0 m. Superimposed on such low roughness values are clusters of higher vertical roughness, with the most statistically significant cluster of high roughness values falling near 4 – 5 m (light blue in Fig. 1). An RMS vertical roughness over 180 – 300 m spatial scales of 5 m is very large; on Earth such values are uniquely typical of rugged deserts or forested terrain (Garvin et al., 1998).

In the equatorial latitudes, many of the highest (non-saturated) RMS vertical roughness appear to be associated with either canyon systems (Labyrinthus Noctis, Northern Valles Marineris; see inset in Fig. 1) or chaos terrain. Only the ejecta and rim materials of large, high latitude impact craters (e.g., Korolev) raise the vertical roughness of the sub-polar region above 5 m RMS (Fig. 1). The highest recorded vertical roughness values (10 – 15 m RMS) all appear to be associated with canyon systems at least partially associated with Valles Marineris. This may be a consequence of extreme local slopes and an absence of mantling materials in such regions.

Figure 2a and 2b are histograms of the vertical roughness calculated from the non-saturated pulse widths for all 18 tracks over the northern plains and the equatorial region respectively. The northern plains show an extremely low

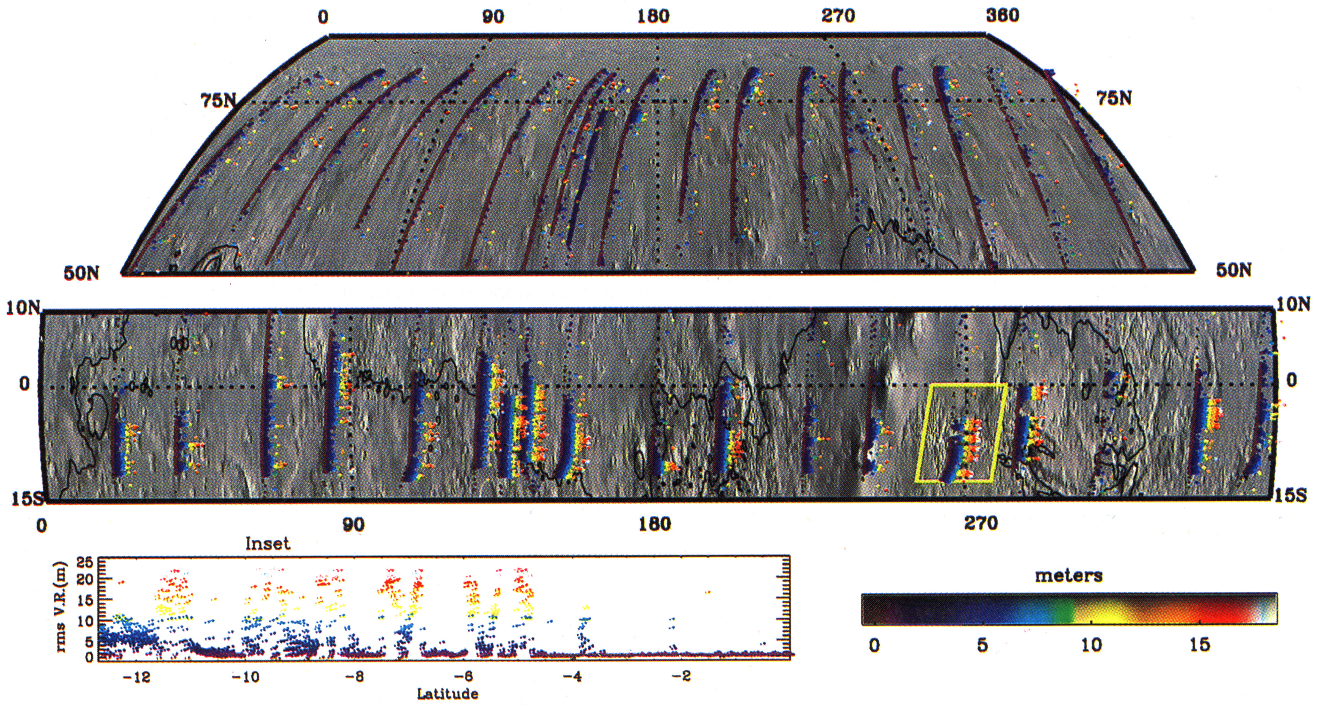

Figure 1. Shaded relief map of Mars derived from the USGS DTM on which are superimposed those portions of 18 MOLA ground tracks where unsaturated data were obtained. The solid black line approximates the location of the crustal dichotomy boundary. For each of the nadir ground tracks the magnitude of the MOLA-derived RMS vertical roughness in meters is displayed as a "fence post" using the color scale shown below the map. Note that the "hotter colors" are used to depict rougher surfaces. A 13° latitude portion of Mars (the yellow box to the right of center) known as Labyrinthus Noctis is shown in the lower left inset, with RMS vertical roughness (V.R.) on the vertical axis.

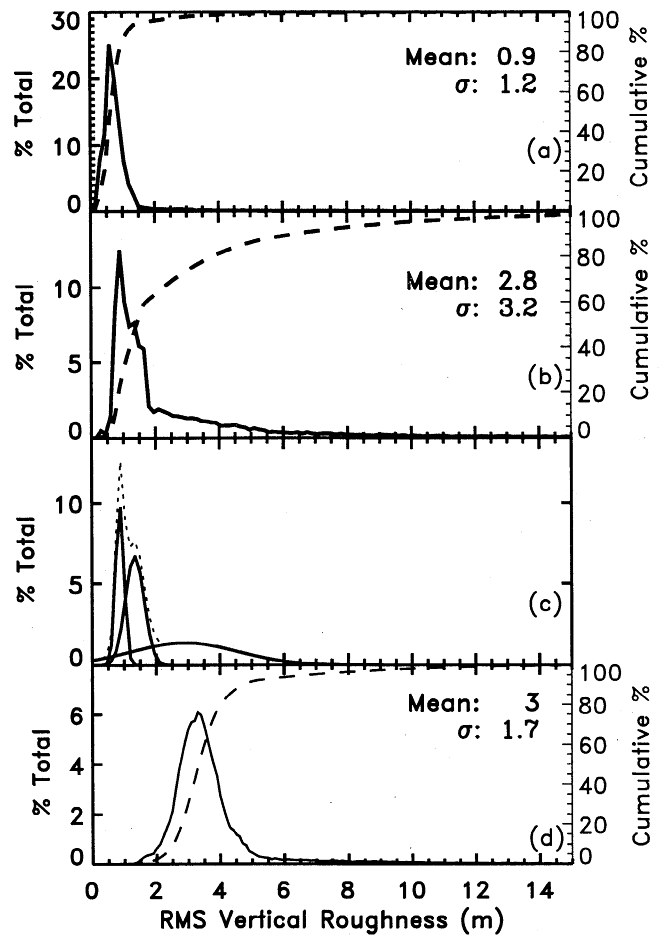

Figure 2. Histograms of: (a) MOLA-derived RMS vertical roughness for the high northern plains [50-80°N], (b) the equatorial uplands [5°N-12°S], (c) gaussian decomposition of the equatorial uplands and (d) Shuttle Laser Altimeter (SLA)-derived RMS vertical roughness for terrestrial deserts.

vertical roughness, with a mean value of only 0.9 and standard deviation of 1.2. In contrast, the RMS vertical roughness of the equatorial region suggests a very curious non-gaussian distribution, with a significant sub-population of higher RMS vertical roughness surfaces extending in the form of a "shoulder" from the basic character of martian landscapes in the northern plains. We have decomposed the equatorial frequency distribution into sub-populations using multi-gaussian methods (Fig 2c). The spatial pattern of the 2 - 6 m "high roughness unit" may be correlated with more geologically active surfaces that have had less opportunity to become deeply dust mantled, perhaps on the basis of their higher local slopes. However, even in these regions of consistently higher RMS vertical roughness, there are intermixed surfaces of "background" roughness (0.5 – 1.8 m RMS), as can be observed in Figure 1.

The onset of higher vertical roughness as one proceeds from polar to intermediate latitudes does not seem to correlate well with the larger physiographic provinces on Mars, such as the hemispheric dichotomy. Although there may be a tendency toward higher RMS roughness in the highland/lowland transition zones, there are clearly other major geologic controls associated with this parameter. For Valles Marineris and its adjacent canyon regions (Labyrinthus Noctis), the overall pattern is one with RMS vertical roughness values above ~ 6 m, but with values as low as 2 - 4 m on the canyon floors and plateau regions. The equatorial hemispheric dichotomy region is marked by a transition to higher vertical roughness, especially in those regions where zones of chaos predominate (Fig. 1: 120 to 150° E). Clearly the hectometer spatial scale vertical surface texture is appreciably different for Northern Hemisphere volcanic plains than for the more heavily cratered uplands in the equatorial region.

A low roughness population with a mean value at 0.9 m RMS is dominant (25% peak frequency) in the high northern latitudes, while a broader population with a mean value at 2.8 m RMS is the most common roughness unit in the equatorial region (peak frequency of 12%). A significant equatorial region sub-population with a broad range of vertical roughness (2 - 6 m RMS) displays a peak occurrence of 2%, while an outlying population with values greater than 6 m can also be discerned. The character of each of these distinctive sub-populations varies in terms of their basic statistical properties (mean, standard deviation). Fig. 1 indicates the spatial distribution of these major "units". The primary population is brown and represents the background roughness of Mars for all regions. A less distinctive violet/purple unit appears to be spatially correlated with the more rugged regions between 10°S and 5°N, and in particular the transition between volcanic plains and the northernmost extent of the highlands boundary zone. It is likely to represent a transitional unit, perhaps dominated by partially dust-mantled landscapes that are older than the younger volcanic regions of the Northern Hemisphere. The third vertical roughness unit is illustrated by the darker blue regions in Fig. 1. In the higher northern latitudes above about 50°N, this dark blue (~ 3 m RMS) unit is very localized and appears to correlate with the largest and more youthful impact craters, as well as with the margins of the northern polar dune fields. However, it is intermittently well represented in the equatorial latitudes, perhaps associated with transitionally rougher and more geologically youthful or active surfaces. The fourth unit (> 6m RMS) is represented by the yellow/tan regions, most of which are highly correlated with uplands and higher relief surfaces associated with regions of chaos near the hemispheric dichotomy, and with the canyonlands of Valles Marineris and Labyrinthus Noctis. The ejecta of the 80-km diameter crater Korolev displays vertical roughness values above 6 m RMS in the polar latitudes.

Figure 1 clearly suggests that while there are spatially distinctive regions of vertical roughness at these length scales (~250 m), there is a continuum such that the smoothest unit (i.e., that with a mode less than 1 m) occurs at all latitudes. For this reason, we believe that localized patches of low relative roughness surfaces are commonplace everywhere on Mars that has been sampled by MOLA to date. Such sometimes isolated patches may represent local zones of dust deposition, perhaps related to their intrinsic low slopes or due to topographic barriers that allow them to act as depocenters. Mars Orbiter Camera (MOC) images discussed in Malin et al. (1998) indicate that uneven, heterogeneous dust mantling is ubiquitous at the scales of the MOLA footprints, except in regions of high topographic gradients (i.e., canyon and crater walls, etc.).

Garvin et al. (1998) discuss the ramifications of the terrestrial RMS vertical roughness distributions, which are largely controlled by the characteristic height of superimposed vegetation, or in the case of deserts, by the vertical structure of local erosional relief (i.e., dunes, gullies, yardangs, etc.). The high mean RMS roughness of tropical forests (7 m) attests to the complexity and magnitude of the superimposed vegetation. On Mars, a small but spatially distinctive sub-population of surfaces associated with the most rugged (at multi-kilometer length scales) terrain attains RMS vertical roughness magnitudes that are comparable to forested regions on Earth. This is not surprising given the observed complexity of such surfaces as observed in recent MOC images (Malin et al., 1998). There are a few mountainous regions on Earth, such as in the Zagros region of Iran, where SLA-based RMS vertical roughness values as large as 9 m are observed in the absence of vegetation. However, RMS roughness values associated with major volcanic edifices on Earth such as Mauna Kea (Garvin et al., 1998), are less than 4 m in magnitude. The significance of the high roughness unit on Mars is most probably related to extreme local slopes at a variety of length scales (100 m to several km) and to the associated minimization of dust mantling in such regions. This agrees with the most recent photogeologic observations (e.g., Malin et al., 1998). However, it is puzzling why this sub-population of martian surfaces is so narrowly distributed (i.e., ~ 1 m total range), given the complexities associated with steeply sloping terrains on Mars.

We have used a MOLA-like laser altimeter, the Shuttle Laser Altimeter (SLA) flown in Earth orbit, to compare the roughness of Mars with that observed on Earth. Data from the SLA-01 mission (i.e., STS-72, January 1996) can be compared to that measured by MOLA if the computation of RMS pulse width from the SLA echo data is accomplished carefully in order to properly emulate the MOLA algorithm for measuring pulse width. We have compared the frequency distribution of RMS vertical roughness for terrestrial deserts sampled by SLA-01 (Fig. 2d) against the distribution of RMS roughness measured for Mars. Terrestrial arid lands with no appreciable vegetation are essentially gaussian in their distribution of vertical roughness with a mean and modal value near to 3 m RMS, and less than 10% of the values in excess of 5 m RMS. The northern plains distribution is gaussian, with a mean value of 0.9 m RMS, and is much smoother than terrestrial deserts. In contrast, 20% of the martian equatorial measurements are above 4 m RMS and the distribution is non-gaussian, with several statistically significant sub-populations, including a broad class with RMS vertical roughnesses in the 2 – 6 m range. As Figure 2d illustrates, terrestrial deserts are far from being uniformly "smooth" at 100 m spatial scales, and only the smoothest 10% of these surfaces are typical of the "average" northern hemisphere plains on Mars. Indeed, there is a sub-population of martian surfaces that are most akin to terrestrial deserts, but they are associated with equatorial uplands and canyon floors.

This adds further evidence for local to regional scale surface processes on Mars that have served to smooth the martian surface at length scales ranging from ~ 100 m to hundreds of km (Smith et al., 1998). Indeed, the major "background" population of surfaces on Mars with RMS vertical roughness values near 1.0 m, are most similar to the roughness expression of ocean surfaces as observed by SLA. While this does not demonstrate a water-related origin for these surfaces, it does amplify the case for surface processes on Mars that effectively promote the development of playa-like surfaces with extremely low local slopes. This could be accomplished in many ways, including dust mantling, desiccation, and rapid resurfacing events. The distribution of MOLA-derived vertical roughness data supports the existence of widespread smooth plains materials on Mars that mimic the very smoothest local surfaces on Earth (i.e., playas and dry lake beds, liquid water etc.).

Summary

MOLA measurements of the vertical roughness of local areas of Mars have been analyzed in order to understand the correlation of image-scale roughness with physiographic features on the planet. Initial results of this aspect of the MOLA experiment have demonstrated that the local martian surface in the Northern Hemisphere is remarkably smooth when compared against similar data for terrestrial surfaces. Large areas of this part of Mars display RMS vertical roughness characteristics that are comparable to the smoothest unvegetated landscapes on Earth. Further, our analysis of MOLA vertical roughness data supports the hypothesis that erosion and dust mantling are controlled by local slopes and that the geologically most dynamic and topographically complex surfaces are rougher than other regions by up to a factor of ten. Global analysis of the MOLA-derived vertical roughness of the martian surface offers promise for independently assessing the local (i.e. 100-200 m) scale geological processes that have dominated the formation of sub-kilometer martian landscapes. Laser altimeter-derived observations of geologic roughness appear to be complementary to those previously derived from radar (microwave) and passive optical methods.

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