1. Introduction

The surface of a terrestrial planet is mainly shaped by several endogenic and exogenic geological processes (e.g., volcanism, impact cratering, and tectonism) [1, 2]. Volcanism can produce a variety of landforms (e.g., lava flows, sinuous rilles, domes and cones), and impact cratering events can lead to rugged cratered landscapes depending on density and shape of craters. Over a long-term geological history, geologic events at different stages formed sinuous rilles, domes and cones, and impact cratering events can lead to rugged cratered landscapes depending on density and shape of craters. All these will provide valuable information about the formation and evolution of the surface of terrestrial planets.

Previous studies show that roughness maps of the Moon, Mars and Mercury possess a distinctive dichotomy between cratered terrains and smooth plain regions [3, 4, 5], and that the scale-dependent roughness is controlled by different geological processes [1, 6]. However, in most of previous studies, different roughness parameters were investigated at different scales, making direct comparison among the three bodies difficult. In this study, we used the latest topography data and mapped surface roughness of the Moon, Mars and Mercury. Based on the statistics of several key roughness parameters for major geologic units on these three bodies and their variations at scales from 0.1 to 100 km, we investigated the effect of volcanism and impact cratering on surface formation and evolution.

2. Data and Methods

In this study, we used laser altimeter data for roughness mapping, including LRO Lunar Orbiter Laser Altimeter (LOLA) data for the Moon (57 m spacing, ~0.1 m precision) [7], MGS Mars Observer Laser Altimeter (MOLA) data for Mars (~300 m resolution, ~1 m accuracy) [8], and MESSENGER Mercury Laser Altimeter (MLA) data (~390 m, ~0.15 m range error) for northern high latitudes (~45°N) of Mercury (to guarantee enough number of independent observation) [9]. In our roughness mapping, we chose the baseline slope ($s_L$), root-mean-square (RMS) height ($\sigma$), the Hurst exponent ($H$), and differential slope ($DS$, $s_D$),

$$s_L = \text{atan} \left( \frac{1}{n-1} \sum \left( \frac{z_i}{\sqrt{n}} \right) \right), \quad \sigma = \sqrt{\frac{1}{n-1} \sum \left( \frac{z_i - \bar{z}}{\sigma} \right)^2} = \sqrt{\frac{1}{n-1} \sum \frac{z_i - \bar{z}}{\sigma}}, \quad s_D(L) = \frac{z(L+1) - z(L-1)}{\Delta L},$$

where $z$ is surface elevation, $\bar{z}$ is the mean height of the topographic profile, and $\Delta z$ and $\Delta L$ are both baseline [4, 10].

At large scales, all the three bodies possess two types of surface: cratered terrains and smooth plain regions. Cratered terrains include highlands on the Moon and Mars, and heavily cratered terrain (HCT) on Mercury. Smooth plain regions include maria on the Moon, lowlands on Mars, and smooth plains (SP) on Mercury. We will calculate the statistical characteristics of roughness parameters for these geologic units, and the distribution of these geologic units are from the geological maps in Wilhelms and McCauley for the Moon [11], Tanaka et al. for Mars [12], and Denevi et al. for Mercury [13].

3. Topographic Roughness of the Moon, Mars and Mercury

![Figure 1. Bidirectional slope, RMS height, and Hurst exponent for the Moon, Mars and Mercury with latitude >45°N.](image1)

The Moon: Lunar maria and highlands show distinct dichotomy in bidirectional slope and RMS height. Mare Tranquilitatis and Nectaris are slightly rougher than Maria Imbrium and Serenitatis. The regions north of Mare Frigoris show lower RMS height and H than typical highlands.

Mars: Bidirectional slope and RMS height over the southern highlands are 2–3 times larger than those of the northern lowlands and volcanic regions. The Amazonia volcanic planitia (Amazonis and Elysium) are the smoothest among geologic units. There is an abrupt increase in Hurst exponent as the latitudes go across 45°N and 45°S, which is similar to zonal belts of slope asymmetry at 40–50° latitude found in Kreslavsky and Head [14].

Table: Topographic Roughness Statistics for Major Geologic Units on the Moon, Mars and Mercury.

<table>
<thead>
<tr>
<th>Planets</th>
<th>Geologic units</th>
<th>Bidirectional slope</th>
<th>RMS height (km)</th>
<th>Hurst exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moon</td>
<td>Highlands</td>
<td>0.81±0.02</td>
<td>17.0±1.3</td>
<td>0.73±0.05</td>
</tr>
<tr>
<td>Mars</td>
<td>Lowlands</td>
<td>0.41±0.02</td>
<td>12.1±1.3</td>
<td>0.77±0.05</td>
</tr>
<tr>
<td></td>
<td>Highlands</td>
<td>1.2±0.02</td>
<td>63.2±2.1</td>
<td>0.82±0.02</td>
</tr>
<tr>
<td>Mercury</td>
<td>SP</td>
<td>2.6±0.02</td>
<td>54.1±0.3</td>
<td>0.66±0.02</td>
</tr>
<tr>
<td></td>
<td>HCT</td>
<td>4.7±0.02</td>
<td>136.9±0.5</td>
<td>0.81±0.02</td>
</tr>
</tbody>
</table>

Median values are given with the 25% (after −) and 75% (after +) percentile points.

Comparison: Median values of RMS height (Table 1) show that lunar highlands and Mercurian HCT are the roughest, the lunar maria and Martian lowlands are the smoothest, and Martian highlands and Mercurian SP are in between. Lunar highlands that were mainly shaped by impact cratering, have the highest median H values (~0.9). The young volcanic plains (e.g., Amazonian planitia on Mars and floor of Geotho basin on Mercury) show an average value as low as 0.5. For geologic units that were shaped by both cratering and volcanism (e.g., Martian highlands and Mercurian HCT), the median Hurst exponents are 0.7–0.8.

4. Conclusions

We mapped and compared the surface roughness of the Moon, Mars and the northern hemisphere (>45°N) of Mercury using high-resolution topography data. Our results show that:

1. The bidirectional slope, RMS height, and Hurst exponent maps for the Moon, Mars and Mercury show a distinct dichotomy between cratered terrains and smooth plain regions. The statistics of these parameters indicate that lunar highlands and Mercurian HCT are the roughest, lunar maria and Martian lowlands are the smoothest, and Martian highlands and Mercurian SP are in between.

2. At hectometer scale, for the Moon and Mercury, there is no significant difference in differential slope between cratered terrains and smooth plains. For Mars, the differential slope maps show that the polar regions are smoother than equatorial regions (45°N–45°S). At kilometer scales, differential slopes of cratered terrains are much larger than those of smooth plains.

3. Median differential slopes show that lunar highlands are smoother than Mercurian HCT at baselines ~0–1 km but rougher at baselines ~1 km, and that they are always rougher than Martian highlands. For smooth plain regions, Mercurian SP is the roughest, and Martian lowlands are the smoothest at all the baselines studied.

In our future work, we will quantify the influences of density and shape of impact craters, volcanism and regolith gardening process on the topographic roughness. We will also compare the effect of different geological processes on different bodies. All these will provide valuable information about the formation and evolution of the surface of terrestrial planets.

References: