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The Surface Roughness of Large Craters on Mercury

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Abstract This study investigates how individual large craters on Mercury (diameters of 25–200 km) can produce surface roughness over a range of baselines (the spatial horizontal scale) from 0.5 to 250 km. Surface roughness is a statistical measure of change in surface height over a baseline usually after topography has been detrended. We use root mean square deviation as our measure of surface roughness. Observations of large craters on Mercury at baselines of 0.5–10 km found higher surface roughness values at the central uplifts, rims, and exteriors of craters, while the crater floors exhibit the lowest roughness values. At baselines <10 km, the regions exterior to large craters with diameters >80 km have the highest surface roughness values. These regions, which include the ejecta and secondary fields, are the main contributors to the increased surface roughness observed in high-crater density regions. For baselines larger than 10 km, the crater cavity itself is the main contributor to surface roughness. We used a suite of numerical models, utilizing the measured surface roughness obtained in the study, to model the cumulative effect of adding large craters to a surface. The results indicate that not all of the surface roughness on Mercury is due to fresh large craters but that impact craters likely contribute to the Hurst exponent from baselines of 0.5 – 1.5 km and the shape of the deviogram. The simulations show that the surface roughness varied around an asymptote at the baselines studied before the surface was covered in impact craters.

Plain Language Summary Impact cratering is the main process by which many planetary bodies are roughened, where an increase in the number of craters is related to higher surface roughness. In this study, we use observations and artificial data to explore how individual complex craters on Mercury can change the surface topography and produce surface roughness. Observations of the surface roughness of complex craters on Mercury found surface roughness related to several different geologic features of the craters. We found that impact craters are the main source of surface roughness on Mercury. We modeled how impact crater density affects surface roughness and found that it is difficult to relate surface age to surface roughness.

1. Introduction

Impact craters modify the topography of planetary surfaces. We can quantify the influence of impact craters on the topography of a planetary surface through a statistical measure of the change in vertical topography (which is often detrended) over a given horizontal scale, surface roughness (e.g., Shepard et al., 2001). Previous studies have shown that regions with higher impact crater density have higher surface roughness value than regions with lower impact crater density (e.g., Fa et al., 2016; Kreslavsky et al., 2008, 2014, 2013; Pommerol et al., 2012; Rosenberg et al., 2011, 2015; Susorney et al., 2017; Yokota et al., 2014); in this study we focus on investigating how surface roughness characteristics can reflect the physical attributes of an individual impact crater (e.g., the crater floor, ejecta, and secondary cratering field) and use a numerical investigation to explore how the regional surface roughness of Mercury is related to large craters (diameters from 25 to 200 km).

Prior investigations of surface roughness on the Moon and Mercury using many different measures of surface roughness found correlations between regions with high surface roughness values and regions with high crater density, regardless of the measure used (Fa et al., 2016; Kreslavsky et al., 2008, 2013, 2014; Pommerol et al., 2012; Rosenberg et al., 2011, 2015; Susorney et al., 2017; Yokota et al., 2014). An implicit assumption in interpreting the apparent correlation between crater density and surface roughness is that the crater cavities...
(the primary topographic depression) are the main factors increasing the measured surface roughness. This assumption has led several authors (e.g., Fa et al., 2016; Rosenburg et al., 2011; Yokota et al., 2014) to propose that surface roughness could be used as a complementary method to crater counts (e.g., Group, C. A. T. W, 1979) to estimate the age of planetary surfaces.

Two studies (Rosenburg et al., 2015; Yokota et al., 2014) investigated in greater detail the relationship between crater density and surface roughness. Yokota et al. (2014) measured the surface roughness of the Moon using the measure of median differential slope (Kreslavsky & Head, 2000) at horizontal baselines ($L$) of $0.15 - 100$ km. The study found that the median differential slope at $L = 20$ km correlated well with the cumulative density of craters ($N$) with diameters greater than $20$ km ($N(>20)$). A second correlation with $N(>20)$ was found at $L = 6 - 9$ km. The study also used simulated topography with craters modeled as modified cones to test whether they could reproduce the correlation of surface roughness with crater density. The correlation at $L = 20$ km was reproduced, but the simulated topography did not reproduce the correlation at $L = 6 - 9$ km. The difference at the smaller baselines ($6 - 9$ km) was attributed to the fact that secondary craters and details of ejecta deposits were not incorporated into the model.

Rosenburg et al. (2015) investigated how idealized crater morphology affected topographic power spectral density on the Moon with a simplified model of crater morphology but did not directly focus on the relationship between crater density and age. The study found that the simulated power spectral slope was dependent on the production function of impact craters. The model successfully reproduced the measured power spectra of the lunar surface at baselines of $0.115 - 1$ km.

Several studies that performed roughness assessments for broad regions across Mercury discussed the increase in surface roughness associated with individual impact craters (Fa et al., 2016; Harmon et al., 2007; Kreslavsky et al., 2014; Neish et al., 2013; Susorney et al., 2017). The centimeter-scale surface roughness of Mercury’s craters was approximated using Arecibo radar (Harmon et al., 2007), and an increase in radar brightness (corresponding to higher surface roughness values) was associated with a few large craters (e.g., the crater Hokusai). The centimeter-scale radar brightness was later attributed to large volumes of impact melt and around craters on Mercury (Neish et al., 2013). More recent studies of Mercury’s surface roughness, at baselines similar to the above mentioned lunar studies, used a range of different surface roughness measurements (Fa et al., 2016; Kreslavsky et al., 2014; Susorney et al., 2017) and data from the MERCURY Surface, Space Environment, GEnchemistry, and Ranging mission. All studies noted that regions of higher surface roughness values correlate with regions of higher crater density (the cratered terrain; e.g., Spudis & Guest, 1988; Trask & Guest, 1975; Whitten et al., 2014) and regions of lower surface roughness values correlate with regions of lower crater density (the smooth plains; e.g., Denevi et al., 2013; Spudis & Guest, 1988; Trask & Guest, 1975).

In the current study, we build upon previous investigations of the surface roughness of Mercury and focus on the surface roughness created by large impact craters. We limit this study to large fresh craters (diameter $>20$ km) with well-preserved rim and ejecta facies since previous studies have observed that the regional surface roughness of Mercury is dominated by such craters (Fa et al., 2016; Kreslavsky et al., 2014; Susorney et al., 2017). Additionally, to resolve the surface roughness of the different aspects of crater morphology (i.e., crater rim and ejecta), we limit the crater diameters studied to diameters larger than 20 km. We focus on the surface roughness of fresh craters where the surface roughness has been minimally affected by degradation. In particular, we want to investigate the source of increased surface roughness around large craters (diameters $>80$ km) in the smooth plains noted in Fa et al. (2016) and Susorney et al. (2017). This study is composed of two parts: first, an in-depth analysis of how surface roughness is distributed in and around individual craters (sections 2 and 3). Second, a numerical investigation (section 4) where we utilize the measured surface roughness values (from the first part of the study) to add multiple craters to an artificial surface. We use the results of both parts to understand how individual craters modify the surface roughness of Mercury, how the accumulation of craters through time modify surface roughness, and how crater density is related to surface roughness (section 5).

2. Measurement of Surface Roughness

To understand how impact craters affect surface roughness on Mercury, we measured the surface roughness of 17 large craters (see Table S1 in the supporting information for list) using individual Mercury Laser Altimeter (MLA) tracks (Zuber et al., 2012). We choose the 17 craters based on the crater freshness and the spatial...
coverage of MLA tracks. Using topography from individual laser altimetry tracks to calculate surface roughness is more accurate than using derived gridded topographic products, which typically are generated by binning and smoothing topography to fill in the topography in regions where no altimetry data are present (see discussion in Barnouin-Jha et al., 2005; Glaze et al., 2003; Robbins & Hynek, 2013). Because MLA tracks are concentrated in Mercury’s northern hemisphere, this investigation is limited to craters in the northern hemisphere.

We used root mean square (RMS) deviation as our measure of surface roughness. RMS deviation is the RMS change in detrended height over a given horizontal scale. We choose to use RMS deviation rather than other measures of surface roughness (e.g., Kreslavsky et al., 2013) for several reasons. First, RMS deviation is commonly used in planetary radar and laser altimetry surface roughness studies (e.g., Fa et al., 2016; Orosei, 2003; Rosenberg et al., 2011) and terrestrial surface roughness studies (e.g., Mark & Aronson, 1984). Second, RMS deviation is related to the proposed self-affine behavior of natural surfaces (e.g., Turcotte, 1997). If individual RMS deviation measurements are plotted against the baselines, they were calculated over in a log-log plot and the resulting plot is linear in log-log space; a Hurst exponent can be fit to the data. A single diagnostic Hurst exponent for a surface has been postulated to indicate that its topography is the result of a single geologic process without any characteristic scale (e.g., Shepard et al., 2001). Additionally, previous studies exploring the relationship between surface roughness and crater densities used other measures of surface roughness rather than RMS deviation (median differential slope; Yokota et al., 2014, and topographic power spectra; Rosenberg et al., 2015). Our use of RMS deviation permits us to explore the relationship of a different surface roughness parameter and crater density.

Larger regional maps of RMS deviation were presented in Susorney et al. (2017) and were used to understand the relative contribution of volcanism, tectonics, and impact cratering to regional surface roughness. In this section, we will briefly review RMS deviation and its relationship to the self-affine nature of topography and how we filtered MLA data before measuring RMS deviation. We then explain how surface roughness maps were produced and how radial plots of surface roughness around large craters were generated.

2.1. Measurements From MLA Data

The surface roughness was measured at baselines of 0.5–250 km with the smallest baseline being constrained by the spacing between individual MLA returns along an MLA track, which vary from 0.3 to 0.7 km. Individual MLA points were evaluated for each baseline investigated to check that the spacing between MLA points within 5 times the baseline on either side of the point was less than the baseline investigated (see Susorney et al., 2017). If the MLA point had appropriate spacing, adjacent MLA points within 5 times the baseline were interpolated to generate a spacing equivalent to the baseline investigated. In Susorney et al. (2017), this methodology (see Figure 3 in Susorney et al., 2017) was compared to topography that was not interpolated and no statistical difference in the resulting surface roughness values was found. Then, 10 times the baseline of interest was detrended to remove broadscale slopes (5 times on either side of the MLA point, following recommendations in Shepard et al., 2001). The difference in height one baseline up and one down from the MLA point was then measured. The change in height \( \Delta h(L)_i \) was then used to calculate \( \nu(L) \) using equation (1).

2.2. RMS Deviation

RMS deviation, \( \nu(L) \), is the change in detrended topographic height, \( h \), over a given horizontal baseline, \( L \), and is defined by

\[
\nu(L) = \left\{ \frac{1}{n} \sum_{i=1}^{n} (\Delta h(L)_i)^2 \right\}^{\frac{1}{2}},
\]

where \( \Delta h(L)_i \) is the change in height and \( i \) is the number of \( \Delta h \) used to calculate RMS deviation. RMS deviation is related to the Hurst exponent, \( H \), which describes how the surface roughness changes with increasing baseline by

\[
\nu(L) = \nu_0 L^H,
\]

where \( \nu_0 \) is the RMS deviation at the unit scale. If the surface has self-affine behavior, a straight line can be fit to the log of \( L \) versus the log of \( \nu(L) \) and the resulting exponent of the fit to the line is \( H \) (Turcotte, 1997). It has been postulated that when a single \( H \) exists for a surface, then a single geologic process without any characteristic scale might control the observed topography (e.g., Shepard et al., 2001). When referring to the results of this study, surface roughness and RMS deviation are used interchangeably.
2.3. Maps of Surface Roughness

To understand how the surface roughness is distributed in and around large craters on Mercury, we generated maps of surface roughness centered on large craters using the Generic Mapping Tools (http://gmt.soest.hawaii.edu; Wessel et al., 2013). Maps were gridded at twice the baseline at which the surface roughness was computed to avoid smearing. This, for example, means that a map at $L = 1$ km would be gridded at 2 km. A continuous curvature spline fit was added to ease presentation of data (Smith & Wessel, 1990). Maps without spline fits were consulted to check that no artifacts were introduced by these fits. Maps were used for qualitative comparisons only, due to sparse MLA coverage which resulted in some bins having less than 100 $\Delta h$.

2.4. Surface Roughness Radial Analysis

In addition to the maps of surface roughness, we also calculated radial profiles of surface roughness around the large craters. For each crater, we sorted all measurements of $\Delta h$ into their radial distance from the center of the crater. We then calculated the RMS deviation for 1-km-wide bins (e.g., the RMS deviation of all $\Delta h$ that were 0–1 and then 1–2 km away from the center of the crater).

3. Surface Roughness Observations of Large Craters

In this section, we use the roughness data products described above to assess the surface roughness in and around large craters on Mercury and explore how the distribution of surface roughness changes with crater diameter. We first look at large craters with diameters ($D$) greater than 50 km, then at large craters with $D$ less than 50 km, and then at an unusual crater, Hokusai. Finally, we use the crater Abedin as a case study for studying the spatial relationship of specific crater attributes and the measured surface roughness for craters with diameters larger than 50 km. Figure 1 shows the locations of craters studied on the surface of Mercury.

3.1. Craters With Diameters Over 50 km, $D > 50$ km

The surface roughness maps of five relatively fresh craters at $L = 1$ km (two of which are on the same map) are shown in Figure 2; the first four of these craters have diameters larger than 50 km. All five of these craters lie in the smooth plains (region of lower crater density compared with the cratered terrain) where the preexisting topography is qualitatively smooth and is not an important contributor to the surface roughness measured in and around these craters (Fa et al., 2016; Kreslavsky et al., 2014; Susorney et al., 2017). The five craters in Figure 2 are considered fresh and minimally degraded (Susorney et al., 2016), and all the craters measured in this study do not appear to have their surface roughness strongly affected by crater degradation.

The craters Abedin (Figures 2a–2c), Stieglitz (the larger crater in Figures 2d–2f), and Gaudi (the medium-sized crater in Figures 2d–2f) all show surface roughness distributions similar to other craters with diameters over 50 km on Mercury. They have smaller surface roughness values in the crater floor, greater values near the central peak and rim, and a large region of high surface roughness values beyond the crater rim. For the 1-km baseline, the range in surface roughness values is from 0.001 to 0.25 km. This region of enhanced surface roughness exterior to the crater rim is not easily attributed to a single aspect of crater morphology and occurs over a region that includes both the continuous ejecta and the secondary crater fields.

Radial plots of the $L = 1$-km surface roughness of Abedin, Gaudi, and Stieglitz are shown in Figures 3a–3c and are also plotted against the radial MLA topography measured in the same 1-km radial bins. The radial plots...
show the same pattern as the maps, with increased surface roughness values around the central uplift (peak or ring) and the crater rim; the crater floors have decreased surface roughness.

The radial surface roughness plots of Abedin and Stieglitz show a decrease immediately exterior to the crater rim but then an increase to form a qualitative local maximum (Figure 3a). We identified this qualitative local maximum in surface roughness through a visual inspection of the crater plots (see Figures S1 and S2). Six of the 17 crater measured have a qualitative local maximum. Additionally, all of the craters that have the qualitative local maximum are larger than 100 km in diameter. Plots of the radial profile of surface roughness for the crater Abedin at $L = 0.5$, $5$, $20$, and $100$ km are shown in Figure 4. The $L = 0.5$-km radial plot shows the same general qualitative local maximum as $L = 1$ km, but the qualitative local maximum disappears in the $L = 5$ km and larger baseline radial plots. In the $L = 20$- and $100$-km radial plots, the surface roughness does not have high...
Figure 3. (a–e) RMS deviation for $L = 1\text{ km}$ (blue) and MLA topography (black) as a function of radial distance from the crater center for the five large craters mapped in Figure 1. The craters Abedin and Steiglitz possess a qualitative local maximum exterior to the crater rim. The diameters of craters with and without the qualitative local maximum are plotted in (f). The Trask freshness criteria classification (1–5 with 5 the freshest; Trask & Guest, 1975) for the craters above is Abedin = 4, Gaudi = 3, Stieglitz = 4, Hokusai = 5, and Egonu = 4. RMS = root mean square.

surface roughness values associated with the central uplift and rim; instead, there is just a single increase in surface roughness associated with the crater cavity.

In Figure 3f, we plot the diameter of the crater studied versus whether it had a qualitative local maximum outside of the crater rim. We observe a clear change in the presence of the local maximum with a crater diameter of 100–120 km. No craters below 100 km in diameter have a local maximum, and all craters above 130 km in diameter have the local maximum. When we produced radial plots of these same craters at $L = 0.5\text{ km}$ (Figures S3–S5), we still observe a qualitative local maximum for those craters where it was previously identified (for the $L = 1\text{ km}$) and also observed local maxima for craters that are 80- to 100-km diameter indicating the presence of a qualitative local maximum in the surface roughness exterior to the crater scales with crater diameter and the horizontal scale over which surface roughness is measured.

In the smooth plains only two craters with diameters over 50 km have overlapping ejecta/secondary fields, Gaudi and Stieglitz. In the map of Gaudi and Stieglitz (Figures 2d–2f), the regions of increased roughness values exterior to the craters overlap, but the measured roughness values are not coadditive. In addition, the enhanced surface roughness exterior to the crater overprints the surface roughness from preexisting smaller craters. The surface roughness did not coadd in any of the baselines investigated. This supports observations in images of the surface of Mercury that show overlapping ejecta combining to produce a similar visual texture.
L = 0.5 km
L = 5 km
L = 20 km
L = 100 km

Figure 4. (a–d) RMS deviation and MLA topography in radial bins from the center of the crater Abedin for L = 0.5, 5, 20, and 100 km. The qualitative local maximum is only present at L = 0.5 and 1 km (previous figure). At L = 100 km there is only one peak in surface roughness for the crater due to the crater cavity itself.

to the cratered terrain (Whitten et al., 2014). Additionally, the radial plots of Gaudi and Stieglitz (Figures 2b and 2c) show similar surface roughness values to each other and the surface roughness values are not higher than the surface roughness values of the crater Abedin (Figure 2a). If the surface roughness was coadding, we may expect the combined surface roughness of Gaudi and Stieglitz to be higher than the surface roughness around other craters that are not adjacent to other fresh large craters. Also, a radial analysis of the surface roughness of Stieglitz broken into four quadrants (Figure S6) around the crater shows no differences in the surface roughness as would be expected in the northern two quadrants if the surface roughness was coadding with the surface roughness of Gaudi. The topography creating this region of high surface roughness values must either completely overprint preexisting topography associated with previous craters or must be producing additional topography that does not generate additional surface roughness at the baselines investigated if a previous crater is present.

3.2. Craters With Diameters Under 50 km, D < 50 km
Craters with diameters under 50 km, such as Egonu (Figures 2j–2l; D = 25.0 km), have surface roughness attributes similar to craters over 50 km in diameter within the crater cavity. Egonu has increased roughness values at its rim, wall, and central peak and reduced values on the crater floor. However, Egonu does not possess a region of increased surface roughness exterior to the crater rim. The radial plot of Egonu (Figure 3e) confirms this pattern: interior to the crater rim, the measured roughness is similar to craters over 50 km in diameter, but no qualitative local maximum is found exterior to the crater rim, consistent with the diameter and baseline dependency noted before. Three additional craters (Grotell, Riveria, and Martial; see Figures S1 and S2) with diameters near or under 50 km show the same geographic pattern in surface roughness as Egonu.

3.3. Hokusai, an Unusual Large Crater on Mercury
Hokusai (Figures 2g–2i and 3d) is a notable exception to the pattern outlined above for craters with diameters greater than 50 km in the smooth plains. The map of the surface roughness of Hokusai has a smaller region of enhanced surface roughness values compared to other craters over 50 km in diameter (e.g., Abedin). Previous studies of Hokusai have noted extensive melt and unusual ejecta (rampart like structures; Barnouin et al., 2015; Xiao & Komatsu, 2013; Xiao et al., 2016). Arecibo radar data noted a region of elevated roughness values around Hokusai (Harmon et al., 2007) likely due to Hokusai having extensive melt, which is rough in radar wavelength-scale (S band) surface roughness (Neish et al., 2013) due to the centimeter-scale structure and smooth at L = 1-km surface roughness since melt will infill rougher topography. Xiao et al. (2014) reported
both lower density and smaller sizes of secondary craters surrounding Hokusai compared with similar-sized craters on Mercury. Impact melt exterior to the crater rim would explain the lower $L = 1$-km surface roughness values since melt would infill the regions of higher surface roughness values observed in other craters over 50 km in diameter. It is also possible that extensive melt in the ejecta reduced the strength of blocks in the ejecta and thus the number of secondary craters around Hokusai (e.g., Schultz & Singer, 1980). The lower density of secondary craters could result in lower surface roughness values exterior to the crater rim. From cross-cutting relationships of distant secondaries and crater rays, Hokusai is believed to be the youngest complex crater on the surface (Xiao et al., 2016), but other young complex craters on the surface do not display the same large amount of melt. Additionally, the MLA coverage around Hokusai is not as dense as the coverage around Abedin, but the radial surface roughness plot had sufficient $\Delta h$ present to calculate RMS deviation (see Figure 2). We do not include Hokusai in our further analysis and discussion because Hokusai is likely a unique crater on Mercury and the geographic patterns in the surface roughness of Hokusai appear to be unique to Hokusai alone.

### 3.4. Abedin

To investigate the origin of the qualitative local maximum in the $L = 1$-km surface roughness maps and profiles, we investigate in detail the relatively fresh crater Abedin. In particular, we focus on whether secondaries or ejecta is the source of elevated surface roughness exterior to the crater since both of these processes will produce topography exterior to the crater that scales with crater diameter.

#### 3.4.1. Geologic Map of Abedin

The geology of Abedin was mapped (Figure 5) using a 250-m/pixel Mercury Dual Imaging System mosaic. The mapping was performed on a sphere in the Small Body Mapping Tool (e.g., Kahn et al., 2011). We focused on identifying the radial limits of the ejecta, crater floor, central peak, and rim. In Figure 6, we marked the radial extent of the crater floor, ejecta, and secondary fields on a radial surface roughness plot. Through the use of the geologic map of Abedin, we observe that the qualitative local maximum straddles the continuous ejecta and secondary fields.

#### 3.4.2. Density of Secondary Craters Around Abedin

To investigate whether secondary craters are correlated with the qualitative local maximum exterior to the crater rim, we compared secondary crater density to surface roughness by calculating the density of secondary craters in 1-km radial bins around the crater Abedin. We first mapped all secondary craters (we assumed that all small craters, diameters under 10 km, that were outside of Abedin’s rim were secondaries for this part of the study) over 1 km in diameter within six crater radii of the center of Abedin. Over 7,000 secondary craters $>1$ km in diameter were identified in the Small Body Mapping Tool (Kahn et al., 2011) using the same 250-m/pixel Mercury Dual Imaging System mosaic used in Figure 5. In Figure 7, the radial density (in 1-km bins) of secondary craters (1–10 km in diameter) was plotted with the $L = 1$-km surface roughness of Abedin against the distance from the center of Abedin. The maximum in secondary crater density is farther from the crater center than the local surface roughness maximum. This observation implies that secondary craters are not the only source of the qualitative local maximum, and the source of the local maximum is likely a combination of the secondary craters and ejecta.
Figure 7. Radial surface roughness distribution for Abedin and the radial density distribution of secondary craters ranging in diameter from 1 to 10 km. The secondary crater density is truncated at a distance of 290 km away from the crater center since we were investigating the qualitative local maximum, which is closer to the crater center. The blue region represents a 1 sigma error bar. The radial mapped distance of the crater floor, ejecta, and secondary fields from Figure 5 are added for reference. RMS = root mean square.

4. Numerical Investigations

We used a numerical investigation to understand how the formation of multiple impact craters influences the regional surface roughness of Mercury. These simulations did not try to recreate the actual topography of a cratered surface (e.g., Gaskell, 1993; Richardson, 2009; Rosenberg et al., 2015; Yang et al., 2013), which must make assumptions of the topography created by craters. Instead, we used the measured surface roughness values and around large craters on Mercury (the results from section 3) to test whether we can recreate aspects of the regional surface roughness observed on Mercury in the smooth plains and cratered terrains using the surface roughness of fresh large craters alone.

4.1. Investigation Setup and Assumptions

In this investigation, we used the measured radial distribution of surface roughness (at all baselines measured of 0.5–250 km) out of four crater radii from the center of five large craters ranging in diameter from 25 to 100 km. Details about the five craters selected are in Table 1. The range of crater diameters was chosen to match the five bin sizes used in crater counts by Ostrach et al. (2015), who investigated the crater size-frequency distribution on the smooth plains and the cratered terrains of Mercury. An artificial 1,000-km by 1,000-km surface was generated with an initial surface roughness value of 0.0 km. Changing this initial value to match background surface roughness, for example, was found to have no influence on the final outcome of the roughness computed for the artificial surface (Figure S7). The Δh from the radial distribution of surface roughness of the five craters was then added to random locations on the surface, and RMS deviation was calculated from the entire surface. The location of each crater was based on the size frequency distribution measured by Ostrach et al. (2015) for either the smooth plains or cratered terrain (see Figures 8a and 8d).

We performed more computationally expensive simulations using a 2,000-km by 2,000-km surface to check for any issues due to the size of our surface. Additionally, we performed a simulation using a 2,000-km by 2,000-km surface where we only measured the center 1,000-km by 1,000-km surface to check for any boundary effects. The results of both of these simulations are in the supporting information (Figures S8 and S9), and the Hurst exponent and shape of the deviogram measured from these two simulations are not different from the simulations run in the original 1,000-km by 1,000-km configuration.

When a new crater was added to the surface, its roughness overprinted any preexisting surface roughness. This assumption prevented us from introducing additional complexity to our numerical simulation. Observations of Gaudi and Stieglitz showed that overlapping regions of elevated surface roughness did not coadd and that the surface roughness of Gaudi and Stieglitz overprinted surface roughness due to an older crater in the region.

Craters were added to the surface until the simulated size-frequency distribution on the surface matched either the smooth plains or cratered terrain as measured by Ostrach et al. (2015). The surface roughness

Table 1
Characteristics of the Five Craters Used in the Numerical Investigation

<table>
<thead>
<tr>
<th>Crater name</th>
<th>Diameter (km)</th>
<th>Longitude (°W)</th>
<th>Latitude (°N)</th>
<th>Freshness classification</th>
<th>Frequency for SP</th>
<th>Frequency for CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egonu</td>
<td>25.0</td>
<td>298.5</td>
<td>67.1</td>
<td>4</td>
<td>1.70 × 10⁻⁵</td>
<td>9.16 × 10⁻⁵</td>
</tr>
<tr>
<td>Rivera</td>
<td>40.0</td>
<td>327.8</td>
<td>69.3</td>
<td>4</td>
<td>8.23 × 10⁻⁶</td>
<td>6.27 × 10⁻⁵</td>
</tr>
<tr>
<td>Tung Yuan</td>
<td>60.5</td>
<td>62.8</td>
<td>75.0</td>
<td>3</td>
<td>3.94 × 10⁻⁶</td>
<td>3.49 × 10⁻⁵</td>
</tr>
<tr>
<td>Gaudi</td>
<td>81.0</td>
<td>290.8</td>
<td>76.9</td>
<td>3</td>
<td>2.15 × 10⁻⁶</td>
<td>1.88 × 10⁻⁵</td>
</tr>
<tr>
<td>Stieglitz</td>
<td>100</td>
<td>292.4</td>
<td>72.5</td>
<td>4</td>
<td>1.07 × 10⁻⁶</td>
<td>7.36 × 10⁻⁶</td>
</tr>
</tbody>
</table>

Note. The freshness classification is scaled 1–5, with 5 being the freshest (e.g., Trask & Guest, 1975). The frequency columns are the values from Ostrach et al. (2015) for the size bin each crater is represented in our model, SP refers to the smooth plains, and CT refers to the Cratered Terrain.
Figure 8. (a–c) Computed surface roughness obtained after six impact craters with diameters ranging from 25 to 120 km are emplaced on a 1,000-km by 1,000-km surface where the initial surface roughness is set to 0. (d–f) The same surface with 88 craters emplaced, this matches the size-frequency distribution of impact craters with diameters between 25 and 120 km in a 1,000-km by 1,000-km area for the cratered terrain (Ostrach et al., 2015). Maps of the surface roughness are shown in (a) and (d), while (b) and (e) show the number of craters per unit area at this point in the simulation (the black line is the target size-frequency distribution). Deviograms (c) and (f) show the calculated surface roughness of the entire 1,000-km by 1,000-km region and can be compared to the observed surface roughness of the cratered terrain (red dashed) and smooth plains (blue dash; Susorney et al., 2017). RMS = root mean square.

of the complete 1,000-km by 1,000-km surface was recalculated after each crater was added (Figures 8c and 8f). We also calculated the Hurst exponent from baselines of 0.5–1.5 km, the same baselines found to have self-affine-like behavior in Susorney et al. (2017).

4.2. Results of the Numerical Investigation

Figures 8 and 9 show the simulated surface roughness, crater size-frequency, and deviogram (RMS deviation versus baseline) of simulated regions where the final crater densities match the smooth plains and cratered terrain, respectively. Figure 10 compares the final deviogram for 30 runs for the simulated smooth plains and cratered terrain to the measured surface roughness of the two regions on Mercury obtained in Susorney et al. (2017).

At baselines of 0.5–1.5 km, the simulated deviograms are approximately linear resulting in Hurst exponents of 0.98 ± 0.01 and 0.99 ± 0.00 for the smooth plains and cratered terrains, respectively. We choose the baselines of 0.5–1.5 km to match the baselines a Hurst exponent was fit to in Susorney et al. (2017) because we compared the results of our simulations to the results of that paper. The values of the Hurst exponent are the mean of 30 separate simulations, and the uncertainties are one standard deviation of the 30 runs. These Hurst exponents are larger than the measured H of the cratered terrain (0.95) and smooth plains (0.88) for the same baselines (Susorney et al., 2017). Fa et al. (2016) measured different Hurst exponents for the smooth plains (0.60) and cratered terrains (0.80) of Mercury, but these were measured over a broader range of baselines (L = 0.4–4.2 km). A larger Hurst exponent means that surface roughness values are larger at longer baseline relative to a small Hurst exponent. This larger increase in surface roughness at baselines near 1.5 km in our model compared to observations of the surface could be due to degradation reducing the topography at the 0.5-km baseline but not reducing topography to the same extent at larger baselines. The complete overprint of preexisting craters in our model and the lack of simple craters and tectonics could also be sources of the discrepancy in Hurst exponent.
Figure 9. (a–c) Computed surface roughness obtained after six impact craters with crater diameters ranging from 25 to 120 km are emplaced on a 1,000-km by 1,000-km surface where the initial surface roughness is set to 0. (d–f) The same surface with 16 craters emplaced, this matches the size-frequency distribution of impact craters with diameters between 25 and 120 km in a 1,000-km by 1,000-km area for the smooth plains (Ostrach et al., 2015). Maps of the surface roughness are shown in (a) and (d), while (b) and (e) show the number of craters per unit area at this point in the simulation (the black line is the target size-frequency distribution). Deviograms (c) and (f) show the calculated surface roughness of the entire 1,000-km by 1,000-km region and can be compared to the observed surface roughness of the cratered terrain (red dashed) and smooth plains (blue dash; Susorney et al., 2017). RMS = root mean square.

Figure 10. A deviogram of the measured (Susorney et al., 2017) and simulated surface roughness for both the smooth plains and cratered terrains on Mercury. Uncertainties associated with the measured surface roughness are from the error of MLA measurements (<1 m) and are smaller than the thickness of the lines plotted. The mean simulated surface roughness of smooth plains and cratered terrains from 30 runs is plotted with a solid line. The gray shaded region represents the one standard deviation of the range of results obtained after 30 runs. RMS = root mean square.
The shape of the deviogram at $L < 40$ km is reproduced in the numerical investigation. However, the simulated and measured deviograms do not overlap each other, with the simulated deviogram having a lower overall surface roughness than the measured deviogram at all baselines. A second deviogram of the smooth plains from measured surface roughness values is also plotted in Figure 10 (Smooth Plains 2); this deviogram was measured away from the smooth plains unit boundary, where boundary effects from the cratered terrain influence the surface roughness (see Susorney et al., 2017). In this second deviogram, the measured deviogram and simulated deviogram are closer in agreement, with a bend in the surface roughness around $L = 30$ km being reproduced in the simulated deviogram although the measured surface roughness of Smooth Plains 2 is larger than the simulated surface roughness of the smooth plains.

The lower surface roughness values and the discrepancy in the Hurst exponent in our simulation compared to measured surface roughness on Mercury is likely due to a combination of the lack of simple craters, tectonics, and large basins (Fa et al., 2016; Susorney et al., 2017) and the complete overprinting of the surface roughness of preexisting craters in our simulations. In particular, the lack of degradation and complete overprinting of preexisting surface roughness is likely not an accurate representation of the evolution of highly cratered surfaces.

5. Discussion

In this section, we use both observations of the surface and numerical simulations to understand how large craters produce and modify surface roughness on Mercury. We also assess any relationship between measured surface roughness produced by large craters and crater density.

5.1. Individual Large Craters

Our results indicate that the distribution of surface roughness around large craters on Mercury at smaller baselines ($L < 10$ km) is well correlated with the morphology of the crater. The largest regional contributor to surface roughness is the area exterior to the crater rim. A few craters with $D > 80$ km can completely dominate the local surface roughness of a geologic terrain with only a few large impact craters (e.g., the smooth plains on Mercury). The origin of the local maximum in the $L = 1$-km baseline is still unclear, but the geologic map from Abedin and the plot of secondary crater density show that the local maximum overlaps both the edge of the continuous ejecta and the secondary field.

The source of the local maximum is likely a mixture of the continuous ejecta and secondary craters, given that the local maximum is straddling the transition between these two regions. The local maximum is sensitive to topography at the scales of 0.5–1 km which would include small secondary craters, but the local maximum is not correlated with the peak in secondary crater density. We would not expect ejecta blocks to be large enough to affect the topography at this scale, and the only other likely source of the local maximum is the hummocky texture found in many ejecta blankets. The local maximum could be the geographic transition between ejecta and secondary fields, but the source of the topography in this boundary region is unclear.

The crater diameter dependency of the qualitative local maximum (e.g., why we do not see the local maximum in Egonu) could be supported by the qualitative local maximum being primarily driven by secondary fields and ejecta since it is reasonable to expect the horizontal scale of these features to scale with crater diameter. Additionally, smaller craters might not produce sufficient fresh ejecta volume (or fragment size) nor fast enough secondary cratering to alter surface roughness significantly at the baselines investigated. We hypothesize that if similar analysis would be performed using a higher-resolution surface roughness data set for Mercury, we would observe a local maximum at smaller diameter craters at smaller baselines.

The importance of larger craters for small baselines supports observations by Fa et al. (2016) and Susorney et al. (2017) that individual large craters appear to dominate the surface roughness at smaller baselines. Simulations of surface roughness by Yokota et al. (2014), using simulated crater topography, did not reproduce the local maxima in roughness at baselines of 6–9 km that was associated with impact craters. The authors hypothesized that it was due to the lack of realistic ejecta and secondary craters in their simulations. Our observation of the importance of ejecta and secondary fields for surface roughness at baselines under 10 km supports the authors’ hypothesis that their inability to reproduce the local maxima in surface roughness at baselines of 6–9 km was due to the lack of realistic ejecta and secondary craters in the simulations.

At larger baselines ($L > 40$ km) the surface roughness of individual craters is dominated by the crater cavity, and the crater rim, ejecta, and secondary craters do not produce clear surface roughness signatures.
This sensitivity of surface roughness to the crater cavity is seen at increasing baselines until the surface roughness is at the scale of the crater radius (Susorney et al., 2017). Unlike at smaller baselines, the surface roughness at larger baselines is sensitive to the crater cavity itself, implying that the surface roughness at larger baselines may be more indicative of crater density.

5.2. Interaction of Multiple Impact Craters

Our observations of the surface roughness of the craters Gaudi and Stieglitz with their overlapping ejecta and secondary fields show that the surface roughness of the exterior of large craters at small baselines does not coadd but simply overprints. When the ejecta and secondaries are emplaced, they blanket the preexisting surface roughness through the direct addition of material from the new crater cavity or from the creation of new secondary crater cavities. We are not sure why the secondary craters or ejecta do not coadd, but perhaps the high-density secondary crater fields on Mercury hide the topography of preexisting secondary crater fields. This observation, while related to the observation of the qualitative local maximum (because both are due to ejecta and secondary fields), is different, as we observe the overprinting at $L = 1$ km in craters below 100 km in diameter.

Observations of the cratered terrain on Mercury noted that the qualitative rough texture of the cratered terrain is created by overlapping ejecta blankets (Whitten et al., 2014). This qualitative observation is similar to our observation of the importance of the region exterior to craters (in particular when these regions overlap) to increase the surface roughness of an entire region at small baselines ($L < 10$ km). Although the result of Whitten et al. (2014) is most analogous to the role of ejecta blankets in modifying the regional surface roughness, we believe that a combination of ejecta and secondaries produce the rough texture observed on Mercury.

The numerical investigation yielded $H$ values for the simulated smooth plains and cratered terrain of $0.998 \pm 0.01$ and $0.99 \pm 0.00$ which are similar to the measured $H$ of the cratered terrain ($0.95 \pm 0.01$) at the same baselines and the lunar highlands ($H = 0.95$ for $L = 0.017–2.7$ km). The topography of the lunar highlands and Mercury’s cratered terrains is both dominated by impact craters at many scales (Smith et al., 2010; Zuber et al., 2012). The similarity among all these Hurst exponents may support the hypothesis that a Hurst exponent is indicative of a single geologic process without a diagnostic scale controlling surface roughness at these scales (e.g., Rosenburg et al., 2011; Shepard et al., 2001), in this case, impact cratering.

5.3. Surface Roughness and Crater Density

Previous studies have proposed that surface roughness can be used to estimate surface age since regions with higher surface roughness values (at baselines of 0.15–100 km) usually have higher crater densities (e.g., Yokota et al., 2014). Here we can use our results to investigate how RMS deviation changes with increasing crater density. Figure 11 shows our surface roughness values for the entire simulated region after increasing numbers of large craters are emplaced on a region for the cratered terrain simulation in section 5 (for $L = 0.5, 1, 5, 10, \text{and} 40$ km). The gray region represents the one standard deviation of 30 runs. The plot indicates that after 15 craters are emplaced, the surface roughness for $L = 0.5$ and 1 km does not increase and oscillates around an asymptote (the variations are within the range of MLA vertical error of 1 m). The surface roughness at 5- and 10-km baselines stops increasing after ~30 craters are added. The $L = 40$-km surface roughness reaches stops increasing after ~80 craters are added, but the uncertainty is large (S10). Surfaces dominated by large craters stop increasing in surface roughness before the surface is completely covered in craters at the baselines investigated.

At $L < 10$ km, the surface roughness measured is dominated by the region exterior to the crater rim which covers a large surface area. It should not, therefore, be surprising that at these baselines the roughness reaches stops increasing after only a few craters are added. This result shows that it is not possible to relate the surface roughness at smaller baselines to crater density/surface age on Mercury for terrains similar to the cratered terrain. At $L > 10$ km, the surface roughness generated by a single crater is dominated by that crater’s cavity. Thus, for these longer baselines, the time required to stop increasing in surface roughness is longer.

This page contains a graph titled “Figure 11. RMS deviation (or surface roughness) measured at five baselines ($L$) computed from the numerical investigation as a function of the total number of craters used in the computation (each point represents five additional craters emplaced in the investigation). The gray region is the one standard deviation of 30 runs employed. These simulations were run until surface roughness did not increase for the longest baseline. RMS = root mean square.”
This is consistent with the results of Yokota et al. (2014) that found a correlation between surface roughness for \( L \) between 20 and 30 km and crater density \( N > 20 \) km). In our investigation, we find that for baselines of 20–40 km it is difficult to identify a simple relationship between crater density and surface roughness alone since there is variation in this relationship, as seen in Figure 11 where variation between simulations for these larger baselines is quite large. While we cannot rule out using the surface roughness at larger baselines as a proxy for crater density/surface age, the variation in the relationship would always be a larger source of uncertainty in any result.

6. Conclusions

For many planetary bodies, impact craters are the dominant source of surface roughness. In this paper, we have investigated how large craters influence the RMS deviation of Mercury. The main results of our study are as follows:

1. For baselines \( L < 10 \) km, large craters on Mercury have larger surface roughness values at the crater rim and central peak and lower values on the crater floor. The region exterior to the crater rim is the largest areal source of surface roughness for these baselines. Exterior to fresh large craters (diameters >80 km) there is a qualitative local maximum in surface roughness that occurs in a region that includes both continuous ejecta and secondary fields.

2. When multiple large impact craters occur near each other, the resulting region of elevated surface roughness exterior to the crater rims does not coadd, but instead, the regions of high surface roughness merge.

3. For \( L > 10 \) km, the surface roughness is primarily due to the crater's cavity (the decrease in elevation from the rim to the crater floor).

4. The large crater Hokusai has a smaller region of increased surface roughness values exterior to the crater rim as compared to similarly sized fresh large craters. This reduction in surface roughness values is likely due to the large amount of impact melt in and around Hokusai and fewer number of secondary craters.

5. A numerical investigation into whether large craters alone can produce the surface roughness measured on Mercury found that the majority of the surface roughness of the smooth plains and cratered terrain can be attributed to large craters but not all. The Hurst exponent from the numerical investigation for both the smooth plains and cratered terrain is similar to the Hurst exponent of Mercury’s cratered terrain and the lunar highlands.

6. The relationship between surface roughness and crater density varies based on baseline investigated. At \( L < 10 \) km, the region exterior to the crater dominates surface roughness and results in a surface no longer increasing in surface roughness after only a few craters have been added to the surface. At \( L > 10 \) km surface roughness appears to be linked with the crater cavity itself and could be a better proxy for age, although there is some variation between identical numerical simulations.

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