1. Introduction

Laser altimeter instruments onboard orbital planetary missions significantly advanced our knowledge of the Moon, Mars, Mercury. Topographic maps derived from the laser altimeter data are widely used in geological studies. In addition to the topographic maps, synoptic maps of topographic roughness can be useful. There are a few reasons, why in some circumstances the use of roughness maps is essential for geologic studies.

First, roughness maps provide a convenient large-scale overview of small-scale textures. To map regional variations of textures solely with topographic maps, a geologist constantly needs to switch from large scale to small scales, which is time-consuming and inconvenient. Roughness maps give a generalized overview of texture variations at large scale.

Second, roughness maps help to focus on typical topography rather than on peculiar features. When we look at topographic maps and images, our eyes see the most prominent features and often miss background textures. For example, when we look at the lunar highlands, we see the distinctive impact craters, and it is very difficult to ignore craters and focus on intercrater textures. Properly designed roughness maps display the most typical topographic textures and ignore rare features.

Finally, roughness maps utilize the exceptional internal precision of laser altimeter data. The precision of the range determination along each spacecraft orbit is much higher than the accuracy of orbit knowledge, and the accuracy of the topographic maps is much worse than the internal precision of the original measurements. In addition, the gaps between orbit tracks are often wider than the distance between elevation measurements along the orbit, and the effective resolution of the topographic maps is worse.
than measurement spacing along each orbit track. Roughness maps rely on and utilize the exceptional internal precision and available along-orbit spacing of the orbital laser altimeter data.

Roughness maps have proven to be useful in planetary geology. Kilometer-scale topographic roughness maps of Mars (Kreslavsky and Head, 2000) generated with Mars Orbiter Laser Altimeter (MOLA) data (Smith et al., 2001) clearly showed many geomorphologic units on Mars, for example, patches of heavily cratered Noachian-age volcanic plains are well distinguished from surrounding heavily cratered highlands. The maps revealed a latitudinal trend in topographic roughness, which was important in understanding the nature of recent climate change on Mars (Head et al., 2003). Cord et al. (2007) used stereo-derived digital elevation models to make decameter- and hectometer-scale roughness maps of some martian terrains.

Kreslavsky (2010) produced maps of topographic roughness of the Moon using data from laser altimeter LALT onboard Kaguya mission (Araki et al., 2008, 2009). These maps revealed the uniqueness of Orientale basin ejecta (Hevelius Formation) in comparison to other impact basin ejecta deposits on the Moon. The use of LALT data, however, is limited because of long distances between measurements along the orbit and a small total amount of data.

Due to its exceptional vertical precision, short along-orbit spacing, and large volume of data, the Lunar Orbiter Laser Altimeter (LOLA) (Smith et al., 2010a,b) onboard LRO is an excellent data source for roughness mapping. The first roughness maps of the Moon with LOLA data were produced by Rosenburg et al. (2011). Kreslavsky and Head (2012) used LOLA-derived roughness maps to analyze the uniqueness of the Hevelius Formation roughness signature. Whitten et al. (2012) use LOLA-derived roughness maps in their analysis of cryptomaria.

In this paper we (1) consider the technique of roughness mapping with LOLA data, (2) discuss the rationale for our choice of the statistical measure of roughness, (3) present global roughness maps of the Moon, (4) analyze the appearance of major geological features in these maps, and (5) discuss primary inferences about surface-shaping and modifying processes.

2. Mapping roughness

In this section we first describe the algorithm we used to produce the maps of roughness. Then we present the rationale for our particular choice of the measure of roughness we use and the other algorithmic details.

2.1. Data processing

We started with the whole set of topographic profiles along LRO orbits from LOLA Reduced Data Records (RDRs) available from the NASA Planetary Data System (PDS). Every time LOLA probes the surface (every “shot”), it obtains range (and inferred elevation) measurements in 5 small (~5 m) “spots”; however, because of the LOLA anomaly (see Smith et al., 2010b for details), only spots #3 and #4 yield good range measurements on the night-side half of the orbits, and near-terminator data are mostly missing. We limited our data processing with a single spot #3: for this spot, the number of good measurements is the greatest. Some isolated data points inside “good” segments of the spot #3 profiles are also missing or marked as “bad” in the data set and discarded. In addition, there are rare cases where elevation measurements are incorrect, but are not marked as “bad”. Maps presented here are made with the entire set of LOLA data obtained during LRO operations in the circular orbit from September 2009 to December 2011 (LRO orbits 1005–11,403), in total about 1.50 × 10⁶ good shots. A typical distance between orbit tracks at low latitudes is on the order of 0.8 km, however, the distance varies widely, and there are gaps as wide as ~4 km.

Topographic roughness depends on spatial scale; this dependence bears essential information, as we will see later in the paper. To characterize it, we map roughness for a set of baselines l. Consecutive shots along each orbit are separated by ~57.4 m; this distance is conveniently constant within ±~3% through the whole data set. Our roughness measure uses baselines with an even number of shot-to-shot steps. Thus, the shortest baseline we can use is 2 shot-to-shot steps, that is l = 115 m. In addition to this, we also present maps of roughness at baselines of 8, 16, and 32 shot-to-shot steps, that is l = 0.46 km, 0.92 km, and 1.8 km.

For each shot, we calculated a proxy for the second derivative ("curvature"), c, of along-orbit topographic profiles, according to the equation:

\[ c = \frac{(h_3 + h_4 - 2h)}{l^2}, \]

where \( h_3, h_4, \) and \( h_4 \) are surface elevations at the given laser shot, and shots a half-baseline ahead and a half-baseline behind, respectively. If any of \( h_3, h_4, \) and \( h_4 \) were missing or marked as bad in the LOLA data set, we discarded such a curvature value. In total, about 6% of data points were discarded in this way. For l in (1) we used actual horizontal distance between the shot locations at \( h_3, \) and \( h_4. \) As we noted above, its difference between this actual distance and the “nominal” baseline of 115 m, 0.46 km, 0.92 km, and 1.8 km does not exceed 3% and causes no bias.

We built the global maps in different map projections; nominally, we used the scale that correspond to 8 pixels per degree sampling, in other words, ~3.8 × 3.8 km² pixel size at the projection’s standard point or line. For each map pixel, we found all LOLA shots located within the distance \( R_{\text{nom}} \) from the center of the pixel. The minimal reasonable \( R_{\text{nom}} \) is \( \sqrt{2}/2 \) of the nominal pixel side: for shorter \( R_{\text{nom}} \), some data would be unused. We used this minimal \( R_{\text{nom}} = 2.7 \) km for all maps, except the longest baseline of \( l = 1.8 \) km, for which we used \( R_{\text{nom}} = 3.8 \) km. For the minimal \( R_{\text{nom}} \), the majority of shots belong only to one pixel, but some of them belong to 2 pixels. Typically, 2–8 orbits contribute to a pixel (except high latitudes); each orbit typically adds a few tens of data points. Some pixels (~1%, depending on the map projection used) have no data. We also considered pixels having too few points (less than 20) as having no data.

Curvatures c within the \( R_{\text{nom}} \)-vicinity of each pixel center are scattered around zero; for rougher surfaces, typical absolute values are higher, and hence the scattering is wider. For each pixel we considered the frequency distribution of the curvature c, and calculated the quartiles \( c_{1/4}, c_{1/4} \) of this distribution. We use the inter-quartile range of this distribution, \( c_{1/4} - c_{3/4} \), as a measure of the distribution width and thus a measure of roughness.

The numerical values of \( c_{1/4} - c_{3/4} \) are not intuitive and difficult to conceptualize, and we normalized them by a typical value for typical highlands. Thus, we defined roughness r at each pixel as:

\[ r = \frac{(c_{3/4} - c_{1/4})}{R_0}, \]

where \( R_0 = 2.3 \times 10^{-4} \) m⁻¹, \( 6.6 \times 10^{-5} \) m⁻¹, \( 4.4 \times 10^{-5} \) m⁻¹, and \( 2.9 \times 10^{-5} \) m⁻¹ for \( l = 115 \) m, 0.48 km, 0.96 km, and 1.8 km baselines, respectively.

The pixels with no data were filled using the roughness of their neighbors. The mean roughness calculated over all pixels with data in some vicinity of the pixel without data was used to fill it; the vicinity was progressively expanded starting from the smallest possible (four neighbors) until the pixel is filled.

Data processing for a single global map takes a few hours on a high-end general-purpose personal computer. The resulting global maps (Figs. 1–3) are available on the Brown University Planetary...
Figs. 1–3 present roughness maps at baselines of 1.8 km, 0.48 km, and 115 m in Lambert azimuthal equal-area projection in a grayscale rendition, with brighter shades denoting higher roughness. The maps have a rather high dynamical range: by changing the stretch of the maps it is possible to reveal some details not readily seen in the figures. For example, white (rough) Copernican-age craters in Figs. 2 and 3 are saturated; a proper stretch reveals details, as shown in Fig. 9. The proper stretch of the 1.8 km baseline map in Fig. 1 can reveal significant roughness variations in the maria.

Figs. 4 and 5 present RGB composites of roughness maps at 1.8 km, 0.96 km, and 0.48 km for red, green, and blue channels, respectively; stretch in each channel was chosen individually to optimize the visual perception of the maps. A greater intensity in each channel denotes higher roughness, which means that again, generally brighter shades correspond to generally rougher surfaces. Color variations characterize the scale dependence of roughness. Quantitatively the scale dependence of roughness can be characterized by so-called Hurst exponent $H$ (see Rosenberg...
et al., 2011 and references therein), a dimensionless number between $0 \leq H \leq 1$. Warm (reddish) tints in the maps (Figs. 4 and 5) mean relatively higher intensity in the red channel and the prevalence of large-scale roughness, which means higher $H$. Analogously, cold (bluish) tints mean the prevalence of small-scale roughness and lower $H$. Color variations are subtle because the range of baselines used is rather narrow.

2.3. Rationale for the data processing algorithm

Our experience shows that the success of geological interpretation of roughness maps strongly depends on a good choice of roughness measure and an optimal choice of mapping technology. A good statistical measure of roughness should possess the following properties. (1) It should correspond to an intuitive perception of "roughness": if, in an image taken at the proper resolution, geological unit A looks distinctively rougher than unit B, then the roughness map at the proper baseline should reflect this difference. (2) The tilt of the surface as a whole should not change roughness values. For example, the variance of elevation at a given baseline is not a good measure of roughness, because it is sensitive to regional slopes. (3) Roughness should characterize a typical surface rather than its prominent features (as discussed in Section 1). For example, the RMS slope at a given baseline, a popular statistic of topography, is not a good measure of roughness, because it is very sensitive to the presence of a small proportion of very steep slopes in the sample; for the Moon, RMS slope would primarily reflect steep features (for example, crater walls). (4) Roughness should characterize topography at a well-defined scale, because the nature of its scale-dependence is an important characteristic of geological surfaces. (5) The statistical measure of roughness should be stable: if there is a homogeneous geological unit, its roughness calculated over a large data set and over a small (but representative) subset of the same data should be similar. For example, RMS slope is often not stable: natural surfaces often have heavy tails of slope-frequency distributions, and the occurrence of rare very steep slopes offset the RMS slope significantly. For many natural terrains the tails of the slope-frequency distribution are so heavy that the RMS slope calculated over a smaller data subset is systematically lower than that calculated over the whole data set. (6) The selected measure of roughness should be tolerant to individual peculiarities of the source data set used. Mapping of roughness (rather than just characterizing different areas) adds two more requirements. (7) Low noise (which is partly, but not exactly, the same as the stability requirement above). (8) Visual sharpness of resulting maps. Our experience shows that the latter is extremely important for successful geological interpretation of the maps.

From this "definition", it is clear that there is no universally good measure of topographic roughness. First, "intuitive perception of roughness" in requirement (1) is quite subjective, and different researchers may have different personal preferences. Second, different data sets have individual problems and peculiarities,
and requirement (6) dictates that different measures are used with different data sets.

Requirements for a “good” measure of roughness are often contradictory, and the choice involves multiple trade-offs. In the case of LOLA data, the high regularity and precision along the orbit tracks and lower precision and irregular gaps between the orbits suggest the use of along-track statistics for characterization of the surface topography. Since all LRO orbit tracks are in the north–south direction, this means that the measure of roughness used is anisotropic, which is not consistent with our intuitive perception of “roughness”. The spurious effect of the anisotropic roughness measure is noticeable, for example, on walls of large (resolved) craters in the longer-baseline maps: the northern and southern walls of the craters are rougher than the western and eastern walls. Topographic data derived from stereo images (e.g., Scholten et al., 2012) are (almost) free from such inherent anisotropy; their use for roughness mapping, however, is limited due to the lower vertical precision in comparison to LOLA. The “full” LOLA shots with good range measurements for all five spots could give a much more isotropic roughness measure, but only for a single baseline of \(~50\) m. Since we aimed to study the scale-dependence of roughness and wanted the same roughness measure at different baselines, we restricted ourselves to bare one-spot along-track profiles.

To meet requirement (2) we followed Kreslavsky and Head (2002) and chose to use the second derivative (“curvature”) of topographic profiles. Another possibility to meet requirement (2) is the differential slope used by Kreslavsky and Head (2000) and Rosenberg et al. (2011). The use of the differential slope instead of the “curvature” yields very similar-looking maps. Calculation of the “curvature” requires at least three data points (Eq. (1)), while calculation of the differential slope requires at least four; because of this, the “curvature” can be a little more tolerant of missing and bad measurements and this is why we prefer to use it here. A popular alternative way to fit requirement (2) is to use slopes (the first derivative) after some detrending procedure that removes large-scale tilts. We preferred not to use this approach because this method gives a worse scale separation (requirement 4) and introduces new subjectivity in the choice of the detrending scale and procedure. The shortcoming of our choice is that the numerical values of our roughness measure are not intuitive.

Calculation of the second derivative at a given baseline is actually an application of some linear filter: a sequence of discrete points representing a profile is convolved with some kernel. This kernel can be chosen in different ways. We chose the minimal kernel defined by Eq. (1): it contains the fewest possible number of points (three) and has the shortest possible support range for a given baseline. The former gives us the best tolerance to missing and bad points (requirement 6); the latter enhances the visual sharpness (requirement 8). The minimal kernel, however, is far from optimal from other points of view: including more points in the kernel would reduce noise (especially, for long baselines) (requirement 7) and

Fig. 3. Map of hectometer-scale roughness of the Moon (115 m baseline). Lambert azimuthal equal-area projection centered at the center of the farside. Latitude/longitude grid is \(30^\circ \times 30^\circ\). Brighter shades denote rougher surfaces. Dimensionless absolute roughness values are defined according to Eq. (2).
Fig. 6 compares our minimal kernel with the popular “Mexican hat” kernel in the spatial frequency domain. The spectra shown in Fig. 6 are ideal power spectra of the result of application of the filters to Brownian motion profiles; similar spectra are expected for real surfaces with a Hurst exponent of $H \approx 0.5$. It is clearly seen that in our case there is some leak of the high-frequency (short baseline) topography, while the “Mexican hat” kernel performs better. The use of the “Mexican hat” kernel, however, is not practical, because at longer baselines it involves many points. If we discarded all sliding windows containing at least one missing point, too few windows would survive. If we somehow replaced missed or bad points using their neighbors, we actually would have different kernels in these cases, and the statistics of the missing/bad points could affect the result: the algorithm could produce artifacts. We decided to sacrifice all advantages of the “Mexican hat” and similar kernels to be sure that our results are free of any artifacts related to missing and bad points.

Our choice of the interquartile range (Eq. (2)) as an estimator for the distribution width works perfectly with respect to the requirements of typicality (3), stability (5), tolerance to unmarked bad measurements (6) and visual sharpness (8). We tried different percentile points $\alpha$ and $1-\alpha$ instead of quartiles $\alpha = 0.25$ and $1-\alpha = 0.75$. The resulting maps were almost indistinguishable with minor variations of the noise level. The lowest noise was for $\alpha$ close to 0.25, thus quartiles are about optimal with respect to the noise requirement (7).

The choice of map pixel size (8 pixels per degree) was dictated by the data point density. The choice of $R_{pix}$ is a trade-off between visual sharpness of the maps (that requires shorter $R_{pix}$) and better statistics/lower noise (that requires longer $R_{pix}$). We chose $R_{pix}$ on the basis of several trials. When maps are analyzed visually as grayscale or color images and compared with images, mosaics of images, and geological maps, a rather high noise level is tolerable, but visual sharpness is highly desirable. To maximize the visual sharpness we used the minimal $R_{pix} = 2.7$ km for all maps, except the longest baseline of $l = 1.8$ km. The latter baseline becomes comparable to the pixel size of 3.8 km; this causes a strong increase in noise; actually, we start seeing the presence/absence of individual sharp topographic features in the footprint rather than typical roughness. Because of this we decided to use a slightly wider vicinity $R_{pix} = 3.8$ km for this baseline.

3. Roughness signature of resurfacing processes and time scales

The most obvious feature of the kilometer-scale (0.48 km, 0.96 km, and 1.8 km baselines) roughness maps (Figs. 1, 4, and 5) is the dichotomy between smooth (dark) maria and rough (bright) highlands. At 0.48 km baseline, typical values of highland rough-
ness are within the range of 0.9–1.1, and that of maria are within the range of 0.4–0.5; in other words, the systematic difference between maria and highlands (a factor of 2) is much greater than the typical roughness variations over maria and over highlands (~20% in both cases). For longer baselines the systematic difference between maria and highlands increases and reaches a factor of 10 at 1.8 km baseline. At this baseline, typical short-range variations of highland roughness are significant (a factor of 3) due to an effective noise increase when the baseline becomes comparable to $R_{\text{pix}}$.

However, typical values over larger areas vary within 30% for both maria and highlands and are minuscule in comparison to the systematic difference between maria and highlands.

The maps of hectometer-scale roughness (115 m baseline, Figs. 2 and 3) look strikingly different, despite the fact that the baselines differ only by two octaves (a factor of four) from 0.48 km. At the hectometer scale, there is no significant difference between maria and highlands. In many locations the mare/highland boundary is not associated with any roughness contrast. All typical roughness contrasts are minor (within 40%, compare gray scales in Figs. 1 and 2), except that of young craters (Section 4.1). Although lowered roughness values tend to be associated with maria, some mare surfaces are rougher than typical highlands, for example, the central part of Mare Crisium has $r \approx 1.1$.

We interpret this striking difference to be due to the principal difference in the processes that shape the surface at hectometer and kilometer scales. The hectometer scale is dominated by formation of small (hectometer-scale and smaller) craters and regolith gardening by even smaller impacts. Fig. 7 illustrates that the difference between typical mare and highland surfaces, considered at the resolution relevant to the hectometer-scale roughness, is not very strong. These LRO Lunar Reconnaissance Orbiter Camera (LROC) images were specially selected to minimize the difference between illumination conditions, so that their direct comparison is most useful.

The typical values of dimensional roughness, $r_0 \approx 2 \times 10^{-4}$ m$^{-1}$ at $l = 115$ m baseline correspond to a characteristic vertical scale of $r_0 l \approx 3$ m, less than a typical regolith thickness. This is consistent with regolith processes being solely responsible for the roughness signatures at the hectometer scales. Both on maria and highlands the population of hectometer and smaller craters is in an equilibrium state, when ongoing emplacement of small craters is balanced by ongoing obliteration of old craters by regolith gardening. Progressively degrading hectometer-scale craters form the background topography in a similar manner on the mare and highland surfaces.

Formation of larger, kilometer-scale craters is not equilibrated with crater obliteration, and there is no uniform equilibrated background topography at such scales. At the longest baseline, $l = 1.8$ km, the characteristic vertical scale, $r_0 l \approx 90$ m, is greater than the typical regolith thickness. This means that regolith

Fig. 5. Kilometer-scale roughness of the Moon rendered as an RGB composite of roughness maps at 1.8 km, 0.96 km, and 0.48 km for red, green, and blue channels, respectively; higher intensity in each channel denotes higher roughness. Lambert azimuthal equal-area projections centered at the center of the farside. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
processes are not responsible for the roughness values at this scale (though they may slightly affect it). At the scale of kilometers, roughness reflects “bedrock geology”: the surface is shaped by volcanic flooding of maria, large impacts, and tectonics.

Exact thickness of regolith layer in highlands is poorly measured and perhaps poorly defined (due to the absence of uniform consolidated substrate); indirect estimates (e.g., Shkuratov and Bondarenko, 2001; Fa and Jin, 2011) yielded the typical highland regolith thickness of $\sim$10 m; recent measurements based on morphology of small craters by Bart et al. (2011) gave estimates within 6–8 m. As the characteristic vertical scale of roughness increases with horizontal baseline, the typical highland regolith thickness intersects this trend at $\sim$1 km baseline, indicating that roughness at scales below this value is controlled by regolith processes while roughness at larger scales is controlled by bedrock topography. Rosenberg et al. (2011) found that the Hurst exponent within the lunar highlands commonly transitions from a high value near 1 to a lower value of $\sim$0.8, with the transition occurring at approximately the 1-km scale, in good agreement with the roughness calculations presented here. This change in slope of the structure function is consistent with a transition between roughness regimes governed by different surface processes.

Formation and degradation of hectometer and smaller craters, and formation and gardening of regolith, are universal processes that occur everywhere on the Moon, to a first order, in a uniform way. Due to this, the difference between hectometer and kilometer scales also reflects different time scales: the hectometer-scale roughness maps show features younger than the characteristic time scale of reworking of the uppermost layer of the regolith, on the order of a meter. Thus, this is a feature of Copernican and, at least partly, Eratosthenian age, while the kilometer-scale rough-
ness shows older features. From another point of view, this distinction represents the time scale of the equilibration of the small crater population.

This clear separation of processes and ages causes the “roughness units” on hectometer-scale and kilometer-scale roughness maps to be different: boundaries outlining units of different roughness on kilometer-scale and hectometer-scale roughness maps often do not coincide. This situation differs significantly from Mars, where, despite a very wide diversity of scale-dependence of roughness for different terrains, the unit boundaries were the same over 4 octaves (factor of 16) of scales, and the color composite of three roughness maps separated by 2 octaves made a nice synoptic overview of martian geomorphologic diversity (Kreslavsky and Head, 2000). On the Moon combining hectometer-scale and kilometer-scale roughness in a single composite does not produce easily interpretable maps. In the rest of the paper we consider scales separately: first, hectometer-scale roughness maps (Figs. 2 and 3) in Section 4 and then kilometer-scale roughness (Figs. 1, 4, and 5) in Section 5.

4. Hectometer-scale roughness

4.1. Craters

Both the roughest and the smoothest terrains on the Moon are associated with large, young impact craters. While the typical variations of roughness over maria and highlands are within the 0.7–1.3 interval, the roughness of the youngest craters and their vicinities varies over a much wider interval, 0.4–5. This observation is well in line with conclusions from Section 3: large young craters are the only resolved features young enough so that the accumulated regolith layer is thin, and regolith gardening processes have not brought the roughness values to equilibrium.

The most prominent, unusually smooth crater-associated terrain is a large sheet of impact melt just outside the Copernican-age crater Rutherfurd (60.9°S 12.1°W, Fig. 8). The median roughness for the smooth area is 0.6, its smoothest part is 0.4. A similar but smaller melt sheet occurs just to the north of Copernican-age crater Glushko (8.4°N 77.6°W, former Olbers A). A few very smooth pixels are associated with large melt pools on the southeastern outer wall of Tycho and just to the north of King.

With these exceptions, all other parts of the youngest craters are rough. Because the maps in Figs. 2 and 3 are stretched to show minor variations of roughness over maria and highlands, the rough young craters there are saturated white. Fig. 9 shows local maps for the largest (D > 70 km) Copernican-age craters; the grayscale is stretched to show crater details; the stretch is the same for all maps. Here, following Wilhelms (1987) and McEwen et al. (1997), we consider craters with prominent bright rays as Copernican; this is not consistent with the redefinition of the Copernican period by Stöffler and Ryder (2001).

It is seen that there are significant variations of roughness both within the craters and between them. It is interesting that the inner walls, where they are resolved in the map, are smoother than the other parts of the craters (see the southern walls of Rutherfurd in Fig. 8, the northern walls of Tycho and southern walls of Hayn in Fig. 9). Unlike the smooth melt sheets outside the craters, the melt pools on the crater floors are rough.

Craters in Fig. 9 are arranged according to their general decrease in roughness. Among the largest (D > 70 km) Copernican-age craters, the median roughness calculated over the whole crater is the highest for Tycho and Jackson, 3.4; it decreases to 2.3 for Copernicus and further decreases to 1.9 for Stevinus and Vavilov.

Fig. 8. Crater Rutherfurd (D = 47 km) in the lower right part of the image and impact melt sheets outside the crater. Portion of LROC WAC mosaics centered at 60°S 13.5°W, local equirectangular projection, north at the top. Insert shows the hectometer-scale roughness (115 m baseline) for the same area; brighter shades denote rougher surface. This map was created in local equirectangular projection with 16 pixels per degree sampling, 1Rpix = 1.9 km.
We interpret these systematic variations in general roughness as the effect of crater age: when a crater ages, it accumulates small impacts, the regolith layer thickens, and regolith gardening mutes hectometer-scale roughness.

Absolute ages of Tycho (~95 Ma) and Copernicus (~800 Ma) are thought to be known from sample data (see discussion by Stöffler and Ryder, 2001). The densities of superposed craters (Hiesinger et al., 2012) are well consistent with the age ratio. They are also consistent with the putative absolute ages, assuming the chronology of Neukum et al. (2001), if the superposed craters are counted on proximal ejecta (see detailed discussion by Hiesinger et al. (2012)). Under the same assumption and limitations, van der Bogert et al. (2010) obtained a ~150 Ma age for Jackson. Our observation that Copernicus is noticeably smoother than Tycho and Jackson is consistent with its noticeably older age.

The chronology of Neukum et al. (2001) yields a formation rate of $1.55 \times 10^{-10}$ km$^{-1}$ Ma$^{-1}$ for large craters $D > 70$ km. This gives one crater per $\tau_{70} = 171$ Ma for the entire Moon. Assuming Poisson statistics of cratering, the $95$ Ma $\approx 0.56\tau_{70}$ age is consistent with Tycho being the youngest $D > 70$ km crater on the Moon. On the other hand, the probability that there are two or more craters of 95 Ma or younger, is rather low, ~11%; thus, if we agree to infereces at the traditional 84% confidence level (“one sigma”), Tycho should be the youngest among $D > 70$ km craters. Similarly, the 150 Ma $\approx 0.88\tau_{70}$ age of Jackson is still consistent with it being the second youngest, while the probability that there are three or more craters of 150 Ma or younger is 6%, and thus Jackson is likely to be the second youngest. This is consistent with Tycho and Jackson being rougher than all other craters in Fig. 9. Our roughness ranking places Copernicus 5th after Ohm ($r = 2.5$) and King ($r = 2.4$), which is perfectly consistent with its age of 800 Ma $\approx 4.7\tau_{70}$. In summary, all known age constraints are consistent with the decrease of crater roughness with time.

4.2. Roughness rays and other lineaments

The roughness map (Figs. 2 and 3) shows a number of long, rough (relatively bright in the map) lineaments; some of them form conspicuous ray systems associated with large young craters. The most prominent ray systems are associated with three large craters, Tycho, Ohm, and Jackson. As we discussed above (Section 4.1), these craters are the youngest craters of their size on the entire Moon. Roughness rays associated with them are long, the longest of them exceeding ~1500 km (~50° of arc) from their craters. Some other Copernican-age craters (like Copernicus and a number of smaller rough craters) have less pronounced systems of shorter and less prominent radial roughness lineaments.

All craters with radial roughness lineaments have systems of bright (high albedo) rays. The bright ray systems of Tycho, Ohm, and Jackson are the most prominent albedo ray systems. The well-defined roughness rays of these three craters generally coincide with their high-albedo rays. However, not all distinctive albedo rays seen on the Moon have noticeable roughness expressions. Long roughness rays are generally straight (following great circles). Roughness is not uniform along roughness rays: they are comprised of irregular, relatively smoother and rougher segments. In the distal parts of the long rays, the roughest segments have $r \approx 1.5–1.7$ and correspond to clusters of impact craters, interpreted to be secondaries from the central crater. It is possible that the entire roughness signature of the distal parts of the roughness rays is caused by the secondaries. This suggestion, however, is very difficult to prove: our measure of roughness is sensitive to back-ground topography, which is not readily apparent in visual inspection of the images. Many obvious clusters of secondary craters do not have a noticeable roughness signature.

A consistent explanation of these observations is aging due to regolith gardening. The newly-formed clusters of secondaries have an initially prominent roughness expression and form roughness rays. With time, processes associated with regolith gardening smooths the craters; the clusters gradually become parts of the equilibrated topographic pattern, and their roughness expression fades away. “Rough” secondary clusters are associated only with the largest craters, because smaller craters produce smaller secondaries that are too small to affect topography at the 115 m baseline.

There are roughness lineaments that are not parts of roughness ray systems and do not have any apparent association with large impact craters. The most prominent features of this type are situated at the north-eastern limb of the Moon (Fig. 10) and are rougher ($r \approx 1.7–1.9$) than crater-associated roughness rays. They coincide with unusually dense elongated clusters of hectometer- and decameter-scale craters (Fig. 11; note that only hectometer-scale craters are resolved on this image; overabundant decameter-scale craters...
These dense crater clusters are highly elongated and linear. We determined their axes and fitted great circles to them. We estimate that in two cases (the cluster in Fig. 11 and the southernmost marked in Fig. 10) the accuracy of our axis direction determination is better than $2^\circ$. The fitted great circles (admitting $2^\circ$ variations of the axes direction) do not extend to the vicinity of any large (>20 km) crater with prominent roughness signature in Figs. 2 and 3. This fact, together with their peculiar morphology, suggests that these dense crater clusters are not typical clusters of secondaries.

The origin of these objects is unknown. A straightforward idea that these are clusters of primary craters formed by tidally disrupted rubble-pile objects seems not to be viable. On one hand, we observe the results of such impacts both on the Moon (e.g., Melosh and Whitaker, 1994) and on other bodies (e.g., Schenk et al., 1996), but these examples look very different: they are chains of larger craters rather than dense clusters of smaller craters. On the other hand, dynamical considerations (Bottke et al., 1997) show that such events are rare and we should not expect a large number of such impacts on the Moon. Another idea is some kind of “sesquinary” impacts: either impacts of the objects ejected from the Earth, or impacts of the objects ejected from the Moon into geocentric orbits and returned to the Moon after one or a few revolutions. Dedicated dynamic modeling is needed to assess the viability of these ideas.

In addition to these enigmatic objects and the roughness rays, the hectometer roughness maps reveal a large number of other rough lineaments. The longest and roughest of them extends from the center farside to the South Pole and farther to the southern nearside (Fig. 3). It has a roughness similar to or a little higher than the most prominent roughness rays. Its roughest segments are associated with clusters of craters very similar to the clusters of distal secondaries within the roughness rays; however, it is not straight. It ends (or begins) close to Jackson, but it is not obvious if it is genetically related to it. There are also numerous low-contrast (just slightly rougher than the background) short lineaments without obvious association with craters.

### 4.3. Background roughness variations

As we noted in Section 3, primary boundaries of geological units usually do not have a prominent expression in the map of hectometer-scale roughness (Figs. 2 and 3). There are some exceptions. The highland–mare boundary can be traced in a few locations. A sharp contrast between volcanic plains of Mare Tranquillitatis (smoother) and Mare Serenitatis (rougger) coincides with a well-expressed geological contact. Weak roughness contours outline units of the Orientale impact basin; a few segments of other impact basin rims can be traced in the roughness map.

There are opposite examples, where roughness contrasts look like contrasts between distinctive units, but do not correspond to known geological boundaries. There is a sharp linear boundary between the southern rough part of Mare Humorum ($r = 1.1$) and the much smoother northern part ($r = 0.84$). This boundary does not correspond to any obvious geological contact, albedo or color contrast.

Aristarchus Plateau provides an interesting example of a roughness contrast that does coincide with a prominent geological contact. The largest pyroclastic deposit on the Moon (e.g., Gaddis et al., 2003) covers the plateau and overlies both more ancient Imbrium basin ejecta and superposed impact-related regolith, and is embayed by mare basalts along the plateau margin (Zisk et al., 1977; Lucey et al., 1986). The pyroclastic deposit is noticeably smoother than typical surfaces ($r = 0.7$) and has a distinctive, sharp boundary.
Pyroclastic material on Aristarchus Plateau is tens of meters thick (McEwcn et al., 1994), thicker than the regolith layer responsible for equilibration of roughness; if the mechanical properties of the regolith forming from the pyroclastic material differ significantly from the typical maria and highlands, this could explain the observed contrast. The second and third largest pyroclastic deposits in Sinus Aestuum (Gaddis et al., 2003) are rather smooth at the roughness map scale, but do not look like distinctive units.

As we already noted in Section 3, roughness variations over typical terrains, unrelated to impacts, are rather small. The roughness of maria varies over the 0.7–1.1 range, with one exception, mare infill of Tsiolkovsky basin, which is unusually rough \( (r \approx 1.4) \). The roughness of cratered highlands varies from 0.9 to 1.3. These variations seem regional: a vast region in the north-eastern-central farside is generally rough, even if we consider surfaces between rougher rays of Jackson and Ohm, and a vast region of the southern farside (similar to the extent of South Pole-Aitken basin, SPA) is generally smooth.

Fig. 12 provides a global view of hectometer-scale roughness variations over the Moon by presenting the roughness map (Figs. 2 and 3) smoothed down to the lowest spherical harmonics. It is seen that at the global scale, the tropics are generally rougher than the poles, and the eastern-central farside is a prominent global roughness maximum. Dynamic considerations and modeling (Morota et al., 2008; Gallant et al., 2009; Ito and Malhotra, 2010; Le Feuvre and Wieczorek, 2011) predicted somewhat higher (tens of percents) effective impact crater formation rates in the tropics than at the poles, and somewhat higher rates at the apex (the center of western hemisphere) than at antapex. The observed global roughness pattern correlates with this predicted cratering rate distribution (although the roughness maximum is shifted westward from the apex). This correlation can be causal: since the equilibrated roughness results from a balance between roughening by hectometer-scale impacts and smoothing by regolith gardening, the higher impact rate may shift the equilibrium toward a higher roughness. This explanation is based on the plausible assumption that the projectiles forming hectometer-scale craters are distributed similarly to the observed larger near-Earth asteroids, while the micrometeorites comprise a different, more isotropic population.

It is seen (Fig. 12) that the global distribution of hectometer-scale roughness correlates well with global topography. The correlation coefficient between roughness and topography for spherical harmonics of degree 2 is 0.94 and is statistically significant (the random occurrence of this high correlation is formally excluded with 99.5% confidence). For degrees 3 and 4 the correlation is also rather high (0.79 and 0.78) and marginally significant (98% and 99%). On the basis of geodynamical reasoning, the equator is close to the topographic highs, and relative roughening of the equatorial region might be caused by more frequent impacts, as discussed above. This explains high values of \( C_{2,0} \) spherical harmonic for both topography and roughness and thus explains some part of the observed correlation. The similarity between other global-scale details of the distributions is difficult to explain; in principal, it might be coincidental. A possible causal explanation could be related, for example, to levitating dust (e.g., Colwell et al., 2007): the dust might tend to migrate toward lower gravitational potential, which might lead to a global topographic trend of regolith mechanical properties, which in turn could cause a dependence of roughness on elevation.

5. Kilometer-scale roughness

5.1. Impact craters and basins

After the mare–highland dichotomy, discussed in Section 3, the most prominent feature of the kilometer-scale roughness maps (Figs. 1, 4, and 5) is the Orientale impact basin (Head, 1974; Head et al., 1993, 2010a). The Orientale basin is seen in the roughness maps as a rough ring comprised of the Outer Montes Rook (the middle of the three rings forming the multi-ring basin), a rough annulus composed of the Hevelius Formation (Orientale basin ejecta) outside Montes Cordillera (the outermost topographic ring) and a set of rough radial rays. The prominent individual rays correspond to chains of large secondary craters well seen in the images (e.g., chapter by McCauley in Wilhelms (1987)).

Other large impact basins do not have a similar roughness expression. Kreslavsky and Head (2012) argued that the difference in exposure to the impactor flux between Orientale, the youngest basin of its size, and other basins, such as Imbrium, is too small to account for the observed difference in the roughness signature. They suggest that basin-forming impacts resurface and smooth the kilometer-scale relief globally due to seismic effects, which occur before the rougher ejecta are emplaced. In this way each basin-forming impact erases kilometer-scale roughness signature of all preceding basins, leaving only the last one. If this hypothesis is correct, all distinctively rough features (at kilometer scales) should postdate the Orientale impact; in other words, they could be of Copernican, Eratosthenian or Late Imbrian age, but not older.

More subdued crater-related features are also observed in the kilometer-scale roughness data in the Orientale region at these scales, despite the superposed ejecta and distal smoothing associated with the Orientale seismic effects (e.g., Kreslavsky and Head, 2012). Fassett et al. (2011) used the identification of pre-Orientale craters and assessment of the level of filling to quantify the thickness of Orientale ejecta as a function of increasing distance from the basin rim (see their Fig. 1b). Other, larger crater to basin-like structures can be identified in the synoptic kilometer-scale roughness data. For example, the presence of the pre-Orientale Mendel-Rydberg basin can be seen in the area south of Orientale in the kilometer-scale roughness maps (Fig. 5). Furthermore, several large pre-Orientale basin circular structures in the very large crater to peak-ring basin size range suspected on the basis of topography (Head et al., in preparation, 2013) can be seen more prominently in the longer wavelength topography (Fig. 1, top). In the area just southwest of the basin, a circular feature in excess of 200 km is partly cut by, but has caused disruption of the continuity of both the Cordillera and part of the Outer Rook Rings (Fig. 5). Just north-west of the Cordillera Ring are two additional large pre-Orientale structures (Fig. 5).

The large young impact craters are rough in the kilometer-scale roughness maps, but the contrast between them and typical high-
lands are significantly lower than for hectometer-scale roughness. A few examples are shown in Fig. 13. While entire craters are rough at the hectometer scale (Fig. 9), at the kilometer scale only the rims and walls are distinctive. It is interesting that a large melt pool in the northern part of the Copernicus floor is very rough at the hectometer scale (Fig. 9), while it is as smooth as typical maria at the kilometer scale (Fig. 13).

The youngest, Copernican-age craters are distinctively rougher than older craters at the shorter, 0.46 km baseline; at longer baselines, a similar difference still exists, but it is not so pronounced. The latter makes these craters bluish in the color composites (Figs. 4 and 5). It appears as if the roughness systematically decreases with age, more rapidly at shorter baselines, and more slowly at longer baselines. The majority of large distinctively rough craters have been mapped as Copernican, Eratosthenian or Late Imbrian by Wilhelms (1987). There are some exceptions; for example, Compton (Fig. 13) was mapped as Early Imbrian. On the basis of its roughness signature we would suggest that it postdates the Orientale basin and formed in the Late Imbrian.

It is clearly seen in Fig. 13 that rough craters are surrounded by rings of relatively smoother proximal ejecta, while farther from the craters their distal ejecta becomes rougher. Tycho (Fig. 9) and the majority of smaller Copernican craters have a similar ring in the hectometer-scale map. The scale of topographic features responsible for the relatively smoother proximal ejecta and the relatively rougher distal ejecta is probably proportional to crater size. On the basis of detailed analysis of images, we interpret the difference being due to the proximal zone of interaction and flow of emplaced ejecta, often coated with impact melt veneers (e.g., Hawke and Head, 1977), while the rougher outer annulus forms where the radial decrease in ejecta density begins to expose individual chains of ejecta that form steeper-sided secondary crater chains. The radial nature of the bright outer annulus (Fig. 13) supports this interpretation.

Outside younger craters and Orientale ejecta, the roughness of the highlands at 0.48 km baseline does not show significant variations. On the 1.8 km baseline roughness map the highlands are covered with a low-contrast pattern of circles, obviously, old (pre-Orientale) craters. In some sense, this pattern should be considered as spurious noise, which results from the fact that this longest baseline is comparable to the sliding window size.

5.2. Volcanic plains

All mare surfaces are smoother than the highland surfaces, as discussed in Section 3. There are roughness variations within maria; they are, however, not readily seen in Figs. 1, 4, and 5 because the stretch is chosen to show the whole dynamic range of roughness. Fig. 14 shows the global km-scale roughness map (analogous to Figs. 4 and 5) stretched to better show the roughness variations in maria. The roughness contrast between maria and highlands is higher at longer baselines, and this is why all mare surfaces are blue in the color composite map (Fig. 14).

The roughness maps reveal the tectonic fabric of the maria, mostly in the form of wrinkle ridges; their east–west segments often appear rougher than north–south segments because of the anisotropy of our roughness measure (discussed in Section 2.3). The few-kilometer-size craters appear as bright (rough) dots. Ejecta of somewhat larger craters appear bluish in the color composite (Fig. 4) because they are not distinctive at longer baselines.

There are significant variations in the background kilometer-scale roughness of the maria. They do not correlate with the variations of hectometer-scale roughness. For example, the division of Mare Humorum into rougher and smoother parts seen in Fig. 2 does not appear in Fig. 14. In contrast to what is observed at the hectometer scale, the kilometer scale Mare Tranquillitatis is systematically rougher than Mare Serenitatis.

The latter difference is a part of the obvious trend that older maria (Hiesinger et al., 2011) tend to be rougher than younger maria. A similar trend has been observed on Mars (Kreslavsky and Head, 2000): a wide range of kilometer-scale roughness spans various volcanic plains from the smoothest and youngest Cerberus Plains in Elysium Planitia (e.g., Vaucher et al., 2009) to the moderately smooth Late Hesperian ridged plains, to the much rougher Late Noachian ridged plains, which are still distinctively smoother than the heavily cratered highlands of Mars. Qualitative comparison of mare roughness (Fig. 14) against crater-deduced mare ages (Hiesinger et al., 2010, 2011) shows, however, that roughness is not always a function of age. In other words, it seems possible to find a pair of mare areas where the younger area is somewhat rougher, contrary to the general trend.

Some boundaries between mare units correspond to distinctive sharp contrasts in roughness, for example, the contact between Mare Tranquillitatis and Mare Serenitatis materials mentioned above, and the contact between Late Imbrian and Eratosthenian lavas in north-central Oceanus Procellarum (Whitford-Stark and Head, 1980; Hiesinger et al., 2011). These prominent geological contacts are well known from maps of color ratios. There are some sharp roughness contacts that do not correspond to well expressed sharp color contrasts, for example, in far north-western part of Oceanus Procellarum. It is possible that these roughness contrasts reveal previously unrecognized contacts between volcanic plains of different ages, or even cryptomaria. Some contacts between mare units are overprinted by later crater ejecta, modified by tectonics, etc., and are not clearly seen in the roughness maps.

A number of light blue areas in Fig. 14 (smooth at 1.8 km baseline, rough at 0.46 km baseline) do not correspond to mare surfaces (they have a high albedo and do not have a mafic spectral signature). Some of these plain areas are cryptomaria (e.g., Antonenkov et al., 1995 and references therein); for example, the typical crypto-

![Fig. 13. Maps of kilometer-scale roughness of several large craters and basins; scales are chosen proportional to the diameters. 1.8 km baseline and local Lambert azimuthal equal-area projection for Orientale; 0.92 km baseline and local equiangular projections for all other craters. Brighter shades denote higher roughness, and stretch is chosen individually for each map to show details; Copernicus is significantly rougher than all other objects. Crater diameters are listed according to Head et al. (2010b), Orientale basin diameter is taken equal to Outer Rook Ring diameter according to Head (1974) and Baker et al. (2012).](image-url)
mare site in the Schiller–Schickard region (Whitten et al., 2012). Cryptomaria are old basaltic volcanic plains covered with a layer of bright felsic highland-like material (Head and Wilson, 1992), typically, some ejecta, and Orientale ejecta in the case of the Schiller–Schickard region. The presence of mafic mare material beneath the ejecta is recognizable due to small dark-halo craters that excavate mare material and show its mafic spectral signature (Schultz and Spudis, 1979). A smooth roughness signature of the old mare surface is overprinted at smaller scales but preserved at larger scales. It is possible (but not certain) that all distinctive areas that appear smooth at 1.8 km baseline are old volcanic plains. The absence of dark halo craters on some of them can be due to unusually low iron content of the lavas, the occasional absence of young enough craters of the proper size to penetrate, unfavorable observational conditions (e.g., very high latitudes always observed under low Sun, which makes it hard to distinguish albedo and spectral details).

6. Conclusions

We constructed maps of the topographic roughness of the lunar surface at baselines from 115 m to 1.8 km using the collection of LOLA along-orbit topographic profiles. The exceptionally high vertical precision of the LOLA ranging measurements and the informed choice of a stable roughness measure, resulted in roughness maps of high visual sharpness and of ready and practical use in geomorphologic studies.

We found that hectometer-scale (115 m baseline) and kilometer-scale (0.46–1.8 km baselines) topographic roughness poorly correlate with each other and reflect different sets of processes and time scales. Hectometer-scale roughness is controlled by regolith accumulation and modification processes and affected by the most recent events in lunar geological history (the Copernican period and, to some degree, the Eratosthenian period, in other words, the most recent ~2 Ga). Kilometer-scale roughness distribution reflects major geological (impact, volcanic and tectonic) events of the last 3.8 Ga of the geological history and to some extent earlier events.

As we have demonstrated, the roughness maps have many potential uses in geomorphological analysis and geological mapping of the lunar surface. For example: (1) The scale-dependent roughness signatures of large (>15 km) impact craters can be used to estimate the relative and absolute ages of the craters; (2) geological studies often include crater counting to infer ages; the hectometer-scale roughness map can be utilized to avoid areas of abundant secondary craters and to assess how typical the crater count areas are in terms of recent superimposed unusual features; (3) the hectometer roughness maps show enigmatic features previously not recognized, for example, Copernican-age dense elongated clusters of small impact craters that are different from typical secondary crater clusters. The maps can aid systematic searches for these types of features; (4) the kilometer-scale roughness maps can be useful in the geological mapping of maria to reveal previously unknown or poorly defined contacts between

Fig. 14. Global map of kilometer-scale roughness of the lunar nearside in simple cylindrical projection. The same RGB composite is used as in Fig. 4 stretched nonlinearly to show better the roughness variations in the smooth volcanic plains. Brighter shades denote rougher surfaces. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
different volcanic plain units and to characterize such units; (5) these maps can also be used to find new and to refine known locations of old volcanic plains overlaid by younger materials.

The maps presented here not only give a convenient overview of topography; they utilize the high precision of LOLA measurements and reveal some peculiarities of topography that cannot be analyzed by LOLA-based gridded topographic maps. The roughness measure used here is not the only statistical characteristic of topography that can be useful in this aspect. Here we used only shot-to-shot profiles; the use of all five spots of LOLA, where they are available, allows mapping of the surface roughness at a shorter baseline; it is also possible to introduce a much more isotropic roughness measure, but only at that short baseline. Convergence of LOLA tracks in the polar areas also provides an opportunity to deal with shorter baselines and isotropic roughness measures. In addition to roughness, principally different statistical characteristics of topography can be mapped. For example, the statistical concavity of along-orbit profiles at a kilometer-scale baseline was used by Kreslavsky and Head (2012) to illustrate the uniqueness of the topographic texture of the Orientale basin and its ejecta, to show that it differs significantly from ways of earlier impact basins such as Imbrium, and to support the hypothesis that basin-related seismic effects have a significant effect on surface roughness.

Acknowledgments

Discussions with Yurii Shkuratov and Erik Ashbaugh were helpful. We acknowledge financial support from the NASA Lunar Reconnaissance Orbiter Lunar Orbiter Laser Altimeter (LOLA) experiment (NNX09AM54G and NNX11AK29G to J.W.H.) and the NASA Lunar Science Institute.

References


