EFFECTS OF INCIDENCE ANGLE ON CRATER DETECTION AND THE LUNAR ISOCHRON SYSTEM: PRELIMINARY RESULTS FROM THE COSMOQUEST MOONMAPPERS CITIZEN SCIENCE PROJECT.

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Introduction: Since Galileo turned his telescope to the Moon, people have been studying lunar craters throughout the centuries. The dawn of the space age provided better telescopes and satellite-based imagery, enabling a significant amount of research to be gleaned from larger craters. However, modern instruments, especially the *Lunar Reconnaissance Orbiter*'s Narrow-Angle Camera (LROC NAC), are capable of imaging the surface at up to 25 cm/pix. With such data, we have entered an era of unprecedented detail for our nearest neighbor.

The LROC NAC data provide an opportunity to examine the very smallest crater populations on the Moon on a wide variety of terrains. In addition, this data set represents the first time that repeat high resolution imagery is available for many planetary locations from a variety of solar lighting conditions. This provides an unprecedented opportunity to explore the effects of solar incidence angle on crater detection. The *Apollo* landing regions are well suited to a study of this kind. Being of particular interest, they have been multiply targeted and so provide the required range of sun angle data. The *Apollo* landing regions are also key terrains that are used for calibrating the lunar chronology system – a system that is used as the foundation for crater age-modeling across the entire solar system. An improved understanding of such sun angle effects has important implications for our knowledge of small crater populations in this area, and so can affect the entire lunar chronology system.

An inhibitor to addressing these questions is the vast number of features that must be catalogued and analyzed to properly characterize these small crater populations. Such a task would take far too long for a single researcher (or even a research group) to complete alone. To address this problem, we are utilizing the nascent CosmoQuest's MoonMappers (MM) project [1] to provide the data necessary for our research. Here, we present results on our progress.

Data Source: The data-gathering process is crowd-sourced by asking volunteers from around the world to identify and annotate craters and other features on small sub-sections of LROC NAC data, presented through the online MM interface [1]. Our current focus is on the *Apollo 15* landing site. Small segments from seventeen NAC strips are being evaluated, and volunteers have completed seven of these to-date, having identified and measured over 1.1 million craters.

Volunteers are shown 450×450 pixel sub-images of the NACs on which they annotate craters and other features they see. Each sub-image must be annotated by 15 different people to be considered complete. When all the sub-images from a given NAC segment are completed, a 3-D clustering code is run [2] and craters with $N \geq 9$ markings per cluster (≥60% found that crater) are saved to a final catalog.

Roughly every 15 sub-images, volunteers are unknowingly shown a calibration image that has already been marked by an expert. After identifying all the craters, they are given feedback on their results and their score is saved for weighting purposes during the clustering. Figure 1 shows that the individual volunteers' markings, and their clustered results, generally have very good agreement with expert markings.

The resulting catalog would be next to impossible for a single researcher or research group to create manually without the assistance of citizen scientists.

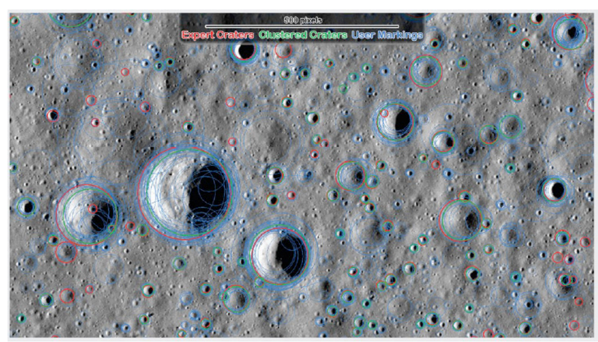

Figure 1: Calibration image with crater data showing individual MoonMappers users' markings (blue), the cluster code results (green), and the expert markings (red).

Results:

Solar Incidence Angle. One of the first studies with modern data to systematically test how crater counts would be affected by incidence angle found non-trivial results, indicating that this could be a significant factor in the number of craters identified, the diameters that were measured, and hence any science that results from these data [3].

To examine this with new data, we are using a large number of images with a wide range of incidence angles spanning 27.5° to 83° relative to normal (noon). A few of the images have repeat angles (*i.e.*, M11394743L/R is at 59.5°, and M119829425L is at 58.2° -- both are being analyzed). The results are presented as cumulative size-frequency distributions (CSFD) in Figure 2.

When the sun is lower on the horizon (*e.g.*, sun angle ~80°), our volunteers tend to find that craters are easier to see. As a result, the shape of the CSFD is what would be expected from a population in production (roughly following established isochron functions). At smaller craters, the curve transitions to a population in empirical saturation (showing a shallower CSFD slope because every new crater that forms removes an equivalent number/fraction of other craters).

When the sun is near normal to the surface (high overhead or a sun angle of ~30° in our study), our volunteers find that craters are much more difficult to identify. We find that the crater populations measured with the sun higher overhead contain ~4x less craters than the population observed when the sun is ~77°. This is as expected, since high sun angles emphasize albedo over topography [e.g. 4] making topographic features more difficult to identify. Overall, these data suggest that the "ideal" sun angle range for crater identification is constrained within ~58° < i < ~77°.

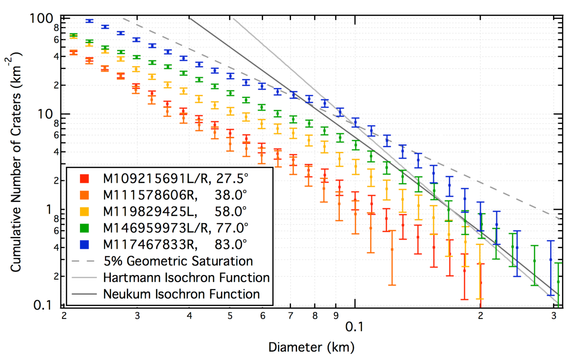

Figure 2: Cumulative size-frequency data for multiple incidence angle images covering the *Apollo 15* site. Seven images have been fully examined by MM users to-date. 2.0 Ga isochrons are plotted over the data, showing agreement with that slope until empirical saturation is reached.

Lunar Chronology. Crater counts of *Apollo* and *Luna* sites form the basis for all crater age calibrations for the Moon and the solar system as a whole. Crater counts written as $N(D)$, where N is number of craters with diameter greater than or equal to D, were completed decades ago for D = 1 km using images from that time, and these studies are still cited as the defining values [e.g. 5-8].

The MM crater count data from the *Apollo 15* landing site provides an opportunity to compare these very localized NAC counts for the ~±0.13° region around the *Falcon* lander (17.1 km^2) with the results of [9], shown in Fig. 3. [9] measured the same NAC image as volunteers (M146959973L) and the data show good overlap. [9] also measured a broader region using archived *Apollo* metric camera images (202 km^2) and an even larger region using LROC WAC (Wide-Angle Camera) images (3052 km^2). All results are consistent amongst themselves, showing good overlap between each other.

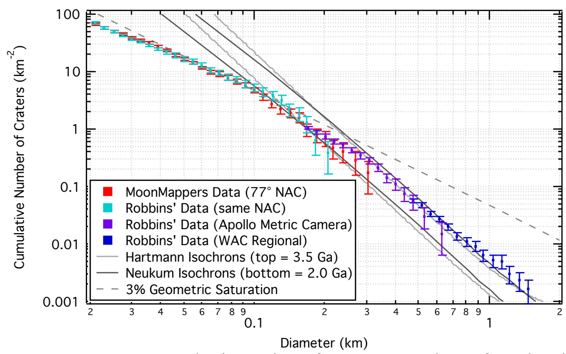

Figure 3: Cumulative size-frequency data for the immediate region around the Apollo 15 landing site, using NAC images with a sun angle of 77° as well as WAC images. Data form MM users is in good agreement with Robbins data. The dashed line is the 3% geometric saturation.

Conclusion: In the less than 1 year since its official launch, MoonMappers volunteers have made over 1.1 million crater identifications and measurements, which when clustered produce a catalog of 10s of thousands of final craters. We are using this data to explore the important question of how solar incidence angle affects crater detection and measurement. This work also fits well within the context of broader crater counts on key lunar chronostratigraphic terrains. As we further develop this tool, we will be able to gather data needed to answer questions that could not be done before.

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