Machine Learning Driven Detection Of 1 Billion+ Lunar Impact Craters In Permanently Shadowed Regions Using ShadowCam Data


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SHADOWCAM

ShadowCam is a NASA-funded instrument hosted onboard the Korea Aerospace Research Institute (KARI) Korea Pathfinder Lunar Orbiter (KPLO) satellite. By collecting high-resolution images of the lunar permanently shadowed regions (PSRs), ShadowCam will provide critical information about the distribution and accessibility of water ice and other volatiles at spatial scales (1.7 m/pixel) required to mitigate risks and maximize the results of future exploration activities. Tens of thousands of high-resolution images collected by ShadowCam represent a perfect resource for machine learning enhanced crater detection algorithms (CDAs).

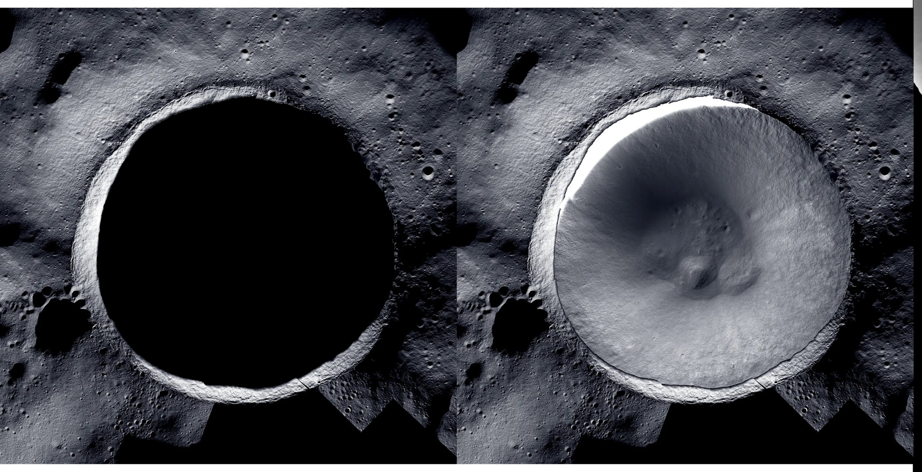
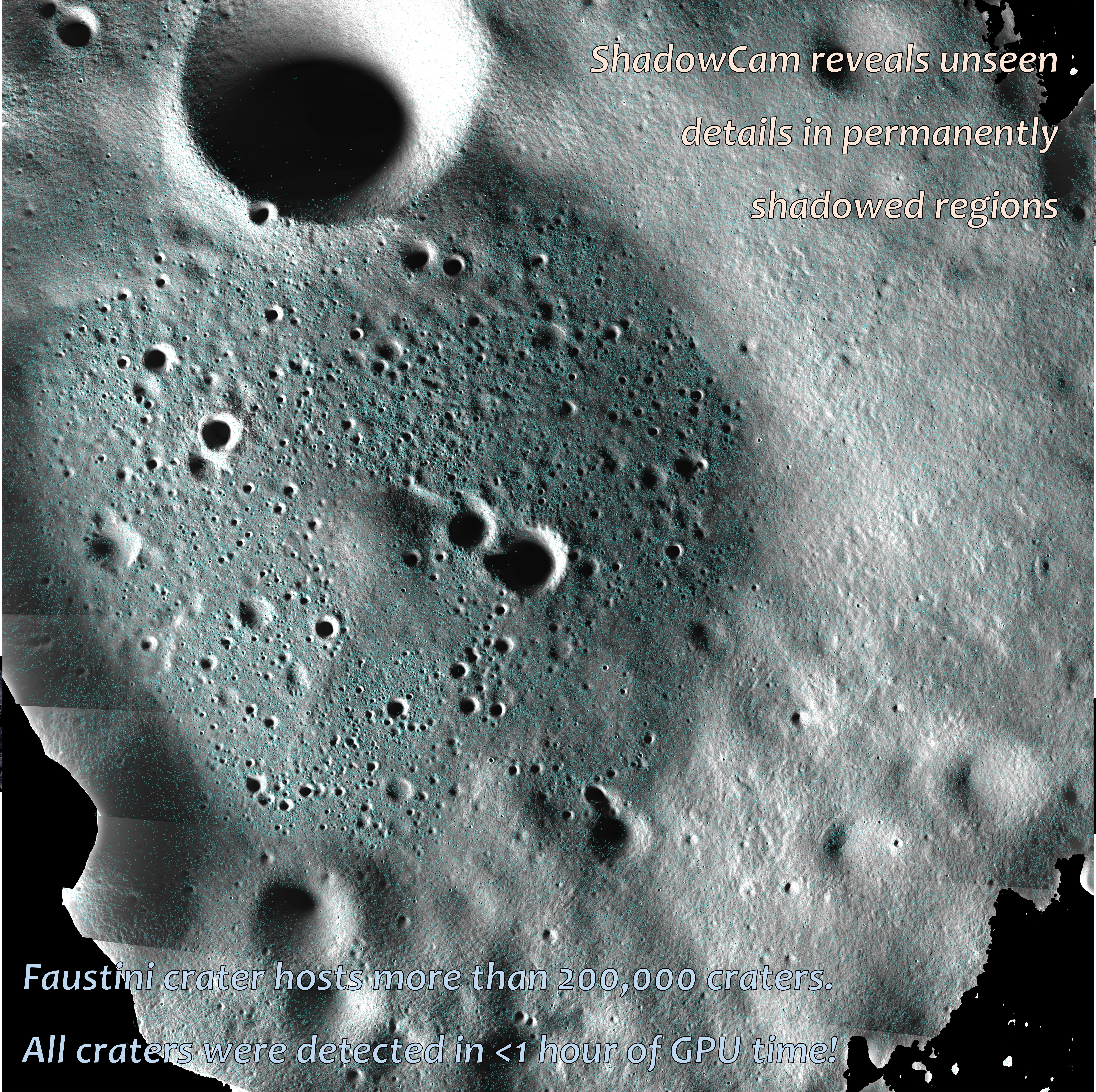


Figure 1. Mosaic of the Shackleton Crater from the Lunar Reconnaissance Orbiter Camera (LROC) images (left) and enhanced by the ShadowCam images (right). LROC captures detailed images of lunar surface but is not sensitive enough to image permanently shadowed regions with high-resolution and signal-to-noise ratio. ShadowCam is specifically designed to detect light in extremely low-light conditions thus able to see what lies in the shadows. However, the directly illuminated lunar surface is too bright for ShadowCam therefore only together with LROC we can see the entire lunar surface.

CRATER DETECTION ALGORITHM

With the advent of machine learning in the last decade we can now process the high-resolution lunar images. In our work we use the YOLOv8 (You-only-look-once) object detection framework designed to provide high speed and accuracy for detection of various objects in images. Our object detection model contains only 1 class: crater and is based on the YOLOv8m model with 25.9 million parameters. The default resolution of our model is 512x512 pixels. The detection model was trained using 5240 impact craters from various LRO-NAC images and employed several image augmentations such as rotation, contrast and brightness variations provided by the *albumentations* library to increase the robustness of our crater detection algorithm (CDA).



We deployed our ML-based CDA on 29,755 images from the PDS ShadowCam dataset, which corresponds to 2.98 TB of image data covering approximately 7.2 million km² of the lunar surface. In this dataset we find 1,381,994,541 impact craters larger than 14 meters in diameter. Note, that the images in the dataset overlap, therefore many craters are detected multiple times at different time and illumination conditions. An example of a sample area is shown in *Figure 2*.

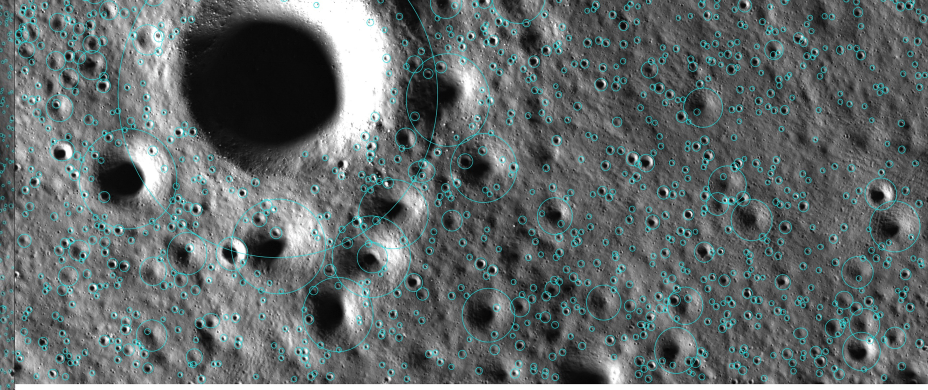


Figure 2. A full-resolution section ShadowCam mosaic of the Faustini crater located at ($x = 82.0 \pm 1.4$ km, $y = 5.0 \pm 0.7$ km). This image contains 1164 impact craters with diameters from 14 m to 1.2 km. We find 98.2% of our detections are true positive detections, while 1.8% are false detections. Additionally, ~1% of craters remained undetected.

We tested the performance of our ML-based CDA on a dataset of 50,000 craters selected from different ShadowCam images and vetted by human researchers. We find that our CDA detects with >98% precision craters with diameters between 14 meters and 4km. Smaller craters are also detected but the performance metrics vary significantly between different researchers. Larger craters are already contained in the Robbins 2019 global crater database and are therefore not the target of our analysis.

FAUSTINI AND SIZE-FREQUENCY

To illustrate the strength of our CDA we analyze the spectacular mosaic of the Faustini crater provided by the ShadowCam team (central Figure). We find 203,481 impact craters in this mosaic covering 1571 km² of the surface area. The analysis of the entire image was done in less than 1 hour on one GPU (NVIDIA A100 – 40GB) provided by the NASA Center for Climate Simulation at the Goddard Space Flight Center. For comparison it would take one researcher 3.5 months of work (assuming 10 seconds per crater and 8 hours of work a day) to mark the same number of craters.

Combining our crater detections with the information about the steepness of each area allows us to for the first time see the effects of slopes on the crater degradation and maturation inside permanently shadowed regions. In Figure 3 we show the cumulative size-frequency distributions of all craters detected in the Faustini crater for 6 different slope ranges (0-30°). We find that steeper slopes retain fewer craters per area for all crater diameters from 16 to 100 meters.

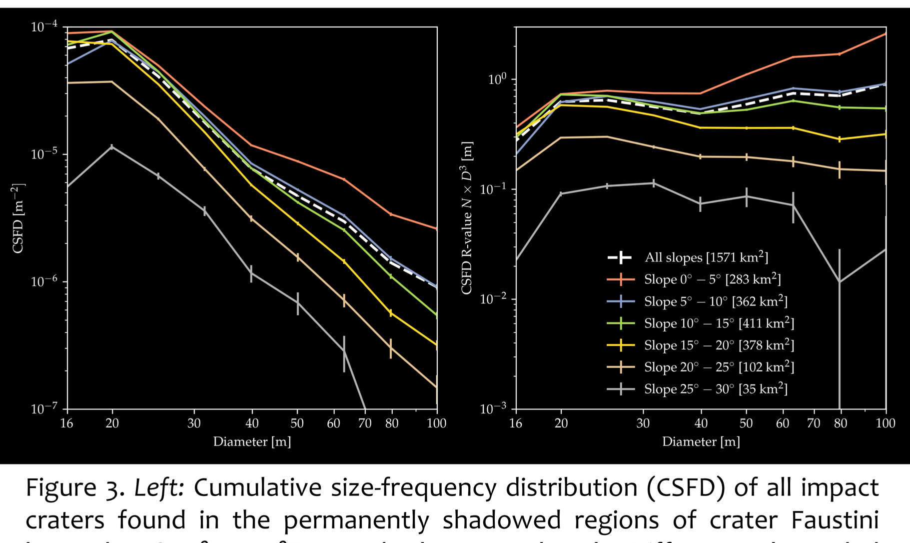


Figure 3. *Left:* Cumulative size-frequency distribution (CSFD) of all impact craters found in the permanently shadowed regions of crater Faustini located at 87.3°S 77.0°E near the lunar south pole. Different color-coded solid lines represent CSFDs broken down by the slope angle obtained from the Lunar Reconnaissance Orbiter laser altimeter (LOLA) map of the south pole, while the white dashed line represents the total CSFD. The CSFD is normalized by the surface area (see the legend). *Right:* The same as the left panel but now detrended by a factor of D^3 forming an R-plot. Both panels show that the steeper slopes retain a smaller number of impact craters than their shallower counterparts and thus experience a different rate of degradation and maturation.

CONCLUSIONS AND AVAILABILITY

Our ML-based CDA is performing well for a variety of impact craters in permanently shadowed regions of the Moon. We are currently processing more ShadowCam images and further improving our CDA by training the detection model on a larger variety of ShadowCam specific craters. With more than 1 billion crater detections and despite overlapping images our work will form one of the largest crater datasets to date. All image data are on PDS. Our results, and code are available upon request until our first manuscript is accepted.