# HORUS – UNPRECEDENTED VIEWS INTO LUNAR SHADOWED REGIONS.

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**Introduction:** The Moon's permanently shadowed regions (PSRs) are believed to host large quantities of (sub)surface water-ice and other volatiles, making them prime targets for future exploration missions, including orbital (e.g., Trailblazer [1]) and surface missions (e.g., VIPER [2]). In addition, astronauts may visit PSRs during the Artemis missions [3]. Despite their importance, the rover/astronaut-scale (<~5 m) surface characteristics and trafficability of PSRs remain largely unknown, mainly because the available data lacks sufficient signal and/or resolution. For example, short-exposure (and thus high-resolution) images of PSRs taken by LRO NAC (Lunar Reconnaissance Orbiter Narrow Angle Camera) suffer from a substantial amount of noise, including dark noise, read noise, and shot (photon) noise, making them largely unusable for science- and/or exploration-related applications.

Here, we demonstrate the capabilities of a machine learning-driven post-processing tool that significantly enhances the signal-to-noise ratio (SNR) of existing LRO NAC images of PSRs, enabling a variety of PSR-related science studies while helping to improve the safety and efficacy of future exploration missions [4, 5] (Figure 1).

**HORUS:** HORUS (Hyper-effective nOise Removal Unet Software) consists of two environment-driven and physics-based neural networks applied sequentially: (1) DestripeNet, which removes the dark noise in the images and (2) PhotonNet, which removes all other noise sources (e.g., shot noise, read noise). HORUS operates on regular and summed mode LRO NAC images and is able to produce denoised images with resolutions of about 1.5 m/pixel, which is a factor 5 to 10 better than existing, long-exposure (LRO and Kaguya/Selene) images of PSRs. By validating HORUS with sunlit-shadowed (in TSRs – transiently shadowed regions) and shadowed-shadowed image pairs (in PSRs) we find that HORUS is able to resolve physically-present features, such as boulders and craters, as small as ~3 m across, and does not appear to add (or 'hallucinate') any false features [4, 5] (Figure 1).

**Application to Artemis and beyond:** HORUS allows us to tap into the vast – and continuously growing – NAC image archive (~200,000 images) over the north and south poles of the Moon, taken over more than ~11 years. HORUS images and derived products can be used for a number of applications, including:

I. mapping and studying the meter-scale geomorphology of shadowed regions – including craters, boulders, and mass wasting features, as well as surface roughness in general
II. looking for surface-exposed ice or frost, as well as geomorphic indications of subsurface ice
III. doing crater and/or boulder counting & surface age estimation
IV. doing change detection and looking for fresh impacts, mass wasting, and other surface processes.

In direct support of future exploration efforts, HORUS can also be used to, for example:

V. plan safe and effective traverses through shadowed regions
VI. provide high-resolution maps that help contextualize in-situ and orbital observations
VII. localize landers and rovers in transient or permanent shadow during and after missions.

In future work, we seek to deploy HORUS to produce and provide data products, such as denoised images, maps, and image time series, in direct support of Artemis and other exploration efforts. An adapted version of HORUS could potentially be applied to images taken by ShadowCam and/or other future missions.

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**References:** [1] Ehlmann, B. et al. (2021) 52nd *LPSC*. [2] Colaprete et al. (2021) 52nd *LPSC*. [3] NASA Artemis III SDT Report (2020) *NASA/SP-20205009602*. [4] Moseley et al. (2021) *IEEE CVPR*. [5] Bickel et al. (2021) *Nature Comms*. [6] Speyerer et al. (2013) *Icarus*. [7] Mazarico et al. (2011) *Icarus*.

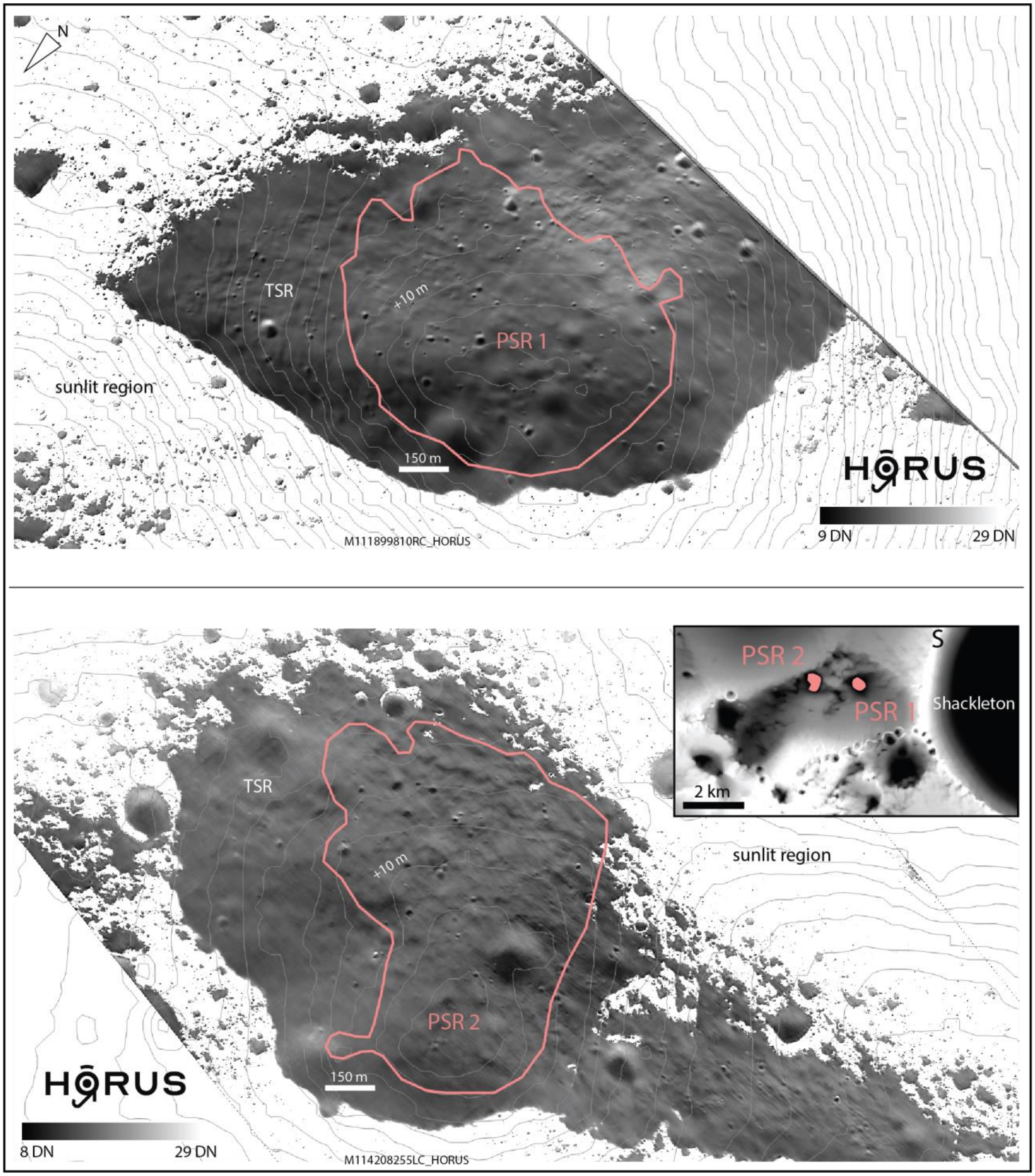


**Figure 1.** HORUS images of two example PSRs (and NAC-observed TSRs) close to the south pole and the Shackleton – Henson connecting ridge (PSR extent indicated in red). Craters as small as ~3 m across are resolved in both regions. Contour lines visualize the local topography (each line indicates a 10 m height difference). Both PSRs are roughly 800 m across, i.e., a size that is highly attractive to exploration but that cannot be covered by long-exposure imaging due to technical reasons (pixel bleed, etc.). Overview map shows the location of both PSRs in the south polar region; percentage-based illumination map in the background [6]. PSR location and extent taken from [7].