LOW-LIGHT IMAGE ENHANCEMENT OF PERMANENTLY SHADOWED LUNAR REGIONS WITH PHYSICS-BASED MACHINE LEARNING

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INTRODUCTION

In recent years the international space community has gained significant **momentum** for continuing the exploration of the **Moon**.

Water is a key resource for establishing and sustaining a human presence.

Water is likely to exist at the lunar poles, specifically inside the permanently shadowed regions (PSRs) - topographic depressions which see no direct sunlight.

However, **direct detection** of surface water-ice has **not yet been possible**.

Bright surface ice could potentially be detected using high-resolution optical imagery from the Lunar Reconnaissance Orbiter Narrow Angle Camera (LRO NAC).

PROBLEM

However, due to the extreme low-light conditions, Charge-Coupled Device (CCD) sensor-related noise and photon (Poisson) noise dominate these images, strongly limiting our ability to make meaningful observations.



PHYSICAL CCD NOISE MODEL

We assume that an image captured by the LRO NAC can be formulated as

 $I = S + N_p + N_d + N_b + N_r$

where I is the raw image in detector counts, S is the mean photon signal, N_p is stochastic photon noise (Poissondistributed), N_d is stochastic dark current noise (Poisson-distributed, from to thermally activated charge carriers in the CCD), N_r is **readout noise** and N_b is **dark bias noise** (deterministic, due to a pixel-to-pixel varying voltage offset applied).

SOLUTION

We use two physics-driven deep neural networks to model and remove CCD-related and photon noise in LRO NAC images. We name the workflow Hyper-Effective Noise Removal U-Net Software (HORUS).



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Map of PSRs (orange polygons) at the lunar south pole. Image credits: LROC/ASU/QuickMap

Physical noise model of the NAC CCD Raw image credits: LROC/ASU/GSFC

DestripeNet predicts the dark bias noise N_b from the **camera environment meta data** available at the time of image capture, and is trained using 100,000+ dark calibration frames as labels. It uses a convolutional decoder design.

RESULTS

We validate our approach by comparing HORUS denoised shadowed images in Temporarily Shadowed Regions (TSRs) to their corresponding overlapping sunlit images.







We apply the two networks sequentially to denoise the images:

<u>PhotonNet</u> predicts the photon noise N_p in the image, and is trained by adding synthetic Poisson noise to 1M randomly selected rescaled image patches of the lunar surface in normal sunlit conditions. It uses a U-Net architecture.

Importantly, PSRs can only be illuminated by secondary light scattered from their surroundings. In order to best match the illumination conditions of the training data to these conditions, we match the distribution of solar incidence angles in the sunlit training images for PhotonNet to the expected distribution of secondary illumination angles in PSRs estimated from 3D ray tracing.

HORUS is able to significantly improve the quality of both synthetically-generated and real low-light images.

Real raw NAC image | Wapowski crater (82.9°S 53.5°E)

Raw image credit: LROC/ASU/GSFC

CONCLUSION

We have shown it is possible to significantly enhance extremely low-light images of PSRs on the Moon. Future work will analyse these images for surface-ice related signals, quantitatively assess performance using TSRs, and investigate joint training of the networks to improve performance.

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CONTRIBUTIONS VTB and BM were involved in the conceptualization of this project. VTB, BM, ILF and LR were involved in the methodology, software, validation, formal analysis, investigation, resources, data curation, writing, preparation, visualization. VTB, BM, ILF, LR, AZ, DW and MOM were involved in the review, administration, supervision. NS and EDE implemented the 3D ray-tracing.



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Standard (sunlit)



Secondary illumination render over Shackleton PSR from 3D ray tracing

HORUS (shadowed)

Our result (HORUS)