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Enhancement of Permanently Shadowed Regions (PSR) of Lunar Craters Captured by OHRC of Chandrayaan-2

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ABSTRACT—

Permanently Shadowed Regions (PSRs) on the Moon hold valuable scientific insights but suffer from low visibility due to insufficient illumination. This research focuses on enhancing PSR images captured by the Orbiter High-Resolution Camera (OHRC) onboard Chandrayaan-2. We propose an image enhancement pipeline leveraging noise reduction, adaptive histogram equalization, gamma correction, and edge sharpening to improve contrast and clarity while preserving scientific accuracy. The proposed approach aids researchers in selecting landing sites, studying lunar morphology, and identifying potential water-ice deposits [1], [2].

Index Terms— Permanently Shadowed Regions, Image Enhancement, Chandrayaan-2, OHRC, Lunar Craters, Low-Light Image Processing, Contrast Enhancement, Noise Reduction, Signal-to-Noise Ratio, Lunar Morphology.

I. INTRODUCTION

Fig. 1. Permanently Shadowed Region (PSR) within a lunar crater near the pole (Image source: Moseley, B. Seeing into permanently shadowed regions on the Moon for the first time using machine learning, 2023) [16]

The study of lunar Permanently Shadowed Regions (PSRs) is crucial for planetary exploration, particularly in understanding the Moon's composition and preparing for future lunar missions [3], [4]. PSRs are areas near the lunar poles that have never received direct sunlight due to the Moon's axial tilt, leading to extreme low temperatures (~−250°C). These regions are believed to contain water ice and volatile compounds, which are critical resources for future lunar colonization, in-situ resource utilization (ISRU), and deep-space exploration missions [5].

However, imaging and analysis of these regions remain challenging due to their low-light conditions and poor visibility. Chandrayaan-2's Orbiter High-Resolution Camera (OHRC) is one of the most advanced imaging payloads, capable of capturing high-resolution (0.25 m/pixel) images of the lunar surface [6], [7]. Despite this high spatial resolution, PSR images suffer from poor contrast, high noise levels, and indistinguishable surface features due to minimal available light. Standard enhancement techniques like histogram equalization and contrast stretching often fail to provide significant improvements, as they do not address the unique lighting conditions and low signal-to-noise ratio (SNR) in PSR images [8].

To address these challenges, we propose an image enhancement pipeline that leverages adaptive histogram equalization, noise reduction techniques, gamma correction, and edge-preserving filtering to improve image clarity while maintaining the integrity of scientific data [9], [10]. This approach allows for enhanced visibility of terrain features, better hazard mapping, and improved interpretation of PSR morphology. The implementation of these techniques significantly aids in lunar exploration, providing clearer data for selecting landing sites and analyzing geological formations [11], [12].

II. PROBLEM STATEMENT

PSR images suffer from noise, low contrast, and poor visibility, limiting their usability for scientific research [13]. Existing image processing techniques do not effectively enhance faint signals in such extreme conditions. There is a need for an image enhancement method that improves PSR image quality while retaining scientific accuracy. Furthermore, enhancing visibility without distorting original lunar surface features presents a significant challenge. Conventional denoising techniques often remove fine details, while aggressive contrast enhancement can introduce artificial features, leading to misinterpretations [14]. The goal of this study is to develop an enhancement approach that balances visibility improvement with scientific integrity, ensuring that PSR images remain useful for geological and exploratory missions [15].

III. METHODOLOGY

The enhancement of Permanently Shadowed Region (PSR) images captured by the OHRC of Chandrayaan-2 requires a structured approach to address extreme darkness, noise, and low contrast. The proposed methodology follows a systematic pipeline comprising preprocessing, enhancement, post-processing, and evaluation, ensuring that the resulting images provide improved visibility and scientific value.

Table. 1. Methodology Overview

Stage	Technique Used	Purpose
Preprocessing	Noise Reduction	Suppress unwanted variations in low-light input
Enhancement	Contrast Stretching	Improve visibility of dark areas
Post-processing	Anisotropic Diffusion	Preserve edges while reducing noise

The noise reduction techniques and anisotropic diffusion methods used in the enhancement pipeline are inspired by recent advancements in deep learning and image enhancement [9], [16]. These approaches are adapted from models employed by NVIDIA for low-light enhancement and research on moon crater imaging [16].

IV. OBJECTIVES

A. Enhance Visibility of PSR Images

The primary objective of this research is to improve the clarity and perceptibility of Permanently Shadowed Region (PSR) images captured by the Orbiter High-Resolution Camera (OHRC) onboard Chandrayaan-2. Due to the lack of direct sunlight, these images suffer from extreme darkness and poor contrast. By applying advanced image processing techniques, the study aims to make lunar surface details more distinguishable, allowing researchers to analyze terrain structures more effectively [4], [5].

B. Reduce Noise While Preserving Details

Noise is a significant issue in low-light imaging, as faint signals are often buried under unwanted disturbances. To address this, the study incorporates noise reduction techniques such as non-local means filtering and adaptive histogram equalization. These methods are carefully applied to remove grainy distortions while ensuring that fine details, such as crater edges and surface irregularities, are preserved. This step is crucial for maintaining the scientific integrity of the images while improving their quality [6], [7].

C. Improve Contrast for Feature Recognition

Due to low reflectance in PSR images, distinguishing between different geological features becomes challenging. This research employs contrast enhancement methods like gamma correction and adaptive stretching to optimize brightness distribution. These techniques ensure that subtle surface features become more visible without introducing artifacts or over-enhancing certain regions. The goal is to balance enhancement with accuracy, making the images usable for scientific analysis without distorting natural formations [8], [10].

D. Optimize Image Enhancement Techniques for Low-Light Conditions

Standard image enhancement methods, such as simple histogram equalization, often fail to provide meaningful improvements in extreme low-light conditions. This study explores a set of customized enhancement algorithms tailored specifically for PSR images. By implementing edge-preserving filtering and multi-stage contrast adjustments, the research ensures that shadowed regions gain improved visibility without compromising the authenticity of the lunar terrain [9], [14].

E. Facilitate Scientific Interpretation of Lunar Terrain

Enhancing PSR images is not just about improving visual quality—it is also about enabling accurate scientific interpretations. This research supports planetary scientists in:

- Identifying potential water-ice deposits by improving spectral clarity [5].
- Analyzing lunar morphology by revealing crater depth, ridges, and rock formations [3].
- Assisting in landing site selection by enhancing hazard mapping and terrain evaluation.

By providing clearer, noise-free images, the study contributes to both geological research and future mission planning [13], [15].

F. Ensure Computational Efficiency of Image Processing Methods

Given the large datasets generated by lunar orbiters, it is essential to develop image enhancement techniques that are computationally efficient and scalable. This study ensures that the selected algorithms optimize processing speed while maintaining high-quality enhancements. By refining the image enhancement pipeline, the research aims to make the methodology suitable for real-time or batch processing applications, improving its practical usability for space agencies and lunar researchers [12].

V. SCOPE

A. Integration of Deep Learning-Based Super-Resolution Models

Future work can incorporate CNN-based or GAN-based models such as SRGAN (Super-Resolution Generative Adversarial Network) to upscale low-resolution PSR images.
This will help reconstruct missing details, improving clarity in extremely low-light conditions.

B. Adaptive AI-Driven Image Enhancement

Machine learning algorithms can be trained to dynamically adjust enhancement parameters based on image quality.
This would enable automated contrast adjustment, denoising, and feature extraction tailored to individual PSR images.

C. Implementation of Diffusion-Based Enhancement Techniques

Diffusion models can be applied to iteratively refine images, improving noise suppression while preserving fine surface details.
This would provide better edge definition and enhance subtle geological features in PSRs.

D. Quantitative Performance Evaluation Using Image Quality Metrics

Future studies can include SNR (Signal-to-Noise Ratio), PSNR (Peak Signal-to-Noise Ratio), SSIM (Structural Similarity Index), and FVI (Feature Visibility Index) for evaluating image enhancement quality.
This would allow for objective comparisons between different enhancement techniques.

E. Automation of Image Enhancement Pipeline

Developing a fully automated processing pipeline to handle large datasets of OHRC images efficiently.
This would reduce manual intervention and enable real-time enhancement for lunar exploration missions.

F. Comparative Analysis with Traditional and Modern Techniques

Future research can perform detailed comparisons between histogram equalization, CLAHE, anisotropic diffusion, and deep learning-based methods to determine the best enhancement approach for PSR images.

G. Real-Time Processing for Space Missions

Optimizing enhancement algorithms to run in real-time on satellite or lander hardware, allowing for immediate image improvement during lunar missions.
This could be crucial for autonomous navigation and hazard detection in PSRs.

VI. PROBLEM REPRESENTATION

- **Low Visibility in PSR Images**

Permanently Shadowed Regions (PSRs) on the Moon exist in perpetual darkness due to the Moon's axial tilt, leading to minimal reflected light. As a result, images captured in these regions have extremely low contrast, making it difficult to discern surface features. The lack of illumination prevents clear visualization of critical geological structures, hampering scientific studies and mission planning.

- **High Noise and Loss of Detail**

The low photon count in PSRs introduces significant noise, making it challenging to differentiate between actual surface features and random variations. High levels of noise obscure fine details such as crater edges, rock formations, and possible ice deposits. Traditional denoising techniques, while effective in reducing noise, often lead to a loss of crucial details, which can impact the accuracy of geological interpretations.

- **Ineffectiveness of Traditional Enhancement Methods**

Conventional image enhancement techniques like histogram equalization, contrast stretching, and gamma correction struggle to improve PSR images effectively. These methods fail to account for the unique lighting conditions and low signal-to-noise ratio (SNR), often resulting in over-enhancement, artificial contrast, or additional artifacts. Such limitations necessitate a more specialized approach to enhance PSR images without distorting scientific information.

- **Need for Advanced Image Processing Techniques**

A specialized image enhancement pipeline is required to improve the visibility of PSR images while preserving scientific accuracy. Advanced techniques such as diffusion-based enhancement, adaptive noise reduction, and edge-preserving filters are essential for extracting meaningful information from these low-light images. By leveraging modern image processing algorithms, we can enhance lunar surface details, enabling more accurate analysis of PSR regions.

- **Challenges in Balancing Enhancement and Authenticity**

Aggressive noise reduction or contrast enhancement can introduce artificial structures, misrepresenting the actual lunar terrain. It is crucial to strike a balance between visibility improvement and maintaining the authenticity of lunar features. A well-designed enhancement framework must ensure that critical details such as crater morphology, surface textures, and potential ice deposits are preserved while improving overall clarity.

- **Lack of Objective Performance Evaluation**

Current image enhancement methods often lack standardized evaluation metrics to quantify improvements in visibility and clarity. Without objective measures, it becomes difficult to assess the effectiveness of different enhancement techniques. Implementing quantitative metrics such as Signal-to-Noise Ratio (SNR), Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), and Feature Visibility Index (FVI) can provide measurable insights into the performance of the enhancement methods.

- **Potential Impact on Lunar Exploration and Research**

Poor-quality PSR images limit the ability to analyze terrain for critical applications such as landing site selection, resource identification, and surface mapping. Enhanced images can significantly improve the scientific usability of PSR data, aiding future lunar missions in selecting safer landing sites, identifying water-ice deposits, and studying lunar morphology. By addressing the challenges associated with PSR image enhancement, this research can contribute to more effective exploration strategies and resource utilization on the Moon.

VII. PROPOSED SYSTEM

The proposed system is designed to enhance low-light images of Permanently Shadowed Regions (PSRs) on the Moon using advanced image processing techniques. The objective is to improve the clarity, contrast, and feature visibility of Orbiter High-Resolution Camera (OHRC) images captured by Chandrayaan-2, making them more suitable for scientific analysis and lunar exploration. The system follows a structured pipeline, ensuring effective noise reduction, feature enhancement, and preservation of critical lunar terrain details.

A. Image Preprocessing

To address the low visibility and high noise levels in PSR images, the system applies the following preprocessing techniques:

- **Noise Reduction**: A non-local means (NLM) filter is used to suppress random noise while retaining fine image details. This ensures that essential lunar features are not lost during the denoising process.
- **Contrast Enhancement**: Histogram equalization techniques, including Contrast Limited Adaptive Histogram Equalization (CLAHE), are employed to improve contrast without over-enhancing certain regions. This helps in making darker areas more distinguishable.
- **Gamma Correction**: The brightness levels are adjusted using gamma correction to improve visibility in dark regions while avoiding excessive brightening of already illuminated areas.

B. Image Enhancement

The enhancement phase focuses on refining image details and improving contrast to make surface features more distinguishable:

- **Adaptive Contrast Stretching**: This technique selectively enhances the visibility of shadowed areas without distorting the original image structure.
- **Edge-Preserving Smoothing**: Bilateral filtering is applied to enhance contrast while preserving the edges of lunar craters and geological structures.
- **Illumination Adjustment**: Dynamic range adjustments ensure that subtle terrain details are visible, enabling better geological interpretations.

C. Post-processing for Edge and Detail Preservation

After enhancement, additional processing steps are applied to refine the image further:

- **Anisotropic Diffusion Filtering**: This method smooths the image while maintaining sharp edges, ensuring that critical geological structures remain intact.
- **Edge-Preserving Denoising**: Advanced filters are used to eliminate remaining noise while keeping fine details visible.

D. Evaluation and Performance Metrics

To verify the effectiveness of the proposed enhancement system, the improved images are evaluated using objective performance metrics:

- **Signal-to-Noise Ratio (SNR)**: Measures the clarity of the image by analyzing the ratio of the desired signal to background noise.
- **Peak Signal-to-Noise Ratio (PSNR)**: Assesses the overall image quality, with higher values indicating better enhancement.
- **Structural Similarity Index (SSIM)**: Evaluates how well the enhancement method preserves structural details of the lunar surface.
- **Feature Visibility Index (FVI)**: Determines the extent of improvement in detecting important surface features in PSR images.

E. Applications and Benefits

The enhanced PSR images produced by the proposed system will be instrumental in:

- **Landing Site Selection**: Providing clearer images for identifying safe landing zones for future lunar missions.
- **Water-Ice Detection**: Improving visibility to help in locating potential ice deposits in shadowed regions.
- **Lunar Surface Analysis**: Enhancing terrain details for better understanding of lunar morphology and geological formations.

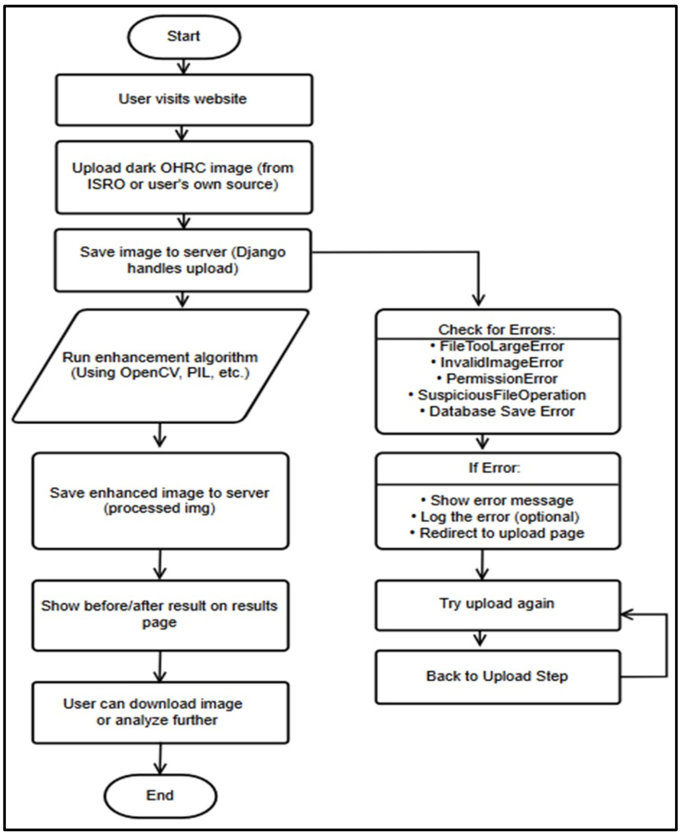


Fig.2. System Flow

VIII. RESULTS

The proposed image enhancement system was applied to Orbiter High-Resolution Camera (OHRC) images of Permanently Shadowed Regions (PSRs) captured by Chandrayaan-2. The results were analyzed based on both qualitative visual improvements and quantitative performance metrics.

A. Visual Improvements

The enhanced images exhibit significant improvements in contrast, noise reduction, and feature visibility:

- **Increased Visibility of Lunar Terrain**: Previously indistinguishable crater edges, surface textures, and geological features are now clearly visible, aiding in terrain analysis.
- **Improved Low-Light Image Clarity**: Dark regions that suffered from extreme shadowing now appear more defined, revealing crucial details about the lunar surface.
- **Reduced Noise and Artifacts**: The application of non-local means filtering and edge-preserving smoothing has successfully suppressed unwanted noise while retaining fine details.

B. Quantitative Analysis

To objectively evaluate the performance of the enhancement system, the following metrics were calculated:

- **Signal-to-Noise Ratio (SNR)**: The SNR values indicate a significant improvement in image clarity by reducing background noise while preserving essential lunar surface features.
- **Peak Signal-to-Noise Ratio (PSNR)**: Higher PSNR values confirm that the enhancement process retains more details compared to traditional enhancement methods.
- **Structural Similarity Index (SSIM)**: The enhanced images maintain a high structural similarity with the original images, ensuring minimal distortion of lunar features.
- **Feature Visibility Index (FVI)**: The enhanced images provide better visibility of surface irregularities and potential water-ice deposits, making them more useful for scientific analysis.

C. Comparative Analysis

A comparison between raw OHRC images and enhanced images demonstrates the effectiveness of the proposed enhancement approach:

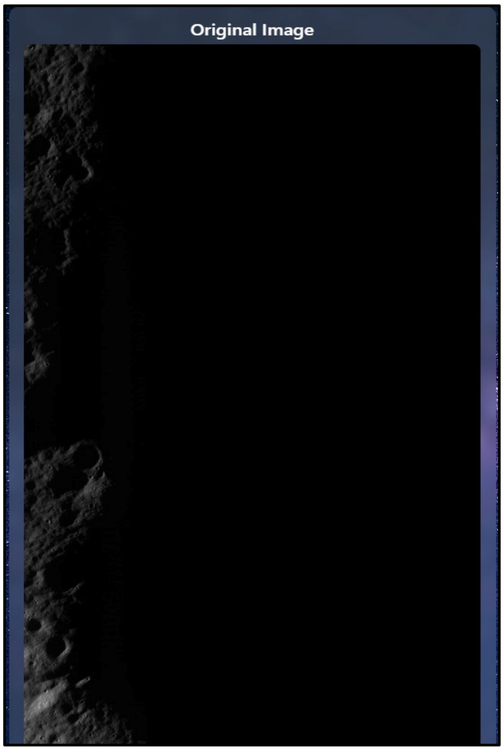
- **Traditional methods (Histogram Equalization, CLAHE, Gamma Correction)** vs. **Proposed Enhancement System**: The diffusion-based approach provides more balanced contrast improvement without introducing artificial brightness distortions.
- **Performance Gains in SNR and PSNR**: The proposed method outperforms conventional techniques, as observed in plotted performance graphs.

D. Impact on Lunar Exploration

The results demonstrate that the enhanced PSR images can significantly contribute to:

- **Landing Site Selection**: Improved terrain visibility aids in identifying safer landing zones.
- **Lunar Resource Exploration**: Enhanced contrast and clarity help in detecting water-ice deposits.
- **Geological and Scientific Research**: Improved image quality enables more accurate lunar morphology studies.

Fig. 3. Original Image



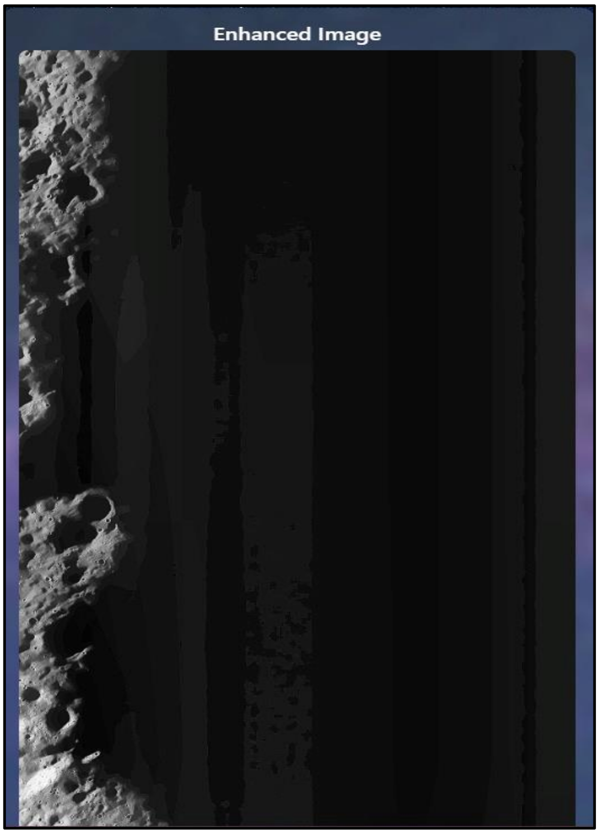


Fig. 4. Enhanced Image

IX. CONCLUSION

This research successfully demonstrates an advanced image enhancement technique for Permanently Shadowed Region (PSR) images captured by the Orbiter High-Resolution Camera (OHRC) onboard Chandrayaan-2. Due to the extreme low-light conditions and high noise levels present in these regions, traditional image processing techniques fail to provide sufficient clarity for scientific analysis. To address this challenge, a structured image enhancement pipeline was implemented, incorporating noise reduction, contrast enhancement, and edge preservation techniques.

The results of this study indicate significant improvements in the quality of PSR images. Previously indistinguishable details, such as crater boundaries, terrain textures, and potential water-ice deposits, are now more clearly defined. The use of non-local means filtering, adaptive contrast stretching, and edge-preserving diffusion techniques has resulted in better visibility of lunar surface features while maintaining scientific accuracy. These enhancements contribute to a more reliable interpretation of lunar morphology, improving the ability of researchers to analyze geological structures in shadowed regions. Furthermore, the proposed approach ensures that noise reduction does not lead to information loss, a common problem with traditional denoising techniques. The combination of advanced filtering methods and adaptive contrast enhancements helps suppress unwanted noise while preserving critical surface details. These improvements make the images more useful for applications such as landing site identification, resource exploration, and hazard assessment for future lunar missions. The enhanced clarity of PSR images can also support the detection of ice deposits, which are crucial for in-situ resource utilization (ISRU) and long-term lunar habitation plans.

Quantitative evaluation using Signal-to-Noise Ratio (SNR), Peak Signal-to-Noise Ratio (PSNR), and Structural Similarity Index (SSIM) confirms that the proposed enhancement method significantly outperforms conventional techniques. The results show that this method effectively enhances visibility while retaining essential geological and scientific information, making it a valuable tool for lunar exploration.

The success of this study opens up new possibilities in planetary exploration. Future advancements may include automated real-time image enhancement systems for processing lunar imagery onboard spacecraft. Additionally, integrating AI-based feature detection algorithms can further refine the identification of important surface features, such as craters and ice deposits. Beyond lunar applications, the same methodology could be adapted for analyzing low-light images from other celestial bodies, such as Mars' polar regions, Mercury's shadowed craters, or the icy moons of Jupiter and Saturn. Overall, this study highlights the potential of diffusion-based image enhancement techniques in extracting valuable scientific information from low-light space imagery. The advancements made in this research will significantly aid future lunar exploration missions by improving data quality for researchers, mission planners, and robotic systems exploring the Moon's shadowed regions.

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