Morphometric Analysis of Lunar Craters Using Chandrayaan-2 DTM Data

1. Introduction

1.1 Importance of Studying Lunar Craters

The surface of the Moon is dominated by impact craters, geological features formed by the collision of meteoroids, asteroids, and comets over billions of years. In the near-vacuum of the lunar environment and with minimal geological activity, these craters are remarkably well-preserved compared to their terrestrial counterparts. They serve as fundamental records of the Moon's geological history, the flux of impacting bodies in the inner solar system, and the processes that shape planetary surfaces. Studying crater morphology, their shape, size, and structure, provides crucial insights into the properties of the lunar crust and regolith, the mechanics of impact events, and the ways surfaces evolve over time due to subsequent impacts and other modification processes. Craters act as natural probes, revealing subsurface characteristics and chronicling the history of surface modification.

1.2 Chandrayaan-1 Mission and Data

India’s Chandrayaan-2 mission, launched in 2019, carried the advanced Terrain Mapping Camera-2 (TMC-2), designed to capture high-resolution stereo images of the lunar surface with ~5 m spatial resolution. Using fore (+25°), nadir (0°), and aft (–25°) views, TMC-2 enabled the generation of accurate Digital Terrain Models (DTMs) for detailed 3D topographic analysis.

In contrast, the original morphometric study of these craters used Digital Elevation Models (DEMs) derived from Chandrayaan-1 data. This project leverages Chandrayaan-2 DTM data, offering improved vertical accuracy and spatial detail, thereby enabling more precise morphometric measurements of lunar craters.

1.3 Project Objective and Scope

This project aimed to implement and evaluate methods for the quantitative characterization of lunar crater morphology, drawing inspiration from the techniques described in the study *"Study of morphology and degradation of lunar craters using Chandrayaan–1 data"* by Nikita Agarwal, Athira Haridas, and Nitin Khanna. While the original study utilized Digital Elevation Models (DEMs) from Chandrayaan-1, we extended the analysis using more recent Chandrayaan-2 DTM data for improved resolution and accuracy.

Unlike the original study, we first performed **crater detection** on the Chandrayaan-2 DTM before conducting morphometric calculations. From the dataset, we identified **7 impact craters** and additionally analyzed **one non-crater image** for comparative purposes. Using **QGIS** (an open-source alternative to ArcGIS), we cropped individual crater regions from the full DTM for focused analysis.

For each detected crater, three key morphometric parameters were calculated:

- The **Depth-to-Diameter (D/d) ratio**
- The **Topographic Roughness Index (TRI)** near the crater rim
- The **maximum slope** along the crater wall

These parameters were then used to characterize crater morphology and assess degradation patterns based on Chandrayaan-2 data.

2. Background: Lunar Crater Morphology and Analysis

2.1 Crater Formation and Degradation

Impact cratering is a fundamental geological process that has shaped the surfaces of most solid bodies in the solar system, including the Moon. The formation process involves the hypervelocity impact of an external body, leading to excavation, ejection of material, and modification of the target surface, typically resulting in a characteristic depression.

Once formed, lunar craters are subjected to various degradation processes over geological timescales. Unlike Earth, the Moon lacks a substantial atmosphere and liquid water, so erosion by wind and water is negligible. Instead, degradation is primarily driven by:

- **Subsequent Impacts:** Smaller impacts continuously bombard the lunar surface,

eroding crater rims, partially filling interiors, and degrading sharp morphological features over time. Ejecta from nearby larger impacts can also blanket and subdue existing crater forms.
- **Mass Wasting:** Gravity plays a constant role, causing downslope movement of loose material (regolith) on crater walls. This leads to the shallowing of the crater floor, rounding of the rim crest, and a general decrease in wall slopes.
- **Seismic Shaking:** Impacts generate seismic waves that propagate through the lunar crust. The cumulative effect of shaking from numerous impacts, both near and far, can trigger slumping and further contribute to mass wasting on crater walls.
- **Space Weathering:** While slower, the constant bombardment by micrometeoroids and solar wind particles can alter the optical and physical properties of surface materials, though its direct impact on large-scale morphology is less pronounced than impact-driven processes.

These degradation processes collectively cause craters to evolve morphologically, gradually transforming fresh, sharply defined craters into more subdued, shallower forms, eventually leading to their obliteration.

2.2 Morphological Indicators

The degree to which a crater has been degraded is reflected in its shape or morphology. Quantitative measurements, known as morphometric parameters, can be used to characterize these shapes and potentially infer the relative age or degradation state of a crater. Key indicators include:

- **Depth-to-Diameter (D/d) Ratio:** This ratio compares the crater's depth (measured from the average rim height to the lowest point on the floor) to its diameter (typically measured between rim crests). It is one of the most commonly used parameters. Fresh, simple (bowl-shaped) craters tend to have a relatively consistent d/D ratio (often cited around 0.2 or 1/5), although studies using high-resolution data show variation, especially for smaller craters (d/D ~0.11-0.17 for fresh craters < 400m). As degradation proceeds, mass wasting fills the crater and erodes the rim, causing the depth to decrease relative to the diameter, thus lowering the d/D ratio. Therefore, lower d/D values generally indicate a more degraded state, although initial target properties can also influence this ratio.
- **Slope:** The steepness of the interior crater walls is another important morphological characteristic. Fresh craters typically exhibit steep inner walls. Degradation processes, particularly mass wasting, tend to reduce these slopes

over time as material moves from the upper walls and rim towards the floor. Measuring wall slope provides a quantitative way to assess this aspect of crater morphology.
- **Topographic Roughness Index (TRI):** TRI is a quantitative measure of terrain heterogeneity, typically calculated as the standard deviation or range of elevation values within a defined neighborhood around each point in a DTM. A higher TRI value indicates greater local elevation variability or roughness, while a lower value signifies a smoother surface. Applied to craters, TRI can potentially quantify the texture of features like the rim or floor. A fresh crater rim might be expected to be relatively sharp and perhaps blocky (higher TRI), while a degraded rim becomes smoother and more rounded (lower TRI) due to erosional processes.

To address this limitation and potentially provide more robust indicators applicable across various crater sizes, Agarwal et al. proposed and utilized additional or refined parameters. Two of these, implemented in this project, are:

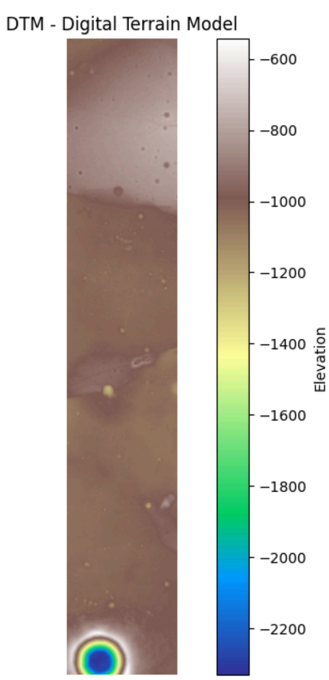
- **Maximum Slope Along the Wall:** Instead of using an average slope, which might mask variations, they considered the maximum slope value found on the crater's interior wall. This metric might be more sensitive to the steepest, potentially structurally controlled or actively eroding parts of the wall, offering a different perspective on wall degradation compared to an average value. It could capture remnant steepness in moderately degraded craters or highlight areas of significant slumping.
- **Topographic Roughness Index (TRI) Near the Crater Rim:** They specifically emphasized calculating TRI in the vicinity of the crater rim. The rationale is that the rim crest is often one of the sharpest features of a fresh crater and is directly exposed to degradational processes. Quantifying the roughness or texture specifically in this zone might provide a sensitive measure of the degree of rim degradation (e.g., breakdown of sharp crests, accumulation of small impact pits) that could help distinguish different degradation classes.

By focusing on these specific parameters alongside the traditional d/D ratio, the approach aims to capture more nuanced aspects of crater morphology potentially linked to degradation, mitigating some limitations associated with size dependency in simpler metrics.

3. Data Source and Preparation

3.1 Chandrayaan-2 TMC DTM Data

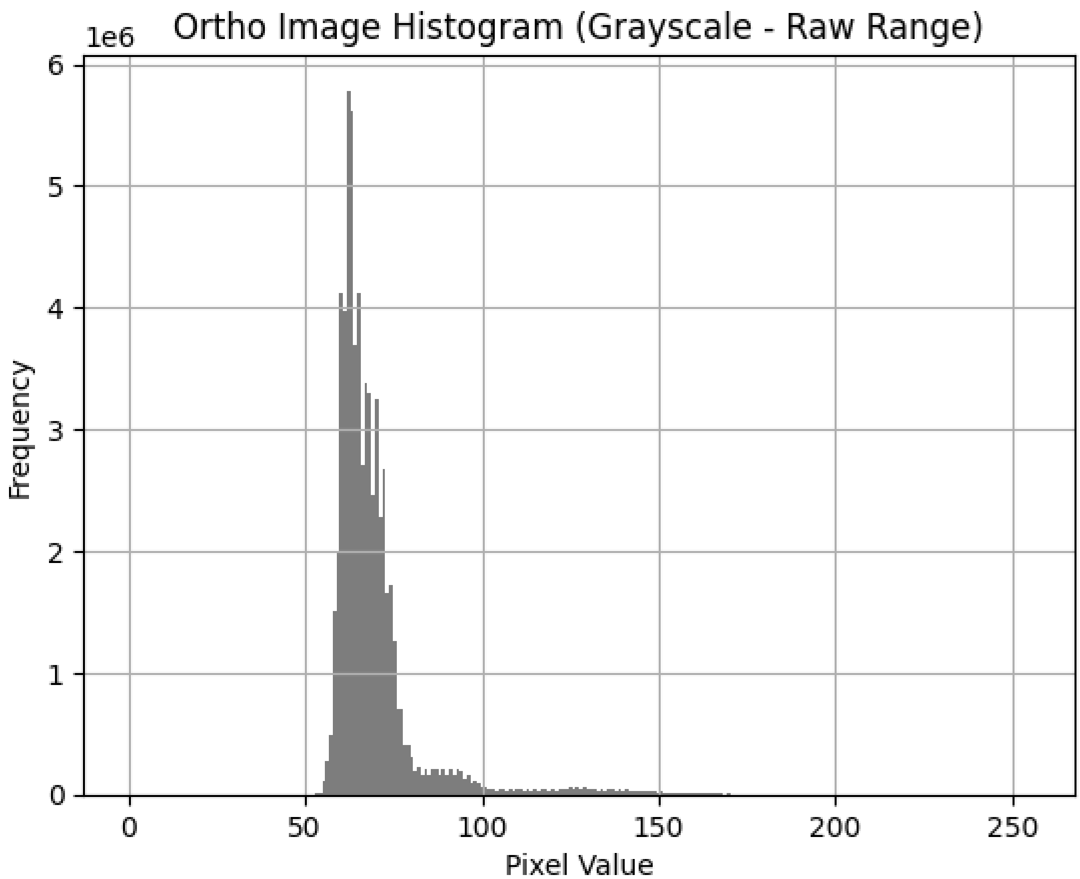
The primary data source for this project was a Digital Terrain Model (DTM) generated from imagery captured by the Terrain Mapping Camera 2 (TMC-2) aboard the Chandrayaan-2 lunar orbiter. TMC-2 was specifically designed for high-resolution topographic mapping, acquiring stereo imagery with a nominal ground resolution of 5 meters from its operational 100 km lunar orbit. Like its predecessor, TMC-2 captured triplet stereo images — simultaneous views in the forward (+25°), nadir (0°), and aft (–25°) directions along the spacecraft's ground track.This triplet stereo capability significantly enhances the reliability and accuracy of DTM generation compared to traditional two-image stereo pairs. The multiple viewing angles improve the chances of successful image matching, especially in regions with complex terrain or variable illumination, and provide greater geometric strength for accurate elevation computation. The resulting DTMs represent the lunar surface as a high-resolution grid of elevation values, suitable for detailed morphometric analysis.



It is important to acknowledge that, like all DTMs derived from photogrammetric techniques, the Chandrayaan-2 TMC-2 DTMs also possess inherent uncertainties. These stem from factors such as image-matching errors, small inaccuracies in spacecraft orientation data, and the interpolation methods used to convert discrete stereo matches into a continuous elevation grid. Although the triplet-view geometry of TMC-2 generally produces high-quality topography, localized artifacts can still occur, which may influence the precision of morphometric measurements—especially for very small or subtly expressed features. Vertical accuracy can vary with lighting, terrain texture and matching performance, but overall the data deliver sufficiently detailed relief for robust crater morphology analysis.

3.2 Study Area and Crater Selection

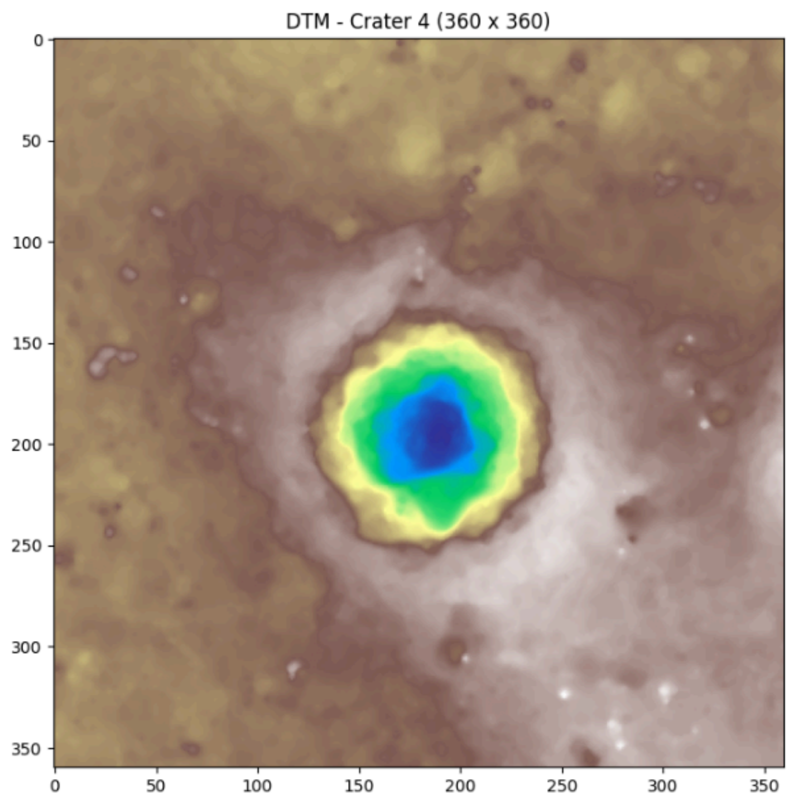
The analysis was carried out on a single DTM file covering a portion of the lunar surface imaged by Chandrayaan-2. Instead of manual GIS selection, we wrote Python scripts to detect craters automatically: we applied Canny edge detection and Hough Circle Transform to the Ortho images, attempted to locate catalogued craters using the Salamuniccar catalog, and finally generated contours directly from DTM elevation values to mark depressions. This workflow yielded seven reliably detected craters. QGIS (open-source) was then used only to crop the isolated crater DTMs after Python had identified their extents.



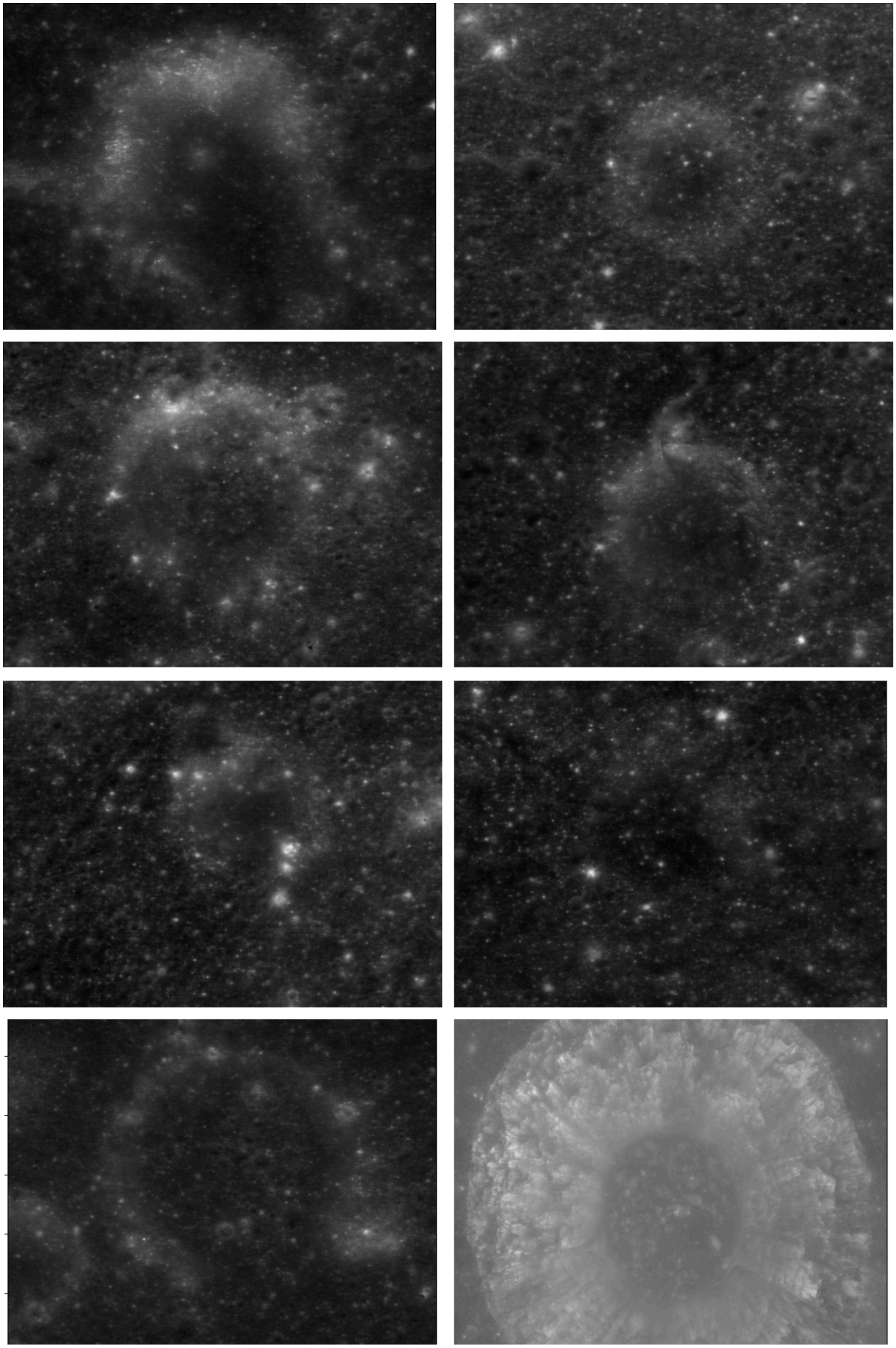
Ortho image was 16-Bit originally we converted it to 8-Bit for the crater detection algorithms to work.

3.3 Crater Isolation

A crucial step in the preparation process was the isolation of each selected crater from the main DTM tile. This was necessary to perform calculations specific to each individual crater's morphology. The isolation was achieved using QGIS. For each of the ~7 craters, a boundary was manually delineated based on visual interpretation of the DTM topography, typically aiming to trace the crater's rim crest. This delineation defined the spatial extent of the crater for subsequent analysis.



Once the boundary (e.g., as a polygon feature) was defined for a crater, the corresponding elevation data from the main DTM was extracted or 'clipped' to this boundary. This resulted in separate, smaller DTM files or raster datasets, each containing the topographic information for just one of the selected craters and its immediate vicinity as defined by the delineated rim. This process ensures that subsequent parameter calculations (depth, diameter, slope, TRI) were performed only on the relevant data for each individual crater. The accuracy and consistency of this manual delineation step are critical, as the defined boundary directly influences the measurement of diameter and the areas used for calculating depth, slope, and TRI.



4. Methodology: Parameter Calculation and Visualization

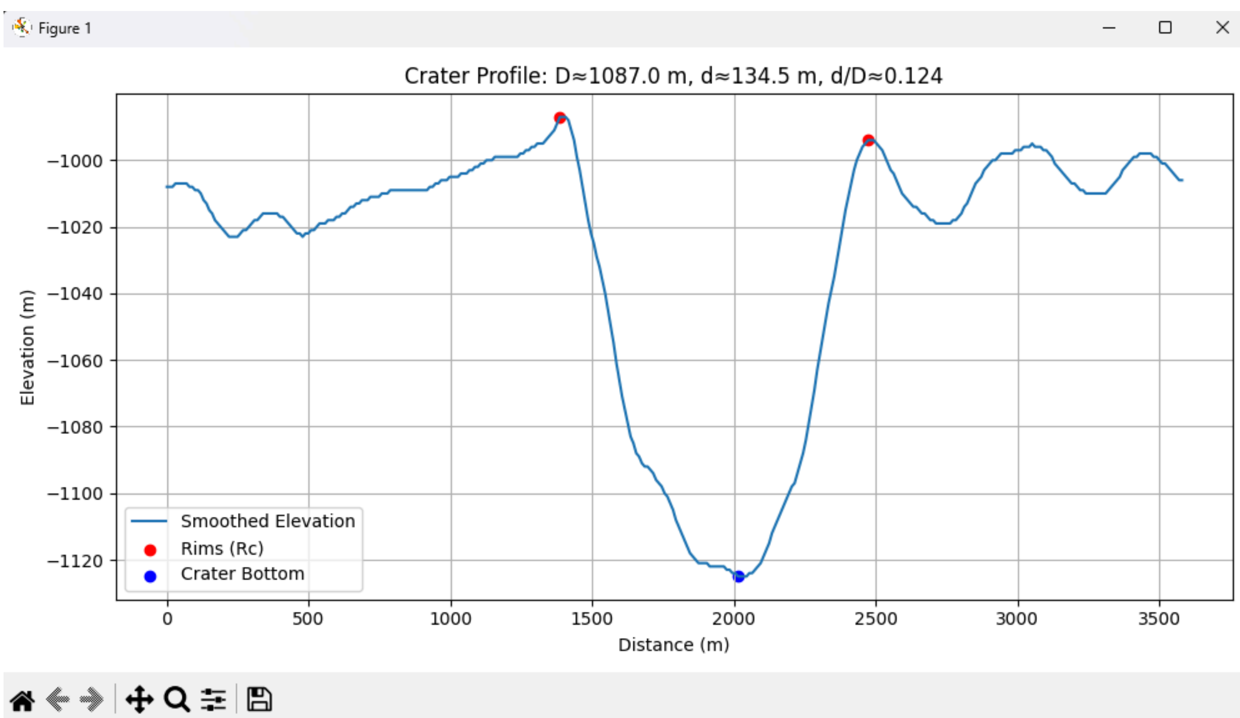
Following data preparation, the core morphometric parameters were calculated for each of the approximately 7 isolated crater DTMs.

4.1 Defining Crater Dimensions (Diameter D, Depth d)

The fundamental dimensions of diameter (D) and depth (d) were determined for each crater. Following the general approach often used in crater studies.:

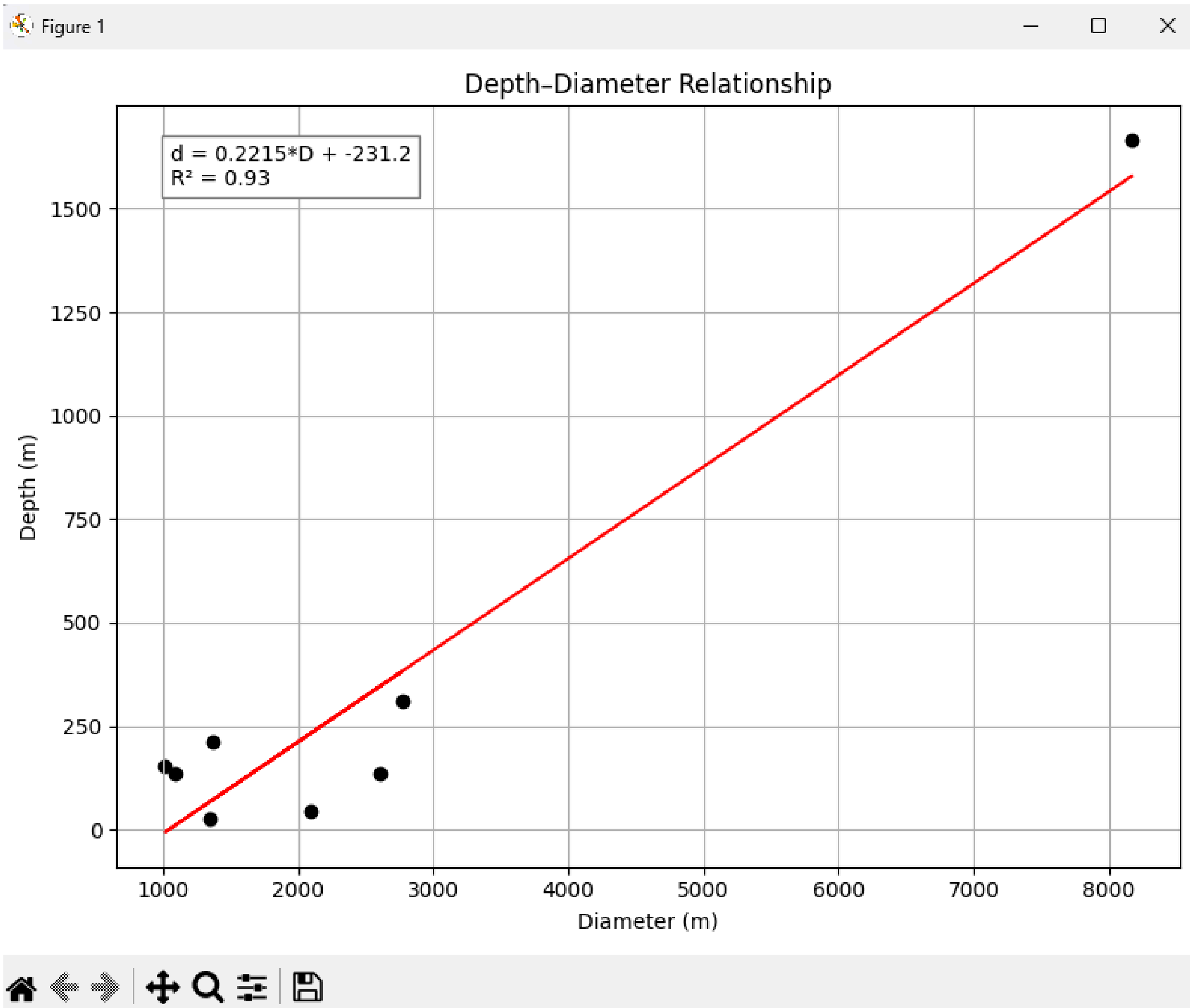
- **Diameter (D):** The diameter was estimated based on the previously delineated rim crest boundary. For relatively circular craters, this could be the diameter of a best-fit circle or an average of multiple profile measurements across the rim. A common method involves defining one or more centerlines or profiles across the crater, passing through the approximate center, and measuring the distance between the highest points on the rim along these lines. The average or representative value was taken as D.
- **Depth (d):** The depth was calculated relative to the rim height. Using topographic profiles extracted from the individual crater DTMs, the depth was determined by subtracting the elevation of the lowest point on the crater floor from the average elevation of the rim crest along the same profile(s) used for diameter measurement.

These measurements provide the basic scale and vertical relief information for each crater.



4.2 Calculating Depth-to-Diameter (D/d) Ratio

Once diameter (D) and depth (d) were determined for a crater, the D/d ratio was calculated simply by dividing the depth (d) by the diameter (D). This dimensionless ratio provides a normalized measure of crater cavity shape.

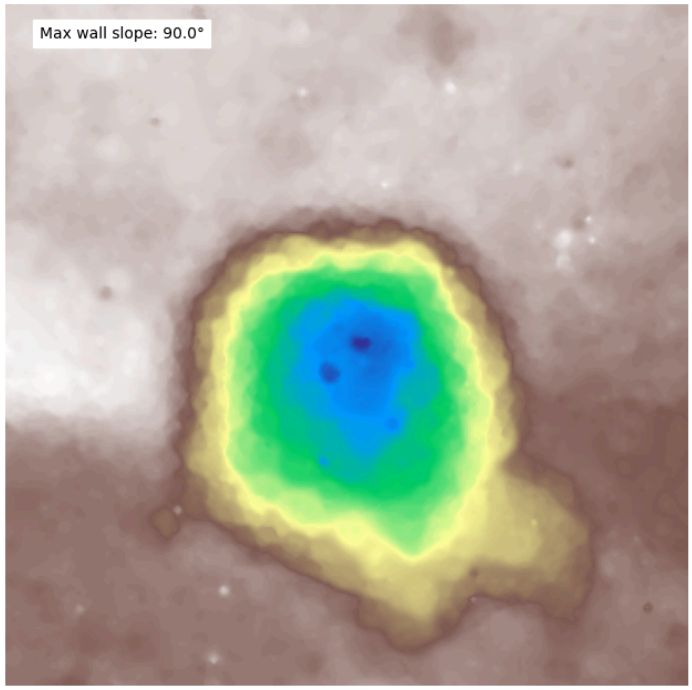


4.3 Calculating Maximum Slope Along the Wall

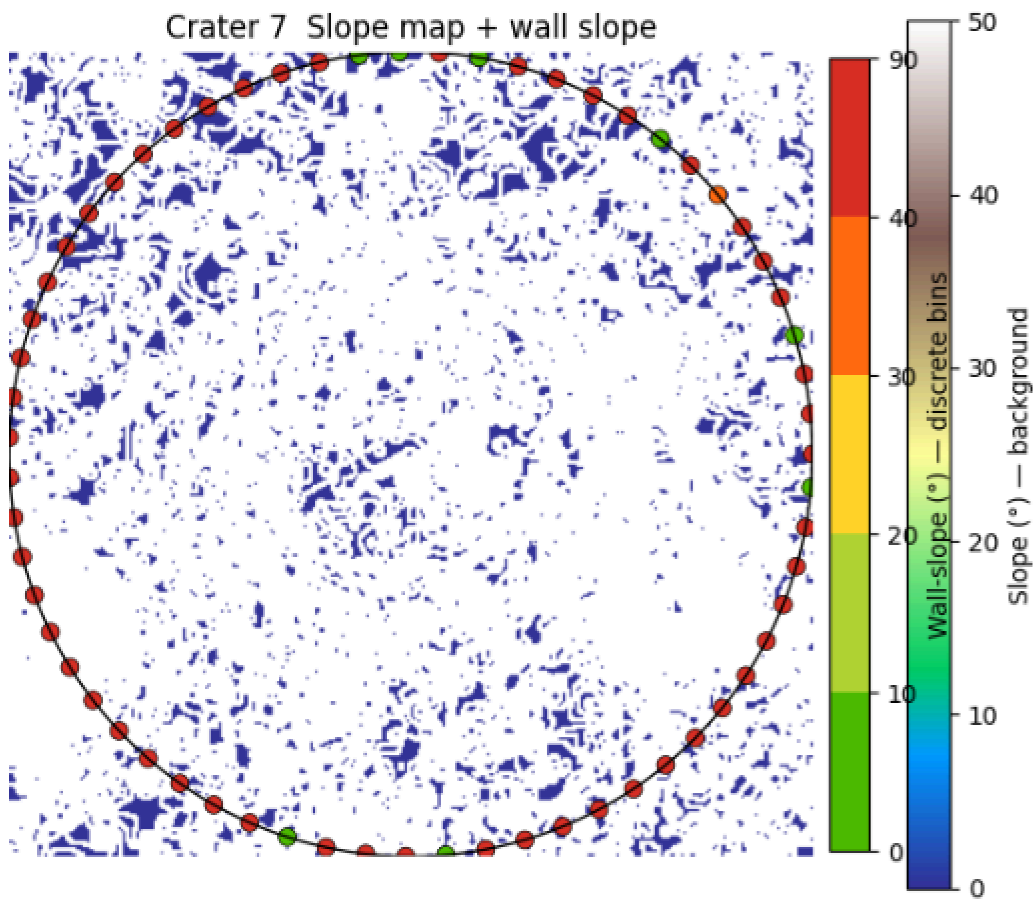
The maximum slope along the interior wall of each crater was calculated using the following steps:

1. **Slope Map Generation:** For each isolated crater DTM, a corresponding slope map was generated using python. This tool calculates the rate of elevation change for each cell in the DTM, typically outputting values in degrees or percent slope.

Crater 2 - Wall Slope Analysis



2. **Wall Region Definition:** The "wall" region of the crater needed to be defined to restrict the slope analysis to this area. This was achieved by identifying the area between the delineated rim crest boundary and the approximate boundary of the crater floor (which could be defined by a break in slope at the base of the wall or as the relatively flat central area). This effectively created a mask or zone representing the interior slopes.
3. **Maximum Slope Extraction:** The slope values from the generated slope map were extracted specifically within the defined wall region mask. The maximum value among these extracted slope pixels was identified and recorded as the maximum wall slope for that crater. This focus on the maximum value, as per the Agarwal et al. rationale, aims to capture the steepest segments of the wall, potentially indicative of structural integrity or localized degradation features.



4.4 Calculating Topographic Roughness Index (TRI) Near the Rim

The Topographic Roughness Index (TRI) in our Python workflow was computed directly from each isolated-crater DTM without any GIS buffering, by using a small local neighborhood to capture the elevation variability around the rim. In practice we did the following for each crater:

1. **Neighborhood smoothing (mean filter)**
   We applied a 2×2 uniform (mean) filter to the raw DTM array via SciPy's `uniform_filter`. This produces a locally-averaged elevation map (MeanDTM), which removes very small-scale noise but preserves the broader rim and wall slopes.

2. **Local range calculation (range filter)**
   In parallel we computed two 2×2 filters: a local maximum and a local minimum of the DTM (using `maximum_filter` and `minimum_filter`). Their difference (MaxDTM−MinDTM) yields a "range image" that measures the full span of

elevation values in each 2×2 neighborhood. This highlights where the terrain is most variable—i.e. where rim crests and wall discontinuities occur.

3. **Normalized roughness index (TRI)**
   For each pixel, we then formed

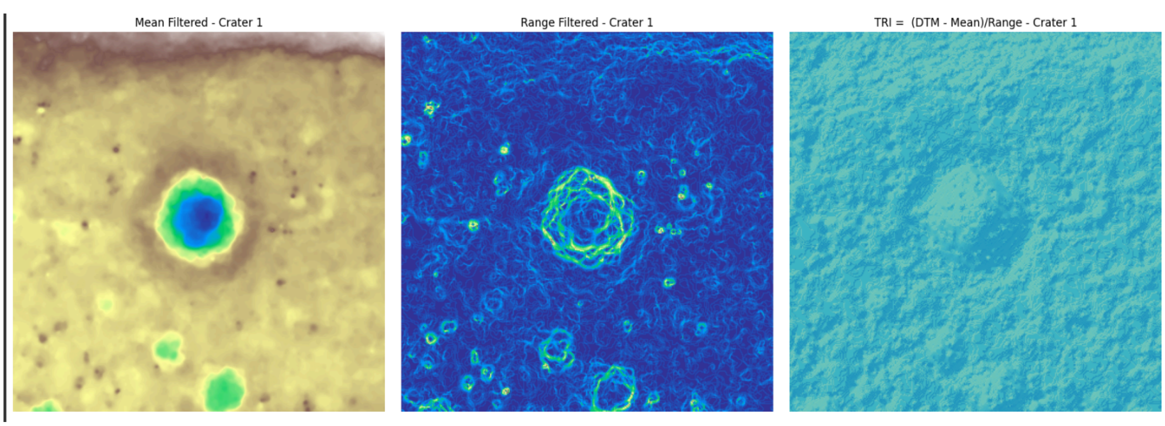
$$\mathrm{TRI} = \frac{\mathrm{DTM} - \mathrm{MeanDTM}}{\mathrm{RangeDTM} + \varepsilon}$$

   where a tiny ε prevents division by zero. This normalization centers the index on zero and scales it by the local elevation span, so pixels on sharp crests or edges (the rim) stand out as strong negative or positive values.

4. **Visualization and rim extraction**

   We display the MeanDTM, RangeDTM and TRI side-by-side to verify the filter behavior. In the TRI image, the crater rim appears as a coherent contour of high contrast. A single-level contour (e.g. TRI = –1.0) or a binary threshold (TRI < –1.0) can then be used to trace the rim edge precisely.

By implementing mean and range filters in Python—rather than buffering in GIS—we obtain a fully reproducible, per-pixel TRI map that automatically emphasizes the rim's roughness for all seven detected craters.



5. Results and Conclusions

5.1 Presentation of Morphometric Data

The primary quantitative outputs of the analysis are the calculated morphometric parameters for each of the approximately 7 craters studied.

5.2 Summary of Project

This project focused on the morphometric analysis of lunar impact craters using a Digital Terrain Model derived from the Chandrayaan-2 Terrain Mapping Camera-2, extending the original study by Agarwal, Haridas, and Khanna (2019), which used Chandrayaan-1 DEMs. We first implemented automated crater detection in Python—applying Canny edge and Hough circle methods on the ortho images, attempting catalog look-ups, then generating elevation-based contours—identifying seven reliable craters (plus one non-crater test area). QGIS (open-source) was used only to crop each detected crater from the full DTM. For each isolated crater, we calculated the same key parameters as the original work—Depth-to-Diameter (D/d) ratio, maximum wall slope, and Topographic Roughness Index (TRI) near the rim crest—using Python filters to reproduce the visualizations and maps presented in the initial study. End-to-end Python workflows generated mean/range/normalized TRI plots and rim contours that closely match the original ArcGIS-based figures.

5.3 Concluding Remarks

The project successfully demonstrated the feasibility of implementing a workflow to extract specific, advanced morphometric parameters from high-resolution lunar DTM data. It highlighted the process of identifying craters, isolating their topographic data, and applying GIS-based calculations to quantify shape characteristics like relative depth, maximum steepness, and rim texture. While definitive conclusions about crater degradation require further analysis and classification beyond the scope of this work, the generated quantitative data provides a foundation for such investigations and showcases the utility of Chandrayaan-2 TMC data for detailed lunar surface studies.

5.4 Future Directions

Several avenues exist for extending or improving upon this project:

- **Expand Sample Size:** Analyze a significantly larger number of craters, potentially spanning multiple DTM tiles or different geological regions of the Moon, to obtain statistically more robust results and assess regional variations.

- **Automate Crater Detection/Delineation:** Incorporate automated crater detection algorithms to identify craters and potentially automate the rim delineation process, reducing subjectivity and enabling analysis of much larger datasets.
- **Implement Degradation Classification:** Attempt to classify the analyzed craters into degradation categories (e.g., fresh, moderately degraded, degraded) based on the calculated parameters (D/d, max slope, TRI) and potentially visual assessment, following classification schemes like those used by Agarwal et al. or others. This would allow for a direct test of the parameters' effectiveness in distinguishing degradation states.
- **Comparative Analysis:** Compare the results obtained from Chandrayaan-1 TMC DTMs with those derived from other high-resolution datasets, such as DTMs from the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC), to assess consistency and potential instrument/data source effects.
- **Explore Additional Parameters:** Investigate other morphometric parameters discussed in the literature (e.g., circularity index, floor diameter, volume, parameters related to ejecta blankets) to potentially gain further insights into crater morphology and degradation.
- **Sensitivity Analysis:** Conduct a sensitivity analysis to understand how the calculated parameters (especially TRI and max slope) vary with different methodological choices, such as the size of the TRI calculation window, the width of the near-rim buffer, or the specific algorithm used for slope calculation.