

# Automated astronaut traverses with minimum metabolic workload: Accessing permanently shadowed regions near the lunar south pole

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## ABSTRACT

The Artemis exploration zone is a topographically complex impact-cratered terrain. Steep undulating slopes pose a challenge for walking extravehicular activities (EVAs) anticipated for the Artemis III and subsequent missions. Using 5 m/pixel Lunar Orbiter Laser Altimeter (LOLA) measurements of the surface, an automated Python pipeline was developed to calculate traverse paths that minimize metabolic workload. The tool combines a Monte Carlo method with a minimum-cost path algorithm that assesses cumulative slope over distances between a lander and stations, as well as between stations. To illustrate the functionality of the tool, optimized paths to permanently shadowed regions (PSRs) are calculated around potential landing sites 001, nearby location 001(6), and 004, all within the Artemis III 'Connecting Ridge' candidate landing region. We identified 521 PSRs and computed (1) traverse paths to accessible PSRs within 2 km of the landing sites, and (2) optimized descents from host crater rims into each PSR. Slopes are limited to 15° and previously identified boulders are avoided. Surface temperature, astronaut body illumination, regolith bearing capacity, and astronaut-to-lander direct view are simultaneously evaluated. Travel times are estimated using Apollo 12 and 14 walking EVA data. A total of 20 and 19 PSRs are accessible from sites 001 and 001(6), respectively, four of which maintain slopes <10°. Site 004 provides access to 11 PSRs, albeit with higher EVA workloads. From the crater rims, 94 % of PSRs can be accessed. All round-trip traverses from potential landing sites can be performed in under 2 h with a constant walk. Traverses and descents to PSRs are compiled in an atlas to support Artemis mission planning.

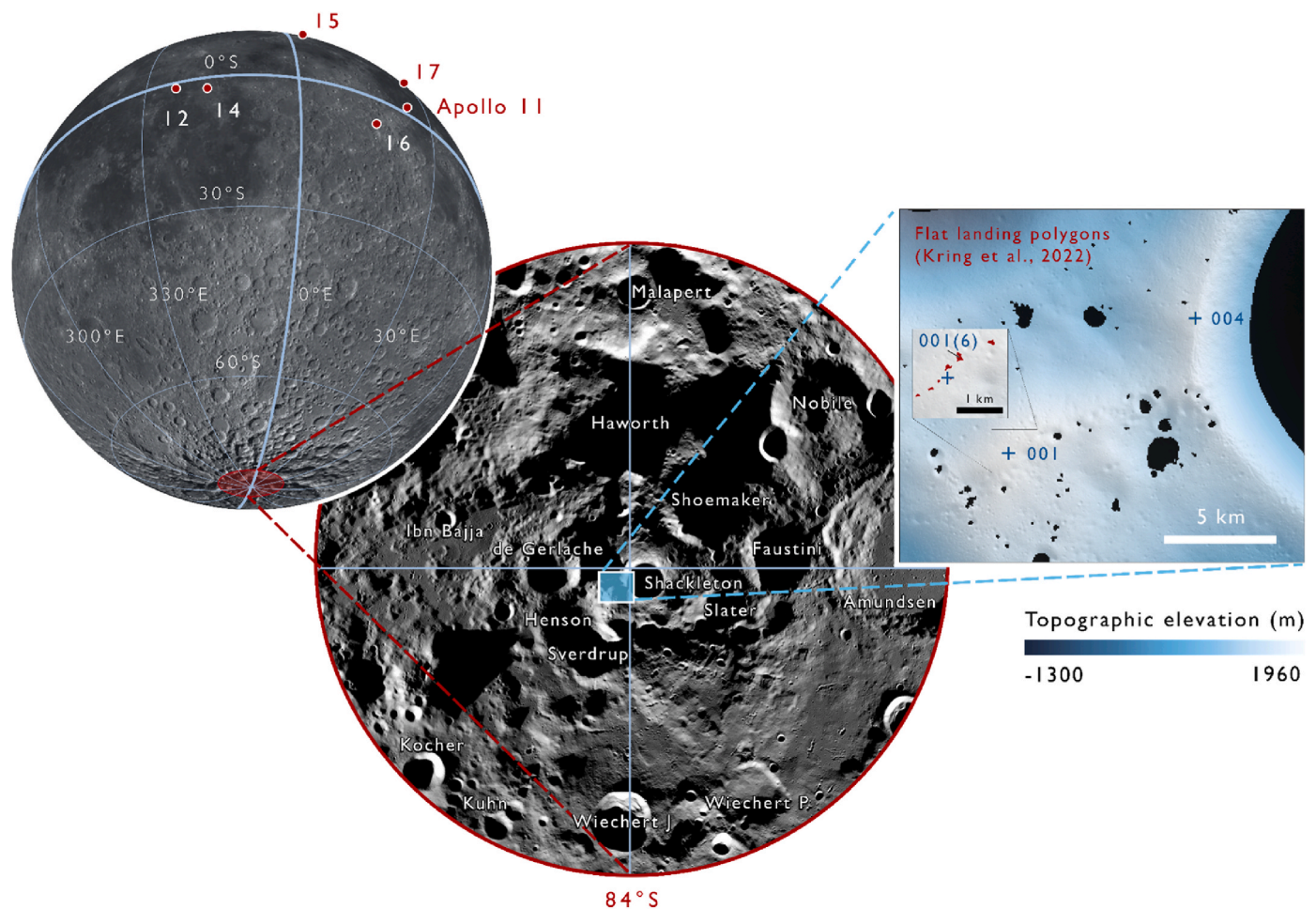
## 1. Introduction

The initial Artemis exploration zone (AEZ) is a region within six degrees latitude of the lunar south pole (Fig. 1). The Sun circumnavigates this region near the horizon, providing near-constant illumination to the highest summits [1–3]. Several of these locations were identified as potential Artemis landing sites [4], in part because solar power can be used to support a sustainable presence.

As the Sun is within a few degrees of the horizon, the topography of the impact-cratered terrain casts long shadows. Some areas are

permanently shadowed regions (PSRs). As noted decades ago [6], these regions are very cold (<120 K) and may trap volatile material like water ice. Such areas could provide another resource for sustained development of the lunar surface; water can be used for crew consumables, radiation shielding, and rocket propellant. Captured volatiles also offer important information about the origin, delivery, and evolution of volatile substances in the Earth-Moon system. In a study commissioned by NASA, the National Research Council (2007) [7] recommended investigations for future crewed and robotic missions to (a) determine the compositional state and distribution of the lunar volatile component, (b)

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**Fig. 1.** Upper left: past crewed surface missions were limited to equatorial latitudes. Middle: Principal craters within the AEZ; the blue rectangle straddling Shackleton crater delineates the considered region of interest. Upper right: topography overlaid on LOLA hillshade (5 m/pixel); black polygons indicate a LOLA illumination data-derived PSR product of four pixels or more (60 m/pixel) [2], while inset red polygons are landing zones that meet Artemis III Human Landing System slope requirements [5]. Data credits: NASA/LROC/GSFC/ASU. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

determine the sources of lunar polar volatiles, (c) understand the transport, retention, alteration, and loss processes experienced by volatile materials in lunar PSRs, (d) understand the physical properties of the extremely cold polar regolith, and (e) determine what the cold polar regolith reveals about the ancient solar environment. These targets are incorporated in the Artemis III science objectives as a series of Goal 2 investigations [4].

Those PSRs, and all proposed Artemis III candidate landing regions, occur within a feldspathic highland terrain that provides opportunities to address many other NRC (2007) exploration science objectives, i.e., to evaluate the bombardment history of the inner solar system; to sample a diverse suite of lunar crustal rocks; to study impact processes; and to study regolith processes [7].

A key to mission success will be accessing promising stations identified in pre-mission mapping. Owing to locally heterogeneous slopes, large elevation changes, and low illumination, extravehicular activities (EVAs) may be challenging. Automating the initial assessment of a large number of potential targets can benefit the planning of these traverses. To filter the abundance of opportunities and more efficiently design routes, we developed a computational mapping tool for calculating traverse paths that minimizes the metabolic workload on crew. We demonstrate its utility by applying to the Artemis III candidate landing region ‘Connecting Ridge’ and potential landing sites therein.

Potential landing site 001 is along the ridge between Shackleton and Henson craters [2,4]. In the vicinity of site 001, seven polygons were

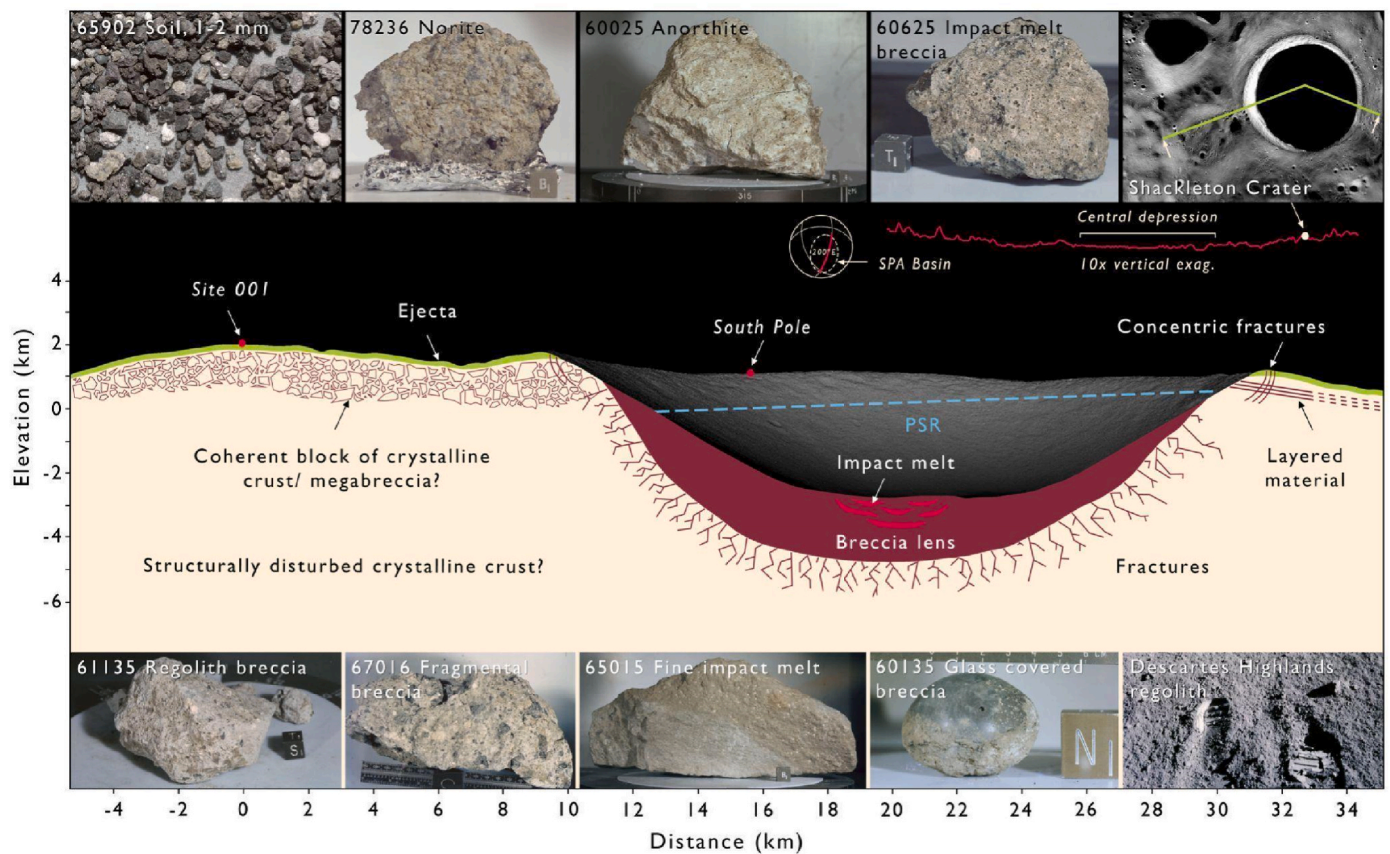
identified as suitable for the Artemis III Human Landing System’s (HLS) requirements for a surface with a slope  $<8^\circ$ , that are at least 100 m from steeper slopes [5]. Among those seven areas, the largest is designated 001(6). Site 004 is on the rim of Shackleton crater. Sites 001, 001(6), and 004 are used here to define a region of interest (ROI)  $18.5 \times 16.2$  km ( $\sim 300$  km<sup>2</sup>) (Fig. 1).

That ROI contains several types of geologic targets [8–12] that astronauts can explore to illuminate the history of the Moon, its neighbor Earth, and the inner Solar System, while also evaluating the distribution of icy resources [4,7]. To illustrate the application of our EVA planning tool we focus on PSR targets, first mapping PSR locations within the region and then applying the tool to calculate EVA routes that minimize metabolic workload. While we demonstrate how the tool can be used to optimize astronaut traverses to PSRs, it can be applied to any other geologic and exploration targets.

## 2. Geologic context

The lunar south polar region is an impact-cratered surface superimposed on the rim of the Moon’s largest impact basin, the South Pole-Aitken (SPA) basin [13]. The SPA basin-forming event, estimated at 4.25 to 4.39 Ga [14–16], generated a series of massifs along its margin, some of which have such high unobstructed elevations  $>1800$  m that they are exposed to sunlight up to  $\sim 85\%$  of the time [1–3,17]. Although primarily feldspathic highland terrain, redistributed material excavated





**Fig. 2.** Interpreted cross-section of the 'Connecting Ridge' (center left) and Shackleton crater. Shackleton impact ejecta blankets the ridge. Drawing upon the Apollo 16 landing site, which also occurred in a feldspathic terrain, one infers a series of lithologies (pictured) might be found in proximity to the 'Connecting Ridge'. Elevation and distances extracted from LOLA and NAC data. Photographs courtesy of LPI Lunar Sample Atlas and Washington University in St. Louis; section developed from Ref. [11]; SPA basin profile from Ref. [25].

from depths of 100 km during the impact [18] may also include contributions from the entire crustal column of anorthosite, troctolite, norite, and gabbro, plus upper mantle lithologies [19,20].

A series of pre-Nectarian (e.g., Haworth,  $4.18 \pm 0.02$  Ga; Shoemaker,  $4.15 \pm 0.02$  Ga; Faustini,  $4.10 \pm 0.03$  Ga), Nectarian (e.g., de Gerlache,  $3.9 \pm 0.1$  Ga), and Imbrian (e.g., Slater,  $3.8 \pm 0.1$  Ga; Sverdrup,  $3.8 \pm 0.1$  Ga) age impact craters [21,22] further reworked those lithological components.

Shackleton crater was the last major impact shaping the region. It has an estimated age of  $3.43^{+0.04}_{-0.05}$  Ga from crater counting [23]. This  $\sim 21$  km diameter by  $\sim 4.1$  km deep feature excavated two lithological units: a massif composed, in part, of anorthosite, overlain by at least one stratified unit exposed on the crater wall that likely represents successive ejecta blankets [11].

The Artemis III 'Connecting Ridge' candidate landing area is blanketed by Shackleton impact ejecta that may be  $\sim 150$  m thick on the rim [10], thinning with distance along the ridge (Fig. 2). Orbital spectroscopy at a spatial resolution of 1 km/pixel indicates the region is dominated by plagioclase [11], with the lowest FeO values ( $\sim 8$ – $16$  wt%) in the AEZ found in the area around Shackleton crater (including sites 001 and 004) [11,24]. These FeO values are consistent with small amounts of mafic minerals that are normally co-mingled with anorthosite but may also represent a contribution from SPA impact melt in the regolith covering the ridge.

Because the terrain encompassed by the AEZ is similar to, albeit much older than, the feldspathic material of the Apollo 16 site, we infer astronauts may traverse (and collect) a surface composed of anorthositic regolith breccias, fragmental breccias, impact melt breccias, and soils (Fig. 2), dotted with a large number of boulders [8]. Obscured

lithologies within the PSR are assumed from a standard model of crater formation and simulation efforts [10,26–29]. The chemical and isotopic compositions of crustal lithologies exposed near the lunar south pole (e.g., anorthosite, norite, troctolite) may contribute to further developing the lunar magma ocean hypothesis [7], and their diversity could help illuminate the evolution of the lunar crust far from the Apollo sites. Impact melts along the ridge could span the range from that of the SPA basin to Shackleton impact events, providing an opportunity to better constrain the age of the oldest basin-forming impact on the Moon, to test the lunar cataclysm hypothesis, and assess the orbitally-determined age of Shackleton to help calibrate lunar crater chronology.

Those cratering processes produced the irregular surface of the AEZ, including depressions that host PSRs. Over geologic time, water and other volatiles transported to the poles may have been trapped in PSRs. The largest deposits of water ice could have been delivered by the oldest crater-forming events and incorporated within their ejecta blankets, then buried by subsequent ejecta [30,31]. Smaller PSRs accessible via walking EVAs will have been produced by younger ( $<100$  million years old) cratering processes. Any ices within those PSRs will likely be dominated by volatiles delivered by solar wind and impacting micrometeorites.

### 3. Data and methods

#### 3.1. Path-finder algorithm

Route design for EVAs has typically been completed manually by geology experts. Owing to recent lunar orbital missions, topographic data is now available at high resolution (up to 5 m/pixel) for elevation

and slope. This accuracy allows the implementation of minimum-cost calculation algorithms to obtain optimized traverses that reduce both distance traveled and the risk from high slopes. Particularly in the context of rover routing design, several efforts have been made to develop algorithms that find the optimal path between two points on a map. Graph theory offers a solution to find the shortest path between nodes in a network, which, for practical purposes, is defined as the raster pixels that comprise a map. We briefly review the main alternatives and highlight the relative strengths of the adopted Dijkstra solution.

The method developed by Ref. [32] incorporates human intervention to fine-tune the path and ensure compliance with mission rules, where small adjustments could have led to improved traverses, such as avoiding violations of the metabolic cost constraint and enhancing visibility and sun score. They note that estimating a low-energy direction of travel mode is possible through the use of the directional height-height correlation function [33]. However, this approach does not explicitly search for the minimum-cost path between two points by evaluating all possibilities in an efficient manner like Dijkstra's algorithm [34].

When planning in high-dimensional and dynamic environments, stochastic algorithms are commonly used. One such approach is random sampling-based planners, such as probabilistic roadmaps (PRMs) [35] and rapidly-exploring random trees (RRTs) [36], which work by sampling a probabilistic graph to find a path to the goal [37]. developed a variant of RRTs, known as RRT\*, that finds asymptotically optimal paths by updating edge connections. However, sampling-based planners can generate poor paths if many suboptimal or undesirable states are sampled, especially when computation is limited. RRTs build a tree structure by randomly sampling points in the search space and connecting them to the nearest point in the tree. They are probabilistically complete, meaning a solution will eventually be found if one exists, but there is no guarantee that it will be optimal. In contrast, Dijkstra's algorithm is a complete algorithm: it is guaranteed to find the shortest path between two points if one exists, although this can be computationally expensive when applied to high-dimensional or complex environments.

Using a heuristic, the graph path search algorithm A\* [37–39] finds a specific start location to the goal in a similar way to Dijkstra's algorithm. However, A\* requires more memory space, as it stores all generated nodes and depends on the quality of the heuristic function, which can affect its performance and optimality.

Field D\* [40] is a variant of D\*, an informed incremental search algorithm [41] that uses linear interpolation to generate smoother paths in non-uniform cost environments. Field D\* is incremental, such that it can reuse previous calculations when the environment changes, whereas Dijkstra's algorithm has to recompute everything from scratch. As we did not consider a dynamic environment, nor real-time updating of obstacles or changes in topography, we did not implement D\* family algorithms.

For simplicity, and because EVAs during Artemis III will be limited to  $6 \pm 2$  h [42], we have considered a fixed temporal lighting condition for a given date, as opposed to other energy budget-aware approaches [3, 43–45].

Considering these different approaches and techniques, we selected Dijkstra's algorithm as the proper solution for computing traverses that minimize the metabolic workload for a specified illumination condition. We establish our criterion for minimum metabolic workload based on the assumption that the traverses will be utilized for round trips, with each EVA involving visiting a single target. Therefore, our priority is to identify paths that strike a balance between minimizing the accumulated absolute slope and achieving the shortest distance possible. By prioritizing both flat terrains and shorter routes, we aim to optimize efficiency while reducing the physical exertion required during the traverses.

We developed a Python pipeline called *MoonPath* that, given a starting point, a maximum slope, and a distance threshold, automatically computes all optimized traverses to nearby accessible PSRs. At the

same time, it also evaluates bearing capacity, temperature, astronaut sunlight incidence (for a given date), traverse walking time, and astronaut-to-lander view opportunity.

### 3.2. Processing pipeline

The data processing pipeline requires a series of baseline data products, which we developed using primary and secondary Lunar Reconnaissance Orbiter (LRO) data products. The topography of the region is assembled using an enhanced 5 m/pixel LOLA data product [46] derived from LOLA Digital Elevation Counts (LDEC), a LOLA Digital Elevation Model (LDEM), and a LOLA Digital Slope Model (LDSM). The published geolocation uncertainty is  $\sim 10$ – $20$  cm horizontally and  $\sim 2$ – $4$  cm vertically for each pixel. Note, however, that  $\sim 90$  % of the 5 m/pixels are interpolated, i.e., do not contain physically measured data.

For visual inspection of the region and to obtain detailed images of the PSRs, we use a 1 m/pixel mosaic of the south polar region [47] which was generated from the 0.5 m/pixel Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) data [48], orthorectified using a 5 m/pixel DEM and registered horizontally to the LOLA global DEM [49]. An assemblage of NAC images downloaded and calibrated using Integrated Software for Imagers and Spectrometers (ISIS) was also mosaiced to create base maps. The data was georeferenced and mosaiced using ENVI and ArcGIS 10.6 software [50].

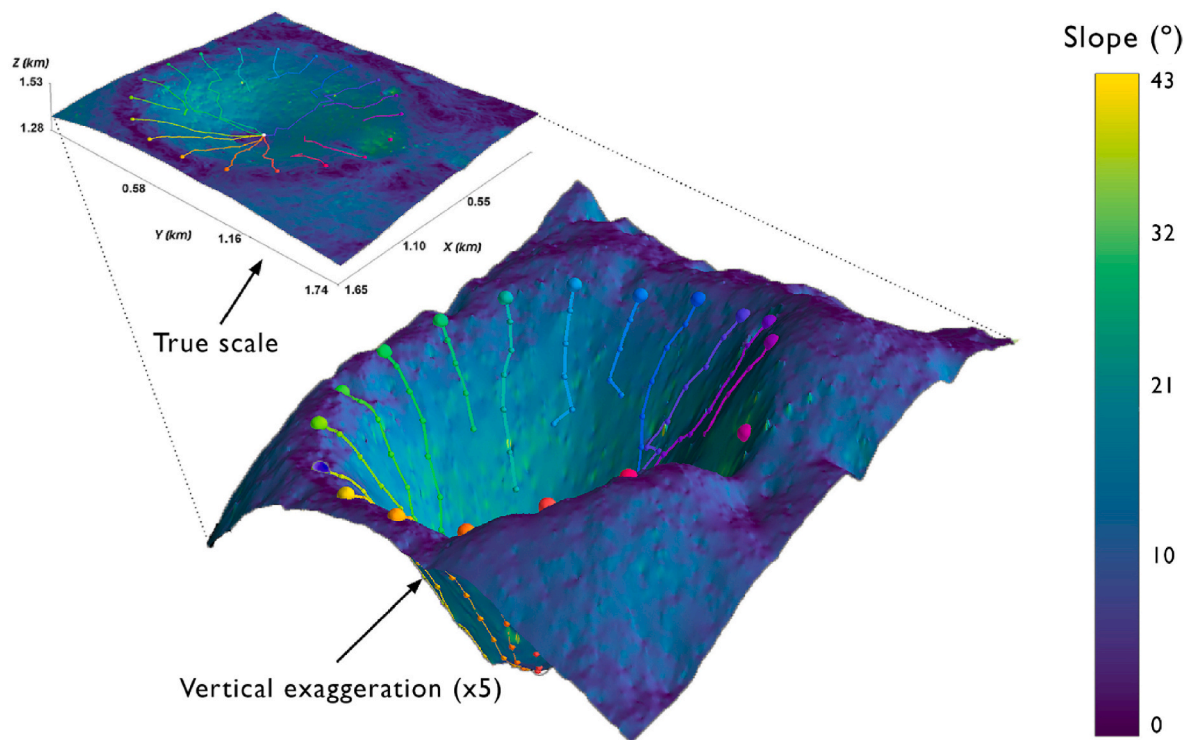
To determine the mean bolometric brightness temperatures,  $\sim 10$  years of nadir-pointing Diviner Radiometer Experiment observations were compiled [51] from 7 IR channels over a wavelength range of  $7.55 \mu\text{m}$ – $400 \mu\text{m}$ . For the present study, we use the Level 4 gridded 240 m/pixel Polar Cumulative Products described in Ref. [52], focused on the southern summer season as indicative of minimum PSR extent and for more favorable exploration conditions at high latitude.

A bearing capacity map with 5 m/pixel resolution was produced following [53] and a variation of Hansen's formula. Because an analysis of Apollo and Lunokhod data recommended bearing capacities of  $>7 \text{ kNm}^{-2}$  [54], calculated traverses are subsequently restricted to those surfaces.

An analysis of Apollo walking EVA speeds [55] was expanded with a new non-linear analysis using transcripts of Apollo 12 (EVA 2) and Apollo 14 (EVA 2) traverses [56]. Of these two missions, the latter covered terrain more akin to upcoming surfaces and astronauts also hauled a Modular Equipment Transporter (MET), analogous to the tool cart/carrier being designed for Artemis III.

The locations of PSRs were mapped by applying a process similar to that of [2], who use 240 m/pixel LOLA data, albeit with the 5 m/pixel LOLA equivalent and the simplification of not considering backscattered (secondary or reflected) illumination. The process is also comparable to that of [1,57], though we do not consider the length of time of illumination nor ray tracing, respectively. Candidate PSRs were generated using the ArcGIS 'Hillshade' function on the 5 m/pixel LDEM product. The simulated Sun was varied around  $360^\circ$  azimuth in  $0.5^\circ$  increments at a maximum elevation of  $2^\circ$  above the horizon, a suitable average for our region as deduced using NASA JPL's Moon Trek Sun Angle and JPL Horizons [58,59]. The resultant illumination map was thresholded and filtered for areas of zero illumination. We then applied four filters. First, two automated methods: (1) removing small noisy PSRs  $<3$  pixels in size, and (2) removing small poorly defined PSRs with  $<3$  LOLA LDEC points inside them. The remaining PSRs were manually inspected and (3) compared with the 1 m/pixel NAC image mosaic, removing candidates within illuminated regions, or (4) removed if, when plotting traverses, local sun ephemeris for PSRs indicated illumination in their centers (as we generate the PSRs with a fixed Sun elevation value, which could return incorrect results where this elevation increases). Additionally, we also mapped PSRs up to  $5^\circ$  solar elevation as this limit is more enduring in terms of potential accumulation of trapped volatiles, with possibility for greater volumes, or perhaps different characteristics. On geological timescales, the axial tilt of the Moon — and hence solar





**Fig. 3.** Illustration of the Monte Carlo technique applied to compute the optimal descent from the rim to the center of the PSR. The mesh 3D model is a 5 m/pixel slope map overlying a 5 m/pixel LOLA DEM. Randomly generated starting points are shown as large dots on the crater edge. Colored traverses are used only to distinguish different paths. The larger mesh has 5x vertical exaggeration.

illumination at the poles — may have shifted significantly after the Cassini State Transition 2.5 Ga [60–62].

The 5 m/pixel LDEM used in our study presents inherent limitations, with approximately 90 % of its raster pixels being interpolated, lacking original topographic height measurements [46]. To mitigate the impact of these limitations on the generated PSRs, we assessed the percentage area of the LDEC raster within each PSR containing non-interpolated elevation data points, ensuring a minimum coverage of 5 % for all PSRs. PSRs with less than 5 % coverage or fewer than 3 LDEC elevation data points were automatically excluded from the analysis. Additionally, we manually removed PSRs that conflicted with the NAC imagery, specifically targeting those situated in illuminated areas.

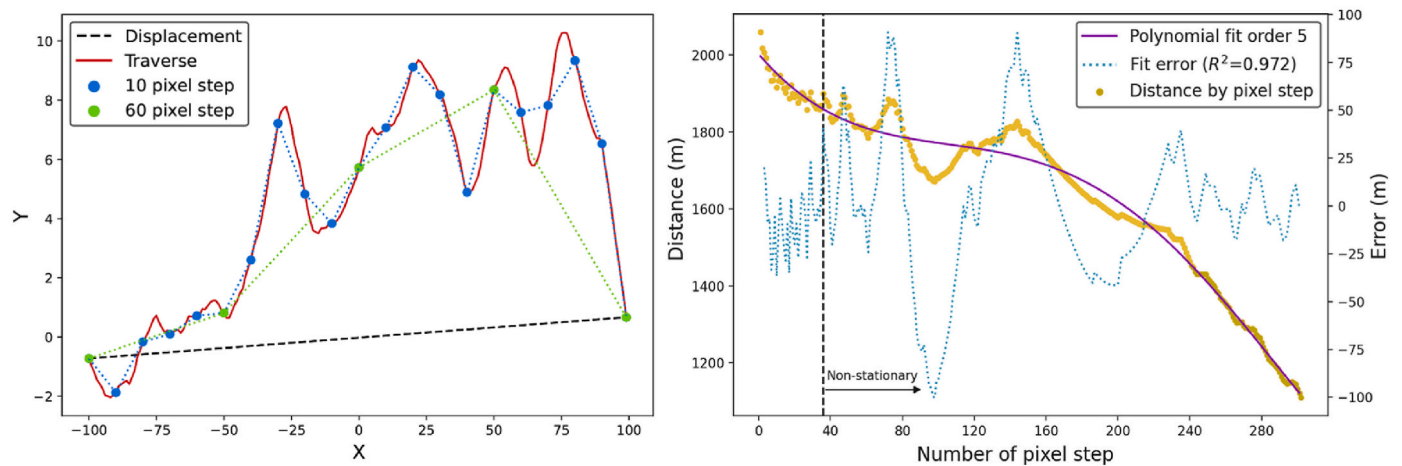
We used Dijkstra's algorithm, as justified, to produce a shortest-path tree from the starting point (landing site or crater rim) to the endpoint (PSR edge or center), allowing both lateral and diagonal movements between adjacent pixels [63,64]. The 5 m/pixel LDSM data is employed as a cost map, using cumulative slope as the optimization metric. The 'best' traverse is chosen by evaluating the lowest cumulative slope result. The algorithm intrinsically considers distance and height. By utilizing the LDSM raster as a cost map, the algorithm rewards shorter paths with lower slopes, as longer distances with lower slopes or shorter distances with higher slopes would result in a worse cumulative slope. Height is considered in the slope (as the cumulative slope is assessed), therefore a greater elevation change over a set distance implies a higher slope (worsening the cumulative slope result). Given that the graph is represented as an adjacency matrix, i.e., a regular and gapless structure, the algorithm effectively balances the trade-off between distance and elevation change, resulting in traverses that minimize the cumulative slope and, consequently, the metabolic workload.

Additionally, we included into our study the locations of isolated boulders identified by Ref. [8] in the vicinity of sites 001 and 004. These features were manually mapped using high-resolution NAC images at approximately 0.5–2 m resolution. The authors stated that they were able to identify objects that spanned at least 3 pixels, suggesting a

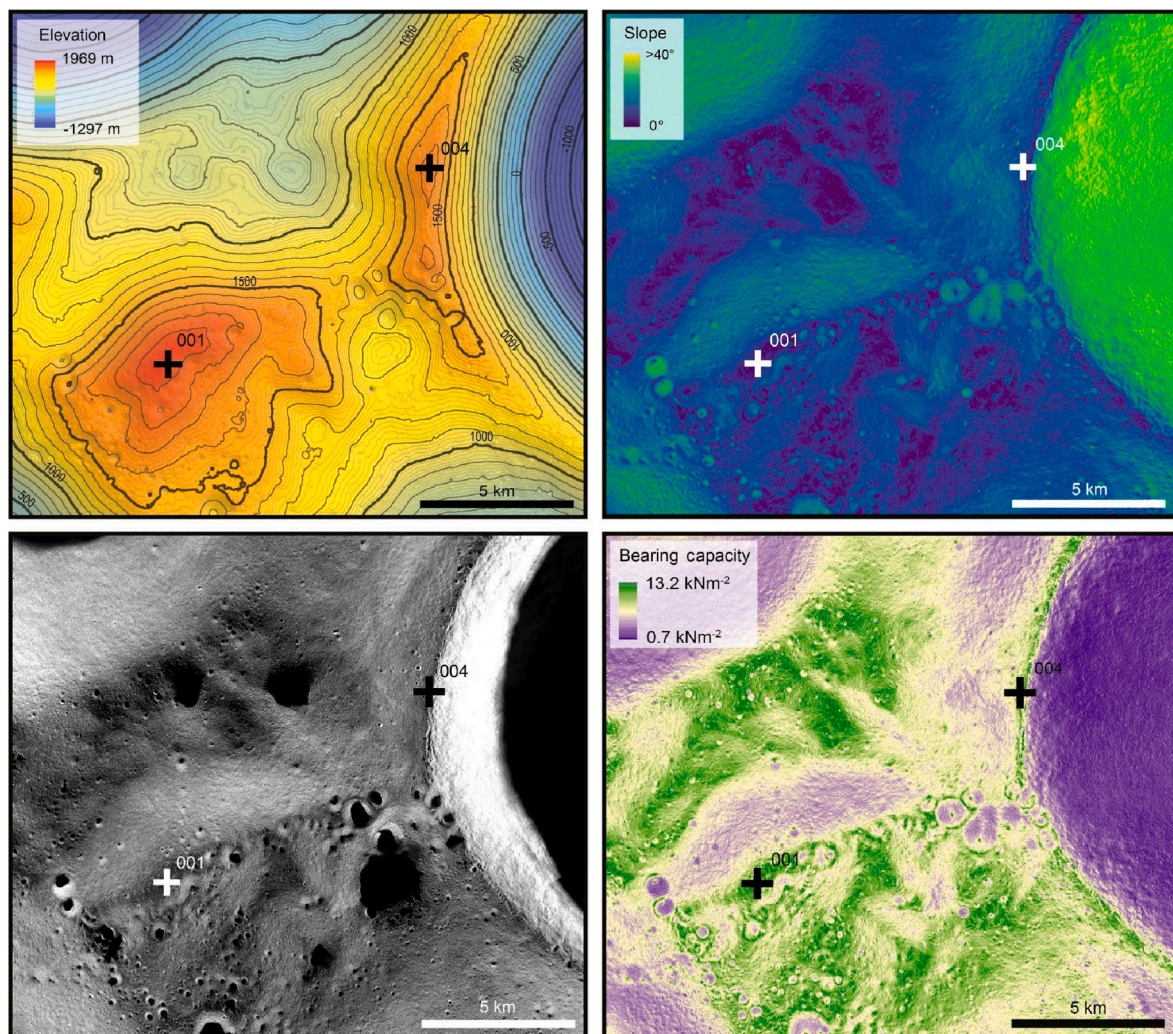
minimum size of 3 m for the mapped boulders. However, no specific information regarding the size of each boulder was collected. Additionally [11], identified within our ROI some of the largest boulders, which measured up to 30 m in diameter. Considering that these are expected to be less common, we adopted a representative size of 5 m for each boulder. By imposing a size of a pixel (i.e.,  $5 \times 5$  m) for the boulders in our analysis, we effectively constrain the potential traverses to avoid these geological features. This restriction is based on the understanding that traversing over or around boulders can pose challenges to astronaut mobility and may impede the efficiency of extravehicular activities.

We adopt thresholds for (1) encountered slopes being  $<15^\circ$ , which is conservative because  $20^\circ$  is considered a permissible limit, and (2) the farthest distance of any traverse point to the lunar lander being no more than 2 km [65]. To obtain a more natural path closer to how an astronaut would walk, we smoothed the slope map under  $5^\circ$  outside craters, meaning slopes  $<5^\circ$  are treated as the same value. For the interior of craters, we did not apply any smoothing. Slopes greater than  $15^\circ$  are not forbidden but highly penalized, as some traverses must pass through a few high slope pixels.

First, we calculated the optimal path from the landing site to each of the vertices outlining the edge of the PSR. In this way, we obtain the shortest traverse featuring the lowest cumulative slope to the edge of a PSR. We then calculated the optimal path from this edge point to the PSR center. In addition, we determined the best descent from any point on the crater rim to the hosted PSR regardless of the landing site for all PSRs in the ROI. This uses the same function described above with an additional step, as the optimal initial point of lowest-cost descent is not known beforehand. We performed a Monte Carlo simulation by generating equally spaced (20 m) random points on the perimeter of the crater to compute the optimized descent from each point. Subsequently, all cumulative slope results (for every rim starting point to every PSR edge) are compared to obtain the best descent. Fig. 3 illustrates the optimized descent computation process. Note that not all starting points have a viable path (truncated lines).

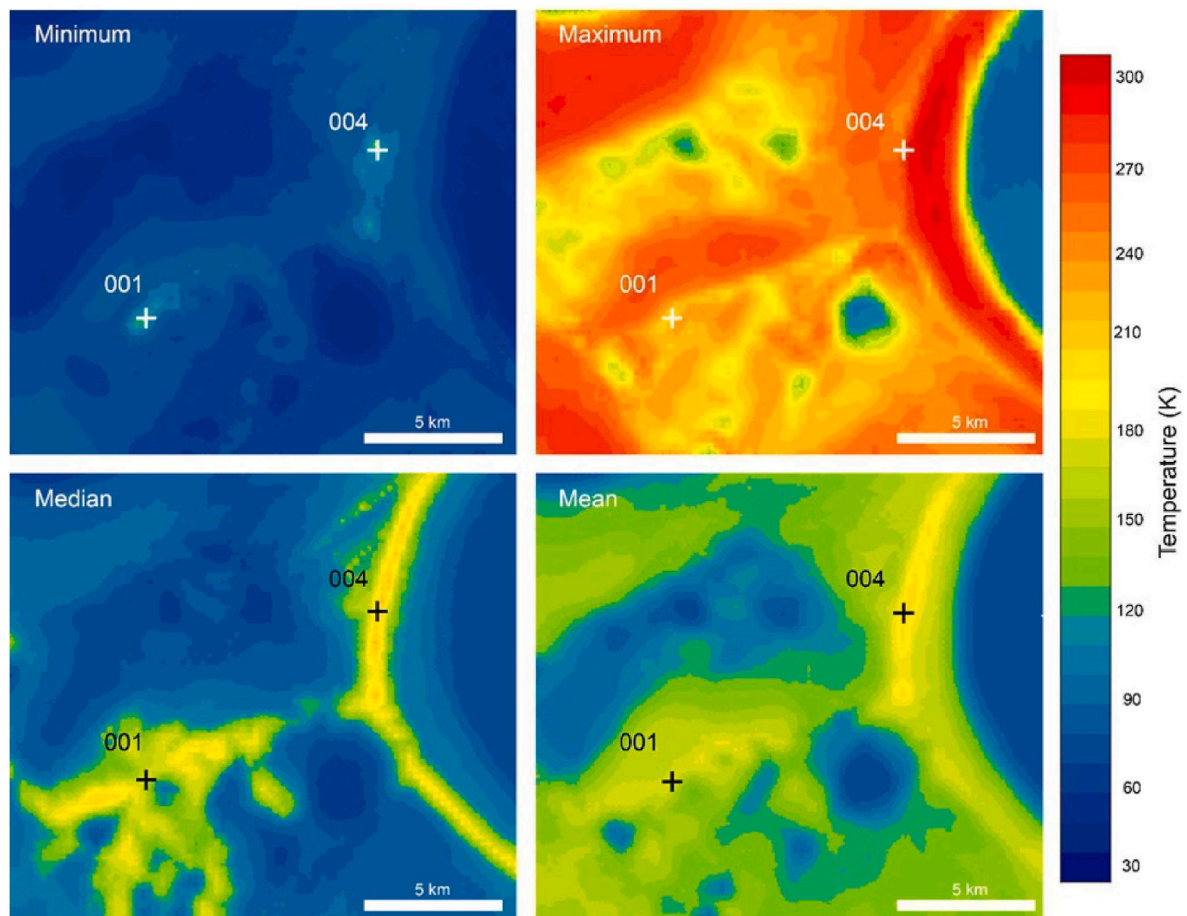


**Fig. 4.** Left: An illustrated example of the coastline paradox, where the distance between two points decreases with increasing pixel size. Blue and green lines show two different sample step sizes used for smoothing, with aliasing-like behavior for the poorly optimized step size. Right: Augmented Dickey-Fuller test applied to the polynomial fit deviation of the distance as a function of the pixel step. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 5.** Top-left: Elevation map (5 m/pixel) of the ROI with 20 m contours, with potential landing sites 001 and 004 (black crosses) both located in areas of high elevation. Top-right: Slope map generated from 5 m/pixel LDEM, with potential landing sites 001 and 004 both located on areas of low slope. Bottom-left: NAC imagery was mosaiced using maximum illumination of pixels. Black areas correlate with areas of poor illumination and/or permanent shadow. Bottom-right: Bearing capacity map generated using LDSM data.





**Fig. 6.** Temperature maps for the ROI generated using Level 4 gridded 240 m/pixel Polar Cumulative Products from Diviner, covering the lunar southern summer during a 10-year period. Potential landing sites 001 and 004 are labeled.

For the astronaut body sunlight incidence calculation (to which we will henceforth refer to as astronaut illumination, that is, the body area percentage that is illuminated by direct sunlight), we chose as a case study the month of maximum solar elevation (or subsolar latitude) for 2025 at landing site 001, i.e., the most favorable month in terms of general terrain illumination conditions. December is the month of 2025 when the Sun reaches its highest elevation ( $2.1^\circ$  on the 16th, for the ROI). In contrast, on 31 December the Sun elevation is  $0.8^\circ$ , representing the worst illumination condition for the most illuminated month of 2025). The position of the Sun is queried to JPL Horizons ephemerides [66]. We select these two days to evaluate the full range of traverse illumination properties.

We estimated when the analyzed illumination conditions will be repeated up to 2029, meaning the obtained results are also applicable to specific days in subsequent years. Illumination conditions on December 16, 2025 will occur again on November 6, 2026, October 26, 2027, and October 14, 2028, while the Sun position on December 31, 2025 will be the same on October 23, 2026, October 12, 2027, and September 1, 2028.

Given that low solar illumination angles cast long shadows, this type of calculation becomes significant to assess temperature variations an astronaut may be exposed to. To properly compute the percentage of an astronaut's body that would be illuminated, we developed a bespoke ray tracing code. Using ephemeris from JPL Horizons, we determined the local Sun position for every pixel and ray traced from each pixel to the Sun. Sunlight is projected onto the lunar surface to evaluate if the elevation of the terrain is higher than the ray. If the line of sight is intersected by topography, the ray is blocked, and the pixel does not receive direct sunlight from this direction. We repeated the process at

20 cm intervals up to a modeled astronaut height of 2 m to calculate the percentage of the astronaut's body in sunlight.

Analogous to the astronaut illumination calculation, we ray-traced the direct view of the Space X Artemis III HLS window (40 m high [67]) from the traverses. For each step we checked the percentage of an astronaut's body (again, from 0 m to 2 m, in 20 cm intervals) in visual contact with the lander. This feature could be of considerable assistance to guide astronauts during their EVAs in absence of geolocation systems, both for self-guiding and to receive directions from the HLS. However, it would be impossible to maintain eye contact if the Sun is directly behind the lander. We also address this Sun view orientation-related problem by computing the angular distance between the astronaut-to-lander line of sight and the Sun position. In this way,  $0^\circ$  means that the line of sight coincides head-on with the Sun and  $180^\circ$  indicates the Sun is directly behind the view.

Regarding distance computation, we emphasize a problem derived from the so-called coastline paradox. The calculated traverse for each PSR does not have a well-defined length, as distance calculations depend on the pixel size of the map, behaving in this way as a fractal dimension issue [68]: the larger the pixel size is on a map, the smaller the computed distance will be (Fig. 4 left). In addition, as the minimum-cost path algorithm is restricted to lateral and diagonal motion between adjacent pixels, this motion will differ from performed astronaut paths which are expected to be more direct and thus shorter. Smoothing is needed to account for restrictive pixel motions and to remove noisy variations inherent in the slope map that overestimate the expected path length. We smooth by sampling traverse pixels at an optimized step-spacing, which must compromise between small spacing (including noisy path motions) and large sample spacing (missing important path



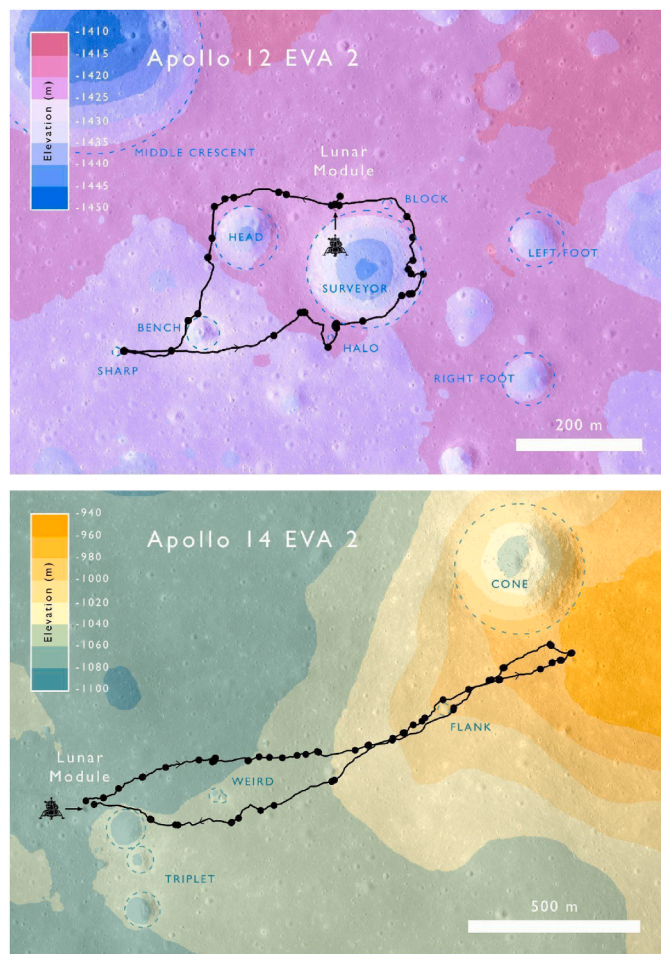


Fig. 7. Top: Apollo 12 EVA 2, with tie points (black dots) created by linking times acknowledged in official transcripts with geological observations and procedures completed on the surface. Bottom: Repeated for Apollo 14 EVA 2.

information). We searched for the largest pixel step before significant traverse features are overlooked, which produces notable variations in the distance with small changes. We estimated this sampling interval for smoothing to generate the minimum realistic distance by increasing the pixel size step until a non-stationary state is reached. An augmented Dickey-Fuller test [69] allows the stationary trend of the path to be analyzed with a confidence level of 99 %, evaluating the deviation of a polynomial fit with at least  $R^2 = 0.8$  (Fig. 4 right). A straight-line traverse will always result in the same computed distance regardless of the pixel size, whilst a meandering path will vary drastically at some pixel-smoothing steps based on the curve shapes.

## 4. Data products and results

### 4.1. Base maps

Fig. 5 displays the base maps derived from LOLA data elaborated in Section 3: 5 m/pixel elevation with 20 m contours, 5 m/pixel slope derived from LDEM, NAC mosaic, and bearing capacity generated using LDSM. Bearing capacity varies from  $\sim 0$  to  $13.2 \text{ kN/m}^2$ , in agreement with maps generated for the Shackleton-Hansen ridge region encompassing potential landing sites 001 and 004 [5].

From 240 m/pixel summer Diviner data (defined as where the subsolar latitude is in the Southern hemisphere at noon local time), we generated average, minimum, and maximum temperature maps, as well as local time maps to evaluate both the lowest PSR temperature and highest temperature encountered during a traverse. Over a 6-h EVA, for

instance, only 12 lunar minutes elapse (normalizing a lunar day of 29.53 Earth days to 24 h), so solar position relative to a fixed point is assumed constant over the duration of a traverse. Whereas seasonality has little influence on surface temperatures at low to mid-latitudes, the interplay of illumination grazing angles in polar regions with topography exerts a significant influence on surface temperature with the position of the subsolar latitude (Fig. 6).

### 4.2. Apollo traverse speed

By comparing maps of traced traverses to transcripts from Apollo 12 and 14 (both EVA 2) missions, way points were generated that link discrete times with spatial positions for a given astronaut (Figs. 7 and 8). Only way points separated by  $> 25 \text{ m}$  were used to ensure traverse speed calculations encompass periods that were predominantly walking, rather than those involving geological activities at stations or short bursts of speed between points of interest.

Apollo 12 (EVA 2) had regular stops, and averages contain the time for geological observations and photographs. Apollo 14 (EVA 2) was characterized by 12 stations for data collection separated by long walks. Data collected on astronaut walking speed provide operational times included in traverse models calculated for this ROI. Traverse coordinates and way points summaries for both Apollo EVAs can be found in the supplementary material (SP-A).

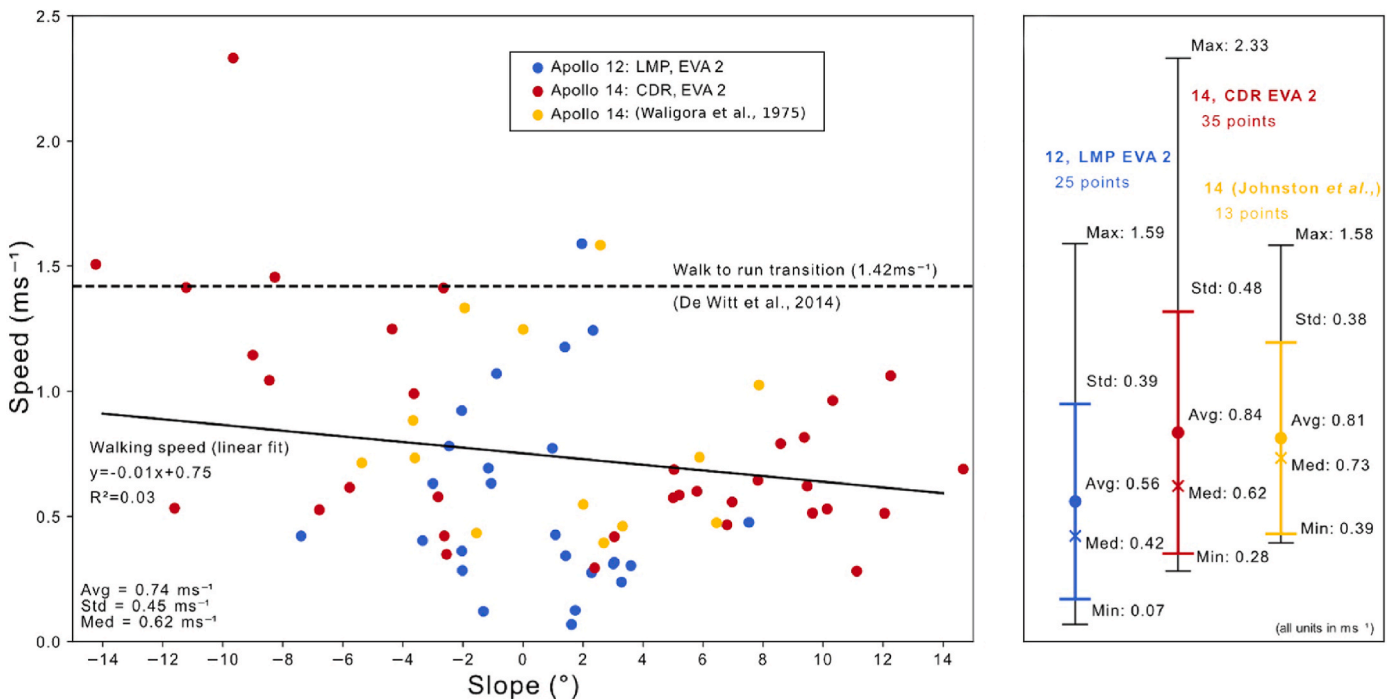
The Apollo 12 EVA 2 traverse lasted approximately 2 h and 45 min, of which only  $\sim 30 \text{ min}$  were spent walking [56]. The astronauts covered almost 1.6 km, reaching a distance of  $\sim 400 \text{ m}$  from the lander, including a 100 m segment at  $14^\circ$  inclination. The EVA recovered  $\sim 18 \text{ kg}$  of geological samples, including cores ( $\sim 60 \text{ cm}$  deep), and rocks from trenched ( $\sim 20 \text{ cm}$ ) material [71]. For this EVA, we calculated an average speed of  $0.56 \pm 0.39 \text{ ms}^{-1}$  or  $2.02 \pm 1.40 \text{ kmh}^{-1}$  (mean $\pm 1\sigma$ , No = 25), and a median speed of  $0.42 \text{ ms}^{-1}$  or  $1.51 \text{ kmh}^{-1}$ .

The Apollo 14 EVA 2 traverse lasted  $\sim 4.5 \text{ h}$ , during which time the astronauts covered  $\sim 2.9 \text{ km}$ , reaching a distance  $\sim 1.4 \text{ km}$  from the lander. Approximately 22 kg of geological samples were recovered, including core ( $\sim 60 \text{ cm}$  deep) and trenched ( $\sim 30 \text{ cm}$ ) material [71]. Due to challenges walking over the rugged terrain, the crew fell behind schedule; notably, the MET proved difficult to transport and for portions of the EVA the crew resorted to carrying rather than pulling it [56]. A summary table of this EVA from *Biomedical Results of Apollo* [55] includes traverse speed between stations, averaging  $0.81 \pm 0.38 \text{ ms}^{-1}$  or  $2.92 \pm 1.37 \text{ kmh}^{-1}$  (mean $\pm 1\sigma$ , No = 13). Because a linear distance is used, this is an underestimate. We calculate a mean speed of  $0.84 \pm 0.48 \text{ ms}^{-1}$  or  $3.02 \pm 1.73 \text{ kmh}^{-1}$  (mean $\pm 1\sigma$ , No = 35) and a median of  $0.62 \text{ ms}^{-1}$  or  $2.23 \text{ kmh}^{-1}$ .

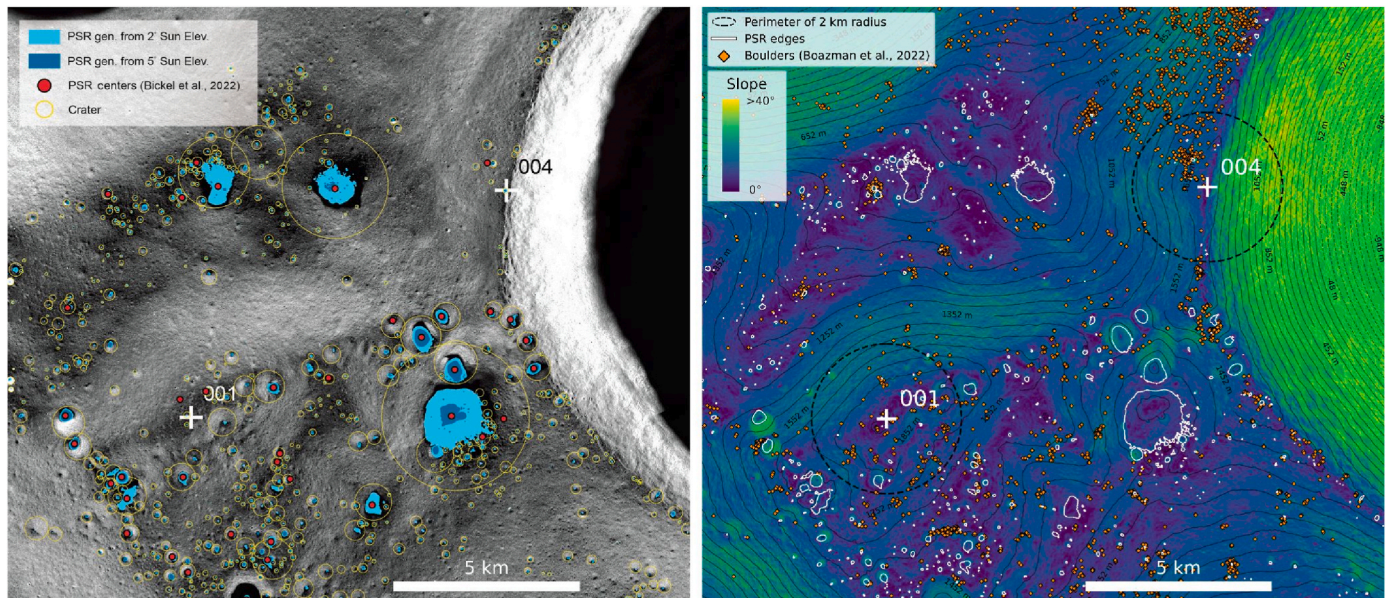
Plotting speed against slope (in the direction of the traverse) indicates a weak positive correlation of noisy data points ( $y = -0.01x + 0.75$ ;  $R^2 = 0.03$ ; units in  $\text{ms}^{-1}$ ), potentially suggesting decreasing speed with a higher slope. Because Apollo 14 involved the cumbersome MET, this trend represents traverse speed with a MET alternated between two astronauts, where the position of only one of the pair was tracked. We take forward an average of the three calculations, returning a mean speed of  $0.74 \text{ ms}^{-1}$  or  $2.66 \text{ kmh}^{-1}$ .

### 4.3. Mapped PSRs and boulders

521 PSRs were mapped within the  $\sim 300 \text{ km}^2$  ROI encompassing the rim of Shackleton crater and the Shackleton-Henson ridge, incorporating those analyzed by Ref. [72] derived from the 60 m product by Ref. [2]. The mean PSR area is  $11,975 \text{ m}^2$ , with a significantly skewed distribution (median =  $1075 \text{ m}^2$ , standard deviation =  $100,859 \text{ m}^2$ ) towards smaller sizes. PSRs range from  $75 \text{ m}^2$  to  $2,144,700 \text{ m}^2$ , or between  $\sim 10 \text{ m}$  and  $\sim 1600 \text{ m}$  in diameter. The PSRs within the ROI have an average LDEC coverage of  $11.22 \pm 2.68 \%$  (mean $\pm 1\sigma$ , No = 521), with a median of 10.8 %. Geolocation uncertainty for the 5 m/pixel DEM is  $\sim 10\text{--}20 \text{ cm}$  horizontally and  $\sim 2\text{--}4 \text{ cm}$  vertically for each pixel [17,



**Fig. 8.** Combined traverse metrics from Apollo 12 EVA 2 (blue) and Apollo 14 EVA 2 (red and yellow) derived from Lunar Surface Journal transcripts and Biomedical Results of Apollo (1975) [70]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 9.** Left: Distribution of PSRs within the ROI, overlaid on NAC 1 m/pixel imagery. Circles denote craters with potential to host areas of permanent shadow. Right: PSR edge distribution within the ROI, overlaid on a slope map generated from 5 m/pixel LDEM with elevation contour lines. Diamonds represent boulders. The 2 km radius perimeter is depicted. Data credits: NASA/LROC/GSFC/ASU.

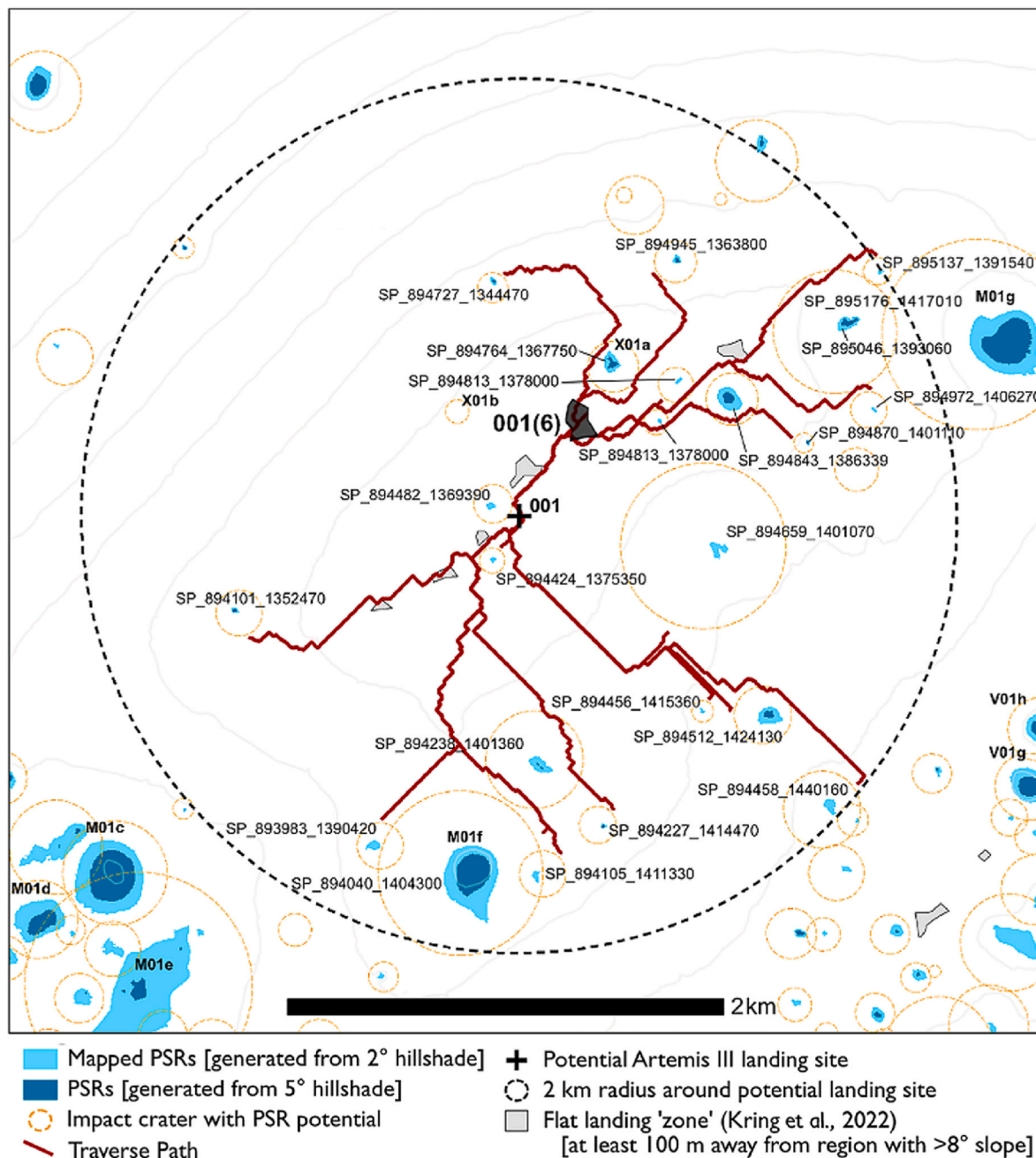
**Table 1**  
Table showing the number of traverses to PSRs with slopes below 5, 10, and 15°.

PSRs accessible	ROI
<15° slope	490 (94 %)
<10° slope	351 (67 %)
<5° slope	74 (14 %)

**Table 2**  
Table showing the number of traverses to PSRs within 2 km radially of potential landing sites 001 and 004 and location 001(6) with slopes below 10° and 15°.

	001	001(6)	004
# of PSRs	22	20	10
<15° slope	20	19	10
<10° slope	4	4	0





**Fig. 10.** Traverse paths within 2 km radius of potential landing site 001 to crater edges that host PSRs. Location 001(6) is labeled for reference. Indexed PSRs from Ref. [72].

46].

Fig. 9 provides a visual representation of the distribution of PSRs within the ROI in this study. This figure includes the overlay of boulders that were extracted from Ref. [8]. The inclusion of boulder locations offers insights into the spatial relationship between PSRs and these geological features, thereby imposing constraints on possible traverses and exploration targets. We capture many smaller PSRs using the finer 5 m/pixel resolution, resulting in high densities of possible targets around both potential landing sites 001 and 004. The highest overall densities of PSRs are found on the flanks of Shackleton crater on either side of the Shackleton-Henson ridge. When comparing the generated PSRs to a slope map, we find PSR density is much lower on steep slopes. This is likely due to a combination of a more generous illumination and a lower density of craters, which erode quicker on steeper slopes [73].

#### 4.4. Traverse and descent to PSRs

An accessible traverse was defined as a walking EVA where the maximum slope does not exceed 15°. Under this definition, 94 % of the PSRs are accessible from their respective host crater rim. We also considered more amiable conditions and determined that with a maximum slope of 10° and 5°, nearly 67 % and 14 % of PSRs are accessible, respectively (Table 1).

There are collectively 34 PSRs within a 2 km radial distance of the two potential landing sites 001 (including flat landing location 001(6)) and 004 (Table 2). Note that because there is only a ~400 m distance between 001 and 001(6), 18 PSRs are accessible from both (see Fig. 10). Fig. 11 depicts the percentage of a traverse path below 5°. Location 001(6) has the largest number of traverses where 75 % or more of the traverse is on slopes <5°. The metabolic demand on astronauts is thus



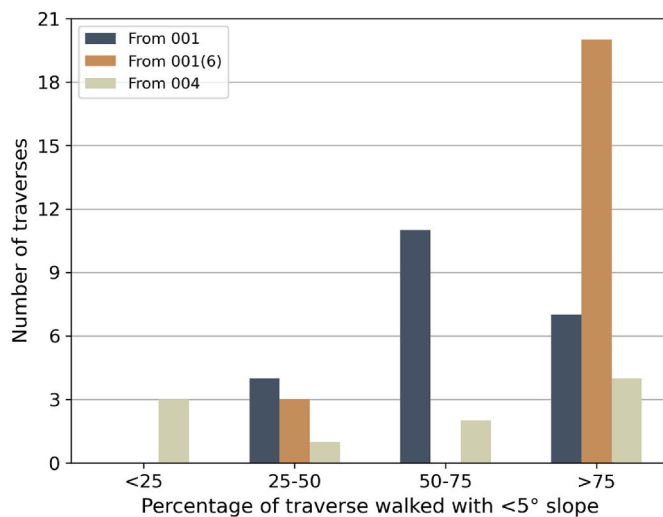


Fig. 11. Percentage of route with slopes less than 5° for traverses within 2 km of potential landing sites 001 and 004 and location 001(6).

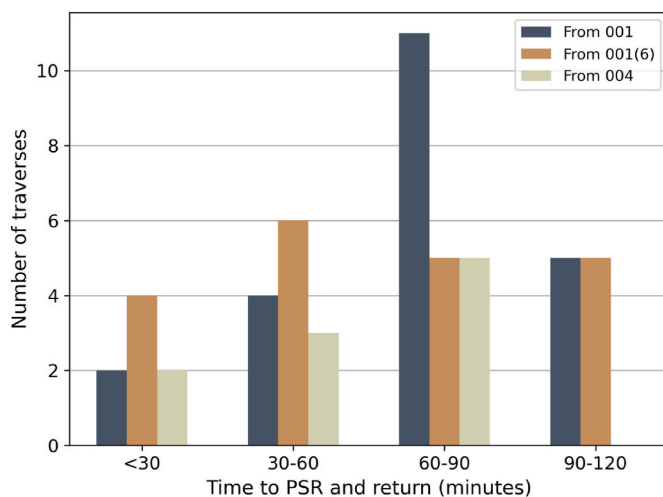


Fig. 12. Number of (round-trip) traverses that can be walked within different time ranges.

expected to be lower. EVA planners using these traverses could incorporate longer walking distances between breaks or include more strenuous tasks such as trenching and coring without risking exhaustion. Fig. 12 highlights the time it takes to make a return trip to PSRs from the potential landing sites, using the average Apollo-derived speed (Section 4). All traverses can be completed in less than 2 h, assuming a constant walking speed of  $0.74 \text{ ms}^{-1}$  (or  $2.66 \text{ kms}^{-1}$ ), with no stops along the way. Traverses from 004 all take less than 1.5 h but feature a higher average slope. There are a total of six round-trip traverses into PSRs from sites 001, 001(6), and 004 that can be completed in under 30 min. These will give ample time for diversions and other activities.

#### 4.5. Atlas

All traverses from potential landing sites, along with the optimal crater descent, have been compiled in an atlas found in the Supplementary Material. Distance, elevation change, slope, bearing capacity, temperature, illumination, direct view from the HLS, and duration (including the return, 'bck') are evaluated for each traverse. Atlas images were generated with Python using the *Mayavi* package [74] and *Matplotlib* [75]. For 3D renderings the scene illumination was selected to

best convey the topography.

The atlas includes the 521 PSRs identified within the ROI, accompanied by host crater and PSR properties, such as shadowed area for 2° and 5° Sun elevation, temperature, coverage (percentage of data points not interpolated), and radius and depth of the host crater (calculated by fitting a plane to the rim for slope correction, prior to computing maximum elevation change). Each PSR spread consists of (1) the optimal descent from any point on  $1.1 \times$  crater rim radius to PSR edge, and continued to its center, for all identified in the ROI (SP-B), and (2) the minimum-cost path from a potential landing site to the PSR edge, continued to its center, if accessible within 2 km radially of 001, 004, or 001(6) (SP-C).

An example from the atlas can be found in the **Appendix: Figure A1** illustrates a traverse from potential landing site 001, Figure A2 exemplifies the spread with associated general values, and Figure A3 offers an optimal crater descent to PSR center.

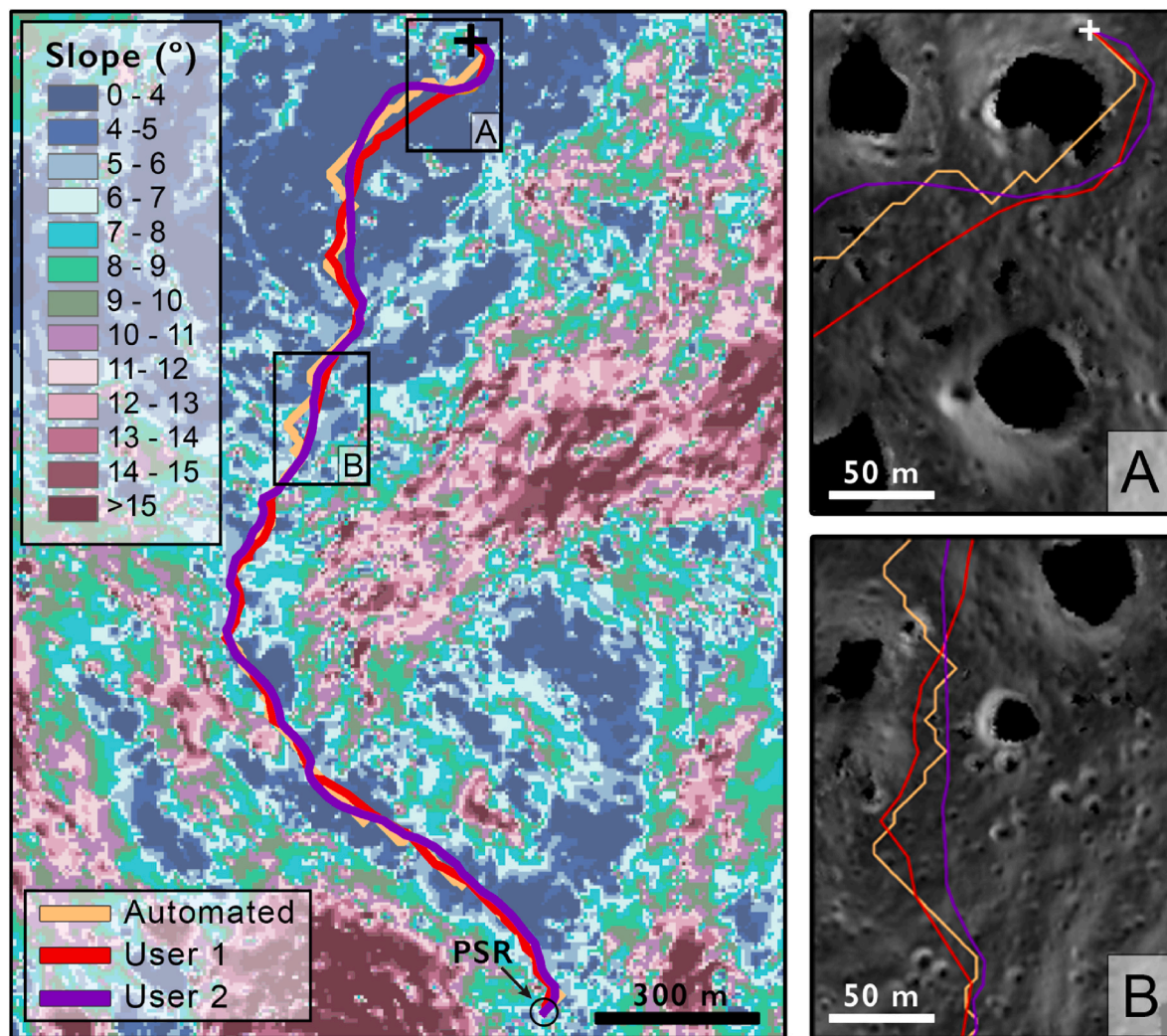
## 5. Discussion

### 5.1. Pathfinding

A quick overview of 521 potential crater descents across variable surface terrain is enabled with the automated computation process to inform EVA opportunities and route-planning. The number of round-trip traverses achievable, notably under 30 min, is promising for the possible diversity of sample conditions. Astronauts need to conserve energy and manage metabolic heat to ensure that they can return to their starting point safely, with sufficient surplus for geological sample collection, which may involve strenuous activities such as hammering, trenching, and coring. EVA execution will undoubtedly also be shaped by the astronauts performing them. Activities along the suggested routes will be influenced by spacesuit thermal measurements [76], to plan future EVA circuits more comprehensively in response to human metabolic predictions.

Additionally, we manually checked and modified two of the automated traverses for testing and comparison purposes. Although we used the highest LDEM resolution currently available (5 m/pixel LOLA DEM; [46]), its resolution is still too coarse to account for all surface variations discernible to astronauts. For manual traverse mapping, a NAC mosaic with a resolution of 1 m/pixel was used. This allows users to identify and avoid small craters larger than  $\sim 2\text{--}3 \text{ m}$  diameter, as well as other potentially hazardous features. Deviation from the automated traverse should be considered when (i) smoothing in areas of gentle slope, (ii) avoiding small potentially hazardous features, and (iii) obtaining specimens for scientific interest or resource development. Automatic traverses can even increase the distance walked to reduce the cumulative slope by making switchbacks. The automated traverse is constrained to the 5 m/pixel raster grid and thus creates a step-like pattern that may not be realistic for an astronaut walking on the Moon. Manual traverse planning can smooth this feature in areas where possible. However, it does not guarantee that the drawn route is closer to natural astronaut movements due to the absence of a 3D perspective.

When comparing automated and manual traverses, there is a negligible elevation change among traverses and users. Distance traveled between automatic and manual traverses differs slightly. In most cases, the manual traverse distance is usually lower than the automated traverse (before applying the minimum realistic distance smoothing), which can be explained by the smoothness of the user-defined path versus the jaggedness of the automated one. The average slope is always lower for the automated traverse. As a minimum-cost path algorithm that uses slope as its main input, this result is expected. Any deviation from the automated path would increase the average slope. When comparing the maximum slope between the traverse approaches no trends are discerned. The comparison shows that in some instances the maximum slope can be reduced to the detriment of the total cumulative slope. Fig. 13 presents a comparison between the path generated by the



**Fig. 13.** Comparison of traverses to PSRs between two user-drawn paths and path-finder algorithm result. Left panel shows the traverses overlaid on the slope map. Right panels show the traverses overlaid on NAC images.

path-finder algorithm developed in this study and two alternative paths created by users. The users manually smoothed the paths and introduced detours based on visual inspection of NAC images. While the automated traverse may be slightly longer, the significant reduction in metabolic workload achieved through lower cumulative slopes ensures optimal energy management during EVAs.

This exhaustive path-finding approach can be applied both to evaluate the range of accessible targets around potential landing sites and assist candidate site rankings, as well as a first EVA filter around those eventually selected. We recommend that manual traverse planning should subsequently be done with high-resolution lunar surface images after down-selecting from the automated traverses to avoid potentially hazardous features unaccounted for.

Astronaut EVA design involves a multi-faceted approach, factoring in several variables affecting metabolic workload. While our study emphasizes distance and elevation changes for efficient round-trip traverse planning, we recognize the significance of additional parameters, such as temperature fluctuations and bearing capacity. Sunlight incidence impacts operations and equipment performance, whilst terrain characteristics are essential for safe mobility. Integrating these variables could enhance traverse optimization. Illumination, communication constraints, and mission goals are also relevant considerations. Sun position and local topography affect visibility and power generation, while communication constraints impact real-time support. We acknowledge

the importance of these factors and their prospective integration into future software iterations.

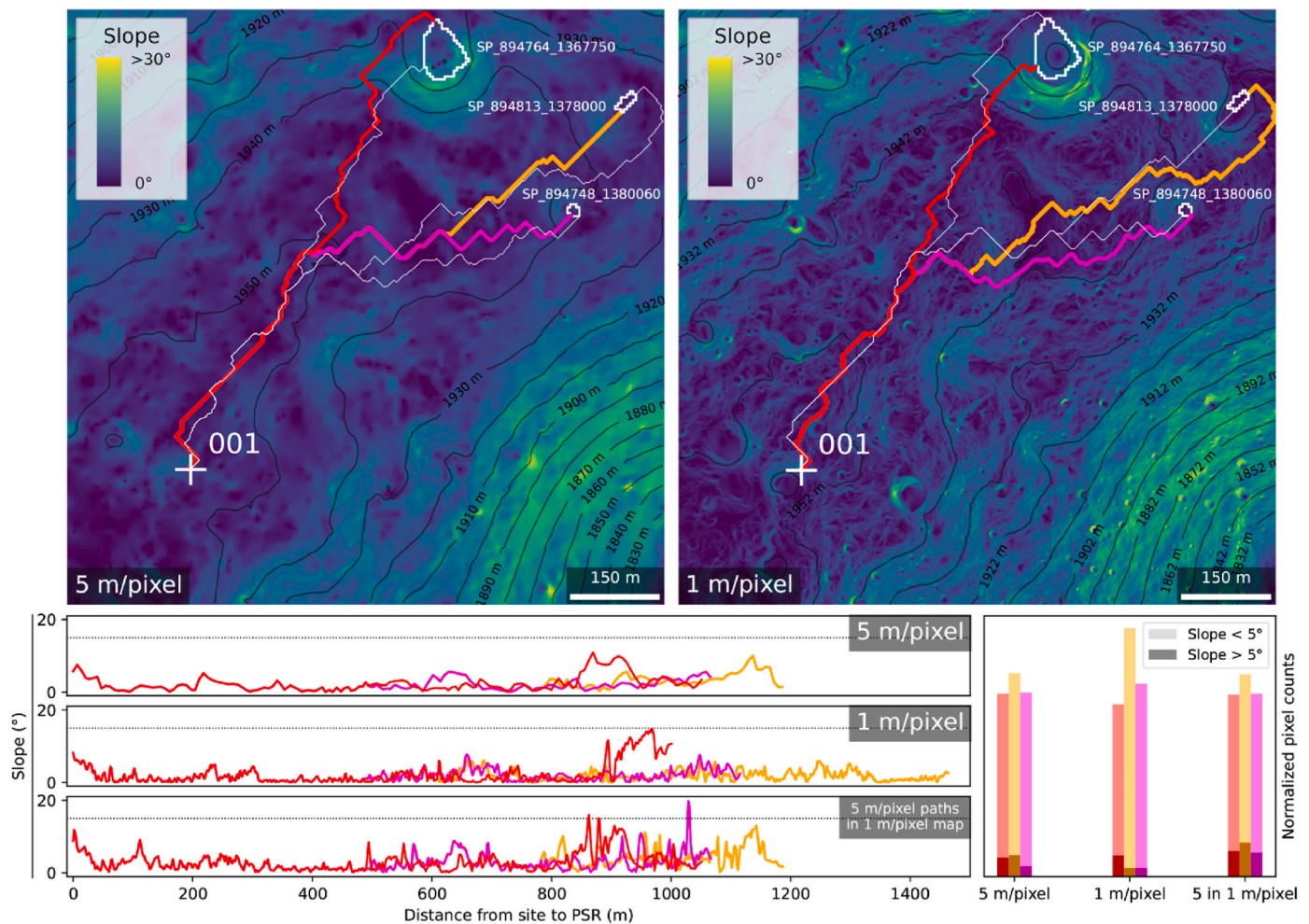
Both the *MoonPath* tool and manual mappers need to download suitable orbital data, demanding a comparable time investment. Once the data is downloaded, our pipeline produces results within seconds or minutes, whereas manual mapping may extend to hours or days. Crucially, this expedited automated method enables mission planners to explore a broader array of quantitatively optimized options.

## 5.2. Traverse properties

Only one of the accessible PSRs has a maximum temperature below 107 K (surface water ice persistence threshold [77], suggesting highest potential for appreciable volumes of frozen volatiles). This PSR (SP\_895711\_1611230) should be reviewed as a potential target. However, it is outside the 2 km range of potential landing sites 001, 001(6), and 004 imposed in this study.

For each traverse, the Sun position can vastly change experienced illumination conditions. As an example of the dramatically different outcomes, we observe that the most and least illuminated traverses are inverted over a period of two weeks. Since potential landing site 001 is on the crest of the Shackleton-Henson ridge, depending on which flank a traverse passes over, the path could be wholly illuminated or completely in shadow.





**Fig. 14.** Computed traverses from site 001 to PSR (closed thick white lines) SP\_894764\_1367750, SP\_894748\_1380060, and SP\_894813\_1378000, overlaid on a slope map with elevation contour lines. The slope profiles of each traverse are shown as a function of the distance traveled by the astronaut. They are categorized into three groups: computed using the 5 m/pixel resolution, 1 m/pixel resolution, and 5 m/pixel resolution interpolated to the 1 m/pixel resolution. A bar chart is also presented to illustrate the distribution of traverses based on pixels they transect, classified into those with slopes above and below 5°. The horizontal dashed line denotes the slope threshold of 15°. Thin white lines superimposed on each map depict the traverses from the alternative resolution to enable easy visual comparison.

Temporal considerations are needed given that conditions such as temperature and illumination can vary significantly. For traverses using illumination conditions on 16 and December 30, 2025, four traverses from 004 and one from 001(6) are more than half conducted in shadow. Specific illumination will vary for other dates, so traverses will need to be considered not only for their scientific targets but the surface environment.

Regarding astronaut walking speed, the walk-to-run transition of  $1.42 \pm 0.24 \text{ ms}^{-1}$  ( $5.11 \pm 0.86 \text{ kmh}^{-1}$ ) calculated by Ref. [78] was used as a reference for comparison. This value matches the upper limit for speed calculated between most way points, suggesting that for sections of the traverse, Apollo astronauts were walking as fast as they could in lunar gravity. In case the rover broke down during Apollo 17 and astronauts had to walk to the LEM, NASA used estimated speeds of  $1 \text{ ms}^{-1}$  ( $3.6 \text{ kmh}^{-1}$ ), or  $0.75 \text{ ms}^{-1}$  ( $2.7 \text{ kmh}^{-1}$ ) if the remaining traverse was over an hour [79]. These figures are consistent with those plotted in Fig. 8. During Artemis III, a nominal speed of  $2 \text{ kmh}^{-1}$  is expected on level surfaces, although this would drop significantly over more challenging terrain [65]. Recent simulations of lunar EVAs using the NASA Mark III suit walked at a comparable speed of  $0.74 \text{ ms}^{-1}$  ( $2.7 \text{ kmh}^{-1}$ ) and  $0.83 \text{ ms}^{-1}$  ( $3.0 \text{ kmh}^{-1}$ ) over a minimum of 500 m with slopes  $-10\%$  to  $+30\%$  [76]. Increased spacesuit mobility is likely to allow astronauts to move and collect data faster, as well as work more independently.

### 5.3. DEM resolution dependency

To assess the impact of DEM resolution on the traverses, we employed a 1 m/pixel DEM generated from NAC images using the shape-from-shading algorithm [80,81]. This high-resolution DEM covers a  $1 \text{ km} \times 1 \text{ km}$  area at site 001, where three mapped PSRs are located. By utilizing this detailed topographic data, we computed the slope map and applied our methodology to determine the minimum-cost path.

In Fig. 14, we present the three computed traverses from site 001 to the PSRs, superimposed on a slope map with elevation contour lines. Additionally, we illustrate the slope profiles of each traverse as a function of the distance traveled by the astronaut. For illustration purposes, the distance measurements are not adjusted using the same correction method as previously described, so distance may be overestimated, particularly for the 1 m/pixel map.

Some differences are evident in the calculated traverses, with variations observed in the approach to crater rims and the descent towards the edges of the PSRs. Utilizing a higher resolution slope map results in meandering paths with less time spent in straight lines, leading, as expected, to longer routes. However, the red path in the 5 m/pixel traverse covers a greater distance as it approaches the PSR from the north. Conversely, the higher resolution path finds a more efficient descent with less overall walking, maintaining slopes below the specified threshold. Despite the orange path covering an additional  $\sim 250 \text{ m}$ , it



achieves a maximum slope of  $\sim 8^\circ$ , compared to  $\sim 10^\circ$  in the lower resolution traverse. The updated map also reveals a steeper slope within the host crater, prompting the algorithm to avoid it. The magenta traverse is slightly longer, with a distinct descent pattern towards the PSR, albeit exhibiting similar slope profiles.

To facilitate a comprehensive comparison, we interpolated the traverses obtained using the 5 m/pixel map. Their superposition on the 1 m/pixel map reveals a notable degradation in the slope profile, surpassing the threshold for two of the traverses. Fig. 14 analysis demonstrates that despite a slight increase in the distance covered, the optimized paths consistently exhibit lower cumulative slope. This is evident in the bar chart as there is a reduction of the number of pixels with slopes exceeding  $5^\circ$ .

The running time bounds of a minimum-cost pathfinder can be defined as a function of the number of edges ( $m$ ) and the number of vertices ( $n$ ). Considering the implementation of binary heaps for priority queues, the theoretical efficiency of Dijkstra's algorithm for connected graphs is proportional to  $m \log(n)$  [82]. The running time for the three traverses compared in this section increases approximately 24 times when incrementing the cost map resolution by a factor of 5. On average, the computation of each traverse compiled in the atlas and its associated properties from site 001 to PSR took  $74 \pm 28$  s on a 2.3 GHz Intel Core i9 (I9-9980HK) processor.

Our analysis highlights the importance of using meter or sub-meter DEM resolutions for calculating optimal traverses for walking EVAs. The findings suggest that automated paths with lower resolution maps may deviate from the slopes experienced at the scale of an astronaut's footstep. By utilizing higher resolution DEMs, we can achieve more accurate and representative slope calculations.

Unfortunately, during the course of this study, sub-meter DEM maps were not available. Nevertheless, once such maps are generated, they can be readily incorporated into our software tool. This flexibility presents a promising avenue for future research and implementation, as the utilization of sub-meter DEMs would enhance the accuracy of automated calculations for determining optimal traverses.

## 6. Conclusions

The Artemis program seeks to return humans to the lunar surface and specifically the south polar region, where PSRs may host near-surface ice, making them critical targets for sample collection and scientific analysis. To design astronaut EVAs, we developed a Python pipeline that automatically models and evaluates the optimized path to all accessible PSRs given a starting point within the vicinity of the 'Connecting Ridge' region. Using high-resolution LOLA data, we identified and mapped 521 PSRs that maintain a minimum area of  $75 \text{ m}^2$  nearby potential landing sites 001 and 004, and a flat landing zone 001(6).

Our *MoonPath* pipeline combines a Monte Carlo approach with

Dijkstra's minimum cost path algorithm to compute the optimal route for EVAs with the most efficient workload criterion, i.e., the traverse to PSRs with the minimum cumulative slope. We have also evaluated temperature, bearing capacity, astronaut illumination, and the astronaut-to-lander direct view along the traveled distance. Based on estimated average path times from Apollo 12 and 14 transcripts, we identify traverses from potential landing sites 001, 001(6), and 004 to PSRs accessible within a 2 km radius under 2 h round-trip. We find that 94 % of all PSRs in the area are accessible from the rim on slopes below  $15^\circ$ . Twenty and 19 PSRs are accessible from potential landing sites 001 and 001(6) respectively, four of which are accessible on slopes entirely below  $10^\circ$ . Traverses around site 004 are more workload-demanding.

To facilitate future mission planning, we compiled an atlas (attached in the Supplementary Material) that includes all 521 traverses and descents to PSRs. This type of information is critical for determining the most efficient circuits to optimize astronaut EVAs and identify accessible potential science targets. Overall, the developed pipeline and traverse atlas can be used to support mission planning for sample collection of potential near-surface ice in the PSRs of the lunar south polar region to address major scientific priorities.

While the utility of the *MoonPath* tool was demonstrated to reach PSRs, the pipeline can be used to calculate minimum workload astronaut paths to any other geologic and exploration targets within the AEZ or elsewhere on the Moon.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

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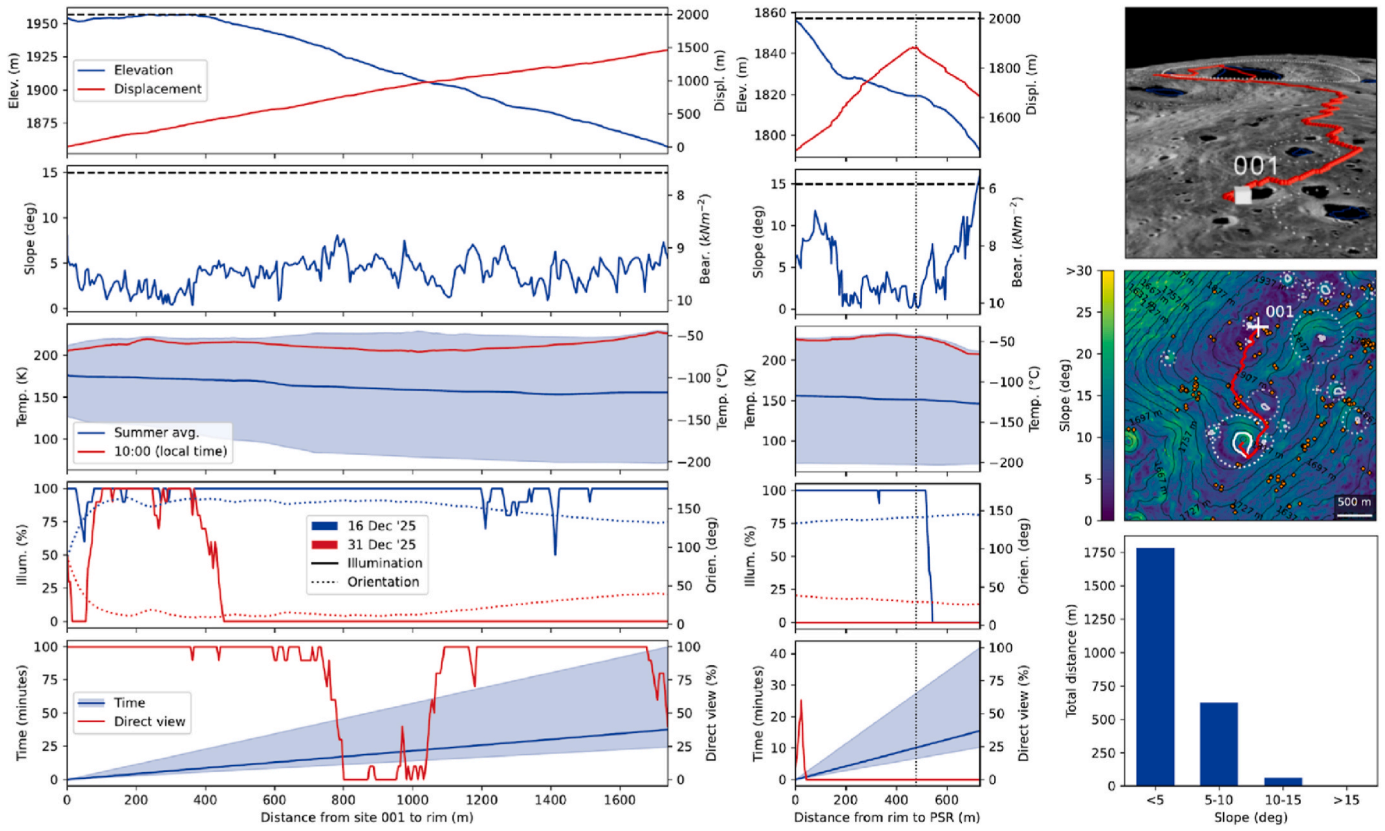
## Appendix A

## SP\_894040\_1404300 (starting at 001)

Starting coordinate (°): -89.4501, -137.3574

Crater rim coordinate (°): -89.4162, -140.8113

PSR edge coordinate (°): -89.4003, -141.0369



**Fig. A1.** Example spread of the traverse and descent, as well as a 2D plot with elevation contours, a 3D plot using 2 m/pixel NAC images and 5 m/pixel LOLA DEM, and a histogram of the distance traveled as a function of the slope.

SP\_894040\_1404300 (starting at 001)

Crater rim coordinate (°): -89.4162, -140.8113

PSR edge coordinate (°): -89.4003, -141.0369

Traverse Characteristics											
Cumulative slope (°):		1795.6									
Distance (m):		1737.9 / 2468.0									
[crater rim/PSR center]											
Displacement (m):		1462.4 / 1686.6									
[crater rim/PSR center]											
To rim time (minutes):		37.6 / 24.3 / 99.9 / 41.0									
[avg/min/max/bck]											
Desc time (minutes):		15.5 / 10.2 / 42.0 / 17.6									
[avg/min/max/bck]											
Elevation (km)				Temperature (°K)				Illumination (%) [16th/31st]			
To rim:		Desc:		To rim:		Desc:		To rim:		Desc:	
Δ:	99.9	64.4		avg:	159.7	149.9		90.9	14.2	54.5	0.0
std:	32.5	14.2		std:	8.1	1.8		26.6	32.9	48.8	0.0
min:	1857.0	1792.6		min:	69.9	146.1		0.0	0.0	0.0	0.0
max:	1956.9	1857.0		max:	233.5	153.1		100	0.0	100	0.0
Slope (°)		Bearing capacity (kN/m²)		Direct view (%)		Sun-HLS view (°) [16th/31st]					
To rim:		Desc:		To rim:		Desc:		To rim:		Desc:	
avg:	3.9	4.7	8.9	8.6	82.6	2.0		151.2	21.1	139.4	32.5
std:	1.6	3.6	0.5	1.1	34.1	8.9		12.8	13.2	3.3	3.4
min:	0.4	0.2	7.6	5.6	0.0	0.0		87.9	8.6	133.0	26.6
max:	8.1	15.9	10.1	10.2	100	60.0		164.7	89.2	145.3	39.1

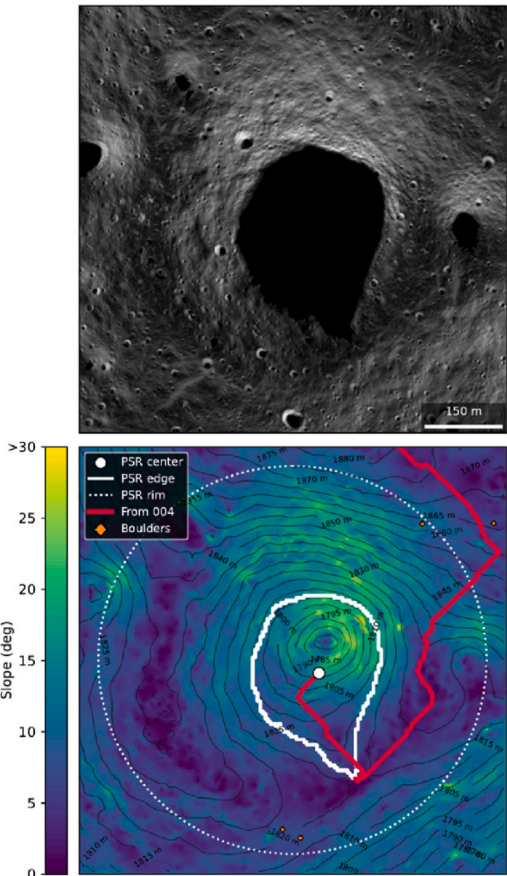


Fig. A2. Example of the tables associated with each traverse with general values calculated, and the 2 m/pixel NAC image and a detailed 2D map of the host crater.



SP\_893858\_1504040 (SP\_BL)

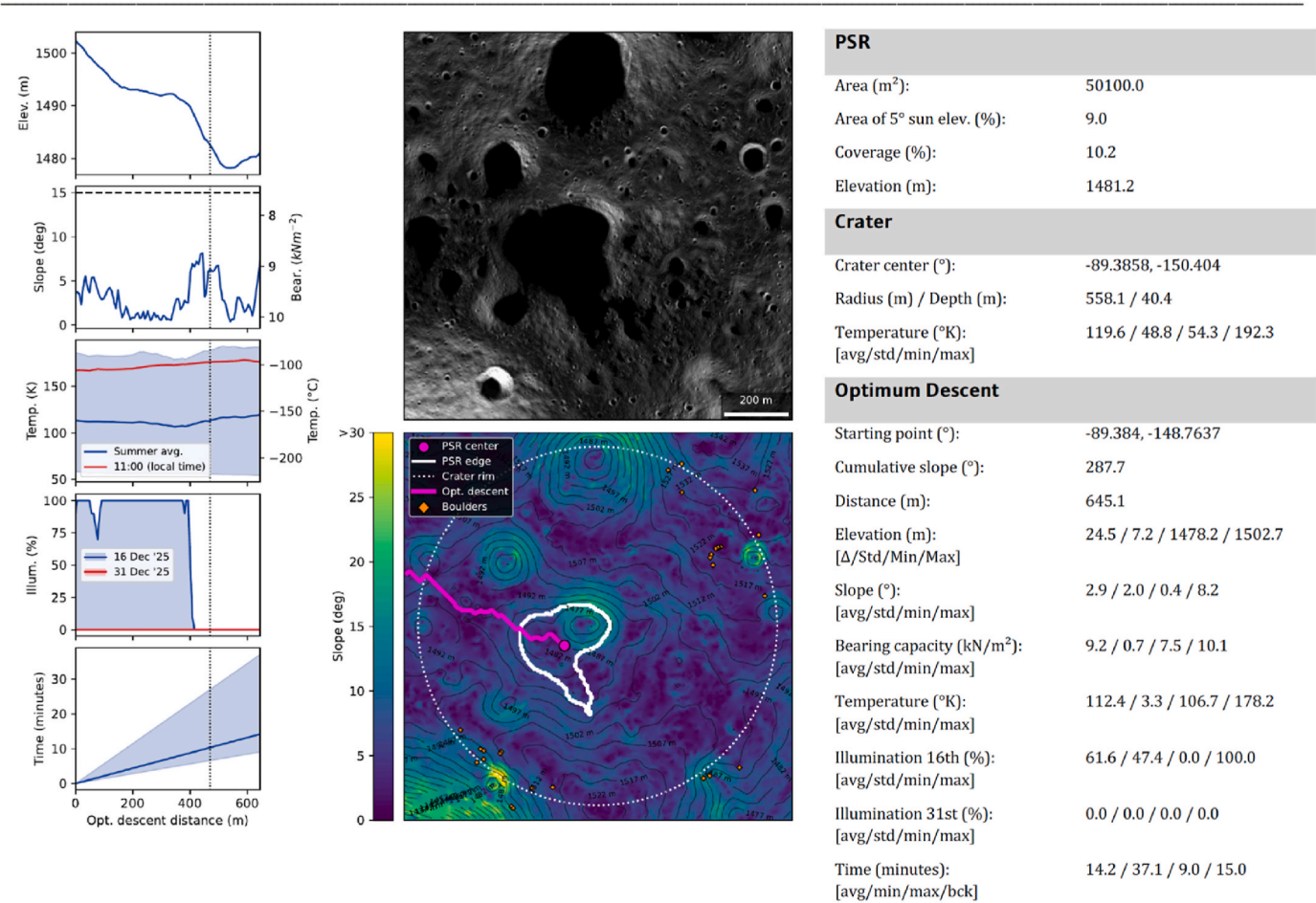


Fig. A3. Example of the tables associated with each PSR optimal descent with general values calculated, and a detailed 2D and 3D image of the host crater.

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.actaastro.2023.10.010>.

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