



## **Traverse Planning for Human and Robotic Missions to Hadley Rille**

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NASA/TM-2008-215367



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**January 2009**

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# Traverse Planning for Human and Robotic Missions to Hadley Rille (report)

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## Summary

On November 6, 2008, we conducted a short lunar traverse planning exercise at the NASA Ames Research Center. The objective was to establish an initial EVA traverse plan for a hypothetical, manned mission to the Apollo 15 region and then to identify where ground-level data (e.g., collected by robotic recon) would help refine the plan. The planning for this mission, which we named “Apollo 15B”, focused on Hadley Rille near Hadley C, and the ejecta blanket from Hadley C that is deposited on to Hadley Rille.

During the exercise, we used a variety of lunar datasets including recent high-res digital scans of Apollo Metric Camera (AMC) images, digital elevation models (created from the AMC images using the Ames StereoPipeline), and other datasets (geologic map, Clementine UV-VIS data, etc.) for planning. All the datasets were registered to the ULCN 2005 control network and viewed in a version of the Google Earth geospatial browser, which we modified to provide lunar distance measurements.

## Science Rationale

For “Apollo 15B”, we selected a landing site south of Hadley C at 25.3N, 2.9E. From this location, both Hadley C and Hadley Rille are directly accessible. In addition, the ejecta blanket from Hadley C, which is deposited on to Hadley Rille, provides a deep sampling of crater materials and serves as a natural bridge across the rille to Montes Apenninus. The following are general comments from Wilhelms (1987) “The Geologic History of the Moon” (USGS Professional Paper 1348) on the Apollo 15 region:

“One of the major objectives of the Apollo 15 mission in July 1971 was to collect samples of the Montes Apenninus. According to impact models based on simple craters, this basin rim material might have come from deep within the Moon. Primitive materials, or at least Pre-Imbrium materials, might have been uplifted and exposed in the Imbrium Basin massifs. Materials of the Serenitatis Basin are likely to be included because that basin’s west rim is cut off by the Apennines and thus lay in the target area of the Imbrium impact. Fewer samples than expected were obtained from the massifs [ggs-during Apollo]. Most that were collected are small and of uncertain geologic context because outcrops are covered by thick colluvium” (pp. 198-201).

“Steep rugged massifs that are among the Moon’s highest mountains form the crest of Montes Apenninus; they probably were uplifted structurally and overlain by ejecta. Large slump masses lie as far as 60 km northwest of embayments in the mountains, which were evidently the sources of the slumps. Most investigators currently believe

that Montes Apenninus are an exterior scarp of an Imbrium Basin smaller than its topographic rim. Others, including me [ggs-i.e., Don Wilhelms], regard an origin as the excavation boundary as much more likely because the Apennines are a massive elevated range of mountains, the largest on the lunar nearside, and because they mark a sharp discontinuity in the textures of basin deposits” (p. 198).

“The Apollo 15 landing was targeted next to a large sinuous rille, Rima Hadley. Several other rilles were considered for landings [during Project Apollo] to determine their formational and to collect samples of volatiles or other exotic erupted materials. Fieldwork on Earth and at Rima Hadley [during Apollo 15] have show that these meandering grooves are probably lava channels or collapsed lava tubes, which are the sites of the last flows of molten magma in a lava unit. Very long and narrow channels are likely to have been channels (always open); others, including Hadley, display alternately roofed and unroofed segments that indicate an origin as tubes. The sources of some lunar rilles are in the terra or at the mare-terra contact. Several appear to have erosionally incised the substrate, including terra material.” (pp. 88-89)

## **Robotic Recon**

NASA currently plans to return humans to the Moon with a campaign of regularly spaced surface missions, possibly beginning with the creation of a polar outpost, followed by sortie mission to other sites anywhere on the Moon. Some missions will consist of cargo-only landings to deliver surface assets including mobility systems, habitats, power, etc. Crewed missions will initially be “extended sortie” (e.g., one to two week) type missions. This means that during the first few years of the new lunar campaign, humans will be on the Moon less than 10% of the time. However, during the 90% of time between crew visits, robots could perform lunar surface tasks under ground control.

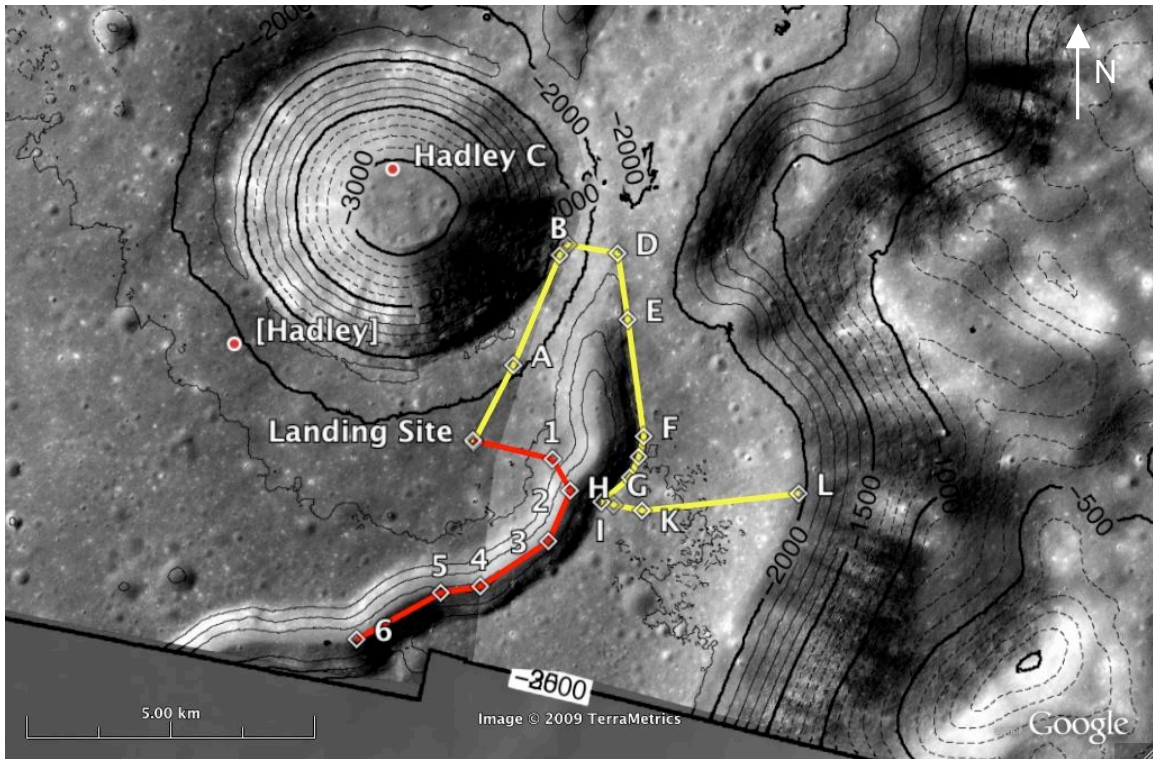
Prior to these surface missions, spacecraft (e.g., LRO) in lunar orbit will be used to map the Moon. Additional remote sensing data is available from Lunar Prospector, Clementine, Apollo metric and pan cameras, and Lunar Orbiter and the continued enhancement of data from these missions. These orbital missions can provide visible image base maps, topographic maps, gravity maps, mineralogical maps, element distribution maps, etc. However, remote sensing data may not be of sufficient resolution, lighting, nor view angle, to provide optimum planning detail for efficient lunar surface activity, such as crew traverses for field geology and feature sampling. Thus, it will be important to acquire supplemental and complementary data on the lunar surface.

Robotic recon (i.e., using a planetary rover to scout planned sorties) can perform this task prior to human surface activity. Scouting is well understood to be an essential phase of field work, particularly for geology, and can be: (1) traverse-based (examining stations along a route); (2) site-based (examining stations within a bounded area); (3) survey-based (systematically collecting data along defined transects) or (4) pure reconnaissance.

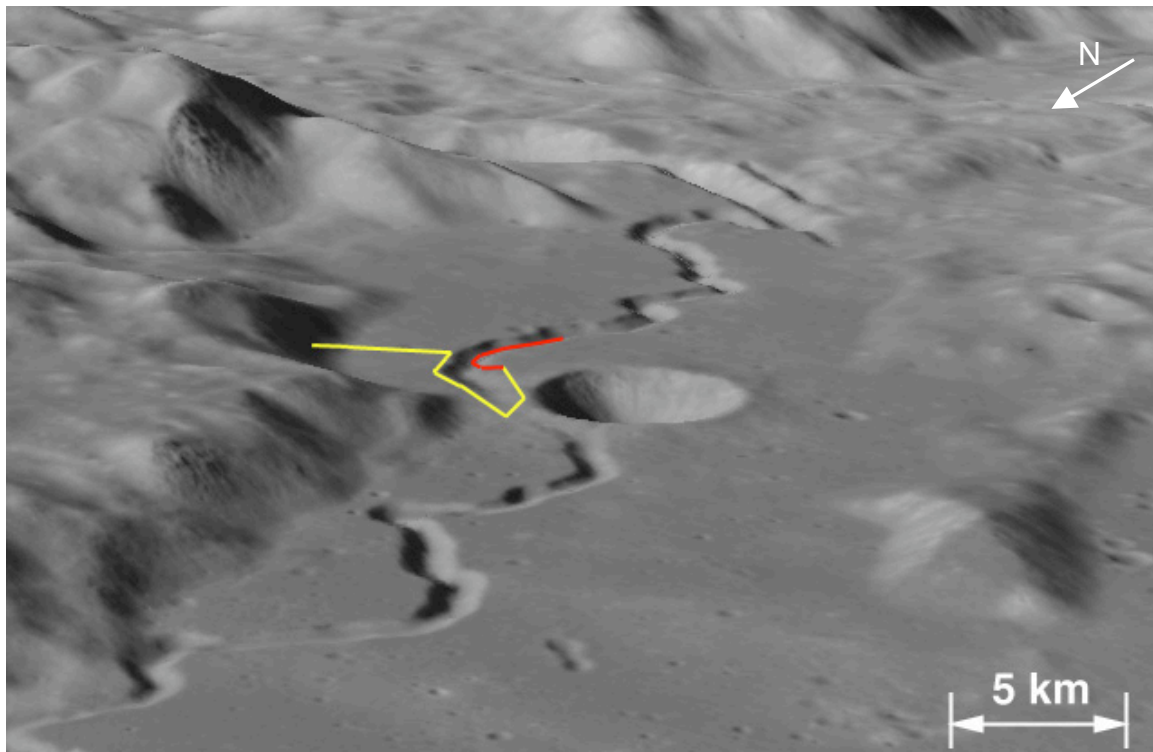
During robotic recon, robot-mounted instruments can be used to examine the surface and subsurface at resolutions (e.g., micron to cm scale) and at viewpoints not achievable from orbit. The data can then be used to prioritize targets of interest to improve the productivity of crew traverses. In addition, robotic recon can help identify and assess terrain hazards, as well as evaluate alternate routes to help reduce operational risk.

## Traverse Routes

We planned EVA and robotic recon traverses to explore the “Apollo 15B” site.



*EVA (red path, stations 1 to 6) and robotic recon (yellow path, stations A to L) traverses displayed in custom version of Google Earth geospatial browser*



*Traverses shown on 3D oblique, south-facing view of Hadley C and Hadley Rille*

The EVA traverse is drawn in red and measures approx. 7 km one-way. The primary objective for this traverse is to directly descend from the landing site into Hadley Rille and then continue along the bottom. We designated six stations (numbered 1 to 6) as navigational via points and sampling locations.

The “robotic recon” traverse (to be performed prior to crew EVA traverse) is drawn in yellow and measures approx. 13 km one-way. The traverse has four objectives: (1) scout Hadley C for possible EVA; (2) cross Hadley C ejecta blanket and assess alternate descent route into Hadley Rille; (3) acquire imagery of planned EVA traverse route from opposite side of Hadley Rille; and (4) scout approach to Apennine Front massif. We designated twelve stations (lettered *A* to *L*) as navigational via points and measurement locations.

### Crew EVA Traverse

For the purposes of this exercise, we assumed that the crew would perform the EVA traverse in Apollo style (i.e., on foot or riding on an unpressurized crew rover). This constrains the one-way distance to a maximum of 10 km for unassisted walkback.

Location	Tasks	Objectives
<b>Landing Site</b>	Sample, core tube and describe/photo-document the mare materials and regolith materials in and around the landing site. Take pans and telescopic photos of the rim of Hadley C, Hadley Rille and the massifs of the Apennine Front.	Sample materials from the outer ejecta blanket of crater Hadley C. Ejecta from Hadley C may include materials from the Apennine Bench Formation or other materials which underlie the volcanic lavas of Palis Putredinis in which Hadley Rille was formed.
<b>Station 1</b>	Sample (rocks and core tubes) and document lava flow materials along short traverse up to the very rim-edge of Hadley Rille. Describe any exposed layering near station and exposed in cross section across Hadley Rille. Obtain pans and telescopic photos of Hadley C, back to LM and across Hadley Rille.	Prepare for descent into Hadley Rille. Use information from robotic recon traverse stations F through I (across rille).
<b>Stations 1 to 3: Traverse into rille</b>	Take 360 degree pans every km; several Microcam images; Lidar scans along rille wall and along rille.	Photo-document Hadley Rille structure.
<b>Stations 3 to 6: Along rille bottom</b>	Sample wide variety of rocks and boulders lying on bottom of rille. Take pans northeast and southwest along bottom of rille floor and walls. Take telescopic photos of wall structure, layering of basalts and talus slumps.	Priority on documenting and sampling any changes in the types of rocks present, as well as describing notable changes in wall structure and layering.



## Robotic Recon Traverse

The robotic recon traverse was planned with the following assumptions: (1) planetary rover for lunar operations (100 kg, 30 deg slope and 20 cm step obstacle capable, lunar night survivable, 50 cm/s max speed); (2) non-contact recon instruments (on planetary rover): 3D lidar (Optech ILRIS-3D equivalent), color panoramic imager (MER pancam equivalent), multi-spectral imager (MER pancam equivalent), high-resolution terrain imager (MER MI equivalent), and ground-penetrating radar (CRUX GPR equivalent); and (3) robot remotely operated from Earth ground-control prior to crew EVA.

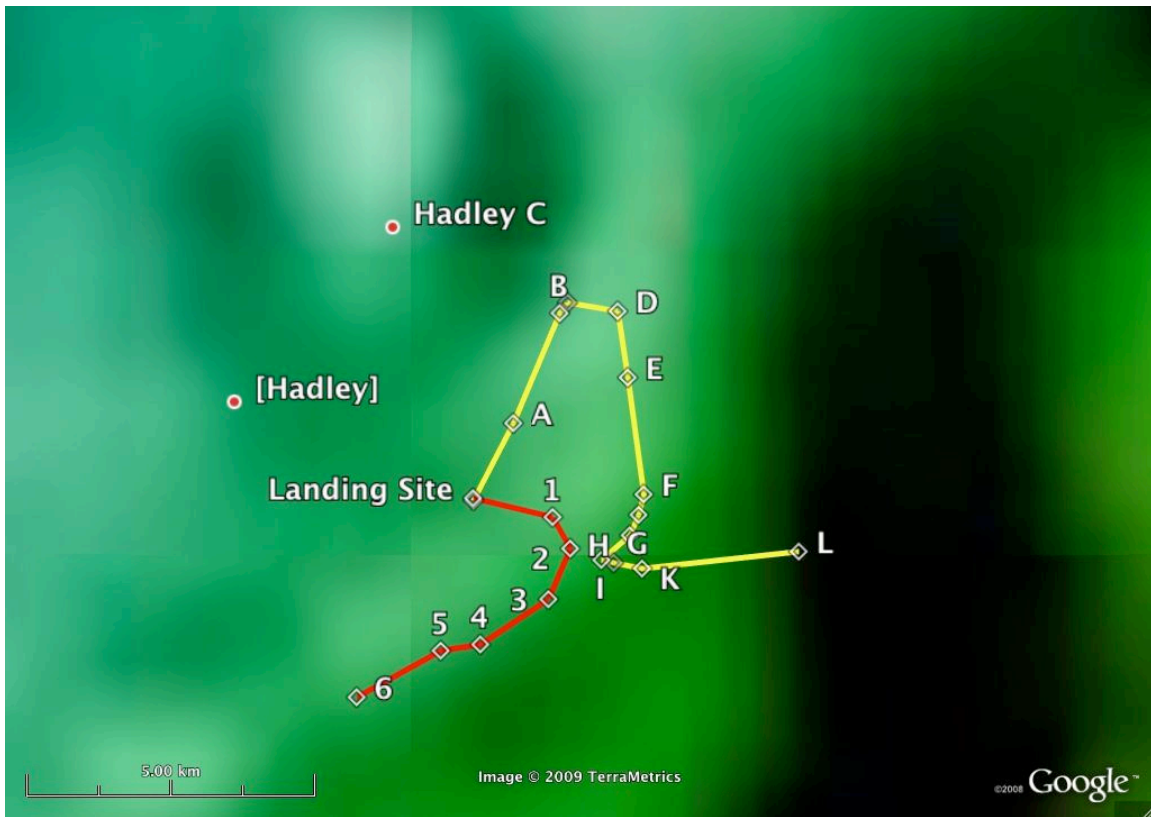
Location	Tasks	Objectives
<b>Landing Site</b>	360° pancam including LM, Hadley C and Hadley Rille; 360° lidar scan; multi-spectral analysis of surface (away from LM descent and astronaut EVA disturbance). Take variety of high-resolution stereo images of surface using nadir-pointing microscopic imager (Microcam). Acquire local area GPR	Fully document landing site. Mineralogical assay. Subsurface stratigraphy.
<b>Station A</b>	Photo-document a wide variety of basalts and other more exotic (perhaps more anorthositic or glassy) materials at the contact zone between the inner hummocky facies and the outer smoother ejecta facies of Hadley C. Take variety of high-resolution close-up surface stereo images. Take 360° pancam and multi-spectral images of the ejecta blanket from Hadley C; take 360° lidar scans of terrain; take microcam images. Acquire local area GPR scans. Carry out multi-spectral analysis of surface materials.	Examine ejecta material from Hadley C, which may well include materials from the Apennine Bench Formation or other materials (e.g., slump materials from Montes Apennines) that may underlie the volcanic lavas of Palis Putredinis in which Hadley Rille was formed.
<b>Stations B and C</b>	360 degree pancam; 360 degree lidar scans; microcam images of surface materials; Perform multi-spectral analysis; Acquire local area GPR scans;	Examine ejecta, which is expected to include materials from deepest part of crater Hadley C excavation into rille—and perhaps material below rille floor.
<b>Stations D and E</b>	360° pancam; Several microcam images; multi-spectral analyses; lidar scans (360° coverage); Acquire local area GPR scans;	Examine top of ejecta deposited into Hadley Rille. Reconnoiter safest and geologically most interesting route up rille wall to surface of Palis Putredinis for traverse across to the Apennine Front massif east of the rille.

<b>Stations F and G</b>	Traverse eastern wall of Hadley Rille. 360 <sup>0</sup> pancams; multi-spectral analysis; Lidar scans along rille and across rille wall and across rille to other side; Microcam images along way of surface materials.	Reconnoiter alternate route for crew traverse into (and/or out of) Hadley Rille: N-S from top of Hadley C ejecta blanket.
<b>Stations H and I: Along crest of rille wall</b>	360 <sup>0</sup> pans that will include across rille and massif of Apennine Front; pans to include details of critical planned stations for Astronaut EVA; Lidar scans covering 360 <sup>0</sup> total field-of-view; Microcam images; multi-spectral analyses; Acquire local area GPR scans.	Document whether surface of uppermost lava flows at rille crest are visible at surface (i.e., regolith thins at crest of rille) as was observed during EVA 3 of the original Apollo 15 mission in 1972. Reconnoiter planned crew descent (looking across Hadley Rille to crew traverse Stations 1 and 2).
<b>Stations J and K: East of rille on lava plans of Palis Putredinis</b>	360 <sup>0</sup> pans that will include across rille and massif of Apennine Front; telescopic pans to include details of critical planned stations for Astronaut EVA; Lidar scans covering 360 <sup>0</sup> total field-of-view; Microcam images; multi-spectral analysis; acquire local area GPR scans.	Photo-document Hadley Rille (alternate vantage points to crew traverse).
<b>Station L: Along contact of Palis Putredinis + base of Apennine Front Massif</b>	360 <sup>0</sup> pans that will include massif of Apennine Front; Hadley Rille and crater Hadley C in distance; Lidar scans covering 360 <sup>0</sup> total field-of-view; Microcam images; multi-spectral analysis; Acquire local area GPR scans.	Extensive photography of rocks and boulders along massif front needs to be carried out in order to document variety of rock types for possible sampling during possible additional astronaut EVA.

## Traverse Planning Datasets

### *ULCN 2005*

Global lunar topography



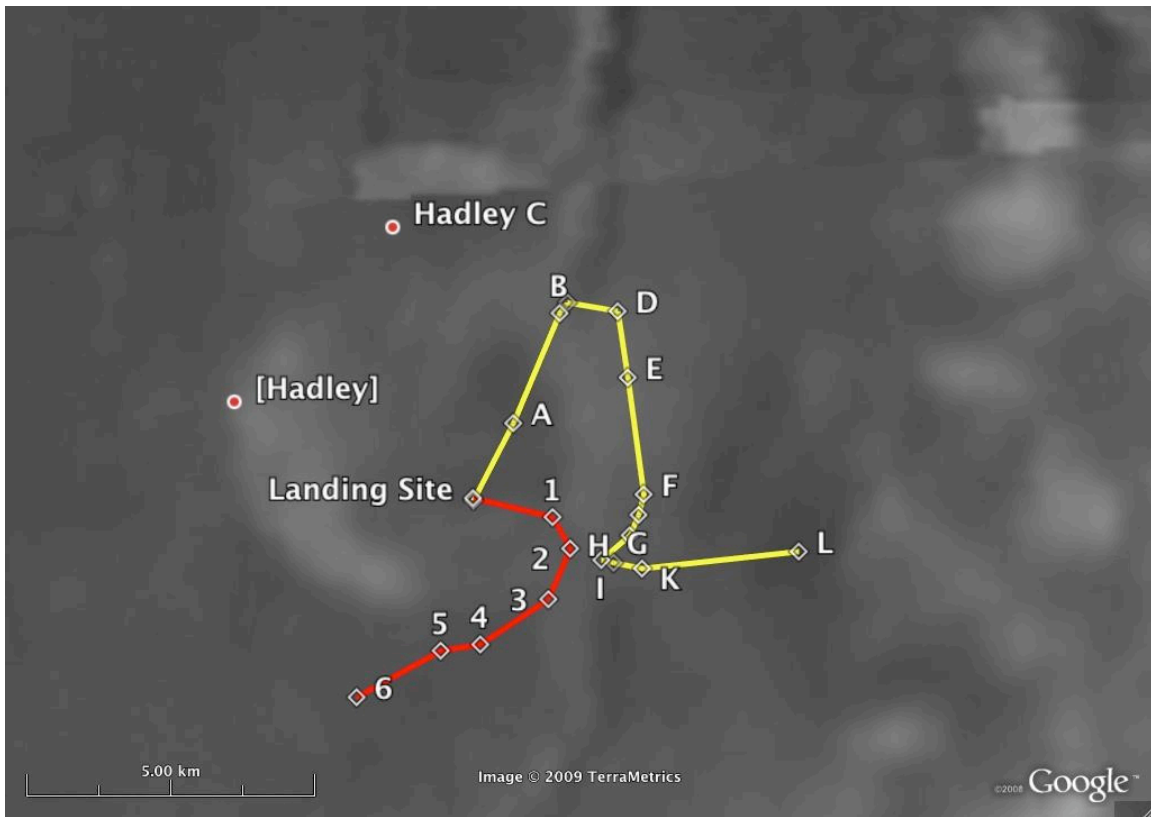
*ULCN 2005 color mapped DEM*

The USGS Unified Lunar Control Network 2005 (ULCN 2005) is the current best source of global lunar topography. The ULCN 2005 serves as the basis for the lunar coordinate system and is based on a least-squares bundle adjustment solution utilizing tie-points in imagery from Clementine, Apollo, Mariner 10, Galileo and Earth-based photographs.

In this layer, the heights in the ULCN have been color mapped and merged with the Lunar Airbrushed Shaded-relief map for visualization in Google Earth.

Credits: USGS Astrogeology Branch; USGS Planetary GIS Web Server (PIGWAD)

*Clementine UVVIS Mosaic*  
Visible image base map



*Clementine UVVIS Base map (100 m/pixel)*

This edition of the USGS Clementine UVVIS (750 nm) base map mosaic has been warped using a 6th order polynomial to the ULCN 2005 control network.

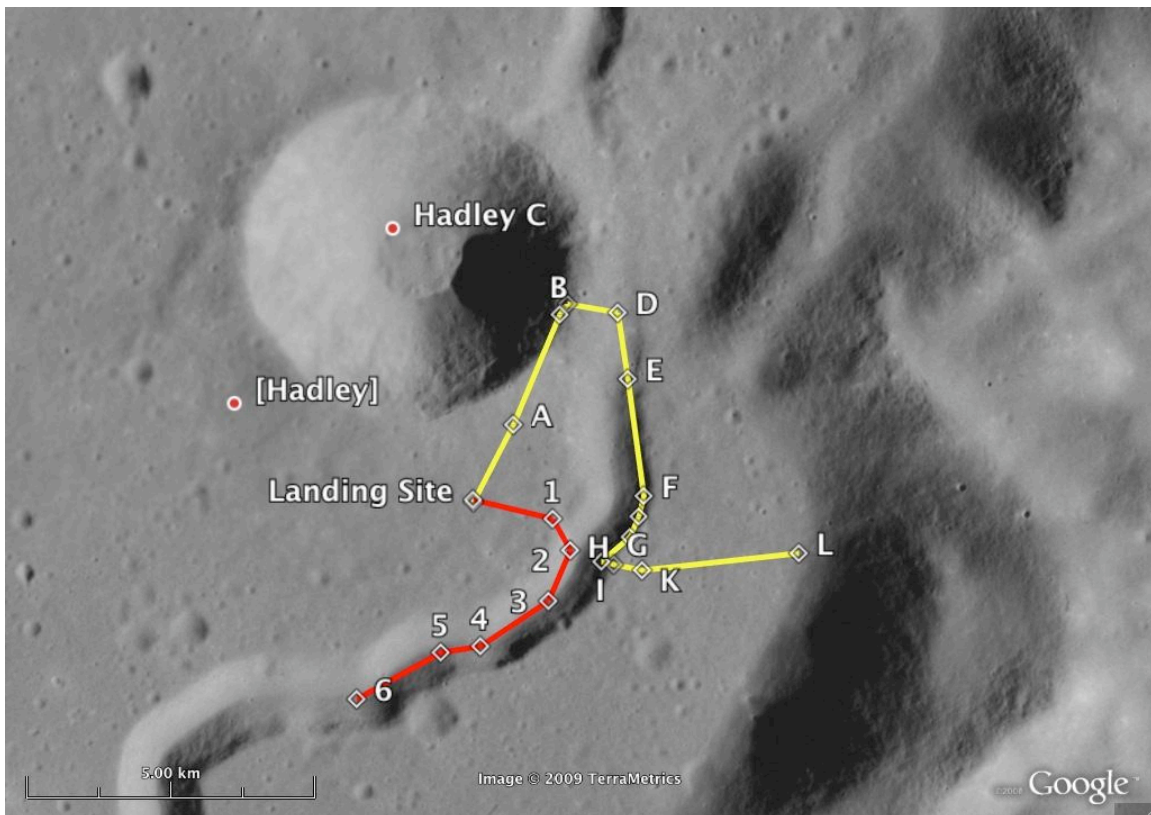
Credit: USGS Planetary GIS Web Server (PIGWAD)

## ***Rima Hadley & Rima Bradley***

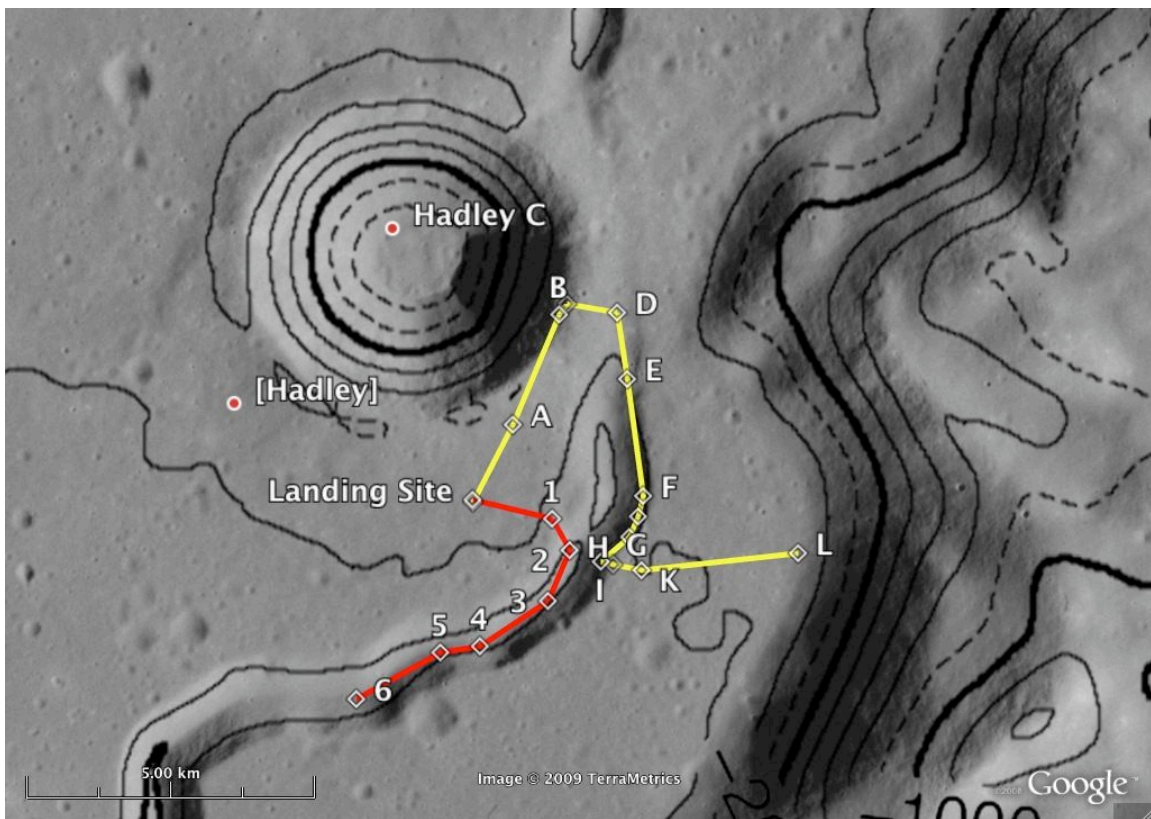
### NASA Ames Automated Stereo Reconstruction

A joint effort between Arizona State University (ASU) and NASA JSC is currently underway to re-digitize the original film negatives from Apollo-era mapping cameras. These new archival scans are of exceptional quality, resulting in digital files that reproduce the full dynamic range (i.e., captures significant detail in highlight and shadow) and resolution of the original film. The scans have also been geometrically controlled and thus are ready for rigorous cartographic analysis.

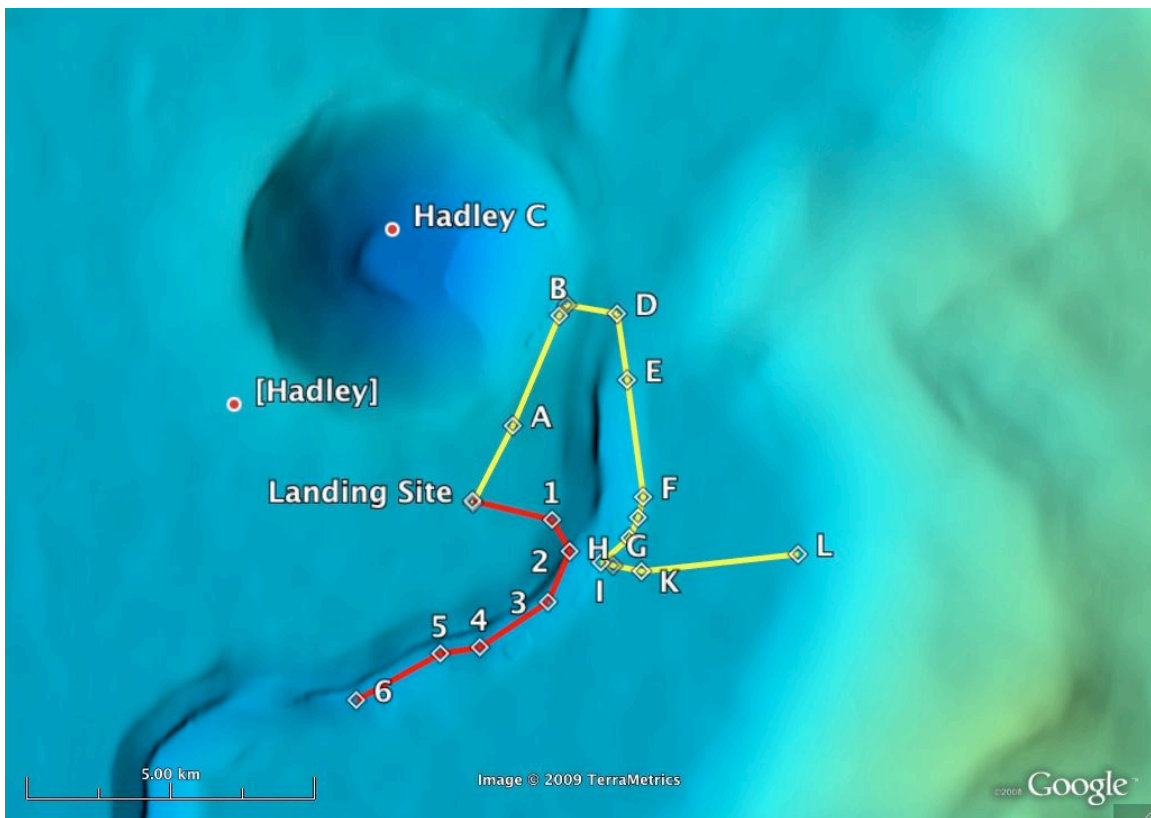
For the lunar traverse planning exercise, we generated image base maps and Digital Elevation Models (DEM) of the Rima Hadley and Bradley region using the Ames Stereo Pipeline (ASP). Adjacent frames from the Apollo 15 Metric Camera imaging system were imported into the USGS Integrated System for Imagers and Spectrometers (ISIS) and then processed using the NASA Ames Stereo Pipeline on an 8-core workstation. Stereo processing took less than an hour and required no human intervention.



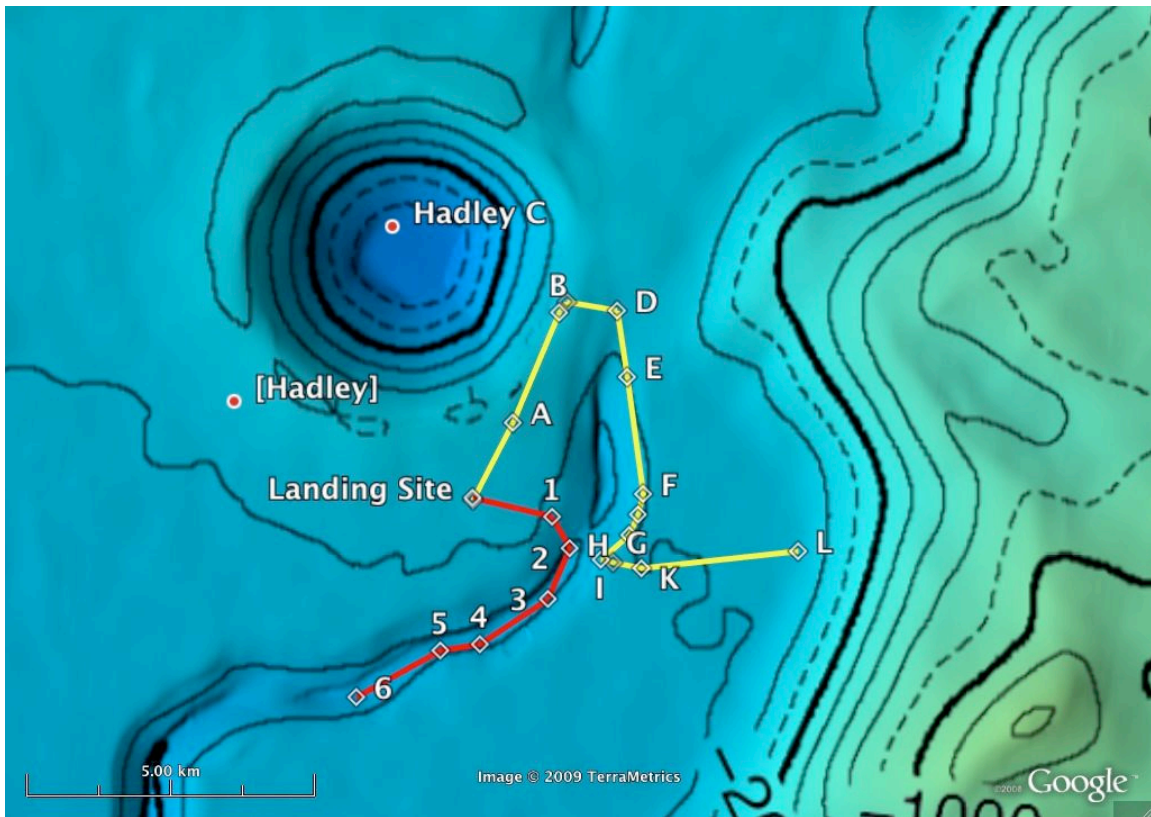
*Apollo Metric Camera image (10 m/pixel)*



*Apollo Metric Camera image (10 m/pixel) with 200 m contours*



*Hill-shaded, colored DEM (40 m/post)*



*Hill-shaded, colorized DEM (40 m/post) with 200 m contours*

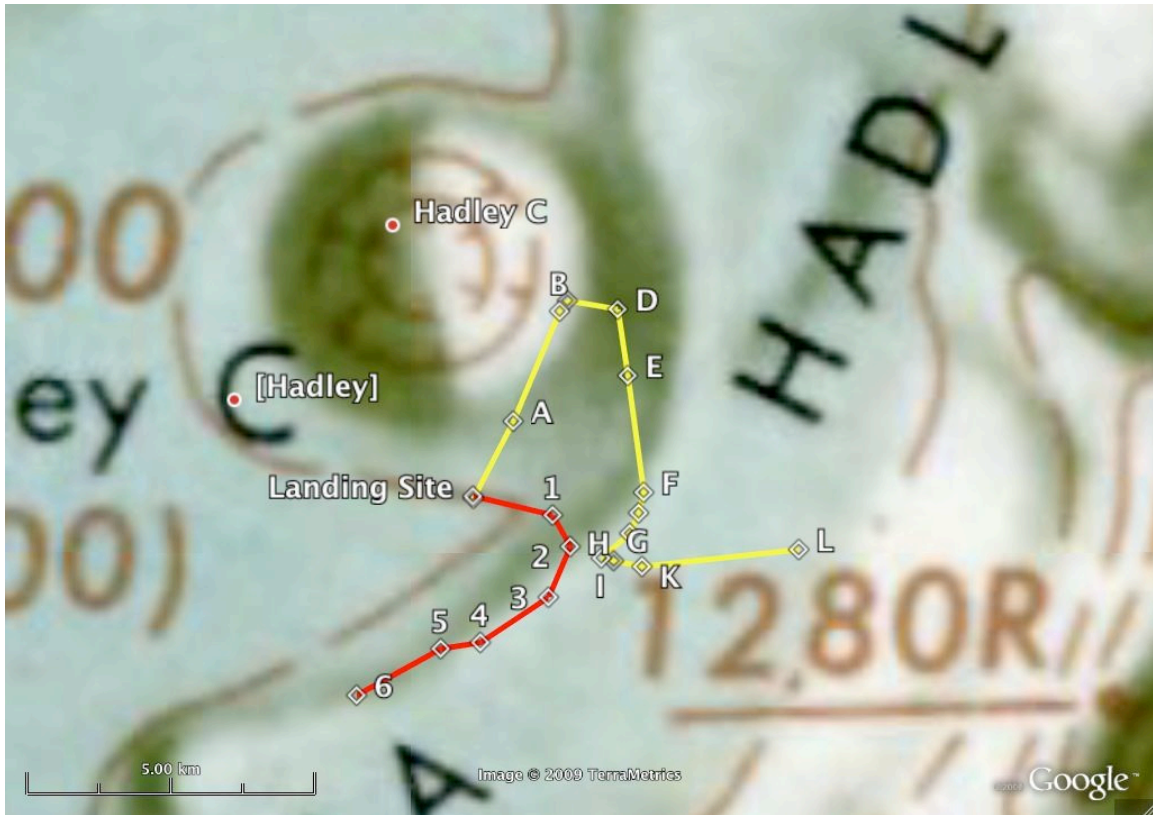
Geo-registration: Preliminary Apollo spacecraft ephemerides were provided by ASU, but these old data contained significant position and pointing errors. Updates were computed via least squares bundle adjustment, thereby improving internal consistency within the stereo pair. Additionally, the images were co-registered with the USGS Hadley Rille Panoramic Stereo Model during the same process. Note: there remains a several hundred meter altitude offset between these NASA Ames-generated maps and the USGS maps due to a difference in the spherical datum reference used.

Source frames: Rima Hadley (AS15 m-1135 and AS15 m-1136) and Rima Bradley (AS15 m-1136 and AS15 m-1137)

Credit: NASA Ames Intelligent Robotics Group; Arizona State University: Apollo Image Archive.

## *Historical Chart: Montes Apenninus*

Lunar Chart (LAC) Series



*Lunar Chart (1:1,000,000)*

The first edition of the 1:1,000,000 Lunar Chart Series was released in January 1967. To this day, it remains one of the most comprehensive sets of printed maps covering the near side of the Moon. The LAC series features topographic contour lines superimposed on top of an airbrushed rendition of the lunar surface.

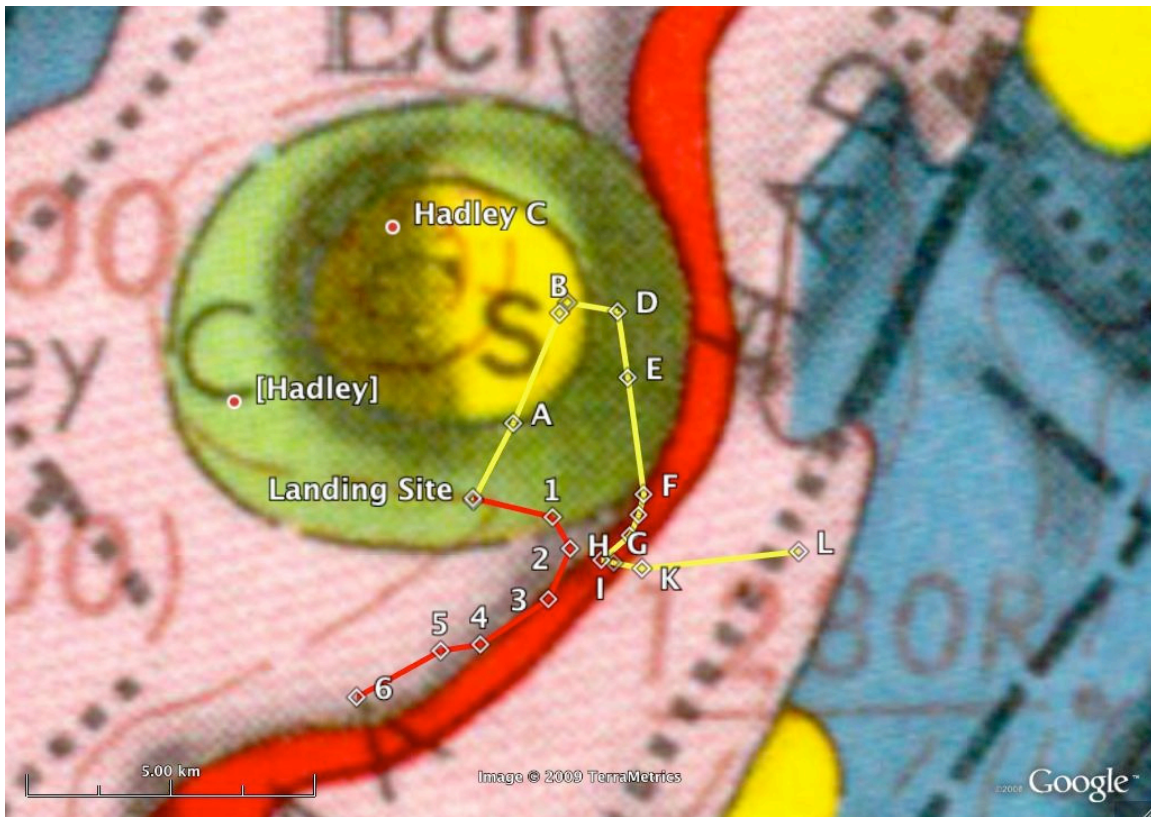
This map covers the Montes Apenninus region of the moon. For other regions, visit the LPI Map Catalog or use the 'Charts' layer in Google Moon ([moon.google.com](http://moon.google.com))

Please note: The map in this overlay has been reprojected for use in Google Earth. The (now historical) information in the map collar may no longer be accurate.

Credit: The Lunar and Planetary Institute (LPI) Map Catalog



**Geology: Montes Apenninus**  
Geologic Atlas of the Moon



*Geologic Atlas (1:1,000,000)*

The 1:1,000,000 Geologic Atlas of the Moon was released in 1963. Though still useful as a comprehensive sets of geologic maps covering the near side of the Moon, the scientific interpretation contained herein should be considered historical, having in some cases been superseded by more modern geologic analysis.

This map covers the Montes Apenninus region of the moon. For other regions, visit the LPI Map Catalog or use the 'Charts' layer in Google Moon.

Please note: The map in this overlay has been reprojected for use in Google Earth. The (now historical) information in the map collar may no longer be accurate.

Credit: The Lunar and Planetary Institute (LPI) Map Catalog

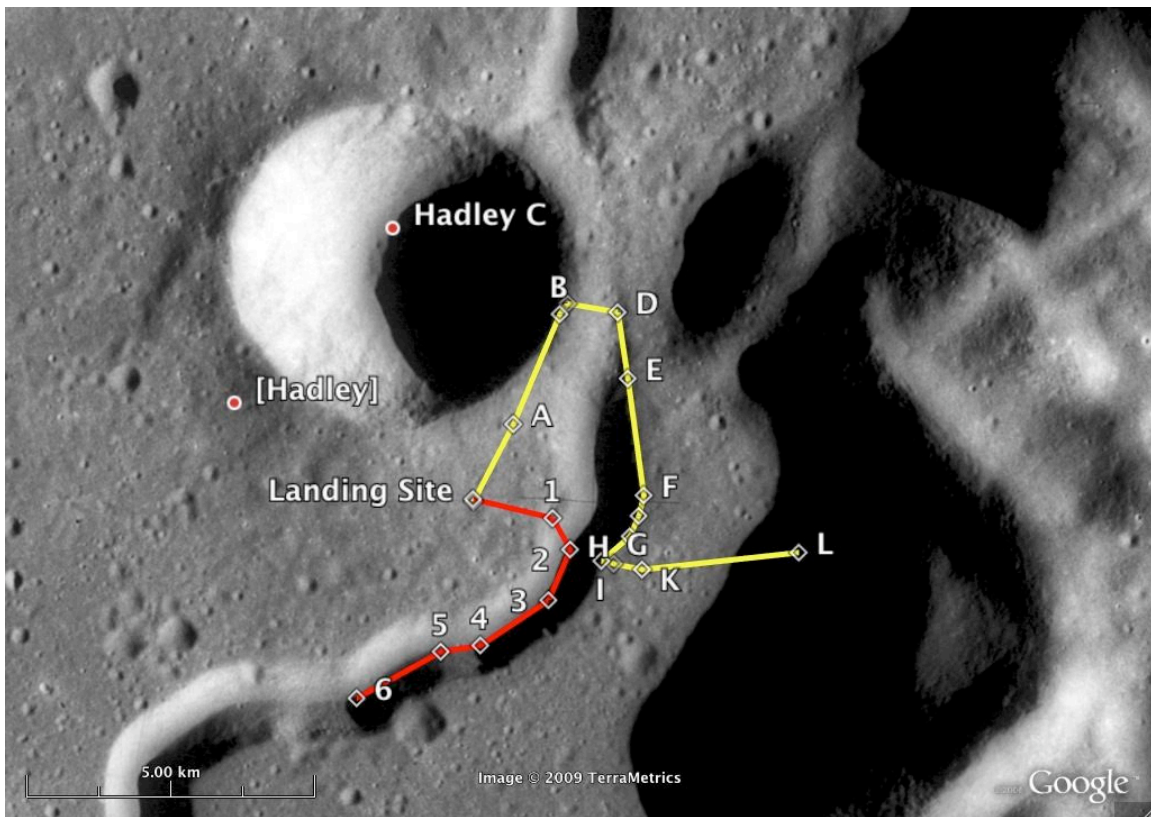
## ***Hadley Rille Stereo Models***

### **USGS Apollo 15**

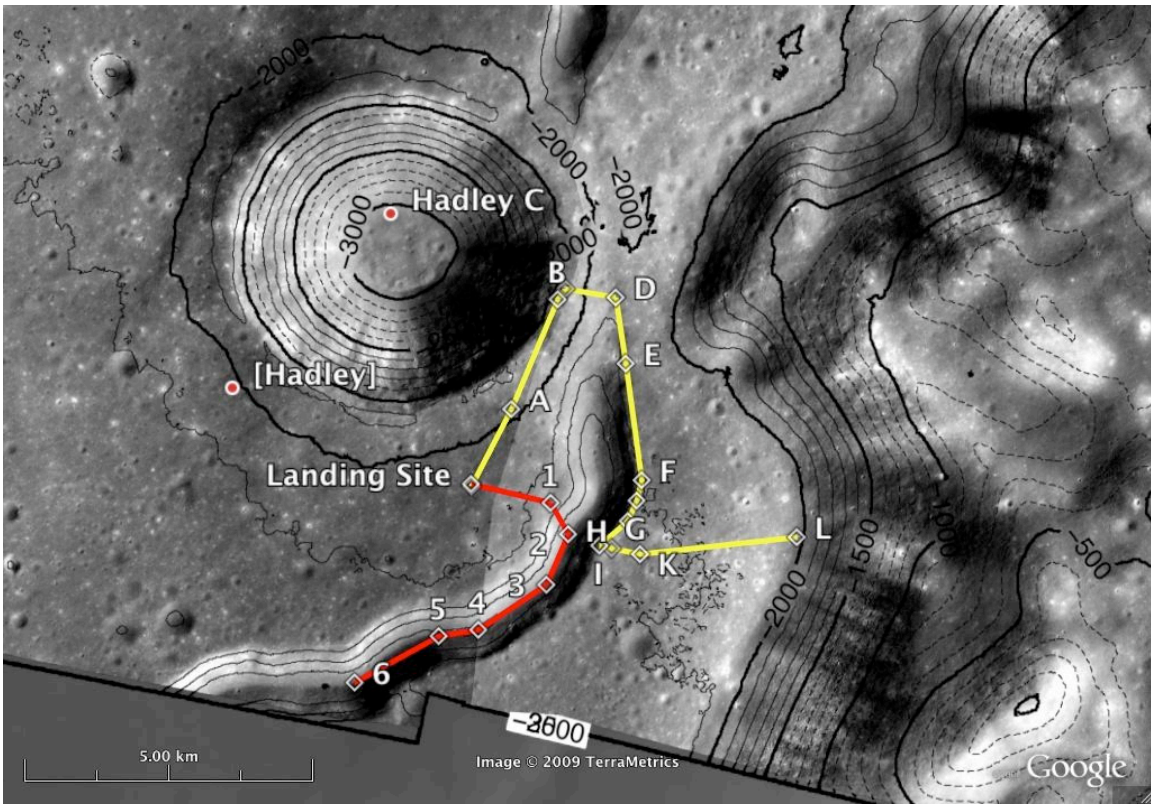
The images and DEM's contained in this collection were generated by the USGS using scans of Apollo Metric & Panoramic Camera film. Stereo reconstructions were carried out on a BAE Systems SOCET SET stereogrammetric workstation. The original data for these maps can be downloaded from the USGS PIGWAD server. Raw data files produced by the USGS were converted into the following:

1. Visible Image: The original full-resolution Apollo image (Metric camera: 15 m/pixel, Panoramic camera: 2 m/pixel), orthoprojected onto the underlying DEM.
2. Visible Image + Contour: Same as above, with superimposed contour lines (Metric camera: 200 m, Panoramic camera: 100 m)
3. Color DEM: A hill-shaded, colored rendition of the DEM (Metric camera: 50 m/post, Panoramic camera: 10 m/post).
4. Color DEM + Contour: Same as above, with superimposed contour lines (Metric camera: 200 m, Panoramic camera: 100 m)

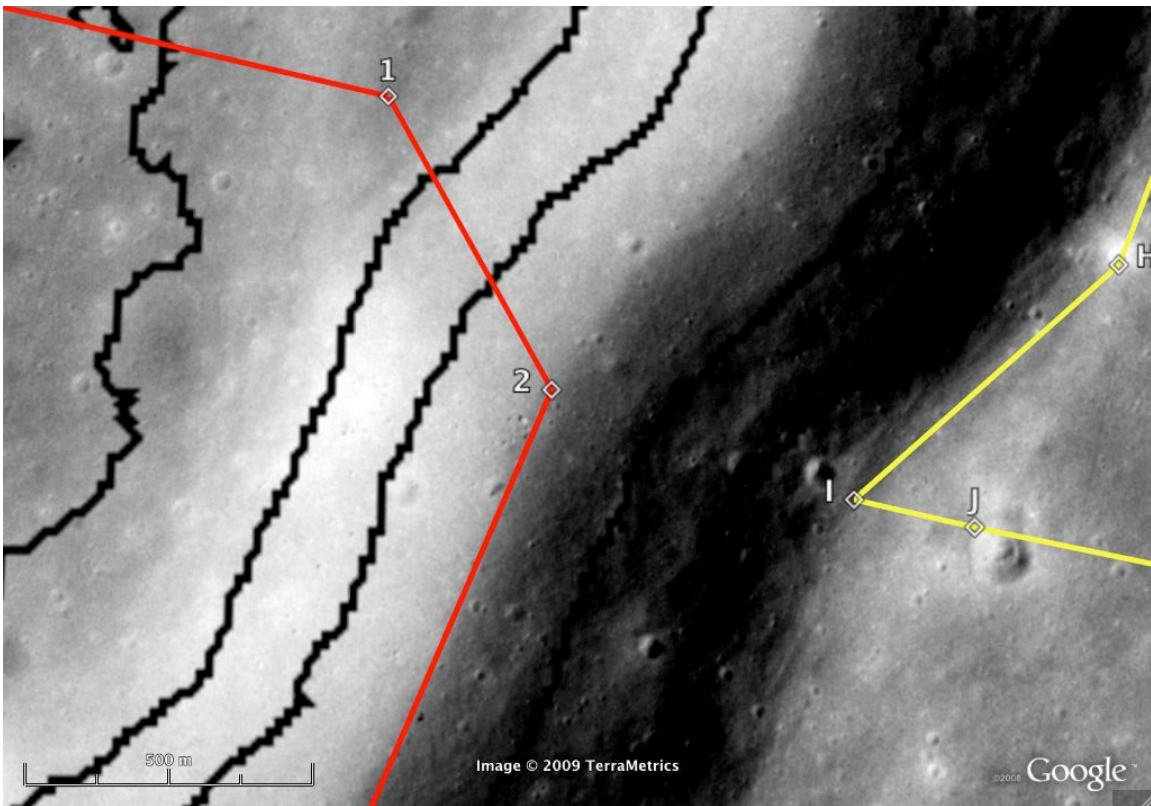
Geo-registration: These images were controlled to an early draft of the ULCN 2005.



*Apollo Metric Camera image (15 m/pixel)*



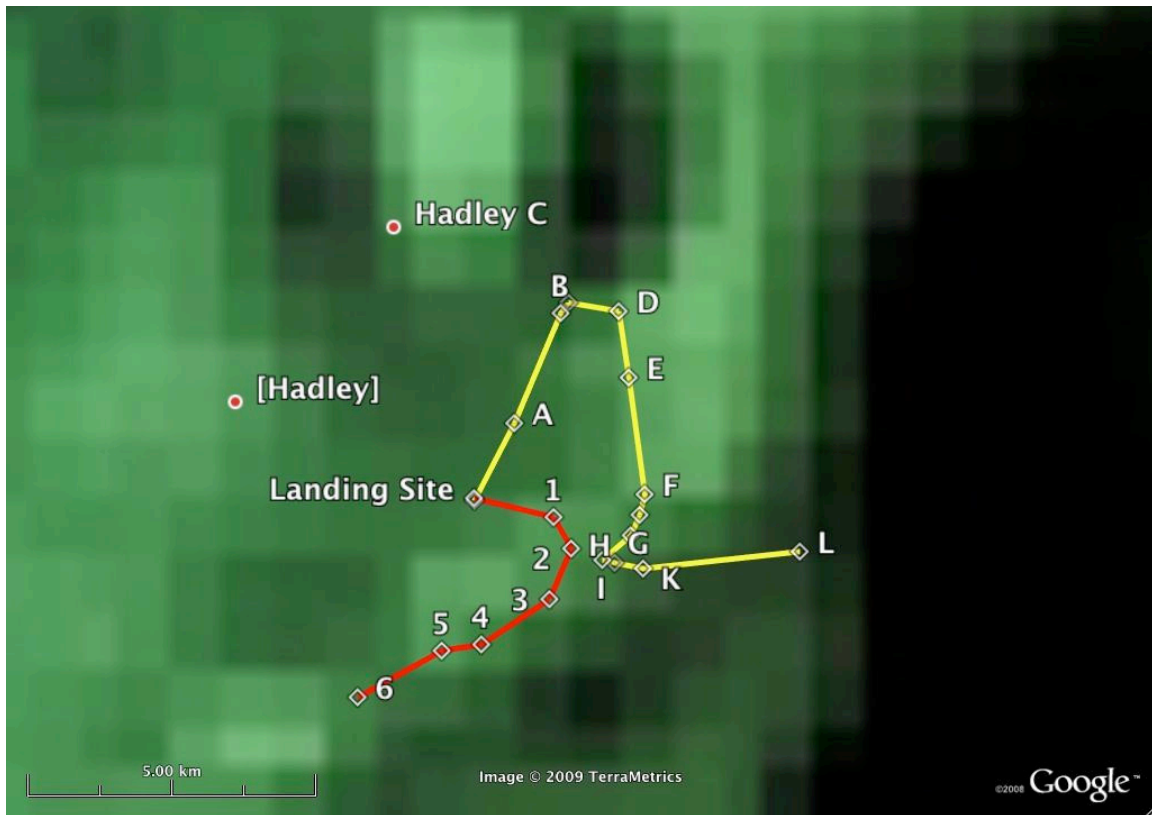
*Apollo Panoramic Camera image (2 m/pixel) with 100 m contours*



*Close-up of Hadley Rille (2 m/pixel) with 100 m contours*

Credits: USGS Astrogeology Branch; USGS Planetary GIS Web Server (PIGWAD)

*USGS Map-a-Planet*  
Supplementary Maps



*Clementine lunar color-coded LIDAR topography (100 m/pixel)*

This collection contains supplemental base layers (mostly derived from Clementine imagery). These layers were converted to KML from the USGS Map-a-Planet lunar WMS server and include:

1. Moon Named Features
2. Clementine Greyscale Basemap
3. Lunar Color-Coded LIDAR Topography
4. Clem-UVVIS Color Ratio Map
5. Clem-UVVIS Multispectral Mosaic
6. Clem-NIR Multispectral Mosaic
7. Lunar Shaded Relief

Credits: USGS Astrogeology Branch; USGS Map-a-Planet

## **Conclusion**

When the new lunar surface campaign begins around 2020, it will be important to make use of technological developments (high-resolution remote sensing, teleoperated planetary rovers, etc.) that have occurred since the end of the Apollo program. Robotic recon, for example, has the potential to significantly improve science return from the lunar surface. In particular, our planning exercise for “Apollo 15B” demonstrates how recon can aid plan prioritization, can supplement and complement remote sensing, and can assess hazards and routes to reduce operational risk.

## **Acknowledgements**

We thank Mark Robinson for the high-resolution scans of Apollo Metric Camera images. This work was partially supported by the NASA ESMD Lunar Mapping and Modeling Project.

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<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>	
<b>a. REPORT</b>	<b>b. ABSTRACT</b>	<b>c. THIS PAGE</b>			<b>19b. TELEPHONE NUMBER (Include area code)</b>	