National Aeronautics and
Space Administration

white paper
2023 Moon to
Mars Architecture

Safe and Precise Landing at Lunar Sites

I. Introduction

The Artemis missions will land astronauts on the lunar surface to leverage the unmatched capabilities of human explorers. These landings will commence long-term exploration and utilization of the Moon by NASA, industry, and international partners for the benefit of all.

With humanity's impending return to the lunar surface, precision landing of human spacecraft on the Moon's surface is a fundamental challenge. The ability to land in proximity to the specific sites with demonstrated value for exploration, commerce, and science will be critical to achieving our Moon to Mars Objectives. Precision landings will enable spacecraft to avoid hazardous features, promote crew safety, co-locate infrastructure, and increase science and exploration returns.

This paper introduces the mechanics of and methodologies for precision lunar landing and explains critical aspects of landing, including vehicle navigation capabilities, plume-surface interactions, geospatial considerations, and science-related needs.

2. Safe and Precise Landing: What Does it Mean?

Precision landing generally refers to the process of navigating a spacecraft to a safe landing location in close proximity to a specified target. For example, a precision landing could be qualified as a requirement to safely touch down within 50 to 100 meters of a given target on the lunar surface.

Precision landing is often coupled with hazard avoidance, resulting in the term "precision landing and hazard avoidance" (PL&HA). Implementing PL&HA systems on a spacecraft enables the landing of multiple assets within a targeted surface region or landing zone while avoiding collisions and limiting damage to existing surface assets. This mitigates the risk of unsafe touchdown for new landers and reduces post-landing travel distances between surface assets.

Literature on PL&HA often conflates precision landing to also imply safe and/or accurate landing. While both precision and accuracy are measurements of error in landing, precision is the measurement of how close landings are to one another, whereas accuracy is a measurement of how close they are to their intended target.

Both accuracy (offset error from truth) and precision (uncertainty of the offset) are crucial for ensuring successful lunar missions, as they allow scientists and engineers to select specific landing sites of interest that better meet science or resource exploration objectives. For the remainder of this paper, the terms "precision landing" and "PL&HA" will be synonymous with safe, precise, and accurate landing.

3. Science Purpose and Needs

Landing at precise locations will help NASA meet lunar science objectives by guiding explorers closer to scientifically rewarding areas on the lunar surface. The Apollo Program demonstrated that landing human explorers near specific geologic features dramatically improves science return. The Apollo missions resulted in paradigm-shifting science discoveries that transformed our understanding of the Universe.

Proximity increases efficiency, effectively utilizing precious crew time and enhancing the quality and accuracy of data collection. That improvement in data collection enables researchers to gain deeper insights into the Moon's history, composition, and geology.

With the limited duration of extravehicular activities, landing in regions that meet illumination and communications requirements and optimizing proximity to areas of scientific interest will be critical to returning precious lunar samples to Earth for further analysis. Furthermore, precision landing near resource- and volatile-rich zones will help us understand and utilize the Moon's resources.

In addition, coupling precision landing with a hazard detection and avoidance system enables the lander to more accurately maneuver clear of hazardous obstacles. An effective PL&HA system could select landing sites with more benign surface conditions to improve lander touchdown stability.

Such a system could also offer mitigation strategies for plume-surface interactions (PSI), where the exhaust from a lander kicks up lunar dust, or regolith. This could help minimize the hazard that ejected regolith poses to surface assets and prevent contamination of scientific areas of interest.

4. Surface Architecture

Precision landing can enable aggregation of surface assets in closer proximity, improving efficiency and risk posture. Whether using robotics or crew members to transfer logistics items, a reduction in distance means a reduction in transfer time and risk.

As an example, landing a logistics module closer to a habitat module would ease the transfer of items from one module to the other. Keeping assets within extravehicular activity walking distances or within rover mobility distances enables efficiency of time spent on science and utilization.

As the number of government and commercial landers on the surface increases, there will be a critical need to ensure that associated keep-out zones are respected. Precision landing capabilities can help achieve this. Additionally, knowing the final, accurate location of the landed asset will enable planning for landing additional assets.

While enabling co-location of surface assets can be beneficial, there are also potential risks. The larger the engine, the higher the potential for PSI events that could damage existing surface assets. There is little lunar atmosphere to slow PSI ejecta during landing, and lunar regolith is essentially shrapnel from meteors impacting the surface without the weathering that takes place on Mars or Earth. While precision landing and close asset aggregation reduce transit times, surface assets will have to mitigate against PSI ejecta, which may require asset hardening.

5. Navigation Capabilities

Consider a typical lunar deorbit, descent, and landing trajectory. A deorbit burn inserts the lander from a low lunar orbit to a transfer orbit with a low periapsis (e.g., 15–20 kilometers). Powered descent initiation occurs at or near periapsis and begins with a braking phase designed to reduce lander velocity as efficiently as possible.

During powered descent, the lander transitions to an approach phase where attitude and altitude ranges permit the use of landing sensors and pilot visual contact with the landing site. At the end of the approach phase, the vehicle is directly above the target landing site and terminal descent begins, with the lander approaching the lunar surface until touchdown.

Throughout these phases, the onboard navigation system must provide accurate and precise estimates of lander position, velocity, and attitude so that the guidance and control algorithms can plan and execute maneuvers that deliver the vehicle to a safe touchdown in close proximity to the target site.

Navigation systems can include an assortment of components: software algorithms, onboard sensors, celestial navigation tools, maps of terrain features, and other devices for external measurements. Over the years, NASA has performed numerous studies and developed many relevant technologies[1] for precision landing through projects such as Autonomous Landing and Hazard Avoidance Technology (ALHAT)[2] and Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE).[3]

The ongoing SPLICE project has been tasked with advancing the technology readiness levels of key deorbit, descent, and landing guidance, navigation, and control systems. The project is also implementing simulation tools for conducting navigation sensitivity and performance studies for autonomous precision landing.

Findings from focal SPLICE navigation studies[4,5] demonstrate how improved physics-based engineering simulations and modeling fidelity can enable rapid, detailed assessments of the integrated performance of these systems. These simulation tools can evaluate the effectiveness of different navigation sensors on overall

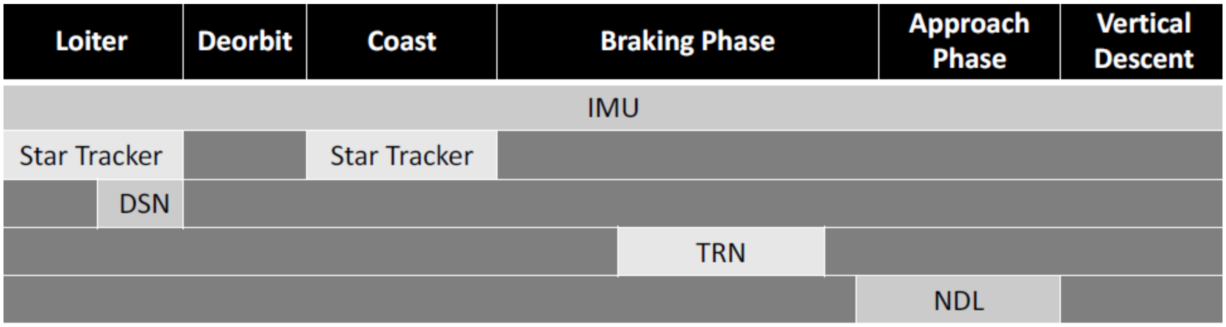

Figure 1. *: Sensor Assumptions Modeled from Lunar Orbit to Vertical Descent [2]. Acronyms: DSN (Deep Space Network), NDL (Navigation Doppler Lidar) velocimeter, TRN (Terrain Relative Navigation), IMU (Inertial Measurement Unit)*

system performance. Sensors that can be integrated into these analyses include an array of inertial and relative sensors on which navigation systems would rely, such as accelerometers, gyroscopes, star trackers, altimeters, velocimeters, terrain relative navigation systems, and hazard detection systems. Figure 1 shows active sensors during particular deorbit, descent, and landing phases in an example scenario.

Powered descent is a short-duration event (approximately 10 minutes). Utilizing Earth-based ground tracking updates for vehicle navigation during powered descent is not feasible due to the turnaround time required to process Earth-based tracking measurements and then communicate them up to the spacecraft. Instead, this phase relies on a lander’s onboard sensors.

Terrain relative navigation matches real-time observations of the lunar surface (e.g., camera images for passive navigation and lidar/radar surface contours for active navigation) to pre-flight maps stored onboard. Terrain relative navigation capabilities can improve lander state knowledge from the initial deorbit and braking burns.

Onboard maps are derived from orbital reconnaissance imaging and digital elevation models generated prior to a mission. Verification and validation of these pre-flight maps are critical to the success of terrain relative navigation. Passive approaches utilize cameras that require surface illumination from the Sun, as well as surface maps obtained or rendered with similar illumination conditions. Active approaches utilize a sensor like lidar or radar that do not require solar surface illumination for imaging; this approach obtains contour maps during descent that are then matched against onboard digital elevation models.

Additional architecture systems such as orbital communications relays, Global Navigation Satellite System (GNSS) signals, ground references, or surface beacons can also help support navigation capabilities for precision landing.[6,7]

6. Geospatial Aspects and Hazard Detection & Avoidance

The lack of an Earth-like atmosphere on the Moon means that even small meteorites impact the surface. This results in regolith heavily covered with impact craters and ejecta of varying sizes. These impact craters, ejecta, and other surface features (e.g., exposed uneven bedrock) present hazards to landers, which typically will have some maximum hazard size and surface slope that can be accommodated by landing systems (e.g., landing gear/mechanisms, footpads).

Lunar surface geospatial data and analysis play a pivotal role in mitigating these hazards. Coordinated data fusion of relevant planetary mission datasets enables detailed evaluation of candidate landing sites. Mapping increases the likelihood that a safe landing can occur in a given surface region.

These analyses examine data to assess terrain types, identify hazards, and evaluate surface illumination conditions. Current knowledge of surface features based on direct observations at proposed Artemis landing sites remains at the scale of meters per pixel. High-resolution mapping techniques such as shape-from-shading[8] may be used to enhance imagery and improve landing site characterization for hazard avoidance planning.

Every lander has engineering constraints related to the size and characteristics of potential hazards that can be overcome during a safe landing. Given enough data from landing site observations and lander capabilities, an informed trade between pursuing further site knowledge versus investing in further lander robustness can be made.

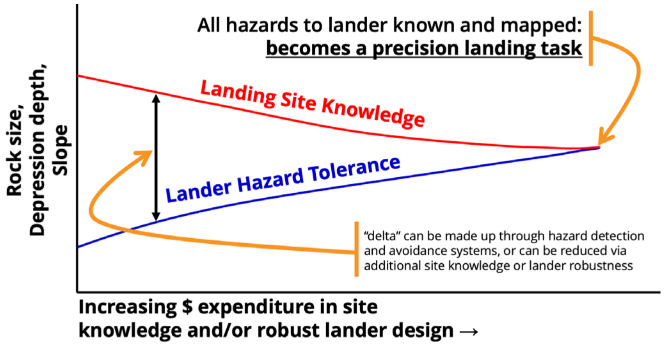

Figure 2. *Site Knowledge vs. Lander Tolerance Continuum*[7]

The trades between lander robustness — a local hazard accommodation size for a given lander — versus site knowledge — the available resolution of features and hazards at a desired landing site — can be summarized as follows:

1. Improved hazard size accommodation by the lander (e.g., through a landing gear redesign)
2. Improved orbital mapping resolution of the desired landing site to identify smaller hazards (e.g., through better or increased orbital observations of the area)
3. Implementation of an onboard hazard detection and avoidance system

The first two options are often constrained by program resources, schedule, and vehicle margins (e.g., maximum size and mass of the lander given launch vehicle constraints or remaining propellant onboard a lunar orbiter for obtaining closer images of targeted landing regions). The third option may be relatively lower cost since it does not require a vehicle redesign or additional mapping from orbiting assets.

A balanced mix of all three options will aid in achieving NASA’s Moon to Mars Objectives. Observations by NASA’s Lunar Reconnaissance Orbiter and other missions have characterized the lunar surface environment very well. These data can inform hardware design choices quantitatively.

NASA has identified a need for a continuous lunar observation capability to preserve and enhance Lunar Reconnaissance Orbiter capabilities. These would be provided through follow-on NASA and/or commercial missions, enabling continued surface situational awareness for planned lunar activities. In addition, international partner missions are collecting valuable datasets that can be leveraged as more nations conduct lunar surface observations.

Hazard detection and avoidance systems can be passive or active, consisting of either:

1. An optical camera able to passively image illuminated localized hazards and indirectly detect them via shadow detection and feature identification algorithms.
2. A lidar able to actively image illuminated, shadowed, or unlighted hazards and directly detect them from point-cloud range data. An onboard hazard avoidance system would use this information to determine a safe landing location within lander performance margins.

Hazard detection may also be coupled with terrain relative navigation systems, either by sharing imaging hardware or through software algorithms.

The needed capability to process orbital lunar surface data to a resolution that provides adequate pre-mission hazard mapping varies by location on the Moon. Some regions will require a lander to have a higher hazard tolerance or higher hazard avoidance capability than others — even with tightly resolved features — due to the size of the hazardous features on the surface. The Moon to Mars Lunar Surface Data Book [9] describes the process to resolve features, assumptions made, and modeling analyses.

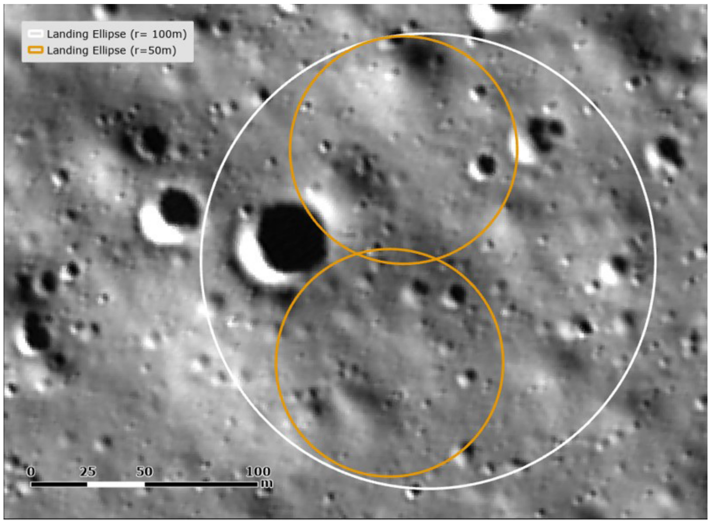

Figure 2. *: r=100m Landing Ellipse vs. r=50m Landing Ellipse (Artemis Geospatial Data Team)*

With the variability of surface crater and hazard size and distribution on the lunar surface, geospatial analyses generally focus on identifying zones with relatively safe landing conditions. In general, greater precision landing capabilities enable access to more surface sites, since smaller areas can be assessed to determine if hazards are present.

Figure 3 includes an example of hazard avoidance by reducing the radius from 100 meters to 50 meters. In the image, the 100-meter-radius ellipse contains one large crater with potentially unsafe landing conditions. However, the 50-meter-radius ellipses can remain safely outside the large crater while still allowing a close enough distance for trips to the crater region, if desired.

7. Plume-Surface Interaction (PSI)

PSI results from rocket engine exhaust interacting with a planetary surface during descent, landing, or ascent.

The Apollo missions experienced regolith ejections that obscured views of the landing site during final approach and touchdown. Apollo 12 sandblasted the Surveyor 3 lander located 155 meters away. Apollo 15 landed on a crater slope, very nearly violating the tilt limit for safe ascent and sustaining structural damage to its descent engine bell, which would mean not being able to re-use that engine for ascent.

The Mars Science Laboratory eroded significant craters with its Skycrane engines. Mars 2020 Perseverance's descent and landing footage showed high-velocity debris and dust that completely obscured the cameras during touchdown. Both the Mars Science Laboratory and Perseverance showed evidence of debris impact damage.

These past missions indicate that PSI can impact safe, precise landings and negatively affect landing sensor performance. Potential risks from PSI vary with lander configuration, concept of operations, and landing site. Many new lunar lander designs use the same vehicle to descend to the surface and later ascend back to orbit (i.e., single-stage) and are significantly larger in size than those flown by Apollo. They also have very different operations, which could result in a very different induced-hazard potential from Apollo.

NASA currently lacks direct in-situ measurements of PSI phenomena, leaving predictions largely qualitative and uncertain. Validation and model improvements require ground testing and in-situ data.

NASA has conducted small-scale vacuum tests with different types of simulated regolith and plans to conduct more complex testing in the coming years to reducing PSI risk for the Human Landing System. The tests would allow the agency to improve models that currently rely on Apollo flight reconstructions.

In addition, upcoming Commercial Lunar Payload Services missions aim to capture PSI data using stereo cameras. These cameras will image the area under the landers during descent and touchdown.

These observations represent a first step in understanding ejecta size and velocity on the lunar surface, which will be crucial to understanding surface asset proximity limitations, what risks exist, and how to mitigate those risks. Various technology efforts are planned or underway across NASA, industry, academia, and international partners for PSI testing, in-situ sensor development, and modeling advancements.

8. Conclusion

Precision lunar landings have become increasingly important as space agencies and private companies aim to establish a robust, long-term presence at the Moon. Though there are many technical challenges to overcome, precision landings represent a pivotal advancement in space exploration technology. The potential benefits include enhanced safety for crewed missions, optimal targeting of scientifically valuable sites, and minimizing site contamination risks. Precision lunar landings will empower scientists to better study specific geological features, conduct experiments, analyze lunar soil, and gather valuable data about the Moon’s composition, history, and potential for future human exploration or resource utilization.

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